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Advances in Materials Technology: MONITOR

Issue Number 4 May 1985

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Dear Reader,

This is the fourth issue of UNIDO's state-of-the-art series in the field of materials entitled Advances in Materials Technology: Monitor. This issue is devoted to powder metallurgy and is addressed to a select target audience of policy makers, scientists, technologists and industrialists in developing countries.

In each issue of this series, a selected material or group of materials will be featured and an expert assessment made on the technological trends in that field. In addition, other relevant information of interest to developing countries will be provided. In this manner, over a cycle of several issues, materials relevant to developing countries could be covered and a state-of-the-art assessment made, hopefully every two years.

The first issue was devoted to steel and dealt in particular with high strength, low alloy (HSLA) steels. The second issue was devoted to new ceramics, also known as fine ceramics, high-performance ceramics and advanced ceramics. The third issue dealt with fibre optics. UNIDO has received good response on the content of these issues as well as on the idea of a monitor on materials.

This issue is devoted to powder metallurgy and contains four articles written by experts in this field. Mr. Edward Epremian, former Special Technical Adviser and Special Assistant to the Executive Director of UNIDO on Energy, who is now a consultant to UNIDO, is one of the contributors to this monitor. Mr. Epremian provided valuable suggestions on the substantive aspects of this series of monitors. A current awareness section includes information on developments in powder metallurgy processes and market trends. A list of publications and information on meetings are also contained in this issue.

The UNIDO secretariat would welcome information on materials and suggestions on the format and content of this issue from readers.

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CONTENTS

CURRENT AWARENESS

Developments in powder metallurgy processes

Comparison of powder metallurgy with other processes

"Comparing PM with other mechanical processes, the fact that it is a substitution process is certainly important. Most of the PM parts have been designed for another process. Some 20 to 30 years ago this was a strength, since the PM process is often a very cheap route and the selling prices were based on the cost of machined parts. Let me say, just as a reminder, that we had produced one part for 30 years with the same selling price, up to 1975. Now its price follows industrial inflation and is produced with no cost benefit.

"The fact that it is a substitution process is now a weakness since those parts for which the competition against machining is easy are made in many plants and sold at the PM market price. For new parts, practical tests are made with ordinary materials obtained by casting, forging, machining, etc.; and then the sintered part is considered valid only when the reduction in price is around 30%, since every customer thinks that new tests are necessary.

"When, by chance, the parts have been designed initially for the PM process, their replacement by an ordinary material is supposed not to cause any problem, and the rival is then considered advantageous with the smallest price difference.

"Hence comes the problem of the mechanical properties of sintered parts and of the knowledge of these properties.

"Varied experience has shown that the behaviour of PM parts is better than can be anticipated by comparing their mechanical properties with those of the other materials; superior wear behaviour is among the 'strengths' of the sintered parts. Unhappily, it is difficult to persuade the customers, since they compare the usual properties, which are not favourable to PM parts, even though those properties are not relevant in practical working conditions.

"The new concepts K_{1c} and ΔK_s, which can be called the tensile strength and fatigue strength of a notched part, are certainly nearer the working practice than tensile strength, limit of elasticity, or elongation before rupture. PM parts are favoured by these new concepts but they are not commonly applied.

"The one 'weakness' which is very often discussed by customers is the lack of elongation, and unhappily a certain number of serious difficulties have occurred in this area. However, in most applications even a small plastic deformation of the mechanical parts cannot be tolerated and the elongation before rupture is useless. Anynow, all our tests prove that a small amount of plastic deformation is necessary to have reliable performance with sintered parts.

"There are two major European car producers who, after a bad experience through using unreliable parts, have no confidence in PM parts. The average quantity of sintered parts is 1.2 kg/vehicle for these manufacturers, compared with the maximum value of 6 kg and a mean value of 3 kg in Europe as a whole.

"The extension of our knowledge of the properties of PM parts, and more generally of how to appreciate the properties needed for a particular end use, is certainly an important factor for development.

"The two preceding considerations are not responsible for the immediate difficulties of PM, but they determine courses of action which influence the development of the PM industry, and which could be along lines that cover the risk of future business depression. When these courses of action have not been efficient, the PM market has fallen in with the general economic situation, and especially automotive production which accounts for more than 70% of the PM market in Europe.

(Extracted from "Strengths and Weaknesses of Modern PM Production Methods" M. Etudies, Powder Metallurgy, 1983, Vol. 26, No. 2, p. 93. Copyright © 1983 The Metals Society, England.)

Energy conservation in powder metallurgy processes

"There are two principal ways in which powder metallurgy could contribute to energy savings nationally:

(i) through improvements to the overall efficiency of energy use in powder manufacturing and part fabrication from powder

(ii) by substituting material and parts made by powder metallurgy for conventionally made materials and components."

"Taking the above two aspects of energy savings in turn, the principal opportunity for improving the energy efficiency of the PM process lies in improvements to the sintering operation. (Since very little metal powder is produced in the UK, opportunities for energy saving in that direction are not considered). The range of reported energy consumptions for sintering is large, extending from low end estimates of 5-8 GJ/t of components sintered to over 40 GJ/t ... at the upper end. Typical figures tend to lie in the range 10-18 GJ/t ... The literature also suggests that a combination of:

careful furnace operation and control
improved furnace design
lower thermal mass furnaces
nitrogen sintering to replace the conventional endothermic atmosphere derived from natural gas

can yield about 40-50% energy savings, even allowing for energy to produce and store the nitrogen gas for the atmosphere.

"These potential savings could well prove to be beneficial to the profitability of a PM process line, offering contributions of around 2-4p/kg of throughput. However, even if it is optimistically assumed that sintering furnaces can be improved by an average of around 5-10 GJ/t of product, this only offers the prospect of about 2,000-4,000 t of coal equivalent of energy savings/annum nationally (the UK throughput of sintered parts is no more than 12,000 t/year). Putting this figure in perspective, the Department of Energy, in its demonstration and R & D programmes, usually considers only projects which can lead to national energy savings of at least 10,000 t of coal equivalent (tce)/year and many projects have potential effects of over an order of magnitude higher than this.

"The second category of energy savings (point (ii) above) offered by the PM industry is more complex analytically and comes from the replacement of conventionally manufactured metal parts and materials by PM routes. As mentioned above, energy analyses involving powder metallurgy are complicated by the fact that the UK imports the bulk of its powders. However, for the purposes of this paper it will be assumed that some indigenous source of powder may become available to

Table 5. Energy consumption of conventional and powder formed ferrous structural parts

Energy to produce 1 te of various items, GJ/te	
Iron powder from ore, Höganäs route to iron powder	21.7
Sintered parts	
blend/compact	0.5
sinter	5-20.0
finish and miscellaneous	2.0
total	7.5-22.5
Energy for 1 te of finished parts with 98% material utilization = 30-45 GJ/te	
Billet steel from ore	
liquid steel (BOS)	26.5-29
soak/primary mill	1.5-2
finishing mill	3-4
total	31-35
(or, if continuously cast	~25-28)
Forged small ferrous parts from billet	
cold crop and heat for forging	3.5-8.5
forge	0.5
heat treatment and miscellaneous	1.5-3.0
total	5.5-12.0*
Energy for forged parts with 70% metal utilization = 38-54 GJ/te	

* Assuming 100% material utilization, see Fig. 5.

supply new markets in the future. By making this assumption, comparisons between the energy requirements of conventional and powder route components can be made for the UK. Table 5 shows, at a simplified level, that the energy required to produce 1 t of forged parts conventionally is similar to that required to produce 1 te of sintered PM parts assuming both routes use material very efficiently. However, as a number of previous analyses have shown, material utilization in the final stages of conventional manufacturing is much lower than with the powder route. A typical small forged part utilizes about 70% of billet material before machining and for many parts the inclusion of machining to final shape reduces material utilization to under 50%, effectively doubling the energy content of the final part. Clearly, this works in favour of powder metallurgy.

"However, the magnitude of the energy advantage afforded to powder metallurgy can be eroded whenever:

(i) sintering energy consumption is high

(ii) the steel for the conventional parts is manufactured by a continuous casting route.

"These points are illustrated in Fig. 5, which shows that inefficient energy use in sintering could mean that, in energy terms, PM would not start to break even with conventional manufacturing until conventional material utilization falls to around 70-80%.

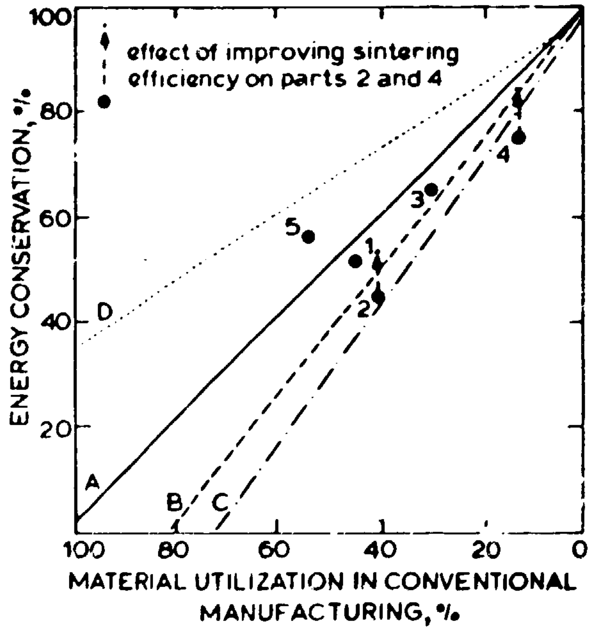
"To show that there is some practical significance to Fig. 5 the relevant parameters for five actual components have been mapped on to the diagram. These are components which were manufactured conventionally and are now formed by PM. Most of these parts actually had more than one forging, heat treatment, and machining operation when they were made conentionally, but they also now have more than one sintering operation in the PM route. Nevertheless, since the need for additional operations appears to affect both manufacturing routes proportionately, the energy savings/material utilization relationship seems to hold tolerably well.

"The above analysis suggests that:

(i) given an efficient use of energy in sintering, the percentage energy savings are approximately proportional to material losses in the conventional manufacturing route

(ii) typical PM parts are probably more energy efficient by about 30-100 GJ/t of parts than conventionally manufactured parts.

Thus, on the basis that the UK manufactures about 12,000 t of parts by PM annually, the industry is probably already saving the UK some 0.36-1.2 million GJ each year (13,000-14,000 tce/year), a worthwhile contribution, and it is at this level of annual energy savings that the Department of Energy's programmes start to focus on new technology. Therefore, if additional markets, comparable to those already exploited, can be opened up, it is in such areas that support might be considered. The opportunities appear to exist and are known to the PM parts manufacturing industry; for example, the development of PM technology for the manufacture of sintered and wrought high duty parts, including medium and high alloy steels, high speed steels and superalloys; the development of sintered powder parts in aluminium and titanium based alloys followed by the sinter forging of these materials. In some of these cases limited production has been achieved already, but there is still room for new ideas to create expansion into the wider markets."



(Extracted from "Prospects for Saving Energy", D.N.E. Rowe, Powder Metallurgy, 1983, Vol. 26, No. 4, pp. 204-205. Copyright © 1983 The Metals Society, England.)

Principal methods for producing aluminium powder

"Between 25 and 30 countries throughout the world are known to have production facilities for aluminium powder. By far the greater proportion of production is spread among a few industrialized countries, some of which employ relatively large plants of 10 kt/year and more capacity. The largest plant has a nominal capacity of 30 kt/year, although this does depend upon the fineness of the powder produced, since it is usual to make very fine powders at a slower rate of output.

"Production covers various forms of powder and a wide span of particle sizes, and includes facilities for producing coarser granules, flake, and other small groups of material. Quality variations may relate to specific production plants, some concentrating entirely on powder from secondary raw materials. This is often dictated by the markets available in the geographical areas which the plants serve. In the more industrialized countries, as one might expect, there is a greater range of quality, both physical and chemical, because of the wider range of applications. The plants in these countries tend to have larger capacities and market their products over a wider area of the world. Some 50-60% of the UK production, for example, is exported.

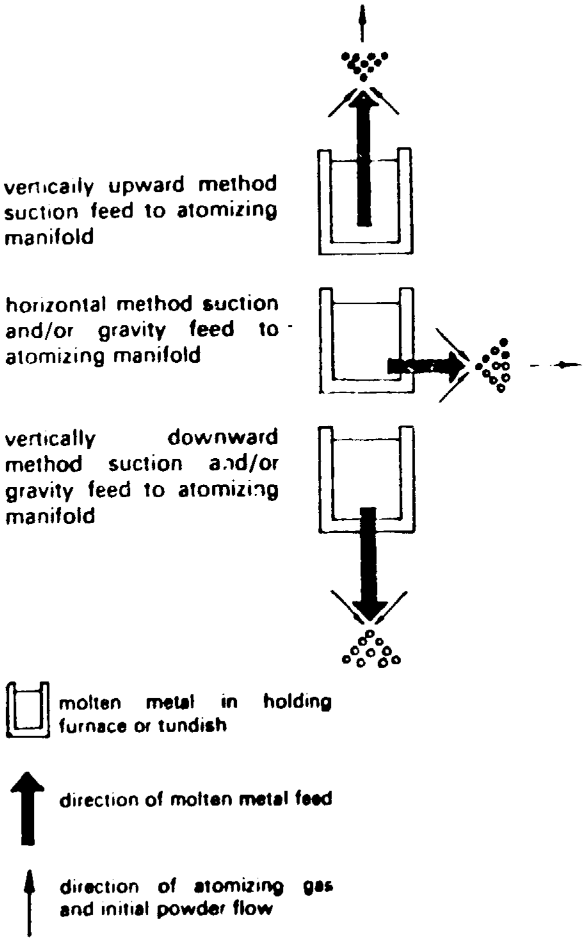
"It is possible to make only very rough estimates of world capacity for the production of aluminium powder in its various forms. The author puts this at around 200 kt/year for all countries excluding the Soviet bloc and China. Again, very approximately, some 40-45% of this capacity is in North America, mostly in the USA; 30-35% in Europe with about one-third of this in the UK; leaving 20-25% in the rest. Much of this capacity is underutilized in the current industrial environment. However, the proportion of underutilization varies considerably from plant to plant and is related to production versatility. More modern plants have usually been designed to manufacture a greater variation of the product, including physical form, chemical purity, and alloy composition. These plants, on the whole, are busier than older installations. There is an important bearing in this fact, both now and in the future, on the availability of aluminium powders which are suitable for PM applications.

"To reduce more massive raw materials, either secondary or primary, to the finer states of division requires a high energy input. In the case of aluminium this may be provided by mechanical means, for example, in the pulverizing of aluminium foil feedstock to form flake or rolled-up granules. It may be provided by a combination of mechanical and thermal energy, for example, in the centrifuging of molten metal to form a peripheral spray of droplets which freeze into spherical, needle shaped, or other forms of particles. Chemical sources of energy by reduction are not employed commercially for aluminium powder production as they are for some other base metals.

"An important energy source is the combination of thermal and pneumatic energy in the twin-fluid atomizing process, the second fluid being a gas. This method is by far the most popular for aluminium powder production. The preference of some manufacturers is for the direction of atomizing to be vertically upward, the pneumatic energy source also being used to suck the molten metal into a refractory jet where it meets the high pressure gas passing through a concentric orifice to disintegrate the metal into droplets (see Fig. 1). Other manufacturers use the same technique but blowing horizontally; whereas others, still using the horizontal direction, avoid the use of the refractory jet by introducing the gas at a distance from the issuing metal stream, rather in the manner of the vertically downward systems used for atomizing higher melting point metals such as copper alloys. The vertically downward assembly is not so popular for atomizing aluminium, although commercial plants of this type are in use. Water, either as liquid or steam, reacting readily with aluminium, is a dangerous medium to employ as the energy-providing fluid to break up the molten metal. There are risks of hydrogen generation causing violent explosive reactions and a further risk of inclusion of bubbles of water trapped in the particles, providing a source of problems in the later processing of the powder. Furthermore, water and steam atomizing of aluminium create thicker coatings of oxide in hydrated form on the surfaces of the particles, limiting the use to which the products can be applied.

"For large scale production air is the usual fluid energy source. Although the oxygen it contains does react with aluminium at the atomizing temperature, a relatively thin tenacious film of oxide forms around each particle. This can cause larger particles to distort during cooling to produce less regularly shaped particles than the spherical droplets from which they were initiated. The oxygen content of such commercially produced powders is usually between 0.05 and 0.5% by weight, corresponding to approximately double these values as oxide. The commercial use of inert gases, either alone or introduced at a critical stage in air atomizing, is a recent development; it is related more to a desire to improve safety and the sphericity of the powder than to reduce the oxide formation.

"Nowadays, the term 'atomizing' is applied to any process in which liquid metal is broken into droplets by the application of an energy source. It is sensible to emphasize the type of atomizing technique employed since the characteristic forms and properties of the powders produced by each method have wide differences. The various methods used for making aluminium particulates provide, therefore, a relatively wide range of forms of material. Only a restricted number of these have applications in PM processing."



1 Twin-fluid (gas) atomizing

(Extracted from "Aluminium powder metallurgy in perspective", P.D. Liddiard, <u>Powder Metallurgy</u>, 1984, Vol. 27, No. 4, pp. 193-194. Copyright (c) 1984 The Metals Society, England.)

Microstructure control during sintering

"Some of the most advanced concepts deal with techniques for controlling the microstructure during sintering. At the sintering temperature, most materials undergo grain growth and pore coarsening, which degrade mechanical properties. Several concepts are under investigation to attain microstructure control by manipulation of the heating rate, sintering time, particle size distribution or inclusion of second phases.

"Nonisothermal sintering treatments have been developed to maintain short exposures to high temperatures to prevent grain growth and pore coarsening. The concept is to heat the compact at a rate sufficiently fast to attain a high degree of sintering. However, there is minimal time to high temperature exposure. Preliminary data show better sintered microstructures with less energy consumption and equal productivity using controlled heating.

"Another concept relies on tailoring the particle size distribution of the starting powder. A uniform particle size powder will have less driving force for grain growth during sintering. Differences in particle size (such as are typical in most instances) result in grain size imbalances which lead to grain growth. A narrow particle size distribution reduces grain growth during sintering and has several beneficial effects. A positive benefit has been demonstrated for copper, titania and urania. Unfortunately, the magnitude of the effect does not seem large unless the particle size is very small. Alternatively, substantial benefit is possible through uniform particle packing using bimodal size distributions and deagglomerated powders.

"Second phases provide for both strengthening and microstructure control during sintering. Small inert dispersoids (typically oxides) inhibit grain growth. Unfortunately, in many cases the dispersoids also inhibit sintering. This may be due to impeded dislocation flow during heating or oxide contamination of the powder. In a few recent studies, dispersed second phases have aided long-term high density sintering. Data on molybdenum suggest dispersed oxides inhibit initial sintering because of less dislocation flow, but aid final sintering because of reduced grain growth. In all such instances better strength, but a decreased ductility, result from second phase additions."

(Extracted from "Innovations in Sintering", The International Journal of Powder Metallurgy and Powder Technology, Vol. 20, No. 3, 1984, pp. 256 and 258. Copyright © The American Powder Metallurgy Institute, USA.)

Improving the machinability of sintered steel by adding manganese sulphide

"One of the greatest advantages that powder metallurgy enjoys over its rivals is that the machining operations which are necessary for most competing methods of parts manufacturing can either be greatly reduced or entirely eliminated. However, there are many parts which because of their shape or the tight tolerances required cannot be made without machining, even though they are manufactured from metal powders. Re-entrant angles, annular grooves, threads, and undercuts are examples of sections that must be machined.

"Since the composition of the material, the porosity of the part, and the sintering can be varied so greatly, the problem of achieving a good sintered material for machining can be very complicated. Porosity causes a constantly interrupted cut, and a consequently accelerated tool wear, which leads to rough finishes and, in many cases, to impairment of surface porosity. Sintered materials, and especially sintered high strength steels, are sometimes reported to have poor machinability. To improve the machinability of these materials the influence of machinability enhancing additives has been studied. However, in most cases the improvement has to be reached without any deterioration in the sintered properties of the material, such as tensile strength and elongation, and without any unfavourable influence on the dimensional change during sintering. Therefore, several additives known to enhance the machinability of conventional steels have been tested with regard to both machinability and mechanical properties.

"Defining machinability is as difficult when applied to powder metals as for other materials. One expert describes machinability as the response of a metal to machining. Another says it is a complex physical property of a metal that involves machinability, finishability, or ease of obtaining a satisfactory finish and abrasiveness: the wear of the tool during cutting.

"In whatever way machinability is defined, it still has to be measured and the method used in this investigation was a drill life test. The advantages of the drill life test are that it is relatively inexpensive, the results are reproducible, and the shape of the test part is not a limiting factor. Generally, there are several criteria used in drill tests:

(i) under varying conditions, the number of revolutions of a standard drill to make holes of a given depth

(ii) for a hole of specific dimensions and under a given machining condition, the time to drill the hole

(iii) under a given set of machining conditions, the number of holes drilled before tool failure.

"The third criterion has been used in the tests described in the present paper. The machinability rating was determined by the number of holes drilled under specified machining conditions until failure occurred. The conditions used in the tests were as given in Table 1. For each material investigated the machinability index was calculated as the average of the numbers of bores obtained by five separate drills. The drills used were all high speed drills taken from the same batch to minimize variations in quality.

"The machinability of solid steel and the influence of different alloying elements to improve the machinability are topics on which very much has been reported in the literature. However, the knowledge of the effect of these alloying

Table 1. Machining conditions used in tests

Drill	High speed steel, SKF-Malcus list No. 100, 3.5 mm dia.
Speed	3000 rev min^{-1} (33 m min^{-1} at periphery of drill size used)
Feed	235 mm min^{-1} (0.08 mm rev^{-1} with speed used)
Coolant	No coolant used
Test specimen	Sintered discs 80 mm dia., 12 mm high
Holes	Through holes drilled one after another at high constant rate
Wear criterion	Totally worn drills

elements on the machinability of sintered steels is quite limited. Therefore, an investigation of several additives known to enhance the machinability of conventional steels was carried out with regard to their influence on both machinability and mechanical properties.

"The additives tested were sulphur, selenium, tellurium, manganese sulphide, and molybdenum disulphide. The base material to which these materials were added was Höganäs grade Distaloy SA, a partially prealloyed sponge iron powder, containing 1.75% Ni, 1.50% Cu, and 0.50% Mo. As sintered, the microstructure of this material consists of Ni rich martensite, upper bainite, pearlite, ferrite, and pores.

... "The different additives and the ways in which they were added to the Distaloy powder are described in Table 2.

Table 2. Additives to Distaloy powder used in tests

Sulphur	Admixture of flowers of sulphur: admixed content of sulphur was 0.15 and 0.25%
Selenium	Admixing of elemental selenium with particle size of about 5μm: admixed selenium content was 0.15 and 0.25%
Tellurium	Elemental tellurium powder having particle size according to Fisher of 4.8μm was admixed to Distaloy SA giving tellurium contents of 0.05, 0.10, 0.15, and 0.25%
Manganese sulphide	MnS was admixed in form of powder with particle size less than 325 mesh; powder was admixed to Distaloy SA in percentages 0.5 and 0.85 giving the mixture sulphur contents of 0.15 and 0.25% respectively
Molybdenum disulphide	MoS_2 with particle size according to Fisher less than 1μm was admixed to Distaloy SA to sulphur content of 0.25%

"The only additive which does not have any detrimental effect on the sintered properties is the manganese sulphide. The tensile strength ... and elongation are roughly the same as for Distaloy SA and, unlike all the other additives, it has no effect on the dimensional change ... The chemical analysis of the sintered parts also shows that no sulphur burn-off has occurred during sintering, which confirms the conclusion that the manganese sulphide is stable during the sintering process."

(Extracted from "Machinability of Sintered Steels", U. Engström, Powder Metallurgy, 1983, Vol. 26, No. 3, pp. 137-138. Copyright © 1983 The Metals Society, England.)

Injection moulding

"One of the first questions often asked is: Do you absolutely need those superfine powders? The ideal powder for injection moulding would be one with low free surface energy for mixing and moulding and one with high free surface energy for sintering. This is accomplished by selecting spherically shaped powders with a fine average particle size (APS). The spherical shape permits a high volume loading as the sphere has the maximum amount of volume for a given surface area. The finer the APS, the higher the surface-to-volume ratio and the greater the curvature of the particles. These important differences from conventional PM result in improved microdensity and greatly increased sintering kinetics. These are essential features since injection moulding produces green parts packed at relatively low pressures (typically around 2000 psi of injection pressure) resulting in porous and fragile compacts just prior to initial particle bonding during the sintering step when all the organic binder has been removed.

"Binder formulation and mixing. Particulate systems consist of two phases - the continuous phase and the discrete phase. The discrete phase consists of the particles, and the continuous phase consists of the material in the interstices between the particles, i.e. the binder. The binder must meet with many functional requirements:

(1) must be a thermoplastic. Thermosets can be used but much of the economy of the processess sacrificed.

(2) non-reactive with disperse phase material.

(3) non-degrading at mixing and moulding temperatures.

(4) minimum residue prior to actual sintering.

(5) non-toxicity.

(6) stable repeatable rheological properties.

(7) inexpensive.

(8) long shelf life.

"The mixing of powdered material and binder establishes the shrinkage of the sintered part. The establishment of the precise shrinkage factor is very important. The absolute value of shrinkage must be known to a high degree of precision, since the mould has to be cut to the shrinkage. Reproducibility of shrinkage from batch-to-batch is equally important to maintain tolerances.

"Moulding. Good understanding of the rheology of metal-filled systems is fundamental to moulding and processing of such mixtures. Controlling the viscosity is essential and this is done by the mould operator by adjusting mould temperature as well as injection pressure and velocity. Temperatures should never be allowed to go above certain limits where cross-linking of the organic binder will be initiated since this would unavoidably lead to irreversible subsequent processing roblems. Common screw and piston plastic injection moulding machines can be sed. Mould design and moulding experience are critical areas which, at this stage f the development of injection moulding, can mean all the difference between success and failure. Certainly not every geometry is amenable to forming by moulding even though some moulds are absolutely fascinating masterpieces of craftsmanship with their intricate internally moving parts, retractable core pins, ejector plates, slide mechanisms, precise registrations, and heat exchanging circuitry. Whenever a new candidate part is examined for a feasibility study it is nearly always partly redesigned in view of the greater freedom offered by plastic forming as compared to traditional machining. This can result in substantial material savings in addition to improved design.

"Binder extraction. The binder must be removed from the moulded components prior to the sintering process, and this is a key operation to success. It can be performed in several ways; e.g. solvent extraction, thermal degradation, melt wicking, vacuum distillation, etc., as long as the following fundamental principles be observed: It is necessary to eliminate the binder as progressively as possible so as to never create a situation of internal pressure within the compact be it by swelling of the polymers, or outgassing of decomposition products.

"Many particulate materials are sufficiently stable at typical binder extraction temperatures; i.e. up to 600F, to support treatment in air but others present highly specific problems and readily oxidise so that protective atmospheres are required.

"It is obvious from our testwork that the presence of metal in the system greatly lowers the activation energy for exothermic oxidation reactions which may set off at as low as 270F.

"Care must be taken in handling the parts; they have very little green strength left after binder extraction and should not be stressed."

(Extracted from "Injection Moulding Produces Complex PM Parts", Metal Powder Report, Vol. 39, No. 1, January 1984, pp. 13-14. Copyright © MPR Publishing Service Ltd., England.)

Solid state metallurgy

"The future of solid state metallurgy, in comparison to today's usual liquid state processes, is a continually expanding one for many fundamental reasons. These reasons are sufficient to assure the eventual displacement of liquid state as the dominant metal production system. The best way to illustrate this eventuality is to look at the history of steel production and determine the future of this massive industry by applying today's technical knowledge and abilities and especially those involving solid state production. Many years ago, the only system for obtaining steel was the solid state production of sponge iron which was then hot worked in a reducing atmosphere to produce armaments, usually, such as swords, spears, axes, suits of armor, etc. Soon after the discovery of high temperature furnace processes which would allow melting of steel, the relatively laborious old solid state processes were soon forgotten and the steel industry, as we know it today, was started. The great industry that was then developed has probably done more to advance our modern society than any other single thing. Its ability to produce strong metal in large amounts at very low cost allowed the development of automobiles, ships, large buildings, home heating systems, electric motors and generating equipment, etc. On such things, most of us are dependent but we also depend on the oil industry which, in turn, depends upon the steel industry for its production capability. It should also be realized that most of the plastics industry depends on it and even our airplanes depend on it for the most critical applications. So today's enormous steel industry quietly influences all of our lives. The world-wide production of steel, however, is very inefficient for two basic reasons. One is the substantial energy losses in its production and the other is the low degree of yield in raw and finished products. Until the last few years, the cost of energy was low and it was so available that it represented a very small part of the total cost. This allowed the use of inefficient processing so that today, even with many different processes and much refinement, the average energy loss from the coking ovens through the blast furnace etc., to the finished steel plate, sheet, bar etc., is about 75%, when the various "yield" losses are considered. In addition, there is much scrap produced subsequently during cutting, forming, trimming and machining operations. It is probable that this loss would also be about 25% in average, and this does not include the energy costs in steel transport, scrap processing and scrap transport.

"So the real energy losses in the liquid state steel industry from ore to finished product probably averages 85% or more. In the past such an inefficiency has been tolerable because of the low cost of energy. Much work is being done now on improving that figure but the degree of improvement possible is quite small compared to what is feasible with solid state production systems.

"The following list of reasons illustrates some of the fundamentals which can increase the efficiency to 50% or more:

1. no cokemaking or pelletizing is necessary;
2. no blast furnaces or steel making furnaces are required;
3. no hot working is necessary after primary formation;
4. the maximum temperature can be reduced to 1100°C, or less;
5. a greatly reduced amount of finishing is possible with little or no reheating;
6. finished steel can be produced with only one heating operation;
7. steel making can be one continuous process from beneficiated ore to sheet, wire, foil, etc.;
8. high carbon or other lower ductility steel can be processed almost as easily as low carbon, high ductility types;
9. much higher yields are possible and 100% is feasible.

"While much of this may seem almost impossible, each statement has been proven by the author. In primary laboratory work the following abilities were established:

1. raw materials converted to high strength steel have been:
    (a) high purity magnetite from triple beneficiated low grade ore powder,
    (b) very low cost by-product magnetite from primary nickel production,
    (c) high purity pigment grade hematite;
2. maximum temperatures of reduction as low as 1000°C;
3. sintering to high density has been accomplished in combination with the reduction operation;
4. the reduced and sintered product has been cold worked to full density and high strength with low and high carbon contents and without any scrap loss;
5. flat rolled shapes have been produced including perforated foil without scrap loss;
6. various materials have been produced including SAE 52100 and M2 high speed steels;
7. the high ductility possible (allows substantial cold working) was demonstrated by the 52100 steel being quite ductile after 85% reduction in a cold swaging machine.

"All of these individual experiments confirm the ability of solid state steel processes to greatly reduce the equipment, man-power and energy requirements for basic steel production but the full continuous principle must still be demonstrated. A variation of this, which requires two heatings, will be used, especially in relatively remote iron mining aeas. The continuous production of iron powder or iron melting stock of high purity at or near the ore source, can be carried out (the cement industry normally practises this principle). Reducing gases can be generated electrolytically or thermally from local raw materials according to the best local conditions. These reduced powders can be transported by mass methods, at very high efficiency, directly to steel users who can continuously produce sintered steel mill products in small mini-plants with the most economical processing for their particular needs. For instance, perforated sheet can be produced continuously in two cold rollings to foil thicknesses. This has actually been accomplished with pure nickel powder to 0.051 mm thickness in one compaction, a short low temperature sinter and a finish rolling. As can be seen from the above information, it is possible to increase the energy efficiency of steel production from today's 15% to 75% or better. Therefore, as the cost of energy continues to escalate, the advantages of solid state will also escalate and this will drive the steel industry to many more and much deeper investigations than those existing today. The industry has already accepted solid state methods and is in production with superior high alloy and heat resistant steel bars by a variety of processes. Stainless steel tubing is also being produced. These developments amply demonstrate that superior properties and a higher production efficiency is possible today."

(Extracted from "The Future of Solid Metallurgy", Powder Metallurgy International, Vol. 15, No. 2, pp. 89-90. Copyright © Verlag Schmid GmBH. 1983.)

Processes for sintering bronze

"Bronze PM parts are practically always sintered in reducing atmospheres using mesh belt furnaces, but in view of the multiplicity of factors involved, it is easy to understand why there is great diversity in practice from one manufacturer to another. When the production of oil-impregnated bearings started, and for many years after, electrolytic copper powder was used, because nothing else was readily available. Tools were designed to take account of the growth, and so when the atomization process was developed such powders were slow to gain acceptance. This was due partly to inbuilt conservatism but also to the fact that new tools would be needed. Gradually, however, the increasing cost advantage of atomized powders coupled with an increased awareness of their technical advantages has overcome these obstacles, and atomized powders now have a large share of the market.

"This has made possible the production of low growth mixes containing a proportion of pre-alloyed bronze. It is advisable to sinter on the hump of the growth/temperature curve as has been stated already, but nevertheless it is by no means uncommon to sinter on the uprising slope of the growth curve using temperature setting, belt speed, and belt loading. Even if the first two are maintained constant, variation in the belt loading will lead to variation in the temperature reached by the parts. It cannot be too often stated that what a thermocouple measures is its own temperature.

"Increasingly, however, the tendency is to use low growth or even no growth mixes, the chief factor preventing more universal acceptance being the existence of large quantities of compacting tools designed for mixes that produce significant growth. With low growth systems an additional feature is that the compacting tools may be used also for sizing. This is of little benefit when large quantities of a bearing are required - more than one set of tools may be required anyway; but it is an advantage for short run production.

"Because the PM bearings market is extremely competitive, cost saving is of major importance. Savings in the sintering operation can be achieved in two ways: by using the shortest practicable sintering time, and the cheapest atmosphere. There can be no doubt that life is easier if the process is done slowly but economic considerations dictate as high a throughput as possible. Limiting factors include the following:

(a) the heating up must be slow enough to ensure safe removal of the lubricant, avoiding blistering and distortion.

(b) time must be sufficient to ensure a near approach to temperature uniformity throughout the individual part, otherwise thicker sections might not be adequately sintered. It follows that large thick-walled bearings need a lower speed than small thin-walled bearings.

"Practice varies considerably, some manufacturers using a total furnace time of as little as 30 min, while others take 2 hr or even more.

"Similarly with atmospheres. Some reducing potential is essential and atmospheres very rich in hydrogen, e.g. cracked ammonia, are in use. At the other end of the scale, some major producers are using exo-gas containing less than 10% of hydrogen. Synthetic nitrogen/hydrogen mixtures and even endo-gas are also used, this last by producers also of ferrous parts whose output of bronze does not justify a separate atmosphere generator. Here again, a richer, but more expensive atmosphere makes the process easier, but there need be no real difficulty if the gas contains more than 10% of hydrogen.

"Bearings have been discussed at length not only because they account for the bulk of bronze parts produced, but also because their production is more complex and involves more interesting problems."

(Extracted from "The Sintering of Bronze", Metal Powder Report, Vol. 39, No. 2, February 1984, pp. 72-73. Copyright © MPR Publishing Services Ltd., England.)

Techniques for producing copper powder

"The main technologies in use for the production of copper powder are, in the historical order, cementation, electrolysis, oxide reduction and atomization. An account is given of the relative growth of each of these, in relation to the physical and chemical properties of the powders obtained, and their compatibility with the final use of the powder.

"Cementation. The raw material may be almost any copper-containing scrap or ore. The first step is chemical dissolution of the scrap (or ore) using an acid or a mixture of acids to facilitate the dissolution. After purification to eliminate the non-metallic substances and certain unwanted metals, the copper solution is treated with a less electropositive metal that displaces the copper in the form of a very fine powder. Iron is normally used, for economic reasons. The powder is washed, neutralised, dried and, if not used directly as catalyst, generally annealed, both to remove the superficial oxides and to agglomerate the particles, enabling the powder to flow, for pressing purposes for instance.

"This process is complicated, labour consuming, environmentally undesirable and is rarely used, except to recover the copper from small quantities of very cheap scrap or lean ore. The quality of the resulting powder is directly dependent on the efficiency of the purification process.

"Electrolysis. This process was, up to recently, one of the most widely used methods for the production of large quantities of high quality copper powder, in both Western Europe and in North America. The raw material is of necessity copper cathodes (used in this case as anodes) or specially melted anodes of refined copper. The electrolyte is copper sulphate and sulphuric acid, from 100 g to 250 g/lit of acid and 10 to 30 g of dissolved copper. The electrolyte temperature varies around 50C and is recirculated with pumps. The cathode current density varies around 3,000-4,000 Amp/m^2.

"This high current density liberates hydrogen at the cathodes and necessitates a continual control and re-adjustment of the electrolyte composition. The cathodes are manually tapped periodically (every 30 minutes or so) to remove the adhering powder, which sinks to the bottom of the bath. When the storage volume below the cathodes is full, the electrolyte is pumped out, and the powder is manually removed from the electrolysis vessel, washed and neutralised.

"The next step is filtration, or centrifugation to reduce the water content of the slurry below 5 to 10%. The wet powder is transferred to a rotary drier, using hot air.

"The powder is rarely delivered as produced; an additional annealing treatment, under reducing gas, followed by a crushing and a milling operation, finally gives a pressing grade copper powder. Providing the process is reliably controlled, the resulting powder is of very high quality, with good compressibility, and is still very largely used by the sintering industry. We will see later how, for economic reasons, this process is now progressively being phased out.

"Oxide reduction. As its name implies, the process starts from copper oxides. One of the most popular raw materials, where available, is the copper mill scale from hot wire drawing of copper. This material must, first of all, be strictly controlled to ensure its homegeneity, then dried and roasted to complete its oxidation. The next step is a magnetic separation to eliminate iron and a milling followed by a sieving to the required particle size.

"The main (and expensive) step is the reduction, normally performed in a continuous band furnace, the product being a sintered copper cake, which has to be crushed and milled.

"If the copper oxide is pure and consistent, the resulting powder is usable for sintering, but its value is strongly influenced by the very high cost of the reducing gas.

"Water atomization. An important feature of this process is the variety of raw materials that can be used. Practically any kind of pure copper scrap, oxidised or not, mill scale, cathodes, wire bars, ingots, is usable without loss. The metal is melted and after control of the oxygen content the liquid metal is transferred to a tundish and atomized with very high pressure water, the powder being collected in a tank. After a filtration that reduces the water content of the powder to 4 to 7%, the powder is dried, then partially oxidised in a rotary furnace, and directly conveyed to a reduction furnace. The cake obtained has to be crushed and milled, then sieved.

"The quality of the powders so produced is very suitable for pressing. It is less suitable for friction parts and dynamo brushes, as it is very difficult to get the low apparent density (below 2.2) normally used for these purposes. In compensation atomization is the only one of the four processes that enables the direct production of prealloyed copper powders.

"It may be mentioned that air atomization also is employed for the production of copper alloys, mainly for spherical bronze for filters, and brass powders, but rarely for pure copper. Gas atomization is however a common method for the production of copper-lead alloys, employed for bimetal bearings, requiring very low oxygen content.

"There are other methods that can be used for the production of copper powder, but they are not used on an industrial scale: for instance, electroerosion, centrifugal atomization.

"Final treatment. It may be pointed out that the different methods described have one feature in common. To be usable as pressing grade powder, the annealing process followed by a crushing, milling, sieving, must be used. Of course, for consistency of the product quality, blending and inspection are compulsory.

"The various powders are shipped in drums, plastic bags, or other containers."

(Extracted from "The Economics of Pressing Grade Copper Powder Production", Metal Powder Report, Vol. 39, No. 4, May 1984, pp. 251-255. Copyright © MPR Publishing Services Ltd., England.)

Atomization of high-lead copper powder

"Metallurgists have for a long time tried to solve the problem of immiscibility between copper and lead and to increase the proportion of lead in Cu-base alloys in order to improve their antifriction and lubrication properties in demanding applications such as those found in automotive sleeve bearings. Methods such as fast cooling of the molten metal which traps the lead particles in the copper matrix (the Gould process) has gone some way towards solving this problem. However, the lead content using this approach is said to be limited to around 22%.

"Omar A.G. Sultan, a former atomic physicist in NASA's Apollo Space programme, and now working with Thonon Industrial Metallurgy, has developed a special additive which stablises the molten copper-lead alloy and allows the production of a heterogeneous Cu-alloy with up to 50% Pb content. In addition to solving the immiscibility problem between copper and lead, Sultan has created an unusual affinity and stability between these two metals in the solid state. The stabilisation of this mixture is quite a significant breakthrough because it allows repeated melting with subsequent solidification at different rates of cooling without any segregation whatsoever and with perfect conservation of the original globular structure in cast materials. This is an important attribute when producing continuous cast ingots which will be remelted in cast component production."

(Extracted from "Breakthrough in Atomisation of High-Lead Copper Powders", Metal Powder Report, Vol. 39, No. 8, April 1984, pp. 466-467. Copyright © MPR Publishing Services Ltd., England.)

Vacuum sintering furnaces

"Some of the more interesting developments in vacuum sintering furnaces are listed below:

(1) There are resistance heated combination cycles with high quality graphite felt insulation for operating temperatures up to 1600C. Graphite felt has excellent insulating and low heat storage properties, and it also helps to reduce the furnace mass and volume. Consequently, heating up

and cooling down times are shortened. Another important point for batch vacuum sintering furnaces is that the idle running energy consumption is kept low.

(2) All the process steps can be done in the same furnace, often in one cycle.

(3) Apart from mechanical automation and interlock systems the actual trend is to apply more automatic control to process cycles. Solid state programmers (microprocessors) provide increased operational ease.

(4) A modern vacuum sintering furnace is versatile, it can be used for different heat treatment, for example such as high temperature brazing of hardmetal tips to steel tools ... Joining techniques are now cost effective ways of manufacturing a new range of PM parts.

"In recent years an increasing number of different types of vacuum furnaces have been used to sinter cemented carbides. However, mass production of, for example, cutting tool tips of wear resistant parts rather demands heat treatment in suitable, energy efficient furnaces, especially if the process parameters, the quantity and quality of the shape and dimensions of the workpieces are often changed. Automation is now of primary importance also in the field of sintering. In addition to relieving workers from elementary operations, there is an urgent need to eliminate human inadequacies and to achieve better and cheaper production.

"The first steps to improved productivity in vacuum sintering has been the installation of continuously operating, automated pusher-type furnaces ... From an economic point of view a continuous furnace is preferable due to its high throughput, constant quality, minimum rejects and its possible automation with the aim of reducing manpower. As no transformation losses occur and the plant is usually operated continuously at working temperature without stops, the power consumption is really low in the mass production of hardmetal. The automatic charging and discharging of the loaded sintering boats takes place from magazines at one end and the same point ... The only remaining manual labour is the placing of the boats onto and removing them from the magazine conveyor. However, a disadvantage of this type of furnace is its limitation to sintering only small components. Nevertheless, they are easy to maintain, provide constant metallurgical results, and have therefore their place in the powder metallurgy industry today.

"Alternatively hardmetal compacts can be sintered in induction furnaces consisting of a graphite susceptor and water-cooled induction coil. The differential pressure between the furnace vessel and work space prevents the binder vapours from settling on cold parts and in effect gives rise to a constant stream of gas passing through the furnace. This in turn acts as a carrier to draw with the aid of the main pump set the vapours through a valve at the bottom to a wax condenser.

"Recent developments in the field of vacuum sintering have led to the successful shortening of the total cycle time in this type of furnace. In principle it is very difficult to cool down a massive load placed in an insulated induction coil. Therefore the cooling process needs several hours resulting in low utilisation rate and throughput in the furnace. With a new rapid cooling system ... it is possible, however, to overcome this disadvantage and to shorten considerably the cooling time in comparison to conventional cooling methods ...

"The cooling of the sintered charge is effected by a gas which is recirculated in a closed circuit with the aid of a fan. The circuit comprises suitably dimensioned heat exchangers. The working pressure of the gas depends on the type of gas used. The cooling time for a 200 kg load with the rapid cooling system has been reduced to 4 hours.

"The claim of cemented carbide producers to manufacture a variety of specially shaped products of different sizes and weights makes batch vacuum sintering furnaces highly desirable. The recently introduced vacuum combination cycle furnaces offer a design with significant improvements over previous furnaces in the sintering of nearly all grades of cemented carbides. In these modern resistance heated, horizontal chamber furnaces ... the entire process of dewaxing, presintering and sintering can be carried out in the same workspace and in one cycle. This not only saves energy and manual labour through the elimination of the cooling stage between the different processing steps, but it also gives a greater flexibility in the production of hardmetals. The batch-type furnace VKUgr, incorporating many features such as combined dewaxing and preheating facilities, and very precisely working gas or vacuum control systems, is suitable for nearly all the various stages of manufacture or in vacuum ...

(Extracted from "Energy Efficiency and Productivity of Vacuum Sintering Furnaces", Metal Powder Report, Vol. 39, No. 2, February 1984, pp. 88-90. Copyright © MPR Publishing Services Ltd., England.)

Powder metallurgy and the aerogas turbine engine

"Since the advent of the gas turbine aeroengine in the early 1940s the development of improved materials and manufacturing processes has been prominent in its continued evolution. Generally, the overall demands on engine designers have remained fairly constant in that the user has always called for improved performance (in terms of higher thrust and lower specific fuel consumption and weight) together with increased durability and reduced overall cost of ownership. These requirements are usually in conflict, particularly from a materials viewpoint, since improved performance is often associated with higher engine rotational speeds, gas temperatures, and pressure ratios, all of which make heavy demands on material properties and hence tend to reduce component life. A sensible balance can often be achieved only by utilizing complex components made using advanced materials and the most recent manufacturing technology. Gas turbine components, therefore, often have a very high prime cost. As a consequence, the aerogas turbine engine has been always at the forefront of advanced materials technology, with many of the materials used in its construction being developed specifically with the gas turbine in mind, e.g. high temperature titanium alloys (IMI 685) and wrought (Nimonic 115) and cast (MAR M 002) nickel base superalloys ... On the processing side, precision forging and casting, unidirectional solidification, electron beam welding, and laser, spark, and other advanced machining techniques are all employed as a matter of routine in modern aeroengine construction. It is no surprise, therefore, to find that any potential material advantages that may be realized by utilizing advanced powder metallurgical technology are not being overlooked by gas turbine manufacturers. Often, it is the demanding requirements of the aerospace industry as a whole (both engine and airframe) that provide the major driving force behind current developments.

"If the overall status of powder technology in the aerogas turbine engine is judged by the number of applications currently in commercial service, then the picture is somewhat gloomy. In spite of all the research and development that has been directed towards powder aluminium, titanium, steels, and nickel alloys, only powder nickel alloys have seen actual service use, and then only in US engines. Both Pratt and Whitney and the General Electric Co. use powder superalloy discs in some of their latest military engines, while the General Electric Co. also uses an oxide dispersion strengthened alloy for a nozzle guide vane application.

"In the aluminium field, powder technology promises the development of stiffer, stronger, higher temperature capability alloys that should be capable of displacing some of the titanium and steel at the front end of the compressor. Even so, temperature capability will still be restricted and new, clean powder production facilities may be required for aerogas turbine applications. Any new powder aluminium alloy will face severe competition from the advanced resin matrix composite materials now under development.

"Conventional titanium alloy manufacturing routes pose few problems and so any future powder applications for critical rotating components will demand the development of novel, advantageous compositions that cannot be handled by conventional processing routes. Hipping-to-shape non-critical components, particularly if of complex geometry, may be cheaper than either a cast or forged product and, as a consequence, may see limited use in future engines.

"Steels, like aluminium, suffer from a dearth of very clean powder. Given an acceptable starting material, there would appear to be scope for powder processing to play an important role in the development of improved bearing materials; work in this area should be encouraged.

"High strength nickel superalloys that are difficult to forge by conventional means can be fabricated into gas turbine discs if powder billet is used. Unfortunately, the full strength potential of these alloys cannot be realized as yet because of defect dominated life limitations. In attempts to overcome this difficulty, appreciable efforts are now being devoted to developing 'defect free' production techniques, to improving methods of non-destructive evaluation, and to implementing damage tolerance design and lifing concepts. If advanced melting procedures are developed as a means of overcoming the defect problem, then it is possible that the cast billet so produced may in itself be forgeable and thereby eliminate any need for powder processing.

"Oxide dispersion strengthened materials show considerable promise for use as small, uncooled turbine blades and if development in techniques for producing cooled components are successful, then opportunities will be widened considerably.

"Currently, it seems RSR nickel alloys show little promise since similar compositions cast as single crystals can have equivalent strength capability. New alloy compositions having a better balance of properties are required before RSR nickel alloys can be considered as leading contenders for aerogas turbine applications."

(Extracted from "Powder Metallurgy and the Aerogas Turbine", M.J. Weaver, Powder Metallurgy, 1934, Vol. 27, No. 3, pp. 134, 139, 140. Copyright © 1983 The Metals Society, England.)

Market Trends

Finland

"Industrial activities in powder metallurgy in Finland take place at Outokumpu OY, Kokkola and OY AIRAM AB KOMETA, Esbo. Outokumpu produces extra fine cobalt powder for cemented carbides and has a production capacity of about 300 tons per year. Airam-Kometa produces about 100 tons/year of tungsten carbide-based cemented carbides. It is mainly used in the production of rock drills, which is the most important product of the company. Manufacture of indexable cemented carbide tips for cutting tools was started recently in a plant including equipment for chemical vapor disposition. Also cemented carbide wear parts are being produced.

"Airam-Kometa was the first company in the world to develop and produce hardmetal tire studs. Today they are the only producer in Scandinavia in this field. Sintered steel holders for the studs are manufactured inside the company. P/M production also includes WC-Cu-based contact materials".

(Extracted from "Powder Metallurgy in Scandinavia", The International Journal of Powder Metallurgy & Powder Technology, Vol. 20, No. 3, 1984, p. 214. Copyright © 1984 American Powder Metallurgy Institute.)

France

"The number of firms involved in the P/M industry in France is very small, a unique situation in industrialized countries. Another important fact is that fluctuations in production rates have been less than in any other country.

"These positive factors however do not indicate that the economics are good. The last recession in the mechanical industries began in 1979 in Europe and in the middle of 1980 in France. At that time there were two main companies for P/M mechanical parts production: Alliages Frittés SA and METAFRAM. Their competition, multiplied by foreign competition of the countries where the recession began earlier than in France, has led to a large reduction of prices especially if we take inflation into consideration.

"Since then Alliages Frittés SA and METAFRAM have merged and now belong to the Pechiney group, the main shareholder of several other P/M plants producing heavy metals or alloys and magnets.

"Production had rapidly increased before 1975 similar to the P/M growth in other countries but has remained almost constant from this time on, with a positive tendency. Roughly 7,500 tons of P/M products are manufactured each year. There are five types of production: powders, electrical contacts, heavy metals and carbides, bi-metallic bearings and mechanical parts. There are three categories of P/M mechanical parts: structural parts, bearings and filters. Since two firms produce several types of P/M products, the total number of firms is six, excluding carbide manufacturers. This production is in the order of 1/25th of the U.S.

"Since 1980, when the last "present status of P/M in France" was published in this Journal, the main change was in the carbide industry when the leading producer was bought by a Swedish firm and experienced a drastic decrease in production.

"Manufacturing developments are now more in the direction of automation and the use of computers than in new alloys or new P/M techniques. More and more, parts are automatically taken from the compaction presses and stocked. This permits the permanent statistic of the last 30 parts pressed on a video monitor and helps the operator to place the average value in the middle of the tolerance and to see the result of his actions to correct the variations. Some presses already have an automatic device for weight correction.

"For sintering, there is a tendency to increase the nitrogen percentage of the atmosphere. The flow of gas is almost entirely toward the entrance of the furnace, so that there exists no more flame curtain at the exit and parts are still cleaner.

"For sizing, devices have been made to index the parts from inside as well as from outside and the speed of these devices has lately been considerably increased.

"Regarding the conception and calculation of tools, much aid is obtained from computers though there is no C.A.O. in operation as yet.

"Hot forging is successfully in operation at Renault but is only slowly developing in other firms. As in many countries, the cost of the parts is too high for a rapid increase in volume.

"Several HIP installations are in operation for carbides and aircraft parts."

(Extracted from "Present Status of Powder Metallurgy in France", The International Journal of Powder Metallurgy & Powder Technology, Vol. 20, No. 3, 1984, p. 205. Copyright © 1984 American Powder Metallurgy Institute.)

Italy

Mr. Gennaro R. DeCristofaro of Merisinter SpA, in a presentation made at PM '84 in Toronto, Canada, said that Italy "is one of the few countries in Europe able to boast of an expanding rather than contracting PM industry with the number of companies producing structural parts and self-lubricating bearings having increased to twenty-three. Many of these are small producers having minimal overheads and they are able in many instances to produce PM parts at prices the larger companies find hard to compete with. To react to this threat, stated DeCristofaro, PM companies are developing more sophisticated products and implementing new production technologies. Only those who succeed in this will surivive, he said.

"Of considerable concern to the Italian PM community is stagnation resulting in excess production capacity among the increasing number of part producers. The resultant reduction in growth will inevitably lead to reduced profits making it difficult for PM companies to generate sufficient funds for future development work to get back into a growth phase. DeCristofaro said that the industry needed a new image in order to underline the cost-effectiveness of manufacturing complex components by PM. It also needs to be more aggressive and innovative, and to co-operate more closely with end-users. Finally, it must focus on selected market segments for development."

(Extracted from "Powder Metallurgy - A Global Perspective", Metal Powder Report, Vol. 39, No. 8, August 1984, p. 450. Copyright © 1984 MPR Publishing Services Ltd.)

Federal Republic of Germany

"... growth in PM parts manufacture in Germany has been fairly slow and is much in line with growth trends in other European countries. West Germany is, however, Europe's largest producer of PM products with total production quantity in weight estimated to be around 17,000 tonnes a year. This is closely related to the number of passenger cars produced in Germany at 3.8 million in 1983. The average weight of PM parts per car in that country is estimated to be 2.5 kg. Iron powder consumption in Germany for all applications was put at 26,000 tonnes in 1983.

"Referring to the future, Albano-Müller stated that the West Germany PM industry was developing products with better material properties, closer tolerances and lower costs. He referred particularly to the technology to produce high density components by high temperature sintering and sizing. He stated that although forecasts for 1984 and 1985 are favourable, the level of production costs in Germany will promote imports of PM parts and make exporting more difficult.

"He also said that the relatively small runs of European car models prohibits the possibility of automating PM structural part production lines, and that the industry can only develop further if it remains flexible, creative, and exchanges ideas for new applications and processes. 'We must carefully develop the confidence of end-users with our products through reliability, quality, and constant improvement of materials and processing', he concluded."

(Extracted from "Powder Metallurgy - A Global Perspective", Metal Powder Report, Vol. 39, No. 8, August 1984, p. 449. Copyright © 1984 MPR Publishing Services Ltd.)

"The German P/M industry can be subdivided into five branches, namely ferrous and nonferrous structural parts, cemented carbides, refractory metals and materials for magnetic and electrical applications, materials for special applications, and powder production. Several companies are only in one of these branches, others are involved in several fields. The majority of P/M companies are medium sized and sell their products. A few P/M producers are part of special department to large metallurgical companies or work as in-plant facilities of companies.

"Ferrous and nonferrous structural parts. This most important sector includes parts of iron, low alloyed steels, stainless steels, high speed steels, copper, bronze, brass, nickel-silver and aluminum. Included are also self-lubricating bearings, filters and friction materials. Production reached more than 18,000 tons in 1982 and is expected to grow to about 19,000 tons in 1983. The main consumers of these P/M parts are the automotive industry (66%), followed by producers of electrical machinery and domestic appliances (18%). About 11% are used for industrial and 4% for office machinery such as typewriters and photocopiers.

"The largest P/M company is the Krebsöge group with production plants Sintermetallwerk Krebsöge, Metallwerk Unterfranken (Bad Brückenau), Sintermetallwerk Lübeck, Sintermetallwerk Schwelm and Pressmetall Krebsöge. Krebsöge was founded in 1943, and is well known for its technology and strong R&D activities. The manufacturing program includes self-lubricating bearings, filters, Fe-, Cu-, and Al-based structural parts and sintered wrought Al-products.

"There is a steady development in shaping and sintering technology. Powder forging is in use for high strength parts, e.g., safety parts for brakes and lifting devices.

"A newly developed shaping method is the ZS-process. It allows design of complex shaped parts of uniform density which until now could only be compacted, if at all, in very complex tools. Cold isostatic pressing is used for threaded and large filter elements. Vacuum sintering is applied in the production of sintered high speed steel parts.

"*Cemented Carbides*. The cemented carbide industry in Germany had its beginnings more than 50 years ago. Annual production is estimated to be about 800-900 tons. This is much lower than the tonnage of sintered structural parts, but is of a similar or even higher economic value.

"The pioneer in hard metal production is Krupp-Widia, Essen, the hardmetal division of the Friedrich Krupp group. Subsidiaries exist in France, Netherlands, Spain, Switzerland, India and England. Production consists of cutting tools and wear resistant parts such as blanks or finished dies for powder compacting tools. Modern production facilities like HIP and CVD coating are used and one of Krupp-Widia's developments concerns a multilayer coating with aluminum oxynitride.

"In addition to hardmetals, ceramic cutting tools and magnetic materials are produced. Magnetic materials include soft and hard magnetic materials, namely Alnico and Ba-ferrites. R&D activities in the hardmetals field are concentrated on production technology, substitution of cobalt, and utilization of titanium carbide and coating technology. In the field of advanced ceramics, 'ductilization is a main goal.'

"*Materials for Magnetic and Electrical Applications, Refractory Metals*. This group consists of hard and soft magnetic materials, contacts for heavy duty and signal circuits, materials for electro-heating elements and lamp filaments.

"Pure iron parts for soft magnetic applications are produced by most of the P/M parts companies previously listed. Permanent magnets are manufactured by Krupp-Widia, Bosch (Herne) and Magnetfabrik Dortmund belonging to Thyssen Edelstahlwerke. Another well known specialist in this field is Vacuumschmelze Hanau (VAC) with production plants in Hanau and Berlin. The first plant produces (among others) wrought P/M materials the latter sintered structural parts. Soft magnetic Fe, Fe-Ni, Fe-Si and Co-Fe, as well as rare earth-cobalt permanent magnets. Other special products are alloys with defined thermal expansion for sealing and nickel-tubes or ribbons for electrodes.

"In the field of electrical contacts, companies like Degussa Frankfurt/Main, W.C. Heraeus, Hanau and Siemens, Erlangen are well known. Degussa produces heavy-duty Ag-based contacts, where CdO is replaced by SnO_2+WO_3. A Pt-10% Rh alloy, dispersion hardened by 0.16% ZrO_2 and exhibiting very high creep strength up to 1400 C, is used as the nozzle material for glass fiber production. W.C. Heraeus manufactures contact materials and Ta P/M products. Recently, activities in special ceramics (AlN and others) were taken up. The company is also involved in the development of surface technologies (different PVD methods) and P/M manufacturing of metal targets or sputtering cathodes. Recent developments at Siemens include composite materials and production techniques, the two- or more-layer pressing technique for contact materials and the cold extrusion of sintered Fe-Cu preforms for manufacturing of parts with high electrical and mechanical requirements. Under development is the infiltration technique of high oxygen affine skeletons (like Cr) with liquid metals. In powder production the company operates an atomization system for precious metals in which even Cd-containing materials can be processed without environmental contamination.

"Other manufacturers of these materials are DODUCO KG. at Pforzheim and Louis Renner at München-Dachau. DODUCO P/M products are sintered or infiltrated contacts from Ag-C, Ag-Ni, Ag-CdO, W-Ag and W-Cu. Cd-free Ag-metal contacts with low Ag consumption and Cu-Cr, W-Cu and W-Ag for vacuum switches are being developed.

"Louis Renner manufactures mainly Mo, W and their alloys including heavy metal, for application as contacts, sealings, electrodes, semifinished parts, structural parts and substrates for semiconductors. ThO_2- and ZrO_2- containing

84ngsten is manufactured for TIG electrodes, and Ag-based contact materials for low voltage applications.

"OSRAM, Münche and Schwabmünchen, is active in refractory metals. P/M activities are mainly concentrated at Schwabmünchen. Principal products are W- and Mo wires and filaments. They are used for internal needs in the production of incandescent and florescent lamps and are also supplied to external users in the form of powders, sintered, rolled or swaged rods and parts, ribbons and wires."

(Extracted from "Powder Metallurgy in the Federal Republic of Germany", F. Thummler and R. Oberacker, Vol. 20, No. 3, 1984, pp. 195, 199-201. Copyright (c) 1984 American Powder Metallurgy Institute.)

Japan

Mr. Hiroyoshi Kurata, President of Hitachi Powdered Metals Ltd; in a presentation made at PM '84 in Toronto, Canada "stated that during the decade 1973-1983 total production of PM products increased approximately 190% from 65,000 to 122,000 tonnes, a figure which includes some 63,000 tonnes of sintered magnets and 2,357 tonnes of cemented carbide. In the same period PM structural increased 2.5 times from 19,000 tonnes in 1973 to 48,000 tonnes in 1983. PM structural part production has risen in each of the past eight years, said Mr. Kurata despite occasional downturns in the Japanese economy. He compared the growth of PM with other metalforming processes: diecasting - 140%; drop forging - 110%; malleable iron castings - 60%, and gray iron castings - 70%. Mr. Kurata also underlined the growing importance of in-plant manufacturing of PM structural parts. This is now estimated to be 30% of all PM production and assuming that most of this represents in-plant production at automotive plants, the rate of in-plant production for automotive use could be as high as 40%."

(Extracted from "Powder Metallurgy - A Global Perspective", Metal Powder Report, Vol. 39, No. 8, August 1984, p. 448. Copyright (c) 1984 MPR Publishing Services Ltd.)

"Production equipment. Japanese mechanical and hydraulic compacting and sizing presses range in capacity from 10 to 200 tons. However an increasing number of presses with capacities of 400 to 800 tons are being used to compact larger parts ranging from 100 to 120 cm^2 in cross-sectional area. There are about 300 cold isostatic presses and 50 hot isostatic presses operating in the P/M industry.

"Most leading Japanese P/M parts manufacturers make their own compacting and sizing tools.

"Sintering furnaces are mostly mesh-belt conveyor or pusher with only a small number of walking beam furnaces. There are very few roller-hearth sintering furnaces. Practically all sintering furnaces are electrically heated. The pusher furnace has an average electrical capacity of 130 kW and an average production capacity of 58 kg/h. Mesh-belt conveyor furnaces have an average electrical capacity of 162 kW and an average production capacity of 360 kg/h. A large mesh-belt furnace with an electrical capacity of 216 kW and a production capacity of 600 kg/h has recently been installed.

"Dissociated ammonia and butane or propane-denatured endothermic gas are widely used as atmospheres. Mixed nitrogen-hydrogen gas with a high nitrogen concentration has been recently introduced. Vacuum sintering is used for hard metal alloys, stainless steels, high speed steel and P/M titanium base alloys. However, the use of vacuum is not extensive because of the need of a special furnace.

"New P/M developments. Recent developments in Japan include very reliable pore-free and homogeneous P/M alloys. They are better than conventional cast alloys in terms of corrosion resistance and mechanical strength at ordinary and high temperatures. These materials are important in the production of small machine parts and also in the development of larger billets, bars and plates.

"This new area of P/M in Japan is still in its early stages. An actual achievement is the 300 tons of P/M high speed steel for cutting tools produced in 1982. About 66% of these materials were made from argon gas atomized alloy powders and 34% by water atomized alloy powders.

"Production of nickel-cobalt base superalloys and pure titanium and titanium base alloys is still in the experimental stage.

"In August 1983, nine leading aluminum manufacturing companies in Japan formed the Aluminum Powder Metallurgy Research Association, subsidized by the Japan Ministry of International Trade and Industry. Through co-ordinated joint research, the association hopes to improve characteristics of aluminum such as heat and wear resistance, toughness and corrosion resistance. Researchers want to take advantage of the particularly fine and homogeneous alloy powders made by P/M rapid solidification techniques. They hope to expand applications in automobiles, aircraft, electrical equipment, bars and plates. An immediate research target is aluminum-zinc-magnesium base extra super duralumin (ESD), obtained by adding large quantities of ferrum group elements to ESD, aluminum-silicon base and aluminum-lithium."

(Extracted from "Present Status of Powder Metallurgy in Japan", T. Watanabe and T. Sakurai, *The International Journal of Powder Metallurgy & Powder Technology*, Vol. 20, No. 3, 1984. Copyright © 1984 American Powder Metallurgy Institute.)

Republic of Korea

"The Korean P/M industry started in the late 1960s without any previous technological basis. Several Korean firms began a joint venture with foreign (mainly Japanese) firms which provided technology as well as production equipment and raw materials. Most of the firms were small and lacked technical expertise. In the mid 1970s, many new firms entered the market t[illegible]t the growing demand within the country, and the resulting high competitio[illegible] markets spurred a rapid absorption of the technology. Currently, tungsten and [illegible]ite products have sufficient quality even for export markets.

"Major P/M products in Korea are Fe structural parts and oilless bearings. Ferrite production also has reached a substantial scale to satisfy the electronics industry. Utilizing a relatively abundant tungsten resource (with an estimated 6% of tungsten ore deposits in the free world), large-scale production of W and WC powder was started in 1975. WC hard metals are now made for domestic and international markets.

"On the other hand, the production of other metal powders and capital equipment (such as presses and sintering furnaces) has been lagging behind due to a limited domestic market and a weak technological base.

"In the beginning the P/M industry imported its powders. But in the mid 1970s, W and WC powder production was started on a large scale from the ores available in Korea. Small-scale Cu powder production also began in the 1970s, and ferrite powder production in the early 1980s.

"Ferrite powder production increased rapidly in recent years because of demand from the electronics industry for ferrite magnets and cores. The raw material was obtained from the Pohang Iron and Steel Mill with an annual production of 10 million tons of iron and steel. The Pacific Metals Company began with production of Alnico magnets in 1978 and started producing Ba-ferrite powder in 1980 with technology imported from Japan. Upon reaching full production in 1983, it produced 5,400 tons, of which 1,200 tons were used for its own production of magnets, 2,400 tons were supplied to Korea Ferrite Company, and 1,800 tons exported to Taiwan.

"The Samwha Industry Co. began pilot scale production of Ni-Zn ferrite powder in 1981 and full scale production in 1982. Production in 1982 was 1,000 tons, which was supplied to Samwha Electronics. Present production capacity is 3,000 tons per year, and the company is planning to double it in the near future.

"The Korea Tungsten and Mining Company is one of the largest producers of W and WC powders in the world. After initially exporting scheelite concentrate, the company developed the technology for producing APT and began exporting it in 1973. In 1976, it began exporting W and WC powders based on technology obtained from the U.S.A. The present total production is 2,800 tons of W, of which 1,000 tons are exported as APT and 1,000 tons as W and WC powders. Major customers are companies in Japan, Europe, and the U.S.A. About 100 tons of WC powder (30% of production) is supplied to domestic firms. Recently, the company developed filament grade W powders and began to export them to Europe and other areas. The company is also planning to expand production to ultrafine and coarse grade WC powders and is developing WC and TiC mixed powders. Powder production technology has considerably improved since the beginning of its own WC hard metals production in 1978, and the firm is putting much effort into developing many varieties of high quality W and WC powders.

"The Korea Nonferrous Metal Powder Company began producing sponge Cu powder in 1977 by an atomization-oxidation-reduction process developed in Korea. In addition to Cu-Sn powder mixtures for oilless bearings, it produces other nonferrous powders such as Al, Zn, Pb, and Al-Mg by atomization for domestic consumption. The Kwang Jin Industry began Cu powder production in the early 1970s. With a small-scale atomizer, it produces bronze powder for filter and other nonferrous metal powders. It has been also supplying electrolytic Cu powders for pantographs and carbon brushes. With the economic recovery, powder production and consumption are expected to increase rapidly in the next few years. Automobile production, for instance, is expected to increase from the current level of 200,000 units per year to 500,000 units in the next five years, and the electronics industry is also expected to grow substantially."

"With the continuous growth of the machinery and electronics industries and availability of skilled engineers, the P/M and ferrite industries in Korea are expected to grow rapidly. Tungsten and iron oxide raw materials will be utilized more fully. The domestic demand for structural parts is steadily increasing, but further improvement in production and quality will be necessary for expansion into international markets. When the demand for Fe powder reaches about 5,000 tons per year, domestic production is expected to begin.

"Ferrite production is expected to maintain a rapid growth rate because of the growing demand from automobile, television, motorcyle, and appliance industries for domestic applications and export. Production of high quality items such as Mn-Zn ferrite core and Sr-ferrite magnets is expected to show more rapid growth. Press and furnace makers are making an effort to increase their share of the market, which currently depends largely on foreign sources.

"P/M and ferrite industries are fairly technology intensive and of small or medium scale. Furthermore, they depend critically on the raw material and production equipment industries. Therefore, they can present unique structural problems during the growing stages in a country like Korea. It will be helpful to assess more thoroughly the current status of the industry and make an effort to forecast for the future. The R&D and educational programs should then be closely linked to the development strategy of this industrial sector."

(Extracted from "Present Status of Powder Metallurgy in Korea", The International Journal of Powder Metallurgy & Powder Technology, Vol. 20, No. 3, pp. 231-234. Copyright ⓒ 1984 American Powder Metallurgy Institute.)

North America

"Kempton H. Roll, executive director of the Metal Powder Industries Federation (MPIF), in his presentation to PM '84 in Toronto, Canada, said that the North American PM industry had recovered from the recession with a 39% increase in iron powder consumption for PM parts manufacture in 1983, and it was looking to a further 27% increase over 1983 figures by the end of 1984. He predicted that compound annual growth rate in North America should rise to 10% by end of 1985.

"The automotive industry remains of critical importance to PM, stated Roll. This is where it began and this is where more than half of the industry's output still goes. The increase in the production of passenger cars in the USA was 33%, and this helps explain the PM industry's rapid recovery and 39% growth during the same period. Roll said that some new developments in the US auto industry included the imminent use of PM forged connecting rods and the design of a PM camshaft made from chromium, nickel, molybdenum, steel. The camshaft could be in production in a 1987 model 4-cylinder (1.9 liter) engine and a new V-6 (3.0 liter) engine. Sintered friction materials used in automobile metallic and semi-metallic brake blocks and linings is another market beginning to emerge for the metal powder market. About 4,800 tons of iron powder are currently used in this application each year. There was, however, a word of caution to PM part producers. Automotive engineers are becoming increasingly reliant on their parts suppliers to bring new products and applications to their attention. This reliance will include foreign suppliers should they be the most competitive, said Roll."

(Extracted from "Powder Metallurgy - A Global Perspective", Metal Powder Report, Vol. 39, No. 8, August 1984, p. 447. Copyright ⓒ 1984 MPR Publishing Services Ltd.)

"P/M Forging (P/F). The hot forging of pressed and sintered preforms continues to grow. They meet the need for high density P/M products possessing superior physical and mechanical properties. About eight firms in North America now offer P/M hot forged steel parts - mostly for automobiles and trucks, off highway equipment, agricultural equipment and industrial roller bearings. In 1983 P/M hot forging production accounted for about 10,000 tons of iron powder. This figure could increase as much as 25% by the end of this year.

"Powder forging is an extension of the P/M process. In powder forging, however, powder of the required composition or alloy is preformed to a green shape predetermined to give the most desirable flow characteristics to full, or nearly full density during hot forming. P/F parts are accurately and economically formed to finished shapes having physical properties equivalent to conventionally forged parts, often with little or no additional trimming or machining. Such parts are satisfying the requirements of many highly stressed components such as roller bearings and automatic transmission parts. A pilot forging facility has been established by one of the leading powder producers to help parts makers and their customers gain experience and familiarity with this technique. Featuring a 700-ton mechanical forging press, continuous belt re-heat furnace, 500-ton hydraulic compacting press and sintering and heat treating capability the service also includes computer-aided design programs to optimize the preform design. P/F or P/M forging appears to be catching on at last because the industry now knows more about the parameters of the process and consumers are realizing that savings of 50% or more over conventional forging are attainable. There is little or no material loss. Secondary machining operations are dramatically reduced. Energy savings and often performance characteristics of the parts are improved.

"With roots going back to the 1950s, it appears now that powder forging is the fastest developing metal forming process. Most of the applications appear to be in larger parts weighing at least 3/4 pounds and complex ones with gear teeth, splines, serrations, cams, and other complex contours normally associated with the powder metallurgy process.

"Cold Isostatic Pressing (CIP). Cold isostatic pressing offers the advantage of being able to compact metal powder over a mandrel to produce a shaped internal cavity, a feature unattainable with conventional die compaction. The mandrel might have a screw thread, spline, or be encased. Isostatic compacting also expands the potential for larger shapes that cannot be made in conventional P/M equipment as well as complex configurations such as internal threads. Much attention is being paid to a cold isostatic pressing system that has proved the technical and commercial feasibility of making iron P/M cylinder liners for automotive gasoline and diesel engines. Most P/M parts made on this system range in weight from four to 27 pounds.

"Hot Isostatic Pressing (HIP). Hot isostatic pressing (HIPing) is moving swiftly ahead after getting its initial impetus from government funded programs for aerospace applications. One US company is now making HIPed and HIPed clad valves and other well head components for oil and gas well drilling. The parts are made from a nickel based 625 alloy powder. P/M provides good mechanical properties and improved corrosion protection over the conventional 4130 alloy.

"For larger valves over 300 pounds in weight 625 argon atomized powder is HIP clad to a low alloy steel body. Carbon steel cans installed in the valve body are filled with powder that is isostatically pressed in an autoclave at a temperature range of 1,700-2,200 F. A complete metallurgical bond occurs through solid-state diffusion. The clad valves can be heat treated to give a minimum yield strength of 75,000 psi with satisfactory ductility. After HIPing, the cans are removed by machining or chemical etching.

"Valves under 300 pounds are being formed in their entirety as as-HIPed products.

"Rapid Solidification Technology (RST). Rapid solidification technology (RST) has at last achieved commercial recognition. First seen decades ago as "splat cooling" it is now being seen as a newly discovered technique for creating an amorphous metallic system. A great deal of attention is being given to the special properties of rapidly solidified powders for high performance applications, all of which could have a profound effect on the metalworking industry.

"Rapidly solidified microstructures hold promise for whole new metallurgical structures offering combinations of properties previously unheard of. Many of the problems that the traditional metallurgist has struggled with for hundreds of years and with which he has had to compromise, can be eliminated by RST. These include alloy segregation; insolubility or immiscibility of high- and low-melting metals or high- and low-density metals; poor properties at high temperatures; high energy cost of shaping high alloy metals such as tool steels or superalloys; and high production costs in terms of labor, quality control and materials conservation. One company, for example, has used RST to atomize a bearing alloy from an insoluble combination of aluminum and lead. These powders are being directly rolled into sheet, circumventing current costly vacuum canning and extrusion or forging.

"P/M wrought aluminum alloys are being made by rapid solidification techniques to provide greater strength, fracture toughness, corrosion and fatigue resistance through improved chemical and metallurgical structure. Compared with conventional alloys, the P/M alloys have a uniform microstructure, smaller grain sizes (8-10 microns) and offer less variation in isotropic properties.

"The US Air Force Wright Aeronautical Lab in Dayton, Ohio has awarded a $5 million contract to develop a P/M process to make sheet and plate for aircraft and aerospace products. The contract calls for producing mill size P/M billets (about 10,000 pounds each) from high strength P/M wrought aluminum alloys. Work will begin with a 7091 alloy (Al, Zn, Mg, Cu, Co). Tests showed the fatigue life of 7091 was almost three times longer than ingot - metallurgy alloy 7075.

"Wrought RST P/M aluminum alloys can also provide excellent long-term corrosion resistance. In exposure tests, the P/M alloys, in peak-strength tempers, showed no evidence of exfoliation during five years of exposure to a sea coast environment.

"Injection Molding P/M (IM P/M). Injection molding of metal powders is on the verge of substantial commercial production with at least 12 companies involved in the business. Rapid commercialization of this technology is seen in the next five years for smaller, highly complex parts made from 316L stainless steel, nickel iron alloys, tungsten carbide and M-2 tool steel. Active markets being pursued include ordnance, biomedical, watches, computers, business machines and orthodontic devices. A housing and hammer for a high-speed computer printout is in full commercial production. Other applications include a nickel iron surgical clamp and parts for an insulin pump. Electric typewriter components are already being produced by this technique which brings together the strength characteristics of metals and the shaping features of injection molding."

(Extracted from "Progress of Powder Metallurgy in North America", The International Journal of Powder Metallurgy & Powder Technology, Vol. 20, No. 3, pp. 188-190. Copyright © American Powder Metallurgy Institute.)

Sweden

"During 1982-1983 the Swedish P/M parts industry went through a major structural change. A new company, Kohlswa Essem AB (KEAB), was formed by a merger of four small producers: Essem Sintermetall, Glissa AB, the Magnet Foundry of Surahammars Bruks AB and the P/M division of Kohlswa Jernverks AB. The new company has production facilities in three locations in Sweden. KEAB has modern equipment with 60 presses in the range of 2-400 tons and seven sintering furnaces covering a temperature range up to 1450 C. Besides this company there are two smaller in-plant P/M production plants in Sweden, belonging to the SKF and Husqvarna groups.

"The total production of P/M components in Sweden in 1983 was 1,100 tons. The structural changes described above were mainly to create enough funds for intensified development and marketing of P/M products. A promotional campaign directed toward potential users of P/M parts combined with an anticipated higher demand for industrial products in general during 1984-1985 is expected to result in increased production and, thus, to an improved degree of utilization of the available production capacity of the Swedish P/M parts industry.

"From the early 1970s there has been intensive development in Sweden of high performance P/M products from inert gas atomized powders using hot isostatic pressing and extrusion processes for consolidation of the powders. It started some 15 years ago with the ASEA-STORA-process developed jointly by ASEA and the Söderfors Speciality Steel Works which then belonged to Stora Kopparberg AB. The process, comprising dry gas atomizing and hot isostatic pressing, is used in Söderfors by Kloster Speed Steel AB to produce high speed steels, to so-called ASP steels. Production capacity has been increased by the introduction of continuous atomizing and shorter compaction cycles. ASP steels are more expensive than the most popular conventional high speed steels and are therefore used mainly for high performance industrial tools, such as cutting tools in the automotive and aerospace industries, and cold work tools for cold extrusion, blanking, and powder pressing.

"Nyby Uddeholm Powder AB produces various types of stainless and nickel based powders by inert gas atomization. Production in 1983 amounted to 6,000 tons, making this inert gas atomized powder unit the largest in the world. Stainless powders are mainly used in the company's own manufacture of seamless stainless tubes. The process which has been used on an industrial scale since 1980, comprises cold isostatic compaction of the encapsulated powder to a relative density of about 85%, heating in two steps followed by hot extrusion. In comparison with other methods for manufacturing seamless tubes, powder metallurgy offers several technical and economical advantages, such as higher material yield, lower energy consumption, a shorter production cycle and higher flexibility as to material compositions.

"The powders produced by Nyby Uddeholm are used also in the company's extruded bars and profiles, and for powder spraying applications. During the last two years the application of hot isostatic pressing in the manufacture of stainless products from gas atomized powders has been explored and taken into production.

"Surahammars Bruks AB belongs to the ASEA group of companies and produces high quality steel powders by a horizontal gas atomizing called the HORGA process. The powders are used for the production of forging blanks and semi-finished products by hot isostatic pressing utilizing the ASEA Qunitus press and including the so-called STAMP-process, which is a modified hot isostatic pressing method developed by Surahammar-ASEA. In order to further exploit these activities, ASEA and Surahammars Bruk as of January 1984 have formed a jointly owned company called ASEA Powdermet. It is the intention to build a large production plant for the manufacture of powder based products by hot isostatic pressing. The plant will be ready for production at the beginning of 1986."

(Extracted from "Powder Metallurgy in Scandinavia", P.G. Arbstedt, The International Journal of Powder Metallurgy, Vol. 20, No. 3, 1984, pp. 209-211. Copyright © American Powder Metallurgy Institute.)

United Kingdom

"Mr. Dennis A. Barrow of Manganese Bronze Ltd., Ipswich, talked about the impact of the recession and restructuring of the UK automotive industry on the PM part production which is said to have fallen 30% in the three year period to 1982. Total production in 1983 was put at 8,500 tonnes which compares with 11,900 tonnes in 1979 and a high of 12,100 tonnes in 1973. However, over the same three year period the average weight of ferrous components has increased from 33.5 to 37 gr, an increase of 10%.

"Barrow compared the pattern of U.K. PM output with car production statistics. PM growth between 1969 and 1979, although at a lower rate than between 1963 and 1969, was maintained until 1979 by which time the level of U.K. car production had fallen to 70% of its 1973 peak. The onset of the oil crisis prompted a great deal of design and 'value analysis' work which resulted in an increased usage of PM components per car - largely for reasons of weight saving and fuel economy. This could account, in part, for the fact that a much lower level of car production managed to sustain a steady level of PM output. Other factors, such as exports also had an effect. The automotive components industry was by this time enjoying increasing success in penetrating overseas markets and the demand for PM components thus created helped to maintain overall PM output whilst U.K. car production was falling.

"Since 1979 other factors started to influence PM output, not the least of which was the worldwide recession. The PM parts industry has reduced its workforce by an average of 40% since 1980. This cutback incurred immense costs but increased profits are now being forecast and the industry was recently reported as 'showing signs of moving out of the disaster zone'."

(Extracted from "Powder Metallurgy - A Global Perspective", Metal Powder Report, Vol. 39, No. 8, August 1984, pp. 447-450. Copyright © MPR Publishing Services Ltd., England.)

Scenario for 1995

"Looking at the world's population ... there cannot be any doubt that people in developing countries will wish to have their share of the world's wealth in the future. And I would like to add that it is their right to obtain this share at an increased rate of realization. Before being more specific about the detailed needs it is important to mention two serious restrictions, i.e., the financial problems of many developing countries and the limited amount of energy available in most of them. Having all this in mind the following postulates can be formulated:

- There will be a dramatic need for cost effective, low energy consuming mass production methods for consumer goods in the developing countries. Vehicles for personal transport, not necessarily cars, perhaps buses, trucks, scooters, bicycles and boats, will be in high demand and also equipment and tools which facilitate the daily work in the home and at work.
- Installation of these mass production methods must not be capital intensive.
- Production equipment, which likely will come from high-technology countries, will have to exhibit one feature more than any other: reliability.

"Turning now to that part of the world which already has a high standard of living based on fully developed technologies and fabrication methods, the scene looks different. Many mass production methods are well established and competing with each other. This competition causes a constant search for improved, more sophisticated machinery. Quite often the components of this machinery have to function at ever increasing speeds ... and have to withstand higher stresses, higher temperatures, or extreme corrosive attacks. Not only production machinery calls for such extremes but also energy generators, and the equipment used in high speed transport and in information processing. The underlying reason for the constant quest for extreme components is the limited availability of energy and raw materials. Taking this into account the above list of postulates for future needs can be continued:

- There will be a dramatic need for the very efficient use of energy. For many energy consuming or energy converting systems this will produce a need for high operating temperatures and for materials to withstand these conditions.

- There will be an equivalent need for the efficient use of raw materials and consequently for near net shape fabrication techniques.

- There will be a serious demand for high performance components, because high performance of equipment in relation to temperature, wear, corrosion, and lifetime, is best suited to guarantee the efficient use of energy and raw materials.

"In summary, the scenario which emerges for the time span until 1995 incorporates a great need for establishing mass production methods in the developing countries and a need for high performance materials and components in the high technology regions of our world.

- In order to realize the potential of P/M mass production in developing countries a considerable transfer of know-how from the high technology countries must be made possible. No doubt, the latter will also benefit from this through the increased opportunities for export of equipment and machinery.

- Combination (and co-operation) of powder metallurgy with other manufacturing technologies ... must be increased in order to shorten the times for development and commercialization of new processes. For instance, if a newly proposed process calls for billet compaction by cold isostatic pressing and consequent extrusion, progress will be fastest if a company experienced in cold isostatic pressing co-operates with a company experienced in extrusion. At present, powder metallurgy is often too introverted to do this.

- There is a lot of P/M development work going on in industries outside the traditional P/M industry. They also appear to be too introverted and rather try to "reinvent the wheel" instead of seeking the co-operation with the relevant P/M experts.

- Co-operation between various disciplines can be reasonably good at the research and scientific level, however, for the implementation of new processes the co-operation at the practical level of the manufacturing engineer and the production personnel are at least as important. The Japanese industrial success arises to some degree from taking this into account seriously.

- One of the foremost recommendations for practical action is therefore my call for true entrepreneurial spirit in setting up strong teams consisting of companies and research institutes complementing each other in their technical skills and knowledge of the market situation. The goal of these teams is the exploitation of the potential of new materials and processes.

- Full exploitation of the P/M potential will be possible only if the user or potential user of the P/M product is fully aware of its advantages. Comprehensive information on technological as well as commercial aspects must therefore be prepared for the user. This is an ideal area for co-operation among P/M companies. Programs in Europe on the characterization of dynamic properties of sintered steels and in North America on improved marketing methods are first examples for such joint activities.

- Agressive development work is expensive. It must therefore also be a co-operative effort of powder metallurgy to make the user of the products interested in accepting his share of the development costs. Or, as Zapf expressed it: If the customers had voluntarily allocated a share of the profits, which they gained from sintered parts, to R&D, it would have been possible to speed up P/M development for their own benefit."

(Extracted from "Looking Ahead to 1995 - The Future of Powder Metallurgy", The International Journal of Powder Metallurgy and Powder Technology, Vol. 20, No. 3, 1984, pp. 241-242; 252-253. Copyright © 1984 American Powder Metallurgy Institute.)

HOT ISOSTATIC PRESSING: AN ADVANCED TECHNIQUE IN MATERIALS TECHNOLOGY

Heinz R. Konvicka*

Introduction

The hot isostatic pressing (HIP) technique has been known to the scientific community for about 30 years. Rather different incentives led to the independent development of this technique. At Battelle's Columbus Laboratory in Ohio, United States of America, scientists were aiming at a suitable technique to clad nuclear fuel by gas-pressure diffusion bonding. In Sweden, the wish to produce synthetic diamonds naturally resulted in the development of high-pressure, high-temperature processes at ASEA's laboratories. A rather long period of more or less academic interest in HIP followed. The process developed to industrial maturity only within the past decade, and is now considered a special area of powder metallurgy (P/M).

In addition to the powder-compaction application for the manufacture of P/M-HIP materials, the HIP technique is also used for healing defects in cast or sintered parts. Increasing importance is giver to the application of this process as a joining technique, known as HIP diffusion bonding, for the manufacture of composite and compound materials. The rather rapidly increasing number of HIP units in the world, currently around 340, documents the importance of this technique for advanced-materials technology. However, at this point it should be mentioned that due to inherent constraints, such as size limitations and cost, HIP will most likely remain a specialized, but indispensable technique for producing comparatively small amounts of high quality, high performance materials.

Although HIP is usually considered a specific branch of powder metallurgy, it is not in classic terms a powder metallurgy technique. It can be described best as gas-pressure diffusion bonding of powder particles that results in homogeneous, isotropic, segregation-free, non-porous solids. Thus, problems frequently encountered in conventional sintering processes, such as wetability, sintering activity or evaporation of easily volatile components, can be almost entirely eliminated. Furthermore, HIP is also successfully employed as a joining technique due to its process characteristics.

From a basic scientific point of view, the HIP process itself is not yet entirely understood. However, the main steps can be described as follows. In the first phase, the high pressure and temperature applied results in plastic deformation of the powder particles, allowing for very close contact of the powder particle surfaces. In the second phase, surface diffusion among the particles occurs, enabling volume diffusion to proceed. Thus, the powder particles are strongly bonded together without involving liquid phases or binder material during the entire process. This process characteristic is not only responsible for the quality of HIP materials, it also allows for the production of materials that cannot be obtained by conventional techniques due to technical and/or economic constraints.

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The HIP process

From the process description given above it is evident that a suitable encapsulation technique has to be employed in order to prevent the pressure medium (argon gas) from penetrating between the particles to be bonded together. Thus, the main process steps consist of: (1) capsule design and capsule manufacture, (2) filling and welding of the capsule, (3) HIP cycle and (4) decapsulation and finishing.

Powder characteristics

Powder material is an essential prerequisite for the process. Numerous processes are available for powder production, detailed descriptions of which can be found in the relevant literature. In the HIP process, powder quality with respect to filling density and contamination by impurities poses the main criterion. Consequently, spherical powders produced by the gas-atomization process are most widely used.

All powder particles have to have the same chemcial composition that has to be identical with the desired composition of the final product. Otherwise, no homogeneous HIP product can be expected. The powder surface has to be free from impurities, especially oxygen or other interstitial element layers, since such layers act as a diffusion barrier, thus preventing satisfactory bonding of the particles. Good flow properties of the powder are necessary to ensure that all cavities of a given capsule are homogeneously filled. The filling density should reach at least 60 per cent in order to prevent unpredictable shrinkage during HIP. Low filling densities require pre-compaction by cold isostatic pressing (CIP).

Capsule design and fabrication

Especially for near-net-shape-parts fabrication, correct capsule design is essential to ensure that all advantages of HIP are used to the maximum extent possible. Thus, the shrinkage during HIP (minimum filling density of powder is 60 per cent, final density is 100 per cent) has to be considered carefully by appropriate calculations. For complex shapes, these calculations have to be completed by empirical tests.

Generally, the capsules are made out of appropriate tubes, sheets, etc. by welding. Leak-tightness is essential. Mild steel is mainly employed as capsule material. Special applications may require special capsule materials, such as stainless steel, glass or molybdenum. For complex structures, a wax model is coated galvanically. After wax removal, the precisely shaped capsule is available.

Filling and welding of the capsule

During the filling procedure, it is essential that all capsule cavities are homogeneously filled with powder. Certain powder materials might also require capsule evacuation and/or baking in a vacuum or inert gas atmosphere before applying the final weld. Contaminations of any kind have to be avoided. The importance of leak-tightness of the final weld is self-evident.

HIP cycle

The basic parameters governing the compaction process are (1) the HIP temperature (T_{HIP}), (2) the HIP pressure (P_{HIP}) and (3) the holding time (t_{HIP}) at T_{HIP} and P_{HIP}. For a variety of materials which are sensitive to precipitation reactions in certain temperature ranges and for HIP diffusion-bonding applications, the cooling rate from T_{HIP} to room temperature is also important (e.g. nickel-based super alloys).

The quantity of the HIP parameters is strictly dependent on the material to be HIPed. Usually, a HIP parameter variation study is done if a new material composition is to be HIPed. From the results of an analysis of material properties after HIP, optimized HIP parameters are chosen. Without doubt, this is a rather time-consuming undertaking. However, it pays off with respect to the constant quality of the final product and also allows for preparing HIP compacts with the desired properties within a certain range. Thus, only a general statment on HIP parameters can be given: T_{HIP} is usually kept in the area of 0.5 to 0.8 of the melting temperature of the material to be HIPed; P_{HIP} amounts to around 100 MPa; and t_{HIP} is typically in the order of several hours. A total HIP cycle usually lasts between 6 and 12 hours.

Decapsulation and finishing

Depending on the materials and shapes involved, the removal of the capsule after HIP can be facilitated by either chemical or mechanical means. Given an optimized capsule design, the final machining effort is reduced to a minimum.

Advantages of HIP

From the description given above, the advantages of HIP can be easily deduced:

- HIP materials are characterized by a homogeneous, segregation-free and non-porous microstructure.
- The mechanical properties are improved as a consequence of this microstructure.
- Quick and economic manufacture of near-net-shape parts is facilitated. The more difficult to machine and the more expensive the material, the more advantageous becomes the HIP route.
- Semi-finished products, e.g. various qualities of tool steel, manufactured from HIP billets by further forming are characterized by improved material properties, thus substantially increasing tool life times in certain applications.
- Material compositions that so far could not be obtained by conventional means (e.g. very high carbon tool steels (3.2 per cent carbon) and composites) are achievable.
- Joining by HIP diffusion bonding is extremely well suited to the manufacture of compound materials. Uniform bonding with proper strength is even achieved when combining materials with rather different properties, e.g. metals to reactive metals, metals to refractory metals, metals to ceramic materials.
- Joining of identical materials allows for the manufacture of uniquely shaped construction parts, e.g. parts with axial, symmetric cooling channels.

Generally, appropriate application of HIP techniques results in reduced material and energy consumption, in savings of finishing efforts, in improved life times of structural components and, thus, in an increase in overall economics.

No direct competition between HIP and conventional sintering processes can be seen. HIP enables the production of a rather small series of full density materials at a rather high level of material costs. Conventional sintering is extremely useful for the large-scale production of complexly shaped parts, e.g. for the automotive industry, with lower densities and at rather low levels of material costs. For sintered hard metals on the basis of tungsten carbide, HIP has become a well-received method to remove residual porosity.

Other powder metallurgy technologies such as Consolidation by atmospheric pressure (CAP), STAMP (developed by ASEA) or powder extrusion are also available. However, they generally require further forging for the manufacture of construction parts. Thus, overall economics is governed by the economics of the forging process.

Application fields of HIP

Defect healing

The high-pressure, high-temperature environment during the HIP cycle facilitates the closing of residual pores in cast or sintered materials. This results in improved material properties or at least in a significant reduction of the scatter band of materials data. Since generally only closed porosity prior to HIP is observed, there is no need for encapsulation because the material itself acts as a capsule. However, this might lead to the necessity to control the pressure gas purity if castings sensitive to gas impurities such as oxygen or carbon-containing compounds (e.g. titanium or titanium alloys) are to be HIPed. Open porosity requires repair welding prior to HIP.

At present, defect healing appears to be the most wide-spread application of HIP. Around 15 to 30 per cent of the production of sintered hard metals on the basis of tungsten carbide are delivered in the as-HIPed condition. Substantial portions of titanium/titanium alloy castings and nickel-based super-alloy castings, as well as some stainless steel castings, are subjected to a HIP treatment. Repair-HIP of turbine blades is also a well-established procedure. HIP treatments have proven successful in many other areas, e.g. in ceramics. However, introduction on a larger scale has not yet taken place.

Powder compaction

Billets. P/M-HIP billets are generally made out of cold work steel or high-speed steel powder. The HIPed billet is forged to semi-finished products such as rods, bars. Forging is usually done since it further improves the toughness of the materials. The size of the billets is governed by the requirements for forging and the available size of the HIP equipment. Billet diameters usually are on the order of several hundred mm; billet lengths are around 1 m to 1.5 m.

Improved mechanical properties, wear resistance and machinability characterize HIP tool materials. This results in increased tool life times. Improvements as high as by a factor 15 have been observed. Several P/M-HIP tool steel qualities have already been introduced in the market.

Near-net-shape parts. A large variety of materials have been successfully compacted by HIP, e.g. various nickel-based super alloys, titanium and titanium alloys, various steel and stainless steel qualities, cobalt-based alloys, chromium, special metals and alloys such as nickel-chromium-silver (NiCrAg) or copper-chromium-zirconium (CuCrZr) and ceramics. P/M-HIP parts are generally used in those cases where they provide improved technical solutions at competitive overall economics. In some cases, HIP might even provide at present the only technical solution to a given material problem. P/M-HIP parts are already successfully employed in off-shore industry, in the power-generation industry and in the extrusion or glass industry. For the future, an increased use in the existing applications and numerous new applications are expected.

Composites. Strictly speaking, a discussion of composites should also be included in the section on billets and near-net-shape parts. However, the specific features of composites justify a separate treatment. Composites can be prepared via the HIP route, when two powders with different chemical composition are mixed prior to HIP. Thus, a homogeneous distribution of the two phases with excellent bonding is achieved. As a typical example of this class of materials, composite used as wear-resistant materials have been prepared by HIP that consist of hard phases such as titanium carbide (TiC), embedded in metallic matrices such as cold work or hot work tool steel. The results show that the HIPed product offers at least adequate and in some areas (e.g. bending strength) even improved properties. The time-consuming and rather expensive conventional process of liquid-phase sintering that is necessary due to wetability and solubility problems could thus be avoided.

Further composites of the steel/alumina and iron/alumina type have also been prepared successfully. However, the work in this area must be considered as being in the advanced-development phase, but appears to offer a promising potential for the future.

Diffusion bonding

HIP diffusion bonding provides an excellent solution for the manufacture of compound materials that are difficult to obtain by conventional joining techniques. There are three different approaches:

- solid/solid diffusion bonding;
- solid/powder diffusion bonding with simultaneous compaction of the powder phase;
- powder/powder diffusion bonding with simultaneous compaction of the powder phases (mixing of the powders has to be avoided by specific capsule design).

The decision as to which approach should be chosen is dependent on factors such as availability of powders, geometry of the final shape and economic considerations. For all approaches, it is essential that the areas to be bonded are enclosed leak-tight. The isostatic pressure applied during HIP results in uniform bonding almost independent of shapes and position of the bonding areas.

Numerous applications demonstrate the advantages of this technique: (1) large (0.5 m by 1.5 m) compound sheets, where one compound is entirely clad by the second component, can be fabricated; (2) comparatively cheap base materials can be combined with rather expensive components such a wear- and/or oxidation-resistant materials in various geometries; (3) foils of 50 μm thickness can be diffusion-bonded to basic structures; and (4) tubes can be clad on the inside or outside with a thickness of several mm. In these and many other cases, HIP diffusion-bonding has provided a technically advantageous and cost-effective solution, sometimes even the only solution available at present to satisfy given material requirements. Far more applications will become available in the future when the method becomes better known in all areas of industry.

General aspects of introducing the HIP technology in developing countries

Technical aspects

Infrastructure. A typical HIP unit consists of an autoclave, equipped with a furnace and an isolation hood, and the auxiliary systems (gas system, vacuum system, cooling system, control board and for larger units a hydraulic system). Various sizes are available ranging from the so-called Mini-hippers (work-load volume up to around 100 mm in diameter and 300 mm in height) up to large HIP units (work-load volume more than 1 m in diameter and several m in height).

Mini-hippers are designed to operate in a laboratory environment. For large units infrastructural requirements vary with size. In order to provide more concrete data, a typical larger size HIP unit of around 0.7 m in diameter and around 1.5 m in height is chosen to serve as a model unit for the ensuing discussion. The following infrastructure is required for this model unit. A building of around 100 m^2 in area and a height from -3 m to +5 m ensures confortable operation of the unit. A crane capable of supporting 5 to 10 tons is essential. An electricity supply of 500 kW, a liquid argon storage tank for 2000 cubic metres under standard temperature and pressure and cooling water with a flow rate of 3 cubic metres per hour must be available. A mechanical workshop should complete the infrastructure: all basic machining operations and sheet-working and welding equipment should be available. However, the equipment of the workshop must comply with the planned product range. It is also recommendable to provide for some laboratory equipment for quality assurance and quality control.

Required personnel. For satisfactory operation of the model HIP unit, one engineer and one operator are required. The engineer should have sound knowledge in electrical or electronic engineering, pressure technique, vacuum technique and construction planning. The operator should have at least a technical background. Proper training might help significantly in reducing potential difficulties. Additional personnel is required for the preparation of work-loads, for the workshop and for quality assurance and quality control tasks. However, the number of people will strongly depend on the product range and output envisaged.

Approaches to impelementation of HIP. Since the technical and market situations as well as the overall economic environment might vary considerably, only general comments on how to best implement HIP operations based on some experience can be given. Local factors have to be considered on a case-by-case basis.

(1) Definition phase

A market survey proves to be a useful tool for analyzing the potential for HIP products qualitatively and quantitatively. From these data, the product range envisaged and an output estimate can be derived.

(2) Planning phase

The size of the HIP unit is determined on the basis of the evaluated information. A detailed analysis of offers with respect to all technical and economic factors allows for the selection of the HIP unit best suited to fulfill the given task. It should also be mentioned that certain import/export regulations might exist. Since delivery times for HIP units are currently on the order of one year, there remains sufficient time for adequate planning and erection of the infrastructure and the supporting structures, the extent of which is dependent on the product range.

(3) Installation and start-up-phase

The typical installation time for the model HIP unit is on the order of several months, if optimum preparation of the infrastructure and the necessary equipment for handling heavy loads is provided. Assistance by the supplier of the HIP unit can be arranged. Upon completion of the installation, all components are checked. In several start-up cycles, the HIP unit is taken into full-scale operation. Local licensing requirements for high-pressure equipment have to be met.

(4) Operation phase

Depending on the HIP parameters, one to two cycles per day can be run in the model unit. Proper maintenance ensures high plant availability, which is essential for the routine production process of the whole enterprise.

Economic Aspects

No exact figures can be given on the economic aspects of HIP operation due to local variations in price and salary levels. However, at present the investment costs for the HIP unit alone are on the order of 0.5 to 2 million U.S. dollars. The investment for the infrastructure and support structure has to be calculated on a case-by-case basis.

For evaluating the operating costs of the HIP unit, the costs for amortization, working hours, electricity and gas consumption as well as other consumables (e.g. spare parts) have to be taken into account. Usually, costs are either given per HIP cycle or per kg of HIPed material for a given material and a given load factor.

The output potential of a HIP plant depends on the plant availability and on the load factor. The reference unit should provide an annual capacity of around 500 t of steel billets (based on one HIP cycle per working day).

High plant availability, a good purchasing policy, especially for powders, a good product policy and quality contribute significantly to ensure the success of HIP implementation and positive overall economics. From numerous present applications of HIP products and their advantages as well as from new developments opening new application fields, very good future prospects for the HIP technology can be expected.

Co-operation and available experience

Due to the high technology involved in HIP, it appears difficult to enter this area without basic experience and know-how. Although it is without doubt possible to gain experience, it is a time-consuming and rather expensive undertaking. Therefore, co-operation with an experienced partner might be benefical for the implementation of HIP. The co-operation agreement will most likely follow the usual lines of technology transfer: know-how transfer, training of personnel, consulting during the planning phase, assistance during installation and start-up, and trouble-shooting in the early stages of routine operation.

The available experience with such co-operation in the field of HIP is rather limited, since only a few HIP units of mostly the lab-scale type are installed in developing countries. However, from numerous other examples of technological co-operation that have been undertaken successfully, it can be concluded that arrangements for implementation of HIP in developing countries will succeed in a similar manner.

POWDER METALLURGY: A SUMMARY ABOUT A TECHNOLOGY OF THE FUTURE

Gerhard Jangg* and Herbert Danninger**

Introduction

In the course of the last 40 years, powder metallurgy - the technology of producing compact materials from powders - has undergone fundamental changes. From a somewhat exotic technology for the production of equally exotic materials, it has been developed into a production technique with almost unlimited possibilities, both concerning the materials produced and the shapes of the parts.

With respect to the powder metallurgy of "conventional" materials, such as iron, bronze, aluminium, the principal advantages of powder metallurgy compared to other production processes are (1) the possibility of producing complicatedly shaped parts in large numbers at moderate cost and (2) the excellent tolerances obtained without the necessity for further machining. For most standards the as-sintered tolerances are sufficient. By calibrating, i.e. re-pressing the sintered samples, often in a special die, the tolerances can be further improved. Furthermore, the powder metallurgy technique enables the production of materials that cannot be obtained by conventional processes, e.g. two-phase alloys with large differences in the melting points. By far the most important of these materials are the cemented carbides, but also important are tungsten-silver (W-Ag) and tungsten-copper (W-Cu) contact materials and cermets, i.e. metal-ceramic compound materials. Numerous materials that could not be melted until recently were produced nevertheless by powder metallurgy, e.g. tungsten, molybdenum, tantalum. Although melting is now possible in arc or electron beam furnaces, the fine, homogeneous microstructure of sintered materials makes them much better suited for further treatment, e.g. rolling, swaging etc. For the same reason, high-speed steels are increasingly being produced by powder metallurgy techniques instead of the usual casting. Finally it must be stated that powder metallurgy is still not at the peak of its development, but that it is still a technology of the future. Both in the field of new production techniques and materials technology, the possibilities of powder metallurgy are being constantly expanded.

The principal steps of the powder metallurgy production process are compaction of the starting powders and sintering, i.e. heat treatment at a temperature below the melting point of at least one component. Further steps may be added according to the type of material to be produced. A flow diagram of the standard production process, from the powder to the final product, is provided in figure 1.

Production of metal powders

The oldest process of powder production, crushing and milling of compact materials, is now used only for some special purposes, e.g. for ferro-alloys and titanium and, after cooling in liquid nitrogen, for stainless steels. Production of iron powders from scrap by crushing is now thoroughly obsolete.

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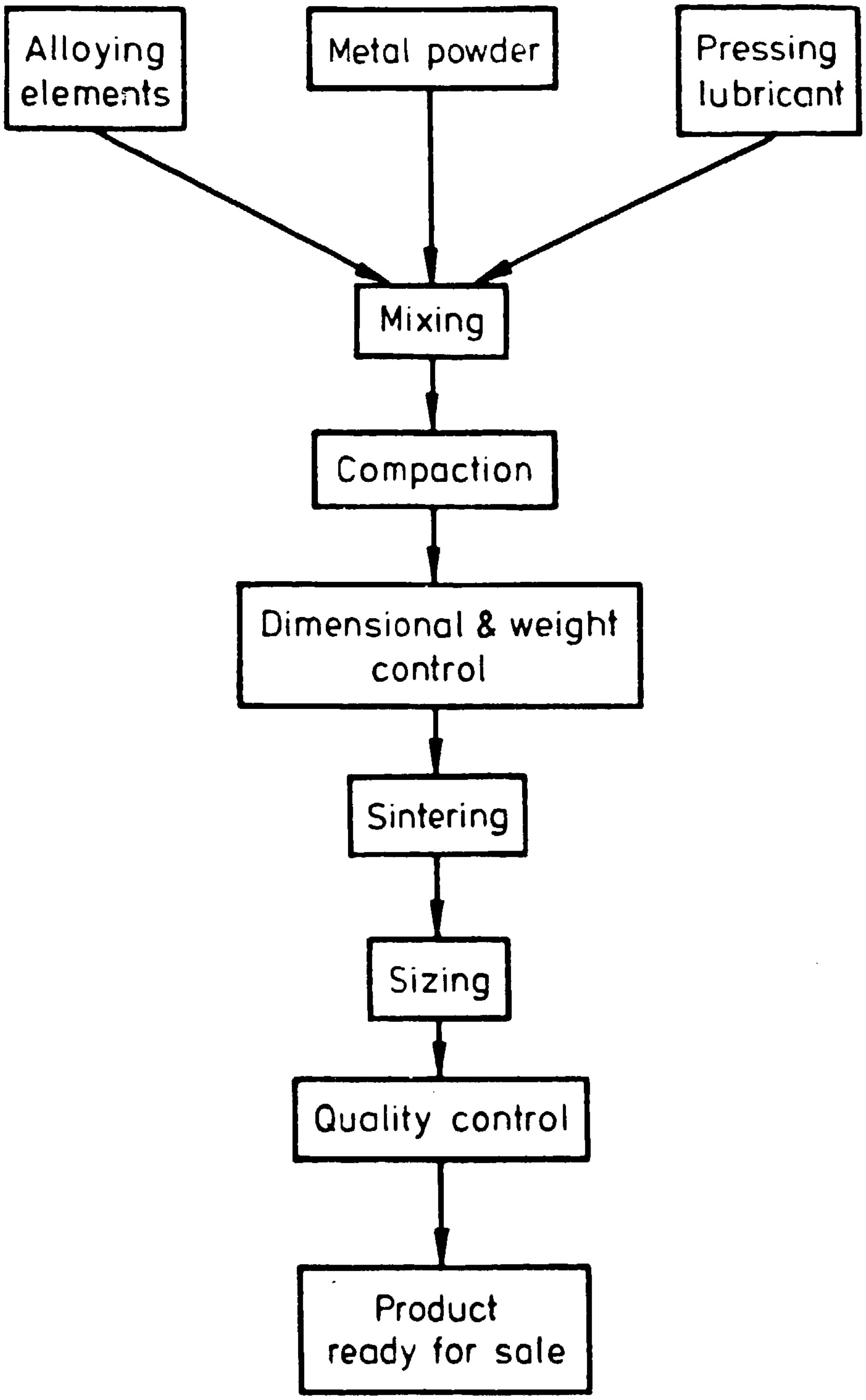
Figure 1. Flow diagram of the standard powder metallurgy production process



Reduction of oxides is the usual production process for molybdenum and tungsten powders, the reduction being carried out with hydrogen in pusher furnaces. Reduction processes are also of great importance for iron powders, more than half of the iron powder being produced by reduction. Selected starting materials - magnetite or rolling scale - are reduced with charcoal or coke or, for purer materials, with reducing gases, especially hydrogen which is however the most expensive variant. Although the reduced powders - sponge iron powders - are increasingly replaced by atomized types, they continue to be used for some applications where low price is decisive.

The most important type of powder production is atomizing: a jet of molten metal is dispersed by air or inert gas or by jets of water. The resulting droplets after solidification form powders that are very well suited for powder metallurgy production. A sketch of a typical atomizing plant is shown in figure 2; the nozzle is shown in detail in figure 3.

Iron may be atomized by both air and water. In the former case, the higher carbon content in the melt is advantageous since the carbon reduces the oxide layers inevitably formed during atomization in a further annealing treatment. With water-atomized powders the de-watering and drying steps are of decisive importance. In both cases the powders have to be finally annealed in hydrogen to remove the last traces of oxygen that otherwise would deteriorate the compactibility. Atomization of alloy melts is often impractical since the alloy powders are harder than the pure materials and thus less compactible. Therefore, for alloyed powder metallurgy parts special powders are usually used, such as those supplied by Höganäs AB, Sweden, of the Distaloy quality. The alloy element particles are sintered to the iron grains, thus preventing segregation during mixing but retaining compactibility. Stainless steel and super-alloy powders are atomized by inert gas, mostly argon. A sketch of a typical inert-gas atomizing plant is provided in figure 4. Similarly the so-called "rotating electrode process," in which a rapidly rotating arc electrode is consumed and dispersed into fine particles, is used only for expensive powders for which the atomizing cost is only of secondary importance. A sketch of such a plant is provided in figure 5.

Aluminium powders are also produced by atomizing. Compressed air is used as a disperser, although precautions must be taken to avoid the very dangerous aluminium dust explosions (temperatures up to 3000°C!). Copper, bronze and tin powders are produced by water atomizing, the process being quite similar to that described for iron.

Direct electrolytic deposition of powders is of importance only for copper, easily compactible powders being obtained directly from the solution. For chromium and manganese a somewhat more complicated process is necessary: the metals are deposited in compact form, but, since they are brittle from co-deposited hydrogen, they can be easily milled. The hydrogen is removed by annealing and the resulting powders are ductile and satisfactorily compactible.

Finally, very fine and pure powders can be obtained by decomposition of carbonyles. Most nickel powders as well as some special iron powders are prepared by thermal decomposition of nickel carbonyle and iron carbonyle.

Generally, the properties required for powder production are sufficient flow characteristics, especially for die compaction, in order to ensure homogeneous filling of the die, and high bulk density to enable the die and punches to be as short as possible. Furthermore, good compactibility, i.e. maximum density of the pressed compact ("green density") at standard compacting pressures, and of course sufficient strength of the compact ("green strength") are also necessary, although the last two properties are difficult to obtain simultaneously. For example

Figure 2. Sketch of an atomizing plant

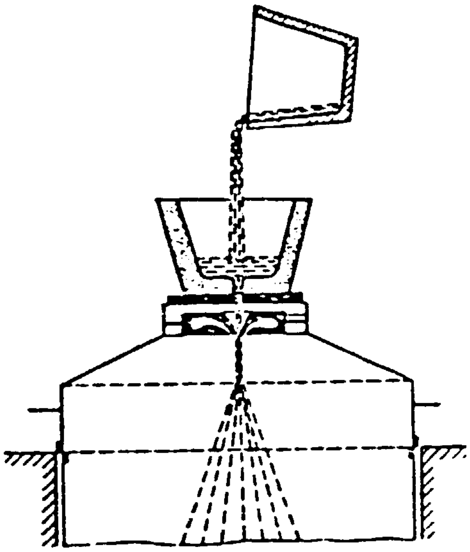


Figure 3. The nozzle of an atomizing plant

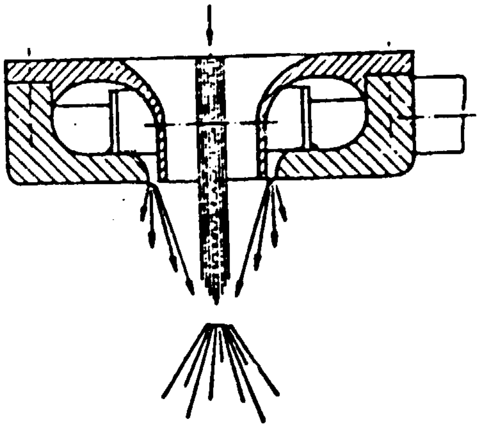


Figure 4. Inert gas atomization unit

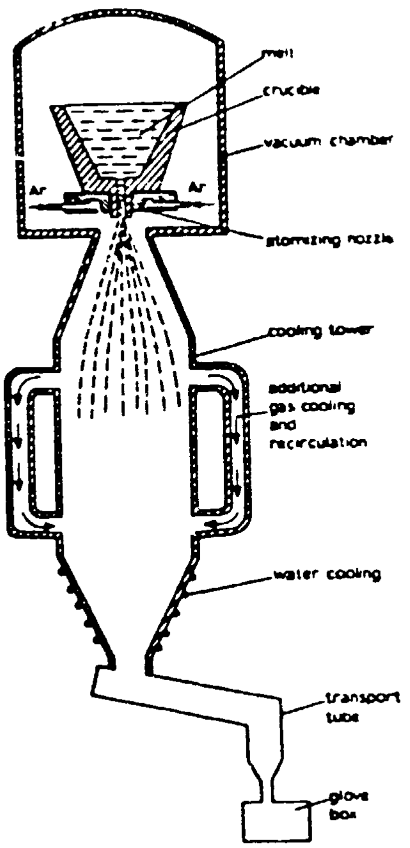
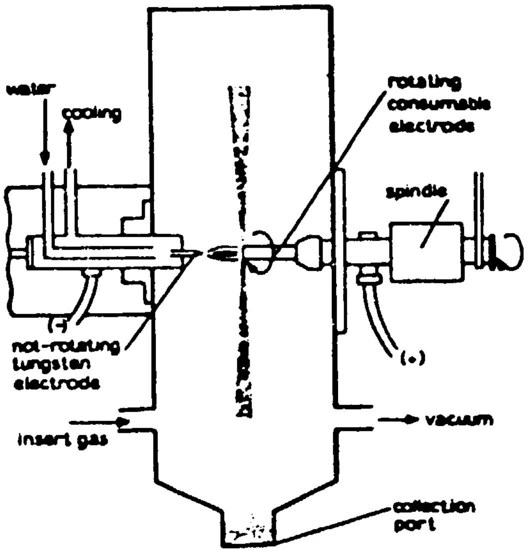


Figure 5. Rotary atomization unit



spherical powders result in the highest green density but in the lowest green strength. With up-to-date iron powders, the compromise is spherical particles with a spongy surface to obtain some green strength. Of course the sintering behaviour of the powders is also of decisive importance: shrinkage, resulting properties at given sintering conditions, etc. However, the most important criterion for powder metallurgy powders, which makes powder metallurgy possible, is the homogeneity of the powders, not only in individual batches but within the powder type. The main advantage of powder metallurgy of "common" metals - iron, copper, bronze etc. - is the excellent reproducibility of properties and dimensions over a large series, which is only possible if the tool adjustment results in the same dimensions and the sintering conditions result in the same properties for the first and last parts of a series, which of course is possible only with really constant powder quality.

The powders must be frequently tested, at least with every new powder charge, measuring flow characteristics, bulk and tap density and green densities at various compacting pressures. Chemical analysis mainly comprises reducible oxygen, determined as weight loss after heating in pure hydrogen (hydrogen loss) and irreducible oxygen, e.g. oxides of silicon and aluminium, etc., which inhibit proper sintering.

Mixing

Due to the demand for homogeneity, especially with alloys, mixing of the powders has to be carried out carefully. Mixing is also necessary for single component materials that have to be die compacted, since pressing lubricants usually are added to the metal powder to reduce friction between the powder and the die wall as well as between the individual powder particles, thus improving compactibility. Stearic acid and various types of waxes are usually employed; the lubricant has to evaporate without residue at moderate temperatures. To ensure homogeneous compactibility and to avoid holes after lubricant burn-out, the pressing lubricant has to be evenly distributed by appropriate mixing. The mixing process has to be carried out cautiously, however, as too energetic mixing might induce cold work in the powders and thus deteriorate compactibility. The mixers used differ widely in size and shape. Double cone mixers, K- and Y-shaped mixers, are the types most frequently used. In any case, dead spots must be avoided, but all powder contained by the mixer must be included in the mixing process.

Compaction

One of the most important steps in the powder metallurgy production process is the compaction of the metal powders to shape them and to afford the required densification of the material. The bulk density of metal powders is between 20 and 45 per cent of the theoretical density. By compaction, the density can be increased, according to the type of compaction process, to between 60 and 100 per cent. The relative density attained by compaction with most materials strongly influences the properties of the sintered part, too.

Die compaction

The most widely used compaction process is die compaction. The tool used consists of a die and an upper and lower punch. The compaction cycle comprises filling the die, application of pressure and removal of the compact. Compaction may be carried out in single-action or double-action presses (see figure 6). In single-action pressing, compaction is relatively inhomogeneous, and this type is therefore used only for small and flat parts. Double-action presses are mainly used: the compaction is carried out symmetrically from above and below, and a small area of lower density remains only in the centre of the part. Double-action pressing enables production of parts with a height up to 80 millimetres. The same

Figure 6. Densification by single action (a) and double action pressing (b)

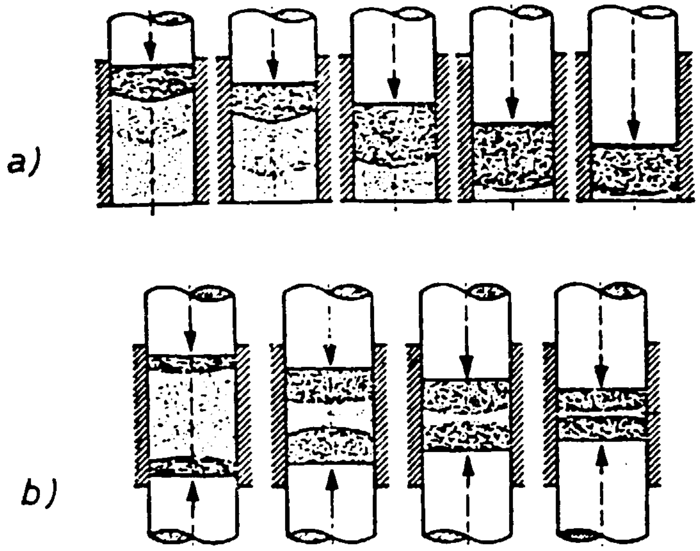
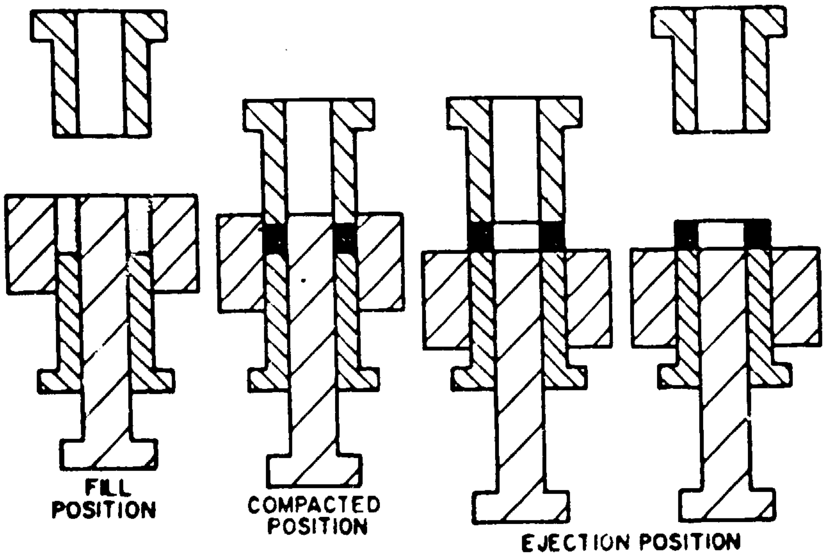


Figure 7. Floating-die pressing tool: removal of compact by withdrawal of die



effect as with double-action may be attained by using sliding dies, i.e. the lower punch is fixed and the die moves axially to the punches. The die is held in the filling position by springs and due to friction moves down during compaction, thus affording the necessary movement relative to the lower punch to result in the same effect as double-action pressing. The ratio between the upper and lower compression zones is determined by the strength of the springs.

Removal of the parts from the die is afforded either by ejection by the lower punch or, in the case of sliding dies, by a downwards movement of the die until the part can be pushed away (see figure 7). Because of the importance of sliding die tools, this second practice is more important than the ejection type, although there are various combinations. For complicatedly-shaped parts, e.g. with steps, the lower punch has to be divided to compensate for the different filling heights. A sketch of such a pressing tool is provided in figure 8. In this case even the upper punch consists of two parts. Caution has to be taken, however, to avoid punches that are too long and thin, since these are prone to fracture. For more complicated parts, even horizontally split dies are used to produce parts that cannot be normally ejected.

Generally, a disadvantage of co-axial pressing is the impossibility of producing parts with bores or profiles perpendicular to the pressing axis. Co-operation between producer and customer is always necessary to check if these features are really necessary. Some shapes that cannot be produced by co-axial pressing are shown in figure 9, along with slightly changed parts that are producible. Very often a small variation that does not affect the function of the part makes it suited for powder metallurgy production.

For compaction both hydraulic and mechanical presses are used, the former being used mostly for larger parts while mechanical pressing is suited more for small pressures, i.e. small parts, and high-compaction rates. The compacting pressure depends on the material, but the upper limit for standard tools is 600 megapascals (MPa).

Isostatic pressing

The second important compaction process is isostatic pressing. The metal powder is poured into an elastic bag with the shape of the desired part and then inserted into a pressure chamber. By hydraulic fluids, pressures of up to 600 MPa are applied, and the pressure is exerted equally from all sides (isostatically). The process is schematically described in figure 10. This homogeneous pressure distribution results in high green densities and is recommendable especially for powders that are difficult to compact in dies, e.g. brittle powders such as molybdenum, tungsten and ceramic powders. Shapes that cannot be die pressed can be produced by isostatic pressing, although the tolerances are not comparable with those attained by die pressing. The pressing rate is also lower, although recently developed automatic isostatic presses enable pressing rates almost as high as with die pressing. For special purposes, isostatic pressing is carried out at elevated temperatures. For this hot isostatic pressing (HIP), the pressure vessel contains heating elements thermally insulated towards the outer shell. Hot isostatic pressing is applied mainly for expensive materials, such as high-speed steels.

Die pressing is also carried out at elevated temperatures, especially for ceramics, although the high temperatures dictate the use of graphite for die and punches. The compacting pressure therefore is very limited. Of much greater importance is powder forging: pre-forms are pressed from the starting powders and pre-sintered. Then they are heated to the required temperature and forged into the final shape. Sufficient material flow during forging is essential for the success of powder forging; thus the pre-forms are always smaller and also less complicated than the final parts. Under favourable conditions, almost theoretical density is attained, and the resulting properties are quite comparable to those of compact materials.

Figure 8. Pressing tool with multiple punches for complicatedly shaped parts

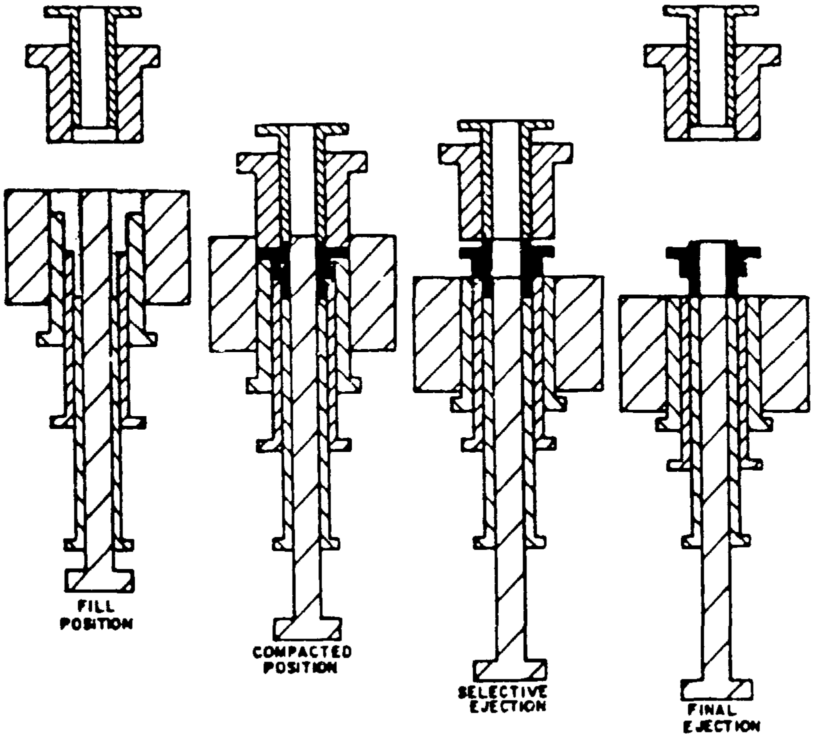


Figure 9. Possible and impossible shapes for co-axial pressing

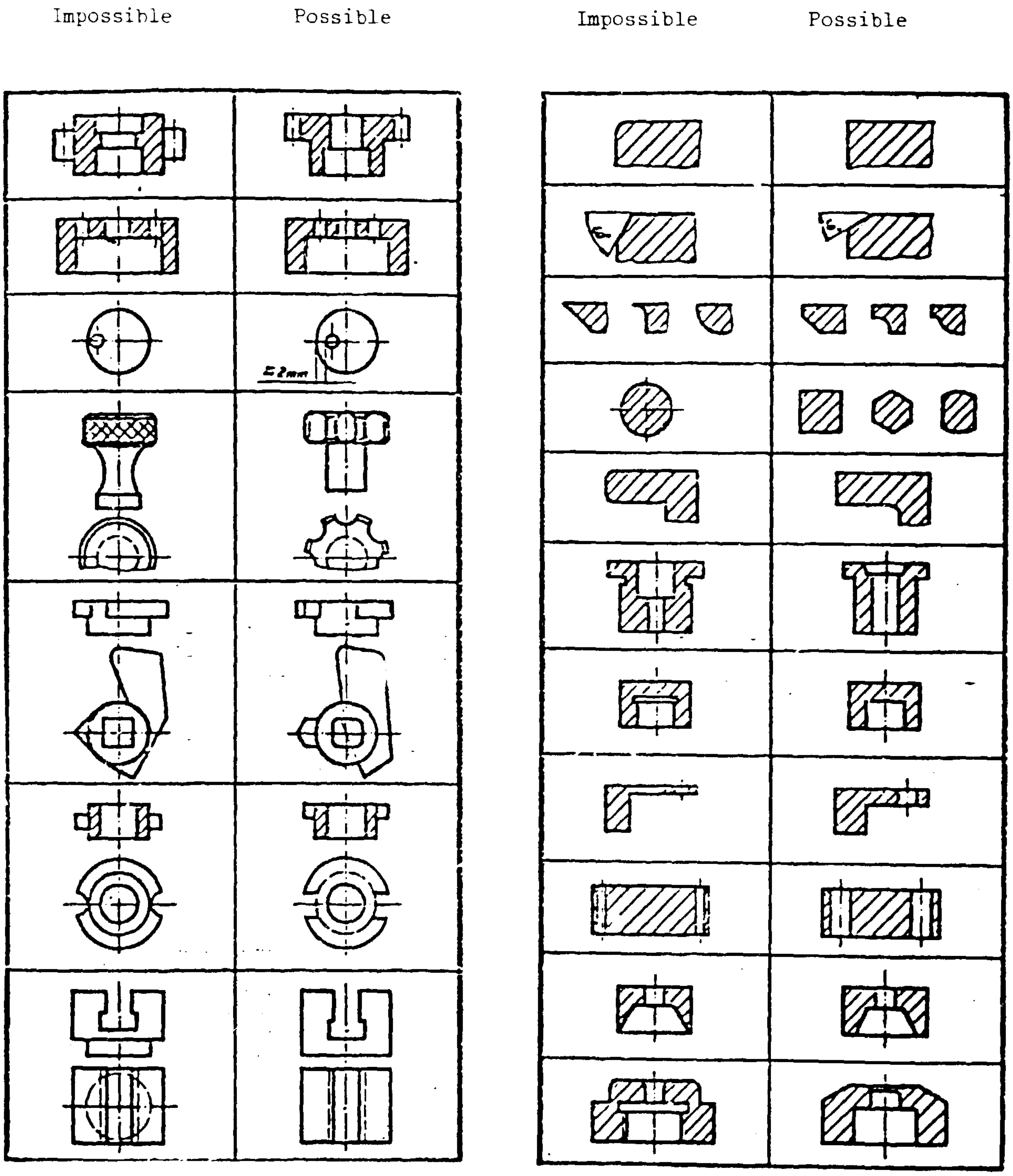
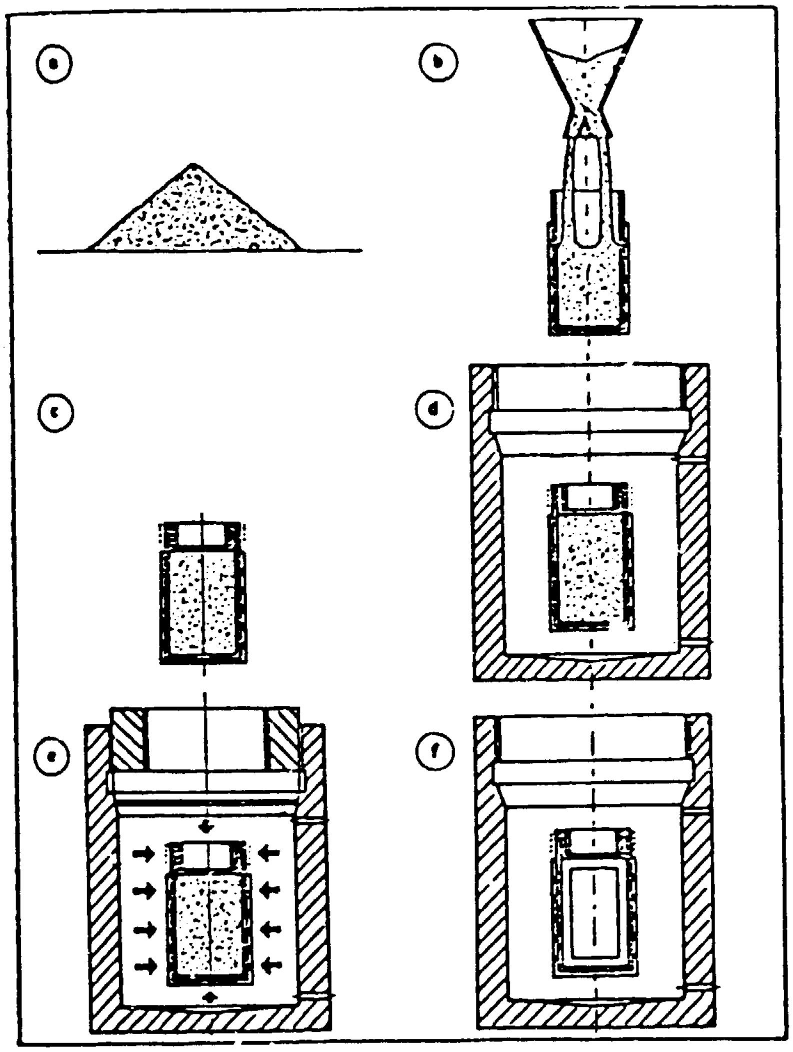


Figure 10. Principal sketch for isostatic pressing



a) material to be compacted (powder)
b) fill-up of flexible form
c) closed and sealed form
d) form in pressure medium in pressure vessel
e) pressurising
f) resulting compact, after decompression

The tolerances attainable are usually better than with the swaging of compact materials, but appreciably inferior to those of pressed and sintered parts because temperature gradients in the parts during forging cause different shrinkage during cooling and may even cause distortion. Powder forging is constantly improved and is thus applied to more and more parts for which the demands are more towards strength and less towards extreme tolerances.

Sintering

The green compacts produced by die or isostatic compaction possess green strength sufficient only for handling, as their strength depends on adhesion of the powder particles. The strength necessary for practical application is obtained by a heat treatment called sintering. Sintering may be carried out at temperatures below the melting point of all components, usually two-thirds to three-fourths of the melting temperature (solid state sintering) or at temperatures where, at least temporarily, the liquid phase appears (liquid phase sintering). A permanent liquid phase causes rapid densification but increases the danger of distortion. If close tolerances are required, solid-state sintering or sintering with only an intermediate liquid phase is carried out, the liquid phase in the latter case appearing only in the first minutes of the sintering process and causing accelerated sintering but no excessive shrinkage.

The mechanisms of solid-state sintering have been thoroughly examined and are comparatively well known. The driving force, at least with single-component systems, is the decrease of surface energy. During the heat treatment, the contact areas between the particles, which are almost points after compaction, grow by diffusion of material from other areas of the particles to the necks (see figure 11). Finally, after rigorous sintering, the contact areas (sintering necks) are almost as large in diameter as the particles themselves, and the pores are almost spherical, thus eliminating notch effects and also increasing strength and ductility. The density usually is not decisively increased, however material is transported out of the original contact zone causing "contact flattening" and thus some shrinkage.

The type of furnaces used for industrial sintering is usually continuous. Batch-type furnaces are used for special purposes, e.g. sintering of very large parts or vacuum sintering. The simplest type of continuous furnace is the pusher furnace: the boats containing the parts are inserted into the furnace one by one and pushed forward, the line of boats thus proceeding through the whole furnace. Belt types are also widely used, the transporting belt material being a nickel-chromium, air-resistant alloy (see figure 12). The temperature limit in this case is 1120°C. For higher temperatures, walking beam furnaces are used, in which a longitudinal beam takes the boats step-wise through the furnace.

The heating elements may consist of air-resistant iron or nickel alloys; they can be used up to 1100°C, but only in a non-reducing atmosphere. For higher temperatures, silicon carbide or molybdenum silicide elements are used in an oxidizing atmosphere and molybdenum or tungsten in reducing and carbon-free atmospheres. Graphite elements are used mainly for vacuum furnaces intended for sintering cemented carbides.

Sintering of metals usually has to be carried out in a non-oxidizing atmosphere, since oxide layers on the powder particles prevent the formation of sintering necks. Mainly reducing atmospheres are employed, the water vapour content of which (expressed by the dew point) varies according to the material to be sintered. With plain iron, for example, the dew point is not very critical; with stainless steels, however, the dew point at sintering temperature must be below -40°C to avoid formation of chromium oxide layers.

Figure 11. Solid state sintering of spherical (a) and irregular (b) powder particles

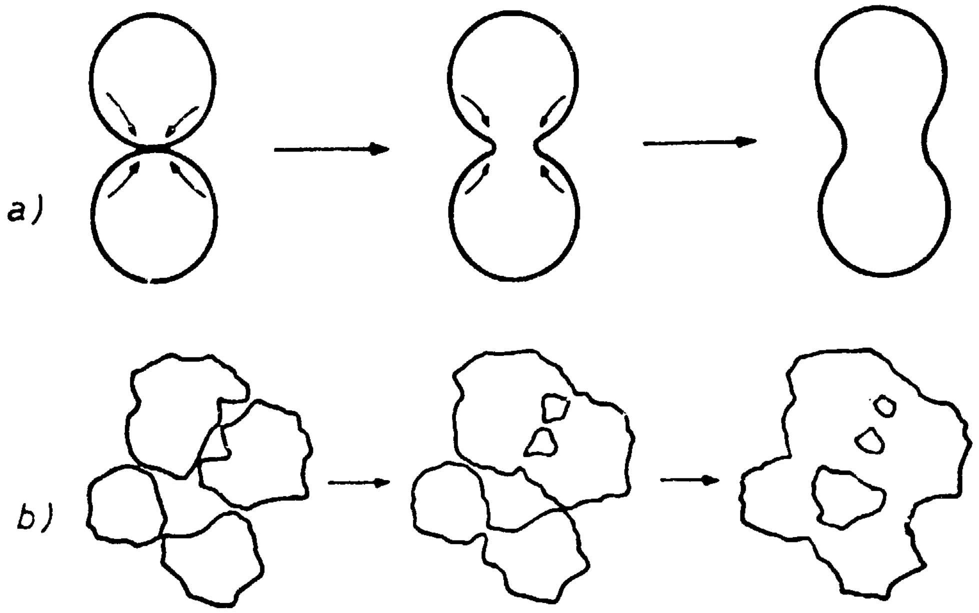
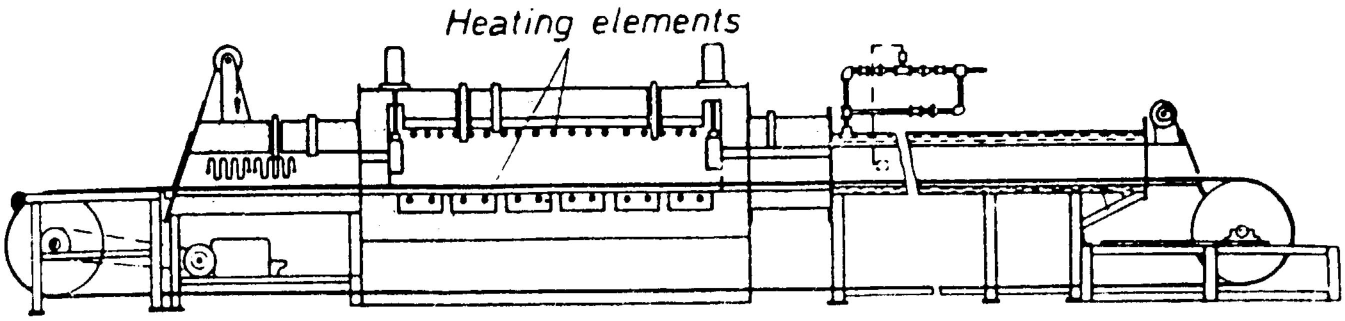


Figure 12. Typical belt sintering furnace for temperatures up to 1,120° C



The most widely used protective gases are pure hydrogen, cracked ammonia semi-burnt hydrocarbons and nitrogen. Pure hydrogen is rather expensive and therefore is used only for special purposes. Molybdenum and tungsten producers who use it for reduction usually have their own electrolytic plants. Cracked ammonia, which is inexpensive and can be transported and stored as liquid, is thermally cracked. The resulting gas (75 per cent of the volume is hydrogen, 25 per cent is nitrogen) is rather dry, but contains traces of uncracked ammonia and is therefore used only if nitridizing cannot occur. It is used mainly for plain iron, copper and bronze. Semi-burnt hydrocarbons are the cheapest protective atmospheres. By varying the hydrocarbon/air ratio, the composition of the gas can be varied: low amounts of air result in an endothermic reaction, and the resulting gas (much hydrogen and carbon monoxide) is carburizing and is therefore used for sintering of steel, the carburizing potential being adjusted by control of the dew point. By converting the carbon monoxide to carbon dioxide and washing it out and then freezing out the water, protective gas consisting of only hydrogen and nitrogen can be produced. If the hydrocarbons are burnt with an excess of air the reaction is exothermic and the gas contains carbon dioxide, water and nitrogen. It is decarburizing and is therefore used for plain iron. Recently, nitrogen from liquid nitrogen tanks has been successfully used for sintering. There are no problems with carbon potential due to its high purity (less than 10 parts per million (ppm) of water). Close co-operation with the supplier of the liquid nitrogen is necessary to avoid unnecessary evaporation losses.

A vacuum is a very unproblematic "protective atmosphere" offering no difficulties with dew point or carbon potential. A limiting factor is the very high price of vacuum furnaces. Vacuum sintering is therefore applied mostly for expensive materials where the cost of sintering is not decisive.

Quality control

Quality control is essential for the production of powder metallurgy parts, the reproducibility of the parts being a main advantage of powder metallurgy as a whole. For parts production, the dimensional tolerances are most important. The samples have to be measured after compaction, after sintering and after eventual calibration, i.e. re-pressing after sintering to final size, to avoid further use of worn-out dies and to control the sintering process. The weight of the green compacts and green density is also tested to ensure constant filling and pressing characteristics of the powders used. The properties of the final products are usually tested following the tolerance and strength requirements of the customer. Sintered density - mostly determined by measuring the displacement in water - and metallographic sections are often required. Testing the mechanical properties comprises tensile strength, hardness, ductility, and eventual impact strength. The necessary test bars are produced together with the parts. For some types of sintered materials, special tests have been developed. For example, the radial crash test is carried out to determine the mechanical strength of bearings.

For industrial use, classification of sintered materials is also important, especially for comparison purposes. There are several systems, one of which was developed by the Metal Powder Industries Federation in New York. In this system, the designation of a sintered material consists of prefix letters, four digits and a suffix letter: the general type of material is described by the prefix letters and the following four digits refer to the composition. With non-ferrous materials the first two digits indicate the concentration of the minor constituent, the last two digits indicate that of the major additive. Therefore CTP-0310 is a bronze consisting in weight of 87 per cent copper, 10 per cent tin and 3 per cent lead. With ferrous materials the first two digits indicate the percentage of the major alloying element and the last two digits the carbon content. For example, FC 0208 is a copper steel consisting of two per cent copper in weight and eight per cent carbon. By adding suffix letter the density range can be characterized.

Properties of sintered materials

The mechanical properties of sintered materials depend on the total porosity as well as on the shape of the pores, which is influenced by the sintering conditions. Rounded pores, which are obtained by high-temperature sintering, have much less adverse effect on the properties than angular pores obtained at lower sintering temperatures. In the latter case the angles act as notches and thus as crack initiators. With plain iron, tensile strengths of up to 250 MPa are attained, the elongation being as high as 30 to 50 per cent with well-sintered samples. The tensile strength is increased by adding copper, tungsten and nickel. These elements, with some amount of carbon, result in tensile strengths of 600 MPa. Still higher strength is obtained by sinter forging, the 1,000 MPa limit being exceeded with special heat treatment.

The elongation of sintered materials is generally inferior to that of compact ones. However, sinter-forged materials are equal or even better than cast materials because of the very fine and homogeneous microstructure obtained by powder metallurgy. Impact strength and fatigue strength depend very much on the shape of the pores. Especially with respect to fatigue strength, rounded pores may even improve the properties compared to compact material because the pores stop cracks by eliminating the notch effect.

As stated above, the usual alloying elements for iron are copper, nickel and molybdenum. These metals are easily reducible and therefore do not need specially pure sintering atmospheres. To some extent, pre-alloyed powders are commercially available.

One of the most important additives is carbon, which is added to the powders as graphite. Natural graphite must be used, as artificial graphite due to its silica content dissolves too slowly in the iron matrix. Lampblack is also not recommendable. Since the natural oxygen content of the iron powders causes some carbon loss during sintering by formation of carbon monoxide, some excess carbon must be added to obtain the carbon content desired. Furthermore, careful control of the carbon potential in the sintering atmosphere is essential to avoid both carburization and decarburization. The maximum strength is reputedly obtained at a carbon content of 0.9 per cent.

The standard alloying elements in cast steels, such as chromium, manganese and vanadium, are somewhat problematic in sintering technology; their high affinity towards oxygen is a distinct disadvantage due to the large surface of the green compacts. Very pure sintering atmospheres are required to avoid oxidation. Furthermore, these elements deteriorate the compactibility of the powder mixtures; therefore they have been used hither to mainly to sinter forged parts where compactibility is somewhat less important.

Of the non-metallic additives, with the exception of carbon, sulphur is sometimes added to plain iron to improve its machinability. Much more important is phosphorus, which is added to iron in quantities up to 0.6 per cent of weight. Today, mostly specially pre-alloyed iron-phosphorous powders are used, small iron phosphide particles being sintered to the larger iron grains. Phosphorous considerably accelerates sintering of iron, as it stabilizes α-Fe (ferrite) whose self-diffusivity is more than one order of magnitude larger than that of the α-Fe (austenite) present at the usual sintering temperatures. Therefore, all sintering processes are decisively faster, and lower sintering temperatures and shorter times are necessary to obtain satisfactory materials.

The shrinkage of plain iron parts and especially of iron-carbon materials is often a problem because of deterioration of the dimensional tolerances; the iron-carbon materials are usually too hard for sizing. The shrinkage can be compensated, however, by adding certain amounts of copper. The density of the iron-copper solid solution is appreciably lower than that of the unsintered mixture, and thus expansion occurs during sintering, compensating for the shrinkage if the correct amount of copper is added.

Typical sintered materials based on iron are soft magnetic materials, which are usually produced from relatively coarse starting powders. Sintering at high temperatures for a long time lowers the coercive force and increases the magnetic saturation. For alternating current applications, e.g. transformer cores, iron-silicon materials are produced that combine low coercive force - thus possessing low hysteresis loss - with high resistivity, which lowers eddy current loss. Due to powder metallurgy production, materials containing up to 6 per cent of silicon can be produced, which are impossible to produce by conventional casting and rolling techniques because of their brittleness. Iron bearings are used for some purposes since they are cheaper than bronze bearings; they must however be protected from corrosion. For better lubrication, unsoluble graphite is added.

As stated earlier, high-speed steels are also increasingly produced by powder metallurgy techniques, although in this case special processes, such as cold and hot isostatic pressing, are employed to avoid any porosity. The fine and very homogeneous microstructure, especially the even carbon distribution, is a distinct advantage compared to conventionally produced high-speed steels.

Sintered copper parts are produced only for some special purposes, e.g. electrical contacts or friction materials. The large majority of copper is used for bronze parts, both copper/tin mixtures and pre-alloyed powders being applied. Self-lubricating sintered bronze bearings are produced today for almost all technical applications, especially where high loads at low speeds occur. Small amounts of alloying elements or graphite are added to the standard composition of 90 per cent copper by weight and 10 per cent tin. To obtain the required tolerances, the bearings are usually sized (calibrated), at least in the bore, although care must be taken not to close the pores by sizing. Essential for satisfactory use of the bearings are suitable lubricants with high chemical resistance against cracking. Typical service life of such bearings is between 3,000 and 10,000 hours.

Bronze is used also for sintered filters. Spherical bronze powders of varying grain size according to the desired porosity (usually 0.1 to 0.5 mm) are poured into moulds and sintered. No pressing is carried out in this case in order to obtain as much porosity as possible.

Sintered aluminium materials have been introduced only recently because pure aluminium cannot be properly sintered due to the very stable oxide layer covering each particle. By the addition of magnesium, copper and silicon, however, an intermediate liquid phase is formed during sintering that penetrates the oxide layers and causes the aluminium particles to sinter together. The liquid phase is absorbed during the sintering process by the formation of a solid solution, and the resulting materials can then be precipitation hardened.

Generally, ready-mixed powders are available from the powder manufacturers that contain all components as well as the necessary amount of pressing lubricant (up to 2 per cent, as aluminium strongly adheres to the tool material). Due to the low hardness of aluminium, the compacting pressures are considerably lower than with iron or bronze, 200 MPa often being sufficient for obtaining the required density. Sintering of aluminium, however, is much more complicated than that of iron, very exact control of the temperature profile being essential, not only during sintering but also in the de-waxing step. Inexact temperature control leads to weak samples and to extreme dimensional changes (expansion or shrinkage). Sintering is carried out in dry nitrogen (dew point $> -40^{\circ}C$); an impure atmosphere considerably deteriorates the mechanical properties. With well-sintered samples, tensile strengths of 100 - 200 MPa are attained, with precipitaton-hardened materials up to 300 MPa. The strength-to-weight ratio of aluminium materials is considerably better than that of iron. Aluminium parts are therefore increasingly replacing iron parts, especially in the automotive industry.

Other materials produced by powder metallurgy techniques are titanium, beryllium, and tungsten-copper contact materials, but they are probably too special to be discussed here in detail.

Economical considerations

As mentioned above, one of the main advantages of powder metallurgy is the possibility of producing complicatedly shaped parts in large numbers with close dimensional tolerances. Due to the relatively high cost of presses, furnaces and, especially tools, cost-effective production is attained only above a certain size of the production batch. The break-even point for powder metallurgy parts production is near 10,000 parts, although this value may vary considerably according to the part produced and the specific production conditions.

For typical iron parts the cost structure may be as follows:

	Large parts (weight approximately 250 g)	Small parts (weight approximately 10 g)
Material cost	30 - 50 %	10 - 15 %
Tooling cost	20 - 25 %	30 - 40 %
Wages, other costs	12 - 20 %	30 - 50 %
Energy	8 - 12 %	4 - 8 %
Protective gases	5 - 10 %	3 - 5 %
Control	negligible	up to 10 %

Powder metallurgy is competing with other production techniques, and this competition is becoming continuously stronger: a lead in one process can be only temporary. The main competing processes are machining (with numerically controlled machines), forging (especially precision forging), casting and injection casting. The criteria for selecting the optimal process are (1) the amount of starting material necessary; (2) energy consumption; (3) necessary investment, and (4) quality of the products. However, powder metallurgy is the more competitive process: the more complicated the shape, the less machining is necessary after sintering and the larger the batch of parts produced.

Since the powders used for powder metallurgy production are generally more expensive than the compact materials, the material cost of powder metallurgy parts may be higher for large parts. It must be taken into consideration, however, that with powder metallurgy almost no material loss or waste occurs, while with machined parts a large share of the starting weight goes into scrap. This advantage in powder metallurgy is especially decisive for expensive materials, such as turbine discs made from super-alloys.

For newcomers in the field of powder metallurgy, most important is the fact that for the production of common iron or bronze parts the investment costs are relatively low. A few presses and a single furnace are sufficient for producing parts of satisfactory quality. The only essential condition, without which production is not possible, is a good tooling shop with experienced tool-makers and adjusters, since both tolerances attained and tool life depend on the ability of the personnel working with them. Table 1 provides an estimation of the investment costs necessary for an average powder metallurgy plant. The powder metallurgy producers in Europe are often small companies, but they all have their group of experienced tool-makers and adjusters that enable the company to remain competitive.

Conclusively, it can be stated that powder metallurgy is a promising technology that is still expanding and that might also be interesting for countries without the long technical experience necessary for most other technologies. The more complicated variants, such as powder forging and hot isostatic pressing, are surely not suited for beginners, but the more conventional pressing and sintering do not present insurmountable problems. If there is really a demand for a large series of parts, powder metallurgy can be regarded as a technology that should be seriously taken into consideration.

Table 1. Estimation of the investment costs for a powder metallurgy plant (production of iron and steel parts, about 60 tons/month)

(Prices in 1983 $US)

The plant can be split up into seven departments:

1. Powder mixing and preparation

1 mixer, about 500 kg powder/batch	$ 8,000
100 powder containers (barrels)	1,500
	$ 9,500

2. Pressing shop (2 work shifts)

1 powder press (hydraulic, 350 tonnes)	$ 350,000
2 powder presses (100 tonnes)	350,000
1 powder press (60 tonnes)	120,000
2 powder presses (40 tonnes)	175,000
1 sizing press (hydraulic, 400 tonnes)	250,000
2 sizing presses (100 tonnes)	250,000
1 sizing press (60 tonnes)	70,000
1 sizing press (40 tonnes)	40,000
	$ 1,605,000

3. Sintering shop (3 work shifts, 5 days per week)

2 automatic sintering furnaces, (80-100 kg/hr)	$ 300,000
Protective gas generator: either	
- An ammonia cracker (starting material liquid NH_3)	$ 60,000
or	
- An exothermic gas generator (starting material methane)	$ 120,000
or	
- A liquid nitrogen tank	The price depends on local conditions

4. Surface treatment (3 work shifts)

Steam treatment

1 furnace	$ 50,000
1 steam generator	20,000
	$ 70,000

5. Oil infiltration (one work shift)	$ 20,000

6. Quality control

instruments, gauges etc.	$ 30,000

7. Tooling shop (one work shift)

2 turning lathes	$ 100,000
1 milling machine	150,000
1 planer	60,000
1 erosion machine	200,000
1 surface grinder	60,000
1 cylindrical grinder	80,000
Gauges etc.	40,000
	$ 690,000

Total cost of equipment (without installations) approx. $ 3,000,000

Required area

Factory buildings	2,000 m^2
Other area	1,000 m^2
	3,000 m^2

Required staff

3 engineers
1 draftsman
10 skilled workers
15 unskilled workers
3 clerical workers

INDIA'S EXPERIENCE IN POWDER METALLURGY

Saurin Chatterjee*

Introduction

Powder metallurgy is now a well-established technology for the mass production of a large variety of structural parts and components such as bearings, gears and pinions, cams and sprockets, pulleys, pistons, filters, tool bits, magnets, friction materials, electrical contact elements and components from refractory metals and a host of other components utilizing metal powders. The basic steps involved in powder metallurgy technology are production of the powder, mixing and pressing/moulding into shapes and sintering. These may be followed by other manufacturing steps such as sizing, coining, repressing and resintering, forging or metal infiltration, as the case may be. The principal advantages of powder metallurgy component manufacture are:

1. Efficient use of raw materials and energy,
2. Production of parts and components with close tolerances that require minimum finishing operations and little machining,
3. Elimination of production steps,
4. Production of complex shapes without any of the additional joining techniques required in alternative production techniques,
5. Flexibility which permits infinite adjustments and modifications to component-making for different end-uses,
6. Production of certain components which can only be achieved through the powder metallurgy route, and
7. Efficient use of capital for the production of parts and components with high technology content.

Early beginning of powder metallurgy in India

Though powder metallurgy technology as it is known and practised today is of recent origin in India, the art and techniques of the use of metal powders were not unknown in India. Traditionally, metal powders, especially gold, silver, copper and the like, have been in common use for medicinal preparations in the traditional ayurvedic system of medicine over the centuries. Metal powders, especially iron powder, must also have been used for other purposes. An early example of the use of metal powder is the famous Ashoka Pillar at Delhi weighing about 6 1/2 tons which was fabricated by consolidation of iron powder. It is said that even larger objects were produced during this period based on the traditional art and technique of powder metallurgy. Metal powders were also used extensively for manufacturing/casting articles of everyday use, especially those made of brass.

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Growth of modern powder metallurgy industry

The first known modern industrial application of powder metallurgy in India was in the hard-metals sector for wire-drawing dies, percussion tools etc. Today the installed capacity for powder metallurgy in the hard metals area is 750 tons per year, excluding the captive capacity in the defence establishments. In the late 1950s, India also started the manufacture of self-lubricating iron and bronze bushes with imported raw materials and equipment. At present, however, most of the raw materials required for these powder metallurgy products are being produced within the country.

With the development of the automobile, domestic appliances, business machines and other industries, iron powder, especially in the form of sintered products and components, came to be widely used. Today over 62 million sintered pieces are being produced in the organized industrial sector of the country, and their production is rapidly rising. In addition, there are a number of units in the small-scale sector which produce a wide variety of powder metallurgy products for which the statistics are not readily available.

Subsequently, non-ferrous powder metallurgy, especially copper and copper alloy powders, came to be applied in the manufacture of a wide range of products including electrical contacts and brushes, friction components, filters and other porous parts. With the improvements in powder production, consolidation processes and equipment, further progress was made by the powder metallurgy industry. A large variety of non-ferrous powders, such as copper, zinc, tin, lead and aluminium, are now manufactured in India. Today, the powder metallurgy industry has established itself as a competitive alternative process for the manufactu structural components for automobilies, domestic appliances, business machines and the like.

Hard metals

The principal powder metallurgy products in the hard-metals field are cutting tips for machine tools and ceramic-coated tool tips over hard metal, tool inserts and disposable brazed tools for one-time use. Percussion tools with P/M hard-metal tips are widely used in mining and quarrying operations, such as coal cutting and rock drilling. The current production is approximately 400 tons per year for both domestic consumption and export. The three major units in this field are Widia India, Sandvik Asia and India Hardmetals. Unlike in the early stages, the entire manufacturing is now carried out indigenously from the raw materials to the finished product using mostly domestic and some imported raw materials. The total value of these powder metallurgy products is possibly higher than that of all other powder metallurgy products used in other areas. Powder metallurgy is also extensively used for cold heading tools such as wire-drawing dies, bar-drawing dies and other wear applications.

Refractory metals

With the development of the industrial base in India, the use of powder metallurgy refractory metals has extended especially for filament making in the electric lamp industry, resistance wires for furnace winding and other industrial applications where high temperatures are involved.

Ferrous powder metallurgy

Iron powder, especially electrolytic iron powder, has found a number of special uses in various industries. It is also extensively used in the manufacture of sintered products, especially for use in the automobile industry and in manufacture of domestic appliances. Other major applications are in the welding-electrodes industry and ferrous foundries, as well as in non-destructive testing of ferrous and non-ferrous components.

In the chemical industries iron powder is used (1) as a catalyst in organic reactions, (2) as a chemical reagent, (3) for carbon estimation and (4) for textile dyes. It is also utilized as a filler in epoxy resins to increase their strength, hardness, weight and magnetic porperties and also for colour matching.

In the pharmaceutical industries, iron powder is used in the manufacture of iron citrate, gluconates, fumerates, succemates, sulphates and EDTA salts. In the agricultural sector, it has found application in the magnetic cleaning of seeds, as well as for enriching animal and poultry feed.

Iron powder production

The powder metallurgy industry in India is relatively small and of recent origin. Iron powder is produced by the electrolytic route, namely by the electrolysis of ferrous sulphate. The total installed capacity is around 1,600 tons per year. Most of the units are in the small-scale sector with production capacities of less than 50 to 100 tons per year. Some of these plants are not equipped with appropriate facilities for annealing or quality control for the production of quality iron powder. Due to the high cost of powder, the production costs have risen substantially. Consequently, the operations of some units have become uneconomic, as their product is no longer competitive in terms of price and quality, leading to low utilization of installed capacity.

Demand for iron powder

The domestic demand for iron powder is estimated at about 3,000 tons per year, constituting 1,200 tons for consumption by the welding electrodes industry, 1,500 tons by sintered products and 300 tons by other applications. Since new plants have been set up for the manufacture of sintered components and the existing plants have expanded their capacity, there have been significant increases in the demand for iron powder in India. The current demand is around 3,100 tons (1984-1985), and it is expected that this will rise to about 8,000 tons from 1986 to 1987 and to 10,800 tons from 1989 to 1990 (see table 1). In view of the rising demand, India has had to resort to substantial imports of iron powder to meet the domestic requirements (see table 2). To remedy this imbalance, additional capacity has been created in order to produce iron powder of various grades, corresponding to varying bulk-density and granulometry, to meet the diverse needs of end-products such as moulding grades and welding grades.

Table 1. Present and estimated future demand for iron powder
(tons per year)

Application	1984-1985	1986-1987	1989-1990
Sintered components	1 500	6 095	8 310
Welding electrodes	1 250	1 500	1 900
Other applications	350	510	600
	3 100	8 075	10 800

Table 2. Imports of iron powder

Year	Quantity (tons)
1973-1974	334
1974-1975	324
1975-1976	461
1976-1977	423
1977-1978	915
1978-1979	671
1979-1980	858
1981-1982	1 109
1982-1983	7 800

Industrial applications of iron powder

As mentioned above, at present the major industrial uses of iron powder in India are for the production of sintered components and coated welding electrodes. In addition some small quantities are used for scarfing, cutting and other applications in alloy and special steel plants, foundries etc.

Sintered components industry

Until recently there were only three major producers of sintered components in the country, but now there are as many as 14 units that are engaged in the manufacture of sintered products from iron powder (see table 3). Of these, five are major manufacturers of sintered products which between them consume at present 50 per cent of the total iron powder consumption by the sintered products industry. Three new units are expected to go into production during the Seventh Five-year Plan (1985-1990). The present consumption of iron powder by the sintered components sector is estimated at about 2,500 tons. It is envisaged that the demand for iron powder by this sector may rise to 6,000 tons for the period 1986-1987 and to 8,000 tons for the period 1989-1990.

The bulk of the demand for sintered products comes from the automobile and farm machinery industries as well as other durable consumer industries, such as refrigerators, household appliances, bicycles, typewriters, business machines. In fact, in the developed countries the automobile industry accounts for over 70 per cent of the consumption of iron powder. In a developing country such as India, sintered parts are not yet extensively used by the automobile industry. However, with the introduction of new technology into the automobile industry and changes in materials/component specification, it is expected that sintered parts will be used to a greater extent in the manufacture of automobiles in India.

To meet the increased demand for passenger cars and jeeps, commercial vehicles, three-wheelers and motor cycles, scooters and mopeds etc., the Indian automobile industry has geared itself to raise its production capacity and to introduce modern technology that would enable the manufacture of more economical and energy-efficient vehicles. Substantial new capacity is also being created for two-wheelers, including motor cycles, scooters and mopeds. The production of agricultural machinery and tractors is likewise being stepped up. With all these developments envisaged in the automobile sector, the consumption of sintered products is bound to increase. The demand for all types of motor vehicles during the Seventh Five-year Plan is estimated at 1,270,000 per year, of which passenger cars number about 150,000 per year (see table 4).

Table 3. Estimated demand for iron powder by sintered components manufacturers (tons per year)

Sintered product manufacturing unit	1983-1984	1986-1987 (estimated)	1989-1990 (estimated)
Mahindra Sintered Products, Pune	300	600	700
Assotex Engg Industries, Bombay	100	750	1 500
Sundaram Fasteners, Hosur	300	2 000	2 500
Andhra Sintered Components, Gundur	-	700	1 100
S.S. Miranda, Ankleshwar	-	1 000	1 000
Akay Sintered Products, Faridabad	200	200	200
Flexicons Ltd., Udhna	60	120	180
Sintering Virmani, Delhi	150	225	300
Goa Sintered Products, Goa	50	90	150
Ashok Sinterings Pvt. Ltd., Delhi	50	65	80
National Sinterings, Lucknow	30	45	60
Clutch Auto, Faridabad	50	65	80
M.M. Sintered Products, Wardha	50	60	70
Hindustan Aircraft Ltd., Bangalore	75	85	105
Arvind Sinterings Ltd., Delhi	30	30	30
Jhansi Sinterings Pvt. Ltd., Delhi	30	30	30
R.K. Jajoo, New Delhi	-	-	225
Total	1 475	6 065	8 310

Welding electrodes industry

Iron powder is extensively used in the welding electrodes industry for coating high-efficiency arc-welding electrodes. The total licensed capacity in this sector is about 742 million running melters (MRM) of electrodes. In addition, new capacity of 200 MRM is now under implementation. Of the 20 units operating in this sector, four major producers - Advani Oerlikon, Philips Electricals and Electronics, Indian Oxygen and D & H Scheron Electrodes - account for 85 per cent of the production in the country and consume at present about 1,000 tons of iron powder per year. The total present consumption of iron powder by the welding-electrodes industry is estimated around 1,200 tons, and this is expected to rise to about 2,000 tons by 1989-1990 (see table 5).

Other industrial uses

Apart from these two major applications for sintered products and welding electrodes, iron powder is also consumed in small quantities in alloy and special steel plants (stainless steels, low alloy steels etc.) for cutting and scarting, in foundries and in non-destructive testing of ferrous products and components. The total current demand for these end-uses is estimated at about 350 tons per year, which is expected to rise to 600 tons by 1989-1990.

Non-ferrous powder metallurgy

As mentioned earlier, the metal-powder industry in India commenced in the hard-metals sector with the production of wire-drawing dies, cutting tips for tools, tool inserters etc., followed by the manufacture of self-lubricating bronze bearings and bushes. Subsequently powder metallurgy based on copper and copper alloys was employed for the manufacture of a wide range and variety of products, such as electrical contacts and brushes, friction and anti-friction components, filters and other porous parts, metal-bonded diamond tools, ceramic tools. Some of the units which produced ferrous sintered products are also engaged in the manufacture of non-ferrous sintered products.

Table 4. Annual demand for motor vehicles in India during the Sixth and Seventh Five-year Plans

Type of motor vehicle	Sixth Five-year Plan (1980-1985)	Seventh Five-year Plan (1985-1990)
Passenger cars	60 000	150 000
Jeeps	30 000	45 000
Light commercial vehicles	40 000	75 000
Medium and heavy commercial vehicles	90 000	140 000
3-wheelers	50 000	150 000
Motor cycles	175 000	350 000
Scooters	400 000	800 000
Mopeds and mini motor cycles	425 000	850 000
	1 270 000	2 550 000

Table 5. Demand for iron powder by welding electrodes industry

Electrode producer	1983-1984	1986-1987	1989-1990
Advani Oerlikon (ADOR)	550	630	730
D & H Scheron Electrodes	300	400	530
Indian Oxygen (IOL)	100	170	290
Philips India (PEICO)	70	80	90
Modi Arc Electrode	25	30	35
Others	155	190	240
	1,200	1,500	1,915

Production of non-ferrous metal powders

Simultaneously there was substantial progress in the production of non-ferrous metal powders and a number of units mostly in the small-scale sector came to be established. At present there are some 18 units producing metal powders and their total installed capacity is around 2,000 tons per year. If the capacities of some of the non-reporting small-scale units were also taken into account, the total available capacity for non-ferrous powder production would be around 3,000 tons to 3,500 tons per year. However, due to wide market fluctuations the actual capacity-utilization has been much lower, at about 60 per cent to 75 per cent. Some quantities of powder are also produced by some of the sintered product manufacturers for their captive use.

The total estimated demand for non-ferrous metal powders is over 3,500 tons per year, mostly for the manufacture of bearings, bushes, metal graphite blocks and structural parts. In addition, some electrolytic and atomized powders find application as catalysts in the chemical industry and as pigments in printing inks. Precise data on the demand/consumption of metal powders by these industries are not readily available.

Today, a wide range of non-ferrous metal powders of various grades and metals are manufactured in the country. These range from the more common brass, bronze, copper, lead, aluminium and zinc powders to cadmium, cobalt, magnesium, nickel, silicon, silver, tantalum, tungsten, zirconium, uranium oxide etc.

Non-ferrous sintered products

There are at present some 15 units that are engaged in the manufacture of non-ferrous sintered products, of which only four units are in the small-scale sector. A large variety of non-ferrous sintered products are being produced by these units, such as bimetal and trimetal bearings, bushes, diamond powder products, bronze filters, friction materials, self-lubricating bearings, silver-graphite contact materials, sintered metal parts and bushes, tantalum capacitors etc. This list is only illustrative, not exhaustive, and the product range is still growing as new applications are being found for non-ferrous metal powders.

Technology and alternative routes of powder manufacture

Several alternative processes have emerged for the manufacture of iron, copper and copper alloy and other metal powders, ever since industrial applications of powder metallurgy were developed. Some of these processes which have played their role in the development of powder metallurgy have now been rendered obsolete with the emergence of newer and more competitive and satisfactory processes. Broadly speaking, the more important processes in today's context are (1) electrolysis, (2) atomization, (3) chemical reduction and (4) hydrometallurgy. Of these, electrolytical and atomization methods are at present more widely accepted and used for commercial-scale manufacture of metal powders. These two process routes account for the bulk of the powders utilized for various structural and non-structural applications. Though chemical reduction is used to a lesser extent, it has a distinct role since the powder produced by this process is well suited for the manufacture of structural parts and several other applications. The hydro-metallurgical process is also well established, especially for the production of copper, nickel and cobalt-based powders.

Electrolytical process

The electrolytical process, because of the simplicity of its operation and excellent control of parameters, continues to occupy a dominant position in the field of powder-metals production, despite the high power inputs and higher costs of production. The powder produced is of high purity. The adaptability of the process to produce a wide variety of non-ferrous metal powders has made it popular with metal powder producers, though it is extremely sensitive to rising energy costs. In India, substantial quantities of pure iron powder continue to be produced by this process.

Atomization

Atomization is primarily the disintegration of a molten stream of metal by high-pressure gas or water jet. This is a well-established process, especially for the production of a wide variety of iron powders as well as copper-based powders of varying alloy compositions and powder characteristics. This is essentially a high-speed production process, rendering control over the parameters difficult. These and other problems concerned with the atomization of melting compositions as well as reactive metals and alloys have been overcome by technological developments in the melting furnaces, atomizer design, quenching process etc.

Apart from the control of the physical characteristics of the powders during the various stages of manufacture, the final control can be exercised during the annealing, crushing and grinding operations. Water jet atomization is commonly used because of its advantages. The amenability of the process to pre-alloying with accurancy is an added advantage. This is particularly useful for the manufacture of low-alloy iron and other non-ferrous powders.

Chemical reduction

Chemical reduction presents an attractive method for the utilization of industrial waste from hot fabricating industries, especially for the production of non-ferrous powders. Copper scale and other oxide wastes are reduced by cracked ammonia or an endothermic gas mixture at elevated temperatures. The reduced product which is in a semi-sintered state is further pulverized mechanically. The purity of the powder obtained is uncertain and limited by the quality of the oxide used. Moreover, inadequate control of the operations and the type of reducing agent employed may often reduce the purity level. To ensure better purity levels and more complete reduction, the use of cracked ammonia as reducing agent is preferable. Moreover, during mechanical pulverization, some of the desirable properties including surface activity may be destroyed. In view of these inherent shortcomings, the prospects of further development in this process appear to be limited.

Reduction of iron ore

The production of iron ore by the reduction of iron oxide and, in particular, the reduction of iron ore by carbon are the oldest methods of producing iron powder. The Swedish sponge-iron process developed by Hoganas in early 1900, although originally intended for manufacturing sponge iron for steelmaking, has now become a primary source for iron powders in the world. The Hoganas process uses pure magnetite ore after beneficiation by grinding and magnetic separation. Coke breeze or another carbon source provides the reducing agent for manufacturing sponge-iron powder. Additionally, limestone is used to react with sulphur contained in the coke and to prevent its inclusion in the iron powder as an impurity. The reduction of oxides to iron takes place at a lower temperature than in the conventional sponge ironmaking and the reduction is carried out in ceramic tubes that consist of silicon carbide. After reduction, the powders are sized by crushing, screening and separation. To make them suitable for use in compaction, the powders are process-annealed and mixed prior to dispatch to consumers. As the iron ore quality available in India is not suitable for this process, India has not opted for it.

Hydro-metallurgy

The hydro-metallurgical process originally developed for extracting copper from lean sulphides, oxidized or complex ores and concentrates, ore tailings and other mining wastes is now extensively employed for the production of not only copper and copper alloy powders but also of other non-ferrous metal powders, especially nickel- and cobalt-based powders. The process consists of first leaching the metal-bearing ore with a leachant and then suitably reducing the aqueous leach liquor by physico-chemical processes such as precipitation, reduction, solvent extraction, cementation, electro-winning. The hydro-metallurgical process has the distinct advantage that it can utilize as raw material a wide variety of industrial wastes, such as low-grade scales, heavily oxidized scrap, floor and flue dust, foundry wastes, spent catalysts, spent pickling liquors, effluent sludges.

Future prospects

Future prospects for powder metallurgy industry will be closely linked to the process and development of the end-use applications and the user industries including sintered-products manufacture. Development of newer end-uses that is bound to take place with improved availability of powders in the market would accelerate the growth of the powder-manufacturing industry. In the context of India's sustained industrial growth and development plans, there are considerable growth prospects for powder-metallurgy industry in the country.

However, certain developments are necessary to meet the growing demand for larger quantities of low-cost powders and some special grade powders for sophisticated and critical applications. These changes will necessarily involve modifications and innovations in powder-production technology in keeping with the need for conserving energy and material resources. Also, sustained promotional efforts and continuing education will be required to popularize and extend the use of powder metallurgy, since it is still comparatively a new development and its full potential is yet to be realized.

The Indian context

In the Indian context, however, the electrolytic process may continue to maintain its prominent position in the near future. Its suitability for small-scale operation with low overheads can more than compensate the higher energy requirements. Atomization is, however, rapidly gaining ground. At present, this process is employed mostly for the production of pigment grade, gold bronze powders, pre-alloyed powders for sintered bearings, filter-grade powders etc. Several units in the small-scale sector produce other non-ferrous powders by this process. With respect to chemical reduction technology, its use is likely to be limited to certain units with an assured supply of better quality raw materials, possibly to produce special grade powders. The hydro-metallurgical process is likely to gain greater popularity since it is economically attractive in view of its ability to use low-grade raw materials entailing relatively lower raw materials cost and recycling of industrial wastes.

While electrolysis will continue to be attractive for small metal-powder units, prospects are equally good for medium- and large-scale powder plants employing atomization technology as well as hydro-metallurgical processes. Future trends favour the installation of integrated units in the medium- or large-scale sector producing metal powders by more than one process, as well as sintered products supported by ancillary units supplying certain grades of powder that will be further processed into special grades of premixed and blended powders.

Research and development

Research and development activities are in progress in a number of research organizations, technical institutes and universities on various aspects of manufacture, industrial uses and special applications of metal powders. Notably, specialized research institutions such as the National Metallurgical Laboratory (NML), Jamshedpur; the Defence Metallurgical Research Laboratory (DRML), Hyderabad; the Bhabha Atomic Research Centre (BARC), Bombay; the Central Electrochemical Research Institute (CERI), Karaikudi; the National Aeronautical Laboratory (NAL), Bangalore; and the Vikram Sarabhai Space Centre (VSSC), Trivandrum have been doing pioneer work in this field. Similarly, considerable research work, both applied and fundamental, is being carried out at the various Indian institutes of technology and a number of other institutions of higher technical education and universities such as Banaras Hindu University, the Indian Institute of Technology in Bombay, the Indian Institute of Science. Some of the major R + D activities are briefly mentioned.

Air-, nitrogen- and water-atomized non-ferrous powders

The Metal Powders Group at the National Metallurgical Laboratory (NML) has been especially active in the development of the production process for metal powders for nearly a decade. The major thrust has been in the area of air-atomized, nitrogen-atomized and water-atomized non-ferrous metal and alloy powders. The know-how developed by NML for a number of these extra-fine gas atomized non-ferrous metal powders has been successfully transferred to industry. These include aluminium and aluminium alloys, brasses and bronzes, tin, lead, copper and copper alloys and solders. Developmental work is also in progress on water-atomized iron and ferrous alloy powders. NML know-how for the production of distilled grade extra-fine zinc dust has also been licensed for commercial production and technology transfer.

These R + D activities have involved a good deal of related peripheral investigations on the extraction of parent metal from leach solutions by absorption on lignite; recovery of parent metal from metal wastes such as drosses; development of compacting/sintering grade powder metallurgy, prealloyed powders and premixes; and other related applications technology.

In the frontier area of geo-, micro-, bio- and hydro-metallurgy, exploratory work is also underway at NML for the production of high-grade bimetal powders from microbeal leach liquors by cementation and dilute solution electrolysis. Work has also been initiated in some areas of application technology for metal powders.

Special materials and superalloys

At the Bhabha Atomic Research Centre (BARC), the research and development work is primarily centred around the powder metallurgy of special materials and superalloys. Some of the investigations in progress are: development of a process to fabricate a super-conductor wire; large-scale fabrication of carbide fuel pellets for the fast-breeder test reactor; silver-nickel composites used as contacts in electrical and electronic industries; investigations of electro-ceramics, based on lanthanum chromite, for use as hot electrodes in open cycle magnetohydrodynamic power generation and ultra-high-temperature heating elements; production of nuclear fuel elements by cold compaction and sintering of uranium oxide agglomerates; preparation of uranium monocarbide insulation pellets for fast-breeder test reactor fuel pins etc.

Special metals and alloys products

At the Defence Metallurgical Research Centre (DMRL) the major research and development activities relate to pilot plant studies of special metal and alloy production; research and development in various aspects of compaction and sintering of metals, ceramics and cermets, compact forging etc. The Central Electrochemical Research Institute (CERI) is carrying out research work in the area of electro-metallurgy and powder production. The National Aeronautical Laboratory (NAL) is investigating titanium-based powder metallurgy alloys. At the Vikram Sarabhai Space Centre (VSSC), research and development work is in progress on powder metallurgy products for aerospace applications.

The production activities of the Mishra Dhatu Nigam (Superalloys Plant, Hyderabad) is closely associated with the work of these laboratories and, within a short period of time, India has been able to produce the bulk of its requirements of highly specialized metals, alloys and other components for its nuclear energy programmes, defence, electronics and other needs. Some research work is also in progress at the research and development centres established by the earlier powder metallurgy manufacturers to improve their products and to develop new products and processes.

Metallic glasses and super-aluminium alloys

Another fascinating development which is engaging the attention of Indian powder metallurgists is the new technology of rapid solidification processing (RSP) of complex alloys into metallic glasses. These metallic glasses belong to a novel class of RSP alloys characterized by their unique compositions, amorphous structures and excellent mechanical, magnetic and corrosion-resistance properties. Rapid solidification techniques such as melt spinning are capable of fabricating metallic glasses in large quantities as continuous ribbons and tapes. Because of the need for extremely fast cooling during processing, metallic glasses can only be fabricated as thin bodies at the present status of our knowledge. Their application in bulk shape products is not yet feasible. However, these metallic glass alloys can be fabricated into bulk shapes suitable for engineering and structural applications. Although the basic process of RSP is well known, information on production technology is not readily available.

India has made a beginning in RSP technology for the production of a new generation of super-aluminium alloys. Laboratory studies at the Banaras Hindu University have already demonstrated the feasibility of their production. RSP technology presents the exciting possibilities of the use of this new class of alloys for a new generation of space applications and missiles with substantial weight savings and service life.

The Powder Metallurgy Association of India (PMAI)

The powder metallurgy activities in India are spearheaded by the Powder Metallurgy Association of India. This organization with a membership of 400 actively promotes powder metallurgy in India. Through its various activities such as publications, seminars, workshops and technical meetings, it successfully disseminates information on the latest developments in the field of powder metallurgy, working in close co-operation with international and Indian organizations in the field.

Acquisition, development and transfer of powder metallurgy technology

India's progress and development in powder metallurgy has followed the traditional growth route. The country made a modest start in powder metallurgy in the 1950's in the hard-metals field, based on imported technology and raw materials. This was followed by its entry in the late 1950's into the production of iron and bronze bushings. With the rapid growth of industrialization under the impetus of the five-year development plans and the consequent rising demand for powder metallurgy products and raw materials, India started with the manufacture of metal powders and sintered products using imported technology and raw materials. A number of industrial units, mostly small-scale and a few medium-scale, were established.

The progress in powder metallurgy witnessed in the earlier years was mostly in the ferrous sector as the demand for sintered products increased, which in turn created a rising demand for iron powder. This led to the establishment of several small units for the manufacture of electrolytic iron powder based on indigenous technology. Most of these units were established by enterprising entrepreneurs, with meagre resources and without recourse to technology inputs. The electrolytic process was well known and, with the technical assistance of some university professors who had specialized in powder metallurgy, these units were able to work out the parameters and develop the requisite know-how. Today, India has achieved a good measure of self-sufficiency in the production of iron powders, although certain grades of iron powder still continue to be imported on a limited scale.

As mentioned earlier, due to the peculiar characteristics of most Indian iron ores and its unsuitability for the production of iron powder by the direct-reduction process, this technique of iron powder-making has not made much headway in India. Efforts are under way however for the production of ferrous powder by the atomization process (which is currently used in Brazil, the Federal Republic of Germany, Japan, USSR, etc).

In the case of non-ferrous metal and alloy powders, however, India until recently was entirely dependent on foreign technology and imports of powders for various end-uses. The earlier plants set up in the late 1950's for producing non-ferrous metals and powders were either foreign collaboration ventures or were manufacturing under license. With the non-ferrous metals technology now available within the country, some of the new units have acquired this technology for the production of air- and nitrogen-atomized non-ferrous and alloy powders (aluminium and aluminium alloys, brasses and bronzes, tin, lead, copper and copper alloys, zinc and zinc alloys, distilled grade zinc dust etc).

With respect to the applications of powder metallurgy, namely hard metals, sintered products and welding electrodes, most of the know-how had initially come through foreign collaboration, joint ventures and licensing arrangements. Recently, however, some new units have been set up in these sectors by professionals who had worked in the earlier units and acquired some production experience. This process of "indigenization" or "Indianization" also received some encouragement by the import-substitution programme and the policy of technological self-reliance. Some of these facets of India's development of processes and experience in powder metallurgy are discernible, although the development did not take place in any definite sequence or chronological order:

- production of sintered components with imported raw materials and technology
- production of some types of metal powders and powder metallurgy products with indigenous raw materials and imported technology (foreign collaboration/joint ventures with or without equity participation)
- production of powder metallurgy products with imported technology (under licensing arrangements)
- production of metal powders and powder metallurgy components with domestic raw materials and technology (Indian enterprises without any foreign collaboration)
- R + D activities and development of new technologies with local raw materials
- Commercialization of indigenous processes and transfer of technology to industry
- development of a R + D infrastructure and consultancy services for installation of plants and export of technology and services.

India has now reached a level of development in powder metallurgy in which there is a balanced mix of imported and indigenous know-how. India is still importing know-how where required and continues to enter into joint ventures/licensing arrangements. At the same time, however, it is stepping up its own R + D efforts, not only in the conventional areas and products but in emerging technologies and frontier areas. The policy of self-reliance in technology and import substitution that the country has pursued over the years is evidently paying good dividends.

Relevance of Indian experience to other developing countries

India's varied experience in powder metallurgy has some relevance to other developing countries that are planning or developing their powder metallurgy industry. Although the course of India's development may not be uniformly applicable to all developing countries due to its diverse techno-economic environment and specific requirements, some broad guidelines can be drawn to indicate the lines or directions for the development of the powder metallurgy sector. Some developing countries have already successfully established sizeable powder metallurgy industry over the years, starting with imported technology, production equipment and raw materials. The Republic of Korea is a good example of a country that not only rapidly absorbed and made good use of imported technology but developed its own processes for the production of copper and other non-ferrous metal powders. There are other developing countries where limited domestic markets, weak industrial and technological bases and lack of resources may be the limiting factors.

Obviously developing countries newly entering the powder metallurgy field will have to rely in the initial stages on foreign know-how for establishing powder metallurgy ventures, based on their requirements. Depending on their industrial development plans and the possible demand for powder technology products, they may identify the powder metallurgy products they would like to take up for immediate development. This in turn would indicate the directions that powder metallurgy development should follow. Assuming that in the first instance the demand for powder metallurgy products will be primarily for sintered components from the automobile, agricultural machinery and domestic appliances industries and other equipment of everyday use, possibly a country could start with the manufacture of various sintered components using imported raw materials. If the demand so warrants, the country could then commence manufacturing ferrous and non-ferrous metals and alloy powders on a modest scale, acquiring the know-how from foreign sources or entering into foreign collaboration. The technological infrastructure also needs to be created for the effective transfer and absorption of the technology. Simultaneously the requisite R + D facilities will have to be developed for the adaptation and improvement of the product and also for developing new processes and products. These activities are aimed at bringing about a measure of self-reliance in technology. In these development tasks the technologies developed by other developing countries and their experience in powder metallurgy may be more suitable and relevant to the conditions existing in the recipient country. The terms and conditions of acquisition and transfer of technology may also be more favourable.

Concluding remarks

India has come a long way in the field of powder metallurgy since the modest beginnings in the 1950's. Within a short span of three decades the country has been able to achieve a measure of self-reliance in the powder metallurgy field both in terms of technology and raw materials. Although early powder metallurgy ventures in the country had been dependent on foreign technology and raw materials, it had earlier relied on its own efforts in setting up powder metallurgy units and in developing suitable technology especially for the electrolytic production of iron powder and some categories of sintered products. With the development of industrial and technological infrastructure and intensive R + D efforts, India has been able to venture far ahead. It has developed its own technologies for the production of various non-ferrous metal and alloy powders and is in a position to share its experience with other developing countries. Many of these processes developed in India have been commercialized since and a number of industrial units are already in operation. India can now offer a comprehensive technology package along with the process know-how and design/engineering consultancy services for the installation of powder metallurgy units of various capacities. Developing countries establishing and developing domestic powder-metallurgy industry can benefit immensely by the experience of India in this field.

References

1. Proceedings of the Symposium on Sintering and Sintered Products, BARC, Bombay, 29-31 October 1979. (New Delhi, Materials Science Committee, Department of Atomic Energy, Government of India).

2. P. Ramakrishnan, Powder Metallurgy Alloys, (New Delhi, Oxford and IBH Publishing Company, 1982).

3. "P/M - the technology for energy and material conservation," paper presented at the PMAI Eleventh National P/M Conference, 8-9 February 1985, Jamshedpur, India.

4. V.A. Altekar, "Powder metallurgy comes of age in India," paper presented at the PMAI Eleventh National P/M Conference, 8-9 February 1985, Jamshedpur, India.

5. P. Ramakrishna, "Present status of powder metallurgy in India," The International Journal of Powder Metallurgy and Powder Technology, vol. 20, no.3, July 1984, pp. 219-223.

6. K.Y. Eun and D.N. Yoon, "Present status of powder metallurgy in Korea", The International Journal of Powder Metallurgy and Powder Technology, vol. 20, no. 3, July 1984, pp. 231-240.

7. W.J. Huppmann, "Looking ahead to 1995 - the future of powder metallurgy", The International Journal of Powder Metallurgy and Powder Technology, vol. 20, no. 3, July 1984, pp. 241-254.

8. P.R. Soni and T.V. Rajan, "Recent development in aluminium P/M products", PMAI Newsletter, vol. 10, no. 3, June 1984, pp. 24-32.

9. K.M. Khandekar and M.D. Diwani, "Production of leaded bronze powder by gaseous atomization", Paper presented at the International Symposium on Brasses and Bronzes, 15-17 December 1983, Bombay, India.

10. Feasibility report for an iron powder plant (10,00 tons/year of iron powder for sintered components, welding electrodes and gas cutting applications) for Indmag Private Limited, Bombay. (Calcutta, M.N. Dastur & Co Private Limited, Consulting Engineers, 1979).

11. M. Viswanathan, "Manufacture of copper and copper alloy powders - current practices and future trends", Paper presented at the National P/M Conference, 9-10 March 1982, Hyderabad, India.

12. Metal powders - a decade of R + D at the National Metallurgical Laboratory. (Jamshedpur, PMAI Eleventh National P/M Conference Souvenir, pp. 4-15).

13. T.R. Anantharaman, "The magic of metallic glasses", IIM Presidential address, Transactions of the Indian Institute of Metals, vol. 32, no. 1, February 1979, pp. xii-xix.

14. Ranjit Ray, "Bulk microcrystalline alloys from metallic glasses", Metal Progress, June 1982, pp. 9-11.

ADVANCES IN POWDER METALLURGY

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Introduction

The production and use of metal powders to make massive materials and shaped objects is an old and well-established art, but this field is currently receiving strong renewed interest because of advances in powder metallurgy technology that offer improvements in metal properties, service performance and economics. These technical advances include the production of very fine metal powders by recently developed rapid solidification techniques, new consolidation methods and the use of these techniques to develop alloys with properties superior to those prepared by conventional metallurgy.

This renewed interest in powder metallurgy is to a large extent based on the fact that many alloy systems produced by the usual processing methods of melting, casting and working of metals have reached a plateau in properties and performance. The rapid strides made in aluminium alloys over the past 30 years have slowed to incremental improvements within the scope of conventional ingot metallurgy. Most of the nickel- and cobalt-base superalloys used in gas turbine engines and similar high-temperature applications were developed in the 1960s. These materials appear to have reached an end-point where further alloy additions to the wrought alloys would impair their capability for hot working, and higher alloying of the cast materials would create an unacceptable lack of toughness. Similarly most of the high-speed tool steels in prominent use were developed 10 to 15 years ago.

The new powder metallurgy techniques offer a means of breaking away from the plateau related to conventional processing to achieve higher levels. This has been demonstrated in aluminium alloys, titanium alloys, superalloys, and high-speed tool steels. These new techniques also make it possible to create new alloys and combinations of materials that cannot be readily produced by other means, such as non-equilibrium compositions produced in rapidly solidified powders and combinations produced by "mechanical alloying". A further incentive for using these new technical advances is the opportunity to realize significant cost savings, particularly in the case of processing expensive materials by reducing the quantity of scrap generated in fabricating finished components.

Powder production

The development of rapid-solidification techniques for producing very fine particles is one of the most noteworthy advances in powder metallurgy. Initially of interest as a means of making glassy alloys, the technology became recognized for its capacity to provide a high degree of control over the microstructure in microcrystalline alloys and hence over their properties.

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A key and common feature of these new techniques is a very high cooling rate, as summarized below:

Process (degrees per second)	Approximate cooling rate
Gas atomization (subsonic)	10^0 to 10^2
Water and steam atomization	10^2 to 10^4
Gas atomization (ultrasonic)	10^3 to 10^5
Metallic substrate quenching	10^4 to 10^6 (particulates) 10^6 to 10^{10} (splat flakes)

As pointed out earlier in the article by Gerhard Jangg and Herbert Danninger, subsonic gas atomization is the most important physical powder production methods and is the basis for extensive industrial practice. For purposes of advanced properties and performance, however, the material obtained from the subsonic process involves some problems. Because of the relatively slow cooling rate, the powders are rather large in comparison with those obtained by the other processes listed. Moreover, these particles suffer from trapped porosity and, more seriously, from satellite formation. The latter consists of fine particles attached to the metal powders, which decrease the packing density of the powder and degrade the microstructural uniformity of the ultimate compact. The rotating electrode process, a version of subsonic atomization, offers an advantage for highly reactive metals (e.g. Ti and Zr) since it does not use a crucible for melting, and contamination from that source is eliminated. The disadvantages of this approach are the cost of electrode preparation and the coarseness (above 200 micron diameter) of the powder.

The ultrasonic gas atomization process is similar to the conventional process with the addition of a series of shockwave nozzles that impose pulsed, ultrasonic gas on the liquid metal stream. The gas jets are generated at high pressure (up to 1,200 psi) and high frequency (about 100,000 cps) with an exit velocity in excess of Mach 2.

According to Grant 1/ the significant operating variables in gas atomization processes include the following:

- Metal stream diameter - the finer the stream the better the interaction between the gas jet and the falling liquid stream. In the ultrasonic process this value is about 5 mm.

- Gas nozzle dimensions - the length and diameter of the nozzles are important in establishing the desired laminar flow of the gas and the gas velocity.

- Gas velocity - this variable is controlled primarily by gas pressure which is easier to monitor. The higher the pressure (velocity), the finer the powder produced.

- Angle between the gas jet and the metal stream - a large angle offers high efficiency of the gas but creates two problems: the lateral spray requires much larger tanks for containment and back pressures are created which interfere with the metal pouring. If the angle of impingement is too shallow, the gas jet is reflected from the surface of the metal stream, causing turbulent gas flow and the production of coarse powders. In the ultrasonic gas atomization process, the included angle between the gas jet and the metal stream is typically about 20°C.

- Liquid metal temperature - superheating (heating to a temperature in excess of the normal casting temperature) is essential. The high temperature provides greater fluidity and solution of refractory surface oxides. Within limits and other factors held constant, the higher the metal temperature, the finer the powder produced.

By manipulation of these process variables, it is possible to obtain particles of various size distributions. Aluminium alloy powders have been extensively produced by this method with the conclusion that the ultrasonic process tends to yield good spherical powder with a small population of satellites and little entrapped atomizing gas. Very fine powders with an average size of 22 microns have been produced.

Water and steam atomization offer the high quenching capacities of these coolants, but at the same time impose more oxidation of the metal than air. This process is useful with materials such as low-alloy steel where subsequent reduction of the oxide formed during atomization can be carried out readily and inexpensively.

Metallic substrate quenching consists of directing gas-atomized metal droplets onto a chilled metal surface. The combination of impact and very high cooling rates produce particulates on the order of 20 microns, or at still higher quenching rates, splat flakes finer than 10 microns. By using a moving chilled metal surface, the technique can produce foil, ribbon and strip. The flat particulates offer potential advantages over atomized powder: fewer problems with oxygen and other surface contamination, greater structural uniformity and the absence of trapped gas. However, at present for industrial scale operations, gas-atomized powder is preferred for consolidation into dense massive components.

Numerous other exploratory and experimental processes for the production of metal powders are being studied. One novel approach is the preparation of powder by spark erosion, a modification of the well-known process of electro-discharge machining. 2/ The latter is often used to cut materials that are too difficult to machine by conventional methods. In the experimental arrangement, a power source is connected to two electrodes submerged in a tank of liquid dielectric. The material to be converted to powder is placed between the two electrodes on a screen through which the powders fall into a collection area in the bottom of the container. Spark erosion occurs when a pulsed electric discharge between the two electrodes creates molten regions on the surface of the metal. The molten particles are rapidly cooled because of their intimate contact with the liquid dielectric. Using various dielectrics, cooling rates of 10^5 to 10^7 degrees per second have been obtained. The high temperatures produced by the plasma (approximately 10,000° C) make it possible to process even the most refractory metals. The size of particles produced in the laboratory have ranged from 75 microns to less than 2.5. In general, the lower the melting point of the metal, the finer the powder produced. A variety of materials have been produced on an experimental basis, including iron, nickel-base superalloys, magnetic alloys and a 78 per cent Si-Ge alloy. The spark erosion of titanium metal in dodecane as the dielectric produced stoichiometric titanium carbide powder; similar processing of iron metal yielded fine powders of stoichiometric Fe_3C. The use of water as the dielectric has provided fine powders of metal oxides and hydroxides. Production rates in the laboratory are about one-half pound of powder per hour when processing iron; presumably the rate can be increased if the process proves to have sufficient technical and economic merit.

While it is not intended in this review to deal with powder characterization, it is important to note that working with the very fine powders produced by rapid solidification techniques requires more attention to this aspect than with more conventional powders. In general, powder characterization includes sampling, morphology (particle size, shape and surface area), crystallographic information, and chemical composition (both bulk and surface). Rapidly solidified particles have a high surface-to-volume ratio and thus are susceptible to surface contamination. The existence of oxides on the surface of an aluminium alloy powder, for example, can lead to the presence of oxide stringers in the microstructure of the consolidated material, resulting in intercrystalline cracking and grain-boundary failure as evidenced by a severe loss in fatigue life. Since the droplets solidify rapidly and freezing first forms an exterior envelope, porosity can be trapped in the particles. Voids, while undesirable in the powder particles, are largely eliminated in the consolidation process, but if the internal pores are occupied by gas, the porosity is much more difficult to remove and in some cases can result in swelling of a component even after hot isostatic pressing or extrusion. In as much as the improved properties of the ultimately fabricated component are directly related to the uniformity and fineness of the microstructure, the size and uniformity of the powder has special significance.

Consolidation

The most highly developed and widespread advanced consolidation technique is hot isostatic pressing (HIP). This method was examined earlier in this monitor by Heinz Konvicka and need not be described here. Of the reported 340 HIP installations in the world, roughly one-third are in industrial production and the balance in research and development use, attesting to the growing commercial importance of HIP and the interest in the technical development of this process. Further work is being done to expand the scope and utility of the HIP process. The working volume is small relative to the size of the equipment and working area. Typically the hot zone is 16 to 40 inches in diameter, and currently the largest is 54 inches. Larger sizes are under development that would provide a hot zone up to 70 inches in diameter and lengths of 80 inches. Development effort is also aimed at increasing the processing temperature. The use of Kanthal resistance heating typically provides 1,200° C, whereas the proposed use of graphite heating elements can bring the temperature up to 2,200° C. Effort is also in progress to improve the understanding of the fundamental aspects of powder metal deformation, densification and fracture behaviour. This information is being used to develop computer-aided design procedures to identify the appropriate process-operating conditions and mould shape to achieve the desired component shape and density.

The emerging consolidation methods have three main applications:

1. Forging preforms

2. Billet stock for mill shapes

3. Near net shapes.

HIP can be used successfully for all three of these purposes, but the process has some drawbacks. With gas as the compression medium, the pressure is limited to about 15,000 psi. This relatively low pressure requires long holding times (several hours) to achieve high density, thus adversely affecting the production rate.

Several pseudo-isostatic processes have been developed to avoid some of the limitations of HIP and provide better methods for fulfilling specific areas of application. Ceracon and ROC (Rapid Omnidirectional Compaction) are pseudo-isostatic since the lateral compression is less than that imposed in the axial direction. This imbalance occurs because the compression medium is a ceramic material. In these processes, pressures up to 60,000 psi are used and compaction is obtained in 5 to 10 seconds at temperature. In both processes, a preform of pre-determined dimensions is used; since the axial and lateral pressures are not equal, care must be taken in the control of process variables to avoid lateral extension of the part or compensate for it in the dimensions of the preform. In Ceracon, a ceramic grain material, such as alumina, is used and can be recycled after compression. The ROC process makes use of a silica-base material that is cast around the preform and is broken away after consolidation; reportedly about half of the silica material can be recycled. Both processes are of interest as alternates to HIP for the preparation of near net shapes.

Another imaginative process makes use of the lost wax method to replicate ceramic shell moulds into which metal powders are introduced and subsequently compressed by HIP to achieve an intricate shape in final form. An experiment with this process on a Ti-6Al-4V alloy yielded a complex component with mechanical properties comparable to the same alloy in wrought form and superior to the cast alloy. The economic attraction of the process is in dealing with materials that normally involve costly machining to obtain the final part and where a significant quantity of scrap is generated in processing a relatively expensive alloy by conventional means.

A number of observers believe that the major future direction in advanced powder metallurgy lies in the integration of powder production and consolidation. Integrated processing rather than performing separate steps should reduce the possibility of contamination, improve quality control, increase the production rate and improve the costs. Extensive work is being done with some significant progress in developing new processes. For present purposes two techniques, spray forming and plasma deposition, illustrate the concepts and the methods.

Spray forming

In the spray-forming process, molten metal is inert-gas atomized to create a dispersion of droplets that are directed onto a surface where they splat and solidify. At high spray density, the splat occurs on a surface covered by a thin film of molten metal (in contrast to other procedures where the splat falls on a solid chilled surface). The deposition mechanism, which can be described as liquid dynamic compaction, produces a high density mass with fine grain size, little segregation and low oxygen content. A variety of shapes and near net shapes can be prepared by the use of appropriate substrates and their movement during deposition. Cylinders are readily made on a rotating mandrel, and disks on a circular platform. Typically about one pound of metal per second goes through the system, of which 60 to 70 per cent is deposited on the dense shape. The overspray is gathered in a cyclone collector for subsequent use.

Either argon or nitrogen can be used as the inert gas in the process, and a key question is whether the use of argon, which costs about eight times as much as nitrogen, is justified. Experimental investigation of this issue as well as the properties and characteristics of nickel-base alloys prepared by spray forming were recently reported 2/ and are summarized below.

Spray-formed deposits of a nickel-base superalloy (IN718) using nitrogen as the gas resulted in a density of 99.5 per cent, whereas the use of argon gave a density of 1 per cent less. Subsequent hot isostatic pressing of the shapes increased the density but the differential persisted; after HIP the nitrogen-treated material had a density of 99.9 per cent, but the argon atmosphere material had a density only slightly above 99 per cent. Metallurgically this difference can be interpreted by the solution and precipitation of nitrogen in the alloy, whereas argon diffuses in the solid with some difficulty, cannot go into solution because of its chemical inertness and can only form persistent voids. Microstructural studies have shown the existence of nitrides and carbonitride precipitates in the nickel alloys; similar study of the argon-processed alloy disclosed voids.

Chemical analyses also point out the nitrogen take-up and the low oxygen levels maintained in the material after spray forming, as seen below:

Material	ppm nitrogen	ppm oxygen
Melt stock	70	4
Argon atomized	90	32
Nitrogen atomized	330	22

The mechanical properties of material produced by the spray-formed process have been compared with those obtained with the same alloy in the cast and the wrought conditions. These data lead to the conclusion that the tensile and yield strengths of spray-formed alloy (nitrogen atmosphere) are significantly better than the same alloy in the cast condition and comparable to the alloy in the wrought condition in three conditions: (1) spray formed, (2) spray formed followed by HIP and (3) spray formed followed by forging. The ductility as measured by elongation in tensile tests is somewhat less for spray-formed material as compared with the conventionally wrought material: 12 per cent as compared with 19 per cent.

Repetition of the above-mentioned experiments with argon-atomized material indicated that the tensile and yield strengths of the alloy are 5 to 10 per cent less than the values obtained with nitrogen as the atomizing gas. In the spray-formed condition, the argon-atomized material displayed lower ductility than the counterpart prepared with nitrogen; after hot isostatic pressing the difference was reversed in keeping with microstructural changes including the precipitation of nitrides in one material and the spheroidization of the argon-filled pores in the other.

This work has demonstrated the potential of spray forming as an integrated process for powder production and consolidation and, at least with the nickel-base alloy used, has shown that nitrogen is prefered over more expensive argon. High-density, fine grain size deposits with uniform and homogeneous structures are produced, and mechanical properties equal to or superior to conventionally processed alloy are achieved.

Various investigators have used this process and its modifications to study the deposition and performance of a wide spectrum of alloys including aluminium alloys, carbon and low-alloy steels, bearing steels, tool steels, stainless steels, titanium alloys, and nickel- and cobalt-base superalloys.

Plasma deposition

This technique is based on a modification of a process that was developed about 20 years ago for the application of special coatings and surface layers of hard, wear-resistant and corrosion-resistant materials for various industrial applications. It is still in extensive use for that purpose. In the present interest, a massive body is built up by low-pressure plasma deposition. The system consists of a plasma gun, a powder supply and a substrate which is preferably mobile, housed in a vacuum chamber. The gun consists of a tungsten anode surrounded by a circular water-cooled copper anode that is electrically powered to create a plasma by ionizing argon or nitrogen (with helium or hydrogen additives). Temperatures of 5,000 to 10,000° C can be obtained and the rapid expansion of the gas within the gun cause the gases and the metal particles supplied through channels in the anode to be propelled through the gun nozzle onto a substrate in the chamber at velocities of Mach 2 to 3. The powder is fed to the system by a gas stream, usually argon. Operationally, the chamber is evacuated to about 10 microns and back-filled with argon to 40 to 60 torr. The power supplied to the plasma gun is enough to melt the powder but not enough to vaporize the metal (powders with a narrow size distribution are required). The distance between the gun and the substrate, typically 7 to 20 inches, is selected to assure that the metal droplets are still liquid upon impact. Deposition rates are considerably lower than the spray-forming process and are on the order of 1/2 cc per second (about 1/100th of spray forming).

In parallel with the development work on the application of this process, studies on the fundamental aspects of plasma deposition are in progress. These include such considerations as the interactions between the plasma and the particles, interactions between the droplets and the substrate, and the structural characteristics of the deposits.

Experimental work has been done on nickel-base superalloys and to a lesser extent on aluminium alloys, copper, and refractory metals. Comparative tests using a nickel-base alloy have shown that plasma-deposited material has a higher yield strength (150 ksi) than the same alloy conventionally cast (130 ksi). It has also been found that heat treatment of the plasma-deposited material increases the yield strength to 160 ksi. Thermal fatigue tests have also shown superior results for the plasma product. On the other hand, the ductility of the alloy in the conventionally cast condition was about 2 per cent points higher; this is believed to be caused by oxygen retained from the raw material powder, creating embrittlement.

The scope and versatility of the process is also being explored and defined. Both the gun and the mandrel or substrate can be rotated during deposition, which opens the possibility of producing various shapes and configurations. Different materials could be deposited in sequence to produce special laminates, or the controls could be altered to produce components with a gradient in chemical composition or a gradient in thermal expansion characteristics. One promising avenue is the production of thin-walled structures that are difficult or costly to fabricate by conventional means.

While the two processes described above characterize what is believed to be a major future direction in this field, these two do not exhaust the possibilities. Still others such as the use of lasers may come into practice in the future, and the rapidly developing nature of this field suggests continued monitoring.

Mechanical alloying

Another consolidation technique of a quite different nature is the mechanical alloying process which is based on high-energy ball milling of powders. Powders of the metallic constituents of the desired alloy, including intermetallic compounds and dispersoids, are ball-milled with agents such as stearic acid and methanol that help control the balance between fracturing of the particles and their welding and alloying. The milling action produces layered composite powders; continued processing leads to a homogeneous distribution of constituents. After milling, the particles are degassed and consolidated by vacuum, hot pressed or extruded, depending on the alloy. The process does not make use of rapidly solidified powders, but a very fine grain size is obtained in the final part by virtue of the severe deformation during milling followed by recrystallization; in some cases the final grain size is less than one micron.

The mechanical alloying process has been applied to various alloy system on the scale of 11-inch diameter billets, and up to an 18-inch diameter. The potential of the process to improve mechanical properties is illustrated below:

Condition	Yield strength in ksi
Coarse-grained Al, conventionally processed	5
Fine-grained Al, conventionally processed	15
Dispersion strengthened Al, conventionally processed	20
Mechanically alloyed (6% dispersion, as above)	60

The mechanically alloyed material offers a significant improvement in yield strenth by virtue of a very fine grain size and a uniform dispersion.

The mechanical properties of aluminium alloys prepared by mechanical alloying (MA) and by conventional ingot metallurgy (I/M) have been compared experimentally, as seen below. IN 9021 is a commercial alloy containing additions of 4 per cent Cu and 1.5 per cent Mg; the other material is a solid solution type alloy containing additions of 4 per cent Mg and 1.5 per cent Li.

	Al-4Cu-1.5Mg		Al-4Mg-1.5Li	
	MA	I/M	MA	I/M
Tensile strength (ksi)	78	68	74	50
Yield strength (ksi)	68	47	64	28
Elongation (%)	13	19	8	18

In both cases, the data indicate a marked increase in tensile and yield strengths with loss in ductility. Further work is under way to develop the process and its application, particularly to aluminium and nickel alloy systems. Exploratory work is also in progress to determine the role of the mechanical alloying process in the field of metal matrix composites, one example of which is the use of silicon carbide particles as a reinforcement in an aluminium alloy matrix.

Before leaving the subject of consolidation, some mention should be made of the advances that are being made in hot forging, a step sometimes used after hot isostatic pressing or extrusion of metal powders. It has been shown with several nickel-base alloys that hot forging further increases the advantage of HIP powders over conventionally processed material with regard to room-temperature tensile properties and both the tensile and stress-rupture performance at 650° C. A critical function of hot forging is to increase the density and this is borne out by an improvement on low-cycle fatigue resistance. Microstructural studies show that fatigue cracks can initiate at pores in the as-HIP condition; the problem is largely solved by the addition of a hot forging step. A significant aspect of the current effort in this field is the development of information on the basic stress, strain and strain-rate relationships at various temperatures for materials of interest. These data are being entered into computer programmes for use in selecting the proper forging conditions. It is expected that in the future, CAD/CAM will provide control of the forging operation, including the definition of the preform shape and dimensions, type of die, temperature, and the compression load and rate. Future work is also directed toward developing greater flexibility to deal with new shapes and new alloys.

Alloys and products

In the foregoing discussion, considerable mention has already been made of the properties of various alloys processed by advanced powder metallurgy to illustrate the benefits derived from the new techniques. In this section, attention is focused on the materials and products since they are the objectives, whereas the processes are the means.

The basic mechanisms by which rapid-solidification processing imparts improved properties to a material are:

1. Decreasing the grain size
2. Extending the solid solubility of alloying elements
3. Refining the size and improving the distribution of intermetallic compounds
4. Increasing chemical homogeneity

Aluminium alloys

These mechanisms are amply demonstrated in the various classes of aluminium alloys, as summarized in the following:

1. Wear-resistant alloys. Aluminium alloys containing 17 to 20 per cent silicon are of special interest to the automotive industry for use in engine pistons and cylinder liners. The silicon addition increases the modulus of elasticity (stiffness) and provides a coefficient of thermal expansion compatible with cast iron. Laboratory tests on Al-Si alloys prepared by advanced powder techniques have been shown to be superior to conventionally processed alloys in wear resistance.

2. High temperature alloys. This family of alloys is intended for service in the temperature range of 230° to 340° C and includes members using alloy additions of FE-Ni, Fe-Ce, Co-Ni or Mn-Fe. All of these materials depend upon the creation of dispersions of intermetallic compounds to strengthen the alloy matrix. Theory, which predicts sharply increasing yield strength with a decrease in the size of dispersion particles and with increasing volume fraction of the dispersions, is borne out in experimental data for these systems.

A potential problem with this class of alloys is the coarsening of the metallurgical structures upon prolonged heating at the service temperatures. This coarsening is related to the diffusion rates and interfacial tensions between the dispersions and the matrix. In general, the tensile and yield strengths of these alloys fall off with increasing temperature. Laboratory results, however, indicate that the Al-Fe-Ce alloy prepared by powder metallurgy is superior in yield strength in the 200° to 300° C range compared with conventional aluminium alloys.

Further, the Al-Fe-Ce alloy retains its high values of room temperature tensile and yield strength after prolonged exposure at temperatures up to 300° C in contrast to the wrought alloy equivalent.

3. High-strength alloys. These materials are of interest for application in aircraft structures, automotive parts, architectural structures, and the chemical industry. Two new powder metallurgy alloys have been developed based on the additions of Zn and Mg that exhibit superior combinations of strength, toughness, and stress-corrosion cracking resistance compared with their nearest equivalent commercial alloys that are prepared by ingot metallurgy. The powder metallurgy materials include a cobalt addition which forms cobalt aluminide particles that contribute to the enhanced properties.

4. High-modulus, low-density alloys. An important objective in material engineering is the development of alloys (or composites) with a high ratio of elastic modulus to density for use in industrial and military applications which are stiffness critical. Aluminium enjoys a low density but suffers from a rather low elastic modulus (about one third that of steel). Among the alloying elements, Li, Si, and Mg have lower density than Al. Of these, Li has the greatest effect in increasing the elastic modulus of Al. Considerable work has been done, therefore, on Al-Li alloys. By conventional processing, these alloys encounter difficulties with regard to segregation in ingots and loss of toughness when processed for high strength. The expectation is that powder metallurgy will overcome these difficulties to provide a new commercial alloy with a significantly higher specific modulus. Despite extensive research and voluminous data, it is not apparent that the quest has been successful thus far. Progress has been made in both powder metallurgy and ingot metallurgy on Al-Li alloys resulting in approximately a 20 per cent increase in the specific modulus, but a material with a sufficient number of the desired attributes has not yet emerged and become a commercial reality.

Aluminium powder metallurgy mill products are being commercially supplied by two firms in the United States of America. Both are currently limited to recently developed high-strength type alloys. One vendor supplies billets of 250 pounds prepared by the mechanical alloying process; the other vendor does not sell billets but offers extruded parts (up to 175 pounds) and forgings (up to 220 pounds).

High alloy tool steels

One of the oldest and most successful applications of powder metallurgy has been the manufacture of cemented carbide cutting tools. Tungsten carbide particles bonded by liquid infiltrated cobalt was introduced in the early 1920s and became a mainstay of the cutting tool industry. Subsequent developments led to the use of other refractory metal carbides (Ti, Nb, V, Mo and Cr) and their solid solutions; the coating of carbide tools for higher cutting productivity and extended tool life; and continued improvements in the technical control and service performance of these materials. That history is well known in the technical and industrial literature and need not be related here. That development, however, provides a background for examining the more recent application of powder metallurgy to the high alloy tool steels (HATS), a sector which has traditionally been based on electric steel-making and ingot metallurgy.

The advantages found with powder metal processing over conventional processing of HATS are numerous:

1. Ingot materials are prone to segregation and to non-uniformity in the size and spatial distribution of the carbides. The powder method eliminates segregation and provides carbides of fine size and uniform distribution.

2. Grindability (as measured by the ratio of the volume of the tool steel removed to the volume of the grinding wheel removed) is roughly twice as good for the powder process. This factor is an important element in the cost of fabricating tool products.

3. The impact properties of the powder product as measured in Charpy C-notch tests is almost double the ingot product; the same has been found with respect to bend fracture strength.

4. Powder material provides better hardenability, i.e. greater depth and uniformity of hardening in heat treatment.

5. Tools fabricated from powder suffer less than half of the out-of-round distortion from the quench and temper heat treatment.

6. The above cited benefits are reflected in superior life and service performance for given grades and compositions of tool steels.

In current full-scale commercial operations, powders are made of established alloy grades which contain various additions of C, Cr, V, W, Mo, and Co. The alloy powders, made in a nitrogen gas atomizer, are collected, screened, canned, degassed, enclosed and hot isostatically pressed. Cans up to 20 inches i- diameter and 94 inches high are processed. These contain 6,000 pounds of powder as compared with the typical size of 1,900 pounds for a melted heat of tool steel; perhaps this is a rare case where the powder route is on a larger scale than the conventional process.

Market products are for machining applications (such as taps, reamers, hobs, drills, broaches, and cutters) and wear-resistant applications (such as punches, stamping and forming dies, rolls, components used in handling and processing abrasive materials, injection and extrusion moulding equipment, and gears).

Titanium alloys

Because of their high-strengh-to-density ratio at both room and moderately elevated temperatures, these materials are used for aircraft structural parts and gas turbine jet engine components. Also the excellent corrosion resistance of titanium and its alloys to a wide range of media has led to extensive use in the chemical industry and other applications involving a corrosive environment. Titanium is not an inexpensive material and requires special care in casting and forging. Being a reactive metal it readily forms oxides, nitrides, and carbides; it cannot be melted in air or handled in ordinary crucible materials.

The attraction of powder metallurgy for processing titanium alloys includes the following:

1. The basic process by which elemental titanium metal sponge is produced generates fine particles. This powder, which normally is recycled as scrap, may be suitable for powder metallurgy.

2. The mechanisms for the benefits derived from powder metallurgy outlined at the outset of this section should be applicable to titanium and its alloys.

3. The existing commercial alloys of titanium were developed for production by currently used processes. It may be possible to develop new and improved alloys which are designed for powder metallurgy methods.

4. One of the strongest incentives is the potential savings in machining costs and reduced scrap losses. A comparison is made below of the weight of six different aircraft structural parts (shafts, pivots, links, braces etc.) with the weight ratios for quantities of material required by the forging route and by the powder method to achieve the finished part. The superior material efficiency of the powder route is clearly shown.

Weight of final part (pounds)	Ratio of forging weight to final weight	Ratio of powder weight to final weight
0.4	11.7	2.7
11.5	15.0	2.7
32.0	3.7	1.7
28.0	6.3	2.0
13.8	6.8	4.1
1.5	4.1	1.3

Attempts to use titanium fines from the metal production process for powder metallurgy have not been entirely successful. The extraction process for titanium involves the reduction of titanium chloride and it is found that chlorine carries over in the powder compacts, creating residual porosity with an adverse effect on mechanical properties. Prealloyed titanium powders have been found to give superior performance to the elemental fines.

The prealloyed powders used in the development programmes have largely been made by the rotating electrode process (a version of subsonic atomization) and compacted by HIP, ROC and extrusion. Laboratory results have shown that the powder method provides mechanical properties, including fatigue strength, equivalent to the standard wrought alloy. Fatigue strength is of specical interest since this is an important performance criterion in aero-applications. It has been learned that contaminants in the powder parts such as SiO_2 and Al_2O_3 degrade the fatigue properties. Various efforts to improve the quality and properties include the preparation of titanium alloy powders with low contaminants using special, dedicated facilities; thermal treatment of the compacts in hydrogen; and the co-reduction of titanium, aluminium, and vanadium salts to produce an alloy powder. New work is also being aimed at the production and compaction of titanium alloy powders of very fine particle size made by ultrasonic atomization.

Another new direction is the investigation of new alloy compositions that are suited to the powder approach. One series of interest is the addition of rare earth metals which can scavenge oxygen from titanium to create dispersoids. Another is the use of low-density additions such as Li, Be and Mg to improve property/density ratios.

Nickel-base alloys

These alloys play a well-established role in the hot parts of aircraft gas turbine jet engines and in similar high temperature applications. After many years of technical development the leading alloys have become very complex constitutionally; many of the alloys have over 12 elements specified in their chemical composition. Such complexity creates a tendency towards segregation, irregular grain structures or non-uniform properties. The powder route is seen as a means of avoiding these difficulties with the added incentives of better material-use efficiency, reduced machining and cost savings.

The early powder work on nickel superalloys was aimed at decreasing the number of steps in the working cycle and improving material efficiency by producing a billet from powders followed by conventional forging, machining and heat-treating operations normally used on cast and wrought parts. Subsequently, hot dies were developed that permitted isothermal, slow strain rate forging of turbine disks from superalloys consolidated by extrusion or HIP. Current work, as reported previously in this review, is aimed at greater use of alloys in the as-HIP condition, HIP to final shape processing, mechanical alloying, and integrated processes for production and consolidation of powders.

The powder metallurgy of nickel superalloys is a steadily maturing field. It has become a commercial reality and the estimated annual usage exceeded one million pounds as early as 1979.

Implications of powder metallurgy for the developing countries

The attractiveness and suitability of powder metallurgy as a new area of industrial activity for a developing country is obviously related to the capacity and capability of the individual country. These considerations include raw material position, availability of personnel, existence of the essential supporting industrial infrastructure, existence of local markets and access to export markets, relevance to the national industrial development policy and plan, and others.

Apart from these general considerations, there are other aspects which are specific to the powder metallurgy field that may be characterized as follows:

1. Powder metallurgy generally requires a large volume of repetitive production. For example, the production of 100 parts would likely be more efficient by other means; however, the need for 10,000 or more identical parts (say for bicycles, mopeds, or cars) could probably be met economically by powder metallurgy.

2. Because of the production volume, industrial powder metallurgy installations are more compatible with large central plants than with small-scale facilities widely distributed within the country. Unlike pottery manufacture, for example, powder metallurgy is not highly compatible with an industrial and social policy which fosters small-scale rural industry.

3. On the matter of scale, there is a great deal more latitude in the size of a powder metallurgy installation than with a conventional metal production and fabrication plant. Moreover, the minimum size for economic efficiency is much smaller for the powder route in keeping with the needs and interests of many developing countries.

4. Participation in the powder metallurgy field does not require fully integrated operation. One can purchase powders for use in producing finished parts or, at the other extreme, produce powders (perhaps based on indigenous raw material) for export. In either case, an industrial strategy can be developed for subsequent backward or forward integration.

5. Much of the basic technology for powder metallurgy is in the technical and industrial literature and as such is freely accessible to a developing country. Rights and know-how for some of the special and advanced techniques are presumably available to others under commercial and financial arrangements.

6. The advanced developments in powder metallurgy have been oriented towards the needs of the industrialized countries, but these new technologies (such as rapidly solidified powders and hot isostatic pressing) will become useful to developing countries that are, or will become, engaged in the powder metals field.

7. Some technologies developed in the industrialized countries may have greater potential use in the developing countries. A good illustration of this point is the rolling of metal powders to produce sheet products.

The process, first developed in the Federal Republic of Germany in the early 1950s, consists of feeding metal powder from a vertical hopper into a pair of converging rolls which compress the powders into a continuous sheet. The compacted material is passed through one or more sintering furnaces and, if desired, through additional rolls, to obtain a continuous coil of the product. The width of the sheet depends on the dimensions of the hopper and the rolls, and the thickness is controlled by the rolling step(s). A variety of metal and alloy powders such as iron, copper, brass and stainless steel can be fabricated into foil, strip and sheet. The process also lends itself to producing special materials: sheet controlled open porosity for use as filters or for impregnation with a lubricant for bearings; bimetallic strip made by simultaneously feeding the two metal powders as parallel layers into the rolling/sintering system; combinations of metals with non-metallics such as abrasives or wear resistant compounds etc.

Commercial use of this process has been limited in the industrialized countries because there is abundant capacity for producing sheet products by conventional ingot metallurgy and the usual rolling procedures. Thus the few powder-rolling facilities which have been installed in the industrialized countries are for special needs.

In contrast to this situation, many developing countries without ingot metallurgy and rolling facilities could fulfill their needs for sheet metal by the powder rolling process.

Some of the incentives for taking this route (as compared with conventional methods) include the following:

1. Significantly lower capital investment
2. Smaller economic scale
3. Greater flexibility and range of metals and alloys
4. Greater versatility in types of products, i.e., porous, bimetallic, composite, etc.
5. As in the case with conventional metallurgy, the technology of powder rolling is already developed and it is a matter of transfer.

It will be of interest to note that metal powder rolling is now being used in at least one developing country. In China where there is significant production of titanium metal, the powder rolling process is used to produce titanium metal foil for the international market.

References

Two major sources of information were used in preparing this review. The contents are also listed.

<u>Advances in Powder Metallurgy</u>, edited by G.Y. Chin (American Society for Metals, Metals Park, Ohio, 1982).

1. "Powder and Particulate Production of Metallic Alloys", N.J. Grant
2. "Powder Preparation: Ceramics", D.W. Johnson, Jr.
3. "Powder Characterization", F.F.Y. Wang
4. "Application of Soil Mechanics Concepts to Ceramic Particulate Processing", G.Y. Onoda and M.A. Janney
5. "Powder Consolidation", A. Lawley
6. "Sintering of Ceramics and Metals", M.F. Yan
7. "Energy Analysis of the Powder Metallurgy Process", S.M. Kaufman
8. "Advances in Powder Metallurgy and Oxide Dispersion Strengthened Superalloys", J.K. Tien and T.E. Howson
9. "Advanced Powder Metallurgy Aluminum Alloys", T.E. Tietz and I.G. Palmer
10. "Porous Materials", R.M. German
11. "Cemented Carbide Cutting Tools", V.K. Sarin
12. "Dense Silicon Nitride Alloys: Phase Relations and Consolidation, Microstructure and Properties", J. Lorenz, J. Weiss, and G. Petzow
13. "The Thin Film Module as a High-Performance Semiconductor Package", C.W. Ho, D.A. Chance, C.H. Bajorek, and R.E. Acosta

Symposium on Advances in Powder Metallurgy, co-sponsored by the American Institute of Metallurgical Engineers and the American Society for Metals, Schenectady, New York, 14-15 May 1985.

1. Keynote Address, F.V. Lenel
2. "Atomization Processes", N.J. Grant
3 "Deformation Processing of Powder Metallurgy Materials", H.A. Kuhn
4. "Liquid Phase Sintering", R.M. German and B.H. Rabin
5. "Emerging Consolidation Techniques", B.L. Ferguson
6. "Fundamental Aspects of Plasma Spraying", D. Apelian
7. "Consolidation by Low Pressure Plasma Spraying", M.R. Jackson and J.R. Rairden
8. "Spray Forming", H.C. Fiedler, T.F. Sawyer, and R.W. Kopp

9. "The Preparation of Powder by Spark Erosion", J.L. Walter
10. "Advances in Titanium Powder Metallurgy", D. Eylon
11. "Microstructures and Mechanical Properties of Titanium Alloys",
    J.M. Smugeresky
12. "Developments in High Performance Powder Metallurgy Aluminum Alloys",
    M.J. Koczak
13. "Processing of Powder Metallurgy Tool Steels", B. Dixon
14. "Microstructural Evaluation of Powder Metall / High Speed Steel",
    S. Kumar
15. "Powder Metallurgy Forging", W.H. Couts, Jr.
16. "Microstructures and Properties of Powder Metallurgy Superalloys",
    W.J. Boesch
17. "Mechanically Alloyed Aluminum and Nickel-Base Alloys", P.S. Gilman.

MEETINGS

New materials

Advanced Materials Briefing (discussions on applications and markets for advanced composites and high-performance ceramics), sponsored by Chemical Week and Strategic Analysis Inc., McGraw-Hill World Headquarters, New York, New York, on June 18 (Contact Gregory Ramsey, Strategic Analysis Inc., Box 3485, R.D. 3, Fairlane Road, Reading, Pennsylvania 19606, U.S.A.)

Powder Metallurgy

EXPLOMET '85, Portland, Oregon, 28 July to 1 August 1985. EXPLOMET '85 aims to provide a forum for the exchange of information on the metallurgical and other materials effects and applications of shock wave and high strain rate phenomena. Among scheduled papers are "Explosive compaction of polymeric and ceramic powdered materials" by T.Z. Blazynski of the University of Leeds and "New trends in explosive powder metallurgy" by R. Pruemmer of the Fraunhofer-Institute für Werkstoffmechanik.

International Powder Metallurgy Conference 1986, Düsseldorf, Federal Republic of Germany, 7-11 July 1985, organized by Ausschuss für Pulvermetallurgie on behalf of the European Powder Metallurgy Federation. The Conference is addressed to all powder metallurgy specialists from research, education and industry, and gives an up-to-date survey of the latest developments in this modern field of technology. The Conference is also of particular interest for users of today and tomorrow of powder metallurgy products because it will point out the immediately impending new ranges of application. The following main subjects are proposed: new powders and their processing; powder characterization; new shaping processes, further processing of powder metallurgy products, compounding techniques, bonding techniques, and coating techniques; semi-finished products of production by powder metallurgy; and new materials. Interested authors are requested to send abstracts of their intended contributions to the conference not later than 1 October 1985 to the Programme Committee, Ausschuss für Pulvermetallurgie, P.O. Box 921, D-5800 Hagen, Federal Republic of Germany.

Fibre optics

"Fiber Optics for the Developing Countries", Cankarjev Dom, Ljubljana, Yugoslavia, 14-18 October 1985. This will be the first international conference and exhibition of fiber optics applications to the developing countries. (For information write to IGI Consulting Inc., 214 Harvard Avenue, Suite 200, Boston, Massachusetts 02134, U.S.A. who are organizing this conference.)

Fiber Optic Communications (Educational Course), George Washington University, Washington, D.C., 26-27 June 1985. (Contact Continuing Engineering Education Program, George Washington University, Washington, D.C. 20052.)

Principles and Applications of Fiber-Optic Communication Systems (Educational Course), San Francisco, California, 9-11 July 1985 (Contact Lightech Inc., 2116 East Arapaho, Suite 515, Richardson, Texas 75081, U.S.A.)

New ceramics

Ceramitec '85, München, Federal Republic of Germany, 15-19 October 1985. Third International Trade Fair. (Contact Munchener Messe- und Ausstellungsgesselschaft mbH, Messegelände, Postfach 12 10 09, D-8000, München 12, Federal Republic of Germany.)

PUBLICATIONS

The following is a partial list of publications published or distributed through the Metal Powder Industries Federation and the American Powder Metallurgy Institute. Address requests to Publications Department IJPM, Metal Powder Industries Federation, 105 College Road East, Princeton, New Jersey 08540, U.S.A.

Progress in Powder Metallurgy, Vol. 38

Handbook of Powder Metallurgy, Hausner and Mal, 2nd edition

Advances in Powder Metallurgy (Chin)

Powder Metallurgy-Principles and Applications (Lenel)

Powder Metallurgy Equipment Manual

Source Book on Powder Metallurgy (Bradbury)

Testing and Characterization of Powders (Beddow and Meloy)