OCCASION

This publication has been made available to the public on the occasion of the 50th anniversary of the United Nations Industrial Development Organisation.

DISCLAIMER

This document has been produced without formal United Nations editing. The designations employed and the presentation of the material in this document do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations Industrial Development Organization (UNIDO) concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries, or its economic system or degree of development. Designations such as "developed", "industrialized" and "developing" are intended for statistical convenience and do not necessarily express a judgment about the stage reached by a particular country or area in the development process. Mention of firm names or commercial products does not constitute an endorsement by UNIDO.

FAIR USE POLICY

Any part of this publication may be quoted and referenced for educational and research purposes without additional permission from UNIDO. However, those who make use of quoting and referencing this publication are requested to follow the Fair Use Policy of giving due credit to UNIDO.

CONTACT

Please contact publications@unido.org for further information concerning UNIDO publications.

For more information about UNIDO, please visit us at www.unido.org

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria
Tel: (+43-1) 26026-0 · www.unido.org · unido@unido.org

14777

ADVANCES IN POWDER METALLURGY

Edward Epremian
Consultant

May 1985

3652

I. 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 which 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 aluminum 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 1960's; 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 aluminum alloys, titanium alloys, superalloys, and high speed tool steels. These new techniques also make it possible to create new alloys and combinations of materials which 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.

II. 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.

A key and common feature of these new techniques is a very high cooling rate as summarized in the following table.

Table 1

Method	Approximate Cooling Rate (degrees per second)
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 in a previous paper in this publication by Herbert Danninger and Gerhard Jangg, subsonic gas atomization is the most important physical powder production method 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 which 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 5mm.

- 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°.
- 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. Aluminum 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 of 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 which 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 superalloy, magnetic alloys, and a 78% 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 are thus susceptible to surface contamination. The existence of oxides on the surface of an aluminum 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 in 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. Inasmuch 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.

III. CONSOLIDATION

The most highly developed and widespread advanced consolidation technique is hot isostatic pressing (HIP). The method was reported on by Dr. H. Kor[illegible]icka in a previous paper in the *Advances in Materials Technology: Monitor* 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 and technical development interest in 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 which 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 behavior. This information is being used to develop computer-aided design procedures to identify the appropriate process operating conditions and mold 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 which 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 molds 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 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 which 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 which 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% 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 8 times as much as nitrogen, is justified. Experimental investigation of this issue as well as the properties and characteristic of nickel-base alloys prepared by spray forming were recently reported(2) and summarized below.

Spray-formed deposits of a nickel-base superalloy (IN718) using nitrogen as the gas resulted in a density of 99.5%, whereas the use of argon gave a density of 1% 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%, but the argon atmosphere material had a density only slightly above 99%. 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 in Table 2.

Table 2

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) in three conditions: (1) as spray formed, (2) spray formed followed by HIP and (3) spray formed followed by forging, are significantly better than the same alloy in the cast condition and comparable to the alloy in the wrought condition. The ductility as measured by elongation in tensile tests is somewhat less for spray formed material as compared with the conventionally wrought material; 12% as compared with 19%.

Repetition of the above mentioned experiments with argon atomized material indicated that the tensile and yield strengths of the alloy are 5 to 10% 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, shown that nitrogen is preferred 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 aluminum 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 which 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, 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 which is electrically powered to create a plasma by ionizing argon or nitrogen (with helium or hydrogen additives). Temperatures of 5,000 to 10,000^{o}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 aluminum 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 increased 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% 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 which 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 which 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 systems on the scale of 11-inch diameter billets, and up to 18-inch diameter. The potential of the process to improve mechanical properties is illustrated in the following table.

Table 3

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 strength by virtue of a very fine grain size and a uniform dispersion.

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

Table 5

	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 underway to develop the process and its application, particularly to aluminum 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 aluminum alloy matrix.

Before leaving the subject of consolidation, some mention should be made of the advances which 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 programs 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.

IV. 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 of the review paper, attention is focussed 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

Aluminum Alloys

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

1. Wear-resistant alloys. Aluminum alloys containing 17 to 20% 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 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 Al-Fe-Ce alloy prepared by powder metallurgy is superior in yield strength in the 200° to 300°C range compared with conventional aluminum 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 which exhibit superior combinations of strength, toughness, and stress-corrosion cracking resistance compared with their nearest equivalent commercial alloys 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. Aluminum 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% 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.

Aluminum powder metallurgy mill products are being commercially supplied by two firms in the USA. 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 1920's 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 in 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 molding equipment, and gears).

Titanium Alloys

Because of their high strength 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 on Alloys and Products 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. In the following table, a comparison is made 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.

Table 6

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

The superior material efficiency of the powder route is clearly shown.

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 programs have largely been made by the rotating electrode process (a version of subsonic atomization) and compacted by HIP, ROC, and extrusion. Labortory results have shown that the powder method provides mechanical properties, including fatigue strength, equivalent to the standard wrought alloy. Fatigue strength is of special 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, aluminum, 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 which 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 tendancy toward segregation, irregular grain structures, on 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 which 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.

V. 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 which 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 toward 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 which 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 Germany in the early 1950's, 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, stainless steel, etc., 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 is 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

The two major sources of information in preparing this review are as follows. The contents are also listed for their interest.

1. Advances in Powder Metallurgy, edited by G.Y.Chin, American Society for Metals, Metals Park, Ohio, 1982.

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

2. 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.

A. Keynote Address--F.V.Lenel

B. Atomization Processes--N.J.Grant

C. Deformation Processing of Powder Metallurgy Materials--H.A.Kuhn

D. Liquid Phase Sintering--R.M.German and B.H.Rabin

E. Emerging Consolidation Techniques--B.L.Ferguson

F. Fundamental Aspects of Plasma Spraying--D.Apelian

G. Consolidation by Low Pressure Plasma Spraying--M.R.Jackson and J.R.Rairden

H. Spray Forming--H.C.Fiedler, T.F.Sawyer, and R.W.Kopp

I. The Preparation of Powder by Spark Erosion--J.L.Walter

J. Advances in Titanium Powder Metallurgy--D.Eylon

K. Microstructures and Mechanical Properties of Titanium Alloys--J.M.Smugeresky

L. Developments in High Performance Powder Metallurgy Aluminum Alloys--M.J.Koczak

M. Processing of Powder Metallurgy Tool Steels--B.Dixon

N. Microstructural Evaluation of Powder Metallurgy High Speed Steel--S.Kumar

O. Powder Metallurgy Forging--W.H.Couts, Jr.

P. Microstructures and Properties of Powder Metallurgy Superalloys--W.J.Boesch

Q. Mechanically Alloyed Aluminum and Nickel-Base Alloys--P.S.Gilman