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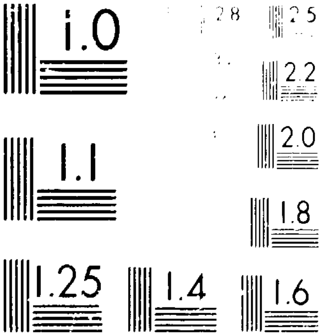
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TECHNOLOGICAL PERSPECTIVES IN THE MACHINE TOOL INDUSTRY
AND
THEIR IMPLICATIONS FOR DEVELOPING COUNTRIES

PART II

Prospective technological developments in the machine tool industry in developed countries *

by

S.M. Patil
UNIDO Consultant

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* This is an advance edition of a UNIDO publication to appear in the Development and Transfer of Technology Series. A summary has already been issued under UNIDO/IS.230.

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References to rupees (Rs) are to Indian rupees. In 1980, the value of the rupee in relation to the dollar was $1 = Rs 7.95.

In addition to the common abbreviations, symbols and terms and those accepted by the International System of Units (SI), the following have been used in this study:

AJM	abrasive jet machining
ATC	automatic tool changer
BHN	Brinell Hardness Number
CAD	computer-aided design
CAM	computer-aided manufacture
CBN	cubic boron nitride
CHM	chemical machining
CIRP	International Institution for Production Engineering Research
CMEA	Council for Mutual Economic Assistance
CMTI	Central Machine Tool Institute
CNC	computer numerical control
CPU	central processing unit
CRT	cathode ray tube
CUPE	Cranfield Unit for Precision Engineering
dB	decibel
DC	direct current
DCs	developing countries
DCS	diagnostic communication systems
DNC	direct numerical control
DRO	digital readouts

EBM	electron beam machining
ECG	electrochemical grinding
ECM	electrochemical machining
EDM	electron discharge machining
EEC	European Economic Community
EMO	European Machine Tool Organization
ENIMS	Experimental Scientific Research Institute of Metal-cutting Machine Tools
EPROM	erasable and programmable read-only memory
FMS	flexible manufacturing systems
GM	General Motors
GPMs	general purpose machine tools
HIP	hot isotatic press
HMT	Hindustan Machine Tools Ltd.
IBM	ion beam machining
IC	integrated circuit
ICAM	integrated computer-aided manufacturing
IMTMA	Indian Machine Tool Manufacturers Association
LAFTA	Latin American Free Trade Association
LBM	laser beam machining
LSI	large-scale integration; large-scale integrated circuits
MDI	manual data input
MVA	*megavolt-ampere*
NC	numerical control; numerically controlled
NICs	newly industrializing countries
NMTBA	National Machine Tool Builders Association
OBI	open back inclinable presses
PAM	plasma arc machining
PC	programmable controllers
PM	powder metal(lurgy)
PROM	programmable read-only memory
PSI	pounds per square inch
PUMA	programmable universal machines for assembly
RAM	random access memory
R&D	research and development
ROM	read-only memory
rpm	revolutions per minute
SCFMO	Syndicat des Constructeurs Français de Machine-Outils
SCR	silicon-controlled rectifier

SIP	Société Genevoise d'Instruments de Physique
UAW	United Auto Workers
UCIMU	Unione Construttori Italiana Macchine Utensili
UMC	unmanned machining centre
UMS	unmanned manufacturing systems
USM	ultrasonic machining
VLSI	very large-scale integration; very large-scale integrated circuits
VUOSO	Research Institute of Machine Tools and Machining
WJC	water jet cutting
WJM	water jet machining

CONTENTS - PART ONE

A GLOBAL STUDY OF THE MACHINE TOOL INDUSTRY AND A CASE STUDY OF THE MACHINE TOOL INDUSTRY IN INDIA

V. A BRIEF STUDY OF THE MACHINE TOOL INDUSTRY IN SOME OF THE LEADING DEVELOPING COUNTRIES

CONTENTS - PART TWO

PROSPECTIVE TECHNOLOGICAL DEVELOPMENTS IN THE MACHINE TOOL INDUSTRY IN DEVELOPED COUNTRIES

CONTENTS - PART TWO, contd.

Chapter Page

CONTENTS - PART THREE

THE IMPLICATIONS OF TECHNOLOGICAL DEVELOPMENTS IN THE MACHINE TOOL INDUSTRY FOR DEVELOPING COUNTRIES

Annexes

Tables

Part one

CONTENTS - PART THREE contd.

Tables

Part one contd. Page

CONTENTS - PART THREE contd.

Figures

Part one

Preface

This study consists of three parts: Part I comprises a global review of the machine tool industry which includes a case study of the machine tool industry in India; Part II considers prospective technological developments in the machine tool industry of the developed countries and Part III discusses the implications for developing countries of technological developments in the machine tool industry and contains recommendations, annexes and a bibliography.

The study is based on replies to a questionnaire sent to leading machine tool manufacturers, designers, production engineers, machine tool technologists, researchers and teachers in production technology and machine tool users throughout the world. While preparing the study, the author attended the 30th General Assembly of the International Institution for Production Engineering (CIRP) held in Australia in September 1980 and he has drawn on the insights gained from discussions held with some of the members of the CIRP and from subsequent visits to machine tool research institutes. Annex I contains an extract from a report of the Technical Policy Board of the the Institution of Production Engineers, United Kingdom; the questionnaire referred to above is reproduced in Annex II and the names of the companies, institutes and individuals visited by the author are given in Annex III.

PART II

PROSPECTIVE TECHNOLOGICAL DEVELOPMENTS IN THE MACHINE TOOL INDUSTRY IN DEVELOPED COUNTRIES

INTRODUCTION

It is not the intention here to forecast technological trends in the machine tool industry using any mathematical techniques like the Delphi, though reference to it is made in Annex I. 1/ Such a study was carried out by a renowned machine tool design and production technologist, Eugene Merchant, Director of Research Planning, Cincinnati Milacron Inc., Cincinnati, Ohio, United States of America and members of the International Institution for Production Engineering Research (CIRP). The present study however, is largely the outcome of the extensive tours undertaken by the author in "seeing things happen" and the discussions held with several well-known machine tool manufacturers, designers, production engineers, technologists, researchers, teachers in production technology and machine tool users. Hence it was hoped that the study could be pragmatic in its approach and not a theoretical prognostication, and its deductions practical and realistic.

1/ "Project Delphi" was the name of a US Air Force-sponsored Rand Corporation study, begun in the early 1950s, with the aim of obtaining expert opinion mainly through questionnaires.

In order to deal with the subject comprehensively, the following aspects have been taken into account: machine tool mechanics and design; cutting tool materials and tool technology; machine tool control systems; non-conventional machining processes; metal-forming machine tools; manufacturing systems/production engineering; automation in production technology.

It is interesting to compare the forecasts of Dr. Merchant and CIRP in 1970 wherever possible with what has actually occurred after a lapse of about 10 years.
In this respect the report by the Technical Policy Board of the Institution of Production Engineers, United Kingdom, on Current and Future Trends of Manufacturing Management and Technology in the United Kingdom, "The Way Ahead", in which such a comparison is made, is interesting.

Annex I contains an extract from this Report pertaining to the chronological summary from 1980 to 1996 which has been derived mainly from the answers to a questionnaire circulated by the Institution of Production Engineers.

Because machine tools are the most important means of industrial production, the development of production technology depends directly and uniquely on the development of modern machine tools, which is why machine tools have to be combined with production technology. In this survey of the latest developments in machine tool technology, therefore, the vital link between these two entities viz. modern machine tools and the development of production technology will be followed.

The enormous changes that are taking place in the realm of metalworking can be attributed to the fast tempo of developments in machine tool design and technology, control engineering and production concepts. The production technology of machining is developing fast to answer the incessant demand from the manufacturing sector. Developments pertaining, among others, to new materials, cutting tools and a new generation of drives are not only influencing the very concept of machining but they are adding a new dimension to the very methodology of machine tool design.

Furthermore new forms of production organisation such as the concept of fully or partially flexible manufacturing systems are emerging. At present by far the most important form of modern technology is computer-aided manufacture (CAM). It has already proved its higher ability to considerably improve production possibilities than all known forms of production techniques put together. For this reason, machine-tool-based production technology is becoming increasingly integrated with the computer.

Machining efficiency is the crucial requirement of a machine tool. Research on the maximum obtainable reduction in machining time and the maximum achievable accuracy and surface finish in machining is going on all over the industrialised world. But the emphasis at present is on the possible reduction that can be obtained in operation time, preparation time and in various non-machining times. Many new technologies covering the fields of machine rigidity, drives and controls have now helped considerably to reduce the non-cutting time and also to cut down the preparation time, specially with the development of new controls and positioning devices. It is the bid for reducing the operation time that has led to the search for better tools and better designs of machine tools having higher speeds and power.

The design of modern machine tools consists of the fusion of several technologies. The design of structure, drive, control and the very design methodology demand a close interaction of mechanical, electrical and electronic engineers besides metallurgists and others from an array of specialised disciplines. The design of machine tool structure is witnessing a quiet revolution. The requirements of high rigidity, light weight and good damping characteristics are forcing designers to evolve new designs using alternative materials and new configurations. The present approach is towards structures using combinations of metals and non-metals to ensure proper thermal stability, static and dynamic stiffness and favourable wear and noise characteristics.

The development of new cutting tool materials is compelling designers to devise drives of high speeds and high reliability. Noise considerations are restricting the use of gear drives at high speeds. SCR - controlled DC motors are being developed to obtain fine steps. Bearing systems are witnessing many changes; the requirements of high speeds, increased stiffness, high accuracy and reduced noise especially are favouring the application of hydrostatic bearings on a much wider scale.

The modern controls are being constantly refined in answer to the demands of higher productivity. The incredible tempo of development in micro-electronics and semiconductor technology is adding new capabilities to numerical controls and the latest microprocessor-based CNC systems demonstrate a level of reliability which was considered impossible only a few years ago. Fault diagnosis, remote diagnostics and self-checking routines have improved to such an extent by the modern trend of microcomputers that unmanned operations appear to be the next goal on the manufacturing horizon.

Spurred by the diverse consumer demands, the philosophy of manufacturing is showing a shift from mass production to large volume production with a built-in flexibility for quick change-over from one component spectrum to the other. The user industries are demanding finer part accuracies, tolerances and assembly requisites to meet the demand for high accuracies of end-products.

The urgent need of the manufacturing sector for multi-function machines to reduce production time and to assure high accuracies of machined components is responsible for the birth of versatile "Machining Centres". The concern of the manufacturing sector to humanise the working environment is forcing designers to view ergonomics as an essential component of machine tool design. The need to conserve material is dictating a shift from cutting to forming. The threatening energy crisis is forcing a keener attention towards energy management in metalworking. All these challenges are changing the very foundation of the design and manufacture of machine tools.

A great many structural changes are expected to take place in the production engineering industries of the West in the wake of innovative technological developments, in particular in information technology and, wherever possible, to accelerate this process of change. In the past advances in production engineering often had a lot to do with breaking down operational sequences into smaller steps, standardising the motions and relating them to people.

However, as a result of modern information technology, a reorientation of industrial production is conceivable and already visible in a few areas in the Western world. It is characterised by greater operational flexibility *vis-à-vis* customer requests and by a reduction in the monotony and one-sidedness of jobs. Apart from the new requirements to be met by production engineering as a result of changing user and worker demands, an innovative boost is expected to be given to production engineering, above all by modern semiconductor technology.

I. MACHINE TOOL MECHANICS AND DESIGN

There is no instant transformation into an era of chatterless machine tools with high metal removal rates, ultra-precision and 100 per cent uptime. Rather, there are signposts pointing to the paths that might be taken in improving the capabilities of metalcutting machines. This in itself is an important contribution to the state-of-the-art of machining. Spectacular advances in the capabilities of today's cutting tools could double cutting speeds for both roughing and finishing and could double feed rates in cutting. Taken together, these offer potential time reductions of 50 to 70 per cent and a further reduction of perhaps 50 per cent is possible if roughing and finishing can be combined into 'single pass machining' at an increased depth of cut. Depending on the application, such savings could increase overall output by 15 to 300 per cent.

Each of the above possibilities, however, adds to the challenge of machine tool design, requiring higher spindle r.p.m., faster feed mechanisms, larger torques and forces, significantly greater horsepower and much increased static and dynamic stiffness.

In the design of a machine tool, the major elements of importance are the structure, drive, guides etc. As already stressed earlier, the design of a machine tool should reflect the confluence of several engineering disciplines. The latest trends bear testimony to an integrated approach to the design of every major element of a machine tool. The design trends in structures, guideways and bearing surfaces, spindle systems, feed drives, accuracy aspects in design and computer-aided design, are briefly outlined below.

Structures

A century of trial and error has evolved today's iron - but both the method of design and its products may not be adequate for tomorrow - even the iron may have to go.

The principal design parameters of the machine tool structure are: stiffness-to-weight ratio, natural frequency and damping from the standpoint of dynamics, dimensional stability, and the long-term stability influencing the retention of accuracy of alignments. Another important parameter arising from ergonomic considerations is the accessibility for loading and unloading the job. This is an important parameter in view of the importance attached to automated loading. This is particularly evident in the slant bed design of modern lathes. The search for cheaper alternatives to cast iron has spurred research on the use of welded structures, concrete and even granite for use in the machine tool structure.

Fabricated steel structures. The need for lighter and stiffer structures has prompted designers to evaluate fabricated welded construction for beds, columns and also for modules which are used in a variety of combinations. Increased stiffness offered by the welded structures used for columns and cross-beams of vertical boring machines is almost 30 per cent over that of cast iron. In addition to the advantages of light weight and increased stiffness, these welded structures are cheaper than cast iron.

Concrete. Reinforced concrete is even cheaper than the welded structures with the added advantage of possessing excellent damping properties. Some manufacturers in the United States are making beds of NC turning machines, using concerete. These structures consist of a sheet-metal casing braced internally by steel rods and filled with concrete to which the machine tool is permanently glued. A special type of concrete which expands on curing is used. The bed of the machine is a closed box section - cast iron in which sand and core are left behind to achieve a high co-efficient of structural damping. This assures a statically and dynamically stiff structure which facilitates a high metal removal rate, high precision and an excellent surface finish in NC machines.

Granite. Future machine tool beds and bases may well be made of stone, particularly from granite because of its strength and easy availability. An indication of this can be seen in a diamond-turning machine installed at the LRL Laboratories in the United States. In this machine, granite is used as both the machine base and metrology base. This is claimed to be the world's first ultra-high precision lathe having straightness errors within 0.025 micron and positional displacement errors within 0.013 micron at all points, thus permitting turning with mirror polish in a single operation. Granite appears to be the most suitable material for such high precision machines because of its low thermal expansion (7.2×10^{-6} /°C) and excellent dumping property rate at 15 times more than that of cast iron or fabricated steel structure. In spite of all these advantages, the cost of processing granite for use as a machine base is still very high.

Guideways and bearing surfaces

New design concepts are now being tried to ensure the longevity of machine accuracy, to reduce periodic maintenance and to easily replace guideway elements without resorting to costly and time-consuming scraping. Recent innovations in guideway technology have resulted in the development of glued-on guides and fixed-on guides.

The glued-on guides are built with hardened or nitrided steel strips of 10-12 mm thickness which are bonded on the properly prepared base structure by using bonding agents like special Loctite or epoxy resins. The fixed-on guides are designed with case-hardened or nitrided steel guides which are bolted or dowelled on to the precision milled, ground or hand-scraped locating surface of the welded or cast iron machine bed/base. This is likely to be the basic design approach for the guideways and bearing surfaces of machine tools in the future.

The cost of such guideways is much less than even the conventional precision milled or hand-scraped guides. They facilitate easy replacement of worn out guides, considerably reducing the down-time of the machine. The mating bearing material on the counterpart can be of cast iron or teflon or any other self-lubricating or tribologically compatible material.

Rolling element guideway bearings. In high precision machine tools and NC machines, there is a marked increase in the application of rolling element bearings for guideways. By careful grading of precision rollers (or balls where a lighter load is to be carried), and by careful calculation of the mean loading per element, a very high precision motion can be achieved by virtue of 'the elastic averaging effect'. Some of the modern jig-boring machines use hollow rollers in the vee-flat in a semi-kinematic configuration. In this case, the hollow roller serves to help the averaging effect, and being slightly over square by about 50 microns, an excellent viscous damping is achieved by the shearing of the oil film in the vee-way across the flat ends of the rollers. With this type of bearing, a coulomb friction of less than 0.003 is achieved ensuring that even under heavy cutting loads, a heavy workpiece can be positioned with an accuracy of one micron.

Hydrostatic oil bearings. The main advantages offered by hydrostatic oil bearings are high stiffness, low friction, high viscous damping and very high averaging effects exhibited by the all-fluid film bearings. During operation, there is no metallic contact. This assures high life and accuracy of the bearing. These bearings are used in machine tools primarily where very high cutting forces associated with high metal removal are encountered and yet a medium accuracy and good finish are demanded. The main disadvantages of hydrostatic oil bearings are their high cost due to the need for auxiliary equipment such as pumps, resistors, and filters, and the need to control very precisely the clearances in the necessarily over-constrained bearing gaps. The temperature rise in the bearing is directly proportional to the clearances and in very high precision applications, it is desirable to control the temperature of the oil in the scavenging/recirculation process, if necessary, by refrigeration.

Aerostatic bearings. Application of air bearings is now widely prevalent, especially for high precision, high-speed grinding machines. The error averaging effect of the air film compensates for errors of circularity in the spindle and the bearing bore. By using these bearings, the roundness error on the finished product is estimated to be considerably reduced. The maximum roundness error of an air bearing spindle so far achieved on a high production grinding machine wheel spindle is 0.00025 mm. The most important advantage is that thermal warm-up normally encountered in rolling element bearing spindles does not exist. Air bearings used in grinding spindles afford a higher quality of form and finish. For much heavier metal removal, using large formed wheels and in-plunge grinding operations, a combination of air and oil hydrostatic bearings are now successfully used to achieve a higher bearing stiffness and better viscous damping under heavy loads.

An ultra-precision surface grinding and slitting machine incorporating these externally pressurised air bearings for both wheel and spindle, and linear bearings of the X and Y motions of the machine has been developed by the Cranfield Unit for Precision Engineering (CUPE), United Kingdom.

Spindle systems

The thermal energy dissipated in the machine spindle-head during operation, leads to considerable thermal dilation which causes spindle drift and spindle droop. These thermal problems can be overcome by controlling and stabilising the operating temperatures of the spindle head and by keeping it cool through refrigeration. The cooling is done in such a way that a temperature of 20°C to 25°C is maintained.

Drift and droop compensation is very important in the case of boring and jig boring machines. The modern trend is to compensate the boring spindle assembly in such a manner that whatever the projection of the spindle, the tool position does not drift or droop. Such compensation is now possible with hydrostatic bearing systems and with pressure feedback in respect of a built-in reference.

Feed drives

Automatic machines and NC machines now demand high acceleration/deceleration and a steady state of operations of the feed drive systems. The innovations in semiconductor technology, servo-drives, electrohydraulic systems and high energy magnetic materials have led to the development of a new breed of feed drives. The electrohydraulic servo-drives and total electronic servo-drives dominate the field at present and the electrohydraulic versions are being phased out because of their low response time, actuation delay and associated problems of noise, heat and cost. The modern NC machines and EDM machines are provided with all electronic servo-drives.

The present generation of high performance drives incorporate any one of the following: (a) DC permanent magnet, direct drive torque motors; (b) DC permanent magnet servo motors; (c) Stepper motors, electric and electrohydraulics; (d) AC variable frequency motors; (e) Brushless DC motors; and (f) Wound field DC motors.

The DC permanent magnet systems are the most commonly used because of the attainable band width and good performance at low speeds with added benefits of less heat, noise and low cost.

Even in Japan, where electrohydraulic stepper motors were widely used till now, because of the simplicity of electronic control, permanent magnet DC motors are slowly replacing them.

The permanent torque motors are a special brand of DC-control motors. They have a pancake form and develop high torque at low speeds without getting overheated. The permanent magnet field does not allow heat dissipation while the motor is on stand-by. Because of these characteristics, they can be directly coupled to the load, offering a very high coupling drive stiffness and even zero backlash with careful mechanical design. These torque motors are highly reliable and durable.

Mechanical drive elements

Along with the direct drive DC servos and torque motors, the most commonly used mechanical drive elements are recirculating anti-friction screws and nuts. But recently the hydrostatically lubricated nut and lead screw systems are finding increased application in the machine tool field because of lower rumble, higher stiffness and low friction. Although the hydrostatic nut and screw systems are more expensive, they provide higher reliability when used in the servo-drive system along with DC torque motors and grating transducers.

Accuracy aspects of design

The design of modern machine tools is aimed towards a high accuracy of the machined components. In this context, not only the earlier-mentioned aspects of stiffness of structures, suitable assembly configurations, required stiffness and reliability of drives, sensitivity of slide motions and thermal stability should be achieved, but also an integrated approach should be adopted for the design of machine and controls.

In view of the enhanced performance requirements of modern machine tools, the design should satisfy a dual purpose. A machine tool has to be endowed with the ability to accurately machine the component and even take over the function of inspecting the machined job. Hence the added function of measuring has necessitated the incorporation of a number of measuring devices and systems on the machine tool. Among the measuring devices incorporated in the machine tool, the most commonly-used position transducers are the inductive scale, absolute digital or incremental type shaft encoders and laser interferometers associated with digital readouts (DRO).

Although the vast majority of servo positioning aids used in NC and CNC machines are the indirect type of transducers like shaft encoders, recently the direct types like inductive scale moire fringe gratings are finding increased use because of their higher precision. In a new optical grating with displacement transducers developed by CUPE, the interpolation of moire fringes from optical gratings is obtained by a scanned photodiode array which enables a very fine resolution from 100 lines per mm transmission grating. This resolution is close to that obtained by laser interferometry but at a fraction of the cost.

Modular construction

A distinct trend towards the modular construction of machine tools is already evident. This trend is strengthened by the need of the metalworking industry to machine a wide range of parts in small and large batches, with an ability to change over quickly from a one part family to another. This can be met best by a system which allows various configurations of machining systems to be built up from a range of standard modules rather than by the inflexible machine parts. Considerable success has been achieved in using modular units for building dedicated grinders for high volume production, but a wider application of the concept to embrace lathes, milling machines, drilling machines etc. has yet to be established. However, as more industries turn to group technology. it is expected that machine tool builders will increasingly adopt this concept of machine building.

Other technical factors encouraging modular construction include the move towards higher speeds, higher powers, variable spindle drives, interchangeable tool turrets, direct drive feed units etc. The first three factors have led NC lathe designs to a concept where the drive motor, gear box and spindle units are separated to limit thermal problems and to isolate sources of vibration. The same considerations are seen in modular grinder designs.

Builders of machine tools also stand to gain by adopting a modular design concept. Short lead times, flexibility in final machine configuration, low inventory and larger batch quantities lead to savings of cost and time in machine tool building. The builder can offer machining systems, tailored to meet customers needs with a possibility of adding more modules when required. All these considerations are prompting a move towards modular design of machining systems.

Computer-aided design (CAD)

Engineering design involves the use of scientific principles, technical information and imaginative manufacturing instructions to make an engineering product from engineering drawings. Every industry and engineering company evolves its own particular design methods and design procedures. A fairly typical design method is as follows:
(a) functional specification;(b) preliminary rough design; (c) estimation and design analysis;
(d) final design; (e) detail design; and (f) drafting. In the modern state of development, computers are being widely used in engineering design. This has led to the development of a new discipline known as computer-aided design (CAD).

Conceptual design. The first two aspects of design viz., functional specification and preliminary rough design, can be considered as a conceptual part of the design process. This is essentially a creative activity. It depends upon the ingenuity, innovative qualities and the feel of a desiger, based on experience and creative ability. Computers have considerable limitations as aids to conceptual designing. Nevertheless, many of the computer methods are valuable to expedite the design process. Computer retrieval of design information is one of them. The designer spends a considerable amount of time searching for information from catalogues, standards, research papers, old designs etc. Computer-managed data banks are available in certain fields to cater to the designer's needs. The designer can have access to such data banks through multi-access channels even from a remote place through computer terminals and the telephone network. Industry's own in-house information retrieval system, based on a minicomputer, is also viable in computer-aided design.

Estimation and design analysis. Next to the conceptual stage is the stage of estimation and design analysis. This stage uses the computer to the maximum extent. Calculation of forces, deflections, stresses, or variations of a proposed design can be performed with a high degree of accuracy by the computer. Estimation of cost is also done very quickly and accurately by a computer.

At this stage the recycling of information is done to alter the rough design and to reanalyse and re-estimate to arrive at a cost-effective and optimum design. If a computer is not available at this stage, the designer usually remains satisfied with one or two trials and waits for the performance report of the design after the prototype is manufactured and tested.

The availability of multi-axes and time-sharing computers and intelligent peripherals like visual display, and graphics terminals have made things easier. The multi-access and time-sharing facility allows the user to communicate directly with a distant computer, send data or instructions via a visual display graphics terminal, and immediately receive back the output on the terminal screen in graphical form. If the designer is not satisfied with the output, then he or she can change some of the input parameters either through the keyboard or in the form of graphical input by using a light pen on the graphic screen and asking the computer for reprocessing. The cycle can be repeated till the required result is achieved. By this method, the user and the computer can work interactively, modifying and improving the design and correcting errors without having to wait for the print-out. This development in computer technology and graphics constitutes an essential part of the CAD approach.

Computer-aided drafting. Once the design parameters and shapes are established through the conceptual and analysis phases, the next step is the production of engineering drawings which is mainly a drafting job.

Development of automated drafting machines; (both drum and flat bed types)have made drafting easier. Once the various design data are available with the computer in the form of co-ordinates, these data can be transformed into an analog drawing by driving the drafting machines as computer peripherals. Computer software is available to deal with two-dimensional and three-dimensional views, automatic dimensioning of part drawings and assembly drawings.

High-speed machining and its implications for the design and mechanics of machine tools

Expected improvements in cutting-tool materials allow an increase in the limits of material removal rate and an increase of maximum speed (to 5000 or 6000 rpm) and feeds by an average factor of about 2, and in power by a factor of perhaps 4.

This requires specific efforts in the development of faster, more powerful machine tools in all categories and extensive R&D efforts in spindles, bearings, drives, slides, motors, transmissions, chucks, tailstocks and structures. Work on these aspects is being carried out in the laboratories, research institutes and machine tool industry in the industrialised countries producing machine tools.

It was estimated that in 1979 the cost of metal removal in USA exceeded $ 60 billion. If special techniques like high-speed machining could reduce that expenditure by 1 per cent, the savings obtained would be enormous. If one reckons the money spent on metal removal in all industrialised countries, even a marginal saving obtained by high-speed machining can release a stupendous amount for new investments.

Along with an increasing awareness and high enthusiasm to share the know-how concerning this new technology, all the leading R&D establishments working on the subject of high-speed machining in the developed countries agree that the machine tool/cutting tool combination should have the following attributes:

(a) stiffer structures to allow not only higher cutting forces (higher material removal rate), less deflection (better accuracy), a resistance to chatter (better surface finish), and reduced tool wear; but when their design is optimised, they allow the use of less structural material, which affects costs. Many parts made today by a rough cut followed by a finished cut should be able to be machined in 'one pass' with a stiffer machine tool. An improved ability to understand, analyse, test and quantify the structural behaviour and parameters, both statically and dynamically, is needed. R&D work being carried out includes theoretical and experimental analysis of structures as to shifting weights and cutting forces; experimental and computation methods for static and dynamic stiffness; damping mechanisms; foundations and vibration testing;

(b) To achieve high spindle speeds, the spindle bearings should be designed to handle the expected loads and speeds. A forward thrust bearing or hydraulically pre-loaded bearing is considered necessary to prevent a loaded spindle from being pulled out of its housing;

(c) The machine should be provided with a protective cover to safeguard the operator and other personnel on the shop-floor from flying chips and broken cutters;

(d) All tooling should be balanced for speed and the tool inserts should be firmly anchored for protection;

(e) The advantages of increasing the number of cycles per unit time in high-speed machining are best achieved with an automatic tool changer;

(f) Automatic work loading/unloading devices are essential;

(g) Faster feed-rates involving table speeds of 800 rpm are considered necessary. However, the table construction may have to be modified to reduce the amount of mass moving at the higher speeds;

(h) Rapid contouring consistent with table feed rates requires a rotary table with a table speed of at least 5 rpm;

(i) Heavy-duty gripping chucks are essential and they should be designed, especially for high-speed turning, to counteract centrifugal forces and to withstand cutting forces.

Knowledge about chatter has improved and there are now several emerging techniques that allow diagnosis and remedy when chatter occurs. However, there is still not a consensus or good understanding, and further research work in this regard is being carried out in the industrially developed countries. It would be ideal if eventually chatter-free machine tools could be designed.

The life of machine tools today is satisfactory, provided the machine tools are properly maintained. Reliability can be improved by careful and thorough testing, better compiling and analysing of failures to guide redesign, duty-cycle recording (to determine how often and how much a machine tool was overloaded), regular condition monitoring, and better protection against dirt, chips or fluids for all covers, switches or seals.

Energy utilisation has not been a major problem since machine tools use relatively little (½ to 2 per cent) of the total plant power, compared with heating/air-conditioning or heat-treatment. Turning equipment off when not in use and other simple steps can be helpful in conserving energy. However, newly-designed machine tools should provide opportunities to improve energy efficiency, for instance, in mechanical transmission of power or in electrical drives.

Detailed evaluations and surveys are being conducted by machine-tool-producing developed countries in (a) chip removal and disposal; (b) reliability and failure modes; and (c) seals, covers and devices to prevent dirt, chip, dust or liquids from reaching moving slides, bearings and switches. The removal/disposal survey is being aimed at modern sensors, future materials and unusual approaches (like building a machine tool upside-down to allow chips to fall). There is little valid data on failure modes, failure rates or component reliability under different duty cycles or operating conditions. Work in these areas is being pursued. Research work is being conducted to identify the weak links in machine tool reliability, to improve preventive maintenance and improve specification and/or acceptance tests. An objective evaluation of designs of covers and seals for guideways, lead screws, racks and bearings can allow longer life, better reliability and less maintenance. Considerable research is being carried out in these areas in many of the industrialised countries.

Among the other features of machine tool designed for high-speed machining, mention has to be made of a facility to programme the cutter paths to obtain the advantage of high feed rates, sensors employed for dimensional control and surface finish, and compensation devices to offset thermal distortions. Vibration and chatter can be catastrophic at high and ultra high speeds. The success or failure of high-speed machining depends to a large extent on the cutter balance. Considerable research work is in progress to solve these problems.

Ergonomics, noise and safety

Even though technology is progressing towards unmanned machine operations and unmanned factories, there is nevertheless a concern for the health and safety of the industrial labour force. Recent years have witnessed a greater emphasis on ergonomics safety and noise considerations in machine tool design. This is aimed at providing operators with pleasant working environments, both from physical and aesthetic points of view. This is seen as an important method of retaining skilled labour in manufacturing and preventing its migration to other areas such as service industries. Recent recommendations on acceptable shop noise levels and mandatory safety regulations point to an increasing liability of the machine tool builders to meet even more stringent regulations in the future.

Proper ergonomic (operator-machine relationship) design is important especially on manually-operated machines. Easy identification of controls, low operating forces, logical grouping and pleasing colour schemes are the major considerations. New concepts are emerging to design a lathe which can be comfortably operated by a seated person, thereby stressing the importance attached to the operator's comfort in the design of modern equipment. With the increasing international trade in machine tools, the trend towards visual communication between human beings and machines through symbols is increasing. Recent work in evolving an internationally recognised code of symbols even for NC and other electronic control systems is a positive proof of this trend.

Present recommendations limit the level of noise to which an operator is exposed to 90 dBA over an eight-hour shift. Machine tool designers, therefore, have to design machines with noise levels of 85 dBA or less at present. So far efforts have been directed towards containment and not noise reduction. New designs are striving to reduce the absolute noise levels of machine tools to 80 dBA. This is expected to have a major impact on machine tool design. Hydraulic and gear drives and pneumatic systems are giving way to quieter, smoother, electrical drives and electronic controls. Non-metallic panels for guards, covers, trays, access doors etc. are used to reduce noise radiation from sheet metal surfaces. Drive paths are made short and stiff with a minimum number of transmitting elements and controlled clearances throughout.

Operator safety is an important aspect of machine tool design and construction. While regulations are more stringent in metalforming equipment, metal-cutting machine tools are also subjected to mandatory safety regulations both in the case of simple manually-operated machines as well as NC and similar advanced machine tools. Guards and seals to protect the operator from chips, coolants and other hazards have already reached a point where there are often limiting factors in quick loading/unloading, measuring inspections in machine tools. This is especially true of grinding machines designed for abrasive machining. These conditions point to new machine configurations in the years ahead.

Future machines may evolve along lines where the guarding is distributed between the machines and the operator rather than being confined to the machines totally. Possible solutions lie in partial curtailment of the working zone, allowing quick and easy access while the operator is placed in an enclosed control station. The use of closed circuit TV can become popular as a visual link between the operator and the machining zone, with remotely-operated systems for scanning the work, gauging and inspection when required. Doubtless such methods will be applied only where the machine and production situations lend themselves to reasonably long operation without operator intervention.

Another solution that is likely to be used is to substitute robots for loading/unloading operations while the operator is sufficiently removed from the machine to avoid hazardous conditions. Such concepts are bound to appear on future machine tools since safety considerations will not be allowed to impair to any extent the productivity of the machine.

Energy management in metalworking

About 1 hp of power is needed at the spindle of a machine tool for producing mild steel or cast iron chips at a rate of 1 cubic inch per minute in milling, drilling or turning. The power required is more in some other alloys and less in materials that could be machined more easily. In other words, it takes about 1/80 kWh to turn out a pile of 1 cubic inch of chips. This in itself does not appear very expensive, but it should be remembered that the energy required concerns only the material cut from the workpiece and it does not include the energy fed to the spindle drive to overcome mechanical losses of gears and bearings and also the electrical losses within the spindle drive motor. Added to this, the following should be considered: the energy input into the coolant pump, the axis drives if it is an NC machine, the cooling system or heat exchanger, the line of compressed air and the lighting for the comfort of the operator, refrigeration, heating, cooling and so on.

In most of the production modes, the actual metalcutting accounts for only 30 per cent of the time the job is on the machine, but energy is consumed 100 per cent of the time. Hence it can easily be surmised that the overall energy efficiency of the operation is at its maximum when the maximum amount of energy is used for cutting or forming the job because this is precisely the time when machine utilisation is at its maximum and the productivity of all energy-consuming components reaches a peak. Though this has not yet been achieved, it is the goal of every management because the total energy input per workpiece is minimised and provides the highest energy efficiency.

The adoption of a manufacturing philosophy, whether computer-based or not, which boosts productivity, also leads to a higher level of energy efficiency. The choice of cutting tools that increases metal removal rates or assures longer tool edge life or reduces the machine down time for tool changing also facilitates and increases both productivity and energy efficiency. In spite of a higher rate of energy consumption, an increased spindle horsepower put into the workpiece raises the energy efficiency by giving a larger share of energy for doing the real job. The modern trends towards higher productivity in machine tools is basically meant to enhance the energy efficiency.

The price of industrial power is about triple that what it was in 1967. Power costs are increasing at a rate of approximately 15 per cent a year and economists are not forecasting a slowing down of this rate even if the current rate of inflation is brought under control. Perhaps the most important factor in machine use, however, is reliability in terms of machine performance and up-time.

Design is often a creative compromise of conflicting requirements. Clever design can increase the output, reduce down time and enhance the universality (flexibility to handle different workpieces and materials). Considerable research is being carried out in the areas of easier chip disposal, improved systems of automated workpiece loading and unloading, safety, ergonomics, energy conservation, faster tool and workpiece clamping and cutting with more than one tool simultaneously.

II. CUTTING TOOL MATERIALS AND TOOL DESIGN

Introduction

The performance of cutting tool material in a given machining application is mainly determined by three important properties: (i) wear resistance necessary to enable the cutting tool to retain its edge and shape cutting efficiency; (ii) hot-hardness necessary to enable the cutting tool to retain its cutting ability and hardness at high temperatures developed at the tool chip interface; and (iii) toughness necessary to enable the tool to withstand forces to absorb shocks associated with interrupted cuts and to prevent the chipping of the fine cutting edge.

Wear resistance and toughness are two characteristics which are interdependent, the gain in one results in a loss in the other. Whereas high-speed steel starts to rapidly lose its hardness at temperatures above 40°C, carbides, ceramics and diamond retain their hardness at very high temperatures.

Several other properties such as co-efficient of thermal expansion, thermal conductivity, grindability, weldability, hardenability, dimension stability and freedom from distortion after heat treatment are of importance. The co-efficient of thermal expansion determines the influence of thermal stresses and thermal shocks on materials. Carbides have lower co-efficients of thermal expansion than high-speed steels and they develop lower thermal stresses; but they are more sensitive to thermal shocks because of their brittleness. With increasing thermal conductivity, the heat produced in the tool chip interface is rapidly dissipated. As the wear resistance of a cutting tool improves, the grindability generally decreases and the grinding costs are increased.

Till 1900 machining was performed either by plain high carbon steel or by air-hardening steel called <u>Mushet</u> steel. Shortly after 1900, high-speed steel was introduced and it has since undergone many modifications. The cast cobalt-base tools introduced around 1915 are employed for machining operations at much higher cutting speeds.

The next notable improvement in tool materials came with the introduction of cobalt-bonded sintered tungsten carbide produced by the powder metallurgy technique. The addition of titanium, tantalum and niobium carbides to basic tungsten carbide vastly enhanced the range of application of carbides. This material used in the form of small inserts, either brazed or clamped to steel shanks, proved extremely popular. Further research and development work in the field of sintered carbides yielded superior varieties of carbides having a thin hard layer of titanium carbide or titanium nitride on a basic carbide substrate. With this development of coated inserts, a 50 to 80 per cent increase in the cutting speed over that of conventional carbides was achieved. Many new types of coated tips with multiple layer coatings are also now being introduced.

Shortage of tungsten has, however, led to the development of many non-tungsten cutting tool materials. Among them the most promising are: solid titanium carbide, and titanium nitride. Ceramic tools exhibit very high hardness and abrasive resistance, facilitating the use of higher cutting speeds. However, their application has been limited owing to their brittleness and lack of strength. UCON, a new tool material consisting of columbium, tungsten and titanium permits a 60 per cent increase in the cutting speed when compared with tungsten carbide. Cubic boron nitride with a hardness second to that of diamond is facilitating speeds five to eight times that of carbide and can be used to cut hardened materials. Polycrystalline diamond bonded to tungsten carbide substrate is now successfully employed for machining non-ferrous materials.

The metal cutting industry in the industrialised countries is constantly searching for better tools and methods which will yield high productivity. In an era of heavy emphasis on NC machines, there is sophisticated and reasonably high horsepower equipment capable of removing metal efficiently, provided the cutting process itself is efficient in control and predictable.

Tool materials

Cast alloys. High speed steels were unsurpassed till the introduction of cast cobalt base alloys. Cast alloys are produced with certain combinations of tungsten, chromium and cobalt having extremely high red hardness, wear resistance and toughness. Since the co-efficient of thermal expansion is the same both for steel and these alloys, the two materials can be brazed or welded without the danger of inducing stresses. The cast alloys bridge the gap between high-speed steel and carbide and to some extent are still being used in the metalworking industries.

Cast alloys have properties intermediate between high-speed steels and cemented carbides. They are less tough and more wear-resistant than high-speed steels; they are used at surface speeds above those of high-speed steels and below those of carbides. Other important characteristics are: high red hardness (can retain edge hardness up to 760° C), a low co-efficient of friction, excellent resistance to corrosion and high resistance to shock and impact.

The cast alloys are used for machining cast iron and malleable iron, alloy steels, stainless steels, non-ferrous metals, bronze, graphite and plastics. The shock and impact resistance of cast cobalt-base alloys allows them to perform better than carbides on interrupted cuts.

Cast alloys can be used in multiple tooling on automatic screw machines and multispindle bar automatics, where all operations do not require the surface speeds of either high-speed steels or carbides. Carbides are used on large diameters and cast alloys on smaller diameters. Cast alloys are also used to cut small diameter jobs.

Cemented carbide. The first major breakthrough in the development of tool materials came in 1926 with the advent of cemented carbide for metalcutting. Earlier, cutting tool materials were mostly produced by molten metallurgy methods and depended on proper heat treatment for hardness and other properties. Therfore, their performance was greatly affected to a large extent by the attendant temperatures of cutting. The carbides, which are now produced by powder metallurgy techniques display very high red hardness (retain their cutting edge up to about 1000°C) and wear resistance and can be operated at very high cutting speeds when compared with high-speed steels.

Initially, straight tungsten carbide with cobalt as the bonding material formed the basic constituent of this tool material which was well suited for machining of short chipping materials like cast iron. Later the range of application was considerably extended by the addition of carbides of titanium, tantalum, niobium etc.

The extent to which carbides have spread may be visualised from the fact that at present in the industrialised countries more than 300-400 varieties of carbides are marketed by various tool manufacturers.

Partly because of low tensile strength and partly due to high costs, carbides were originally used as small tips for inserts brazed to a tougher and a less costly steel shank material. The cost of carbide has now come down appreciably and it is only a fraction of what it was some years ago. Still, it is invariably used along with steel shanks on which it is clamped or brazed except in the case of very small tools. Though simple and cheap, the brazing process is now disappearing since it has certain drawbacks. Brazing, even carefully done, may subject the carbide to internal stresses owing to the different co-efficient of expansion of steel and carbide. These stresses alone may not be large enough to damage the tips, but when coupled with normal cutting stresses, they may cause failure of the tip.

Regrinding of brazed carbide tips is also a problem and the grinding stresses may cause cracking of the tip. The geometry and finally the performance of the carbide tools depend on the skill with which brazing is done and grinding is carried out. These problems assume greater proportion when multi-point tools like milling cutters have to be sharpened where the accurate maintenance of relative positions of the cutting edges are needed. In addition, some of the newly-developed grades of carbides are indeed difficult to braze. Recently-introduced coated carbides are not suitable for brazing because the subsequent grinding removes the coating.

The concept of the throw-away type insert overcomes the disadvantages of the brazed tool and offers considerable economy, higher productivity and operational convenience. Elimination of regrinding and other troubles associated with poor grinding, accuracy of tool geometry and reduced tool inventory are some of the advantages realised by these tools. Since regrinding costs are completely eliminated, they can be subjected to the maximum wear at high speeds than those used as brazed tips. With the use of pre-sintered chip-breaking on throw-away inserts, better chip control is achieved.

A shortage of tungsten has led to the development of many non-tungsten cutting tool materials. Among them the most promising are the titanium carbide and titanium nitride tool materials. The bonding materials used are nickel and molybdenum. These tools have greater solubility in nickel and molybdenum than tungsten carbide in cobalt. This results in high strength of materials with good resistance to chip tool welding and reduced friction between the chip and the tool. Because of their higher thermal conductivity, temperatures produced at the cutting point are lower. They have a very low density, about one third to one half of tungsten carbide alloys, and this leads to low heat absorption which is a critical factor for extended tool life. They also have a transfer rupture strength comparable with that of tungsten carbide, exhibit higher hot hardness and do not form a built-up edge on their rake faces, consequently producing a good surface finish on jobs.

Titanium carbides and titanium nitrides have been used to bridge the gap between the tungsten carbide and ceramics for finishing and precision machining operations at speeds as high as 450 m/min and with light to moderate feeds and cutting depths.

These could also be used on high-temperature alloys with poor machinability and on hard alloy steels.

The potential for major development in carbide cutting tool material depends primarily on the availability of cobalt. The supply of this essential material is controlled by governments and a cut-off would hinder the development efforts in carbide tools.

Coated carbides.

Furthermore, in the case of conventional cemented carbide grades, a compromise has been sought between wear resistance and toughness. In principle increased wear resistance also means reduced level of toughness and vice versa. Therefore the emphasis in the development of cemented carbides is on improving the wear resistance while retaining adequate toughness. This has led to the development of coated carbides in which a microscopic layer of wear resistance material (titanium carbide, titanium nitride) is chemically coated over a tough carbide substance to attain a single grade of carbide having the property of both high wear resistance and toughness.

Coated carbides are rapidly changing the composition of cutting tools. These tools account for approximately 25 per cent of carbide-insert use and that figure may increase to 80 per cent depending on material conditions. However, if these tools are to be used at their optimum capacity and provide full economic return, machine spindle speeds, horsepower and feeds will have to be increased which is what is happening in the designs of machine tools produced in the industrialised countries. In micro grain carbide, the particle size of the carbides is reduced to submicro level. It is found that micro grain carbides exhibit significantly higher traverse rupture strength at any given hardness level than conventional carbides. They are used for severe metalcutting operations which require a higher strength than those of conventional grades of carbides. They are recommended for applications where high-speed steel or cast alloy tools are too fast, or where cutting speeds are slow for carbides, or where carbides fail by chipping.

Because of their high strength, coated carbide tools are being extensively used in positive rake angles in machining high nickel base alloys (super alloys). They are also recommended for cut-off tools since the slow speed encountered towards the centre of the bar does not affect these tool materials. They are also recommended for form tools.

Ceramics. Among the numerous ceramic tool materials available, the best results are obtained with aluminium oxide combined with small quantities of various other oxides. Ceramics are hard and have a high degree of compressive strength even at elevated temperatures. They have a good abrasive resistance to cratering, a low frictional co-efficient and they are not sensitive to the higher range of temperatures encountered in practice. Ceramic tools can retain their cutting edge hardness up to about 1400°C and exhibit uniform strength up to 1220°C. Because of these properties, they are being used in the industrialised countries for cutting tough material at high speeds and at higher temperatures as compared to other tool materials. However, the relatively low transverse rupture strength of ceramics - about one half to one third of carbide - is a serious limitation which has been restricting their wider applications to that of uninterrupted cuts.

Ceramics, having higher hot hardness and greater resistance to wear, are employed for increasing productivity and lowering costs. Ceramics provide good surface finish and quality and they eliminate finishing operations like grinding. Cast iron, noted for its abrasive characteristics, can be machined to a smooth bright finish using ceramics. Heat-treated steel as hard as 65 Rockwell 'C' can be finished by ceramic tools up to 0.5 µm surface finish, often eliminating the grinding operation with considerably improved tool life vis-à-vis the carbide. High temperature alloys such as hastalloy, Stellite and Monel can also be machined using ceramics. Ceramics are used for special turning, long tube boring, cylinder liner boring etc.

Ceramic tools have the potential to increase cutting speeds by a factor of 5 to 10 but their toughness will have to be increased before they can be widely used. The wide use of ceramics would require some refinement in machine tool technology. During the next five years, ceramics will continue to make an inroad, but at as slow a rate as that experienced during the past five years.

Ceramics and cermets have been used for cutting tools for the last 20 years and they have developed a definite place, within limits, in metalcutting. Many of the earlier aluminium oxide ceramics are no longer available, because they are not good enough to compete with the more recent hot-pressed, high purity aluminium oxide inserts.

Of more significance, however, is the so-called cermet material which contains 15-30 per cent titanium carbide in addition to aluminium oxide. There are a number of producers of high quality materials in this class which compete in the high-speed cutting range.

In addition to these more conventional cermets, there have been others in which additives, such as molybdenum and molybdenum-carbide or tungsten carbide, have been used with aluminium-oxide (Al_2O_3) instead of titanium carbide. None of these has yet proved viable as a cutting tool. Extensive research is being conducted in this area by the cutting tool manufacturers.

Diamond. Diamond, because of its high modulus of elasticity, chemical inertness and exceptionally high hardness, is ideal for obtaining fine surface finish and accuracy. Though the initial cost of diamond is high when compared with high-speed steel or carbide tools, the cost per piece machined with diamond is invariably much lower.

Diamond is chemically inert and takes a high polish. Because of this property, chips do not adhere to its surface when machining non-ferrous and non-metallic surfaces. Diamond has high hot hardness but excessive heat causes diamond to crack, and oxidation of diamond starts at about 800°C. Therefore an abundant supply of cutting fluids should be used without any interruption and light feeds should be employed. The diamond cutting edge is extremely smooth, keen and accurate. It is completely free from sawtooth irregularities inherent in a carbide tool, and hence the modern trend is that the diamond tool is employed more for precision application.

Diamond is extremely brittle and it chips or fractures if it is not properly handled. It should be used on machines with minimum vibration or chatter and should be protected from shock loading.

Diamonds of various forms are used in many industrial applications such as grinding wheels, dressing tools, drawing dies, hones, lapping compounds, cold drills. As a cutting tool, diamond is mainly used for machining non-ferrous metals like aluminium, brass, copper, bronze and other bearing materials; non-metallic materials like epoxy resins, hard rubber, glass; and precious metals like gold, silver and platinum. In light-alloy pistons, nearly all surfaces are diamond turned and bored, especially where higher silica content is involved. Sintered bearings, which cannot be machined by other tool materials, are machined by diamonds. Commutators are turned with diamond tools to have a smooth surface with clean boundaries. They are generally used for finishing cuts and are not recommended for ferrous materials. Polycrystalline diamond is used for machining glass, reinforced plastics, utectic and hyper-utectic aluminium alloys and other materials having hard and soft structures which prevent interrupted cuts. They are also used in milling.

UCON. The modern trend in the industrialised countries is a greater application of UCON. UCON is a nitrided refractory metal alloy and it is a compound of 50 per cent columbium, 30 per cent titanium and 20 per cent tungsten developed by Union Carbide, United States of America.

The untreated inserts of UCON having a hardness around 200 BHN are nitrided in a nitrogen atmosphere at a very high temperature. The surface hardness of the finished insert is greater than that of ceramic and, towards the centre, it is softer than steel. Because of this non-homogeneity, the application of UCON is limited to throw-away inserts.

UCON cuts very cool. It has excellent thermal shock resistance, high hardness and toughness. It also exhibits excellent resistance to diffusion and adhesion wear (chip welding). It is claimed to give three to five times more edge life than conventional carbides.

UCON is recommended for roughing, semi-roughing and finishing cuts in turning, facing and boring. It operates in the speed range of 250 to 500 m/min on steel of 200 BHN. It is not generally applied to milling, parting-off or for operations using form tools.

Cubic boron nitride. Next to diamond, cubic boron nitride (CBN) is the hardest substance known. It consists of atoms of nitrogen and boron with a special structural configuration similar to diamond. Cubic boron nitride is sucessfully used as a grinding wheel on high-speed steel tools providing good surface finish, precision and high output and also on titanium, stainless steel and Stellites. The second application includes grinding of hardened steel lead screws, splines, threads and ball and roller-bearing parts. Because CBN cuts cool, grinding defects such as burrs and thermal shocks are not produced. It is also used for grinding the slideways of cast iron beds and housing-type components.

Tool design

Chip breaker. Long and unbroken chips produced while machining ductile materials are difficult to handle and are injurious to the operator. The sole purpose of the chip breaker is to break chips into convenient sizes for easy disposal and to protect the machine surface from rubbing against chips. Various chip breaker designs and configurations have been conceived to obtain effective chip control.

Various types of chip breaker and inserts are: the external chip breaker, the moulded chip insert and the variable width chip breaker. The moulded chip breaker design evolved with the advent of centre-lock-type tool holders. In this design the chip breaker grooves are formed at the sintering stage. They are built in single, double, triple, multiple and variable width configurations. The variable width chip breaker consists of an insert with a varying groove to enable the insert to handle a wider depth of cut.

Tool geometry and configuration. The land angle inserts have been designed for use in heavy roughing and light finishing cuts. A new land geometry was first evolved by Kennametal of the United States. In this design the chip leaves the rake face very quickly, thus reducing the chip-tool contact length and transferring very little heat to the insert. This reduces the cutting temperature and results in improved tool life. Another advantage is that by avoiding the back wall of the chip groove, cutting forces are reduced and the metal removal rate is increased. The chip breaks with a natural curl and facilitates improved chip control at both ends of the feed range which helps in easier programming of NC machines.

Wave-shaped insert design. The single-sided negative insert in this design is provided with a wave-shaped edge geometry having double chip-breaking groves and a mini-chip breaker near the nose radius to compel the chip to curl against itself. This wave-shaped cutting edge provides a positive angle of inclination and reduces cutting forces. In this design the axial and radial forces are reduced to 20 and 30 per cent respectively and the tangential force by about 10 per cent vis-à-vis the standard negative insert. The insert also helps to use positive or negative rake for negative rake tool holders.

Kenturn tooling system. The inherent disadvantages of indexing throw-away inserts right on the NC machine tool have prompted Kennametal of the United States to design the Kenturn tooling system. This system provides rapid changing of qualified tooling, with tool holders held in place by a ball-lock mechanism. This uses the concept of quick indexing of a cartridge-carrying insert. The compact design of this system affords space for 12 tools on a 6-station turret, thus doubling the tool capacity. It is claimed that this system enhances the machine tool's productivity by 25 per cent besides increasing its versatility.

Kennametal have a system which combines high performance insert with a reliable coated carbide. The system is called Kentrol. It has a new carbide insert geometry and a multi-faced coating, designed for extremely tough machining applications. Its land-angle shape allows freer cutting and very high metal removal rates; and the coating allows for heavy interrupted cutting, past runout and scale. It is an extremely reliable coating. The clean rake surface presents lower resistance to chip flow and thereby encourages higher feed rates. It has high chip controlling ability along with the natural advantages of using high-speed rates to reduce unit-power consumption.

Qualified tool holders. Especially while using automatic or copying or NC machines, an important factor is the positioning of the cutting edge in both X and Y axes. Normally. tool positioning error is doubled in turning because of the tool cutting on diameters. Since many NC centres have a programmable resolution of 0.002 mm and also since closer tolerances are insisted upon in precision machining, greater attention is paid to accurate tool setting. Another critical requirement is the repeatability in positioning the tool in automatic tool changers. To respond to these requirements, qualified tool holders are designed where certain critical nominal dimensions are qualified over the specified radius of the insert within about ± 0.05 mm. The qualified tool holders eliminate the need to individually size every tool. Roughing cuts can be taken without the need for a trial. In qualified tool holders all control dimensions are nominal for both manual and computer programming. Besides eliminating the present presetting stand, the set-up time is greatly reduced by using qualified tool holders.

Major constraints in tool design. Chip control is normally accepted if there is no danger to the operator, no damage to the workpiece and if the chips are small enough to handle easily and safely with either manual or automatic means. These are important in the case of NC machines where snarled chips can cause a lot of damage and interrupt production. But in the designer's eagerness to bring chips under control, he or she may be tempted to over-control them when extremely tight, dark blue chips are formed or when inserts cause severe chatter or break prematurely. This may be avoided by going in for a lower metal removal rate but the vestiges of over-control will still remain in the design.

Increased metal removal rates through an increase in feed rates appear attractive but this is beset with a lot of problems. An increase in the depth of cut or speed poses several problems. In the case of depth of cut there are limitations. For example, if the depth of cut is doubled, twice as much power is required at the tool point. If power and rigidity are available, then an increase in depth of cut can be effective. But the wider chip may be either too difficult to break or may become too crowded or deformed. This will require even more power than originally anticipated.

Even though modern machine tools are cutting much faster, there are some limitations to increasing speed. Tool life deteriorates drastically with speed because of the significant increase in abrasion and temperature on the flank, rake face and nose radius of the insert. Flank wear is really the most important cause for the end of the tool's life. By understanding the interrelationships between speed and feed, productivity increase and tool life can be balanced. The real key is the feed rate but the feed rates are again limited by the insert geometry. This brings the designers back to square one and so the search goes on for the ideal geometry, optimum speeds and feeds and material characteristics to answer the demands of production. In the quest for higher metal removal, better tool life and productivity gains, the search for better tool designs will continue for a long time and this trend is well discernible in highly industrialised countries.

III. MACHINE TOOL CONTROL SYSTEMS

Introduction

In the industrially advanced world, a spectacular state of a new art of manufacturing is emerging. This is based on the changing nature of the information stream that runs a manufacturing enterprise. In the past, human beings were both the translators and transmitters of information. The operator was the ultimate interface between the design intent as incorporated in the machine drawing or instructions and the functioning of the machine tool. Human beings used mental and physical abilities to control the machine tool.

However, computers are increasingly becoming the translators and transmitters of information and numerical control (NC) is perhaps the most representative of the kind of control that plugs into a data stream with the minimum of human intervention. Historically, numerical control certainly has been the most significant development of the electronic revolution as it affects manufacturing engineering.

The possibility to store information at a low cost and to compute and regulate on the basis of stored information has considerably automated the production cycle. Storage, computation and machine regulation is done according to the principle of digital technology, that is by employing a large quantity of evaluated symbols and with elements of semiconductor technology. In other words, the building blocks of modern electronics hold the key to control technology. There are some basic aspects of machine tool controls which are important to the user and manufacturer alike. They are: (a) operation and programming; (b) operation safety; (c) cost; (d) flexibility and extendability; (e) integration and standardization.

A numerically controlled machine tool is a machine which grinds, drills, turns and/or cuts according to a predetermined programme. Its work cycle is recorded on perforated cards or tapes or on magnetic tapes. Commercial production of NC machine tools began in the United States as long ago as 1952. Their application was limited but in the past decade, they have become significantly more clever, compact and cheap , partly thanks to the silicon chip and the associated micro-electronic technology.

Though initially numerical controls were built to prove their efficacy in machine control, many of the above factors associated with the new art of manufacture were not considered. But now numerical control is no more an engineering curiosity. It has come to occupy an important place in the very concept of production engineering. The development of NC, rendered possible by the phenomenal growth in semiconductor technology and digital science, is being guided to make it an invaluable tool of production, with all the attendant care towards reliability and cost.

A decade ago, numerical control was a means of controlling automatically machine movements with the help of coded numerical instructions. These instructions were contained in a punched tape. The coded tape was the heart of the NC and it was responsible for controlling the sequence of machining operations, machine positions, spindle feeds and rotational directions as well as a host of other functions like control of coolant pump.

But in the last ten years, NC has undergone phenomenal changes. The transistors have given way to integrated circuits. The advances in computer technology have helped to replace all logical hardware. Decision circuits are replaced by executive software in the form of minicomputers. The NC guided and controlled by computer has given birth to the Computer Numerical Control (CNC) which is the heart of modern machining centres. Part programming, inter-active computer graphics, adaptive control, microcomputer code, servo-mechanisms, human engineering and on-line diagnostics have been added to those mundane aspects of process planning, and others such as interchangeability, mainterance, cutting tools, chatter and surface finish.

CNC system. The architecture of the CNC system is entirely different from a conventional hardwired system. The concept of CNC is akin to the digital computer concept. Any digital computer has three major parts: the Central Processing Unit (CPU) does the arithmetic and logic operations; the Memory stores the data to be processed; and the Control Instructions and the Peripherals actually form the link between the computer and the outside world. For the CNC, the machine and various other equipment to be controlled form the peripherals.

The major constituents of the CNC system are the computer and the executive programmes, data handling, machine axes controls, controls pertaining to machines,magnetics etc.

All functions for controlling the operations of NC machine tools are synthesised by the logic designer by evolving a combination of logic modules consisting of gates, flip-flops, counters, shift resistors etc. along with the necessary peripheral devices.

Different approaches,using the same type of logical elements as the basic hardware, can be employed to obtain the same end-results. This gives rise to a non-standard system design requiring for each system a large variety of spares. This leads to a large inventory. It was therefore realised that efforts had to be made for standardising the system design of the hardware. The evolution of large-scale integrated circuit technology (LSI) brought NC system designs closer to this achievement. The design was done around a computer capable of meeting the requirements of any machine. The computers used in such NC systems are either minicomputers or microprocessor-based computers with a standardized hardware architecture. Other peripheral devices are kept unchanged, but the corresponding interface circuits are modified to cope with the new type of hardware. The requirements of each individual machine tool are met by a software programme called the "Executive Programme" which is a part of the control. It contains the command logic which determines how the control is to perform its functions such as operating the tape reader, translating the programme tape and sequencing the machine tool. In other words, the controller's own logic is actually a computer programme instead of specialised electronic circuits. The actual hardware remains standard and fixed with the different design approaches. But any software, once developed successfully, needs no maintenance. Hence, standardized system design is achieved with a minimum of maintenance requirements.

A computerised controller needs fewer electronic components and fewer circuit interconnections. The tape reader which is the most vulnerable equipment in a workshop environment is removed from on-line operations during machining, thus leading to improved reliability.

The number of printed circuit boards are reduced and the same control may be used for a 3-axis machine or a 5-axis machining centre. This reduces the inventory of spares for single or several CNC units, even if different machines are involved. Software, once developed successfully, needs no maintenance. Personnel training is reduced because only one system has to be maintained and serviced. Debugging of any malfunctioning of the system is much easier in the computerised system because of diagnostic programmes. Even a less skilled person having a basic knowledge of operation can isolate a problem down to a sub-system or the card level.

Computerised control systems offer more flexibility since modification of the software programme is simpler, quicker and cheaper than in the case of the hardware of a conventional NC system. This facilitates the inclusion of additional features by augmenting the software in standard building blocks. Though it may involve a marginal hardware modification it is less costly to make a CNC system compatible with any shop's unique problems and practices. Newly-developed options can also be added after installation to upgrade the equipment. This facility eliminates the danger of premature obsoloscence although rapid progress in electronics indicates that machine tool controls become obsolete in three to five years. Part programmes are stored in the computer memory and then made available for machining. This feature is particularly helpful in repetitive production. Execution of short blocks is not limited by the reader speed because the access time for the data stored in the memory buffer is negligible.

A new part programme can be actively generated or an existing part programme can be modified inside the computer's memory. This facility simplifies changes in geometry, feed, speed and optimisation during tryout. Consequently, the time for tape proving and debugging is reduced, thus considerably enhancing production time.

The computer and the properly designed software have made increased sophistication of the CNC control possible. In the conventional NC, this increase in sophistication necessitates more hardware with a consequent rise in costs.

CNC capabilities. All the machine axis irregularities may be measured and inserted in the control software so that in subsequent programmed operations, the absolute accuracy of movement is maintained. It is thus possible to produce a part which is even more accurate than the machine itself. This feature facilitates programming, optimises machining conditions and achieves consistent surface finish and accuracy.

To reduce the machine set-up time, and to compensate for tool wear, the offset data can be stored in the memory and called at any appropriate time. Use of thumb wheel switches for storing data as in hardwired controllers is eliminated. Virtually an unlimited number of offset information can be provided.

In the case of tool breakage, the machining operation can be stopped and the tool can be changed without destroying the programmed data.

The present trend is to use a programmable machine interface where a machine interface ladder network can be programmed in software. This has helped the machine tool builder to eliminate a considerable number of relays, contactors and timers that are used in machine electrics and magnetics. Changes in the interface do not require corresponding hardware changes. The ladder network can be displaced on CRT. This feature is an extremely valuable tool in debugging the machine interface programme, enhancing the reliability of the system. Since a great deal of hardware is in CNC systems, diagnostics is a very important tool to trouble-shoot the faults that are developed in the course of operation in hardware circuits of the systems. Since a computer used in a CNC system has the ability to perform different tasks under different programmes, a proper programme can be written to make the computer work like a circuit tester instead of an NC controller, thereby providing a diagnostic programme.

MDI controller. The latest trend in simplified CNC control of individual machines has led to the microprocessor-based Manual Data Input (MDI) type of control system. MDI controls go beyond the digital readouts (DRO), by adding slide drives but they do not stop there as advancing micro-electronic technology puts new skills at the machinist's fingertips. Among the synonyms for MDI controls are such terms as "tapeless NC", "memory NC" and "operator programme NC". These terms are every bit as valid as MDI. Many MDI controls can be converted into classic NC systems by plugging in an optional tape reader, and most present-day NC systems incorporate programme editing features that make them fully capable of accepting manually input part programmes.

Most of the well-known NC machine builders like Cincinnati Milacron, Kearney & Trecker, Warner & Swasey, Allen-Bradley, General Numeric and Fanuc have brought out this type of CNC system. In the MDI system, the operator has a choice of either making the programme by machining the first part manually to automatically record the machine slide and tool movements, or using the Keyboard for input of work cycle commands from a programme sheet on the basis of the part drawing. Since this does not make use of the punched tape, the tape reader which is normally a source of trouble is totally eliminated. If required, the part programmes located in the system memory are transferred to a magnetic cassette for permanent storage. General Numeric provides a plug-in cartridge having Random Access Memory (RAM) with a nickel cadmium cell. An editing facility is also provided to make any part changes in the programme. MDI systems are lower in price and smaller in size than the conventional CNC system. The only limitation of the MDI at present is that the controls are made for machines with only up to three axes. These controls are ideal for adoption in machine tools built in the developing countries like Brazil, India and the Republic of Korea.

Direct numerical control (DNC). Direct numerical control (DNC) is an extension of the CNC concept. In DNC, a central computer controls simultaneously a number of NC or CNC machines. DNC, according to the definition of the Electronics Industries Association, is a system connecting a set of numerically controlled machines to a common memory for part programme or machine programme storage with a provision for on-demand distribution of data to machines. The DNC system has provision for collection, display or editing of part programme, operator instructions or data related to the numerical control process. Though the concept of DNC is not new, it has yet to spread widely in the manufacturing sector. There are also many shortcomings of these systems which have to be debugged. However, the main reason for the DNC not becoming so popular is the initial high cost of investment. Another reason is that a universal DNC system with a wide range of applications has yet to be created. The utilisation of the DNC system for maximum productivity has yet to be proved.

DNC level I and level II are the two schemes of DNC systems that are in use now. White-Sundstrand and Allen-Bradley offer a DNC minicomputer that stores all machine data post-processed for a specific machine on a master disc file. The minicomputer sends the machine data on a real time basis to each NC machine interfaced to it. In this case, there is no 'stand-alone' NC system for the NC machine. There is a limitation on the number of NC machines interfaced to one minicomputer as the computer works on a real time basis. One major disadvantage of this system is that if there is a malfunction in the minicomputer then all the NC machines connected to this computer will be down. To overcome this drawback, a standby minicomputer is used which can take over in the event of malfunctioning in the DNC minicomputer. The other remedy is to switch to the DNC generation level II system, where each NC machine has its own stand-alone CNC system. These individual CNC systems receive data from the DNC minicomputer. Here, even if the DNC minicomputer fails, the machines can be operated with the help of their independent CNC systems. If these individual CNC systems are provided with floppy disc data storage, then a considerable amount of data can be transferred from the DNC minicomputer to these systems.

DNC offers several operative advantages. The tape reader, which is usually the most down-time-prone component of a machine control unit, is bypassed. Secondly, a programme in a computer storage is much easier to access for use in operation, for revision or editing or for quick and easy interaction between the programmer and the machine tool. The same computer that directs the operation of a machine tool can also be used for auxiliary purposes such as down time recording, performance tabulation, real time machine status and other operational items of interest to the management. An advance design DNC unit can also be utilised to sense operating conditions and also to make modifications in programmed instructions. DNC does require programmers and supervisors having a thorough knowledge to exercise full and optimum control. DNC systems can be extremely effective when combined with first-rate systems know-how but the initial cost is still very high and needs software support of a very high calibre.

Recent trends in NC of machine tools. The use of a general purpose minicomputer as a part of a system and the use of software applicable to the minicomputer are now being discontinued. Control systems built with microprocessors and with dedicated software constitute the architecture of the CNC system.

Microprocessors are currently used in two configurations: in bit-slice architecture to construct a microcomputer which in all respects fulfils the function of a minicomputer and for microprogramming. The designer of a CNC system is thus offered the flexibility to formulate his or her own macro instruction sets. Hence it is now possible for many of the NC systems builders to change over from the minicomputer version to the microcomputer version without changing the system's software. Westinghouse, Bendix, Standard and General Automation, Fanuc, Siemens have changed over to microprocessor-based systems keeping the same software that was developed for their minicomputer systems. This has proved very economical as no additional investment is required on software development.

The second configuration of the microprocessor-based CNC system is to use three 16-bit microprocessors and to assign certain tasks to each of them, viz, one for part calculation, one for axes drive and one for 1/0 interface. Similarly, Allen-Bradley's 7100 CNC uses three 16-bit microprocessors, one each for axis drive, front panel interface and central processing unit (CPU). In this architecture, as the tasks are divided among the microprocessor, the CPU co-ordinates these tasks between the microprocessors.

In the earlier CNC systems, magnetic-core memory was used as the main memory of the system. This provided a non-volatile memory but was more expensive and also temperature sensitive. Hence this is now replaced by semiconductor memories, like the Random Access Memory (RAM). Since these are volatile, a battery back-up is provided to retain the information in the memory in case of main power failure. Also these RAMs are now available in 16-bits configuration, in a single chip. Other types of memory chips like the Read-Only Memory (ROM), Programme Read-Only Memory (PROM), Erasable and Programmable Memory (EPROM) are used to store the management and control information. These are non-volatile memories. The latest trend is to store the system-executive software in PROMs. Formerly this software was on punched tape and was loaded through the tape reader into the main memory, but quite often this information in the memory was lost due to electrical disturbances in the workshop environment or a power failure. A CNC system like the Vax minicomputer developed by Digital Equipment Corporation (DEC), United States of America, uses a floppy disc for storing an executive software. This is non-volatile and has proved very useful.

NC perspectives. The development of computer technology has made possible the introduction of NC machine tools which themselves have drastically changed the technology. Further improvements in controls are foreseen such as those to increase their capability and their memory to allow more functions to be monitored and/or controlled. Rapid progressive electronics causes machine tool controls to become obsolete in three to five years. There will be new complex, high performance controls as well as simpler low-cost versions suitable for less complex parts and versions compatible with manufacturing systems.

Computers have proved themselves in stand-alone machine tool controls. CNC units have been replacing hardwire NC. PCs (programmable controllers) are replacing hardwired relay logic. Computer reliability has been remarkable, and controls have helped to increase machine up-time and the time needed to correct failures. A modular control design that allows for add-on capability with additional functions can improve flexibility and reduce costs. In addition to the Central Processing Unit (CPU), the use of more computers is foreseeable as (a) supervisory computers in the DNC or machining system comprising several machine tools; (b) as an aid to optimisation and shop performance, a small hand-held computer or microprocessor and/or small personal computer; and (c) as a tie-in of machine tools to a computer-assisted comprehensive operations-control system in the company.

Some of the directions for improving the machine tool control units are: integral adaptive controls; features to assist or speed up accuracy measurement of the machine tool; using the computer and display already embedded in the machine tool for training of operators or maintenance personnel; novel schemes of error compensation; additional diagnostics; devices to reduce set-up efforts and time such as tool-set stations or feeler probes placed in the tool holder with automatic adjustment for toolwear or fixture positions; on-the-machine inspection of geometry or surfaces with automatic correction; record keeping of machine utilisation or cutting tool life; self-healing or self-repair after diagnosing a certain failure such as a broken drill; and the ability to modify a programme on the shop-floor or record the events of the last minute or two prior to a failure.

Standardisation of interfaces or language/ data communications is an important concern as are terminology and methodology for maintenance. Strong efforts are being made to evolve a set of standards.

Interactive graphics, a powerful emerging technology, has an increasing key role in providing visual displays for monitoring and command/ control at each step in the manufacturing process, from design to cutter motion and interaction to complete manufacturing systems. Improvements through three-dimensional modelling of parts and clearer communication between the devices and the operator are being investigated further intensely.

Verification of input data prior to running a programme on a machine can be very cost-effective in batch production of complex parts. The spin-off benefit is to prevent production machine tools from being used extensively for tape checking.

Adaptive controls although having been pursued for about 15 years, have found acceptance only in a limited application. Improvements in understanding the cutting processes, the variation of cutting conditions and more reliable sensors need to be developed. Good sensors for toolwear, tool breakage and geometric dimensions or contours, preferably of the non-contact type, and demonstrations of specific complete adaptive control systems have yet to be perfected.

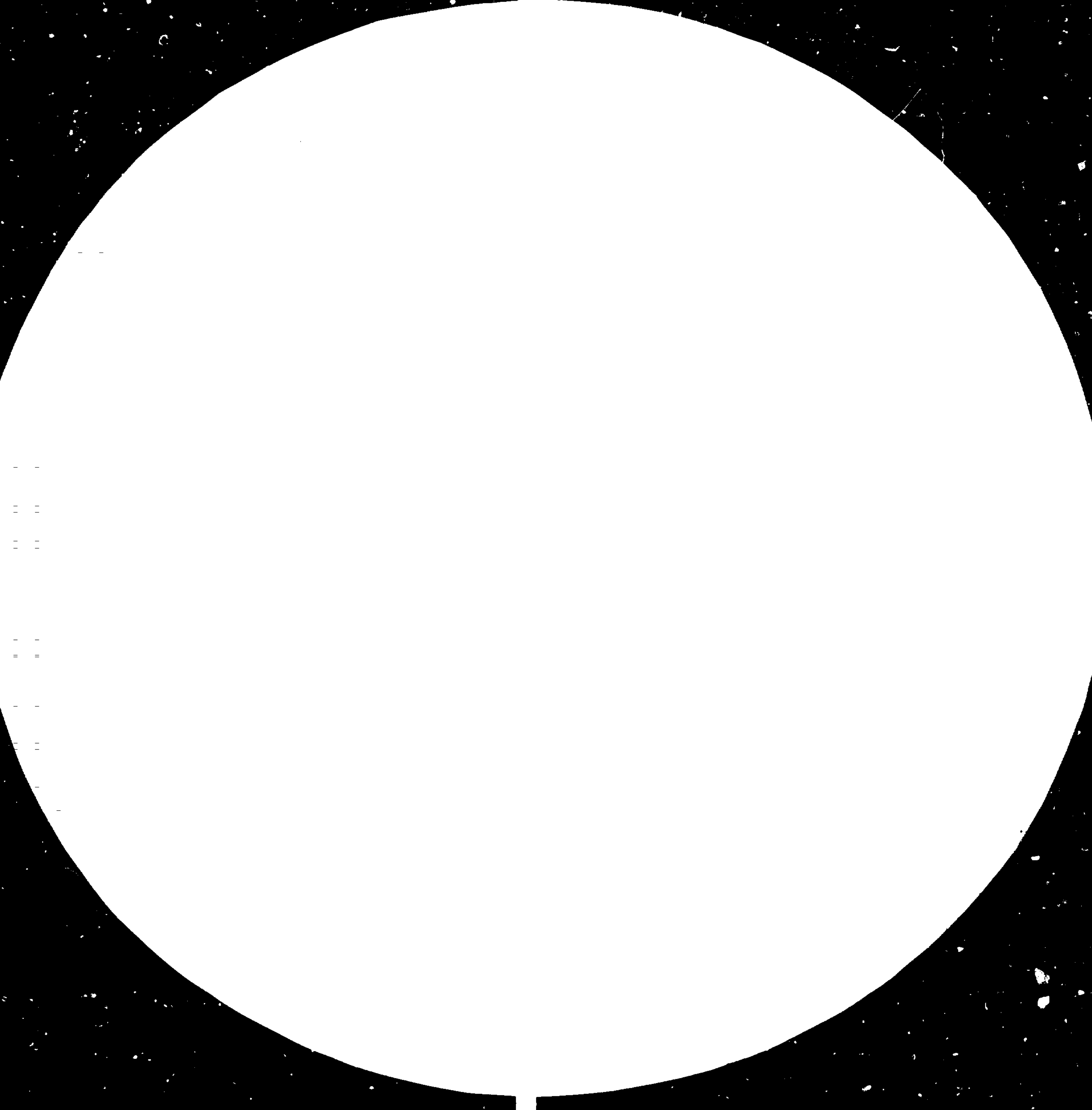
There is a need to develop more and better sensors, techniques for identifying intermittent errors and diagnosing more of the mechanical failures through signature analysis or other techniques. Novel diagnostic approaches are also needed such as those that can predict a failure and permit orderly shut downs of operations rather than unscheduled emergency stops.

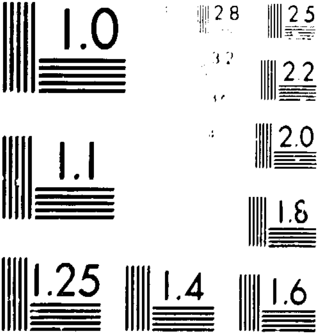
Future NC systems will be microprocessor-based and provided with computer graphic display. With Computer-Aided Design (CAD) the use of this graphic display will be extended to the NC systems, resulting in the interactive graphic CNC system.

General Numeric has already brought out their "Ultimate TG" microprocessor CNC for turning machines with facilities for automatic programming and interactive graphic display. Here the CRT can display the appearance of the finished part, the programmed tool part, the actual position value, the system parameters, programme data, tool offsets and diagnostics. A paging facility is provided for viewing long programmes on the CRT display.

Automatic programming will be another feature in CNC to attract users of NC machines. Here the post-processor is built into the software of the system. The operator need only enter the basic dimensions of the workpiece, the codes for the tools used, the offsets, feeds, speeds and some simple instructions through the keyboard. The built-in software does the necessary computation, calculates the arc centre and programmes itself.

In the field of diagnostics for maintenance of CNC systems, remote diagnostics will be commonly employed in future. The Numeric Easy Automatic Telephone (NEAT) service of Giddings & Lewis and





MICROCOPY RESOLUTION TEST CHART

Diagnostic Communication Systems (DCS) of Kearney & Trecker are two such remote diagnostic facilities presently offered to NC users in the United States. Remote diagnostics involve the use of a telephone to transfer digital information between the CNC system under trouble-shooting, and the central computer used for diagnostics at the manufacturers' premises. The central computer is able to make a multitude of analyses, checks on both the control unit and the machine elements, thus rapidly pin-pointing solutions to malfunctions and also spotting potential sources of failure. This system acts as an expert on the shop-floor, talking the same language as the equipment and eliminating communication problems, delays in problem - solving, and saving expenses by the travelling field service engineers. This facility can also be extended to other countries by using a satellite communications link.

Electronics from the most sophisticated computer to the circuitary in a simple drive or a sensor have introduced versatility to manufacturing technology. Advances in electronics are expected to increase cost-effective production.

Electronic control, for example, will change the concept of a stand-alone machine and will allow the machine to function as a part of a system. The machine cycle will be altered either by remote command or by some conditions sensed at the machine such as a process variable or the position of a surface.

Machine performance will be monitored by electronic sensing devices. The information thus obtained will be useful for diagnostic analysis as well as for management decision-making on machine utilisation.

To be useful, however, machine feedback will have to be communicated to someone besides the machine operator and so control at the machine will assume the additional responsibility of a communications terminal. Electronic technology, such as the data transmission and line protocol, will help create an information flow that will make the machine an integral part of the manufacturing system.

Knowledge of software design and system integration then will become necessary in manufacturing plants. A good software designer, for example, will be able to maximise hardware utility and create flexible systems that others can repair and alter. A systems' integrator should understand and determine how all the elements work in relation to each other.

At present there is no general consensus on what the responsibilities of the systems integrator should be, or whether it is even a necessary function. Its value will have to be determined, however, before complex systems can be developed and implemented.

Producing NC tapes through voice command is already a reality. A speed processor that converts a programmer's analog voice signal into the digital language of the computer permits part programmes to be generated by vocalising the data.

Fujitsu Fanuc's latest brain to come on to the market is its System 6. Introduced in 1979, the System 6 incorporates large custom-integrated circuits and the latest techniques in electronics such as high-speed microprocessors and bubble memories making it a more reliable and more economical version of the model it replaces. It is capable of operating a robot, thus eliminating the need for a separate NC system for the robot and it uses only about half the parts of the earlier System 5 Fanuc is now developing a System 9 which will reduce the number of parts still further through the use of very large-scale integrated circuits (VLSI). Research on this is being done in co-operation with Siemens of the Federal Republic of Germany. Production was originally planned for the latter part of the decade but may now start earlier as Nippon Electric Co. has recently announced that it can mass produce VLSIs.

Soon microprocessors will start replacing wheels, gears and mechanical relays in a variety of control applications, because it is more efficient to move electrons around than mechanical parts.

Machine design to suit NC/CNC. More sophistication is now built into machine tools to machine a part in a single set-up. Simple 2-axis lathes have given way to 4-axis lathes and turning centres. Similarly 4-axis and 5-axis machining centres are replacing 3-axis milling machines. Automatic tool changers (ATC) with large tool magazines and chains to store up to 70 tools or more, constitute a standard feature of the modern machining centre. The contouring table is now used as the 14th axis of a machining centre instead of an indexing table. Pallets are used to reduce workpiece set-up time.

Turret lathes are now the most common NC machines. The present trend is to have a single combination turret which can hold tools for both internal and external diameter turning. However, a lot of care is required in planning the tool layout and to ensure that there is no interference between the tools and the chuck while machining the internal and external diameters. Production centres are available on which all basic machining operations like turning, boring, drilling and milling can be done in one set-up. A spindle can also be indexed and moved up and down to do many milling jobs.

Control systems are now being built into the machine tool itself as an integral part. Builders of CNC systems now offer control systems in the form of different modules so that a machine tool builder can buy only the modules required and accommodate them in their machine structure. By this modular concept, it is possible to eliminate bulky stand-alone enclosures, to amplify machine electrics and to avoid having long interface cables. This concept has cut down the cost of NC machines.

IV. NON-TRADITIONAL MACHINING METHODS

The increasing use of difficult-to-machine materials, such as hastalloy, Nitralloy, vespalloy, nimonics, carbides, stainless steels and heat-resisting steels in the aerospace, nuclear, communication engineering industries and for the manufacture of military hardware has spurred the development of non-traditional machining methods. The conventional machining processes have become inadequate to machine these materials from the standpoint of rigid quality standards and economic production. Besides, machining of these materials into complex shapes is difficult, time-consuming and sometimes impossible.

Non-traditional machining techniques have overcome some of these machining difficulties. These non-traditional methods are classified according to the nature of the energy employed in machining, viz., thermal and electrothermal chemical and electrochemical and mechanical.

In the thermal and electrothermal methods, the thermal energy is employed to melt and vapourise tiny bits of work materials by concentrating the heat energy on a small area of the workpiece. By continued repetition of this process, the required shape is machined. These methods include electron discharge machining (EDM), laser beam machining (LBM), plasma arc machining (PAM), electron beam machining (EBM) and ion beam machining (IBM).

The chemical and electrochemical machining methods involve a controlled itching or anodic dissolution of the workpiece material in contact with a chemical solution. These processes include chemical machining (milling and blanking), electrochemical machining (ECM), electrochemical grinding, electrochemical honing and electrochemical deburring.

In the mechanical methods of non-traditional machining, material is primarily removed by a mechanical erosion of the workpiece material. The mechanical methods include ultrasonic machining

(USM), abrasive jet machining (AJM) and water jet machining (WJM).

Non-traditional machining processes find application over all metals and alloys. This is in contrast to the conventional machining processes which vary in their application depending upon the strength and the hardness of the material. Among the non-traditional processes themselves, there is a good degree of variation in respect of their application on different work materials.

The application of non-traditional machining processes is also influenced by the workpiece shape and size to be produced viz., holes, through holes, through cavities, pocketing, surfacing, through cutting etc.

The other parameters of comparison between conventional and non-traditional machining on the one hand and among the non-traditional machining methods on the other are, with regard to material removal rates: the power consumed and the accuracy and surface finish that can be achieved.

Non-traditional machining processes cannot at present completely replace conventional machining methods of metalworking. They also do not offer the best solution for all applications. They should only be viewed as complementing conventional metalworking methods. The suitability of any of the non-traditional machining processes for a specific application should be judged from the standpoint of increased reliability of the process, better assurance of quality and the ability to machine workpieces which cannot be machined easily by any conventional methods.

Electron discharge machining (EDM). The EDM process involves a controlled erosion of electrically conductive materials by the initiation of a rapid and repetitive spark discharge between the electrode tool (usually cathode) and workpiece (anode) separated by a small gap of about 0.01 to 0.50 mm known as the spark gap. This spark gap is either flooded or immersed under a dielectric fluid. The spark discharge is produced by the controlled pulsing of direct current between the workpiece and tool. The dielectric fluid in the spark gap is ionised under the pulsed application of the direct current, thus enabling a spark discharge to pass between the tools and the workpiece. Each spark produces enough heat to melt and vaporize a tiny volume of the workpiece material leaving a small crater on its surface. The energy contained in each spark is discrete and it can be controlled so that the material removal rate, surface finish and tolerance can be predicted.

EDM equipment manufacturers offer a variety of machine tools, ranging from small machines to massive units resembling heavy presses. The chief influencing factors on the design of EDM equipment are the number of components to be produced in one set-up, accuracy required, size of the workpiece, size of the electrode, depth of cavity and orientation of cavity.

Nearly all EDM machines consist of a base, a column and a head. The column is fixed to the base and supports the head. A co-ordinate table which supports the workpieces is usually mounted on the base. Machines with fixed work tables are also available. A dielectric tank is constructed around the table and is provided with an automatic level controller. It is also equipped with safety devices to shut down operation in case the temperature exceeds a certain limit.

Workpieces can be mounted on the machine table (fixed or co-ordinate types)with any suitable work-holding fixtures. However, it should be ensured that there is a good circulation and flushing of the dielectric fluid. It is sometimes convenient to hold the workpieces on suction and injection pots which provide built-in arrangement for circulation of dielectric fluid. Manufacturers of EDM equipment supply these suction and injection pots and also rotary tables with a built-in arrangement for providing circulation of the dielectric fluid through the workpieces. EDM is well suited to make intricate dies and the Société Genevoise d'Instruments de Physique (SIP) have developed a heavy spindle EDM machine for the manufacture of fine dies mainly needed in the watch and instrument industry, with CNC control.

Wire-cut EDM is a comparatively new concept, pioneered by the Swiss firms AGIE and Charmilles. A small diameter wire is used as the electrode to produce intricate shapes in steel plates. The table of the machine is provided with numerical control to perform complex motions required by the workpiece. The speed rate in this process is constant but if any abnormal conditions in the spark gap occur, the machine table stops until favourable conditions in the spark gap are restored. The travelling wire EDM machines are extremely well suited for the production of extrusion dies, blanking dies and punches, press tools and sintered compacting dies.

Impediments to easy EDM machining can be summed up in three fundamental complaints: poor flushing in tight quarters; slow-cutting at fine finish settings; and preferential wear on the leading edge of the electrode, where it is usually least tolerable. In the final stages of finishing a complex cavity, it is not uncommon for all three to occur at once.

And so the electro-orbiting attachment, which promises to solve all three of these problems, has been developed which has a special attraction for EDM users. Simply by stirring the electrode around in the cut, the device facilitates flushing, which improves cutting rates at the low current settings used to produce the finest finishes. An added touch of sophistication, an orbit that expands as the electrode plunges into the cut, distributes wear between the leading edge and the sides of the electrode. Development of orbiters has been an elaboration of these basic ideas. Highly sophisticated orbiters are today available, manufactured in Switzerland, Sweden, the United States and Japan, all having electronic CNC systems. Orbiters are made either as an attachment to the vertical ram or as a table-mounted device that orbits the workpiece. Long electrode life, better flushing, finer finishes are among the claims made by these EDM orbiter manufacturers.

Electrochemical machining (ECM). Electrochemical Machining (ECM), is the controlled removal of metal by anodic dissolution in an electrolytic medium in which the workpiece is the anode and the tool is the cathode. Two electrodes are placed close together with a gap of about 0.5 mm and immersed in an electrolyte which is normally a solution of sodium chloride (common salt).

A typical ECM machine consists of a table for mounting the workpiece and a platen fixed on the ram or quill for mounting the tool. Vertical box frame ECM machines have excellent rigidity and are preferred for precision work. They also have the advantage that the work area is effectively sealed off on all sides. They are however disadvantageous if heavy workpieces and toolings are to be handled. Vertical 'C' frame machines offer greater accessibility to the workpiece and tooling, but lack rigidity, and hence are not suitable for high precision work. The horizontal frame machines offer excellent accessibility to the working area and also possess adequate rigidity. However, the tooling used on these machines should have adequate rigidity because of overhang. The choice of such machines is made only for bulky components.

Under ideal conditions and with properly designed tooling, ECM is capable of holding a tolerance of the order of ± 0.02 mm or even less. Repeatability of the ECM process is also very good. This is largely due to the fact that the tool wear is virtually non-existent. On a good machine, tolerance can be maintained on a production basis in the region of ± 0.02 - 0.04 mm.

Tooling design is the key to successful application of ECM. There are two aspects of the design of ECM tooling. The first is the determination of the tool size and the second is the appropriate machining conditions necessary to produce the required shape.

The ECM technique poses no significant threat to conventional machining because the economics of application of ECM are justified only in specialised areas where conventional machining is not feasible. One of the main applications of ECM is in the aerospace industry to machine difficult-to-machine materials omplex-shaped parts.

Electrochemical drilling is extensively used for drilling the cooling holes in gas turbine blades. The chief advantage of this process is that the holes are burr-free and can be made in thin workpieces. Deburring by the electrochemical method is slightly different from ECM in that the tool and the workpiece are placed in a fixed relative position with a gap of 0.1 - 1.0 mm. The tool is positioned near the base of the burr. Specially built machines for deburring are now available on the market.

In electrochemical grinding, a metal-bonded grinding wheel impregnated with diamond abrasive is made the cathode and the workpiece the anode, as in ECM. The electrolyte which is usually sodium nitride with a concentration of 150 - 300 per cent/litre of water is wetted through nozzles into the wheel rather than the work, and the wheel is submerged. Actually, abrasive grains on the surface of the wheel act as a peddle which picks up the electrolyte and causes a pressure to build up at the work area.

Though basic operating principles of electrochemical grinding (ECG) and ECM are the same, there are differences in application and methods of functioning. Whereas in ECM the tool never touches the workpiece, in ECG, the metal bonded grinding wheel lightly touches the workpiece. The metal removal is largely brought about by electrochemical action and only 10 per cent of the volume of material is removed by abrasive action of the wheel. The process therefore is ideal for grinding carbides, carbide tools and work of complex shapes.

Chemical machining (CHM). Chemical machining (CHM), is the stock removal process for the production of desired shapes and dimensions through selective or overall removal of material by controlled chemical attack with acids or alkalies. Areas from where material is not to be removed are protected from attack by masking. Nearly all the materials, from metals to ceramics, can be chemically machined. There are two types of chemical machining viz., chemical blanking which is used for cutting or stamping parts from thin sheet materials and chemical contour-machining or chemical milling for the selective or overall metal removal from a thick material. The CHM process is employed where blanking or metal removal is difficult or impractical by the conventional machining processes because of material hardness, brittleness, size of part, complexity of shape or thinness of the part.

Chemical blanking is used chiefly on thin sheets and foils. In most applications, photoresist (photo-sensitive masking) is used to define the location on the workpiece at which the material is to be etched.

One of the major applications of chemical blanking is in the manufacture of burr-free, intricate stampings. Typical chemically-blanked parts include laminations for electric motors and magnetic recording heads, slotted spring discs, gaskets, meter parts, camera parts, fine screens, and helicopter vent-screens.

Chemical milling is primarily used to machine preformed aerospace parts to obtain a maximum strength-to-weight ratio. Employing this method, aircraft wings and fuselage sections are made with integral stiffeners of optimum cross-section throughout their entire length. Chemical etching is used for engraving highly intricate details on nearly any metal and to produce printed circuit boards.

Ultrasonic machining (USM). Ultrasonic machining (USM) is a process in which a cutting tool oscillates at high frequency, about (20,000 cps) in an abrasive slurry. The tool has the same shape as the cavity to be machined. The high-speed oscillations of the tool drive the abrasive grain across a small gap of about 0.02 - 0.10 mm against the workpiece. The impact of the abrasive is uniquely responsible for the material removal. The method is chiefly employed to machine hard and brittle materials, which are either electrically conducting or non-conducting.

USM is particularly useful in micro-drilling holes of up to 0.1 mm. The size is limited only by the strength of the tool, the size of abrasive particles and methods adopted for circulating the abrasive slurry. A tool as large as 85 mm diameter is used on a machine with a capacity of 2.5 kW. Larger holes can also be cut by trepanning. The depth of hole obtained is limited by the tool wear, slenderness ratio of the tool and the ease of supplying the abrasive slurry to the working gap. Depth-to-diameter ratios of up to 10 are quite common.

Abrasive jet machining (AJM). Abrasive jet machining (AJM) is the removal of material from a workpiece by the application of a high-speed stream of abrasive particles carried in a gas medium from a nozzle. The AJM process is much finer and the process parameters and the cutting action are carefully controlled.

The process is used chiefly to cut intricate shapes in hard and brittle materials which are sensitive to heat and have a tendency to chip easily. The process is also used for deburring and cleaning operations. AJN is inherently free from chatter and vibration problems. The cutting action is cool because the carrier gas serves as a coolant.

Aluminium oxide is the preferred abrasive in the majority of applications. Silicon carbide is also used in certain cases. The abrasive particle size is a dominant factor in AJM and the best results have been obtained with a particle size in the range of 10-15 mm. In addition to the above abrasives, dolomite (calcium magnesium carbonate) of 200 grit size is found suitable for light cleaning and etching. Sodium bicarbonate is used for extra fine cleaning operations. Glass beads of different diameters, 0.3 to 0.6 mm, are used for light polishing and deburring.

The major field of application of the AJM process is in the machining of essential brittle and heat sensitive materials like glass, quartz, sapphire, semiconductor materials, mica and ceramics. The AJM process is used in drilling holes, cutting slots, cleaning hard surfaces, deburring, scribing, grooving, polishing and radiusing. Delicate cleaning, such as removal of smudges from antique documents, is also possible with AJM.

Laser beam machining (LBM). Laser is the acronym for Light Amplification by Stimulated Emission of Radiation. It is an electro-optical device that converts energy into intense light energy. Laser beam machining is a machining process in which work material is melted and vaporized by means of an intense monochromatic beam of light called the laser. The heat produced in small areas where the laser beam strikes can melt almost any of the known materials. This property of the laser is now being made use of in machining difficult-to-machine materials in engineering industries. Laser is an electromagnetic radiation. It produces monochromatic light which is in the form of an almost collimated beam. A very wide range of materials can be processed by laser. Complex shapes can be cut with extreme accuracy and reproducibility. Single batch or production quantities may be programmed direct from component drawings, thus eliminating the delays and costs associated with tooling up.

Recent developments in industrial aspects of the laser have resulted in the successful application of CO_2 gas lasers for accurate and speedy cutting of a large range of materials, some of which have attendant difficulties when cutting is attempted by conventional processes.

The laser is a relatively new tool available to industry and recent technological advances now make it a realistic alternative to more conventional industrial cutting methods. Perhaps the greatest feature offered by the laser is the diversity of materials that can be processed and consequently there is a potential for its application in many industries.

The ability of the laser to cut material is virtually unaffected by properties such as hardness, brittleness, electrical and thermal conductivity, heat resistance, magnetism, flammability and so on. Extremely hard nickel cobalt alloys cut as readily as mild steel; for example, ceramics, timber, rubber, leather, asbestos, plastics are all able to be cut with the laser.

Laser-cut components feature an excellent surface finish and normally no rework is necessary. This results from the highly localised thermal input; thermally insulating materials exhibit no heat effect at all adjacent to the cut, and metallurgical disturbance to sheet metal is comparable to that occuring at a sheared edge. Acrylics cut by the laser feature a polished appearance, whilst timber displays a darkened edge which attractively enhances the grain.

As the kerf is only 0.1 to 0.22 mm, the intricacy of shape does not fundamentally limit this process and often complex shaped components which would defy manufacture by conventional means can be produced.

The costs and delays associated with press-tooling are eliminated by laser cutting and thus particular economics arise where relatively low batch production or prototype work is involved. Slots, holes, cut-outs and contoured shapes may be achieved without reliance on existing tooling.

The manufacture of plastic, metal or wooden lettering for the sign industry by this process is unsurpassed. Laser cutting of plywood has for some years been a reality in the packaging industry.

The laser beam is used in metrology. Spherical test parts for qualifying diamond turning optical machines used in the manufacture of critical optical surfaces are fragile. A non-contact laser sweep-gauge prevents surface damage while testing spherical contours which are diamond turned.

Laser beams **are also** used for testing alignment of slideways and straightness of parts to a very high degree of accuracy. Laser interferometers are commonly used for this purpose in the machine tool industry.

The laser can be used for cutting as well as for drilling. The material removel rate in LBM is comparatively low and is of the order of 4000 mm3 per hour. The holes drilled by the laser are not round. In order to overcome this difficulty, the workpiece is rotated as the hole is laser-drilled. Other problems associated with laser drilling are the taper and the recast structure in the heat-affected zone. Taper of 0.5 mm per 10 mm drilled depth can be expected sometimes. In order to achieve the best possible results in drilling, it is imperative that the material be located within a tolerance of ± 0.2 mm of focal point. Therefore, while drilling thicker materials, it is required that the focal point is moved down the hole as it is drilled.

LBM at present is suitable only in exceptional cases like machining very small holes and cutting complex profiles in thin hard materials like ceramics. It is also used in partial cutting or engraving. Though LBM is not a mass material removal process, because of its rapid repetitive machining characteristics and ease of control, it is possible to use this process in mass micromachining production. Other applications include sheet metal trimming, blanking and resistor trimming.

Electron beam machining (EBM). Electron Beam Machining (EBM) is a metal removal process in which a pulsating stream of high-speed electrons, produced by a generator is focused by electrostatic and electromagnetic fields to concentrate the energy on a very small area of work. As the electrons impinge on the work with velocities exceeding one-half the speed of light, their kinetic energy is transformed into thermal energy and they vaporize the material locally. The process takes place in a vacuum chamber (10^{-5} to 10^{-6} mm of mercury) to prevent scattering of electrons by collision with gas molecules.

While electron beams are beginning to be used extensively for welding, their machining applications are still restricted. EBM is generally limited to drilling extremely small holes and cutting narrow slots or contours in thin material to close tolerances.

The electron beam has gained a very wide application in welding compared to machining. Since the electron beam can be focused to an extremely small diameter (0.25 mm and lower), the melting and fusion can be confined to a thin slice of workpiece. The main attraction of EB welding is its ability to make clean deep welds with very little heating in the surrounding metal.

EB welding has proved highly useful in repair work. Defects in castings, for example, can be corrected in the final stages of machining without the risk of distorting the machined casting. Another attractive feature of EB welding is that dissimilar materials can be welded together such as carbon steels to stainless steels, ferrous to non-ferrous, dissimilar hard metals.

Plasma arc machining (PAM). Plasma Arc Machining (PAM)is a material removal process in which the material is removed by directing a high velocity jet of high temperature (11,000 to 30,000° C.) ionised gas on the workpiece. The relatively narrow plasma jet melts the workpiece material in its path. Because of the high temperatures involved, the process can be used on almost all materials including those which are resistant to oxy-fuel gas-cutting.

The obtainable cutting rates in PAM are 250 to 1700 mm/min depending upon the thickness and material of the workpiece. For example, a 25 mm thick aluminium plate can be cut at a speed of 750 mm per minute while a 6 mm carbon steel sheet can be cut at 4000 mm per minute. The use of water injection can increase the cutting rate in carbon steel to 6000 mm per minute for a 5 mm thick plate.

PAM is chiefly used to cut stainless steels and aluminium alloys. It is preferred to oxy-fuel cutting because it produces comparatively smoother cuts and is free from contamination.

Ion beam machining (IBM). Ion beam machining, IBM or etching is generally classified among the thermo-electric processes along with electro beam, laser beam, plasma arc and electric discharge machining. Unlike most of these techniques, however, this process does not depend on the heating of materials to the point of evaporation. Instead, it removes material by sputtering of ions. This sputter etching mechanism is basically simple. A stream of ion bombards the surface of the target material. Each bombarding ion dislodges surface atoms by transferring kinetic energy from itself to the atoms.

The use of IBM to remove material has found only limited application. It is applied mostly in micromachining (etching) of electronic components like computer memory, figuring optical surfaces and for the precision fabrication of fine wire dies in refractory materials. The IBM process is also used for the disposition of a thin film of material, particularly in electronic industries.

Water jet cutting (WJC). Cutting brittle, soft or sticky materials, fabrics, felt, rubber or honeycomb structures or readily inflammable materials is often possible only with considerable outlay or not possible at all using conventional cutting methods. A water jet which is accelerated up to over twice the speed of sound opens an entirely new scope on cutting such materials.

The Jet-cutter system has been successfully used in Europe and the United States particularly in the aircraft industry, for the following materials: leather, plastics, rubber, paper cardboard, corrugated cardboard, plywood, mineral and wood fibre boards, textiles, insulating materials, metal foils, glass and carbon fibre, reinforced plastics, ceramics and asbestos.

The high pressure Jet-cutter process provides a number of significant advantages over the traditional methods. The water is completely dustless as the water jet "binds" the material being cut. Material loss is minimised with the width of cut being less than 1 mm and in some instances as small as 0.1 mm as in the case of corrugated cardboard.

In some production processes, high pressure water cutting has advantages over the laser beam method because no heat is developed during the cutting operation. This eliminates the danger of fire or explosion and the problem of heat-induced damage to materials.

In addition, high pressure water jet systems enable the cutting process to be guided at close tolerances in all three planes, with no formation of "edges" on the material and no development of side pressure when cutting curves.

The Jet-cutter comprises two basic units: the pump unit and cutting unit. The necessary pressure is developed in two or more stages in the oil pump unit. Primary pressure is reached in the hydraulic aggregate which is then changed to pressure water in the pressure intensifier. The water jet is then carried through a tube to the cutting station via an accumulator. The range of the unit for adjustment generally is from 15,000 to 60,000 psi, which enables the operator to select the optimum rate for cutting a particular material. The cutting consists of a table compatible with the production process (to suit the width and type of material) and a nozzle fitted with a diamond orifice jet of extremely small aperture. The water medium does not require any purification and can be drawn direct from the main supply and it is possible to reclaim the used water. The velocity of the jet causes a natural vacuum at the point of cutting. The cutting dust is extracted and removed with waste water. As cutting forces can only occur in the direction of the jet, it is possible to execute complicated shapes without deforming the material. As a result, cutting soft elastic or sticky materials is just as easy as cutting fabrics or honeycomb structures of the most simple shape.

The water jet cuts without generating heat. This is important, for example, in the case of synthetic fibre fabrics when the structure of these fabrics may not be modified at the point of cut. The absence of heat and the absence of any form of sparking is extremely important when working with readily inflammable materials.

The quality of cutting is excellent and as a result of the minimal slit width hardly any material is lost. The cut is generally without any burr formation on the back of the workpiece. Hence it eliminates the need for deburring the workpiece.

Automatic tracking accessories enhance the jet cutting capabilities. One example of this is the unit to cut leather for car upholstery to required patterns. This unit is presently cutting up to eight layers of leather at a time at a speed of 10 metres per minute.

Quite a few hot spots in aeroplanes require high temperature resistant materials for items such as washers, baffles, insulators and engine brackets. At the Lockheed Corporation, Georgia, U.S.A., many of those parts are made of asbestos. The danger of asbestos machining have been well documented and Lockheed could not comply with many safety regulations of the United States Government. As a result, the company installed a cutting system that uses a high pressure stream of water - a <u>Jet-cutter</u>, which allowed the production to continue. The localised vacuum system created in the cutting area reduced dust emission to well within the regulations. Besides the environmental benefits, the company achieved a number of manufacturing improvements including savings in labour and materials, a better quality of cut and increased capacity for multi-shape cutting.

V. METALFORMING MACHINE TOOLS

Right down to the third quarter of this century, metalcutting has dominated over metalforming in metalworking industries. The share of production of metalforming machines as a percentage of total production of machine tools in the world was hardly less than 10 per cent during the 1940s and 1950s. However, now the concern to conserve materials, the rising cost of energy and the need to explore new routes of production have given metalforming a lot of significance and metalforming machines like mechanical and hydraulic presses - single column open back inclinable types, heavy duty straight and double column types, forged types - press brakes, shears, and guillotine machines constituted more than 25 per cent of the total world production of machine tools during 1979. There are signs that this share will go up to a further 30-33 per cent by the end of the century.

The plastic deformation of metals takes place in two ways: by bulk deformation and by incremental deformation. Metalforming machines were built till 1960 to accomodate workpieces formed by the bulk deformation process. These were the conventional forges and presses but now the incremental deformation processes are finding wider application. These are in a way non-traditional forming methods. These include helical rolling, ring rolling, spinning and flow-forming. These non-traditional methods and other high-speed forming techniques like fine blanking, and NC punching powder metallurgy (PM technology) are partly responsible for a discernible shift from cutting to forming.

High-speed forming. A great deal of interest is now shown towards various methods of forming metal at very high speeds. A lot of developmental efforts on a wide variety of processes have resulted in some high-speed forming techniques which have become important in industry by replacing conventional methods.

The development of new high strength alloys combined with the need to produce parts of more complicated form has increased problems associated with forming on conventional presses. Many manufacturers would prefer to form parts rather than use the often wasteful cutting methods, but the high capital cost of conventional forming machines and dies and tooling has precluded use for all but high/very high mass production purposes. The possibility of cheaper equipment has thus stimulated interest in high-speed methods.

The main customers for the heavy duty high-speed presses are the automobile industry and agricultural machinery manufacturers including lawn and garden equipment manufacturers. In the highly sophisticated line, the aerospace industry is another pace-setter of designs of metalforming machines. The United States aerospace industry will soon fabricate much of its sheet metal components with the help of computers. Super plastic forming and diffusion bonding are some of the metalforming manufacturing processes in the aerospace industry. Titanium at a temperature of 900° to 950°C makes a workpiece so pliable that it can be formed into complex shapes at low pressures typically at 150 psi. At 2000 psi bonding is possible. Although the hot isostatic press (HIP) is still at the laboratory research stage, it has a greater potentiality and could be designed for the production of several tonnes of aerospace components per day. It has been recognised that the HIP process of forming is a fast growing technology with an increasing potential in both the aerospace and non-aerospace fields.

Normally, a press-brake is designed with an allowance for deflection under load. Engineers frequently confronted by press-brake application in which bends are required at loads less than, or greater than normal, have come up with a design that permits precise bends to be made under either of these conditions. It eliminates the need for dies shimming, a lengthy and troublesome procedure.

Development engineers at the U.S. Steel Corporation have designed and built a stamped-steel automotive exhaust manifold that weighs 60 per cent less than its cast-iron counterpart. Weight reduction, hence energy saving, was the main objective but faster engine warm-up and noise reduction are additional benefits. Many automobile manufacturers are interested and keep close watch on developments in stamped engine components.

Internal combustion engines will never be stamped out like wheel covers, but in eight to ten years from now most of their components could be products of press working shops. Moreover, their exhaust manifolds and piping ahead of the catalytic converter could consist of stampings even sooner.

There are a great many presses being used in the automobile industry and these are continuously being improved in design. The greater capacity 1500 - 5000 tons, suitable also for deep-draw metalforming operations, give greater production, higher quality of pressed components like bodies, doors, panel and bumper stamping for cars and trucks, built with advanced designs of safety accessories. However, more sophisticated application of forming presses is seen in the aircraft, space and armament industries. In the production of military nardware, new technologies are being used in the assembly line of transfer presses to produce cartridge cases of higher calibres.

Cold forging. The cold forging of steel has been considered as a method of improving utilisation in the manufacture of engineering components. Though this process is still not considered as a route to produce components difficult to make by other methods, in view of the rising cost of material and the low recovery price of swarf, cold forging is now receiving a lot more attention. In cold forging, usually the starting billet is progressively changed in shape until the final form is achieved. This involves different deformation processes combined in an arbitrary sequence. The basic sub-processes involved are extrusion, upsetting or heading, drawing, ironing, swaging, expanding, threading and form-rolling. Some of these are briefly described below.

Extrusion. Extrusion is a particularly versatile manufacturing process in which the cross-sectional area of the billet is reduced during deformation. Symmetrical products which are variants of the basic shapes like rods, tubes and cans are readily made. Material may be deformed at one end or both ends of a billet, simultaneously or sequentially. Depending on the conditions, material may flow preferentially in one direction and this flow may have to be stopped after that part of the desired shape has been achieved in order that material may flow in the less-preferred direction to complete other parts of the desired shape. Flow is rarely restricted in all directions because billet volume (weight) can vary and excess volume can result in unacceptably high tooling stresses or even tool failure.

Upsetting (heading). In upsetting, a billet is subjected to compressive deformation, generally in the direction of its axis, to enlarge the cross-section area over a part or the whole of its length. In heading, the enlargement is confined to one end of the billet and is basic to the production of fasteners. A punch moving along with the die axis upsets that part of the billet which protrudes from the die into a form determined by the geometry of the mouth and the punch head. In general, lengths up to about 2½ billet diameters can be upset **without** bending in a single blow and up to about 4½ billet diameters in two blows and up to 6½ billet diameters if a sliding punch supports a part of the billet during upsetting. Cracking is avoided if the maximum upset diameter does not exceed 2½ billet diameters in free upsetting or 3-4 billet diameters in constrained heading of mild steel.

Ironing. In ironing, the product (solid or tubular) is pushed through a die and its external diameter is reduced. Because the product is not wholly constrained by the tooling, the reduction in diameter which can be achieved is limited by the onset of buckling in the solid product, tearing of the base in the tubular product and by the upsetting of the product material immediately ahead of the die. The process has been extensively used to produce stepped shafts used in electric motors and tubular components of large length/diameter ratios.

Press equipment and tooling. Each operation involving a change of shape of billet material requires appropriate tooling, which may be set up on a single press in batches or may be set up in separate presses and the components produced on an in-line basis. If demand exists, a series of presses may be linked for automatic feeding and transfer along the line. Alternatively, all the forging operations may be undertaken in a single tool containing the necessary stations mounted in a single press of sufficient capacity to perform all operations in a single working stroke. In this case, a transfer feed is provided to convey the partly formed billet from station to station. Where small components or fastener type products are required in very large numbers, these can be formed in multi-station progressive cold heading machines which perform the above functions at a very high speed.

As product volume grew at Caterpillar, U.S.A., the company began to use special machines for a few parts, then for a few more. Its automatic forging line for track links using mechanical presses remains a classic model after many years of use, although it remains a line that the company rarely lets anyone see.

The working parts of cold forging tools comprise a punch or punch/mandrel, a container consisting of a shaped insert and one or more prestressing rings and an ejector. Much more is now known of the stress distribution in items of tooling following extensive experimental research and analytical studies. This has considerably aided tool design and provided a better basis for assessment of tool life.

At present the manufacture of tooling items by the conventional machining of bar material produced by the powder metallurgy route shows greater promise than the manufacture of individual tooling items by the direct compaction and sintering of powders although the latter route is also being pursued.

Fine blanking presses. A part made by the blanking process is essentially a finished part. A triple-action sturdily built press exerts forces on equally sturdy specially designed tooling and, with precision unattainable on conventional presses, shears a part with smooth-edge contours from stock as thick as 20 mm. The part may be pierced, counter sunk, bent or coined. It may become flatter. Offsets may be formed in it without loss of dimensional accuracy. Most important, many if not all secondary operations that may have been required to produce it by previous conventional methods are bypassed. The real advantage of fine blanking is the time and money it saves.

The Swiss discovered these compelling advantages in the early 1940s, when they succeeded in stamping sheet metal into office machine parts with tooling that firmly held the stock around the punch perimeter and had a very small punch-to-die clearance, much less than in tools for conventional stampings. Edges were sheared smooth throughout full stock thickness, and removal of small burr on the part edges was a very minor operation.

The fine blanking process has gained rapid acceptance in Europe and not just in the office equipment field. Its cost-and energy-saving capabilities were strong incentives in Europe as they are now for most of the world.

Fine blanking works because punch-to-die clearance is very small compared with that normally used in conventional press working and the forces exerted by sturdy triple-action presses produce a blanking action that is actually cold extrusion. Tooling is normally designed so that the punch-to-die clearance is about 1 per cent stock thickness or about ½ per cent on each side of the part. For some of the heavier fine blank jobs, for example parts that are 10-12 mm thick, the clearance can be as small as 0.0004 mm. An interference fit (negative clearance) is never used.

So far, the ingenuity of fine blanking, press builders and tool makers have produced parts with precise contours and flatness. The process will not usually flatten distorted stock except in areas that are coined or if the counter punch is shaped properly.

Burrs produced by fine blanking are small and easily removed by such methods as belt sanding, disk grinding or tumbling. Sanding is generally used for large, heavy and flat parts, especially those that are long and narrow. Such parts must not have any bends or projections on the burr side. Small fine-blanked parts, either flat or three-dimensional are usually deburred in tumbling equipment.

Semi-piercing, in which stock is not punched through, is one of the fine blanking practices. Coining is a variation of semi-piercing that is also prevalent in fine blanking work.

Tolerances. The dimensional accuracy of a fine-blanked part depends on the quality of tooling and the thickness, strength and quality of the stock, as well as on the part's size and configuration. In general, these could be very close to ± 0.0008 mm for external dimensions and internal holes and flatness; for coined parts of ± 0.0004 mm per 25 mm. Closer tolerances are possible under special conditions. These figures are for steel; tolerances are somewhat wider for aluminium or brass. Tolerances in conventional press-working by contrast are three to four times less tight.

Fine blanking presses are built with three actions whose stroke, length and force can be separately controlled or preset. These presses are also built to withstand the substantial forces - many of them diagonal - inherent in the process and to support their tooling in precise alignment.

The larger presses are completely hydraulic but the main blanking action in a line of presses in the smaller tonnage range from 25 to 350 tons is powered primarily by mechanical means.

Fine blanking tools are usually the single-stage compound type although progressive tooling is required for certain jobs. Providing positive guidance and positioning of the main and inner form punches, the tooling is more rigid than compound tools for conventional press-working because the forces brought to bear on the workpiece are higher.

Overall clearance between the punch and the die in fine blanking is another point of difference between the fine blanking and conventional press working. In the latter, it can be as large as as 10 per cent of the material thickness compared to 1 per cent in fine blanking. And since a die opening and punch sides in fine-blanking tools are not tapered , but are straight and remain so for their full life, part uniformity can be maintained. In fine blanking, the press is an accessory to the tooling; tooling being the key element in the process of producing clean cut through the entire thickness of stock with no distortion except for a slight turnover at the tool entry edge and a small easily-removed burr at the exit edge.

A new era in NC punching. Flat metal was first punched by numerical control in 1955. At the Machine Tool Show in Chicago, United States, that year, visitors saw the world's first NC punching press. The début had far-reaching repercussions and triggered major changes in machinery for producing holes and contoured cuts in sheet metal plates and structural steel members. It also affected the operation of companies that bought such equipment, boosting their manufacturing efficiency.

In fact everyone, including manufacturers of controls, tooling and auxiliaries, benefited from the adoption of NC by the metal punching industry just as builders and users of metalcutting machinery have reaped the reward from NC since its introduction in the industrialised countries. The widespread acceptance of this type of punch press control stimulated new press designs and improvement on earlier designs. In recent years, it has spawned hybrid machines that not only punch but also cut by plasma arc or laser beam and even perform such functions as milling.

Computerised numerical control (CNC) entered the metal punching field in 1972 and provided even greater benefits. CNC drastically reduces NC-programming time and effort - as well as production cycles. It manipulates the punch controlling numbers electronically, performing such tasks as optimisation of punching instructions and other such number-juggling that an 8-track punched tape could never do. Although CNC is more expensive than NC, most punch press manufacturers now offer it as a standard; if it is an option, most customers usually take it and most users with just an NC punch press eventually buy it.

NC or CNC punching machinery differs from conventional mechanical hydraulic or pneumatic presses in that the workpiece is positioned under a basic punch that is gripped by a turret bushing or an adapter in a single-station type of press. Die sets of the type used in conventional press working operations - often complex and costly - are not used. Workpieces can be the size of a small barn door, far larger than the largest now accommodated by today's open-back-inclinable (OBI) and straight-side presses. Four column platen presses, with unitised tooling, might handle large expanses of sheet metal but for most jobs, the set-up time and cost would make them costly to operate.

The strongest advantage of NC punching equipment is the adaptability of its workpiece positioning mechanism to that kind of control. Moreover, the beam lines that fabricate structural shapes as well as flats use NC for X-axis motion and punch actuation, and some use it for tool shifting as well.

None of these beam lines uses it for tool changing, however. For such machinery, NC can govern handling systems beyond the punching stations, increasing efficiency because the workpieces are often long and heavy.

The third category of NC punch press designed for punching (and frequently for drilling) long lengths of thick plates, uses NC to govern not only the X-axis motion but also the Y-axis positioning of the tooling. The Punchmatic Model of Cincinnati Inc. and the Peddinghouse line of Fabriplate plate punchers are typical of this type of machine.

On most sheet metal and plate machines, however, NC not only governs the X and Y axis positioning of the workpiece and actuation of the punch but also selects the correct tooling at the right moment in the punching programme on presses with automatic tool changers. These machines represent a new generation of metalworking machines.

All punching machines including the NC models are built around one basic concept: a punching mechanism, a workpiece positioner and a structure on which they are mounted and operate. Beyond this fundamental definition, however, almost all makes and models differ from one to another.

Powder metal technology (PM). This method of forming finished to almost-finished components is gaining popularity in the manufacturing industry. More and more parts in the instrument industry, aerospace and automotive industries are advantageously exploiting this technique. PM carbide tools, high-speed cutting tools, vacuum and nitrogen atmosphere for sintering PM, low-cost PM brass, liquid phase sintering are some of the applications. Test results on aluminium PM parts compacted with shock waves have proved successful and parts which could not be made in one piece with conventional PM compacting techniques are being injection-moulded. These and other innovative techniques in PM and injection moulding could be employed to produce many difficult-to-machine complex parts.

Non-traditional forming processes. The ability to mould clay and knead foodstuffs came instinctively to human beings. It is only in recent years that modern technology has focused its attention on these instinctive arts of forming and developed the incremental deformation technique to create some important processes of non-traditional forming.

Instead of the brute force used in bulk deformation techniques, the incremental deformation techniques employ force purposefully and skilfully. These non-traditional forming presses are helical rolling, ring rolling, spinning, flow forming and

and rotary forging. Of these processes, rotary forging, spinning and flow-forming are now the most popular.

Rotary forging. Rotary forging consists of two opposed rotating, circular, contoured dies aligned on a single axis. One of the dies is constrained from making an axial movement and is offset at a fixed angle in relation to the other die which can move easily. A circular billet compressed between the two dies can be indented over a limited area by means of an axial force. Subsequent rotation of these two dies in conjunction with continued compression causes the plastic deformation produced by the progressive indentation through the billet. Once the workpiece achieves the required shape, compression ceases and the axially moving die is retracted. The resulting component reflects the shape of the dies, and the deformation mode produces a multidirectional grain-flow-structure which is not produced by conventional processes.

A recent variation of this technique, with a vertical axis, is known as rocking-die forging. It consists in its basic form of a wide angled conical upper platen, located with its apex inverted in the die holder. The die holder has its longitudinal axis offset to the vertical axis by a small angle. In turn, the die holder is seated in a bearing and is usually constrained only to rock about the vertical axis.

By using this process in practice, a wide variety of component shapes have been forged, the complexity of shapes being determined by the configurations of both the dies. The components that can be manufactured by this process are mostly disc type, such as clutch discs, pulley sheaves, gear wheel blanks, inertia wheels etc. The job thickness in this process can be as low as 6 mm to as high as 200 mm and diameters ranging from 25 mm to more than a meter.

The increasing emphasis of noise limitation in the manufacturing field has led to the development of various types of noiseless riveting processes for assembly operations. Impact riveting, which is popular even now, has the inherent disadvantages of shock and vibrations leading to unpleasant noise levels depending on the size, hardness and the ratio of the spread to the diameter of the rivet. In impact riveting, the rivet head is deformed beyond its elastic limit, destroying its molecular structure. Often the spring-back action after the impact leads to loose assemblies.

Rotary cold forming methods of riveting, because of the continuous and gradual spreading of the material, are practically noise-free and are credited with a number of advantages. Rotary cold forming riveting methods can be classified into (a) roller spin riveting; (b) orbital riveting and (c) radial riveting. Of these, orbital and radial riveting methods are similar to cold form rotary forging except that the shapes and the forces involved are comparatively small.

Roller spin riveting. Even though the orbital and radial heading processes were patented as early as 1905, they came into commercial use only around 1960. The roller spin riveting head consists of two split rollers mounted on an axis held in a holder. When the holder is rotated under vertical pressure, the head is formed gradually.

Even though this process produces more uniform heads compared to impact riveting, the surface finish produced is not of high quality because of the difference in the contact velocities at different radii of the rollers.

The tooling in this process is expensive and the tool wear is rapid. The size requirements may pose problems in places of restricted accessibility.

Orbital and radial riveting. Orbital and radial methods of riveting are similar and involve a characteristic wobble motion of the tool. In orbital heading the tool is held in a freely rotating spindle, the axis of which is positioned at an angle, usually 3° to 6° to the axis of the housing, so that the spindle axis intersects the axis of the housing at the face of the tool. The rotation of the housing provides a circular orbital motion to the top of the tool. With this movement and the tool on contact with the rivet head, the face of the tool gets a wobbling motion without any relative rotation. As the tool comes in contact with the workpiece, it makes a line contact starting from the periphery and moving towards the centre.

During this process, a wave of material mass moves ahead of the line of contact, the amount of material mass depending on the pressure applied. Because of very low friction, the heat produced in this process is negligible and the resulting surface is free from tearing marks. As only a minute quantity of material is displaced in each revolution, the axial pressure required is only about 10 per cent of that required in impact forming of the head.

The radial riveting method is similar to that of orbital riveting except that in this process, the rivet head is formed by the movement of the tool point along a series of cylindrical loops that overlap tangentially at the centre to produce a rosette pattern. In the radial riveting head, the tool is not free to rotate as in the case of the orbital riveting head, but it makes a point contact compared with the line contact in the orbital method. Consequently, the pressure needed to form the rivet head is 10 to 20 per cent less than that in the orbital method. Hence this process is specially useful for small and delicate parts.

Metal spinning and forming. In conventional spinning, which is basically a manual operation, an annular ring of the circular blank of a thin gauge material is formed to the desired shape of the finished utensil. While there is a change in the diameter of the blank and finished vessel, there is practically no change of thickness between the formed side walls and the base. During the process, the flow of material follows the laws of equal surface area and equal material volume. However, the process is slow in comparison with deep drawings and for consistent operations requires highly skilled operators. This process is highly suited for ductile materials such as soft aluminium and its alloy.

Future of forming. Metalforming is bound to attract greater attention in the future because of the growing concern to conserve material and restrict energy input to optimum levels. Forming is increasingly preferred because it not only makes a more prudent use of material, but also has in-built possibilities of better control over material properties.

The future of forming is bright because it affords reduction in machining sequences which are otherwise inevitable in metalcutting. The newly developed high precision die casting and forging techniques, precision blanking and sheet metal working methods and advances made in powder metallurgy, fine blanking, NC and CNC punching, investment castings and cold extrusion, explosive forming, electrohydraulic forming, electromagnetic forming, compressed gas forming, water hammer forming and fuel combustion forming are offering production managers more economical routes of production. Even though tooling costs of metalforming machines are high at present, future research efforts may bring down their costs particularly using NC and CNC in the manufacture of dies and tooling.

VI. TECHNOLOGICAL TRENDS IN PRODUCTION ENGINEERING

As mentioned earlier, the development of production technology depends directly and uniquely on the development of modern machine tools, cutting tools and machine tool controls. With spectacular and innovative developments taking place in all these entities, equally if not more spectacular progress and development in manufacturing methods in the metalworking industry could naturally be expected. Today, production engineers have at their disposal machine tools, cutting tools and unimaginable facilities of micro-electronics to develop software systems which combine the benefits of all these newer developments in evolving highly productive systems of manufacture. Computer technology, microprocessors and minicomputers have become the prime agents of the spectacular changes taking place in production engineering. The control of machine tools and manufacturing processes by computer is the present-day trend. Computer monitoring or control of plant operation is the most significant trend in the metalworking industry. Computers are being used to solve scientific and engineering problems related to product design and production engineering. They are being used in manufacturing, in planning to stimulate the flow of parts and assemblies, eliminating bottle-necks in advance. They are being used to control inventories of raw materials, parts and assemblies and to monitor production operations, controlling them completely in some cases. Scheduling is being computer-controlled, the objective being to keep machines and production lines as fully loaded as possible in order to receive maximum return on the company's investment and facilities.

Probably the biggest advantage of computers in metalworking plants is their ability to keep track of what is going on, on a real time basis. Alerted by computers, management is able to make decisions when they are needed and when the trouble occurs. The managers are able to study metalworking operations in their plants in greater detail to find where process improvements - better flows of parts and materials between machines and tools, better allocation of manpower and brain-power - will pay off. Many routine management decisions are being made by computers freeing management from some of the day-to-day boredom of life in the metal-working industry and giving them time for longer term strategic planning that is so very necessary for the success of the metalworking business.

By far the most important form of modern production technology is computer-aided manufacture (CAM). It has already proved its superior ability to considerably improve production possibilities than all the other known forms of production techniques put together. It is for this reason that machine tool-based production technology is becoming strongly integrated with the computer.

Robots have been on the industrial scene since the early 1960s. But the first models were 'hulking brutes'. The new breeds are sylph-like and are far brainier, thanks to today's micro-electronic technology. They are nimble jacks-of-all trades. A typical model can be fitted with a variety of hands, mechanical "grippers" to pick up parts and are being provided with scanning eyes to pick and transfer and load whatever is desired by the programme engineer.

The unmanned factory of the future is shaping up fast on the computer, much quicker than previously estimated.

Manufacturing saw its first revolution in the latter half of this century with the advent of NC. It can be termed a revolution because it freed manufacturing engineers from their total dependence on the skilled machinist to obtain parts of acceptable specification and held out potential for complete control of the machining operation by the methods engineer. Manufacturing is now on the threshold of a second revolution. The computer promises to give management complete control over the whole manufacturing operation, from design to dispatch. Computer-aided design (CAD) and computer-aided manufacture (CAM) are terms which symbolise engineers' attempts at transferring all of the routine functions in manufacturing operations to the electronic computer, vesting in it a limited supervisory control and using its data processing capabilities to optimise the manufacturing operations. Electronic control of manufacturing operations is advancing as rapidly as development of software - always the bottle-neck in such cases - will permit.

Three major factors have combined in the last decade to advance manufacturing to its present stage. They are: the increasing cost and shortage of skilled labour; the higher productivity and automation (including NC) of new machines offered by machine tool builders; and the availability of reliable low-cost computers in the last five years.

Skilled labour is becoming scarce and wage rates are climbing. There is a gradual shift of the labour force away from the manufacturing into the service industries in countries like Belgium, the Federal Republic of Germany, Japan, Sweden, the United Kingdom and the United States of America. This trend may increase as working weeks shorten and leisure and the entertainment services attract more and more people.

There is an increasing demand for variety to meet changing and varied customer taste. Average lot size has decreased in recent years, even in traditionally mass-producing industries like the automobile. Today, people rarely talk about mass production; they talk about high volume. The former implies millions of identical parts while the latter means production at the same high rates but with the ability to adapt to customer preference. To meet higher performance standards, and safety and ecological regulations, manufacturing tolerances are becoming finer. Economical methods of working to higher accuracies are becoming more popular.

The need to economise on material consumption is a major consideration in the manufacturing processes. Additionally, a large number of new materials, generally of high strength and performance, are evolved to meet product requirements.

The overall effect of these factors has been to demand from manufacturing operations full optimisation of all the three resources - labour, materials and machines. Optimisation technology in manufacturing is engaging the attention of top management.

Computers in manufacturing. Currently emphasis is on linked machines, integrated systems and computer-aided manufacture. The stand-alone NC machine and groups of NC machines are now widely accepted methods for batch manufacturing. Future computer-aided manufacturing (CAM) systems will probably be formed by linking first one and then several CNC machines with automatic work handling and/or robotics with overall control by means of hierarchical computer systems. The next logical progression will be linked multiple systems of this type with automated assembly and these could possibly be the forerunner of an unmanned factory.

Direct Numerical Control (DNC) of NC machines from a central computer has taken a back seat whilst recent attention has been focused on a systems approach to batch manufacturing, namely Flexible Manufacturing Systems (FMS) and Unmanned Manufacturing Systems (UMS). All the integrated CAM systems are aimed at batch manufacturing, have a high level of materials handling and have integrated control systems. Hence they can be considered as an extension of the DNC systems with the inclusion of management information systems, work transport and possibly tooling transport systems.

In Japan, the United States of America, several of the East European countries and several of the West European countries, commercial DNC installations and integrated work transport systems have been introduced. The Japanese project on the Automated Factory is an indication of their lead in batch manufacturing.

Integrated manufacturing. An integrated manufacturing system is one that combines a number of hitherto separate manufacturing processes so that they can be controlled by a single source, relative to each other. The chief benefits of so doing are: reduction in lost time caused by inter-stage movement of the components being made; improved machine tool utilisation; reduction in manpower; reduction of work in progress; and greater flexibility of component batching and loading.

Presently the majority of systems developed have concentrated on the machining processes involved and, in particular, prismatic parts manufacture. A truly complete integrated manufacturing system would require the same degree of co-ordination and control to be applied to other major operational areas, i.e. production of rotational parts, fabrication and assembly.

However, the main concern has been with the application of this type of manufacture to small batch production which constitutes a significant proportion of manufacturing output in almost all countries. It has been estimated that the difference in cost between mass production and small batch production of the same components can be as much as 30 to 1 and an appropriate expression of the cost target for integrating manufacturing systems could be the mass production of one-offs.

Integrated manufacturing systems of some form for machining components have been in commercial use for about 22 years in the industrialised countries and existed in experimental form for some years before that. Early systems included manually-operated standard machine tools, fed by automatic means from a common source, as well as a limited number of machining centres coupled with palletised loading and unloading.

The real breakthrough, however, was dependent on the design of reliable comparatively low-cost control systems which became available in the late 1960s. From this point on, it was possible to design systems which would achieve a sufficiently long mean time between breakdowns to make them economically attractive, always assuming that the standard of the mechanical functions was of an equal order.

Production could now be accurately planned through a complex system of machining operations and the manual content was reduced largely to that of inspection of piece-parts and tooling to maintain the standards of accuracy and finish demanded by the specification of the component. The machine-controlled environment on and off the shop-floor could yield efficiencies not previously considered attainable in this type of production.

Because of the high operating efficiencies leading to greater tool cutting time, a group of eight machines can be equated to 100 conventional machines in output, especially on small batches up to 50 parts. The average number of machines in a system varies between five and nine machining centres, though the greatest number recorded in one system is 70 in the United States at the Sundstrand Corporation. With high operating efficiencies (in some cases over 90 per cent) the output from a single system can be as high as 4,000 pieces a month on a three-shift basis, thus giving to the batch production of small quantities, the volume outputs of mass production equipment.

Computer-aided manufacture (CAM). A computer-aided manufacturing system (CAM) is a closed loop regulating system whose primary input dimensions are demand (requirements) and product idea (creativity) and whose primary output dimensions are finished components (finish-assembled, tested and ready for use). It represents a combination of software and hardware consisting of the methodology of production, production planning, production control as well as the choice of production aids including machine tools. It can be realised by systems engineering methods and it offers a possibility of total automation through flexible and adaptive means. The most important aid to achieve this goal is the computer. This is the basic concept and it constitutes the basis and guiding factor for the development and application of computers for integrated production. This is generally called computer-aided manufacture.

In other words, computer-aided manufacture (CAM) is a conglomerate concept where the ability of the computer is used at every stage of manufacturing by evolving a cellular structure. Though this type of manufacturing may appear akin to the transfer line concept, CAM has the flexibility unlike transfer lines to alter the type of product and also the product-flow sequence from machine to machine. The alteration of product flow sequence is done in such a manner as to keep the idle time of any machine to the minimum. Such a flexibility is achieved because of the monitoring and control exercised by the central computer.

The availability of DNC and computer controlled installations are having a major impact on manufacturing philosophy as a whole. The flexibility offered by new hardware and software is encouraging a shift from fixed programme mass production facilities to variable programme automation. It is now realised that the best benefits of computer control are only obtained in a kind of group technology where the machines are linked by automatic transfer systems and the computer keeps a continuous track on a variety of components as they go through the manufacturing cell.

The DNC computer is now extended to handle management functions within the manufacturing cell such as scheduling, inventory, materials management, budgetary control, and reporting. The integration of a number of such manufacturing cells into a single manufacturing facility through a central computer will complete the cycle giving rise to the integrated manufacturing system. Such systems are required to have a hierarchical line of computers at different levels. Information and feedback from various cells go back to the central large computer, which possesses powerful software capable of dynamically programming the whole operation of the optimum utilisation of all resources. The addition of automatic warehouses, assembly, test and dispatch systems is also proceeding partially, leading to the capability of automated unmanned manufacturing.

It is important to note that computer-controlled manufacturing systems exist even today at various levels of development. An excellent example is Fujitsu Fanuc's Hino facility which uses computers and NC to automate the production of NC systems and NC drilling machines.

The motive force behind this strong and all-pervasive trend of computer-aided manufacturing system in modern factories is a combination of long-range economical and social factors. These factors have exerted an enormous influence on modern concepts of industrial production. It is important to correctly understand these factors so that the technological development is properly steered and the resultant technological developments are purposefully applied.

Economic factors. The decisive long-range economic factor which governs the structure of industrialised nations is the constant need to reduce the cost of production to achieve higher real growth. It is also known that the processing industry today constitutes the most important segment of production in industrially advanced countries. While the processing industries account for one third of the gross national product (GNP), the service sector accounts for almost half of the GNP in industrialised nations. It is true that the service sector is important for a good standard of living and for a better quality of life. But it does not create any wealth. This obviously leads to the conclusion that the processing and manufacturing industry produces about two thirds of the wealth of an industrialised nation. The remaining growth can be attributed to primary products like agriculture, sericulture and mining.

Higher living standards, improved quality of life, better employment opportunities and general welfare of a country depend directly on the cost factors of producing wealth. Since the manufacturing/processing industry creates almost two thirds of the real growth in the industrialised countries, any reduction obtained in the cost of production can be of the utmost significance. It is recognised now that computer-aided manufacture offers more avenues of reducing production costs than all other known techniques. Therefore all industrialised countries want to develop and apply computer-aided manufacture as soon as possible. This again implies world-wide development of modern machine tools and an intense concentration of computer-optimised automated production systems.

Social factors. The most important long-range social factor influencing the manufacturing industry is the trend towards a post-industrial society. The attitude of the workers towards their working methods are changing. They show an increasing disinclination towards the existing nature of work in factories. There is an unmistakable trend that more and more workers in the industrialised countries are preferring jobs in the service sector. For example, in the United States of America, in the course of industrial development, the proportion of workers in agriculture fell from 90 per cent in 1870 to a mere 4 per cent in 1976. Correspondingly, there was an increase in the number of those employed in industry in the nineteenth century. However, in the last few years, the percentage of workers in the industrial sector fell from 30 per cent in 1947 to 24.6 per cent in 1970 and it stood at only 21.7 per cent in 1978. A study conducted by Rand Corporation has estimated that by 2000 only about 2 per cent of the work-force will be employed in industry. Although more reserved estimates put it at 10 per cent. However, in all the industrialised countries, the lack of industrial workers will be more acute in the coming years.

This work-force migration adds directly to and puts social pressure on the manufacturing and processing industry of the industrialised countries which has to produce more and remain productive, irrespective of the fact that its work-force is preferring slowly but steadily the more attractive milieu of the service sector. This pressure on the manufacturing industry can be mitigated by computer-integrated production systems.

Technological evolution. As a consequence of the long-range economic and social factors influencing industry, a number of national plans have been drawn up at present in the industrialised nations to accord priority to the development and application of computer-aided manufacturing systems and computer-optimised and automated machine tool systems. The governments, the universities and the industrial establishments are working as a team to promote this. Even though the realisation of fully computer-integrated production systems is the long-range plan, there is a clear awareness that the change from the present industrial methods, know-how and machines require an evolutionary process to reach the ultimate goal. The applied strategy, therefore, consists of developing and applying individual, practical and economic steps in the form of short-term research, development and application programmes having the following two main principal characteristics:

(i) The step should result in adequate gains to justify its adoption and to produce profits on the invested capital to finance the next steps of R&D investigations;

(ii) Each step should be a link in the chain to achieve the final goal of fully computer automated optimised and integrated production.

Among the various programmes under execution in the highly industrialised countries; the following seem to find maximum attention:

(a) Creation of software modules by developing individual software modules which can be coupled with one another quickly at a later time to produce a complete software programme suitable for various production applications. Such investigations are making tremendous progress in Czechoslovakia, the Soviet Union and other CMEA countries as well as in the Federal Republic of Germany, Japan and Norway. The U.S. Airforce is fostering a programme called ICAM (Integrated Computer-aided Manufacturing) and Computer Aided Manufacturing International, U.S.A. is busy with several programmes for the development of software for integrated production;

(b) Development and application of part family production and production cells are a prerequisite for the application of hierarchical computer systems and for the development of flexible production systems. In the Federal Republic of Germany, the Netherlands, Norway, the United Kingdom and the CMEA countries, intensive work is going on in this direction;

(c) Rapid progress has been achieved in the development and application of comprehensive computer-controlled operations of machine tools and computer monitoring of production processes by employing numerical controls, computer-integrated controls, direct numerical controls and hierarchical computer systems in Bulgaria, the Federal Republic of Germany, Hungary, Japan, Norway, the Soviet Union, Sweden and the United States of America;

(d) Investigations on the development and application of computer-controlled industrial robots for automatic manipulation of workpieces and tools, and the operation of machine tools and production aids of various types are progressing in Bulgaria, the Federal Republic of Germany, Hungary, Japan, Norway, the Soviet Union, Sweden and the United States of America;

(e) Rapid progress has been achieved in the development and application of computer-controlled flexible production systems evolved on the concept of automatic production cells in countries like Japan and the German Democratic Republic. Recently, Bulgaria, Czechoslovakia, the Federal Republic of Germany, Hungary, Norway, the Soviet Union, the United Kingdom and the United States of America have begun work in this field.

Flexible machining systems (FMS). There is no generally agreed-upon definition for what have come to be called flexible manufacturing systems but there is no denying that within the last five to seven years, a more responsive yet automated way of addressing the needs of manufacturing has evolved. This new method relies on three distinguishing characteristics: (a) potentially independent NC machine tools; (b) a transport mechanism; and (c) an overall method of control that co-ordinates the function of both machine tools and the conveyor system so as to achieve flexibility.

Within this broad scope, there are any number of individual approaches towards striking a balance between high output on the one hand and great flexibility with a concomitant reduction in output volume on the other.

The main purpose of flexible machining systems is to integrate the various functions in the same machine tool to form a flexible manufacturing cell which is a module of a flexible manufacturing system.

Each flexible manufacturing cell is an autonomous module whose functions are supervised and controlled by a microprocessor-based computer. The various functions of the individual cells are:

(a) supply of blanks, tools, gauges, devices;

(b) clamping devices which include identification, selection, transport, orientation, loading, positioning, clamping, declamping, interlock supervision and other such step-by-step operations;

(c) all operations like measurement of the workpiece, adjustment of clamping devices, material handling/positioning are accomplished automatically;

(iv) all interlocks, lubrication failure and such other malfunctions like tool breakages are automatically monitored by sensors.

Each cell basically caters to a particular machining process like turning and milling. The different cells are connected by transport devices into a flexible manufacturing system and the co-ordination of the simultaneous activity of all the cells is accomplished by the process computer hierarchy so that from raw material to the end-product the complete production process is automated.

An alternative concept of a flexible machining system envisages a manufacturing cell which performs various machining processes like turning, milling, and boring as a part of one individual cell. In this case, the material handling functions are reduced. An existing stand-by robot or an integrated robot performs the workpiece handling and the function of handling the measurement device.

Maximum utilisation of the cutting capability of the machine tool is ensured by an adaptive control. Suitable sensors to monitor process parameters are incorporated in the manufacturing system. The CNC system integrates the whole control strategy for utilisation of installed capacity, reduction of idle time and also to take care of the thermal effects of component accuracy.

Several manufacturing cells linked by a transport system, additional handling devices and an automated storage and a retrieval system for the workpiece, tools etc. can lead to the concept of an automated factory. The ultimate optimisation is envisaged by a hierarchical set-up, wherein all cells at a ligher level are controlled by a centralised DNC-type computer and all production groups are linked to a minicomputer, providing a basis for the complete on-line optimisation of material flow, scheduling, routing and full automation of production.

Computer-integrated flexible manufacturing systems are thus gaining increasing acceptance and importance in batch production. Of the approximately 52 flexible manufacturing systems developed up to 1979, about 40 have been put into operation, mainly in the Federal Republic of Germany, Japan and the United

States; nearly 70 per cent of them being for prismatic components.

Flexible manufacturing systems based on group technology or cell production principles using NC machines and gauging equipment are now being installed with robot handling devices and palletised conveyor supply units to machine families of parts.

Development is also proceeding with the automation of metalforming machines using minicomputers and microprocessors. Programmable turret punches, auto-controlled guillotines and shears, and manipulative equipment are in use. Robot developments applied to metalforming operations will enable a considerable degree of automation in this class of piece-part manufacture. It is now possible to construct metalforming production cells with the aid of robots that will blank, pierce and bend a family of components using a common stock material.

The manufacture of fabricated piece-parts whether forged, welded, sintered or similarly processed is being automated with the use of robots;

and major developments are taking place in Italy, Japan, the United Kingdom and the United States of America.

The automation of assembly operations remains problematical except for flow-line manufacture. But again, robotic and computer developments will have a considerable impact on these operations in the immediate future.

Czechoslovakia and Poland are the biggest machine tool builders in the CMEA countries outside the German Democratic Republic and the Soviet Union and both are actively developing flexible manufacturing systems. The main reason is that batch production constitutes a large proportion of engineering component manufacture in both these countries and both are short of skilled labour.

Flexible manufacturing system development in Czechoslovakia has concentrated on prismatic and, latterly, flat milled and bored components. Poland has developed a number of flexible turning systems, though recently has begun work on a flexible milling and boring system.

Most FMS developments in Czechoslovakia have been focused on the country's machine tool industries, whereas Polish systems have been designed for general engineering such as the production of shaft-like components for the electrical motor, earth-moving, coal mining and commercial industries.

Czechoslovakia has progressed as far as developing direct numerical control systems (DNC), pallet exchange and transport systems, a novel stacking-crane box pallet system, and automatic tool/raw material/work-in-progress stores are concerned.

Group technology. One of the methods of solving the problem of conflict between productivity and flexibility in the computer-integrated flexible manufacturing system is Group Technology (GT). GT is a progressive management concept employed in an engineering industry within the framework of an integrated manufacturing system. The application of group technology in a purposeful manner can result in economic benefits of mass production even in large and medium batch production. In addition to streamlining production through the rationalization of components, it also helps to establish better co-ordination between the production wing and the other functions like design, methods and sales engineering. The fact that more than 80 per cent of the engineering industries of the world are engaged in medium and small batch production should give the concept of group technology a new significance.

The traditionally laid out production lines on the basis of functions viz. turning family, drilling and boring family etc. lead to a lot of production delays because of inherent limitations in production control. A group technology-based production system organises the production facilities in self-contained and self-regulating groups each of which undertakes complete manufacture of a family of components with similar configurations and manufacturing characteristics. The different cells of the GT system virtually function as small factories within the main factory. This assures reduction in throughput time, work in progress, inventory, setting time, work handling, jigs and

and fixtures etc. This concept improves design rationalisation, job satisfaction and production control. NC shops are at present major areas where group technology is employed. But with a shift from hardwired NC to software-based controls like CNC, much of the essence of group technology will trickle down to the software.

Computer control and inspection of machine tools. The evolution taking place now in the direction of computer control and inspection of machine tools constitutes the most progressive field of development of modern machine tools. It is aimed at exploiting the enormous potential of NC through computer-based control, the DNC and the hierarchical computer system. This potential is ever increasing in its scope by the advances which are being continuously made in the field of computer technology.

The application trend is more and more towards minicomputers at the work place. Because of the linkages between the work stations, the trend is towards a decentralised computer which, in a way, is a partial separation between the data processing and control function. This is especially true of computer-based control of machine tools. The far-reaching development of coupling the computer with the machine is facilitating versatile control possibilities offered by computer technology. The computer has thus become the most modern device for error diagnosis and correction on modern machine tools. This has facilitated a new approach to the supervision of machine tools because it is now possible to automatically detect the various errors and malfunctions, both in the electronic and mechanical systems. Thus the possibilities offered by computer technology not only provide the basic testing method during the trial run of the newly-developed machine, but also the possibility to automatically find out the existing error and the potential sources of manfunctioning even in the normal working range of machine tools. While detecting even the initial signs of an error or a malfunction, the computer immediately flashes out a signal to the operating personnel and thanks to the diagnostic abilities of the computer, the maintenance personnel immediately receive intimation on the cause and methods of correcting the disturbance.

The new capabilities of the computer are finding immediate application in modern machine tool technology. The future trend will be towards the development of methods which facilitate automatic correction of malfunctions. Given this possibility, the computer as soon as it detects conditions leading to an error will alter machine parameters in such a manner that the error will not actually take place. In the case of malfunction, the computer will send a command for the replacement of the defective electrical or mechanical module. Thus it is now possible to operate machine tools without operating personnel.

Metrology and inspection. Metrology is going through a revolution brought about by the integration of electronics with the science of measurement. Developments in inspection and gauging equipment are aimed at matching the high production rates of modern machine tools and meeting the requirements of finer measuring resolution and higher accuracy. A large degree of automation is also being built into these systems for compatibility with automated manufacturing systems.

Major trends in gauging and inspection equipment point towards an increase in speed and accuracy of measurements. Systems using opto-electronics and electrical contact to replace electromechanical probes have been specially developed and there is a clear trend towards remote sensing of size using laser and similar devices.

A complete shift to digital display of information in most measuring equipment, including such devices as hand-held micrometers, is now evident.

Different devices are being integrated with <u>measuring centres</u>, especially in post-process inspection equipment. Application of minicomputers and output devices such as plotters, printers and CRT displays are developed for inspection equipment to achieve rapid and accurate processing and presentation of metrological information.

An increase of two orders-of-magnitude in accuracy has been obtained in the resolution of measurement. With the advent of the job shop laser, it is now possible to measure distances down to 0.01μm whereas five years ago, there was a practical limit of resolution of 1μm using gauge blocks.

Progress in measuring techniques has been so rapid that the resolution and accuracy of gauging have reached limits governed by the inherent instability of the machine/workpiece system. The stress on machine design to achieve higher final part accuracies is now greater. The drive towards even higher part accuracies continues, justified on the grounds of lower rejections, requirements of automatic assembly, longer final product life, legislation to reduce noise levels, needs of related technology like fabrication of integrated circuits.

The development of compact, rugged and reliable electronic probes has made possible in-process gauging on transfer lines and other automatic manufacturing systems. Systems are now being developed to use this capability in the adaptive mode to correct job or tool setting to achieve the required size. Automatic gauging systems are also applied on equipment used for automated assembly. There is no doubt that the future will see more such applications in industries like electronics, instrumentation, electric motors, precision mechanics, cameras and bearings. Modular automatic inspection systems have already been developed to fit automated production lines ranging from automobile to bearing manufacture. These modules can be combined to suit gauging requirements on a wide variety of parts and incorporate devices to load, transfer, index and unload parts and segregate them into acceptable and rejected lots.

Assembly. Assembly with its high labour content is an area holding potential for profitable automation. Mass production industries in the West have made considerable progress in this direction.

So far, automated assembly has been applied only to subassemblies. Even in the automobile industry, considered highly automated in the United States, automated assembly has been applied only to subassemblies like the rear-differential axle and brake-drum. There is, however, a continuing search for methods to extend automatic assembly to whole products. Modern systems integrate assembly, inspection and testing into one automatic process. Automobile engine assembly is one area which has seen the application of such concepts with the process being controlled and monitored by computer.

Future design of automatic assembly equipment will incorporate gauging also. This will have an impact especially on the electronic industries. Mechanical assembly is now trying to use such systems in situations where parts may get jammed together or deformed during assembly without the knowledge of the operator.

Controls for assembly machines have also seen much development. Programmable controllers are commanding many assembly machines surpassing even computers and hardwired controls in a number of applications.

Fasteners have seen much progress in recent years. New bolts, screws, nuts and rivets make assemblies easier, faster, cheaper and adaptable to automation. The newest concept is a system which sets bolts under a kind of adaptive control that shuts down the fastener driving tool when a preset torque - rotational angle combination - is reached.

Industrial adhesives are taking over many areas now served by mechanical fasteners. Developments are

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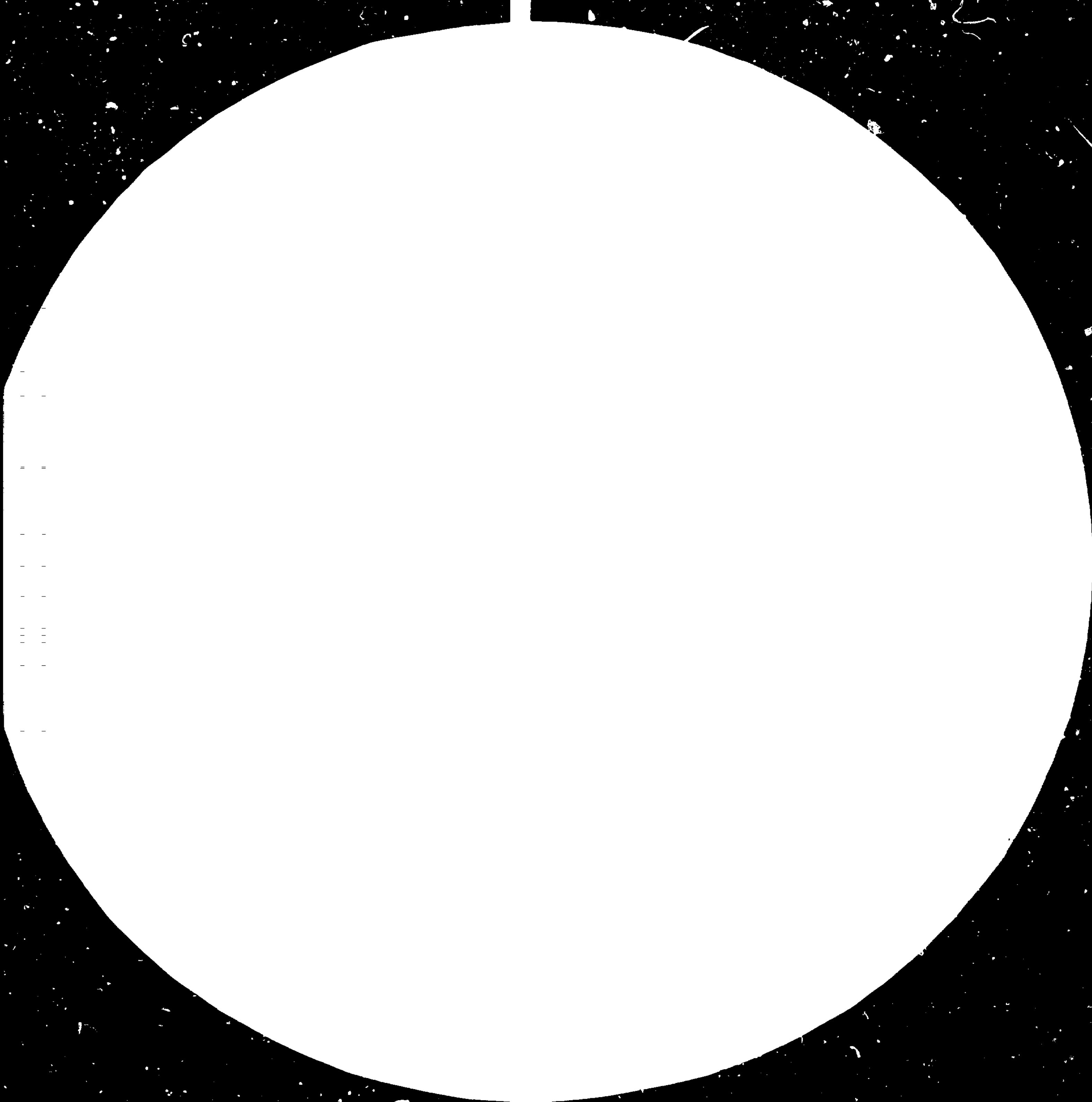

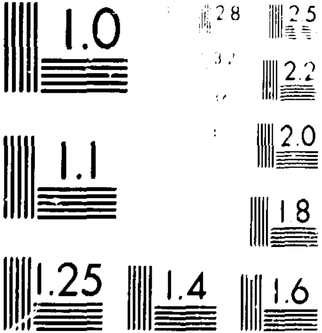

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in progress to quote the adhesives automatically and hold the assembly in a fixture for a regulated time before releasing it. Techniques of adhesive bonding, originally developed for aerospace applications, will cause a revolution in mechanical assembly if applied properly.

Materials handling. Materials handling systems are being integrated increasingly with operations in the plant. These systems employ driverless trucks, conveyers, monorails, sorters and stock pilers in materials handling.

Storage systems are employing taller stacks because of the increased cost of floor space. To combat stock pilferage, increased use of driverless order pickers operating within a locked room are under development.

Computers are obvious tools for application in materials handling systems. It is reported that over 100 materials handling systems in the United States are operating under computer control. Foundries will be a major target for automated computer-controlled materials handling systems in the years ahead.

VII. AUTOMATION AND FUTURE TRENDS IN THE MACHINE TOOL INDUSTRY

Robots

Robots have been on the industrial scene since the early 1960s, but the first models were big affairs designed mainly for difficult and hazardous jobs. Tedious, laborious, repetitive and hazardous jobs in manufacturing industry were the areas where the robots were applied hitherto.

Thanks to today's micro-electronic technology, robots have computers that enable them to learn a succession of tasks and versatility that promises to render obsolete a good deal of what is currently thought of as automation. Robots in fact are the latest in automation, of programmable or flexible variety. As distinct from the automatic mechanism, a robot generally has a multiple degree of rotary and linear freedom which can be actuated individually and simultaneously to approximate closely the physical motions of a human being performing the same tasks. Robots have been developed which simulate closely the variety of movements possible with the human upper torso, shoulder, arm, elbow, wrist and hand.

Whereas the earliest robots were controlled by programmes set with limit switches, modern robots are programmed by a minicomputer to which they are temporarily attached. Robots have been developed which can be automatically programmed or "taught" a sequence of movements by a human operator who guides the robot through the sequence.

Compared with previously-built robots, the new robots are nimble jacks-of-all trades. A typical model can be fitted with a variety of hands, a mechanical gripper and activated to pick up parts and pass them along a spray head that converts the robot into a painter, or an arc that turns the robot into a welder. Such robots load and unload parts from furnaces, stamping presses and conveyors, and a few of them perform their jobs while driving conveyors. They also quench red hot parts, lubricate dies in stamping machines, drill holes, insert screws and grind parts. Robots are involved in the inspection of finished products. At Texas Instruments, for example, dozens of computer-controlled small robot arms with TV camera eyes, spot pocket calculators moving down a conveyor belt, pick them up and place them in an automatic electronic inspection station. Perhaps most remarkable of all, robots are starting to assemble components in factories. Over the next 12 months, General Motors will install 10 Programmable Universal Machines for Assembly (PUMAs), which among other things will partly assemble armatures for electric motors, screw small electric bulbs into instrument panels and help put the windshield washers together. PUMA is in the vanguard of an array of small and relatively inexpensive robots that are taking over more and more jobs that were previously performed by human beings.

Robots are presently applied in diverse tasks which include loading and unloading machine tools and presses, removing parts from die casting machines, materials handling and transfer, especially in foundry and forge, painting and even simple assembly operations. The automobile industry in the the United States uses robots extensively in the welding line.

Developments are taking place with the use of the addition of a device to give 'sight' and to give touch to robots. By imparting "intelligence" to robots, they can be made to take tactical decisions in carrying out the assigned tasks by using visual and tactile feedback.

It is important to note that prototype robots with rudimentary sensory feedback are already functioning in some countries. However, a general application of such advanced robots in industry will depend on the cost of such units and the ease with which they can be programmed.

The application of TV and holographic techniques is having a major impact on the development of robots capable of seeing and recognising three-dimensional objects, especially when the objects are presented to the robot in a random orientation. This device can retrieve a freely hanging carbon brush (randomly oriented) and place it in an assembly machine for insertion in a fractional horsepower motor. Robots equipped with sight and touch sensors will certainly find wider application in the automated assembly systems of the future.

Advanced projects have been conceived not only for adapting the commercially available robots for various production processes, but also for developing them further for the present as well as for future requirements of computer-aided manufacturing systems. Some of these projects are meant to ascertain the software and the hardware requirements of individual robot stations for future application in an integrated production cell and later in an integtated sheet metal working centre consisting of several cells.

Two key developments have brought industrial robots to life. One was technological: the development in the mid-1960s of the microprocessor, a computer so small that it can be fitted into a silicon chip, no bigger than a pea. As the computer shrank in size and cost, it suddenly became practical as the brains to run a robot. The second development was wage inflation. Two decades ago in the United States, a typical assembly line robot cost about $ 25,000; that plus all operating costs over its eight-year lifetime amounted to roughly $ 4.50 an hour, slightly more than the average worker's wages and fringe benefits then prevailing.

Today, that typical robot costs $40,000 (they range from $7,500 to $150,000) and it can still be paid for and operated at about $5 an hour. However, a worker in the United States often costs today $15 to $20 an hour. The robot revolution is just beginning but it is already moving fast.

The Japanese are resolutely pressing forward in the field of robotics. In January 1981, Fujitsu Fanuc planned to open a new $38 million plant in which robots will work 24 hours a day to produce more robots (100 a month). It may be that Japan will end up being the one who makes the modules and parts that go into everyone else's robots.

Today roughly 10,000 robots are in operation in Japan as against 3,000 in the United States, 850 in the Federal Republic of Germany, about 600 in Sweden and 500 in Italy. Although for various reasons Japan leads in employing robots in its manufacturing industry all, including Japan, the United States and many European nations, are equally determined to exploit robotic technology. For instance, automobile manufacturers in the United States are the biggest users of robots in the industry. General Motors (GM) is in the lead with 270 robots installed followed by the Ford Motor Co. with 236, the Chrysler Corporation with 100 and the American Motors Corporation with 10. The robots are used for welding chiefly, but they are also used for painting.

Programmable Universal Machines for Assembly (PUMA)

PUMA will take over a number of jobs at GM including fairly complex ones that involve putting things together. At a Delco Products plant in Rochester, New York, PUMA will be instructed to reach out, pluck a tiny electric armature out of a furnace in which the temperature is running at 230° C, attach a commutator-ring to the armature, put on some resinous material, and replace the armature in the furnace for curing.

The computer programme is the key to turning robots into assemblers. More advanced robots, such as PUMA can be told what to do by typing the instructions on a computer keyboard in a "language" that includes about 100 English words such as "here" and "move". Eventually, robot enthusiasts say that the evolution of robot language will make it possible to give robots spoken or typed commands such as "assemble the carburettor".

This is no pipe-dream. At SRI International, U.S.A., to cite one instance, robots have already been taught to obey one-sentence spoken commands, relating to portions of an assembly job.

Industrial robotics is a technology in which the United States is at the forefront of innovation. Robots have been more extensively used in Japan possibly because the need has been more urgent in a labour-short country like Japan. But the newest and most sophisticated robots in the United States can perform more chores than their overseas counterparts. The United States now leads the world in the pursuit of further advances. Even so, when the various strengths and weaknesses of all countries, including the United States, Japan and the European nations are balanced out, basically they are all about even in robotic technology. What matters, however, is what happens from hereon.

Unmanned machine work - unmanned factories

Having effectively eliminated the need for skilled operators for most machining operations in the 1960s and 1970s, machine tool builders in the

Japan, the United States and other industrialized countries are now turning their hands towards eliminating the need for operators altogether in 1980s. The goal appears to be reliable unmanned machining systems for the 1980s and early 1990s that can substantially boost machine tool throughput, assure strict adherence to hard-to-meet quality control standards, minimize in-process inventories and guarantee production rates by eliminating the last major machining variable. This is not the unmanned factory, not yet anyway. In the industrialised countries, hard as it is to train and keep skilled workers, current economics still do not justify the high cost of developing and building an unmanned manufacturing facility. This is specially true when one considers the fact that the computer network required to operate such system barely exists on paper right now. But it is the next step down the road to the unmanned factory of the future, and the concept is beginning to gain acceptance in many areas of manufacturing.

The difficulty of finding qualified workers in the highly industrialised countries is not the only factor leading manufacturers to look at unmanned machining systems. New government regulations regarding quality control, the rising demand for higher product efficiency - and the closer tolerances and improved repeatability that higher efficiencies entail - and the continuing need to slash product costs to maintain competitiveness in an increasingly competitive world market are all factors that manufacturers are taking into account as they develop capital spending strategies for 1980s. As the costs of capital rise, its fuller utilisation has become most important. Skilled workers all over the world, particularly in the highly industrialised countries, besides having become prohibitively costly to employ, are not willing to work right shifts nor willing to accept continuous overtime. Hence in order to utilize the plant and ensure continuous operations to recover the high costs of machining at today's price levels and write off the investments before the plant becomes obsolete, unmanned night shift operation of machine shops has become an accepted feature in the highly industrialized countries.

It is not surprising that Swedish companies are among the first to put the unmanned machining centres into production. High labour costs and the trade unions' willingness to accept automation are key factors. The unmanned machining centres (UMCs) delivered by Kearney & Trecker, United States, to ASEA, the electrical equipment manufacturers, and to Bofors, the armament makers, are in operation in Sweden. In this system, Milwaukee-Matic machining centres are automatically fed, palletised, passed via carousel magazine. The UMC system is aimed at increasing the number of machines that a worker can handle, reducing inventory, and speeding production throughout.

Any country that develops the capacity to run its factories around the clock (in all three shifts), seven days per week, with only a few human workers will have a tremendous economic advantage.

Unmanned manufacturing and assembly operations in industry have been viewed with some dismay by social scientists all over the world, particularly by the developing countries, who have been one of the important sources, providing migrant labour to the industries in the developed countries. However there are two views: one is that large numbers of economically active workers , both domestic and foreign (coming from poor developing countries) would lose their jobs through a greater degree of automation in industry. But the other viewpoint which is equally strong is that automation, like the use of industrial robots to do dirty work, has diminished alarms of loss of jobs and, in a way, kept the labour unions mostly at bay. Welding cars and spraying paint are stupefying jobs, and besides they are ideally done at temperatures higher than a worker can stand. For instance, in one of the Westinghouse factories in the United States, as many as 25,000 workers may lose their jobs due to attrition and there is no way to replace them all. People joining the labour force in industrialized countries do not want the dirty jobs. The main task is to train people for the skilled jobs that are in demand in today's labour market. "New jobs have always come from new technologies".[2] One reason why Japan has been able to shift so extensively to robots is that the Japanese corporations have a tradition of caring for their employees' health and safety and they do not want them to work on dirty jobs or in hazardous occupations.

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[2] "The Robot Revolution", Time magazine, 8 December 1980.

But as robots take over more and more jobs - and they can do more pleasant and interesting jobs as well as the dull and dirty ones - the labour unions' acquiescence may change. After all, the rate of unemployment is already increasing due to high inflation in all the Western industrialised countries and retraining of all the workers, including those retrenched by the high degree of automation, may not be possible. Furthermore, retraining will not be possible because there could be no jobs for which workers could be retrained.

Today factory workers and their unions in industrialized countries are not worried so much about automation. For one thing, automation frankly has not reached that stage yet. But as more and more industrial jobs are taken over from human beings by automation, there may be some problems from the organised labour, social scientists and governments of the countries involved. Already there are a few rumblings. It is certainly clear that the future will bring a need for different skills and possibly greater competition for jobs.

Automation, leading to unmanned factories, is technologically feasible in industry, yet its effect on people could cause insoluble social problems. The concept of unmanned factories may, therefore, progress haltingly though the scope for unmanned operations under certain special circumstances will increase in the developed countries.

Perspectives - future vistas. Developments in machine tool designs have been taking place at a rapid pace in the last 10 - 15 years. These developments have been in response to the increased demands made of manufacturing technology through the influence of factors such as the scarcity and shortage of skilled labour, the need for flexible manufacturing lines, the production of a larger variety of goods in smaller lots, higher part accuracies and a wider range of stock materials to be worked. The most important single aim throughout has been to design machine tools to achieve higher productivity.

Developments in machine tools will continue to be influenced with added emphasis on meeting specific governmental and social regulations affecting the working environment.

The accent on increased productivity will continue. As machines become more sophisticated and costs climb, productivity increases will be measured in real terms and machine tool builders will be frequently called upon to demonstrate them and other economic gains to the user.

Design of machines and controls will place emphasis on high reliability in operation. Down time on versatile highly productive machines becomes very expensive. For a small shop it can spell financial disaster. Builders should study the users' difficulties and the machine down time data so that the design can be changed to [illegible] reliability.

Factors that reduce the usefulness of machines involve not only machine down time due to failure but time lost in set-up, operator absence, unavailability of material stock, tooling problems etc. Better monitoring and sensing techniques will allow users to measure utilisation precisely. Quick, easy and reliable servicing will become a major factor in evaluating future designs. Advances in electronics and electrical systems will have a major influence on the configuration and design concepts of future machine tools.

The machine tools of the future will have higher accuracies to meet the requirements of increased precision on components. Regulations on noise levels will be enforced on future metalworking equipment. This factor is likely to force designers to evolve new alternatives to present methods and will have a major influence on machine tool designs. The safety of operators will contribute to machine design concepts in no small measure. Since regulations will be enforced on existing as well as new machines, employers are likely to incur considerable costs in equipping the already installed machines with mandatory safety equipment. Ecology is another consideration. Pollution is another factor which also has to be reckoned with in future technological developments in metalworking machine tools.

The machine tools of the future will be required to work a wider range of materials including harder and stronger ones. Optimisation of cutting conditions will therefore be very important in the years ahead. The need to catch up with automation is likely to revolutionise all aspects of machine tool technology.

Machine tool versatility will replace some traditional metalworking skills and reduce labour demands, but will also increase the need for new skills. The traditional machine skills and knowledge will be replaced by skills in programming, development of software, and electrical and electronic maintenance systems.

As machines become more productive and down time more expensive, all aspects of the operator from surveillance to job knowledge will become more important. Machine operations requiring minimal input will reduce the demand for skilled labour, helped by such developments as adaptive control, surface sensing and automatic cycle adjustments and performance monitoring.

Keeping highly productive machines running will require top maintenance skills and alert machine builders will enhance these skills by providing machines with built-in diagnostic and documentation capabilities.

In general, the technological outlook is one of continued improvement in machine tool productivity and versatility and of reduced requirements of operator skills. There is, however, one area in which little work is being done but in which developments are necessary if these other goals are to be achieved. That area is the control of metalcutting chips. Many of the situations requiring operator action in metalcutting operations relate to chips in unwanted or unpredicted places causing tool breakage, misalignment, malfunction of chip handling equipment etc.

What is ahead in the field of production technology and machine tool development? This can be estimated perhaps with the help of a few technological forecasts. Very recently, the Society of Manufacturing Engineers, U.S.A., made three forecasts on the future of production technology based on the Delphi technique. These forecasts concern machining, production systems and assembly. These predictions provide a useful answer to the question. Out of the 133 queries in the preliminary round 99 or 74 per cent related directly to the subject of computer-aided manufacture. Selected forecasts given below provide an excellent insight into the direction and time span of future developments in this most important technology of metalworking.

Around 1985. Assembling jobs will be integrated with the other production routines making use of computer-aided manufacturing systems. At least 25 per cent of the firms representing a cross-section of the industry in the advanced countries will apply software systems for the automation and optimisation of various stages of production planning, e.g., machining sequence, selection of suitable machine tools, clamping devices, sequence of operations, tool selection and optimal cutting conditions.

Around 1987. About 15 per cent of the total machine tool production will not consist of single purpose machines but will constitute component blocks of flexible production systems where the manipulation of workpieces between individual work stations will be done automatically and controlled by a central computer.

Around 1990. The advanced development of sensors will facilitate robots to attain human capabilities in the final assembly sequences. Computer-aided design (CAD) techniques will be employed for the design of 50 per cent of the newly-designed production aids.

Around 1995. Almost 50 per cent of the direct work in the final assembly of automobiles will be achieved by programmable automation and robots.

Around 2000. Based on these forecasts, it is presumed that even before the end of this century, many changes in machine tools and production technology will take place around a computer, viz., computer-aided design and fully integrated computer-aided manufacture and automatic assembly using modern robots extensively.