Author - Industry Canada - Metals and Minerals Processing
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1998 POWDER METALLURGY WORLD CONGRESS & EXHIBITION,

GRANADA, SPAIN

As with most metal-related conferences, virtually all countries with a manufacturing sector were represented, however the concentration of country of origin of delegates was striking: while of course Spain, as host country was well represented, the bulk of delegates were from the UK, Germany, US, Japan, France, Sweden, and Switzerland.

There were over 800 seminars plus a small trade show. The following is an overview of information gleaned from these seminars, from show displays and literature and from discussions with attendees. (Some market share and size figures varied considerably according to source.) The reader is advised to consult an excellent overview of the PM process prepared for the European Powder Metallurgy Association at **http://www.epma.com/process/welcome.html**

This is a rapidly growing industry. Worldwide consumption is said by one source to exceed one million tons per year, most of which is consumed by the automobile industry:

	Europe	North America
Automotive	69%	70%
General Mechanical	13	8
Electric equipment/appliances	17	15
Other	1	7

The average North American car now incorporates over 30 pounds of PM parts, which represents double digit growth over the past few years. Use intensity is expected to grow to 50 pounds by 2000. European vehicles are said to use half as much, however this is expected to double by 2000.

There are two significant levels of value-added in this industry: manufacture of the final part and manufacture of the powder. Following are some comparisons of base metal prices and powder prices provided in *Metal Powder Report* for August 13, 1998:

US $/lb

Metal	LME	EPMA
Aluminum	.64	2.46
Copper	.79	1.56
Lead	.26	1.14-1.33

Lead	.26	1.14-1.33
Tin	2.82	3.34-3.59
Zinc	.50	1.48-3.20

PM Applications

PM applications are wide, in some cases apparently unrelated, and growing rapidly. The EPMA "Global Showcase" booth had some 226 diverse products made from PM including various automobile engine, transmission, & shock absorber parts; power tool & household appliance parts; hard materials & high speed steels; electrical & electric motor materials; aerospace parts; MIM parts; magnets; filter & friction materials; and various parts used in new technologies.

For the sake of convenience, PM products can notionally be divided into two groups: those processes and applications for which PM is the only or best means to achieve a particular outcome, and those in which it offers cost savings over conventional processes, *if* PM parts can be consistently produced with properties equivalent to those of forgings, castings, stamping, etc.

PM Preferred

PM may be the preferred technology because of its process advantages or end product properties:

- PM can be used to produce **refractory metals**, which are otherwise hard to produce because of their high melting points. These metals are also more ductile when produced by PM.
- PM is also used to produce **composite materials,** either combinations of insoluble metals or metal and non-metallic combinations. There are several subcategories of note under this heading:

  Hardmetals or cemented carbides, of which tungsten carbide is the most popular, are used for cutting tools and hard duty dies.
  Diamond cutting tools.
  Wrought products enjoy superior strength due to the distribution of oxides within the metal matrix.
  Friction products, such as brake pads, have non-metallic materials within the metal to increase friction.

- There are two important product categories in which controlled porosity, rather than maximum density are the goal. These are metal
  - *filters* and *self-lubricating bearings*.
  - *High speed steels* and *nickel-based superalloys* produced using PM have improved microstructures and therefore better properties.
  - *Rapid prototyping* and *direct manufacturing* are achieved by subjecting successive layers of metal powder to selective laser sintering.
  - *Magnets*

Cost Savings

Much of the growth potential for PM falls under this heading, particularly with regard to the auto industry. This is contingent upon PM parts equalling the performance of the incumbent cast or forged parts. PM is said to offer major cost savings due to higher yield, and therefore reduced remelt cost, and near-net shaping which eliminates subsequent expensive machining costs.

SEMINARS

SEMINARS

Novel Stainless Steels for Metal Injection Moulding

- stainless steel accounts for more than 50% of MIM sales
- 17-4PH accounts for more than 90% of these in the US
- 316L austenitic comprises more than 80% in Europe
- desired properties for products in contact with body: antiallergenic (no nickel), nonmagnetic and higher hardness -material used for MIM called Catamold (R) Panacea - a Cr-Mo-Mn steel was developed as a substitute for Cr-Ni steels
- most of the MIM market has been converted from investment casting

Hollow PM Parts Made with Gas Assisted Technology

- this is a technology adapted from thermoplastic injection moulding
- feedstock is injected normally and then pushed forward with a medium pressure injection of nitrogen
- there is no holding pressure
- there are a number of shape restrictions:
    - avoid sharp edges
    - maintain uniform thickness
    - width should be a maximum of 3-5 times height
    - length should be a minimum of 5 times height
    - a hole is required to allow gases to escape while sintering
- there are several advantages:
    - 50-70% material savings
    - new designs are possible
    - reduced cooling time
    - uniform shrinkage
    - lower residual stress
    - reduced clamp force required
    - longer flow path
    - decreased debinding time (one quarter)

Full 3-Dimensional Finite Element Analysis of Powder Injection Moulding Filling Process including Slip Phenomena

- this is an effort to model flow into the mould of a powder/binder mixture - it takes into consideration slip phenomena, yield strength, and shear stress
- the process is temperature- and material dependent - flow and heat transfer are the principal phenomena modelled
- this project is an advance over the slip velocity model in that it takes into consideration the effect of a thin binder layer between the powder and mould wall
- a 3D analysis is necessary because of the frequency of thick sections in MIM parts

High Density Processes for PM Parts

- the increasing emphasis in the automotive industry on component miniaturisation implies increased part strength -in PM this implies higher density
- two elements for achieving this are warm compaction and die wall lubrication
- a critical determining parameter is the ratio of the pressure surfaces to the part cross section - with

a critical determining parameter is the ratio of the pressure surfaces to the part cross section - with a fixed lower punch (used only for ejection) there are three sources of pressure: lower punch, upper punch, and radial pressure

- die wall lubrication was found to be the most fruitful variable: pressure from the lower punch is approximately equal to the upper, surfaces are smooth, and green strength is higher
- warm compaction (@ 120C) , with a 1% lubricant, was not found to affect radial pressure significantly
- lubricant was found to be the major determinant of density, and external lubricant, which results in no lubricant in the compact, was best

Porosity & Properties of Warm Compacted High Strength Sintered Steels

- this study compared warm vs. cold pressing, the latter being pressed at room temperature
- warm pressing is done at 130C, sintered, repressed at 150C and then subjected to a main sintering at 1120C
- the sinter density, yield strength, impact energy, etc. were higher with warm compaction due to the high density
- pores are smaller and density higher (7.21 vs 7.36)
- fatigue strength as well is better than with a simple 2P2S processes
- lubricant, which is different than with other processes, is totally removed

Behaviour of Steel Powder Mixes Processed by Warm Compaction

- malleability of steel increases with temperature, which implies a decreased yield strength, which gives higher density and up to double strength at 120-130C
- warm compaction improves flowability, compactability, and friction at the die moulds- the latter implies better compaction and ejection (low force and good surfaces) and low die stress
- lubricant and binder, which become pores during sintering, can be reduced
- pore free density of 98% can be achieved in the green compact - higher levels will cause lamination cracks
- increased lubricant content reduces density, which explains the move to die wall lubricants
- lubricant as well affects the compressability and ejection performance (and therefore surface quality)
- the binder affects flowability, stability, dusting resistance, and stability of apparent density
- properties are important to the process:
- in green & sintered states
- for part to part consistency
- for resistance to production variations
- the optimum temperature for increasing density of the green compact is 90-120C due to "springback" at ejection
- "springback" is the expansion of the part as it is ejected from the die - it is said to be a function of temperature, pressure, & part height - an optimal density with minimum springback can be achieved at 110C
- much of the density lost due to springback can be recovered in sintering

Mechanical Alloying as a Processing Route for Nb_3 Al-Base Alloys

- Nb_3 Al has been identified as a potential structural alloy for aerospace due to its high temperature capability, relatively low density, and oxidation resistance-however it is too brittle at room temperature and has low strength at high temperatures.
- solution to these drawbacks was to reduce the grain size and make them more homogeneous

solution to these drawbacks was to reduce the grain size and make them more homogeneous

- achieved by mechanical milling an 82% niobium, 18% aluminum powder mixture for 85 hours, then hot pressing at 1150C - after 45 hours of milling you have a supersaturated niobium solution.
- resultant properties: increased yield strength at RT & elevated temperatures (starts to fall off @ 1000C), limited ductility
- increase in strength due to finer grains and oxide dispersion
- the researchers will now experiment with the addition of chromium and vanadium

Rapid Characterisation of Machinability on PM Steel Parts

- this was a very interesting seminar in that it recognised that defects often only become apparent during the last operation, machining, whereas they may have been introduced in one of the first steps, far removed both in terms of time and geography -clearly this can be true for many processes
- some of the negative characteristics that may arise and not be discovered until machining:
    - porosity - may cause cutting discontinuity and reduce conductivity
    - hardness & strength variations
    - variable carbon content - .3% perlitic preferred
- these all imply a lack of knowledge of the parameters of the part and the cutting tool
- an early test, with results within 10-20 minutes must be available for performance on a sintered part
- the speaker reviewed existing measuring techniques, such as the amount of metal cut before tool failure, measurement of required cutting force, surface quality, counting the number of holes drilled until tool failure, and cutting temperature.
- the method proposed is timing the drilling of a 2mm hole 9mm deep at a constant thrust at high speed, and low force with no lubricant

Enhancing the Machinability of Powder Forged Components

- PM parts may offer advantages over conventional forged parts- these may be process or material based
- MnS is added to steel powder to improve its machinability but it was thought it could have other effects
- an experimental drill was set up to measure feed, speed, torque, and thrust nine times per second
- MnS was found to be an effective lubricant, yielding less oxidation and larger chips
- thrust and torque are good indicators of machinability and MnS was found to improve these.

Material Development for High Fatigue Endurance Limit

This paper dealt with the development of high strength and fatigue resistant materials and processes for production of gears, connecting rods, etc.

- target properties were density 7.4 gm/cm^3 and fatigue endurance @ 300 MPa.
- undesirable properties to be eliminated included inclusions and interconnected pores
- molybdenum content was increased to .8% and blended with nickel and graphite to stabilise the austenite
- warm, high pressure compaction (900 MPa @ 130C) was applied and sintering carried out at 1120C.
- the addition of up to .8% graphite and tempering improved performance
- at high densities inclusions have a major negative effect but at lower density (7-7.1) they are insignificant

Fatigue Properties of Advanced High Density PM Alloy Steels for High Performance Powertrain

Applications

- the issue dealt with bending fatigue in transmission gears and clutch plates and fit in sprockets and connection rods
- PM steel @ 7.0 gm/cm^3 can replace conventionally forged steel in a limited range of stressed applications
- to expand the range of PM applications to connecting rods and transmission gears performance must be improved
- potential areas of improvement include alloying, high temperature sintering, and increased core or surface density
- the goal was to try to equal the properties of AISI 1020 hot rolled steel
- addition of Mn quadrupled performance and addition of Mo improved by 20%
- alloying and high temperature sintering will not deliver the desired properties
- core densities of 7.5 and selective surface densities of 7.8 were achieved
- conventional impact tests did not work since the samples bent rather than breaking - a notched test would have to be used
- the PM product was compared with steel in terms of tensile and yield strengths, elongation and hardness
- localised full densification of highly stressed surfaces was used in an attempt to limit stresses to the thin surface layer
- the outcome was that the PM product can match (90%) the performance of steel with selective densification
- as well, shot peening can be used to increase fatigue resistance of high density sintered products
- it was concluded that PM can compete with steel for high stress automotive application.

Optimisation of Thermal Debinding by Using Drying Theory

- there are a number of factors limiting MIM growth:
  - danger of damaging the green compact - cracks, blisters & deformation
  - time- and cost-intensive
  - high cost of technical development
  - there are both material- and process-specific influences
  - existing analytical and empirical models have limitations- this paper explained a semi-empiric model based upon drying models since the processes are analogous
  - binder evaporates at the surface and is carried to that surface by capillary action, however at some point capillary forces are not strong enough to carry the binder to the surface
  - this point is a function of the compact's capillarity and diffusivity
  - binders used were polyethylene wax, stearic acid and paraffin
  - the model permits determination of debinding characteristics as a function of gas flow, temperature, heating rates, holding time and shape of the compact

New PIM Joining Process for more Functional and Complicated Parts

- PIM is capable of producing near net shape, highly dense, high performance complex parts, however the use of a die limits the configurations possible
- this paper discussed the joining of two similar (iron and iron) and dissimilar (carbonyl iron and stainless steel) PIM parts using the wax exuded during debinding
- a solvent is used for partial debinding and the exuded wax bonds the two parts - final debinding is performed thermally and the part is sintered
- increasing temperature with solvent binding can cause deformation
- coating with Al O can prevent deformation up to 358C

- coating with Al_2O_3 can prevent deformation up to 358C
- in the case of iron & iron, with increased temperature and the Al_2O_3 the shear surfaces between the parts are increasingly rough, implying a stronger join
- the shear strength at 358K is the same as for a single piece
- in the case of joining iron and steel at 358K, the surface was similarly rough, however the different shrinkage rates resulted in a crack at the join in a hydrogen atmosphere - joining in a vacuum improved this - the hydrogen atmosphere caused decarburising and a change from a martensitic to ferritic microstructure
- iron and stainless steel joined well at 1573K, with shear strength the same as a single piece
- as one increases the temperature of the stainless steel, the join becomes perfect, but there is some alloying and nickel diffusion at the interface
- it was concluded that these results offer great potential for increasingly complex PIM parts

Sintering Behaviour of PIMed w-15%Cu Nanocomposite Powder

- the application envisaged by this investigation was PM mounts for ceramics in microelectronic heat sinks, motherboards and flanges
- desired characteristics included:
    - thermal expansion coefficient equal to ceramics
    - high thermal conductivity
    - full density
    - homogeneous microstructure
    - no additives
- a W 10-15%Cu alloy was used because of the following properties:
    - high thermal conductivity
    - dimensionally stable
    - high strength
    - microabsorption
    - complex shaping

- tungsten particle size is critical
- WO_2 and CaO (15%) and methyl alcohol were attrition milled for one hour, dried at 60C, and then subjected to a H_2 atmosphere at -70C
- the goal for the PIM part was full densification, isotropic shrinkage and homogeneity
- after debinding the compact showed good shape and no surface defects, and soundness after sintering
- as debinding heat approached 1250C (at 5C/min) shrinkage anisotropy for PM & PIM parts converges, although the shrinkage and shrinkage rate of PM is greater than PIM during heat up
- the PIM part is microstructurally homogeneous and displays smaller grain size

Manufacturing & Characterisation of Low Density Titanium Parts

- there is a growing demand for near net shape low density structural parts - focus has been on titanium, aluminum, stainless steels and nickel
- this paper focussed on production of low density titanium PM parts using such "space holders" as high temperature melting organic compounds, alkali salts, and such low melting temperature metals as magnesium, silicon, and lead
- the latter are favoured because of their reactivity with the substrate and residual impurities
- the resulting foam can be used for energy, sound, and heat absorption as well as physical support
- Ti and the spaceholder were mixed, pressed, and heated to 1250C

Ti and the spaceholder were mixed, pressed, and heated to 1250C

- two spaceholders were used, urea and a urea and titanium hydride mixture
- the porosity achieved was 70-80%
- an angular spaceholder yielded a more homogeneous and porous structure than a spherical one
- titanium hydride has smaller particles and is easier to compact than titanium
- a Ti and TiH_2 mixture is more stable, has fewer contaminants and sinters better
- speculation for the future includes a biocompatible Ti alloy and an ability to vary porosity with the shape of the spaceholder

Process for Making Metallic Foam using Powder Metallurgical Method

- this paper discussed a process of mixing a metal powder and foaming (gas releasing) agent to produce a foam structure - aluminum, steel, lead and zinc were used
- aluminum is heated to 616C at which a metal hydride converts to hydrogen - the yield is 80-90% porosity
- benefits include:
  - low density
  - efficient energy absorption
  - high bending stiffness
  - decreased conductivity
  - mechanical and acoustic damping
  - machinability
  - recyclable
- variables include:
  - alloy
  - density/porosity
  - morphology - shape of pores
- problems have been encountered in working with steel since the foaming agents react, however 60% porosity have been achieved
- applications:
  - heat exchangers
  - removable filter material
  - shaping through extrusion
  - crash absorption
- experiments showed that a steel profile with aluminum foam inside is 2.5 times stronger than a hollow steel profile
- the technology allows the production of 3D parts which are stronger than mere stamped parts
- metallic "sandwiches" are also possible
- possible properties include 10X stiffness and half weight
- work is now in progress on a continuous foaming process which would allow virtually endless steel/aluminum foam sandwiches with a .5 mm steel skin

Sintering& Characterisation of High Porous Metal Fibre Structures and their Use Especially as Absorption Material

- traditionally there is a broad range of applications in long life filters with more than 95% porosity -they show rigid structure and chemical and biological resistance, thermal shock resistance, hot corrosion resistance and good mechanical properties
- 35% porosity can be achieved with spherical powder, 50% with nonspherical and 95% with fibre - at the same time there is increased strength and plasticity
- fibres can be manufactured by shaving, foil rolling or bundle drawing, however these methods are

expensive, vulnerable to contamination and limited by the materials' properties

- this author introduced the process of "crucible melt extraction" in which an extraction wheel picks up molten metal from an induction heated crucible and flings it out so that it solidifies into fibres of 50-700m
- some of the characteristics of conventional fibre sintering are:
  - low contact between fibres
  - low consolidation and therefore weak bonding
  - little actual sintering
  - contamination and oxidation
  - short sintering time and low temperature
- the author, working with Al, Cu, NiAl and stainless steel, produced structures with fibres 12-25 mm X 80-200 m and 70-96% porosity - the sinter temperature is varied with fibre diameter
- Al and Cu must be sintered in a vacuum near their melting points
- stainless steel is sintered in a vacuum or an H_2Ar at 1250C and Ni_3Al in a vacuum
- the product displayed a uniform hardness (except Ni_3Al) and element distribution
- finer fibres yield better sound absorption
- sintering temperature can be reduced by coating the fibres

Needs of the Global Automotive Manufacturer

- there are a number of changes in powertrain technology in response to government and consumer demand which imply changes in materials requirements
  - smaller engines
  - higher power density
  - decreased cost, increased quality, reliability and durability
  - changes in transmissions include wider ratios, more speeds, and increased power density (power transmission capacity of two meeting surfaces) requirements
- a number of opportunities were identified according to material:

  Aluminum
  - transmission oil pumps
  - balance shaft gear
  - connecting rods - presents a problem because of thermal fatigue >150C

    However such issues as wear resistance, consistency, thermal fatigue, elastic modulus, and cost must be solved

  Ferrous Alloys
  - subassemblies
  - manual transmission synchronisers
  - auto transmission gears and pinions
  - pistons, connecting rods, wrist pins, and bearings
  - planetary ring gears

- auto manufacturers want to switch from castings to PM because of reduced cost due to near net shaping and improved performance due to increased power density capabilities
- key requirements include tooth bend fatigue strength and surface contact fatigue resistance
- a major problem in the case of gears is that tolerances do not increase with the size of the gear
- a number of requirements were identified to improve PM's competitiveness in automotive:
  - 97% density to a depth of .8 mm

97% density to a depth of .8 mm
- designers need one common global standard
- a property data base for physical properties-PM is at a disadvantage to forging and casting
- reduce time required to produce a NNS specimen for testing
- ISO standards for designers, not PM technologists - easily understood and comparable
- improve PM technology - powder fill & flow, modelling of compaction a& sintering
- gearing requirements include increased power density and load carrying capacity and dimensional accuracy

The determinative competitive factor is "What is the auto industry willing to pay to save a pound?" e.g. Aluminum is half the weight of steel, but you don't achieve that full saving because of its inferior properties, for example because of its greater flex- the rule of thumb is that the saving is <40% -also aluminum has a shorter life because of fatigue

Development of Corrosion-Fatigue Resistant Diffusion-Bonded Pump Impellers from Stainless PM Steels

- the opportunity for PM in this case is, ironically, the small size of the market - 50-1000 per year- which is not economic for casting
- the impeller is a complex assembly to be produced by sinter joining two PM parts
- two discs are pressed at 1000C and then sinter joined at 1280C
- .2% copper and .7% phosphorus were added to control shrinkage of the two components during sinter joining and to increase density and grain coarseness
- this process resulted in a corrosion-and stress-resistant product in which property advantages were even greater than cost advantages

Development and Application of an Optimised Coating on Shock Absorber Components

- the goal was to reduce the friction coefficient and increase wear resistance in shaft guides and piston valves
- the requirements are dimensional accuracy, hardness & strength, and purity >99.3%
- traditionally the shock absorber piston had a 1 mm plastic band on it for a seal
- the PM piston has a .8m ceramic layer sprayed on instead
- this new product was concurrently engineered by the PM supplier, manufacturer and customer

Recyclability and Life Cycle Environmental Loading of PM Products

- the object was to make a life cycle assessment using ISO 14040 and 14041 standards
- this is composed of two elements, the environmental impact of the various processes and the recyclability of the alloys
- a typical Fe-C-Cu steel was analysed
- emissions of various pollutants relative to the strength of the product were analysed - sintering appears to produce most of the emissions ((SO_x, NO_x and GHG)
- recycling issues centred on the tendency of steel to trap other elements
- there are three types of recycling: alloy to alloy, extraction, and dilution
- the recyclability is determined by the degree of dilution required
- PM alloys are the worst for recyclability and FeCu is worst of these
- two means of improvement were identified:
  - restrict use of rare metals to the critical area of the part
  - control properties by altering the microstructure , rather than by adding other elements

Note: The EPMA had a large booth demonstrating the range of PM applications. One display was

Note: The EPMA had a large booth demonstrating the range of PM applications. One display was particularly relevant here. Apparently cars can have up to 80 electric motors. When a vehicle is crushed it becomes almost impossible to separate the steel laminations from the copper windings. Friable steel PM laminations have now been developed to permit easier separation of the laminations and windings.

3D Modelling of Hot Isostatic Pressing

- this was an experiment to analyse the efficacity of a thermomechanical simulation (Precad) against an actual manufactured part
- the part was HIPed, cold compacted and sintered - density and grain size were analysed
- meshing took 4 (2D)-72 (3D) hours depending on the mesh size - the only difference was the lack of shape accuracy with the large mesh.
- the 2D model showed a 9C gradient against the 3D 19C gradient
- the 2D error was greater than the 3D error (-.44 vs .001)
- the conclusion was that large mesh can safely be used for general design and fine for local detail

Performance of Joints Obtained by Fusion Bonding of PM Bronze to a Steel

- because of the brittleness of porous PM, bronze bearings must be press fit' ... el shells
- press fitting is now generally just used for high density PM
- there are several stages of diffusion bonding:
    - contact
    - formation of grain boundaries
    - grain boundary diffusion
- a 10% tin bronze powder containing 1% graphite was pressed and sintered to 25% porosity
- the two parts were diffusion welded at 5, 15, 25 and 50 MPa, 600, 700, 740, & 800C, and for 5, 30, 60, 90, 120, & 150 minutes
- welding strength was directly proportional to time, and a hydrogen atmosphere significantly accelerated the process above argon
- copper diffusion accelerated significantly above 25 MPa
- copper diffusion has a linear relationship with temperature above 650C
- there was no joining at 5 minutes or less than 650C
- porosity migrates to the interface

Joining of MMCs to Metal

- this was an experiment joining 20% carbon fibre composites
- the two materials were CuCr1 and CuZr1 based
- a cam part and gear part were diffusion bonded during sintering: the gear was warm compacted and the cam conventionally compacted - they were press fitted and sintered at 1200C with an ammonia atmosphere - then heat treated
- the difference in expansion makes diffusion bonding possible at temperatures above 1037C

Warm Flow Compaction Process for Complex Shaped PM Parts

- the issue is to get powder to move perpendicularly to the punch direction
- current practice requires complex tooling or subsequent machining to provide detail
- normal powder develops cracks in the cross flow due to different densities
- warm flow compaction enables wide undercuts, perpendicular holes and threading due to adjustment of pressure and lubricant content
- the process is said to fall somewhere between MIM and die pressing

- the process is said to fall somewhere between MIM and die pressing
- the material used was Dintaloy AE, 20% carbonyl iron and 3% binder - pressed at 600 MPa and 130C
- this yields a low density compact (<7) because of the high binder level, so must be sintered at a higher temperature
- a +-shaped part was produced without cracks, despite its width being greater than its height
- an asymmetric part and one with a threaded cross directional core were also successfully produced
- the binder seems to have been the basis of the success - it is a lubricant and affects the flowability of the powder, since they form a highly viscous mixture, more like a liquid than a powder
- the binder is at a higher level than conventional PM but lower than MIM
- there is no flow of the part during sintering
- advantages of the process include:
  - highly complex parts possible
  - variable density possible
  - high sinter density
  - no additional debinding step
  - no sinter distortion
  - can use conventional PM equipment
- disadvantages include:
  - fine powder is more expensive
  - higher shrinkage
  - lower press density

Materials Development for Lasersintering

- powders for laser sintering are generally plastic coated
- the process of direct particle sintering/melting requires smaller particles
- in conventional sintering the particles are not fundamentally changed unlike laser sintering, where all is melted
- necessary powder properties include:
- free flowing
- particle size must allow a reasonable finish
- binder must melt and "backbone" the powder to deliver required properties
- powder flow is affected by particle shape & size distribution, but the finer the powder the less it flows - the best combination is <50m and rounded
- there are various means of producing metal powder and some are suitable for laser sintering and some not:

Method	Shape	Size Distribution	Suitable?
Sponge iron	irregular	wide	no
Water atomised	irregular	wide	no
Gas atomised	spherical	medium	yes
High pressure water	irregular	medium	no
Close-coupled gas	spherical	medium	yes
Ultrafine gas	spherical	medium	yes
Carbonyl nickel	spiky	narrow	no

- there are three types of atomising: open, closed and ultrafine which produce increasingly better there are three types of atomising: open, closed and ultrafine which produce increasingly better yield and decreasing cost due to reduced recycling - however the ultrafine with a mean size of 11-13m doesn't flow well

- the ultrafine cannot therefore be used by existing laser processes however modifications are being made and there is potential for better finish

Potential of the Phase-Doppler-Anemometry for the Analysis and Control of the Spray Forming Process

- this experiment dealt with the use of two laser beams projected through or in the front of the spray cone - they take 50,000 measurements of particle size, density and velocity per quarter second
- potential applications include analysis, modelling and process control
- increased gas pressure yields smaller particles and higher velocity
- variables are gas pressure, melt temperature, substrate distance from the nozzle, and nozzle size

New Magnesium Wrought Alloys Made by Spray Forming

- magnesium's microstructure limits its deformability - a new wrought alloy with better strength and ductility is required
- variables for spray forming (using argon plus 1.5% O_2) include melt temperature, melt stream temperature, flow rate, pressure, spray distance, reduction temperature, and extrusion temperature
- Mg-Ca and Mg-Al-Ca alloys as well as conventional ones were used
- sprayed and extruded alloys gave a fine and homogeneous 100% dense microstructure due to fast solidification
- without the extrusion, density is 98% due to porosity
- at room temperature ductility and tensile strength are better than cast or diecast parts
- Ca improves ductility at higher temperatures

Use of Multiphase Jet Solidification for the Production of Prosthetic Hip Joints

- the goal was freeform fabrication of such surgical implants as hips, knees, spinal components and orthodontics by PIMing 316L steel or titanium-based composites
- a key objective was to minimise the removal of healthy bone, which implies a customised structure
- desired properties include high strength, surface hardness, biocompatibility, low modulus, corrosion resistance, and good surface finish
- conventionally machining, forging and investment casting have been used for prosthetic parts - PM and PIM are rare
- in the process in question a 2D CT scan is performed on the patient - this is converted to a 3D CT image and then to a solid model- damaged bone is notionally removed and a replacement hip designed- this file is then transferred to a rapid prototyping machine
- properties of the joint are determined by the powder and sintering so existing PIM-based data can be used
- the green part is machinable
- the result is significantly reduced recovery time and a much better knitting of the bone and prosthesis

Effect of Mechanical Alloying on Selective Laser Sintering of Hard Metal Powders

- the goal is to do SLS without binders, using commercially available laser sinterable powders (the actual physical phenomenon is liquid phase sintering)
- applications envisaged include production of mould inserts for plastic injection moulding, dies, die

casting dies and EDM
- preferred materials for these applications are tungsten carbides, borides, and iron carbides because of their wear and mechanical resistance
- SLS is a preferred process because these materials are hard to machine
- the result of the effort was disappointing, yielding only 40% density and rough surfaces - it is speculated that copper infiltration might improve this

Rapid Laser Forming of Titanium Structures

- the envisaged application is free forming 100% dense aircraft parts in sizes up to four metres by 1.4 metres to replace short run casting and forging at lower cost
- this offers the following advantages:
- low cost
- flexible - no moulds or dies
- 10% of conventional production time
- lot sizes of 1-50 pieces
- software driven
- chemistry can be changed during the build
- decreased material and machining cost (80-90%)
- one week turnaround
- 100% dense
- can use the laser to add Ti to forgings or castings, for example to repair faulty structures

Lead times (weeks)

	Forging	Casting	Laserform
material supply	52	0	2
tooling	16	4	1
part design	16	20	1
Machining & heat treating	16	6	6

- either prealloyed or mixed elemental powders can be used
- +/- 3 mm repeatability is possible with NNS of +.03" -.05"
- metal deposition is at a rate of 2-15 pounds per hour
- custom alloying is possible
- time and material savings are better than 90% - production time can be reduced from up to 18 months to 30 hours
- the laser can be angled at up to 60, so ribs, webs, flanges and rings can be produced
- high aspect lugs and extensions can be added onto castings and forgings to save die and mould costs

Accuracy of Making Rapid Prototypes in Metal

- the objective was to achieve 99.9% accuracy
- factors affecting the amount and speed of shrinkage include materials, additive, binder, temperature, time and to a lesser degree atmosphere
- binder and the addition of iron were found to affect dimensional control
- increased temperature and longer sintering normally increase shrinkage
- dimensional change of <.1% is possible

- dimensional change of <.1% is possible

Plenary Session -Europe

- hardmetal production has increased since 1988, with a tripling of volume since 1985
- major growth has been in densities over 7
- growth in ferrous PM has been over 19% since 1977
- market is divided as follows (tonnes)"
    - hardmetal 1.8
    - structural parts 12
    - magnets .9

or

- automotive 80%
- machinery parts 15%
- electrical machinery 5%

- use intensity is 7 kg/car (5.7 in 1994) vs 14 kg in North America
- the MIM market is 50 million ECU, representing 500 tonnes of feedstock
- research needs:
    - concentration in MIM in base standards
    - modelling
    - improvement of product, process and machinery design
    - better control of compact defects
    - development of nondestructive testing

Plenary Session - North America

- the market is estimated at 487,000 tons, representing a 12% increase

Iron

- enjoyed average growth of 10.84% over past six years
- powder makers will have expanded capacity to 658,000 tons by the end of 1998

Aluminum

- market is 2,000 tons - will increase to 10,000 within five years
- market increased 30% in 1997 and 11% estimated this year

Stainless steel

- the market increased 33% in 1997 and will grow 10% in 1998
- principal use is in exhaust systems and ABS sensor rings

General

- the copper market is 20,429 tons, up 7%
- the world market for iron & steel was estimated at 700,000 tons with copper at 48,000

Automotive

- use intensity is 32.5 lb./vehicle, an increase of 5% over 1997 -should increase to 50 lb. by 2000
- the major area of growth is substitution for ductile iron
- GM has 184 parts that could be converted to PM
- larger Ford vehicles, such as the Explorer and Crown Victoria will be the first to reach 50 pounds - conversion of the pinion and pinion carrier frame within 18-24 months will increase PM use by 14 lb/transmission
- Chrysler will be using PM for a truck engine by 2001
- for PM to be attractive to automakers suppliers must expand to provide systems, by developing joining technology so they can produce components
- this implies consolidation of the industry, which is already evident in GKN's acquisitions

Conclusion This subsector produces major value added at both the powder production and the manufacturing stages. The former is likely more substantial in Canada at the moment and is also a major source of exports. It is clear that research is exploding on many fronts including process and process control, materials and material characterisation, and applications.

It would appear as well that there are two major potential areas of growth, automotive, and laser sintering (rapid prototyping & direct manufacturing of short run products).

Auto manufacturers seem to be very supportive of the subsector's developing products with performance characteristics (toughness and power density) adequate for automobile use. PM's near net shape capabilities make it very attractive in terms of eliminating costly subsequent processes such as machining. If the speakers' predictions are at all accurate, we can expect phenomenal growth in the near future (if 70% of PM products are automotive and use intensity is expected to double in Europe and increase 50% in North America by the year 2000). Reference to the current consolidation of the industry, particularly acquisitions by GKN, plus the emphasis on PM joining technologies, suggests that the automakers' requirement for component rather than part suppliers is recognised.

There are said to be over 30 rapid prototyping processes and most of these are PM based. To the extent that the manufacturing sector adopts rapid prototyping as a process necessary to be competitive, both in terms of reduced time to market and reduced costs, then one can expect substantial PM growth.

Direct manufacturing of short run products, whether one custom-made hip joint or 1000 pump impellors appears to be another area of strong potential, again in terms of time to market and substantially reduced cost. Existing technologies like casting or forging may be uneconomic in these quantities and fabricating too labour-intensive.

Finally, technical development in traditional PM and in MIM continues at high speed improving process and product and broadening the range of PM applications.

Like their competitors using other processes, manufacturers using various PM processes clearly recognise and are addressing the need for reduced time to market, improved physical properties and consistency, the need for improved material and process parameter data, the need for improved consistency and process control, etc.

Raymond Horton

Tel: (416) 954-1430 Fax: (416) 973-5131