A Manufacturing Process for Precision Engineering Components

METAL INJECTION MOULDING


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Powder Metallurgy

Metal injection moulding (MIM) is a development of the traditional powder metallurgy (PM) process and is rightly regarded as a branch of that technology. The standard PM process is to compact a lubricated powder mix in a rigid die by uniaxial pressure, eject the compact from the die, and sinter it.

Quite complicated shapes can be and are regularly being produced by the million, but there is one significant limitation as regards shape. After compaction in the die the part must be ejected, i.e. pushed out of the die cavity. It will be obvious, therefore, that parts with undercuts or projections at right angles to the pressing direction cannot be made directly. That limitation is substantially removed by the metal injection moulding process.

Metal Injection Moulding

The use of injection moulding for the production of quite intricate parts in a number of plastic materials has been known for many years, and most of us come into contact with them in some form or other every day. One important feature of such parts is that they are relatively cheap. However, for many engineering applications these thermo-plastic materials have quite inadequate mechanical properties. They are relatively soft, have limited strength and do not resist elevated temperatures.

Some improvement is made possible by the use of solid fillers - ceramic or metal powders - but the real breakthrough occurred when it was found possible to incorporate a very high volume fraction of metal powder in a mix so that, instead of a filled plastic part, a plastic-bonded metal or ceramic part is produced. Careful removal of the plastic binder leaves a skeleton of metal or ceramic which, although fragile, can be handled safely and sintered in much the same way as traditional die compacted parts. After sintering densities of 95% or more are reached and the mechanical properties are, for that reason, generally superior or equivalent to those of traditional PM parts.

The basic steps of the metal injection moulding (MIM) process are shown schematically in Fig. 1.1. Some examples of parts produced by this process are shown in Fig. 1.2.
The rheological properties of the feedstock, that is the powder/binder mix, are of major importance. The viscosity at the moulding temperature must be such that the mix flows smoothly into the die without any segregation, and the viscosity should be as constant as possible over a range of temperature. However, the mix must become rigid on cooling. These requirements dictate the properties of the binders used, and to some extent, the granulometry of the powder. Let us look first at the powders.

2.1 Metal Powders

Almost any metal that can be produced in a suitable powder form can be processed by MIM. Aluminium and magnesium are exceptions because the adherent oxide film that is always present on the surface of powder particles inhibits sintering. The list of metals that have been used in metal injection moulding includes many common and several less common metals and their alloys - plain and low alloy steels, stainless steels, high speed steels, copper base alloys, nickel and cobalt base superalloys, titanium, intermetallics, magnetic alloys, refractory metals and hardmetals (cemented carbides).

The most promising candidates from the economic point of view are the more expensive materials. This is accounted for by the fact that, unlike alternative processes that involve machining, there is practically no scrap which helps to offset the high cost of producing the powder in the required form. Scrap is of lesser significance in the case of inexpensive metals.

The term 'suitable powder form' deserves clarification, and it can be seen that the issue is not clear cut - there are conflicting requirements. Particle shape is important for a number of reasons. It is desirable to incorporate as high a proportion of metal as possible, which means that powders having a high packing density are indicated. Spherical or near spherical shape should, therefore, be preferred, but the risk of the skeleton going out of shape during the debinding process is increased (there is no metallurgical bonding between the particles as happens in a die pressed compact).

Average particle size and particle size distribution are also important. As is well known, fine powders sinter more readily than coarser powders. Therefore, they are the best choice for MIM, but there are a number of limiting factors. The following table compares the different powder production techniques and their relative cost for MIM powders.
Ideal powder is said to be as follows:

- tailored particle size distribution, for high packing density and low cost (mixture of lower cost large particles and higher cost small particles)
- no agglomeration
- predominantly spherical (or equiaxed) particle shape
- sufficient interparticle friction to avoid distortion after binder removal
- small mean particle size for rapid sintering, below 20 micrometer
- dense particles free of internal voids
- minimized explosion and toxic hazards
- clean particle surface for predictable interaction with the binder.

In reality, of course, the choice is restricted to what is available, but growing demand has stimulated a major effort by powder manufacturers to produce powders that meet the special requirements of MIM.

### Table: Comparison of Small Particle Production Techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>Size [µm]</th>
<th>Shape</th>
<th>Materials</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas atomisation</td>
<td>5 to 40</td>
<td>spherical</td>
<td>metals, alloys</td>
<td>high</td>
</tr>
<tr>
<td>Water atomisation</td>
<td>6 to 40</td>
<td>rounded, ligamental</td>
<td>metals, alloys</td>
<td>moderate</td>
</tr>
<tr>
<td>Carbonyl</td>
<td>0.2 to 10</td>
<td>rounded to spiky</td>
<td>metals</td>
<td>moderate</td>
</tr>
</tbody>
</table>

(From 'Injection Moulding of Metals and Ceramics' by RM German & A Bose, published by MPIF, Princeton, USA, 1997. Reprinted with permission)

### 2.2 Characterisation of MIM Powders

The test methods commonly applied in powder metallurgy to characterize powders such as sieve analysis, flow rate or compressibility are not applicable to MIM powders as their particle size is at least an order of magnitude smaller than of powders used in die compaction. Applicable test methods are the determination of the envelope-specific area (ISO 10070) and gravitational sedimentation (ISO 10076). These tests give an indication of the particle size and shape.

The test method recommended for characterizing the particle size distribution of MIM powders is laser diffractometry/scattering (Fig. 2.2). The technique has a large dynamic range (between 1 and 1000µm) that covers well the size range of interest in MIM technology. A typical plot of the volumetric particle size distribution of a gas atomized 316L powder for the manufacture of MIM parts exhibiting the accumulative and differential curve is shown in Fig. 2.3. The mean particle size D(50) and the 10% and 90% values D(10) and D(90) are given as the intersections of the accumulative curve with the respective percentages.
Scope of measurement and special considerations

1. The reporting of particle size data by means of laser diffractometry is based on a large and statistically relevant number of particles.
2. The method applies in particular to the measurement on spherical powders.
3. It is understood that the measurement in particular is applied to the quality control of metal powders.
4. Errors are in particular related to sampling procedures arising from the difficulty in sampling a specific powder sample from a powder lot.
5. Sampling should follow documented procedures for proper division of powder samples into increasingly smaller portions, as defined in ISO 3954.
6. Measurements can be done with any kind of laser diffractometer. Procedures and reporting should follow the standard ISO 13320.
7. The measured particle size distribution should be presented as volumetric or weight size distribution.
8. The mean and median sizes on volumetric/weight basis, D(50), and the D(10) and D(90) sizes should be specifically reported. If appropriate, the standard deviation should be included.
9. The following notes should be included in the test report:
   - type of distribution (Gaussian, skewed),
   - particle shape (spherical, irregular),
   - specific surface area or shape assessment parameter,
   - specification of technique applied (wet or dry),
   - measuring parameters (dispersant, flow rate, volume-percentage of powder, temperature, focal distance, analysis time, optical model, equipment manufacturer, any specific observation/comments),
   - reference sample (type and result).
10. An assessment of the particle shape by scanning electron microscopy and/or specific surface area measurement according to ISO 10070 should be included for non-spherical powders.
11. The reported data should be based on repeated measurements. The number of measurements should be enough to secure an accuracy of better than 10% related to the D(50) value.
12. It is understood that the technique is not appropriate to yield comparative data between different laboratories.

Special precautions and pitfalls

- The state of dispersion of the powder should be especially considered. For powder possessing specific size, shape and surface properties that enhance agglomeration, notes on this should be included (agglomerated/non-agglomerated powder). Any effect of continuous evaluation of size distribution towards finer size is an indicator.
- Specific care in sampling should be taken to avoid settling effects.
- The use of surfactants when applying the wet dispersion technique is recommended.

Other test methods applicable to metal powders for MIM are powder sampling (ISO 3954), the determination of apparent and tap densities (ISO 3923, ISO 3953), oxygen content (ISO 4491) and carbon content (ISO 7625).
2.3 Binders

The binder is critical - some would say the most critical factor in the successful production of injection moulded components. To some extent the exact compositions and procedures are still proprietary secrets; however, for the most part binders are mixtures of organic compounds, the main ingredients being natural waxes or synthetic polymers. Other substances may be added to modify the properties. The table below shows the main binder systems in use today for MIM.

<table>
<thead>
<tr>
<th>Binder</th>
<th>Main Ingredients</th>
<th>Polymer Backbone</th>
<th>Additives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermoplastic</td>
<td>paraffin / microcrystalline / carnauba / beeswax / vegetable / peanut oil, acetanilide, antipyrine, naphthalene, PEG</td>
<td>PE, PP, PS, PA, PE-VA, PE-A, PP-A, PMBA-E-VA</td>
<td>stearic / oleic acid and esters thereof, phthalic acid esters</td>
</tr>
<tr>
<td>Polyacetal Binder</td>
<td>polyoxymethylene</td>
<td></td>
<td>proprietary</td>
</tr>
<tr>
<td>Gelation Binders</td>
<td>water</td>
<td>methyl cellulose, agar</td>
<td>glycerine, boric acid</td>
</tr>
</tbody>
</table>

Table: 2.2 (Courtesy of F Petzoldt, IFAM)

As has been indicated earlier, the least possible amount of binder should be used, but the appropriate volume fraction of powder depends on the powder characteristics. In industrial practice, the volume fraction of powder varies from about 0.5 to 0.7.

It is usual to convert the powder-binder mix, the so-called feedstock, into solid pellets by a granulation process. These feedstock pellets (Fig. 2.4) can be stored and fed into the moulding machine as required.

2.4 Mixing

Tumbler mixers - such as double cone mixers for example - which are widely used for the dry blending or mixing of powders - are of little use for MIM mixtures. For these it is necessary that a shearing action takes place. Several different types are available: Z blade and planetary mixers are examples. When large amount of work is needed to secure feedstock homogeneity, twin-screw extruders can be used for the final feedstock preparation. A major objective is to ensure that the whole of the surface of each particle is coated with binder. Sometimes the powder is pre-processed in order to facilitate and intensify the contact between particle surface and binder.

2.5 Characterisation of MIM Feedstock

Many MIM parts manufacturers buy their ready-to-use feedstock from specialized suppliers. A consistent feedstock quality must be maintained in order to provide a high quality of the end product, both in terms of material properties and dimensional accuracy. Test methods for feedstock characterization should be agreed between the supplier and the parts manufacturer.

The test methods proposed here have been agreed by the European MIM industry and are commonly used because they are simple and inexpensive. They should be preferred wherever appropriate. However, they do not provide a thorough knowledge of the feedstock, but rather a set of characteristic values that allow to compare different batches of feedstock of the same composition. As feedstock characterization is still a relatively young field of research, new and better test methods may be developed in the future.

Fig. 2.4: MIM part and feedstock pellets
Shrinkage

The shrinkage from the mould dimensions to the final dimensions of the MIM component can be regarded as a property of the feedstock. A draft standard has been proposed for the determination of the shrinkage. It is reprinted in this brochure. Fig. 2.5 shows a test sample for the determination of the shrinkage of which two diameters are measured perpendicular to each other.

Fig. 2.5: Sample for shrinkage measurement (Courtesy of BASF)

Feedstock Homogeneity

At least two types of homogeneity have been identified. First there is the homogeneity related to the composition of the feedstock, i.e. the powder content in each feedstock pellet. Second, there is also a homogeneity measure associated with the dispersion of powder within the feedstock pellets.

Inhomogeneities within individual feedstock pellets are of less interest as they are eliminated during the melting and injection moulding process. Variations in the powder content, however, can lead to a loss of dimensional control of the final product.

Concerning the homogeneity of the powder content, gas pycnometry or a liquid immersion technique can be applied to measure the density of granules. General requirements for pycnometers are described in ISO 3507. Standards describing liquid pycnometry are EN 725-7 for ceramic powders and ISO 2738 for PM materials, and for gas pycnometry possibly also ISO 3838 for solid and liquid fuels.

Fig. 2.6: Schematic of a gas pycnometer

The basic design of a gas pycnometer is shown in Fig. 2.6. It consists of a sample cell and an expansion cell. The sample is placed in the sample cell, the valve is closed and the sample cell is pressurized ($\Delta P_1$). Then the valve is opened and the pressures are allowed to equilibrate in both cells ($\Delta P_2$). The two pressure readings allow to determine the sample volume from the equation $V_{SAMP} = V_{CELL} + V_{EXP} / (1 - \Delta P_1 / \Delta P_2)$. The density is then calculated as the weight of the sample divided by its volume.

For gas pycnometry, an accuracy of 0.02% and 0.03%, respectively, can be expected. Five repeated measurements on the same sample are usually sufficient, whereby density variations down to 1% should be traceable.

Feedstock Rheology

The feedstock viscosity is a very important property in MIM technology, which determines how well the material can be transported and fed into the die cavity. When the flow behaviour is considered, one should bear in mind that the term viscosity can have different meanings depending on the actual conditions of testing.

Regarding the flow through a channel or orifice, which is encountered in capillary rheometer techniques, low viscosity is associated with easy flow of the feedstock. Ideally this flow would reflect the inherent properties of the feedstock. This is the case if the flow is laminar as for a homogeneous feedstock showing no wall-slip behaviour. Capillary rheometry is, therefore, an important tool if the effect of a wide range variation of the (apparent) shear rate on the (apparent) viscosity is of interest.

Of particular importance for a proper formulation of the feedstock is the so-called critical loading. This is the limit of the powder content above which the relative viscosity increases significantly. The critical loading can be determined from the viscosity measured as a function of the powder load at a fixed shear rate.

In polymer science, there are various other techniques employed to study the rheological behaviour, e.g. by controlled stress and controlled strain rheometers. However, their applicability to MIM feedstock testing remains to be validated. It should be noted that these more sophisticated methods can provide a deeper insight in the state of dispersion of the powder in the feedstock, i.e. how well the powder is dispersed in the binder.

For the communication between a feedstock supplier and a parts manufacturer the most crucial need is actually the quality assurance of MIM feedstock with specified properties. This requires a reliable, standardised measure for an easy assessment of such quality assurance. For this purpose, the Melt Flow Index (MFI) test, i.e. melt mass-flow rate (MFR) or melt volume-flow rate (MVR) testing of thermoplastics as described in ISO 1133, is available. This characteristic is derived by means of passing a certain amount of feedstock through a channel during a fixed period of time. MVR is measured in cm$^3$/10 min, MFR in g/10 min. An automatic distance-time-measurement can be monitored (procedure, type B). The test temperature and load applied depend on the polymeric material tested, i.e. the binder in the case of MIM feedstock. For MIM applications, reported MFI values should be encompassed with information on the load or weight that is used, the temperature and test procedure.
3.1 Injection Moulding

The machines normally used for this part of the MIM process are substantially the same as those in use in the plastics industry (Fig.3.1). The screw from which the mix is extruded into the die cavity is located in a heated cylinder. The temperature of the cylinder and the nozzle is carefully controlled to ensure constant processing conditions. The die temperature also is controlled - it must be low enough to ensure that the compact is rigid when it is removed.

In addition to this process called high pressure injection moulding there are also medium and low pressure injection moulding processes in use. The advantages of lower injection pressures are lower investment costs for equipment and tooling.

3.2 Binder Removal

The removal of the binder from the green part is a key step of the process and one that requires most careful control. There are several basic processes:

1. Heating of the green compact to cause the polymer binder to melt, decompose, and ultimately evaporate. This must be done with great care in order to avoid disruption of the as-moulded part, and in this connection the use of binders with several ingredients which decompose or evaporate at different temperatures is advantageous. The process normally takes many hours. The time required for binder removal depends on the wall thickness of the part.

2. The catalytic decomposition of polyacetal MIM feedstock using gaseous nitric acid or oxalic acid has greatly reduced the time for binder removal and the risk of part disruption. Equipment has been developed whereby catalytic binder removal and sintering can be executed in a continuous process (Fig.3.2).

3. An alternative binder removal process is to dissolve out the binder with suitable solvents such as acetone, ethanol or hexane. Some binder constituents are even water soluble. Normally heating is required as a final step to complete the removal by evaporation.

4. A very efficient way of solvent binder removal is the application of supercritical carbon dioxide. The supercritical state of carbon dioxide which is acquired at an elevated pressure and temperature is intermediate between the gaseous and the liquid state. It is characterized by a very low viscosity of the solvent which minimizes the binder removal time.

5. Other less commonly used binder systems use gellation, e.g. with mixtures of cellulose and gums, and freezing of an aqueous slurry containing also organic ingredients. Drying is then used to remove the water and create a network of open porosity before the residual binder is evaporated in a thermal process.

During the binder removal process, the strength of the compact decreases markedly and great care is necessary in handling the 'brown' parts as they are called.
3.3 Sintering

Sintering is the heating process in which the separate particles weld together and provide the necessary strength in the finished product. The process is carried out in controlled atmosphere furnaces - sometimes in vacuum - at a temperature below the melting point of the metal.

Sintering in MIM is substantially the same as that used for traditional PM parts. It can be carried out either in a gaseous atmosphere or in vacuum. Because it is essential to avoid oxidation of the metal, the atmospheres used are generally reducing. Apart from protecting the metal, such atmospheres have the further advantage of reducing the oxide on the surfaces of the powder particles. This surface oxide increases with decreasing particle size. As MIM uses finer powders, this is, of course, of greater significance in MIM than it is with traditional PM.

The composition of the sintering atmosphere used depends on the metal being sintered. For many metals a straightforward atmosphere containing hydrogen is all that is required, but in the case of steels which have carbon as an essential alloying element, the atmosphere must be either inert or contain a carbon compound or compounds so that it is in equilibrium with the steel, i.e. it must neither carburise nor de-carburise the steel.

The fact that the powders used are very much finer in MIM than those used in PM means that sintering takes place more readily by reason of the higher surface energy of the particles.

As the 'brown' part is extremely porous, a very large shrinkage occurs during sintering (Fig.3.3) and the sintering temperature must be very closely controlled in order to retain the shape and prevent 'slumping'. The final part has a density closely approaching theoretical, usually greater than 95%, and the mechanical properties are similar to those of wrought metal of the same composition.

3.4 Post-Sintering Operations

The properties of MIM components can be improved by many of the standard processes that are applicable to wrought metals and/or PM components, e.g. case hardening, electroplating, etc.

Often, the surface region of a MIM part is fully densified (Fig. 3.4), so that the residual internal porosity does not negatively affect post-sintering operations.
4.1 Tensile Properties

Tensile Test Samples

Due to the specific rules for shape design in MIM it is obvious that tensile test samples which can be manufactured without additional machining operations have distinct advantages both in terms of cost savings and technically. As MIM is usually a net-shape or near-net-shape manufacturing process, the technical advantage is that the surface condition of the test samples is the same as that of the MIM component. This is why the MIM industry, at an early stage already, has developed its own tensile test sample geometries. These so-called MIMA samples, designated after the American Metal Injection Molding Association by which they have first been proposed, were adopted by the ISO 2740 standard defining tensile test samples in powder metallurgy. European MIM manufacturers found that these test samples which have been designed with holes in their clamping heads in order to facilitate clamping tend to fracture outside the gauge length if weld lines or cracks are formed due to irregular mould filling. In order to avoid this problem, an additional shape was proposed which is almost identical to the MIMA shape, but where the holes at the clamping heads are missing (Fig. 4.1). The mould dimensions (diameter at the gauge length: 5.0 mm) are between the large MIMA sample (diameter at the gauge length: 5.82 mm) and the small MIMA sample (diameter at the gauge length: 3.8 mm). All three sample geometries have been admitted and integrated in ISO 2740.

Mechanical Properties Achieved by Tensile Testing

One of the strengths of metal injection moulding is the wide range of materials that can be manufactured in this technology. Many ferrous alloys are produced in MIM, the most widely used being stainless steel. Heat treatable alloy steels are used for high strength requirements. Soft magnetic alloys are also available. Non-ferrous materials include cobalt and nickel base alloys, niobium, titanium and tungsten.

Table 4.1 lists mechanical property data that have been determined for a range of materials processed by MIM. More mechanical properties are given in the Draft Standard on Mechanical Properties of MIM Materials at the end of this brochure.

<table>
<thead>
<tr>
<th>Mould Dimensions</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measure [mm]</td>
<td>37.6</td>
<td>5.0</td>
<td>75.0</td>
<td>5.0</td>
<td>30.0</td>
<td>7.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Tolerance [mm]</td>
<td>± 0.4</td>
<td>± 0.02</td>
<td>± 0.5</td>
<td>± 0.02</td>
<td>± 0.1</td>
<td>±0.1</td>
<td>±0.01</td>
</tr>
</tbody>
</table>

Fig. 4.1: Tensile test sample proposed by the European MIM industry
4.2 Fatigue Strength of MIM Materials

The European MIM industry is undertaking great efforts to provide design engineers with comprehensive material property data as is required by finite element analysis (FEA) and other design software. The determination of these characteristics, in particular fatigue properties, is costly and time consuming. So far, only a few data are available, but these demonstrate that heat-treated MIM steels have a high potential of fatigue properties.

### MIM Materials for High Loading Applications

Two steels have been selected as representatives of heat treatable high strength materials: the precipitation hardening MIM-17-4 PH stainless steel and the low alloy MIM-4340 steel. The latter is representative of conventional quench-and-temp heat treatments. The high strength potential of these steels as produced by MIM technology has been demonstrated and the results could be the basis for the development of new MIM products for high loading applications.

#### Table 4.1 (From ‘Injection Molding of Metals and Ceramics’ by RM German & A Bose, published by MPIF, Princeton, USA 1997. Reprinted with permission)

<table>
<thead>
<tr>
<th>Material</th>
<th>Composition, wt.%</th>
<th>Density %</th>
<th>Yield Strength Rp0.2 MPa</th>
<th>UTS MPa</th>
<th>Elongation %</th>
<th>Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1020 steel</td>
<td>Fe-0.2C</td>
<td>96</td>
<td>185</td>
<td>380</td>
<td>23</td>
<td>-</td>
</tr>
<tr>
<td>4140</td>
<td>Fe-1Cr-0.4C</td>
<td>97</td>
<td>390</td>
<td>580</td>
<td>15</td>
<td>18 HRC</td>
</tr>
<tr>
<td>4140 (HT)</td>
<td>Fe-1Cr-0.4C</td>
<td>93</td>
<td>1240</td>
<td>1380</td>
<td>2</td>
<td>40 HRC</td>
</tr>
<tr>
<td>4340 steel (HT)</td>
<td>Fe-2Cr-1Ni-1Mn-0.4C</td>
<td>96</td>
<td>480</td>
<td>620</td>
<td>6</td>
<td>20 HRC</td>
</tr>
<tr>
<td>4640 steel (HT)</td>
<td>Fe-2Ni-1Mn-0.4C</td>
<td>97</td>
<td>1400</td>
<td>2000</td>
<td>3</td>
<td>30 HRC</td>
</tr>
<tr>
<td>gold, 18 ct.</td>
<td>75Au-12.5Ag-12.5Cu</td>
<td>75</td>
<td>108</td>
<td>147</td>
<td>1</td>
<td>66 HRC</td>
</tr>
<tr>
<td>hastelloy</td>
<td>Ni-28Mo-2Fe</td>
<td>97</td>
<td>350</td>
<td>800</td>
<td>40</td>
<td>30 HRC</td>
</tr>
<tr>
<td>inconel 718 (HT)</td>
<td>Ni-19Cr-18Fe-5Nb-3Mo-1Ti-0.4Al</td>
<td>100</td>
<td>1130</td>
<td>1330</td>
<td>14</td>
<td>-</td>
</tr>
<tr>
<td>iron</td>
<td>Fe-36Ni</td>
<td>98</td>
<td>240</td>
<td>425</td>
<td>40</td>
<td>65 HRC</td>
</tr>
<tr>
<td>iron</td>
<td>Fe</td>
<td>96</td>
<td>105</td>
<td>220</td>
<td>35</td>
<td>50 HRF</td>
</tr>
<tr>
<td>iron-copper steel</td>
<td>Fe-2Cu-0.8C</td>
<td>95</td>
<td>-</td>
<td>700</td>
<td>10</td>
<td>92 HRC</td>
</tr>
<tr>
<td>iron-chromium steel</td>
<td>Fe-1Cr-0.5C</td>
<td>94</td>
<td>-</td>
<td>600</td>
<td>10</td>
<td>90 HRC</td>
</tr>
<tr>
<td>iron-molybdenum</td>
<td>Fe-5Mo</td>
<td>98</td>
<td>210</td>
<td>410</td>
<td>34</td>
<td>66 HRC</td>
</tr>
<tr>
<td>iron-nickel</td>
<td>Fe-8Ni</td>
<td>96</td>
<td>255</td>
<td>715</td>
<td>24</td>
<td>75 HRC</td>
</tr>
<tr>
<td>iron-nickel</td>
<td>Fe-60Ni</td>
<td>96</td>
<td>170</td>
<td>420</td>
<td>20</td>
<td>50 HRC</td>
</tr>
<tr>
<td>iron-nickel steel</td>
<td>Fe-2Ni-0.5C</td>
<td>97</td>
<td>215</td>
<td>450</td>
<td>20</td>
<td>75 HRC</td>
</tr>
<tr>
<td>iron-nickel steel (HT)</td>
<td>Fe-2Ni-0.5C</td>
<td>94</td>
<td>1230</td>
<td>1230</td>
<td>1</td>
<td>45 HRC</td>
</tr>
<tr>
<td>iron-nickel steel</td>
<td>Fe-2Ni-0.9C</td>
<td>96</td>
<td>450</td>
<td>650</td>
<td>9</td>
<td>90 HRC</td>
</tr>
<tr>
<td>iron-nickel steel (HT)</td>
<td>Fe-7Ni-0.5C</td>
<td>95</td>
<td>1420</td>
<td>1460</td>
<td>1</td>
<td>46 HRC</td>
</tr>
<tr>
<td>iron-phosphorus</td>
<td>Fe-0.6 P</td>
<td>99</td>
<td>260</td>
<td>280</td>
<td>2</td>
<td>80 HRC</td>
</tr>
<tr>
<td>iron-silicon</td>
<td>Fe-3Si</td>
<td>99</td>
<td>345</td>
<td>520</td>
<td>25</td>
<td>85 HRC</td>
</tr>
<tr>
<td>iron-silicon</td>
<td>Fe-6.5Si</td>
<td>99</td>
<td>-</td>
<td>375</td>
<td>0</td>
<td>37 HRC</td>
</tr>
<tr>
<td>kovar or F15</td>
<td>Fe-29Ni-17Co</td>
<td>98</td>
<td>350</td>
<td>520</td>
<td>42</td>
<td>60 HRC</td>
</tr>
<tr>
<td>nickel-iron</td>
<td>Ni-20Fe</td>
<td>91</td>
<td>-</td>
<td>470</td>
<td>31</td>
<td>53 HRC</td>
</tr>
<tr>
<td>niobium superalloy</td>
<td>Nb-10W-10Ta</td>
<td>98</td>
<td>315</td>
<td>440</td>
<td>25</td>
<td>20 HRC</td>
</tr>
<tr>
<td>stainless 17-4 PH</td>
<td>Fe-16Cr-4Ni-4Cu</td>
<td>96</td>
<td>750</td>
<td>900</td>
<td>10</td>
<td>25 HRC</td>
</tr>
<tr>
<td>stainless 17-4 PH (HT)</td>
<td>Fe-16Cr-4Ni-4Cu</td>
<td>96</td>
<td>965</td>
<td>1140</td>
<td>12</td>
<td>35 HRC</td>
</tr>
<tr>
<td>stainless 304L</td>
<td>Fe-18Cr-8Ni</td>
<td>97</td>
<td>240</td>
<td>480</td>
<td>35</td>
<td>85 HRC</td>
</tr>
<tr>
<td>stainless 316L</td>
<td>Fe-17Cr-12Ni-2Mo-2Mn</td>
<td>96</td>
<td>220</td>
<td>510</td>
<td>45</td>
<td>75 HRC</td>
</tr>
<tr>
<td>stainless 316L duplex</td>
<td>Fe-21Cr-9Ni-3Mo-2Mn</td>
<td>95</td>
<td>230</td>
<td>540</td>
<td>43</td>
<td>80 HRC</td>
</tr>
<tr>
<td>stainless 410L (HT)</td>
<td>Fe-11Cr-0.5C</td>
<td>97</td>
<td>410</td>
<td>650</td>
<td>5</td>
<td>20 HRC</td>
</tr>
<tr>
<td>stainless 420 (HT)</td>
<td>Fe-13Cr-1Mn-1Si</td>
<td>92</td>
<td>690</td>
<td>1440</td>
<td>6</td>
<td>47 HRC</td>
</tr>
<tr>
<td>stainless 430</td>
<td>Fe-17Cr-1Mn-1Si-1Ni</td>
<td>93</td>
<td>230</td>
<td>395</td>
<td>25</td>
<td>68 HRC</td>
</tr>
<tr>
<td>stainless 440C (HT)</td>
<td>Fe-17Cr-1Ni-1C</td>
<td>96</td>
<td>410</td>
<td>620</td>
<td>2</td>
<td>43 HRC</td>
</tr>
<tr>
<td>stellite</td>
<td>Co-28Cr-4W-3Ni-1C</td>
<td>99</td>
<td>-</td>
<td>1020</td>
<td>3</td>
<td>40 HRC</td>
</tr>
<tr>
<td>super invar</td>
<td>Fe-32Ni-5Co</td>
<td>98</td>
<td>-</td>
<td>285</td>
<td>40</td>
<td>65 HRC</td>
</tr>
<tr>
<td>titanium</td>
<td>Ti</td>
<td>95</td>
<td>1100</td>
<td>1300</td>
<td>16</td>
<td>-</td>
</tr>
<tr>
<td>Ti-6-4</td>
<td>Ti-6Al-4V</td>
<td>98</td>
<td>800</td>
<td>880</td>
<td>12</td>
<td>35 HRC</td>
</tr>
<tr>
<td>tool steel</td>
<td>Fe-6W-5Mo-4Cr-2V-1C</td>
<td>99</td>
<td>-</td>
<td>2000</td>
<td>0</td>
<td>66 HRC</td>
</tr>
<tr>
<td>tungsten heavy alloy</td>
<td>W-8Mo-8Ni-2Fe</td>
<td>100</td>
<td>-</td>
<td>1115</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>tungsten heavy alloy</td>
<td>W-5Ni-2Cu</td>
<td>98</td>
<td>-</td>
<td>1050</td>
<td>10</td>
<td>35 HRC</td>
</tr>
<tr>
<td>tungsten heavy alloy</td>
<td>W-4Ni-1Fe</td>
<td>99</td>
<td>-</td>
<td>650</td>
<td>20</td>
<td>50 HRA</td>
</tr>
<tr>
<td>tungsten heavy alloy</td>
<td>W-5Ni-2Fe</td>
<td>100</td>
<td>-</td>
<td>660</td>
<td>30</td>
<td>25 HRC</td>
</tr>
<tr>
<td>udiment 700</td>
<td>Ni-18Co-15Cr-5Mo-4Al-3Ti</td>
<td>100</td>
<td>910</td>
<td>1340</td>
<td>14</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4.1 (From ‘Injection Molding of Metals and Ceramics’ by RM German & A Bose, published by MPIF, Princeton, USA 1997. Reprinted with permission)
Fatigue Strength

Test specimens from several parts manufacturers were investigated in order to have a representative data base. Axial fatigue tests were performed in the R = 0 loading mode (pull-pull test) at a frequency of 20 Hz. Tensile test specimens according to ISO 2740 were used as moulded, i.e. without machining, grinding or polishing the sample surface in the gauge length. The fatigue limit was determined at 2x10^6 cycles. The test results obtained for MIM-17-4 PH are shown in Fig. 4.2. The plot shows that the samples of some manufacturers have an even longer fatigue life than others. Further improvement of the fatigue life can be expected with optimized manufacturing, surface quality and heat treatment. The lower limit of the fatigue strength was determined at 280 MPa.

The MIM-4340 material specimens exhibited a high surface quality with very little pores at the surface or underneath, although the total porosity was about 4%. From literature, for a wrought SAE 4340 material, similar heat treatment and tested by plane bending, fatigue strength at 10^6 cycles of about 660 MPa was reported [P.G. Forrest, Fatigue of Metals, Pergamon Press Ltd, 1962]. The results obtained for the MIM-4340 material are at a fatigue limit of approximately 500 MPa (Fig. 4.3). These results demonstrate that MIM materials can have a promising fatigue strength if particular care is taken in the manufacture of MIM parts. Particular attention is recommended on mould preparation, e.g. mould parting lines (as the majority of failures occurred along this line) and a high surface quality in order to achieve appropriate fatigue properties.

Heat Treatments

The heat treatments recommended for MIM-17-4PH and MIM-4340 were chosen in order to achieve a compromise between high strength and hardness as well as sufficient toughness and ductility.

MIM-17-4 PH
Solution treatment: 1h/ 1050°C in vacuum
Ageing: 4h/ 480°C in air

MIM-4340
Normalising: 20 min / 870°C in vacuum
Hardening: 15 min / 840°C in nitrogen, then oil quench
Tempering: 2h/ 425°C in air
5. Designing for MIM

5.1 MIM Part Design Guidelines

Generally speaking, any shape that can be produced in thermoplastics by injection moulding can be produced in metal by MIM, but there are certain limitations to this general rule in both cases.

A collection of MIM parts is shown in Fig. 5.1. These are examples of the shape complexity of MIM components. The case studies in this brochure provide further illustrations of the complexity of parts designed for MIM.

![Collection of MIM parts showing shape complexity](Courtesy of BASF)

Table 5.1 gives some general guidelines for designing MIM parts.

<table>
<thead>
<tr>
<th>Restrictions</th>
<th>Desirable Features</th>
<th>Allowed Design Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>• no inside closed cavities</td>
<td>• gradual section thickness changes</td>
<td>• holes at angles to one another</td>
</tr>
<tr>
<td>• no undercuts on internal bores</td>
<td>• largest dimension below 100 mm</td>
<td>• hexagonal, square, blind and flat bottom holes</td>
</tr>
<tr>
<td>• corner radius greater than 0.075 mm</td>
<td>• weight under 100 g</td>
<td>• stiffening ribs</td>
</tr>
<tr>
<td>• 2° draft on long parts</td>
<td>• wall thickness less than 10 mm</td>
<td>• knurled and waffle surfaces</td>
</tr>
<tr>
<td>• smallest hole diameter 0.1 mm</td>
<td>• assemblies in one piece</td>
<td>• protrusions and studs</td>
</tr>
<tr>
<td>• minimum thickness 0.2 mm</td>
<td>• flat surfaces for support</td>
<td>• external or internal threads</td>
</tr>
<tr>
<td>• range weight 0.02 g to 20 kg</td>
<td>• small aspect ratio geometries</td>
<td>• “D” shaped and keyed holes</td>
</tr>
</tbody>
</table>

Table 5.1 (From ‘Injection Moulding of Metals and Ceramics’ by RM German & A Bose, published by MPIF, Princeton, USA, 1997. Reprinted with permission)
feedstock to flow from thick to thin sections as it enters the mould cavity. Ideally, the flow path from the gate should impinge on the wall of the cavity or a pin as shown in Fig. 5.5. A flow path of thin to thick, generally, will cause voids, sink marks, stress concentrations and flow lines on the part surface.

Many MIM components are produced using multiple cavity tooling, where each cavity must be identical to the others. To ensure part reproducibility, the gate and runner system to each cavity must be carefully sized and located so that each cavity will be filled with the identical amount of feedstock at a balanced fill rate. Since the gate will leave a mark or impression, its location must be carefully selected with regard to part function and appearance.

**Part Ejection from Mould Cavity**

Draft, or a slight taper, may be required for the ejection of parts from the mould cavity. This is particularly true for core pins, and the need increases with the depth of the hole or recess being formed. When draft is required, an angle from 0.5° to 2° is generally sufficient. Knock-out ejector pins are usually required for removing parts from the mould, and good design of these pins is critical to minimise flash marking of the parts.

**Reducing Stress Concentrations**

Sharp internal corners and notches should be avoided because they cause stress concentrations. Thus generous fillets or radii, which will also improve feedstock flow during moulding and assist in the ejection of the part, should be considered. Both inside and outside corners should have radii as large as possible, typically not less than 0.4 to 0.8 mm.

**Design of Threads**

When required, external and internal threads can be automatically moulded into the part, thereby eliminating the need for mechanical thread-forming operations (Fig. 5.6). Internal threads are typically moulded by using automatic unscrewing devices, but this route is often not cost-effective and tapping should be considered.

**Mould Parting Lines**

Mould parting lines are formed by the opposing faces of the mould, in the plane where the mould halves are separated to permit removal of the part, as was shown in Fig. 5.6. With moulds of normal construction this feature is transferred as lines or witness marks onto the surface of the part.

**Undercuts**

Undercuts, classified as internal and external are often required for part function. Undercuts may increase tooling costs and lengthen cycles, but this is dependent on the type and location of the undercuts on the part. External undercuts, often specified on MIM parts for ‘o’-ring seating, can be formed by using a split cavity mould. As with the threaded components, there will be two parting lines 180° apart on the surface of the undercut, which may be objectionable in an ‘o’-ring groove. Internal undercuts can be formed by using collapsible cores. However, most MIM parts are relatively small and cannot accommodate this approach. Designing MIM parts with internal undercuts or recesses is not recommended.
Mould Fill Design

Fig. 5.7 and Fig. 5.8 demonstrate the usefulness of mould design by computer simulation with the MOULDFLOW® software. The part in Fig. 5.7 exhibits a weld line in a critical position of high stress. This weld line can be moved to an uncritical position by re-design. The gate position was shifted and a flow deflection was achieved by reducing the wall thickness (Fig. 5.8). The mould design software system is suitable to optimize part design, mould filling and gating in single and multicavity moulds.

5.3 Size of MIM Parts

There is, theoretically, no limit to the maximum size of part that could be produced, but economic considerations restrict the sizes that are currently viable.

There are two important factors in this connection:

1. The larger the part the greater is the proportion of the overall cost that is attributable to the raw material which is costly. The total cost of the powder is a linear function of the weight of the part, but in the case of parts produced by machining from solid bar stock, for example, the machining costs increase with increasing part size at a much lower rate.

2. The thicker the section the longer the debinding time, and thus the higher the cost of that part of the process. At the present time, the limiting thickness seems to be about 30 mm.

5.4 Dimensional Accuracy of MIM Parts

One of the most frequently asked questions when a new application is considered refers to the dimensional tolerances that can be achieved by MIM processing. In order to provide background input data for the assessment of the dimensional accuracy of MIM parts, real part data have been collected from several European manufacturers.

For dimensional tolerances (critical measures) the limits according to the table below have been proposed.

<table>
<thead>
<tr>
<th>Nominal size [mm]</th>
<th>General [± mm]</th>
<th>Investment Casting D2 (1992 P690) [± mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;3</td>
<td>± 0.05</td>
<td>± 0.12</td>
</tr>
<tr>
<td>3 – 6</td>
<td>± 0.06</td>
<td>± 0.15</td>
</tr>
<tr>
<td>6 – 15</td>
<td>± 0.075</td>
<td>± 0.15</td>
</tr>
<tr>
<td>15 – 30</td>
<td>± 0.15</td>
<td>± 0.20</td>
</tr>
<tr>
<td>30 – 60</td>
<td>± 0.25</td>
<td>± 0.30</td>
</tr>
<tr>
<td>&gt;60</td>
<td>± 0.5% from nominal size</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2: The MIM data has been obtained in accordance with Standard DIN ISO 2768. Better tolerances for some critical dimensions can be achieved in MIM after optimising design and process.
These dimensional tolerances can only be achieved on critical dimensions under favourable moulding conditions. Mould parting lines, varying wall thickness and other factors can adversely affect the dimensional accuracy of a part.

In Fig. 5.9, the tolerances of MIM parts are compared to the ISO tolerance classes IT 7 to IT 12. Although not identical, the tolerances of MIM parts are very similar to the IT 10 class between 3 and 35 mm. Below 3 mm, MIM is better than IT 10 and above 35 mm it is somewhat worse than IT 10.

Besides the dimensional accuracy, it is also necessary to consider:

- angular tolerances
- surface finish
- radii

Here, angular tolerances are identified to be ±40' or for improved performance criteria ±30'.

The surface finish may be $R_a = 4 - 20 \ \mu m$ depending on the type of material. MIM materials on the basis of carbonyl iron with a powder particle size of less than 10 $\mu m$ tend to have a smoother surface than materials made from atomized steel powders which are considerably coarser.

Surface finish of MIM parts is appreciably better than most investment castings. However, profilometer readings may be affected by residual porosity and are subject to interpretation. The method of measuring surface finish should be agreed upon by both the customer and the vendor. The surface finish of MIM parts can be improved by conventional processes such as grinding, lapping or burnishing.

Radii should generally be at least 0.3 mm. Further details related to radii are given in the guidelines for MIM design.

The following general rules should always be observed when dimensional tolerances of a MIM part are specified:

- tolerances specified should be no closer than absolutely required for satisfactory performance
- close tolerances should not be specified for parts having major wall thickness variations
- close tolerances on several dimensions of a part usually result in increased part cost
- close tolerances should not be specified across a parting line or for dimensions controlled by movable cores or sliding cams.

5.5 Comparison with Competing Technologies

MIM is essentially a technology for producing complex shape parts in high quantities. If the shape allows the production of the part by, for example, conventional pressing and sintering (and mechanical properties are adequate), then MIM would in most cases be too expensive. However, if the required number of complex parts is higher than a certain amount, MIM is cheaper than machining.

The effect of the volume production on cost is shown in Fig. 5.10. This diagram shows that, for example, for the smallest part weighing 4.5 g the cost per part falls from $1.4 for an annual production of 250,000 pieces to $0.2 for 3 million or more. This figure also shows the influence of part size on the cost factor - the bigger the part the smaller is the gap between the cost of 250,000 and 3 million pieces. A typical competing process to MIM is investment casting and the table below compares the characteristics of parts produced by the two processes.

In regard to many features MIM comes out on top. However, this does not tell the whole story, and many shapes that are possible by MIM cannot be produced by other routes. MIM certainly has advantages compared with investment casting in the case of high numbers of small parts, and of course in non-castable alloys.

<table>
<thead>
<tr>
<th>Property</th>
<th>Investment casting</th>
<th>MIM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. bore diameter</td>
<td>2mm</td>
<td>0.4mm</td>
</tr>
<tr>
<td>Max. depth of a 2mm dia. blind hole</td>
<td>2mm</td>
<td>20mm</td>
</tr>
<tr>
<td>Min. wall thickness</td>
<td>2mm</td>
<td>≥0.3mm</td>
</tr>
<tr>
<td>Max. wall thickness</td>
<td>unlimited</td>
<td>≤30mm</td>
</tr>
<tr>
<td>Tolerance at 14mm dimension</td>
<td>+/- 0.2mm</td>
<td>+/- 0.075mm</td>
</tr>
<tr>
<td>Surface roughness $R_a$</td>
<td>5 $\mu m$</td>
<td>4-20 $\mu m$</td>
</tr>
</tbody>
</table>

Table: 5.3
6. Preparation of MIM Parts for Microscopy

6.1 Object

The present guidelines are intended to specify the operations required for the preparation of MIM samples for microscopic examination.

6.2 Parts to be examined

It is of interest to examine MIM parts at different stages of manufacturing.

Green parts

The microscopic examination of green parts is useful to identify defects in samples (cracks, bubbles, shrinkage porosity, welding lines, etc.). It can also be of interest, depending on the part geometry and the type of powder used, to examine the homogeneity of the powder - binder mixture after injection, and, if necessary, the repartition of different powders (nature or shape) if the powder used is not homogeneous.

Brown parts

Brown parts are very brittle because the binder has been removed. If there are defects in the parts, they will break more easily along these defects. The location of defects can be determined in this way, and examination of the broken section will give information on the nature of the defect (crack, bubble, etc.). A low magnification is needed because of surface roughness.

Pre-sintered parts

If the binder is very soft or brittle, it could be difficult to obtain a satisfactory preparation of green parts. Then, parts have to be debound and sintered until the beginning of neck formation between particles. The part sounds like a metallic one, but is still very close to the dimension of the green part (shrinkage from 2 to 5%). The defects present in green parts remain quite identical in pre-sintered parts and can be examined more easily.

Sintered parts

Microscopic examination of sintered parts is mostly used for porosity, cleanliness and microstructure. This examination is essential for the metallurgical characterisation of MIM parts.

6.3 Preparation of samples

Scanning electron microscopy (SEM)

For SEM examination, a preparation of MIM parts is not always needed. Parts may be introduced in the electron microscope as whole or broken parts, and examination shall be conducted on the external surface or on broken sections. If chemical analysis is required, and especially semi-quantative analysis, the sample has to be prepared as for optical microscopy, and analysis shall be done on the polished surface.

NOTE: For SEM examination, the sample has to be electrically conductive. Surface metallisation or a conducting mounting resin would be used if necessary.

Optical metallography

General

As most MIM parts have thin walls, it is almost impossible to do a metallographic examination without mounting the sample in a suitable polymer resin. Section for examination would preferably be done in sections of the sample of special interest. Such sections might be:

- Defect areas
- Welding lines
- Segregation areas
- Any section where specific information is expected

If nothing special is searched for, the sample should be cut in the middle, or at any more convenient position.

Preparation of green parts

The preparation of green parts may vary greatly, depending of the nature and the mechanical properties of the binder. If the binder is hard and stiff, the sample shall be prepared as sintered samples (cf. 3.2.3). If not, a part of the sample including the section to be examined shall be embedded in a cold mounting resin, preferably one specially designed for metallography. After complete polymerisation, the embedded piece is cut with a high speed circular saw.

The following conditions have been found efficient:

<table>
<thead>
<tr>
<th>Saw wheel</th>
<th>high strength steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>63 mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Number of teeth</td>
<td>128</td>
</tr>
</tbody>
</table>

Cutting speed (peripheral) : 600 m/min

Translational speed : 0.3 mm/min

On such samples, polishing is impossible. The binder would be removed and broken before a smooth surface could be achieved, and the metallic content that can be seen then is far less than the actual content. Examination shall be done directly on the cut surface. The remaining roughness prevents the use of high magnification, but powder shape and powder distribution can be examined and analysed. During cutting, some of the powder particles may be removed from the polymer matrix, but the holes appear clearly in a darker colour and can even be used for image analysis.
NOTE: Preparation of green parts is sometimes very difficult, especially for unskilled operators. Every time it is possible and acceptable, examination of such parts should preferably be done on pre-sintered parts.

Preparation of pre-sintered and sintered parts

A. Cutting of the sample

Special care has to be taken with respect to holding of the part during cutting, in order to prevent the sample from being crushed, deformed or deteriorated. Cutting may be done using an abrasive cutting machine using thin abrasive or diamond-rimmed wheels. During cutting, intensive cooling will protect against structure modification and damage due to overheating.

Sawing may also be applied. Using a standard hacksaw will leave burrs and a rough and disturbed surface, so that some tenth of millimetre have to be removed during grinding. A fine blade saw, similar to those used by jewellers, may conveniently be used for cutting MIM samples.

If the part is smaller than the mounting mould, cutting may not be required. If no specific section has to be examined, the whole part can be mounted; however, a sufficient grinding will be necessary.

B. Mounting

The most common mounting method for metallographic samples is hot compression mounting. Both thermoplastic and thermosetting resins may be used if they have sufficient hardness and low shrinkage. However, green parts, pre-sintered parts and some very brittle parts require cold mounting. Curing the cold-setting resin in vacuum or pressurised atmosphere will improve impregnation in pre-sintered samples. It will result in a better strengthening of the MIM part, and an easier polishing because of low or zero porosity.

If the parts are to be examined both with optical and electronic microscope, it can be convenient to use an electrically conductive resin (containing for example carbon, silver or copper powder). Such a conductive mounting is also used for electrolytic etching of the samples.

The position of the sample in the mounting resin has to be thoroughly defined and recorded. If the mounting resin is transparent, the position can be verified, and corrected if necessary before complete polymerisation. If the resin is opaque, it is of great importance to be sure that the sample is correctly positioned before pouring the resin, and to ensure that it remains in the correct position. Special holders could be used for this purpose.

C. Grinding

A sufficient thickness shall be removed from the cut surface before final polishing, in order to eliminate the burrs and structure modification resulting from cutting. Experience is of some help for determining the thickness to be removed. Examination of the surface after grinding at a low magnification is sometimes useful for evaluation of the result. Grinding can also be used for removing material until a specific area or defect in the sample is reached.

Grinding is a critical step of preparation. Incorrect grinding may lead to a partial closing of pores by plastic deformation or pores may be filled with grinding debris. An enlargement of pores may occur, due to break-out or rounding of material at pore edges. Automatic grinding discs under water-cooling shall be used. The pressure on the sample is decreased as the grit size is decreased.

After each step, and especially after grinding, the sample has to be thoroughly cleaned. Running water followed by isopropyl alcohol ultrasonic cleaning is suitable.

D. Final polishing

Optical microscope metallography needs flat and mirror polished surfaces. Polishing is conducted as for every metallographic sample, and finished with diamond powder paste with particle size of 6, 3 or even 1 µm. Special care has to be taken to prevent contamination of the polishing discs. Abrasive particles may remain in the pores if they are smaller, and fall out on the next disc. If particles are larger than the pores, they may stick in the pores and scratch the sample surface when they are removed.

As during grinding, thorough cleaning of the sample between each operation is essential. Electrolytic polishing cannot be used because of its effects on pore edges.

6.4 Examination

Optical microscope

A first examination of the unetched sample using low magnification allows to select the surface(s) for further examination. The sample should be examined first for pore size. Homogeneity of pore size and pore distribution in the matrix should be pointed out. Then, the sample should be examined for cleanliness. The classification of pores and inclusions will be defined in another document.

Examination is done at x100 magnification. Higher magnification is used to discriminate between pores and inclusions, and for a better view on pores, especially when incorrect metallographic preparation is suspected. Additional polishing using diamond powder can be applied in order to find out whether the pore size has been correctly determined.

Etching may be used for different purposes, e.g. to

• reveal the microstructure,
• identify specific phases (delta ferrite for example),
• discriminate the inclusions,
• verify that the pores have not been occluded with burrs or foreign particles.
Etching is done chemically or electrochemically and chemical reagents used are similar as those used for general metallography. A list of such reagents is given in the table below for information.

**Scanning Electron Microscope**

The use of SEM is very useful as an additional examination tool. It should give additional information on the surface of the parts, and it is an essential tool for determining the composition of inclusions. Its use for corrosion byproducts identification and chemical analysis of the material can be considered.

**Image analysis**

An image analysis software is highly recommended, especially for the interpretation of the porosity (size measurement, number of pores per unit surface, size distribution, etc.). Its use will be defined in the document related to the classification of porosity.

---

### Most commonly used etching reagents

<table>
<thead>
<tr>
<th>Application</th>
<th>Etchant</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron and steel</td>
<td>Nital: Immerse 5-15 s or more. 1-5% conc. HNO₃ in ethanol</td>
<td>Immerse 5-15 s or more.</td>
</tr>
<tr>
<td></td>
<td>Picral: Immerse 15-30 s. Concentration to be adjusted as a function of the structure. picric acid in ethanol</td>
<td>Immerse 15-30 s. Concentration to be adjusted as a function of the structure.</td>
</tr>
<tr>
<td>Iron - nickel</td>
<td>Marble's reagent: Immerse or swab 5 s to 2 min. 10 g CuSO₄ + 50 ml HCl + 50 ml H₂O</td>
<td>Immerse or swab 5 s to 2 min.</td>
</tr>
<tr>
<td>Copper and Cu alloys</td>
<td>4% FeCl₃ in H₂O</td>
<td>Swabbing 10-20 s.</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>Glyceria: Immerse 1-2 min. 10 ml conc. HNO₃ + 15 ml HCl + 35 ml glycerol</td>
<td>Immerse 1-2 min.</td>
</tr>
<tr>
<td></td>
<td>Murakami’s reagent: Swab or immerse. Can also be used at boiling temperature, and up to 10 g K₃Fe(CN)₆ for refractory metals. 10g KOH (or 7g NaOH) + 4g K₃Fe(CN)₆ + 100ml H₂O</td>
<td>Swab or immerse. Can also be used at boiling temperature, and up to 10 g K₃Fe(CN)₆ for refractory metals.</td>
</tr>
<tr>
<td></td>
<td>10 ml HNO₃ + 2 ml HF+ 100 ml H₂O</td>
<td>Caution with HF!</td>
</tr>
<tr>
<td>Titanium and Ti alloys</td>
<td>10 ml HF + 5 ml HNO₃ + 85 ml H₂O</td>
<td>Caution with HF!</td>
</tr>
</tbody>
</table>

*For additional information, see also:*

- ASM Metals Handbook - Volume on Metallography
7.1 Foreword
The preparation of samples produced by metal injection moulding (MIM) for metallographic examination is somewhat different from the usual metallographic preparation. Information on the procedures used to prepare such samples can be found in Section 6 “Preparation of MIM Samples for Microscopy”.

7.2 Optical microscopy

Equipment
An optical microscope of high quality allowing for magnifications of about x50, x100, x200 and x500 is required. A microscope scale is necessary for the determination of dimensions.

Fig. 7.1: Optical microscope for metallography
(Courtesy of BASF)

A photographic equipment is required for manual dimensional measurements and documentation. When image analysis is used, digital images are acquired from a camera and treated in a computer by a specific software (Fig. 7.1).

Porosity
Porosity is first examined on unetched samples, then again on etched ones if necessary.

Examination of the pore distribution
The homogeneity of the pore distribution is checked at a low magnification (x50). If the homogeneity of the porosity is sufficient, the examination and measurement can be done on any part of the surface. If there is a different pore density in certain parts of the surface, further examination has to be conducted separately on each representative part. The general indication of the pore distribution has to be recorded (for example, lower porosity near the surface of the sample on 0.6 mm thickness).

Characterisation of the porosity
Characterisation of the porosity shall be done at x100 magnification. The surface is chosen for its typical representation of the porosity and for its optical quality (flatness, state of polishing, absence of scratches, etc.). It can be advantageous to examine the same area after additional polishing in order to be sure that the pores have not been closed by the preparation of the sample.

The characterisation of the porosity shall include the following information:

1. Localisation of the investigated area, if significant
2. Shape of pores
Evaluation of the shape is done using the shape of the majority of pores. It is either said to be "rounded or spherical pores" or "irregular pores". When pores are irregular, a more specific description of the actual pore shape may be added if necessary.
3. Mean size of pores
The mean pore diameter is determined using image analysis or by dimensional measurement of a sufficient number of visible pores (> 10 % of total) and calculation of the mean value.
4. Abundance of pores
Pore abundance is determined as the ratio between the number of pores within the measured area and the total measured area. When using image analysis, this value is commonly referred to as "counts/area". In addition, the area of pores divided by the measured area can be of interest.

Example for manual measuring and counting
If the investigated area is Fig. 7.2(a), a practical way to count and measure is to divide the surface area into several smaller areas, as in (b), then to count the number of pores in one or several areas. When a pore is part of two different areas, it has to be counted only in the area where its lower right part is situated. In (c), the mean diameter of a non-spherical pore is obtained as the mean value between the minimum dimension (a) and the maximum dimension (b).

Fig.7.2: Micrograph surface for pore size investigation (Courtesy of CETEHOR)
Verification of the Porosity

The sample is then etched in order to reveal the microstructure of the material. When the sample is examined with the same magnification as before, it should show a porosity of the same shape, dimensions and distribution. If a large difference is shown (more than a normal slight enlargement of the pores due to chemical dissolution of the pore edges), the sample has to be polished again cautiously and the characterisation of the porosity repeated.

Inclusions

If the presence of inclusions is suspected, refer to the following paragraph.

Cleanliness

Cleanliness of the sample is characterised by the nature, the number and the extent of inclusions. Inclusions are unintentional metallic or non-metallic impurities of a composition substantially different from the base material. Optical microscopy does not always allow to distinguish inclusions from pores. The use of a higher magnification of x500 or more can sometimes show if a pore is really a pore or an inclusion. In case of doubt, the first operation is a thorough cleaning of the sample, using alcohol and ultrasonic agitation. If doubt remains, etching may be used to identify inclusions. Some specific reagents can be found in specialised books, like in the Metallography volume of Metals Handbook (ASM). A good reagent will apply to inclusions a specific colouring different from that of pores and matrix.

A convenient way to determine inclusions is to use a scanning electronic microscope (SEM). A specific part of this guide is dedicated to the application of this equipment.

After identifying inclusions, the characterisation shall be done in the same way as for porosity. The use of image analysis is sometimes difficult because of the slight difference in shape, colour and appearance between pores and inclusions. Manual selection of inclusions, if they are not too numerous, may be a practical way to solve this problem.

Etching

The chemical reagent may be chosen from the list supplied in the table of the "Guide for the Preparation of MIM Samples for Microscopy". Special care has to be taken because of the porosity of the etched material. Rinsing and drying shall be done very cautiously in order to remove every trace of the chemical reagent. If liquid remains in pores, it can be released during the examination and affect the quality of the image, and even attack the equipment, especially on inverted microscopes.

Examination

After a first examination at a magnification of x100 for verification of the porosity (see above), the proper magnification is chosen for the identification of the different phases and for metallographic inspection.

Grain size measurement

If required, the grain size can be determined. The procedure described in the standard ISO 643 is appropriate also for MIM materials.

Delta ferrite

Particular attention should be given to delta ferrite. This phase occurs in austenitic stainless steels (316L for example) which are widely used in MIM technology. It appears at the grain boundaries when the stainless steel has been heated to a sufficient temperature. When examined in white light, this phase appears in a very light bluish colour.

The presence of ferrite shall be reported and the relative abundance of this phase may be evaluated.

Defects

Definition

A defect is an occurrence which can affect the appearance, the shape or the properties of the part. This includes injection defects (welding lines, incomplete filling, sink marks, etc), heterogeneity of the material, voids and cracks. A void is significantly larger than a pore and has a dimension of more than 100 µm in its longer dimension.

Defects are systematic or random. Systematic defects are inspected and identified far easier than random ones.

Detection and characterisation of defects

Defects which are visible at the surface of the part can be detected on green or sintered parts by visual inspection, using eventually a magnifying glass or a microscope. Several non-destructive test methods may be applied depending on the nature and size of the defect. Penetrant testing and magnetic particle inspection are efficient for the visualisation of superficial cracks in magnetic materials. Eddy current testing does not seem to have been widely used for this purpose at the present time.

When the defect is internal, it is more difficult to find, unless the defect is suspected or if the internal defect generates an external modification of appearance. Internal voids and cracks can be located using radiography or ultrasonic echography if they are big enough. Smaller defects of less than 1 mm dimension are detected through x-ray micro-tomography.

**Fig. 7.3: Microstructure of MIM-316L etched with glyceregia (Courtesy of CETEHOR)**

Microstructure

Examination of the microstructure of MIM parts is conducted only on sintered parts. The procedure is very similar to the one used for materials of other origin, the only difference being the fine and uniform porosity in most MIM materials (Fig. 7.3).
The destructive detection of defects is conducted on green and brown parts by breaking or slicing the parts. Examination of the broken or cut section gives information on the location and the nature of defects (see Guide for the Preparation). Microscopic examination is also of use for the examination of defects. However, it is uncertain that the fracture of the sample is going through the defect, except when the defect location is suspected and when the defect size is very large or extended in the part.

### 7.3 Scanning Electron Microscopy (SEM)

**Equipment**

SEM is a very useful equipment for the examination of materials. It uses an electron beam for excitation of the materials that are examined. The secondary electrons emitted by the material are used to produce a video image of the surface. Due to the large depth of focus, this image is well defined and shows the superficial relief. By enlarging this image, SEM allows a very large range of magnification, typically from x20 to x200000.

The use of an energy diffraction spectrometer (EDS) attached to the SEM allows to analyse the local material composition, using the energy of the x-ray emitted by the material.

### 8. Corrosion Resistance of MIM Stainless Steels

#### 8.1 Object

The present guidelines are intended to provide manufacturers and end users of stainless steel parts manufactured by metal injection moulding (MIM) with a basic understanding of the interrelations between corrosion resistance, microstructure and manufacturing conditions.

Recommendations are given how to define and test the corrosion resistance of MIM parts made from MIM-316L stainless steel.

#### 8.2 Corrosion Testing

The test method recommended for stainless steel MIM components is neutral salt spray (NSS), carried out in agreement with ISO 9227. Experience shows that a 200 hours NSS test is long enough to characterise the corrosion resistance of 316L MIM parts. For a better understanding of the corrosion phenomena, the samples can be examined after 24, 48 and 100 hours. The admissible corrosion, however, should be agreed between manufacturer and customer. The normal requirement is a maximum corrosion of less than 10% of the surface.

The following corrosion test methods have been critically evaluated.

- Neutral salt spray test
- Synthetic sweat test
- Artificial saliva test
- Stress corrosion test
- Susceptibility to intergranular attack
- Passivation potential measurement
- Pitting potential measurement

Stress corrosion and intergranular corrosion of MIM materials are not significantly different from wrought steels. In addition, the test samples required are very specific and the test is not easy to apply to finished products. Information about these specific corrosion conditions is also generally of low interest. Therefore, these corrosion tests are not very well suited for the characterisation of the corrosion resistance of MIM parts.

Passivation current measurements are performed on samples with a defined geometry and are not suitable for testing finished products. Pitting potential measurements are a little easier to carry out, but the values found are not always in good agreement with the salt spray results.

The synthetic sweat test is a very fast and effective test when applied for 24 hours according to NF S 80-772. This test is only qualitative, but it is in quite good agreement with the salt spray test within a 10 times shorter period.
This test can be useful for the evaluation of the performance in a very short time. The information is especially relevant when comparative tests are performed.

The neutral salt spray test does not require a specific sample geometry. It can be performed on any component shape and is the most widely used and accepted corrosion test in industry. It is recommended for MIM parts. The results can best be compared with each other.

8.3 Interrelation between Corrosion Resistance and Other Properties

On the basis of more than 300 samples of 316L stainless steel MIM parts, the results of salt spray testing have been evaluated. Most of these tests have been conducted for 200 or 600 hours. Observation of the evolution of the corrosion phenomena (stain, pitting, rust, rust drips) and of the percentage of the surface affected by corrosion together with a metallographic analysis allows to interpret the results.

The corrosion behaviour of MIM parts depends largely on the manufacturing conditions. In many cases it is possible to find interrelations between the corrosion resistance and other properties such as porosity, density, phases in the microstructure, grain size, or mechanical properties. Corrosion resistance and other properties have been compared in order to understand the reasons for differences in the corrosion behaviour and to modify the manufacturing process in order to improve the results of corrosion testing if necessary.

Mechanical properties

No clear relationship exists between tensile strength and porosity or microstructure of the material. Too many parameters affecting the tensile strength have differing effects on the corrosion resistance. Considerable differences have been found in the strength of tensile test specimens supplied from different sources, but they cannot be related to the corrosion resistance.

Porosity

A clear relationship exists between the density and the measured porosity. The porosity itself has no noticeable influence on the corrosion resistance. However, the presence of open porosity and significant surface roughness can lead to an increase of the corrosion of the material, mainly due to crevice corrosion. Surface recesses can also be preferential sites for adhering impurities that can produce local corrosion.

Grain size

The best corrosion resistance is connected with the smallest grain size. This small grain structure is also of great importance for machining and polishing of the materials. The conditions of sintering and cooling are very important as far as the grain size is concerned.

Delta ferrite

The percentage of austenite transformed into delta ferrite during sintering is directly connected to the thermal cycle applied for sintering, and then to the grain size. Most samples having a good or very good corrosion resistance contain some delta ferrite and have a fine grain size (no. 5 or more). However, a too large quantity of ferrite is detrimental when high quality finishing is required. Heterogeneity on the surface due to delta ferrite can also have a detrimental effect on corrosion.

Carbon content

The effect of the carbon content on the corrosion resistance of 316L is well known. Low or very low carbon austenitic stainless steels are required for a good corrosion resistance. Even with powder of good quality, if the material is contaminated by carbon coming from the binder, its corrosion resistance can deteriorate.

Chromium content and chromium distribution

Chromium is essential for the formation of the passive film on the steel surface. If some chromium is evaporated during vacuum sintering, the superficial concentration of chromium can fall down below 12%. The material is then easier to corrode. During cooling, chromium can also react with carbon in order to form chromium carbides which precipitate at the grain boundaries. They form the discontinuities which allow corrosion to start. As the carbides precipitate more easily at the interfaces of ferrite and austenite, a too large quantity of ferrite can be harmful. The temperature should be reduced very quickly from 900 to 600°C in order to limit the chromium carbide formation.

Other effects

Different metallurgical problems have been discovered on some samples and can be the cause of poor corrosion resistance. The presence of impurities or inclusions, for example iron contamination of the metallic powder in the feedstock, leads to localised pitting. Intermetallic phases or mixed carbides (Cr + Mo for example) can be produced in some particular conditions, especially when a high temperature is maintained for a long time.
SPORTS GOODS AND HAND TOOLS
(Mimecrisa, Ecritesa Group, Spain)
These parts for personal and professional hand tools and sports goods are made from case hardened steel like MIM-8620 with a surface hardness of 700 HV10 and fully hardened steel (arrow tip) MIM-Fe8Ni0.6C with a hardness of 50 - 55 HRC.
A traditional costly manufacturing route of bending, welding and machining has been replaced by MIM. Close tolerances of ± 0.3 % are achieved, thin walls of 1 mm ending in sharp corners and an external thread are possible directly by using MIM technology (see arrow tip).

SAW BLADE FASTENER (Parmaco AG, Switzerland)
This part is used to mount the blade of an electric handheld keyhole saw. It connects the blade to the oscillating drive. The material is MIM-316L stainless steel at a density of 7.75 g/cm$^3$. Overall dimensions are 19x12x9 mm and the weight is 11.7 g. Two gates are used in moulding to ensure a good filling of the die. Tolerances on parallelism and the flatness of the slot surface are better than 0.05 mm.
This MIM part was previously made by investment casting, but the tolerances were not good enough to ensure trouble-free functioning. MIM offers closer dimensional tolerances, a better surface finish (Ra 3.2 µm) and a considerable cost reduction.

MIM PARTS FOR AUTOMOTIVE TRANSMISSION
(GKN Sinter Metals, Germany)
The three components shown here are part of an automotive transmission. They serve to synchronize the reverse gear. All parts are manufactured from MIM-Fe2Ni low alloy steel at a minimum density of 7.4 g/cm$^3$ and case hardened. The tensile strength required is higher than 450 MPa and the hardness is 500 - 750 HV1. A special design feature of the braking disc (in the middle) is the internal toothing whose dimensional accuracy is improved by a sizing operation.

BURNER CHAMBER (GKN Sinter Metals, Germany)
This part weighing approximately 40 g is the burner chamber of an automotive heater used in cars and trucks. The part is made from MIM-316L stainless steel at a minimum density of 7.3 g/cm$^3$. Besides resistance to heat and oxidation, gas tightness is required. Only the outer diameter is finish machined for a close fit. Special design features include a lateral through hole at a 9º angle and the engravings on the inside which are produced during moulding.

PISTON COOLING NOZZLE (GKN Sinter Metals, Germany)
A MIM part and a tube are assembled and brazed to form this nozzle which cools the piston in a V8 engine. The nozzle is built into the engine block and directs a defined oil jet stream onto the bottom side of the piston. The close dimensional tolerances and the slot required for brazing can best be produced by MIM. The material is MIM-Fe2Ni at a minimum density of 7.5 g/cm$^3$, the part weight is 11 g.

MAGAZINE CATCH (Metalor 2000, Israel)
This part is made from the alloy grade MIM-8620 and is used in the mechanism of light arms. The parts are case hardened with a surface hardness according to the requirements of the drawing of 82-85 HR15N and a case depth of 0.15-0.25 mm. The part has slots in different directions and a blind hole. The MIM technology offers to the end user 45% cost savings as compared to machining.
PART OF WATCH CLASP (HOPTEC, France)

The part was previously made by machining (milling and drilling). The perpendicular axis (small pin) was subsequently welded. MIM technology brought simplification of the manufacturing process and cost savings. Thanks to MIM it was easy to shape all the functions (holes, pin and clip area) at the same time.

This MIM part is made of MIM-316L stainless steel. The weight is 1.08 g. Dimensions are 16.0x8.0x1.5 mm with height of pin 3.3 mm. The density after sintering is 7.86 g/cm³.

Regarding corrosion resistance, this component conforms to the watch industry standards ISO 9227 (salt spray test) and N.I.H.S. 9611 (exposure to artificial sweat) after polishing.

WRISTWATCH BRACELET CLASP (HOPTEC, France)

These parts are made of MIM-316L stainless steel. Overall dimensions are 40x10x2 mm and 40x3x2 mm, weights are 2.56 g and 3.72 g. Ejector pins can be designed with customer’s logo. These two parts are assembled in-house. The finishing operation is bending to attain the wrist shape. The density after sintering is 7.86 g/cm³.

BINOCULAR FRAME HINGE (HOPTEC, France)

This part is an intricate component previously made by several processes: investment casting + stamping + welding and machining. Thanks to MIM these processes are combined in only one. Finishing operations are drilling and thread cutting. The surface finish is achieved by glass grinding. The overall dimensions of this binocular frame hinge are 7.40 x 18.00 x 5.50 mm. This part is made of MIM-316L stainless steel. The weight of the part is 1.38 g. The density after sintering is 7.87 g/cm³.

Regarding corrosion resistance, this component conforms to the eyewear industry standards after polishing (ISO 12 870 and NF 80 - 772: exposure to artificial sweat).

CAM (HOPTEC, France)

The overall dimensions of this MIM part are 6.90 x 3.20 x 2.50 mm. Diameters of the holes are 1.05 mm with tolerances of ± 0.015 mm. The weight is 0.22 g and its density is 7.88 g/cm³. No machining is needed after sintering. This part, made of MIM-316L stainless steel, is welded to a stainless steel wire.

The picture shows the 3 stages of MIM process: green part, part after debinding and finished part after sintering.

PACKING MACHINE ASSEMBLY
(Mimecrisa, Ecrimesa Group, Spain)

Group of parts for a clamping device of a packing machine that are produced of the precipitation hardening stainless steel grade MIM-17-4 PH aged to 40 - 45 HRC at a density of 7.65 g/cm³. The material exhibits a high tensile strength (UTS 1200 MPa, yield strength 1000 MPa and elongation 5%) which is required for press fitting and mechanical fatigue strength of the assembly in the machine.

When several MIM components of a device are produced and assembled, a close cooperation between MIM producer and customer is advantageous in order to define the dimensional tolerances actually required by the application.
SAFETY LOCK *(Metalor 2000, Israel)*

This part is used in a light arm and has been specially designed for MIM production. The part is made from MIM-4340 low alloy steel, sintered to a density of 7.50 g/cm\(^3\) and has a hardness of 40 - 44 HRC after heat treatment. The material has a tensile strength of 1550 MPa, yield strength of 1340 MPa. The part is characterized by sharp edges and internal radii of 0.15 mm. In comparison with manufacturing by machining MIM technology provides a 70% cost savings to the end user.

OPERATOR *(Metalor 2000, Israel)*

This part is used in a light arms mechanism and is made from MIM-17-4 PH stainless steel. Due to the complicated shape, conventional manufacture included EDM machining. Therefore the part was very expensive. MIM technology cuts the manufacturing cost to one third. The parts are heat treated with a hardness of 35 - 39 HRC, tensile strength of 1100 MPa, yield strength of 980 MPa.

AERIAL HOUSING *(Metalor 2000, Israel)*

This part is used in an aerial housing assembly of a mobile telephone. It is made from MIM-316L stainless steel. The part has a complicated shape with several through holes in different directions and comparatively thin walls. The mechanical properties are tensile strength - 480 MPa, yield strength - 160 MPa, elongation - 55%. MIM technology offers a price reduction of 80% to the end user.

ADAPTER *(Metalor 2000, Israel)*

This part is used in a mechanism of a sewing machine and has a complicated shape with several slots, protrusions, body size and blind holes in different directions. The part is made from MIM-316L stainless steel and has the following mechanical properties. Tensile strength - 480 MPa, yield strength - 160 MPa, elongation - 55%. MIM technology offers a 60% price reduction to the end user.

W-Cu/Mo-Cu-HOUSING FOR HIGH-FREQUENCY MICROELECTRONIC PACKAGING

Advanced high frequency circuits are integrated on highly sensitive gallium arsenide (GaAs) chips. These chips produce a considerable amount of heat. A special housing material is required that drains and dissipates the heat due to a high thermal conductivity. Further, a low thermal expansion coefficient is needed in order to reduce the thermal stresses due to temperature changes. Tungsten and molybdenum pseudoballoys fulfill these requirements. The parts shown here are made from a Mo60/Cu40 alloy. The thermal expansion coefficient is \( \alpha = 9.7 \) ppm/K, the tensile strength is \( R_m = 490 \) MPa. The parts have been developed in the research project BMBF 03 N 1030 and the development is continued with the objective of a dimensional upscaling.
CASE STUDIES

CAMERA MECHANISM COMPONENT
(Manganese Bronze Components Ltd, United Kingdom)

1.9 g camera mechanism component manufactured from MIM-17-4 PH stainless steel. Designed from the outset as a MIM component. Extremely complex geometry manufactured as a single piece. 2 mm diameter off-centre hole is 17 mm long with a wall thickness of 0.26 mm.

AUTOMOTIVE TURBOCHARGER VANE
(Manganese Bronze Components Ltd, United Kingdom)

Weighing in at 5.2 g and with an overall length of 27.5 mm, this component was previously manufactured by laser cutting from profile rolled strip. The MIM component is manufactured from MIM-310 stainless steel to critical vane profile tolerances with no secondary operations.

INDUSTRIAL ANALYTICAL EQUIPMENT
(Manganese Bronze Components Ltd, United Kingdom)

32 mm square and weighing 38 g this precision component was previously machined from three separate components and assembled by vacuum brazing. The threaded MIM component is a one piece moulding manufactured from MIM-316L stainless steel with no secondary operations and is being supplied at a cost which is cheaper than the previous assembly cost alone.

CAMERA WINDING MECHANISM
(Manganese Bronze Components Ltd, United Kingdom)

Previously assembled from two machined blanks this MIM component is manufactured from MIM-17-4 PH stainless steel as a single moulding incorporating four different precision gear forms.

OPTO-ELECTRONIC PACKAGE
(Manganese Bronze Components Ltd, United Kingdom)

Previously fabricated by furnace brazing five pieces of cut sheet. The MIM component is manufactured from kovar as a single piece moulding. Lead-in wires are attached and the component is coated in gold. Critical features are expansion coefficient and flatness.

WATCH COMPONENTS
(ETA SA Fabriques d’Ebauches, Switzerland)

These watch components such as blanks, bracelet segments, buckle parts with part weights between 1 and 2 g are made of stainless steel MIM-316L. The density required is 7.92 to 7.95 g/cm³ to guarantee a very high polishability. All these parts are MIM net shape parts (except surface finishing).
WATCHCASES *(ETA SA Fabriques d’Ebauches, Switzerland)*

ETA turned to metal injection moulding for its range of SWATCH IRONY watchcases because of significant cost savings compared with the traditional manufacturing process. The cases which follow the same basic design as for the plastic SWATCH, are made of stainless steel MIM-316L. Density after sintering is 7.90 to 7.95 g/cm$^3$. Generally, tolerances must be maintained at ± 0.02 mm. All watchcases are polished or brushed to provide the excellent surface finish required by marketing. Particular attention has been paid to health and safety issues, such as the prevention of nickel allergy by avoiding high nickel contents; only 316L is permitted for watchcases and watch components.

FIREARMS COMPONENTS *(Mimecrisa, Ecrimesa Group, Spain)*

These MIM parts weighing between 5 and 65 g are made of low alloy steels like MIM-4140 or MIM-Fe8Ni0.6C. Densities are 7.45 g/cm$^3$ and 7.55 g/cm$^3$ or 96% of full density. Through hardening to 40 HRC is applied. Parts can also be manufactured from stainless steel MIM-17-4 PH (density 7.65 g/cm$^3$) which is age hardened to 40 HRC using the same injection tool. Safety levers and stoppers were tested for fatigue strength under shooting conditions. No machining is needed, simple coining operations are used in some cases. The traditional manufacturing route by investment casting plus machining has been successfully substituted with a high cost reduction and greater freedom of design.

GEARS FOR ELECTRIC TOOTHBRUSH *(Schunk Sintermetalltechnik, Germany)*

A set of two gears is used to transmit the oscillating motion of the toothbrush drive to the rotating bristles. The gears are manufactured from MIM-316L stainless steel. Corrosion resistance against water and tooth paste having pH values ranging from 4 to 10 is required as well as sufficient strength and resistance to abrasion by the polishing ingredients of tooth pastes. Dimensional tolerances met are between ISO 9 and 10. The production rate is up to 30,000 parts per day.

STEERING LEVER *(Schunk Sintermetalltechnik, Germany)*

This part is supplied for use in an automotive steering assembly. It is made from MIM-4340 low alloy steel and hardened after sintering. The lever is electroplated with zinc and black chromatized in order to provide the required corrosion resistance.

REVERSE GEAR STOP *(CM Pulverspritzguss, Germany)*

This reverse gear stop is used in the gearbox of passenger cars. The part design was optimized on the basis of FEM analysis in order to guarantee sufficient strength of this thin-walled component. It is made from MIM-Fe8Ni. The part weight is 23 g and dimensional tolerances of ± 0.05 mm are met. The finished component is co-injection moulded with a component made from long fibre reinforced PA. The sandwich structure of this composite part is characterized by excellent strength and stiffness due to the external steel body and a noise-damping and wear resistant inlet.
1. Metal injection moulded materials - Feedstock characterisation
Determination of the shrinkage
Draft European Standard, September 1999

1. Scope

This European Standard specifies

- the shape and dimensions of the mould cavity used for making test pieces for the determination of the shrinkage of a material suitable for the metal injection moulding (MIM) process;
- the test procedure to be applied for the determination of the shrinkage of metal injection moulded materials.

2. Field of application

This European Standard is applicable to all MIM metals and alloys, including hardmetal.

3. References

EN 23 954, Powders for powder metallurgical purposes - Sampling
EN 23 369, Impermeable sintered metal materials and hardmetals - Determination of density

4. Definition of the shrinkage

The linear shrinkage \( d \) is the change of the dimension of a MIM test piece in relation to the dimension of the mould cavity in which it has been injection moulded, given in percent of the mould cavity dimension. The knowledge of the shrinkage is required to predict the final dimensions of a sintered MIM component produced in a mould cavity of given dimensions. Further, the shrinkage is often used as a characteristic value of the raw material used in metal injection moulding (feedstock).

The shrinkage is defined as:

\[
d = \frac{L_0 - L}{L_0} \times 100 \text{ [%]} \tag{1}
\]

where

- \( L_0 \) = Dimension of the mould cavity
- \( L \) = Dimension of the sintered test piece

Alternatively, the shrinkage may be defined by the shrink factor \( S \) which is the ratio between the mould dimension and the dimension of the test piece.

\[
S = \frac{L_0}{L} \tag{2}
\]

5. Manufacture of test pieces

5.1 Raw material sampling

The raw material used for injection moulding, the so-called feedstock, shall be a representative sample of a production size lot or, if a smaller quantity is prepared for the test, the constituents shall be representative samples. Sampling shall be carried out in accordance with EN 34 954.

5.2 Mould cavity specifications

The test pieces for the determination of the shrinkage shall have the shape of a coin with dimensions of the mould cavity used for injection moulding of these test pieces as shown in Fig. 1.

- The outer diameter of the mould cavity shall be in the range \( D = 26 - 30 \) mm.
- The height of the mould cavity shall be in the range \( h = 4 - 6 \) mm.
- The gate shall have a diameter of less than 2 mm and be located in the centre of the coin face.

5.3 Injection moulding

Injection moulding shall be carried out under standard manufacturing conditions. All deviations from standard conditions shall be documented and reported with the results.

First samples shall be rejected until steady manufacturing conditions have been achieved. Then a consecutive batch of a statistically relevant number of test pieces shall be moulded for testing.

5.4 Binder removal and sintering

Out of the injection moulded test pieces every second piece shall be taken and forwarded to further processing. The remaining pieces shall be retained for measurements in the green state.

The process of binder removal and sintering shall be performed under the same conditions as are normally used in the series production of MIM components made from the investigated material. All deviations from standard manufacturing conditions shall be documented and reported with the results.

6. Procedure

a) Measure the dimensions of the mould cavity to the nearest 0.001 mm.

b) Optional: measure the diameters of the injection moulded pieces in two positions perpendicular to each other and measure the heights to the nearest 0.01 mm.

c) Measure the diameters of the sintered pieces in two positions perpendicular to each other and measure the heights to the nearest 0.01 mm.

d) Measure the densities of three representative sintered test pieces in accordance with EN 23 369 to the nearest 0.01 g/cm\(^3\).

e) Calculate the average (arithmetical mean values) and the standard deviation of the measured dimensions according to standard statistical procedures.

f) Calculate the shrinkage or the shrink factors for each mean value according to equations (1) and (2). Normally the shrinkage of the average diameter shall be reported.

g) Optionally the standard deviation of the measured dimensions may be reported.

7. Test report

The test report shall include the following information:

a) Reference to this European Standard;

b) All details necessary for identification of the test samples;

c) Any particular manufacturing conditions deviating from standard conditions;

d) The number of test samples evaluated;

e) The density of the test pieces (average of the three measurements);

f) The results obtained;

Details of any occurrence which may have affected the results.

Fig. 1: Specimen shape for the determination of the shrinkage (dimensions of the mould cavity)
2. Metal injection moulded materials - Specification of mechanical properties
Draft European Standard, April 2000

1 Scope
This European Standard is intended to provide the design and materials engineer with the necessary information for specifying the materials of structural components manufactured by the metal injection moulding (MIM) process. It defines material designations, the limits of chemical compositions and guaranteed minimum values of mechanical properties. This standard is designed to avoid misunderstandings between the manufacturer and the purchaser of MIM parts and should assist them both in the effective selection of the proper material for a given product.

2 Field of application
This European Standard specifies material properties for structural parts manufactured by the MIM process. It must not be applied to parts manufactured by classical powder metallurgy routes such as the press-and-sinter or powder forging technologies.

3 References
ISO 2740: Sintered metal materials (excluding hardmetal) - Tensile test pieces
ISO 3369: Impermeable sintered metal materials and hardmetals - Determination of density
ISO 4498: Draft Standard
Sintered metal materials, excluding hardmetals - Determination of apparent hardness and micro-hardness
ISO 6892: Metallic Materials - Tensile testing at ambient temperatures

4 Explanatory notes and definitions
4.1 Selection of MIM materials
This standard has adopted the concept of minimum mechanical property values for the use in structural applications. These values may be used to determine the material best suited to the particular application if the part is manufactured by the MIM process.
Before a particular grade of material is selected, a careful analysis of the part design and its end use is required, including dimensional tolerances and an analysis of part design versus tool design. The final property requirements of the finished part should be stipulated between the manufacturer and the purchaser. Issues such as static and dynamic loading, wear resistance, machinability and corrosion resistance may also be specified.
To select a material optimum in both properties and cost effectiveness, it is essential that the part design and the application be discussed with the MIM parts manufacturer.
The minimum values for MIM materials are expressed in terms of yield strength (0.2% offset method), ultimate tensile strength and percentage elongation in the as-sintered or heat treated condition. In the heat treated condition, minimum property values are given for the lowest and the highest reasonable apparent hardness.
4.2 Evidence of mechanical properties
The tensile properties utilised for establishing this standard were obtained from tensile specimens prepared according to ISO 2740.

Tensile properties obtained from test specimens machined from commercial parts or from non-standard MIM test specimens may vary from those obtained from specimens prepared according to ISO 2740.
Therefore, evidence of mechanical properties for a particular component - unless otherwise agreed between the manufacturer and the purchaser - shall only be obtained by the testing of tensile specimens according to ISO 2740. The specimens have to be manufactured from the same batch of material as the parts, have the same density and to be sintered and heat treated along with the production parts.
Defects introduced during the processing of the actual parts, however, may limit properties which were obtained in the tensile specimen. Additional quality inspection of the parts, such as X-ray examination, may be necessary to satisfy that the minimum property requirements are met if proof testing is not used.

4.3 Proof testing
The practical method of demonstrating the strength of a component through a static or dynamic proof test stipulated between the manufacturer and the purchaser of the part is highly recommended. If possible, this test should be related to the actual function of the part, e.g. break load, bend test, pull test, etc. It is recommended that such tests supplement the material specification designated in the blueprint.
For example, it may be agreed that the breaking load should be greater than a given force. If that force is exceeded in proof tests, the minimum strength is demonstrated. The first batch of parts can also be tested in service and demonstrated to be acceptable. The static or dynamic load to fracture is determined separately and these data are statistically analyzed to determine a minimum breaking force for future production batches. Exceeding that minimum force on future lots is proof that the specified strength requirement has been met.

4.4 Density and residual porosity
MIM materials are usually processed to near full density. Where not otherwise specified, ferrous MIM materials contain less than 5% residual porosity. These pores are finely dispersed, well rounded and isolated and have no access to the surface of the component, so that MIM materials are impermeable to gases or liquids. The densities of MIM components shall be determined according to ISO 3369 or by a gas pycnometer as stipulated between purchaser and producer.

4.5 Heat treatment
Many MIM materials (except for the austenitic stainless steels) may be heat treated to increase strength, hardness and wear resistance. Ferrous MIM parts containing 0.3% or more carbon can be quench hardened and tempered. Tempering is required after quenching for stress relief, optimum strength and durability. The tempering temperature is a major factor in determining the final strength and hardness of the material. These two properties can be varied over a wide range using different tempering temperatures. Therefore, the hardness level acquired after heat treatment should always be stated with quenched and tempered MIM steels. The mechanical properties given in this standard for the heat treated condition are minimum values obtained at the lowest and the highest reasonable apparent hardness levels attained with different process temperatures.
Ferrous MIM parts processed with little or no carbon may be case hardened for a high surface hardness while retaining core toughness. Martensitic and precipitation hardening stainless steels (e.g. MIM-17-4 PH) may also be heat treated for increased hardness and strength. Most MIM materials respond well to normal wrought heat treating practices and procedures, usually in gaseous atmospheres or in vacuum. It is recommended that the heat treatment procedures for any MIM material should be established in cooperation with the MIM parts manufacturer in order to achieve the desired balance of final properties in the finished part.

5 Material designation

Materials produced by the metal injection moulding process shall be designated by the prefix "MIM-" followed by the designation of the alloy grade.

Where applicable, the designation of the alloy grade follows the well-established designation of wrought steels; e.g. the AISI-designated stainless steel 316L produced by MIM is designated as MIM-316L whereas the DIN-designated 42CrMo4 produced by MIM is designated as MIM-42CrMo4. If possible, both designations, AISI and DIN, may equally be applied such as MIM-42CrMo4 = MIM-4140.

Alloys with no corresponding wrought steel of the same composition are usually designated by an abbreviation of their alloy composition. The alloy Fe-2% Ni, for example, has the designation MIM-Fe2Ni.

6 Chemical composition

The chemical composition of each material lists the principal alloying elements by minimum and maximum percentage. The balance is always iron (Fe). “Other elements” includes the total other elements by difference and is reported as a maximum percentage. These may include unintentional impurities as well as other elements added for specific purposes.

7 Mechanical properties

For the determination of mechanical properties ultimate tensile strength, yield strength, elongation and apparent hardness, the standards ISO 2740, ISO 3369, ISO 4498, ISO 6892 (see section 3) should be applied.

8 Material specifications

In the following, a selection of typical ferrous MIM materials is specified. The list of selected materials represents the current status of standardisation and will be continuously extended. The property values of tensile strength, yield strength and elongation given in the tables are minimum values for the as-sintered (AS) and in some cases heat treated (HT) condition. Because of the small number of materials currently specified, a subdivision into different steel groups has not yet been implemented. This is foreseen as a future development of the standard. Until then, the materials are arranged in the order of increasing content of alloying elements.
### 8.1 MIM-42CrMo4 / MIM 4140

**Chemical composition of MIM-42CrMo4 / MIM-4140**

<table>
<thead>
<tr>
<th>Material</th>
<th>C [%]</th>
<th>Si [%]</th>
<th>Mn [%]</th>
<th>Cr [%]</th>
<th>Mo [%]</th>
<th>Others [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIM-42CrMo4 / MIM-4140</td>
<td>0,35-0,50</td>
<td>≤ 0,40</td>
<td>≤0,90</td>
<td>0,90-1,20</td>
<td>0,15-0,30</td>
<td>≤ 1,00</td>
</tr>
</tbody>
</table>

**Mechanical properties of MIM-42CrMo4 / MIM-4140, as sintered, minimum values**

<table>
<thead>
<tr>
<th>Material</th>
<th>Ultimate tensile strength [MPa]</th>
<th>Yield strength [MPa]</th>
<th>Elongation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIM-42CrMo4 / MIM-4140</td>
<td>700</td>
<td>400</td>
<td>3</td>
</tr>
</tbody>
</table>

**Mechanical properties of MIM-42CrMo4 / MIM-4140, minimum values, heat treated to an apparent hardness level of 25 and 50 HRC**

<table>
<thead>
<tr>
<th>Material</th>
<th>Apparent hardness</th>
<th>Ultimate tensile strength [MPa]</th>
<th>Yield strength [MPa]</th>
<th>Elongation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIM-42CrMo4 / MIM-4140 (HT)</td>
<td>25 HRC</td>
<td>750</td>
<td>600</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>50 HRC</td>
<td>1300</td>
<td>1200</td>
<td>2</td>
</tr>
</tbody>
</table>

### 8.2 MIM-Fe2Ni

**Chemical composition of Fe2Ni**

<table>
<thead>
<tr>
<th>Material</th>
<th>C [%]</th>
<th>Ni [%]</th>
<th>Mo [%]</th>
<th>Others [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIM-Fe2Ni</td>
<td>≤ 0,10</td>
<td>1,50-2,50</td>
<td>≤ 0,50</td>
<td>≤ 2,00</td>
</tr>
</tbody>
</table>

**Mechanical properties of MIM-Fe2Ni, as sintered, minimum values**

<table>
<thead>
<tr>
<th>Material</th>
<th>Ultimate tensile strength [MPa]</th>
<th>Yield strength [MPa]</th>
<th>Elongation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIM-Fe2Ni</td>
<td>260</td>
<td>110</td>
<td>20</td>
</tr>
</tbody>
</table>

### 8.3 MIM-Fe2Ni0.6C

**Chemical composition of MIM-Fe2Ni0.6C**

<table>
<thead>
<tr>
<th>Material</th>
<th>C [%]</th>
<th>Ni [%]</th>
<th>Mo [%]</th>
<th>Others [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIM-Fe2Ni0.6C</td>
<td>0,40-0,70</td>
<td>1,50-2,50</td>
<td>≤ 0,50</td>
<td>≤ 2,00</td>
</tr>
</tbody>
</table>

**Mechanical properties of MIM-Fe2Ni0.6C, minimum values, heat treated to an apparent hardness level of 30 and 55 HRC**

<table>
<thead>
<tr>
<th>Material</th>
<th>Apparent hardness</th>
<th>Ultimate tensile strength [MPa]</th>
<th>Yield strength [MPa]</th>
<th>Elongation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIM-Fe2Ni0.6C (HT)</td>
<td>30 HRC</td>
<td>800</td>
<td>700</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>55 HRC</td>
<td>1200</td>
<td>1000</td>
<td>2</td>
</tr>
</tbody>
</table>

### 8.4 MIM-4340 / MIM-40NiCrMo6

**Chemical composition of MIM-4340/MIM-40NiCrMo6**

<table>
<thead>
<tr>
<th>Material</th>
<th>C [%]</th>
<th>Si [%]</th>
<th>Mn [%]</th>
<th>Cr [%]</th>
<th>Mo [%]</th>
<th>Ni [%]</th>
<th>Others [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIM-4340/MIM-40NiCrMo6</td>
<td>0,35-0,50</td>
<td>≤ 0,35</td>
<td>≤0,80</td>
<td>0,70-1,40</td>
<td>0,20-0,30</td>
<td>1,40-2,00</td>
<td>≤1,00</td>
</tr>
</tbody>
</table>

**Mechanical properties of MIM-4340/MIM-40NiCrMo6, as sintered, minimum values**

<table>
<thead>
<tr>
<th>Material</th>
<th>Ultimate tensile strength [MPa]</th>
<th>Yield strength [MPa]</th>
<th>Elongation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIM-4340/MIM-40NiCrMo6</td>
<td>800</td>
<td>650</td>
<td>8</td>
</tr>
</tbody>
</table>

**Mechanical properties of MIM-4340/MIM-40NiCrMo6, minimum values, heat treated to an apparent hardness level of 25 and 48 HRC**

<table>
<thead>
<tr>
<th>Material</th>
<th>Apparent hardness</th>
<th>Ultimate tensile strength [MPa]</th>
<th>Yield strength [MPa]</th>
<th>Elongation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIM-4340/MIM-40NiCrMo6 (HT)</td>
<td>25 HRC</td>
<td>900</td>
<td>750</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>48 HRC</td>
<td>1600</td>
<td>1400</td>
<td>2</td>
</tr>
</tbody>
</table>
### 8.5 MIM-Fe8Ni

**Chemical composition of Fe8Ni**

<table>
<thead>
<tr>
<th>Material</th>
<th>C [%]</th>
<th>Ni [%]</th>
<th>Mo [%]</th>
<th>Others [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIM-Fe8Ni</td>
<td>≤ 0,10</td>
<td>6,50-8,50</td>
<td>≤ 0,50</td>
<td>≤ 2,00</td>
</tr>
</tbody>
</table>

**Mechanical properties of MIM-Fe8Ni, as sintered, minimum values**

<table>
<thead>
<tr>
<th>Material</th>
<th>Ultimate tensile strength [MPa]</th>
<th>Yield strength [MPa]</th>
<th>Elongation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIM-Fe8Ni</td>
<td>380</td>
<td>210</td>
<td>20</td>
</tr>
</tbody>
</table>

### 8.6 MIM-Fe8Ni0.6C

**Chemical composition of Fe8Ni0.6C**

<table>
<thead>
<tr>
<th>Material</th>
<th>C [%]</th>
<th>Ni [%]</th>
<th>Mo [%]</th>
<th>Others [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIM-Fe8Ni0.6C</td>
<td>0,40-0,70</td>
<td>6,50-8,50</td>
<td>≤ 0,50</td>
<td>≤ 2,00</td>
</tr>
</tbody>
</table>

**Mechanical properties of MIM-Fe8Ni0.6C, minimum values, heat treated to an apparent hardness level of 35 and 50 HRC**

<table>
<thead>
<tr>
<th>Material</th>
<th>Apparent hardness</th>
<th>Ultimate tensile strength [MPa]</th>
<th>Yield strength [MPa]</th>
<th>Elongation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIM-Fe8Ni0.6C (HT)</td>
<td>35 HRC</td>
<td>800</td>
<td>700</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>50 HRC</td>
<td>1300</td>
<td>1100</td>
<td>2</td>
</tr>
</tbody>
</table>

### 8.7 MIM-17-4 PH / MIM-X5CrNiCuNb17 4

**Chemical composition of MIM-17-4 PH / MIM-X5CrNiCuNb17 4**

<table>
<thead>
<tr>
<th>Material</th>
<th>C [%]</th>
<th>Si [%]</th>
<th>Mn [%]</th>
<th>Cr [%]</th>
<th>Ni [%]</th>
<th>Cu [%]</th>
<th>Nb+Ta [%]</th>
<th>Others [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIM-17-4 PH/MIM-X5CrNiCuNb17 4</td>
<td>≤ 0,07</td>
<td>≤ 1,00</td>
<td>≤ 1,00</td>
<td>15,0-17,5</td>
<td>3,00-5,00</td>
<td>3,00-5,00</td>
<td>0,15-0,45</td>
<td>≤ 1,00</td>
</tr>
</tbody>
</table>

**Mechanical properties of MIM-17-4PH / MIM-X5CrNiCuNb17 4, as sintered, minimum values**

<table>
<thead>
<tr>
<th>Material</th>
<th>Ultimate tensile strength [MPa]</th>
<th>Yield strength [MPa]</th>
<th>Elongation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIM-17-4 PH/MIM-X5CrNiCuNb17 4</td>
<td>800</td>
<td>660</td>
<td>3</td>
</tr>
</tbody>
</table>

**Mechanical properties of MIM-17-4PH / MIM-X5CrNiCuNb17 4, minimum values, heat treated to an apparent hardness level of 30 and 40 HRC**

<table>
<thead>
<tr>
<th>Material</th>
<th>Apparent hardness</th>
<th>Ultimate tensile strength [MPa]</th>
<th>Yield strength [MPa]</th>
<th>Elongation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIM-17-4 PH/MIM-X5CrNiCuNb17 4 (HT)</td>
<td>30 HRC</td>
<td>850</td>
<td>700</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>40 HRC</td>
<td>1200</td>
<td>1000</td>
<td>2</td>
</tr>
</tbody>
</table>

### 8.8 MIM-316 L / MIM- X2CrNiMo 17 13 2

**Chemical composition of MIM-316 L / MIM-X2CrNiMo 17 13 2**

<table>
<thead>
<tr>
<th>Material</th>
<th>C [%]</th>
<th>Si [%]</th>
<th>Mn [%]</th>
<th>Cr [%]</th>
<th>Ni [%]</th>
<th>Mo [%]</th>
<th>Others [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIM-316 L / MIM-X2CrNiMo 17 13 2</td>
<td>≤ 0,03</td>
<td>≤ 1,00</td>
<td>≤ 2,00</td>
<td>16,0-18,5</td>
<td>10,00-14,00</td>
<td>2,00-3,00</td>
<td>≤ 1,00</td>
</tr>
</tbody>
</table>

**Mechanical properties of MIM-316 L / MIM-X2CrNiMo 17 13 2, minimum values**

<table>
<thead>
<tr>
<th>Material</th>
<th>Ultimate tensile strength [MPa]</th>
<th>Yield strength [MPa]</th>
<th>Elongation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIM-316 L / MIM-X2CrNiMo 17 13 2</td>
<td>450</td>
<td>140</td>
<td>40</td>
</tr>
</tbody>
</table>
Literature
3. 'Powder Injection Molding' by R. M German, Metal Powder Industries Federation, reprinted 1995
5. 'Injection Molding of Metals and Ceramics' by R. M. German, A. Bose, MPIF 1997

This literature and much more is available at the EPMA, Shrewsbury, UK.

Acknowledgements
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“Why you Should choose Powder Metallurgy”

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