1. Introduction

Metal Injection Molding (MIM) is a process which offers advantages over conventional production methods for parts with complex shapes and large production runs. Starting from fine metallic powders, a homogeneous feedstock is produced by mixing with a thermoplastic binder. The thermoplastic binder serves to combine in one manufacturing process the shaping capability that is well known from polymeric materials with the also well established powder sintering technology. After the molding stage the shaped parts are liberated of the binder and the remaining powder preshape is then sintered to a high density part.

The Catamold feedstock is based on a Polyacetal binder, a semi-crystalline thermoplastic material which has good processing characteristics, high dimensional stability, high rigidity and good warm strength. Their good overall property profile make polyacetals the preferred material in demanding applications like precision mechanics, but these advantages in the molding phase can also be utilized in powder injection molding equally well.

However, the decisive advantage of Polyacetal as binder for Catamold® feedstock is the ability for rapid catalytic debinding. In the presence of a suitable catalyst, Polyacetal can be depolymerised far below the melting point to yield the gaseous constituent monomer. Thus catalytic debinding allows binder removal from the molded shape by a controlled, smooth development of gas from the solid binder along the lines of a shrinking unreacted core model. A small amount of residual binder, necessary to confer a certain strength for handling the powder preshape, is then easily eliminated in the early stages of a conventional sintering cycle. Subsequent sintering then allows densification, without application of pressure, virtually to the theoretical values of the metallic material. The processing properties of the highly loaded Catamold® feedstock in the injection molding, debinding and sintering steps are discussed in the following chapters.

2. Injection molding

Compared with plastics, Catamold® has higher thermal conductivity, greater density and higher viscosity. These differences must be taken into account when choosing the right machine, designing the mold and during processing.

2.1 Injection molding machine

Molding machine: For the production of MIM parts using the Catamold grades normal hydraulic or electric injection molding machines can be used. Electric machines, having a faster control feedback loop, may offer advantages in critical applications due to the more exact speed control during injection and hold stages.

Screw geometry: Catamold® can be processed using standard screws for thermoplastics. Choose a screw where the shot volume matches the plasticising capacity reasonably well, otherwise the excessively long residence time may lead to binder degradation which is witnessed by the appearance of gas bubbles. A low compression three zone screw (compression ratio 1:1,6 preferably, maximum 1:2) is recommended. Screw diameters of 18-25 mm are common.

Nozzle: Catamold® is best used with an open nozzle; the very simple, flow-friendly shape dissipates little energy during injection.

Check ring: In order to prevent back-flow into the screw channel during injection, the screw for Catamold® should be fitted with a check ring. This improves the piston action of the screw during injection and in the pressure hold phase. A reversal of the direction of flow due to inexact control in the critical solidification stage may be the precursor to planar particle stacking faults and this will be detrimental to the integrity of the sintered part.

Wear protection: Nitrided or through hardened screws and nitrided cylinder liners are normally adequate for Catamold® processing. Screw tips and check ring should always have nitrided protection.
Mold design: Designing of the mold is a complex process which requires precise knowledge of the processing behavior of Catamold®, the intended application of the part and the commercial factors involved. For example, the number of parts to be produced together with the size of the available injection molding machine and its utilisation rate can determine the requisite number of cavities in the mold. Taking into account the function of the part, the possible positions of gates, parting surface and ejector pins are then examined. The mold filling behavior must then be pictured for various gate variants, and the best position determined. This shows whether a single parting surface is sufficient or whether a more complex mold with two parting surfaces will have to be constructed. When the basic mold design is ready, the detailed design can begin.

Gating system: Since the viscosity of Catamold® is higher than that of most thermoplastic materials, the pressure drop in the gating system should remain as low as possible. This is achieved by the following measures:
- Runners as short as possible.
- Runner cross section as large as possible.
- Runner cross section round.
- Avoid sharp bends.
- No unnecessary acceleration or deceleration.
- Hot runners are rewarding to reduce pressure loss and cycle time.

Gate: The gate should fulfill the following criteria:
- Uniform mold filling.
- Minimal reworking.
- As large as possible to minimise pressure drop.
- Position at the thickest section.
- Direct the jet of melt along or against a wall or pin.

All known gate types are used. Since the majority of parts in powder injection molding are relatively small, the pin gate is the most frequently used. The tunnel gate is particularly suitable owing to automatic degating during demolding. The gate is the narrowest point in the runner. The cross section and number of gates must be selected such that damage or separation owing to shear does not occur.

Molding: Design of Catamold® parts essentially follows the relevant guidelines for the design of molds for thermoplastics:
- Avoid unnecessary and particularly abrupt differences in wall thickness.
- Use stiffening ribs instead of thick walls.
- Core out thick sections.
- Avoid sharp corners, at least 0.3 mm radius.
- Symmetrical pressure application for relatively long free-standing cores.

The following points in particular should be observed when designing Catamold® moldings:
- Owing to the strong jetting tendency, the melt should be diverted on entering the mold.
- Contact of flow fronts (weld lines) away from the gate can form a potential weak point, in particular in relatively large parts, owing to heat loss.
- If more than one flow front moves away from the gate, one of them frequently comes to a halt, and cools, as soon as the flow resistance increases. The areas of the molding behind this front are only completed when all the other areas of the cavity have been filled. These also represent potential weak points of the molding.

Demolding: In order to ensure damage-free demolding and to avoid problems during the molding process, the following aspects should be observed owing to the relatively small shrinkage during cooling of Catamold®:
- 0.5 - 1° tapering should be provided for surfaces in the demolding direction. These surfaces should be polished.
- It is beneficial for the ejectors to contact the part over the largest possible area and without tilting. Profile ejectors should be provided for critical molding areas.

Venting: It must be ensured that included air can escape from the mold to avoid the well-known “diesel” effect. If the air cannot escape via ejector pins or splits at the runner end, it is best to provide special venting means. Good venting slots (depth 0.01–0.02 mm) at the end of the flow path are essential and also there where air is trapped. Supplementary ejector pins are useful to vent pockets of trapped air.

Mold temperature control: Since the mold temperature is one of the most important parameters in processing of Catamold®, uniform temperature control (± 2°C) of the mold must be ensured. Therefore a thermally insulating plate between mold and clamp plate is recommended. Depending on the molding geometry, mold surface temperatures of up to 140°C should be achievable. Owing to its high thermal conductivity, the material cools considerably during mold filling near the surface if the mold temperature is too low. Solidification results in a considerable reduction in cross section, preventing uniform filling of thin zones. Oil temperature control units (3-6 KW) are recommended for mold temperature control.
**Flow behavior:** The flow behavior is shown in Fig. 1 for the example of Catamold® 316LG. The viscosity level is higher than for conventional thermoplastic materials. The pseudoplasticity, i.e. the drop in viscosity at higher shear rates, is more pronounced than in plastics. The consequence of this is that the flow-related increase in pressure for filling narrow cross section gates compared with large gates is relatively small.

**Inspection and Maintenance:** As venting is often essential, regular disassembling and cleaning of the mold is a prerequisite for maintaining quality in large series. Cleaning interval frequency depends on the quality and condition of the mold (wear) and on the operating conditions used. This may range from every 10,000 shots under very unfavourable conditions to every 200,000 shots. Extremely high pressures and temperatures will lead to more frequent maintenance and high wear rate. The mold design should be changed when possible. Use a suitable high temperature lubricant sparingly for moving parts. Grease or oil will ooze from ejectors and cause welding line problems. Wear of the mold will accelerate when flash is appearing and this may affect the operating conditions and the quality of the parts. When the mold is disassembled inspect the gate size regularly for wear. Inspect multi-cavity tools for different wear rates. Do a short shot filling study regularly to detect unbalanced cavities in time.

**2.3 The injection molding operation**

The molding quality is determined mainly by the following parameters:

- Temperature (of the material, cylinder and mold).
- Time (for the injection, hold pressure, cooling).
- Pressure (injection, hold and back pressure).
- Injection speed and screw feeding speed.

**Plasticising:** Catamold® is a homogeneous granular material which does not require further homogenisation. It should be melted under the gentlest conditions so that unnecessary overheating and shearing is avoided. In conventional injection molding machines, the optimum screw speed is between 20-50 RPM or 3-5m/min circumferential speed. However, the extended plasticising time does not adversely affect the overall cycle time, since the cooling time, which is longer anyway, can be utilized for this purpose. To avoid shear heating the temperature profile of the barrel is between 170°C and 190°C.
Looking at the region of the gate, the pressure increases with increasing flow resistance consequently with the flow path in the mold (Fig. 2). Depending on the mold geometry, maximum hydraulic injection pressures from 600 to 1800 bar are required, 1000 bar being typical. Achievement of volumetric filling, i.e. complete expulsion of air from the mold cavity, represents completion of the injection phase. Switch-over to the hold pressure is then carried out via a distance, time or pressure signal.

**Hold pressure:** The hold pressure phase follows completion of the injection phase and ends when atmospheric pressure is reached in the cavity. The hydraulic hold pressure in the machine can be switched off as soon as the sprue has solidified and the gate has been sealed off, since it is no longer possible to affect the molding via the machine pressure. The gate sealing point can be determined experimentally by measuring the molding weight as a function of the hold time set. A stepwise increase beyond the sealing point does not result in a further increase in weight. The hold time should be limited to this time.

**Cooling:** After completion of the hold stage the part is allowed to continue cooling to complete solidification and gain the strength for demolding. A rough guideline is: Cooling time (in seconds) equals wall thickness squared (in mm).

**PVT-diagram:** Compaction and cooling in the mold can also be represented in a PVT-diagram (Fig. 3), which shows the change in specific volume as a function of temperature and pressure. The material is injected at a processing temperature of 180°C and compacted to the hold pressure (mold internal pressure of about 800 bar) with virtually no cooling (A → B). In addition to volumetric mold filling, material is also packed into the mold. After the hold pressure has been reached, the material initially cools at virtually constant pressure. It passes through the crystallization range, during which the specific volume drops constantly since molten material continues to flow into the mold. The volume shrinkage which takes place during cooling is thus compensated. At the end of the crystallization range (point C), the sprue solidifies. The material that has flown into the mold, which is now sealed, continues to cool at constant volume. A pressure reduction takes place, since the material shrinks further. When ambient pressure is reached (point D), the part is under no pressure in the mold. This is the ideal time to remove the molding.
If the hold pressure were set at a higher level, the part would still be under pressure when the mold temperature is reached and would relax in the demolding direction on opening. This should be avoided owing to the anisotropies that would be introduced, besides problems with ejecting. The pressure and mold temperature therefore cannot be varied independently.

These interrelationships also make it clear that void-free parts can only be produced if the gate is in the region of greatest material accumulation.

Since the molding contains regions which do not solidify until significantly after sealing of the gate, it is no longer possible to introduce sufficient material to compensate volume shrinkage. The outer skin of the molding rapidly forms a stable frame on solidification. In general, voids or pores form in the areas where the melt solidified last in the interior.

**Shrinkage:** According to DIN 16901, shrinkage in injection molding is the difference between the dimensions of the mold and the dimensions of the molding (in the cooled state) relative to the mold dimensions. Shrinkage is composed of a number of elements. This is illustrated in Fig. 4 by the example of a part injection molded from Catamold® 316LG: The dimensions of the mold are about 0.2% greater at the processing temperature (130°C) than at room temperature owing to thermal expansion. This effect counters shrinkage. If the hold pressure is set correctly, the molding is demolded under atmospheric pressure at the mold temperature. The dimensions of the green compact immediately after demolding correspond to the mold dimensions at the mold temperature. The part then cools to room temperature (from D to E, Fig. 3), while the volume of the part shrinks isotropically by 2.2% and the length, depending on the degree of filling, by around 0.7%. The overall linear shrinkage of the green compact is thus about 0.5%.

**Fig. 3: PVT-chart for Catamold® 316LG**

**Fig. 4: Shrinkage during molding**
3. Debinding

**Debinding principle:** Catamold is totally unique in its ability for catalytic gas phase decomposition of the binder. This ability is innate to the chemical structure of Polyacetal. The polyacetal chain is characterised by recurring carbon-oxygen bonds as depicted in Fig. 5. The oxygen atoms in the polymer chain are susceptible to acidic attack, causing the macromolecule to split off successively \( \text{CH}_2\text{O} \) (formaldehyde) units when it is exposed to a suitable acidic catalyst. The catalyst used for the debinding process is gaseous nitric acid, with a concentration of > 98.5%.

This residual organic fraction is expelled in the subsequent sintering process.

The reason why this reaction is so eminently suited for debinding in powder injection molding are the conditions under which this reaction can take place. Debinding proceeds at a high speed at 110°C, which is far below the melting range of Polyacetal, 150°C – 170°C (this is not identical with the solidification range of Figure 3), so the polymer is directly converted from a solid into a gas. The binder-gas interface proceeds inward at a linear speed of 1–2mm/h, depending on the Catamold grade. The small formaldehyde gas molecules (boiling point –21°C) are able to escape easily and without disrupting the powder particle packing structure through the already porous outer zone of the part (Fig.6). At the same time the binder still is fully rigid, lending the parts a continuing stiffness during debinding, avoiding any plastic deformation and resulting in better tolerances.

After completion of Polyacetal removal there is a residual amount (usually around 10 weight % of the original binder content) of an acid resistant binder component which confers a certain strength for handling to the preshaped powder.

**Debinding oven:** Fig. 7 (page 7) shows how the debinding process has been implemented in practice. The parts to be debinded are placed on support plates on oven grids. The oven is equipped with a fan to ensure thorough mixing of the gases. A small amount of the catalyst is metered into the oven via a pump and subsequently evaporates in a ceramic or glass dish. The carrier gas used is nitrogen.

A laboratory oven (50 l) requires about 40 g/h of nitric acid and 500 l/h of N\(_2\). Larger batch debinding ovens up to 430 liter volume are available from several oven manufacturers. The debinding process also allows the use of continuous debinding ovens and this is common practice in MIM using Catmold.

In the 1h purge cycle before commencing debinding, the oven receives an inert atmosphere, at the same time allowing the green parts and the oven to warm up to 110°C. A too long debinding time does not harm the parts, while too short debinding produces scrap. It is therefore recommended to start generous, decrease the debinding time in one hour steps until the weight loss starts to decrease and then return to the previous debinding time.

The exhaust gas is disposed of in a two-stage burner. In the first stage, the reaction gas is
Debinding rate: Typical speeds of the debinding front at an oven temperature of 110°C are between 1 mm/h and 2 mm/h. The debinding time will increase if the oven loading is increased. Leaving the parts in the oven in excess of the minimum debinding time generally has no harmful effect on the parts.

Process control: For process control, it is useful to debind one or more control parts. The final weight of the parts allows the degree of debinding to be determined. The debinding state can also be assessed from the fresh fracture surface. A core which has not been debound is immediately apparent in the fracture mirror and displays a different color. More details are discussed in 9.

Continuous debinding: The short debinding times of Catamold® moldings have also made it possible to use a continuous debinding and sintering oven. (Fig. 8) Like the batch oven, the continuous oven also uses a nitrogen/catalyst mixture. The gas stream flows against the transport direction of the parts and is extracted at the top for combustion. On entering the oven, the parts pass through a prewarming lock, which prevents condensation of the catalyst on the surface of the parts.

Support of the parts: The type of support of the parts in the debinding oven depends on the part geometry. Moldings are positioned with the best standing side on the trays. The distance between the parts should be sufficiently large that unhindered gas exchange can still take place. The debinding time can be shortened by placing the parts on a perforated sheet or on a wire mesh so that gas exchange can also take place the parts beneath.

Debinding temperature: The lower practical limit is 100°C to keep a safe distance from the dewpoint of nitric acid, the upper limit is in principle set by the softening point of the binder (150°C-170°C). In practice the upper temperature is 140°C. 110°C-120°C are recommended as standard.

Nitric acid: in principle the debinding speed can be increased with the acid flow, but beyond 40ml/h (50g/h) at 500l/h nitrogen flow rate the concentration of oxidising gases plus the formaldehyde from debinding can, in extreme cases, lead to conditions of spontaneous combustion. Our recommendations and specifications are based upon experience with > 98,5% nitric acid. The debinding process functions also with less concentrated acid, but the use of less concentrated acid is at the producer’s responsibility.

4. Sintering

Sintering involves thermally activated transport of material on an atomic scale, resulting in a decrease in the specific surface area of the
powder particles. The growth of particle contacts and the reduction in the pore volume result, in macroscopic terms, in shrinkage of the parts. The aim of sintering is to modify the properties of the article, which is highly porous in the de-bound state, towards the properties of a pore-free material.

**Shrinkage process:** Exposure to heat produces a material-typical shrinkage behavior, as shown by the dilatometer curve in Fig.10. The measurement is based on the temperature profile described in Fig. 9. For Catamold® FN08, shrinkage commences as low as 600°C. Up to about 900°C, the shrinkage rate constantly increases. The parts then shrink significantly more slowly and approach the final value asymptotically. It is striking that the shrinkage process for Catamold® 316LG commences much later at about 1100°C. However, total shrinkage for this material is significantly less owing to the high degree of filling and is only achieved at higher temperatures. In order to get narrow dimensional tolerances, the maximum shrinkage should be achieved. If the sintering process is terminated much before the asymptotic end value has been reached, slight temperature differences in the oven cause considerable scatter of the part dimensions.

<table>
<thead>
<tr>
<th>Catamold®</th>
<th>hydrogen</th>
<th>nitrogen</th>
<th>vacuum</th>
</tr>
</thead>
<tbody>
<tr>
<td>FN02</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>FN08</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>8620</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>42CrMo4</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>100Cr6</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>430</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>316L</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>17-4PH</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>W</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>

| (✓) | recommended | (✓) | possible |

**Table 1: Sintering atmosphere (examples)**

Slight temperature differences in the oven cause considerable scatter of the part dimensions.

**Support during sintering:** The greatest challenge in supporting the parts during the sintering process is to avoid hindering the high shrinkage. The trays must be sufficiently smooth and must not interact with the part. Long overhanging ar-

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*Fig. 9: Temperature profile during sintering*

*Fig. 10: Shrinkage profile*
Eas tend to bend. If warping cannot be avoided, it must be seen whether molded cross-pieces or supports can solve the problem. However, this would require an additional step to remove these elements at a later stage.

5. Properties

The range of Catamold® products extends from pure iron and iron/nickel alloys to highly alloyed stainless steels, soft magnetic materials, tool steels and special alloys. More information about that you will find in the current Catamold brochure. Please find the Catamold product range in our current Catamold brochure or on our web site www.basf.de/catamold.

Density: The density achieved in the finished parts is a measure of the sintering quality. The higher the density achieved, the better, in general, the technological properties. Given appropriate process control, the density of Catamold® materials ranges from 96 to 100% of the theoretical value. The remaining pores are very small and uniformly distributed. Since they are virtually spherical, these pores are not responsible for crack initiation.

Dimensional accuracy: The accuracy of the linear shrinkage usually achieved in the MIM process is shown in the table 2. In reference to standard DIN ISO 2768 the following typical tolerances apply to MIM parts. In order to observe these tolerances, shrinkage is tested on each production batch.

<table>
<thead>
<tr>
<th>Nominal dimension</th>
<th>Tolerance +/- mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 3 mm</td>
<td>0.05 mm</td>
</tr>
<tr>
<td>3 – 6 mm</td>
<td>0.06 mm</td>
</tr>
<tr>
<td>6 – 15 mm</td>
<td>0.075 mm</td>
</tr>
<tr>
<td>15 – 30 mm</td>
<td>0.15 mm</td>
</tr>
<tr>
<td>30 – 60 mm</td>
<td>0.25 mm</td>
</tr>
<tr>
<td>&gt; 60 mm</td>
<td>+/- 0.5% of the dimension</td>
</tr>
</tbody>
</table>

Table 2: tolerances, MIM Expertenkreis Germany

The dimensional accuracy actually achievable by the processor depends amongst others on the quality of the production equipment. Fig. 11 shows the stages during which shrinkage occurs in the MIM process. It is immediately evident that the sintering step provides the greatest opportunity for modifying shrinkage and therefore demands particular attention.

Mechanical properties: Typical values which can be achieved with Catamold® materials, given correct processing, are listed in Table 3. These guide values can in some cases be modified considerably by the processing.

Sintering of Catamold® FN02 and FN08 under pure hydrogen gives a virtually carbon-free ferritic structure. The increase in hardness of Catamold® FN08 to 120HV compared with pure iron (Catamold® FS: 60HV) is a major reason for alloying with nickel. Under nitrogen, the initial maximum carbon content of 0.3-0.5% is retained.
Fatigue properties: The fatigue properties of Catamold® FN02, 8620 and 42CrMo4 are discussed in 2. Table 5 shows the summarised data. The fatigue properties are excellent compared with P/M technologies and there need be no reluctance to use MIM steels where dynamic loads are applied.

Surfaces: After sintering, Catamold® parts have a surface roughness in the order of magnitude of the powder size (Table 4). Stainless steel parts with a density of about 99% of the theoretical value can easily be polished after sintering. Parts made from low-alloy steels can be blued, chrome-plated or nickel-plated.

### Table 5: Fatigue strength

<table>
<thead>
<tr>
<th>Catamold®</th>
<th>FN02</th>
<th>8620</th>
<th>42CrMo4</th>
</tr>
</thead>
<tbody>
<tr>
<td>as sintered</td>
<td>150 MPa</td>
<td>200 MPa</td>
<td>150 MPa</td>
</tr>
<tr>
<td>heat treated</td>
<td>250 MPa</td>
<td>500 MPa</td>
<td>500 MPa</td>
</tr>
</tbody>
</table>

### Table 3: typical mechanical Properties of selected Catamold grades

<table>
<thead>
<tr>
<th>Catamold®</th>
<th>condition</th>
<th>density [g/cm³]</th>
<th>yield strength $R_{0,2}$ [MPa]</th>
<th>tensile strength $R_m$ [MPa]</th>
<th>elongation [%]</th>
<th>Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>FN02</td>
<td>sintered in H₂ case hardened</td>
<td>7.5</td>
<td>150</td>
<td>250</td>
<td>25</td>
<td>100 HV10, 600 HV10</td>
</tr>
<tr>
<td>FN0205</td>
<td>sintered in N₂ heat treated</td>
<td>7.5</td>
<td>170</td>
<td>380</td>
<td>3</td>
<td>120 HV10, 340 HV10</td>
</tr>
<tr>
<td>FN08</td>
<td>sintered in H₂ case hardened</td>
<td>7.5</td>
<td>210</td>
<td>380</td>
<td>15</td>
<td>120 HV10, 600 HV10</td>
</tr>
<tr>
<td></td>
<td>sintered in N₂ heat treated</td>
<td>400</td>
<td>700</td>
<td>400</td>
<td>3</td>
<td>2100 HV10</td>
</tr>
<tr>
<td></td>
<td>heat treated</td>
<td>1100</td>
<td>1250</td>
<td>530 HV10</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>heat treated</td>
<td>1100</td>
<td>1900</td>
<td>530 HV10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8620</td>
<td>sintered in H₂ case hardened</td>
<td>7.4</td>
<td>400</td>
<td>650</td>
<td>5</td>
<td>190 HV10, 650 HV1, 800 HV1</td>
</tr>
<tr>
<td>42CrMo4</td>
<td>sintered in N₂ heat treated</td>
<td>7.4</td>
<td>400</td>
<td>650</td>
<td>6</td>
<td>180 HV10</td>
</tr>
<tr>
<td>100Cr6</td>
<td>sintered in N₂ heat treated</td>
<td>7.4</td>
<td>500</td>
<td>900</td>
<td>5</td>
<td>230 HV10, 70 HRC</td>
</tr>
<tr>
<td>430</td>
<td>sintered in H₂ heat treated</td>
<td>7.6</td>
<td>200</td>
<td>350</td>
<td>30</td>
<td>125 HV10</td>
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<tr>
<td>316L</td>
<td>sintered in H₂ heat treated</td>
<td>7.8</td>
<td>180</td>
<td>510</td>
<td>50</td>
<td>120 HV10</td>
</tr>
<tr>
<td>17-4PH</td>
<td>sintered in H₂ heat treated</td>
<td>7.6</td>
<td>660</td>
<td>950</td>
<td>3</td>
<td>320 HV10, 38 HRC</td>
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<tr>
<td></td>
<td>heat treated</td>
<td>950</td>
<td>1100</td>
<td>8</td>
<td>42 HRC</td>
<td></td>
</tr>
<tr>
<td></td>
<td>heat treated</td>
<td>1050</td>
<td>1180</td>
<td>8</td>
<td>42 HRC</td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>sintered in N₂ heat treated</td>
<td>8.1</td>
<td>800</td>
<td>1200</td>
<td>1.2</td>
<td>520 HV10, 66 HRC</td>
</tr>
<tr>
<td>W</td>
<td>sintered in H₂</td>
<td>17.8</td>
<td></td>
<td></td>
<td></td>
<td>320 HV1</td>
</tr>
</tbody>
</table>

and results predominantly in a perlitic structure, which is then also readily hardenable.

Catamold® 8620, 42CrMo4 and 100Cr6 are sintered under nitrogen. Catamold® 8620 can be hardened to 650 HV1. After appropriate heat treatment, tensile strengths of 1450 MPa along with good toughness are achieved with Catamold® 42CrMo4. For Catamold® 100Cr6, the usual hardness levels of above 700 HV10 (60 HRC) can be achieved.

With Catamold® 316LG, very low carbon contents of ≤ 0.03 % are achieved under reducing atmospheres. Sintering under vacuum produces a somewhat coarser grain structure with rather fewer micropores than does sintering under hydrogen. The typical tensile strength is 510 MPa, and hardness is 120 HV10. The usual corrosion tests for this material are passed easily.

Sintering of Catamold® 17-4PH under hydrogen produces a virtually pore-free, two-phase structure with a hardness of about 320 HV10. The desired precipitation hardness of 42 HRC can be achieved by heat treatment. This material likewise exhibits good corrosion resistance.
Magnetic properties: Catamold® feedstock grades are available in nonmagnetic steels like 316L, ferromagnetic steel e.g. 430 and soft magnetic alloys e.g. FeSi3. More information (hysteresis curves) is available.

Corrosion resistance: Catamold® feedstock grades are available in corrosion resistant grades and in low alloy grades, details are discussed in 8.

Recycling: If the Catamold feedstock has been processed properly, recycling is possible. Common practise is to maintain a 50:50% mixture of virgin and recycle feedstock. The number of times Catamold can be recycled depends on the product processed, the accumulated residence time in the cylinder and the shear stress during molding. In extreme tests with 100% recycle we found 3-5 passes, starting with virgin feedstock, were possible without a significant loss in moldability and quality.

Table 4: Surface roughness

<table>
<thead>
<tr>
<th>Catamold®</th>
<th>FN08</th>
<th>316LG</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_z$</td>
<td>9,2 µm</td>
<td>10,4 µm</td>
</tr>
<tr>
<td>$R_a$</td>
<td>1,4 µm</td>
<td>1,6 µm</td>
</tr>
<tr>
<td>$R_m$</td>
<td>11,6 µm</td>
<td>12,4 µm</td>
</tr>
</tbody>
</table>

6. Applications

Typical applications for the MIM process are in all industrial applications e.g. the automotive-and machinery industry, in jewelry production, in machine parts, ironwork and medical equipment, and a variety of applications in machine construction (gear wheels, levers, etc.). See picture gallery Fig.14.

The MIM process offers greater design flexibility. In general, the MIM process gives much higher densities (96 - 100%) and consequently a much better mechanical property spectrum than powdermetallurgy. While the hardness of the starting powders in the press sintering process is crucial for achieving a solid compact, this factor plays virtually no role in the MIM process. The greatest cost factor in the production of long runs is for the pressing molds, while costs in the MIM process are predominantly determined by the starting powder.

Compared with investment casting, the MIM process gives narrower tolerances and better surfaces. Compared with cast steels, the structure in the MIM process is homogeneous throughout the entire thickness. The tendency to warp during subsequent heat treatment is much lower. Heat treatment can be omitted entirely for stainless steels and low-alloy steels. Production close to the final contours also has major advantages if corresponding material is difficult or impossible to machine.

Overall, the MIM method presents considerable potential for automation. An important step toward utilizing this potential is the continuous plants for Catamold® which are already in use today, as shown in Fig. 13. Coupling with the injection process brings the concept of a fully automatic MIM plant within reach.

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**Note:** The information submitted in this publication is based on our current knowledge and experience. In view of the many factors that may affect processing and application, these data do not relieve processors from the responsibility of carrying out their own tests and experiments; neither do they imply any legally binding assurance of certain properties or of...
suitability for a specific purpose. It is the responsibility of those to whom we supply our products to ensure that any proprietary rights and existing laws and legislation are observed.

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Fig. 14: picture gallery

rings: Catamold P.A.N.A.C.E.A.

medical part: catamold Titanium

burning chamber Catmold 316 LG

latch for convertible top: Catamold FN02

spectacle part Catamold 17-4PH

wheels and plunger: Catamold Titanium and 17-4PH