

Metal Injection Molding for Superalloy Jet Engine Components

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METAL INJECTION MOLDING FOR SUPERALLOY JET ENGINE COMPONENTS

The Metal Injection Molding [MIM] process is a combination of powder metallurgy technologies and the shape making capability of plastic injection molding. Major market segments for MIM are consumer electronics, automotive, firearms and medical. MTU Aero Engines GmbH advanced the MIM process using high temperature superalloys powders. Optimized thermal processes and superalloy powders utilize nearly the full potential of the superalloys challenged by the required high dynamic strength and aerospace quality. Compressor vanes and small retainers are now proving their quality in a test engine accompanied by the evaluation of material data. The development of MIM superalloy aerospace parts emerges the usage of MIM to more technically sophisticated applications.

1.0 INTRODUCTION

Within the past decades, aero engines have been continually improved in terms of performance, durability and reliability. Airlines and passengers rely on a steadily increased level of safety and performance. On the other hand, there is the airlines' demand for cost savings. The aero engine manufacturers compete to meet their customers' requirements. Therefore, cost reduction is given high priority in development. Mainly for high-pressure compressors, MTU has been thoroughly investigating Metal Injection Molding (MIM) for achieving cost savings. MIM is regarded as an innovative, net-shape processing approach for compressor components. The MIM process is a combination of powder metallurgy technologies and the shape-making capability of plastic injection molding. Major market segments for MIM are consumer electronics, automotive, firearms and medical applications. When used in aero engines MIM components have to meet challenging technical requirements to be successful. With respect to costs, investment castings are usually most attractive for jet engine parts which are subject to low or moderate mechanical loads in operation. Since material strength values achieved by MIM parts can exceed those of castings, MIM can be further developed for the preferred low-cost processing route for highly loaded components which exhibit complex shapes and are produced in large quantities.

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Metal Injection Molding for Superalloy Jet Engine Components

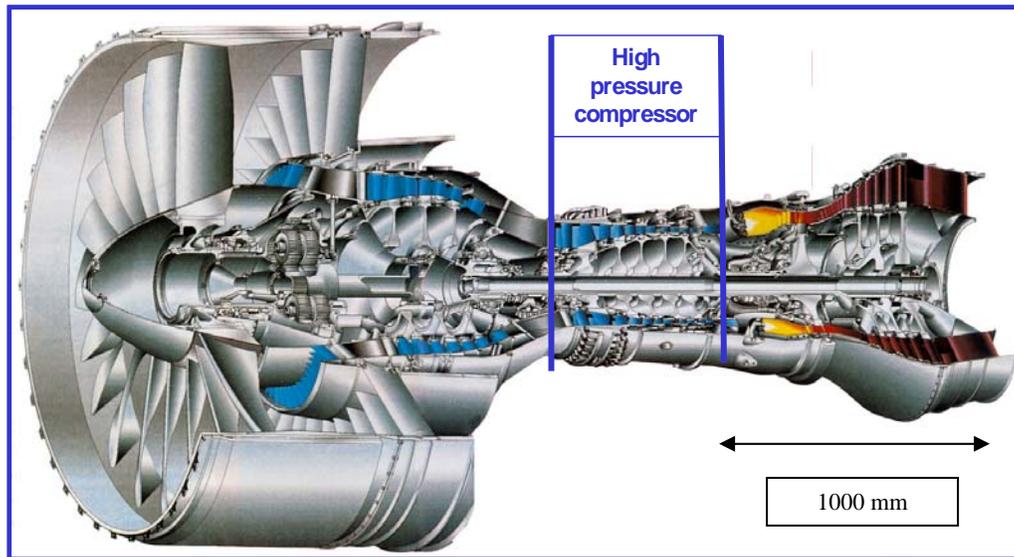


Figure 1: Aero engine overview

2.0 MIM AERO ENGINE PARTS

An aero engine consists of roughly 80.000 parts of different materials and sizes. The size of the parts covers a wide range. The injection molding process and the laws of sintering limit the MIM process to a comparatively small part size. In an aero engine the size of parts depends on their position along the gas path. Casings, disks and fan blades can exceed more than one meter in length or diameter. In common aero engines the size of parts located in the high-pressure compressor (Figure 1) is best suited for the MIM process.

In general, the MIM production route has its economical advantages for high volume parts. Compressor vanes, for example, provide an adequate volume. The loading of the stator vanes is usually lower than that of rotating blades.

The number and the size of high-pressure compressor vanes make them attractive for the MIM process. Therefore the stator vanes have been selected as the preferred parts for a first application of MIM (Figure 2/3).

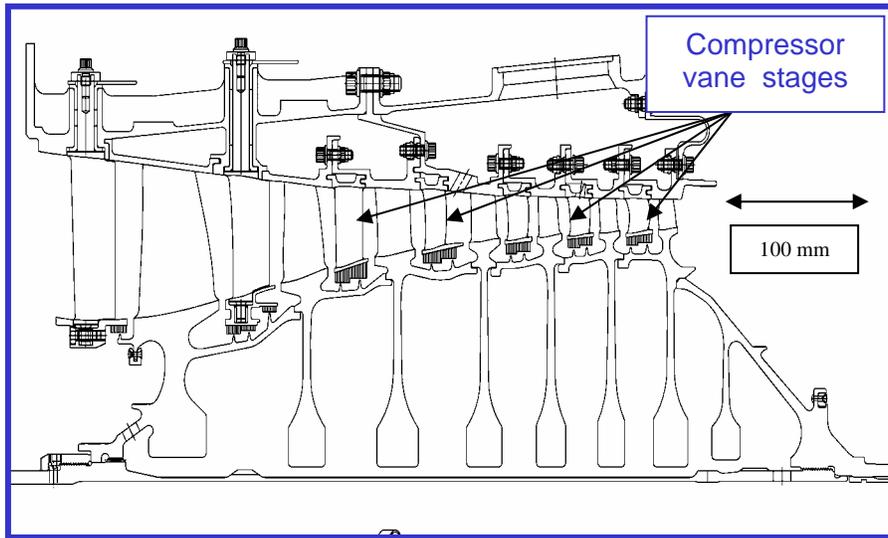


Figure 2: High-pressure compressor (schematic)

State-of-the-art stator vanes are manufactured from forgings by milling or electrochemical milling. They are clustered by brazing. A vane cluster is built up by 4 to 6 single vanes. The vanes are subject to high vibration stresses and thus require reliable fatigue strength. Therefore the quality of the material must meet more stringent requirements than most of the already successful MIM applications of other business fields.



Figure 3: Single MIM Compressor vane

2.1 MIM Alloys for Jet Engine Parts

With regards to which materials are used for manufacturing jet engine compressors, the volume of titanium- and nickel-base alloys remained quite constant over the last decades. The high-pressure compressor vanes are usually made from nickel-base alloys as they are exposed to an operating temperature of up to about 650 °C. Nickel-base alloys are generally the materials of choice in the hot zones of aero engines. The aero engine industry identified a number of different nickel alloys for their applications. The ingots as well as elemental

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powder of these superalloys can be used either for forging, investment casting or for generating powder. The availability of these materials provides a dependable base also for long-term MIM development. Also nickel superalloys are less sensitive to imperfections than titanium alloys. But nickel alloys are not yet very common in the MIM industry. The powder is expensive. The process for nickel alloys is tricky as compared with steel. There is a considerable effort necessary to develop a MIM process for nickel alloys. However, for various industrial high- temperature applications, including aerospace, there is an increased interest in MIM components made from Ni-base alloys [1]. The objective of MTU is to replace costly vanes, e.g. precision forged or electrochemically milled parts. This provides a chance for MIM also to be economically successful with nickel alloys. Apart from the vanes, some other small wrought parts can also benefit from a standard nickel alloy MIM process.

2.2 MIM Benefits for Jet Engine Parts

The key for cost reduction with MIM is the net-shape capability of the process. MIM parts can substitute wrought parts without or with minor changes in design. With MIM, the required machining operations are minimized. For example, complex and/or tiny design features like edges, threads or weight-reducing pockets are already shaped into the green body upon molding. Although upfront engineering cost (molds, setters) are higher than for conventional machining. However, machining requires much more expensive setups as the shape gets more complex. The manufacturing cost advantages of MIM result from short injection times, high-volume batch processes for debinding, sintering and heat treatment. The net shape capability further reduces the wasting of material which adds to the cost savings. MIM also shows advantages as compared with investment castings. Investment casting of small parts often suffers from the mass difference between the part and the molten metal flow path (“runner”). An unfavourable mass difference can lead to warping, alloy segregation and voids. Additionally, casting often requires extensive machining to achieve correct dimensions and surface finish.

The strength of the material is also an important consideration in choosing among machining of forgings, investment casting and MIM. Figure 4 schematically shows the correlation between strength and cost.

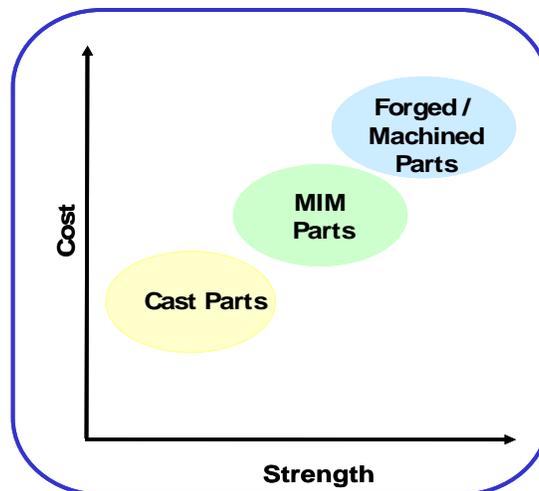


Figure 4: Schematic comparison between strength and cost for different manufacturing routes

Especially when expensive materials like nickel alloys are used, net-shape manufacturing is a key success factor with regard to costs. With MIM, material waste is minimized and a nearly 100% material usage can be achieved [2]. Reducing costs for waste as well as for energy is a main advantage of the MIM process with respect to the future material and process development challenges for aero engine companies presented in [3].

3.0 MIM PROCESS STEPS

Basic MIM process steps (Figure 5) are:

- mixing of metal powder with binder (feedstock)
- molding of feedstock into a green body
- removal of binder using solvents and/or by thermal processes
- sintering to high density
- hot isostatic pressing (HIP) for full density.

With regard to shaping the raw part, Metal Injection Molding is very similar to the injection molding process used for plastics. A homogeneous feedstock, consisting of metal powder of a certain grain size distribution mixed with an organic binder, is pressed through screw and barrel and then injected into the mould cavity. The MIM process can produce special imperfections depending on the different production steps and the vane geometry. Thin sections of the part hamper the flow of the feedstock in the mould and can cause porosity. The very thin section of the leading and trailing edges might be a critical feature. An optimized gating system and optimized injection parameters are important for the homogenous density of the green part.

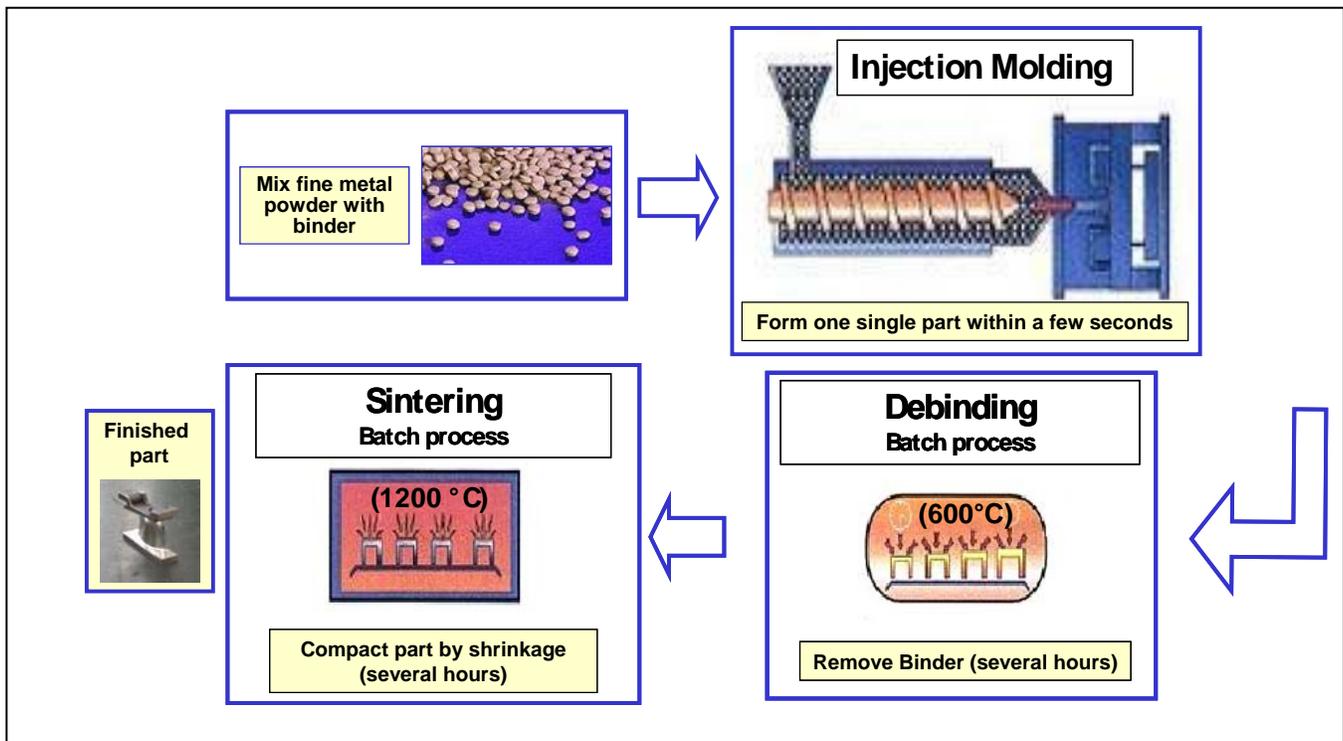


Figure 5: MIM production process steps (schematic)

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After a short cooling, the green body is ejected from the tool. This quick injection process is very suitable for mass production. However, the parting lines of the mould and the ejectors can mark the parts in unfavourable areas. This has to be taken into account in the mould design and construction.

Removal of the binder is achieved by a batch process. A solvent applied and/or thermal debinding for several hours dissipate the binder usually at temperatures below 600°C. The residual amount of binder must be carefully kept under control. The part without binder (so-called “brown part”) is porous and fragile. The brown parts are carefully transformed to the sintered condition.

Sintering is also a batch process in which defined heating and cooling rates are used. Depending on the alloy type, the maximum temperature may reach about 1200°C. During sintering the densification of brown parts takes place by diffusion and closing of porosity. For highly loaded parts, any residual porosity is eliminated by successive hot isostatic pressing (HIP, batch process). Usually, the “as-sintered surface” needs a surface finishing treatment of the airfoil section. But also machined airfoil surfaces require further processing by tumbling or grinding. The tumbling process parameters can be adapted to suit the MIM surfaces.

3.1 MIM Powder

The powder manufacturing process starts with a conventional high-quality ingot of the nickel alloy. The ingot is melted and atomized in an argon atmosphere to avoid oxidation of the alloy. The pollution of the particle surface with oxides degrades the sinter activity. The powder is sieved to obtain the desired particle size distribution. The powder particle size distribution used for a specific part depends on:

- required strength
- minimum thickness
- specified surface quality (roughness).

The powder particle size distribution must be specified to achieve an optimal powder filling. Round powder particles give the best filling. One threat for the strength of MIM parts are inclusions and impurities. Ceramic impurities can be released by the ceramic crucible, for example. Breakouts of the atomization nozzle can also contaminate the powder. The use of ceramic filters in front of the atomization nozzle helps to reduce and limit the size of the ceramic impurities of the crucible. These imperfections are further reduced to a defined limit by sieving. In addition, foreign particles can result from binder residues. These residues form carbides with the alloy during the following thermal treatment. Usually, the carbide agglomerations are located between the powder grains. They directly mark the grain boundaries. The permissible maximum size and concentration are determined by extensive static and dynamic strength investigations of samples and parts. Compliance with specifications is monitored by metallographic examinations. A consistent process control helps ensure the defined quality standard.

3.2 Control of Sintering

During sintering and densification, linear shrinkage in the range of 12 – 15% occurs, mainly depending on powder/binder volume content. The volume change between a green and a sintered compressor vane is shown in Figure 6. Obviously, control of the sintering process is a key success factor. The sintering process for high-quality parts is characterized by:

- a uniform temperature distribution within the sintering furnace
- an optimized sinter temperature program to achieve a high sinter density and the required microstructure, e.g. grain size
- special setters in order to prevent shape deviations and distortions
- adjusted heating and cooling rates to restrain distortions and shrinkage stress

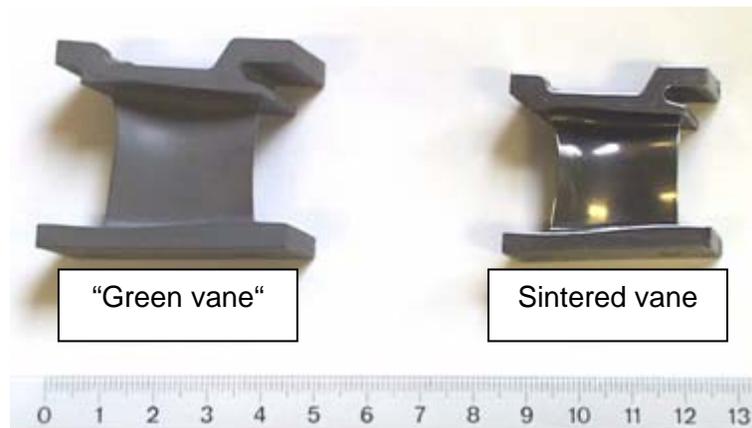


Figure 6: Comparison of green vane and sintered vane

An inhomogeneous thickness distribution of the part is prone to cause shrinkage cracks. Overall tolerances are also influenced by shrinkage distortion. An adequate design of the setters eliminates shrinkage cracks and reduces distortion to an acceptable level.

Quality also includes low porosity. A certain porosity remains after sintering. If some of these residual pores are connected to the surface, they cannot be closed by compaction of the material by successive hot isostatic pressing (HIP). Isolated pores generally do not cause damage. Nevertheless, the effects of a concentration of such pores may be the same as those of one large imperfection.

With the application of optimized sintering and thermal treatment parameters similar strength and ductility values are achieved as with forged materials. MIM materials strength values matching or being close to those of forged materials have been reported in other publications [2], [4]. This applies also to the fatigue strength, determined on specimens by high-cycle fatigue testing at relevant operating temperatures. The results of testing show a measurable advantage over similar alloys in the cast condition. One reason for the high strength is the grain size of the MIM material. Grain size is related to strength. The sintering cycle (time, temperature) governs the grain growth. The achieved grain size ensures sufficient fatigue strength of the MIM material for jet engine applications.

MTU's MIM development program also demonstrated that engine vanes with a complex 3D design could be net-shape processed by a stable, well-controlled sintering process. The vanes were produced with high dimensional quality. A low surface roughness was achieved. The single vanes meet the quality requirements for subsequent manufacturing steps, i.e. brazing to form a vane cluster consisting of four vanes. After successive brazing of a conventional honeycomb seal onto the inner shroud, vane cluster prototypes were qualified for engine testing (Figure 7).

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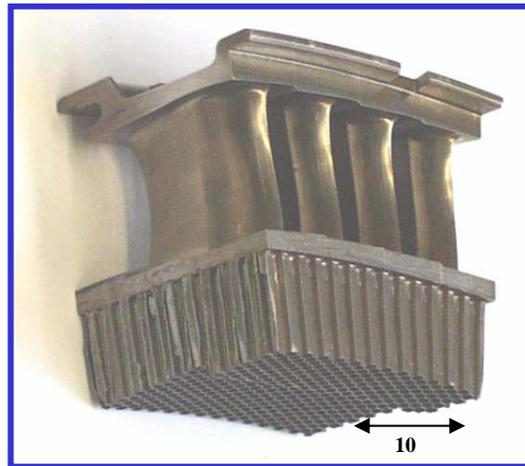


Figure 7: MIM vane cluster prototype for engine testing

4.0 OTHER MIM APPLICATIONS

Honeycomb seals (Figure 8) for turbines are another potential MIM application, since they exhibit a complex shape and a high production volume. Prototypes have been processed starting from a nickel-base powder to demonstrate the basic feasibility of MIM. They are scheduled for rub-in tests in a turbine test rig environment. Plans are to adjust the abrasion capability of the MIM material by inclusions or intentionally induced porosity. Powder metallurgy opens up new routes for a special material design which cannot be realized by conventional casting or forging approaches.

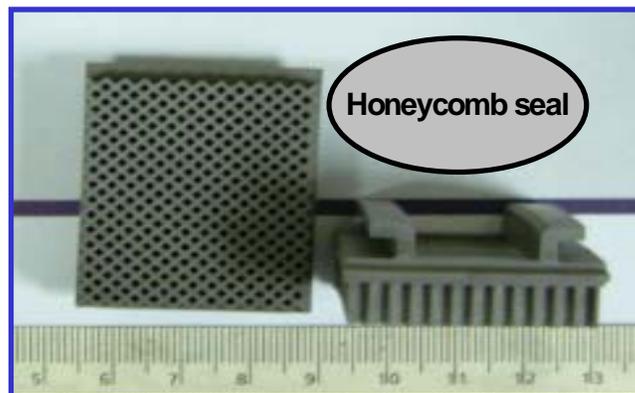


Figure 8: MIM honeycomb seal for turbine applications

Figure 9 depicts further examples of potential MIM parts for jet engines. The figure shows adjusting levers, locking nuts or retaining plates. The parts are small enough for MIM. They are needed in adequately large quantities. The complex shapes include tiny features.

High strength is required. Investment casting will not work without extensive machining. The way to MIM for these parts will be opened by using a standard MIM nickel-base alloy and the related production process.



Figure 9: Potential MIM jet engine parts

5.0 CONCLUSIONS

The MIM net-shape molding technique is a cost saving approach for manufacturing compressor parts. Although investment cast parts can outperform MIM in terms of cost, MIM is especially competitive with tiny complex geometries that require considerable machining and are also too small for accurate investment casting. In addition, the strength of MIM materials exceeds that of castings and nearly approaches the values of forgings.

Part size is generally a limit for the MIM process. Therefore, potential jet engine parts for MIM are mainly located in the high pressure compressor with operating temperatures up to 650°C. The operating temperature calls for nickel-base superalloys. Nickel-base superalloys and their powders are commercially available. The MIM powder is atomized from ingots or elemental powder and the powder is sieved to meet the high aerospace quality standard. Engine safety standards demand the reduction of inclusions to a specified level. Compressor vanes are a challenge for the MIM process because of the required strength and their complex geometry. Optimized process parameters can control MIM-specific imperfections within acceptable limits. The specification for powder molding, debinding and sintering results from an intensive development process. All end users of innovative materials demand a relatively high level of maturity before committing to a new process. MTU Aero Engines already started full scale engine tests with successfully developed MIM vanes and small parts. Additionally, there are plans to benefit from the possibilities of powder metallurgy to refine the functional performance of honeycomb seals.

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- [1] P. A. Davies, G.R. Dunstan, A.C. Hayward, R. L. Howells, “Metal Injection Molding of Heat-Treated Alloy 718 Master Alloy”, PM 2004 World Congress, Vienna
- [2] M. Bulger, “Metal Injection Molding”, Advanced Materials & Processes, March 2005, pp. 39
- [3] R.E. Schafrik, “Materials for Next Generation Aero-Propulsion Turbine Engines”, Int. Symp. on Airbreathing Engines (ISABE), 2001, Paper N° 1103



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[4]D. Deming, “Metal Injection Molding”, Advanced Materials & Processes, March 2003, pp. 30

[5] R. M. German, “Powder Injection Molding – Design and Applications”, publ. by Innovative Materials Solutions Inc., Pennsylvania State College, USA, 2003

MEETING DISCUSSION – PAPER NO: 9**Author: S. Sikorski****Discusser: M. Hicks**

Question: You showed some good examples of MIM components in development – have any components gone into production yet?

Response: No, we are doing tests on an engine.

Discusser: C. Bampton

Question: Any H₂ in the sintering furnace atmosphere?

Response: This is proprietary.

Discusser: X. Wu

Question: What alloy is used in MIM component?

Response: This propriety

Discusser: J. Allen

Question: What is the practical minimum wall thickness which can be produced by the MIM process?

Response: It is between 0.4 – 1.0 mm

Discusser: J. Allen

Question: 1. Minimum tickness that can be produced? 2. Are parts in production?

Response: 1. For vanes, typically ½ mm to 1 mm. 2. No, but engine tests are underway.

Discusser: Unidentified

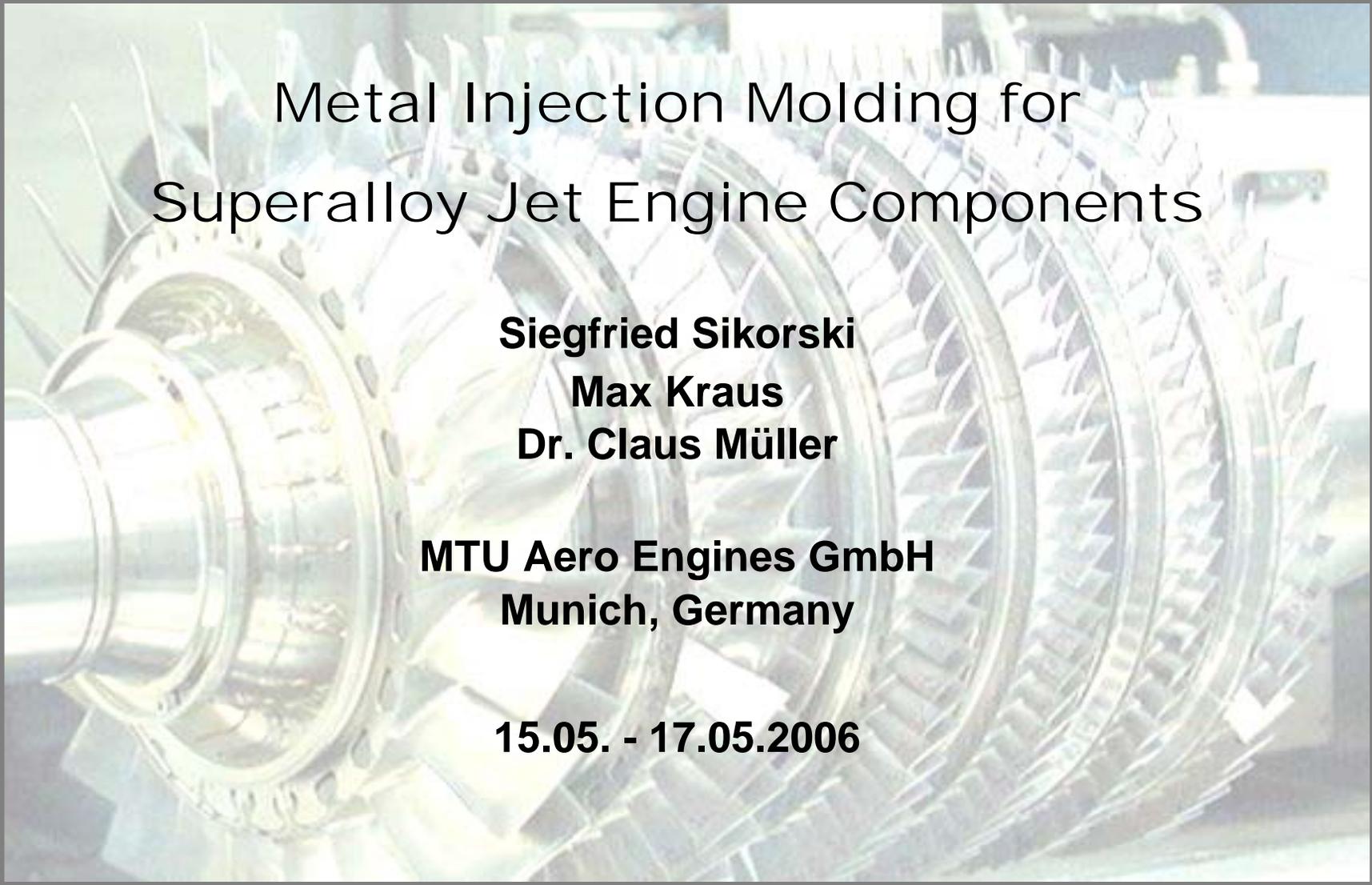
Question: 1. What alloy is being targeted? 2. Is N₂ used during sintering?

Response: 1. Proprietary info. Ni-base alloy. 2: Proprietary info



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Superalloy Jet Engine Components**

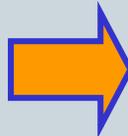
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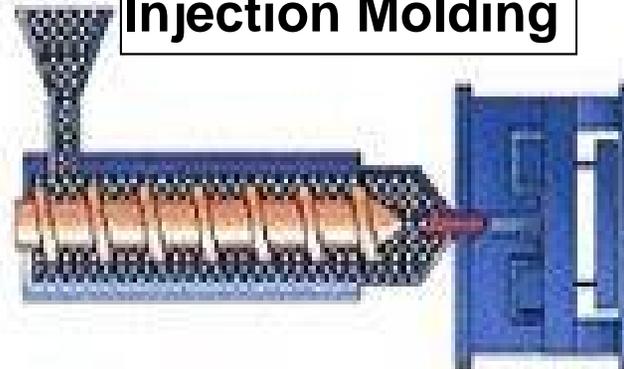
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MIM Production Process

Mix fine metal powder with binder



Injection Molding



Form one single part within a few seconds

„green“
part

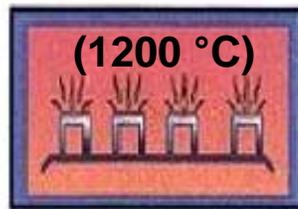


Finished
part



Sintering

Batch process

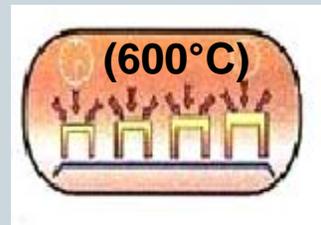


Compact part by shrinkage
(several hours)

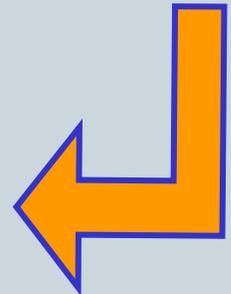


Debinding

Batch process



Remove Binder (several hours)

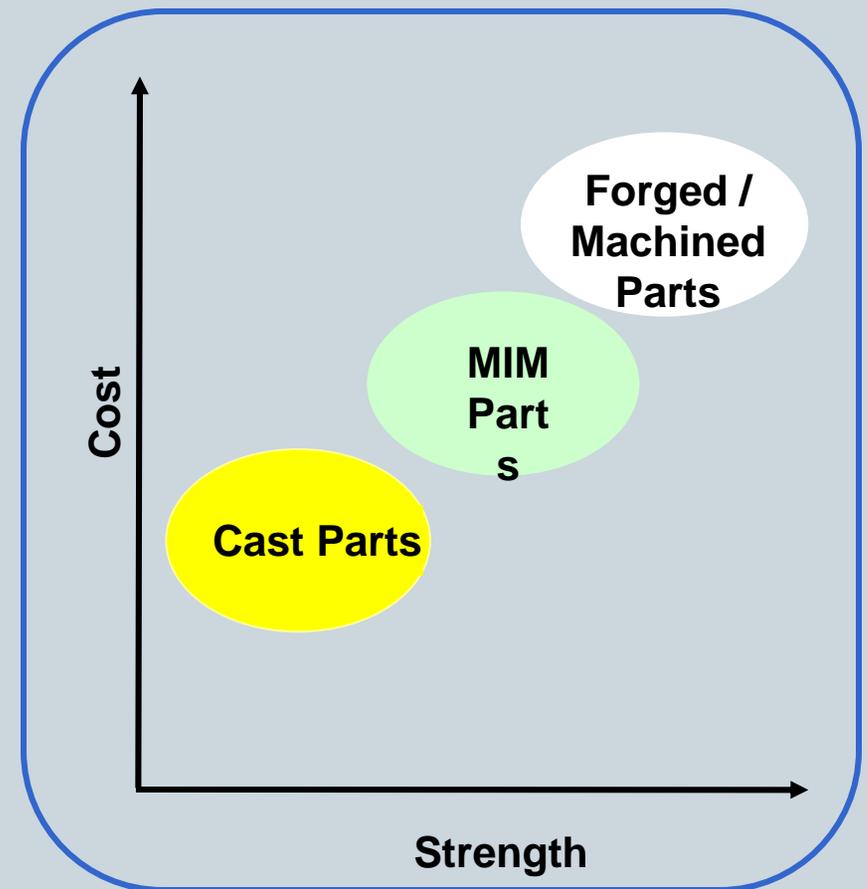


Cost Benefits of MIM Net-Shape Manufacturing

Batch processes save costs and time compared to milling or electrochemical milling

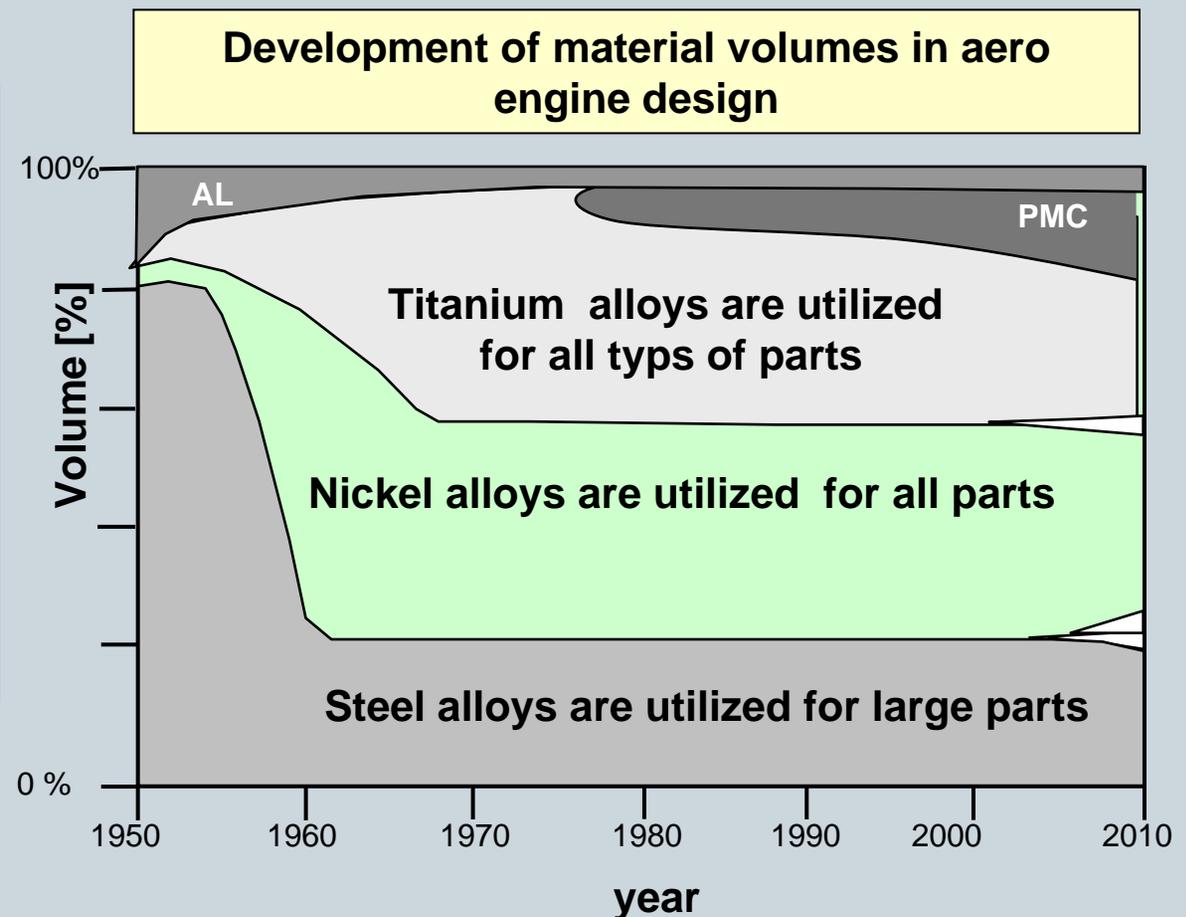
Net-shape approach reduces waste of expensive raw material

Laborious machinable alloys can be processed at reasonable expenses



Alloys for MIM Jet Engine Components

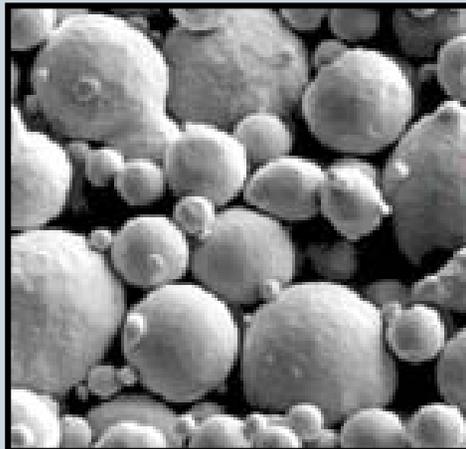
- Nickel alloys are used for parts with large numbers of items
- Nickel powder alloys are already utilized for discs
- The MIM process can be matched to commercialized Nickel alloy powder



Preparation of Powder for High Strength MIM Alloys

A sieving process keeps
the size of the powder
grains within limits

The grain size distribution
needs specifications



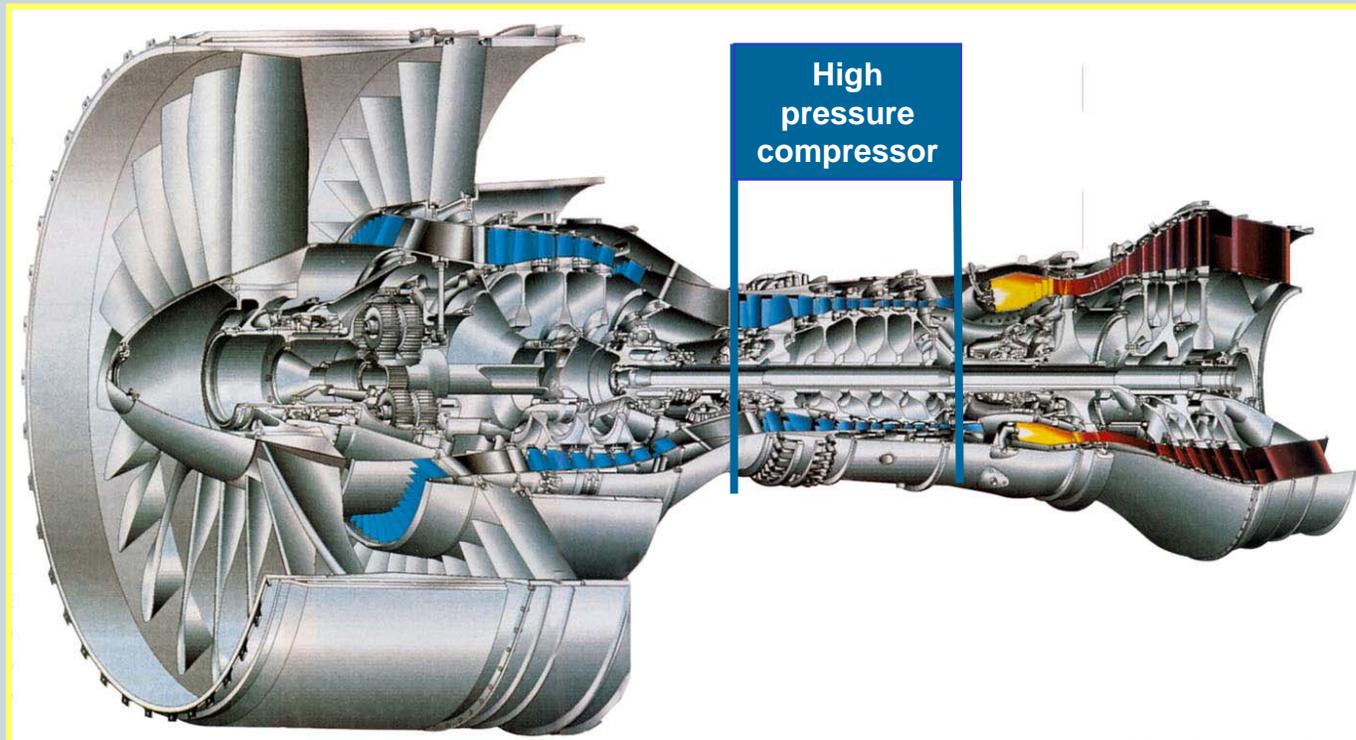
Pure Nickel alloy powder
micrograph



The pollution of the grain surfaces with
oxides

influences the sinter activity

Application Range for Metal Injection Molding (MIM) Parts

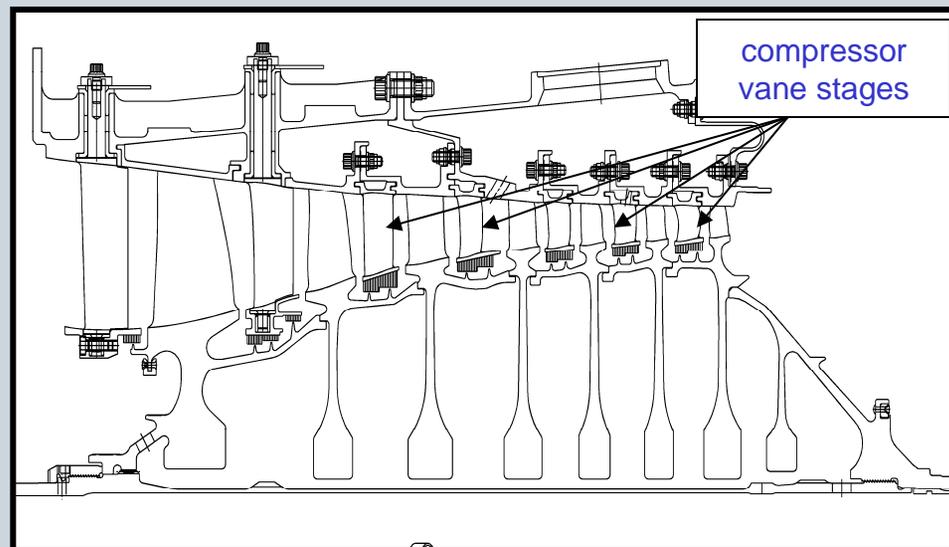


The size of high pressure compressor parts fits best for MIM production process

MIM for Compressor Vanes

One compressor stage typically includes 80 - 150 vanes

Economic advantage of MIM depends on the number of similar parts



High Pressure Compressor (Schematic)

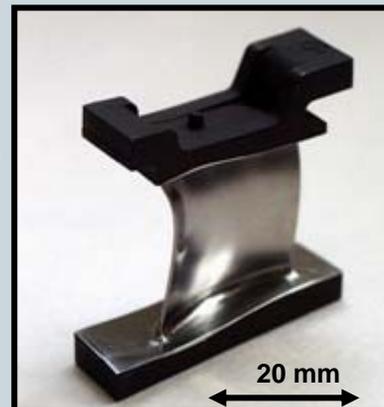
MIM process copes with the weight of compressor vanes (typically 5 - 150 g)

Challenges for the MIM Process

Inhomogeneous thickness distribution can cause shrinkage cracks

Shrinkage distortions influence tolerances

Mold parting lines generate marks at sensitive edge areas



Prototype MIM compressor vane

Mold flow is hampered by very thin sections

Control Parameters of the Sintering Process

The sinter temperature controls the

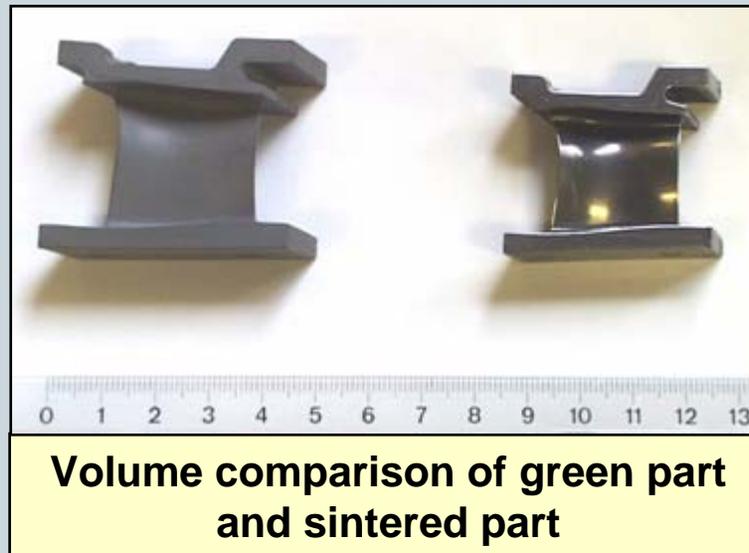
microstructure

A uniform temperature distribution avoids density variations

The sinter temperature governs density

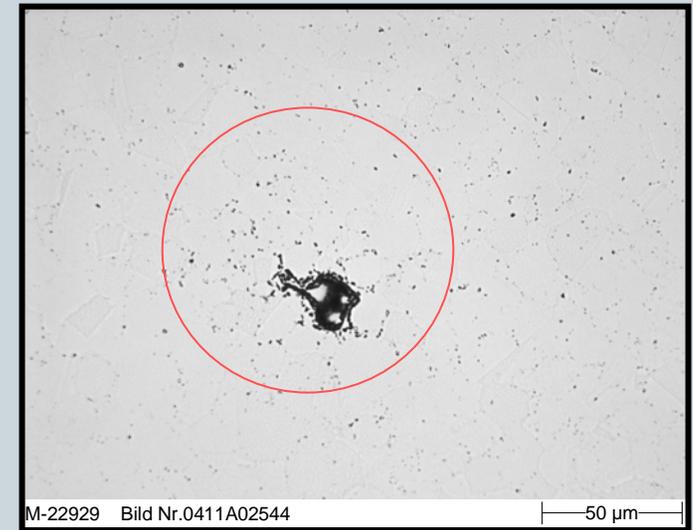
Optimized setters prevent shape deviations and distortions

Adjusted heating and cooling rates restrain distortions and shrinkage stresses



Quality Management for Powder Imperfections

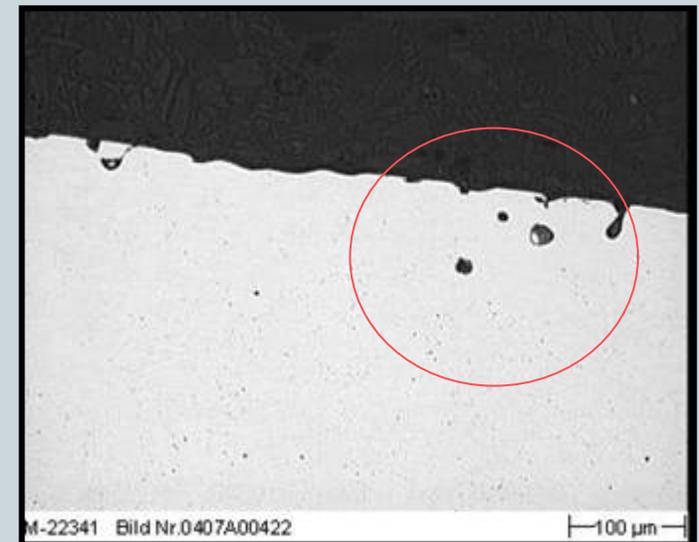
- Wear debris from the melting vessel and the powder spray nozzle can cause inclusions
- Residual binder forms carbide agglomerations at sinter temperature
- Defect probability limits must be defined by an investigation programs



Micrograph picture of a carbide agglomeration

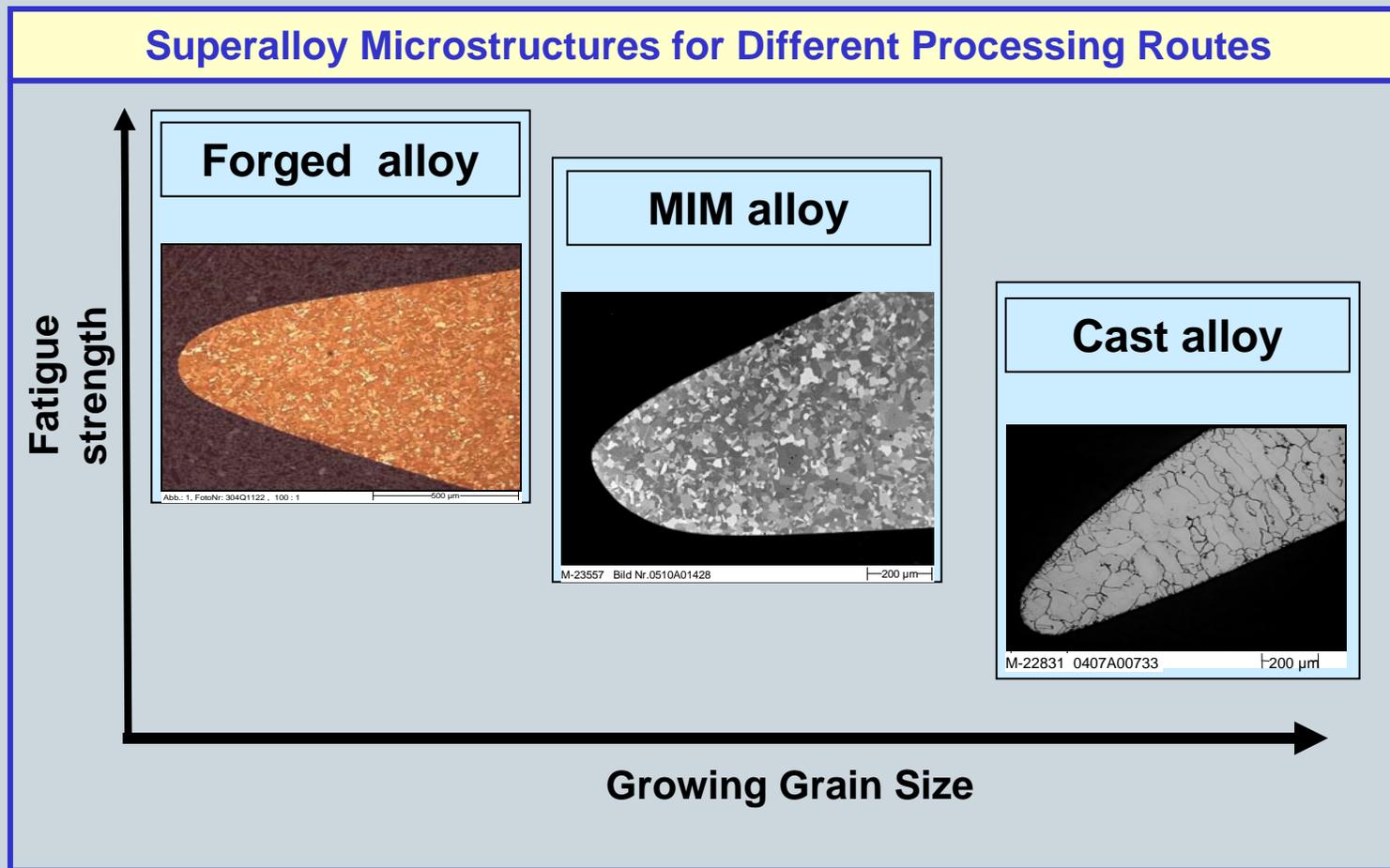
Quality Management for Porosity

- Residual open porosity can occur near the surface
- Optimized sintering parameters can reduce porosity significantly
- Metallography assures the compliance with defined limits



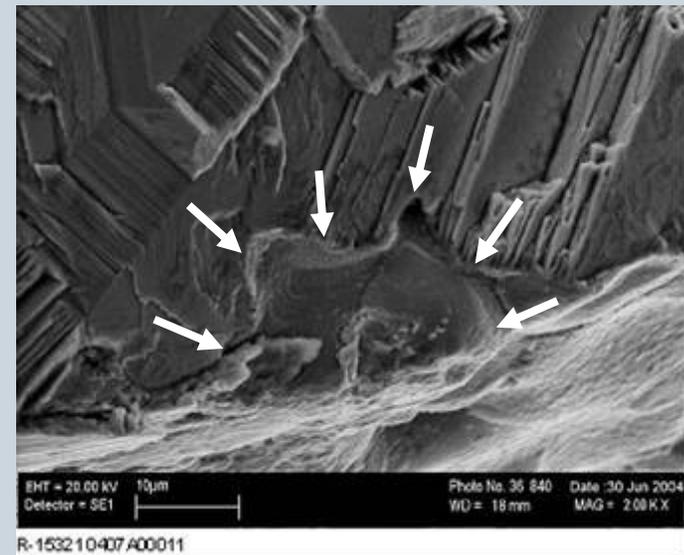
**Microscope picture of porosity
close to the surface**

MIM Alloy Grain Size



MIM Superalloy Strength

- MIM alloys achieve the static strength of forged material
- The fatigue strength of MIM alloys is acceptable smaller compared with forged alloys
- The MIM strength exceeds values of cast material

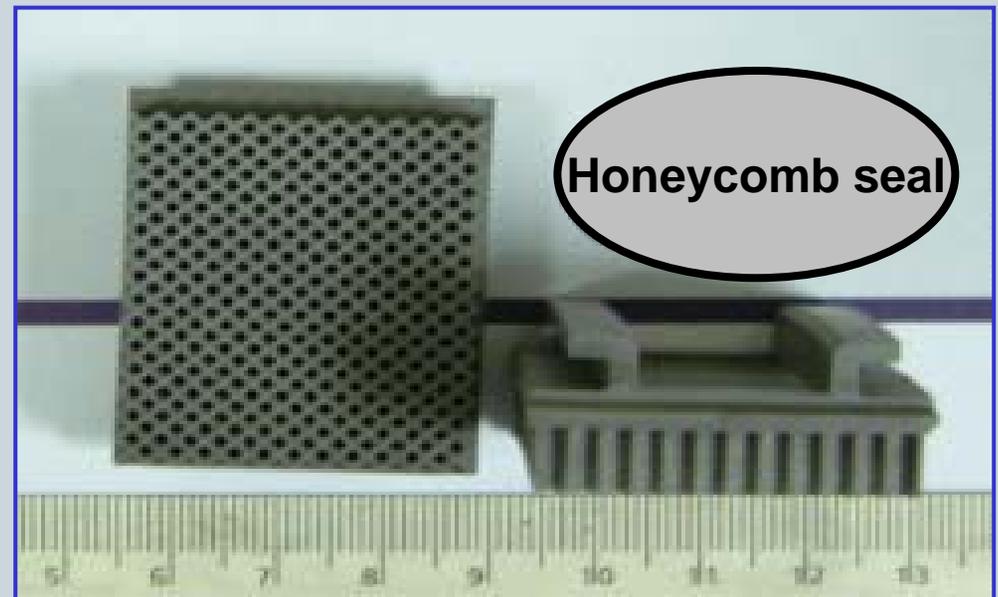


Fatigue crack in MIM material

Options for Further Jet Engine MIM Parts



Rotating retaining plates



MIM turbine seal segment

Conclusions

- The processible size of MIM parts cope best with the size of the high pressure compressor
- Nickel alloys are the preferential materials for MIM compressor parts
- The strength of MIM material nearly equals the strength of wrought alloys
- The challenges of high quality require a considerable amount of development work
- The cost advantage of MIM arises at a sufficient large number of parts



Four MIM vanes brazed together for a vane clusters



AVT – 139 on “Cost Effective Manufacture via
Net Shape Processing”

Tank you for your attention