Development of Metal Injection Molding Process for Aircraft Engine Part Production

IKEDA Shuji : Manager, Engine Technology Department, Research & Engineering Division, Aero-Engine & Space Operations
SATOH Shigeyuki : Senior Researcher, Materials Department, Research Laboratory, Corporate Research & Development
TSUNO Nobuyasu : Materials Department, Research Laboratory, Corporate Research & Development
YOSHINOUCHI Takashi : Engine Technology Department, Research & Engineering Division, Aero-Engine & Space Operations
SATAKE Masayuki : Production Planning Department, Manufacturing Division, Aero-Engine & Space Operations

Metal Injection Molding (MIM) is a net-shape process for producing metal parts that combines the design freedom of plastic injection molding with material strength near that of wrought metal. IHI has been developing the MIM process for low-cost manufacture of high pressure compressor vanes which are used in aircraft gas-turbine engines. Material tests have been carried out on the vanes and the test results show good performance. Measurement of the dimensional precision of the prototype compressor vane has shown promising results. This paper describes the status of MIM process development at IHI.

1. Introduction

Metal Injection Molding (MIM) is a relatively new production method(1), (2) that was developed in the 1970s. In the MIM process, fine metal powder is mixed with a thermoplastic resin called the binder, and the mixture is then processed into a molded body with a complex shape by the same injection molding method as that for general plastic. After that, the binder is removed from the molded body by heating or using a solvent, and the resulting molded body is sintered at high temperature to obtain the final product. Compared to conventional powder metallurgy, MIM can make a product with higher density, which is to say increased strength.

High pressure compressor vanes used in aircraft gas-turbine engines are made of a heat-resistant nickel-based superalloy, which is a difficult material to cut. Also, the need to improve aerodynamic performance creates a strong tendency to employ a thin three-dimensional shape for a vane, and therefore the assembly process of high pressure compressor vanes is complicated. If such parts can be produced by MIM-based integral molding, production costs could be significantly reduced.

Meanwhile, since parts produced by MIM have mainly been put into practical use for automobiles and consumer electronics use, most MIM parts are made of iron-based alloys such as stainless steel. For this reason, data on MIM parts made of heat-resistant nickel-based superalloys such as those to be used for aircraft engines is scarce.(3), (4) Furthermore, since the parts contract and deform during sintering, the larger the parts, the more difficult it is to secure dimensional accuracy. In order to apply MIM to aircraft engine parts, these problems need to be resolved.

For this reason, in this research, material data on MIM test bars was obtained using metal powder of Alloy 718, a heat-resistant nickel-based superalloy. Also, test production of a high pressure compressor vane for an aircraft engine was carried out using our unique binder with excellent shape retention properties, and the binder's deformation suppression effect on this part having a relatively large size for a MIM part was examined. In this paper, we will introduce the obtained MIM material data and the result of the test production of the high pressure compressor vane.

2. Unresolved issues in using MIM to make aircraft engine parts

MIM uses alloy powder which means that MIM parts contain fine pores (porosity). **Figure 1** illustrates the structure of a

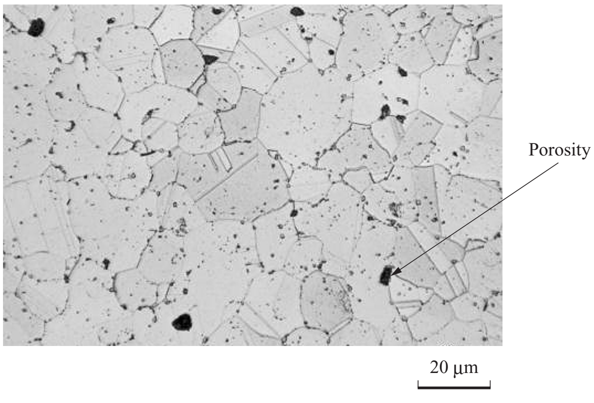


Fig. 1 Typical microstructures of MIM

MIM material. The particle size of the alloy powder considerably influences the features of the metal structure such as porosity and grain size. Decreasing the particle size results in improvement of sinterability; however, the specific surface area is increased, and therefore oxygen concentration tends to increase. To apply MIM to aircraft engine parts, we need to grasp the influence of the powder used on the MIM parts' material strength.

MIM requires debinding and sintering processes after molding. During these processes, scattering of binder in the gaps between metal powder particles causes shape deformation. **Figure 2** illustrates deformation after debinding and sintering. Furthermore, since densification requires sintering at high temperature near the melting point of the alloy, creep due to gravity has to be taken into consideration. Larger-sized parts lead to larger deformation, and consequently the necessary level of dimensional accuracy cannot be secured. As a result, MIM is often used only for the production of parts weighing a few grams to a hundred grams. To apply MIM to aircraft engine parts, a certain level of dimensional accuracy needs to be secured in parts weighing at least 100 to 200 g, and therefore how to suppress deformation during debinding and sintering is a critical challenge.

3. Test method

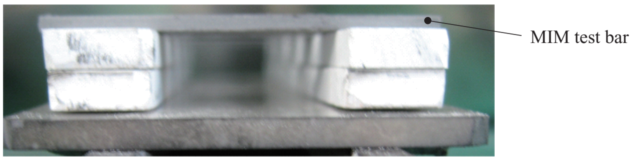
3.1 Production of Alloy 718 sintered body by MIM

Figure 3 illustrates the MIM process. First, a binder made from multiple thermoplastic resins and wax, and fine Alloy 718 powder (< 22 μm) were uniformly mixed by a mixer to produce feedstock. Then, the feedstock was filled in a mold, and molded using the same type of injection molding machine as that used for plastic part production. Since the molded body contracts during sintering as the gaps generated by removal of the binder are filled by the alloy, the size of the molded body needs to be determined taking this contraction into account in advance. The molded body taken out of the mold already had the shape of the part, and the binder had already been removed by heating and using a solvent. Finally, the resulting molded body was placed in an atmosphere furnace and sintered at high temperature.

3.2 Material test of MIM material

It is important for aircraft engine parts to have sufficient material strength. The high pressure compressor vane defines airflow channels, and therefore it needs to have sufficient fatigue strength especially against vibration. To examine the material properties of a part produced by MIM, a test bar illustrated in **Fig. 4** was used to conduct a tensile test and various fatigue tests. Also, to examine the influence of microporosity generated in the part produced

(a) Before debinding and sintering



(b) After debinding and sintering

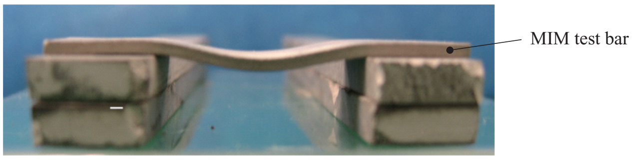
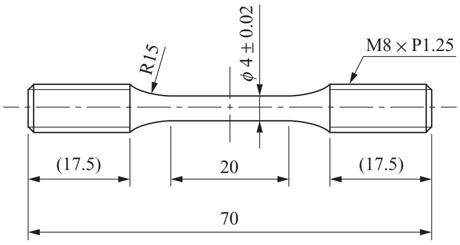


Fig. 2 Deformation during debinding and sintering

(a) Tensile test bar



(b) Fatigue test bar

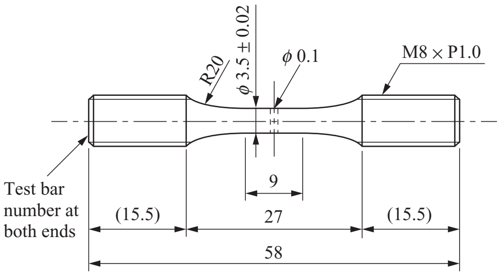


Fig. 4 Geometry of the tensile and fatigue test bar (unit:mm)

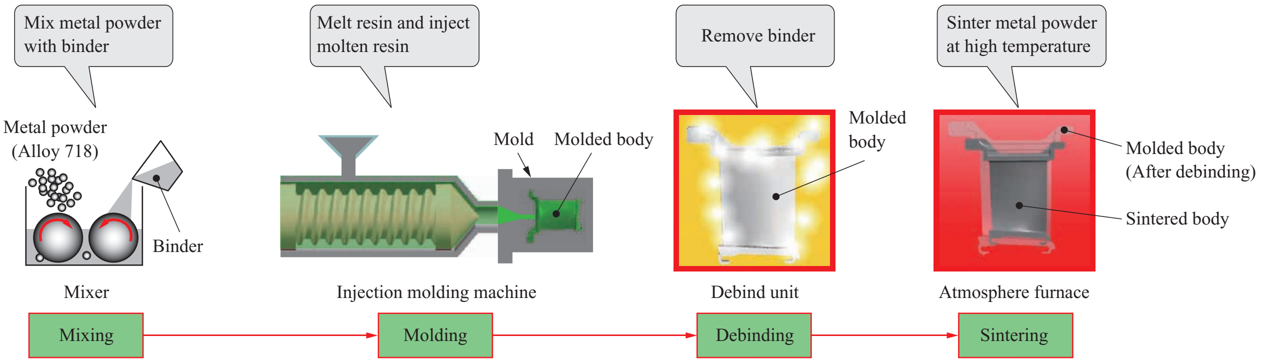


Fig. 3 Schematic diagram of the MIM process

by MIM, we deliberately added a ϕ0.1-mm artificial defect as a micropore by machining the surface of the test bar illustrated in **Fig. 4-(b)**, used the bar to obtain fatigue strength data, and compared the results with those obtained for the test bar without an artificial defect.

Furthermore, to examine the influence of oxygen content, metal powder produced by a water atomization device and metal powder produced by a gas atomization device were prepared, and the influence of oxygen content on the fatigue strength of parts produced by MIM was examined. **Table 1** lists oxygen concentrations and other components in the Alloy 718 metal powders.

3.3 Test production of high pressure compressor vane

The test production of a high pressure compressor vane for an aircraft engine was carried out for the purpose of using MIM to produce a part to be applied to an aircraft engine. **Figure 5** illustrates a cross sectional view of an aircraft engine and **Fig. 6** illustrates an external view of a high pressure compressor vane for an aircraft engine. A high pressure compressor vane is usually produced as one part by using a complicated process to assemble subparts produced by cutting and press molding. Also, a fixed number of vanes are annularly assembled to make a complete annular form, and they are used in that form. Since high pressure compressor vanes have a weight of several hundred grams, it was expected that the deformation would be too large to secure dimensional accuracy. Therefore, a high pressure compressor vane was test-produced using our unique deformation-resistant binder that has superior ability to maintain a shape, and the produced high pressure compressor vane was compared with one produced using conventional binder.

Table 1 Composition of Alloy 718 metal powder

Production method	Chemical compositions					
	Mo	Al	Ti	NbTa	C	O
	wt%					ppm
Gas atomization	3.12	0.66	0.98	5.14	0.05	300
Water atomization	3.02	0.27	0.73	5.01	0.05	4 900

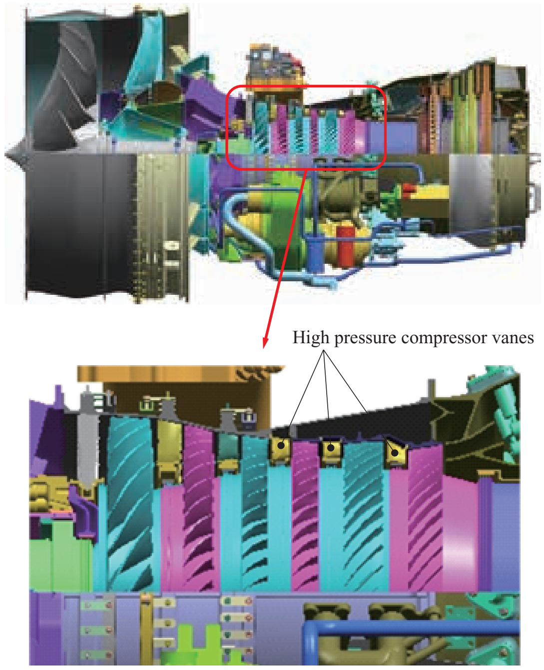


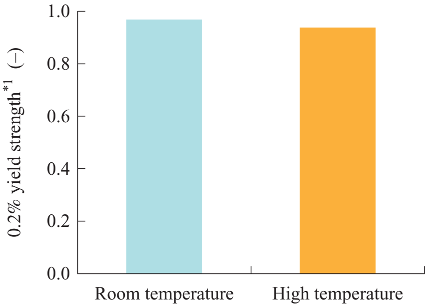
Fig. 5 Cross sectional view of aircraft gas-turbine engine

Fig. 6 External view of compressor vane

4. Results and discussion

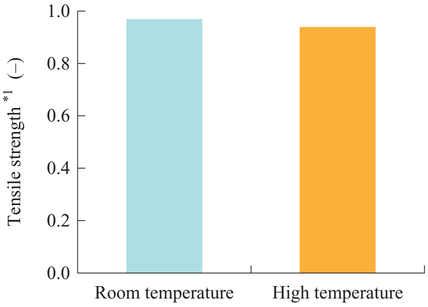
4.1 Material test

Figures 7 to **9** illustrate various results of the tensile test.



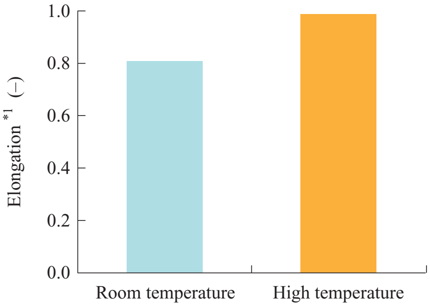
(Note) *1 : Ratio of MIM material to wrought metal

Fig. 7 0.2% yield strength of MIM Alloy 718



(Note) *1 : Ratio of MIM material to wrought metal at 0.2% yield strength

Fig. 8 UTS of MIM Alloy 718



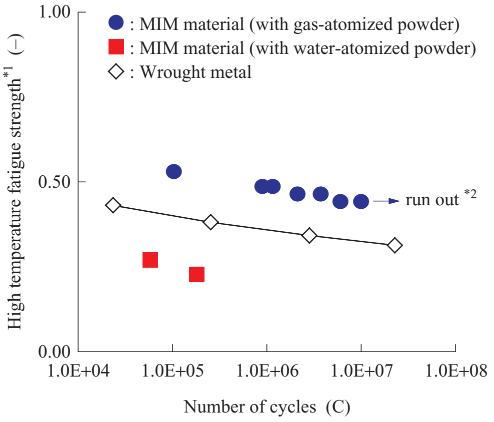
(Note) *1 : Ratio of MIM material to wrought metal

Fig. 9 Elongation of MIM Alloy 718

The test results show that the test bar produced by MIM has tensile strength equivalent to that of wrought metal, and elongation of the test bar has a value sufficient for practical use. **Figure 10** illustrates the results of a high-temperature fatigue strength test. From the test results, it turns out that the MIM material using the gas-atomized powder has higher values than those of the wrought metal in the range of high-cycle fatigue strength, which is important for a high pressure compressor vane. The reason why the MIM material using the gas-atomized powder has such high strength even though it has a density less than that of the wrought metal is probably that the test bar produced by MIM using the gas-atomized powder has a smaller grain size than that of typical wrought metal in terms of metal structure. **Table 2** shows a comparison of the grain size between the wrought metal generally used for high pressure compressor vanes for aircraft engines and the test bar produced by MIM.

Meanwhile, from the test results using the water-atomized powder having higher oxygen concentration, it also turns out that it has significantly less strength. Finer metal powders have a larger specific surface area, increasing oxygen concentration, which means there is a risk of reduced strength. This problem can be solved by using the metal powder produced by gas atomization, which can reduce the oxygen concentration. Use of the gas-atomized powder can achieve a higher fatigue strength than that of the wrought metal as illustrated in **Fig. 10**.

Figure 11 illustrates the results of the high-temperature fatigue test of the MIM material produced using the gas-atomized powder and that has the ϕ0.1-mm artificial defect. The test results show that the strength of the MIM material is equivalent to that of the MIM material without an artificial defect, verifying that the ϕ0.1-mm surface defect does not influence the fatigue strength.

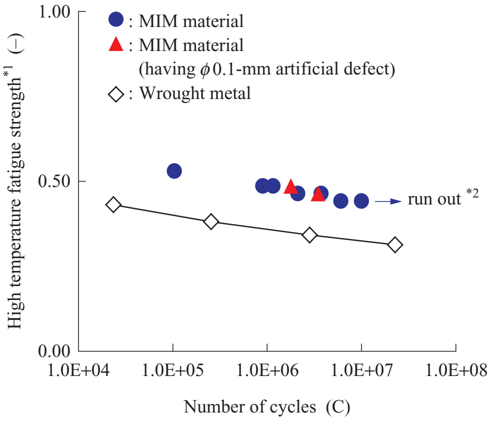


(Note) *1 : Ratio of stress amplitude to tensile strength
*2 : Fatigue breakage does not occur even after reaching the predetermined number of cycles.

Fig. 10 S-N curve of MIM Alloy 718

Table 2 Comparison of grain size

Test bar material	Average grain size (μm)
Wrought metal	90
MIM material	30



(Note) *1 : Ratio of stress amplitude to tensile strength
*2 : Fatigue breakage does not occur even after reaching the predetermined number of cycles.

Fig. 11 S-N curve of MIM Alloy 718 with artificial defect

4.2 Test production of high pressure compressor vane

Figure 12 illustrates a prototype of a high pressure compressor vane made of a MIM material using conventional binder. The prototype using the conventional binder has large deformation and is unable to fulfill the requirement for dimensional accuracy. **Figure 13** illustrates a prototype of the high pressure compressor vane using our unique deformation-resistant binder. In comparing them, it can be verified that deformation of the prototype using the deformation-resistant binder is sufficiently suppressed. The reason for this is probably that the binder that causes less deformation is also used during the debinding and sintering processes, and the conditions for debinding and sintering are optimized to prevent any cracks or bulges from occurring. From the results of the test production, we believe it is possible to fulfill the requirement for dimensional accuracy of a high pressure compressor vane, even though it is larger than most parts made of MIM materials.

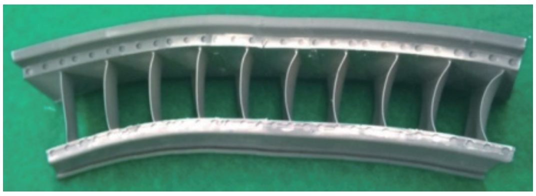


Fig. 12 Sintered prototype vanes using conventional binder

(a) Side view **(b)** Front view

Fig. 13 Sintered prototype vanes using new binder

5. Conclusion

We have verified that the MIM material has high fatigue strength and sufficient material strength for application to high pressure compressor vanes. We have also found that use of the deformation-resistant binder can sufficiently suppress deformation during debinding and sintering. From the above results, we believe it is possible to apply MIM to high pressure compressor vanes for aircraft engines.

The application of MIM to high pressure compressor vanes enables cutting and assembling processes to be eliminated, and costs to be significantly reduced in comparison with conventional producing methods. This improves cost competitiveness in compressor production, the driving force for increasing our market share of high pressure compressors (which is the core part of aircraft engines) in the international joint development of aircraft engines.

We will secure the dimensional accuracy of compressor rotor blades, which require higher quality than vanes, as well as larger-sized parts, and thereby expand the scope of application of MIM to further improve international competitiveness.

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