Rapid Prototyping of Turbocharger Turbine Housings through Powder Bed Fusion Additive Manufacturing

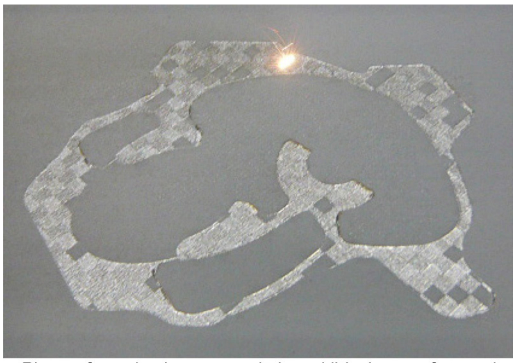
Photo of a turbocharger part being additively manufactured

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To leverage the rapidly-increasing demand for turbochargers into an increase in the number of orders, it is important to shorten the development cycle and reduce the time required before presenting a prototype to the customer. The interface shapes of the compressor cover and turbine housing, both of which are parts of a turbocharger, are specific to each car type. Moreover, as these parts are manufactured by molding, their production lead time is long. In an attempt to eliminate the need for molds and shorten the lead time, the applicability of metal additive manufacturing to compressor cover and turbine housing production was evaluated. In its application, the metal additive manufacturing element technologies introduced in Vol. 55, No. 2 of the Mitsubishi Heavy Industries Technical Review were employed. Handling the issues particular to compressor cover and turbine housing prototyping including the optimization of build conditions suitable for conventional casting materials, mechanical property evaluation of the built parts, evaluation of the internal flow path geometry and evaluation of performance as a turbocharger, Mitsubishi Heavy Industries Engine & Turbocharger, Ltd. (MHIET) has succeeded in reducing the lead time required for turbocharger prototyping to one-third or less.

1. Introduction

With the potential of leading to better fuel economy and reducing exhaust emissions, turbochargers are in increasing demand. To increase the number of orders, we have taken on the challenge of responding promptly to the needs of our customers by reducing the lead time required for development. In prototyping a turbocharger, producing compressor cover and turbine housing prototypes is a time-consuming process because the interface shapes vary depending on the car type and the production processes involve molding. Therefore, reducing the time required for prototyping these parts has been regarded as critical.

In metal additive manufacturing, parts can be made directly from 3D models without molds being created, so its application to the prototyping of parts that are otherwise produced by molding can be expected to reduce the time required before delivery. Therefore, we prototyped a compressor cover and turbine housing through metal additive manufacturing to establish a process with a shorter production time (if molded, it would normally take about one month).

For the application of metal additive manufacturing, we considered factors such as the materials to be used, part sizes and operability of 3D printers, and decided to adopt laser powder bed fusion 3D printing. The issues to be addressed when using metal additive manufacturing to prototype compressor covers and turbine housings are: (1) the selection of a suitable powder form of the casting material, (2) Optimization of additive manufacturing conditions for the powder selected in (1), and (3) the evaluation of the internal flow path geometry of the prototyped parts. This report mainly presents the results of turbine housing prototypes. **Figure 1** shows flow charts for prototyping.

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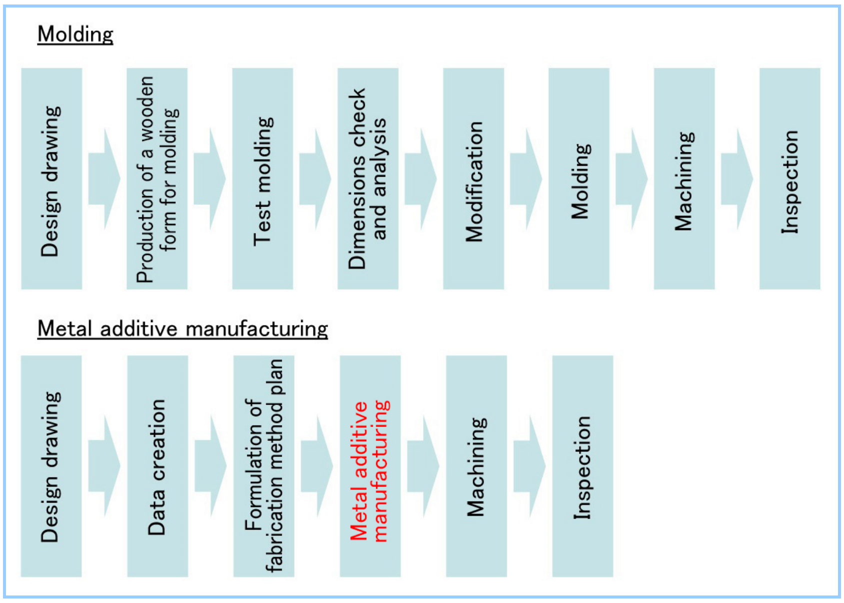


Figure 1　Flow charts for prototyping by molding and metal additive manufacturing

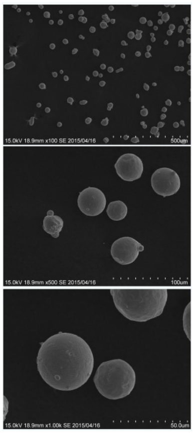
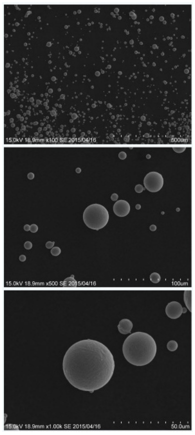
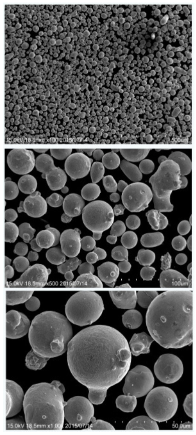
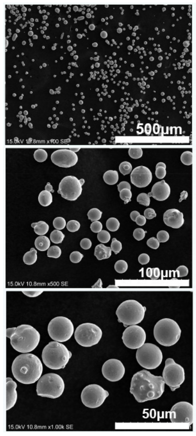
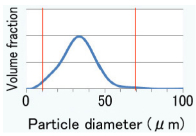
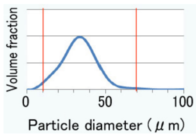
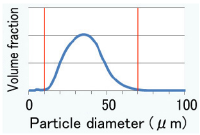
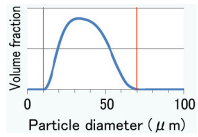
2. Selection of the powder raw material

As the casting materials used to produce turbocharger parts are not available commercially in a powder form that is suitable for metal additive manufacturing, these materials have to be powdered from scratch. In powder bed fusion metal additive manufacturing, the powder raw material needs to be laid uniformly (several dozen micrometers in thickness), thus requiring superior fluidity. Spherical, gas-atomized powders of 10-45 μm in diameter are generally used as a raw material. Therefore, we formulated a powdered raw material that has the same composition as the casting material, which was followed by the particle size classification. Based on the results of (1) morphological observation by electron microscopy, (2) laser diffraction particle size distribution measurement and (3) fluidity evaluation according to the time required to flow through an orifice, four types of powdered metals were selected. **Table 1** shows these four types of powder raw materials in terms of electron microscopic images, particle size distribution and the time required for 50g of powder to flow through an orifice of 3.15 mm in diameter. The electron microscopic images indicate that sample powders of all types have a spherical morphology. However, the particle size distribution measurement results show that powders A and B contain particles with a diameter of >70 μm and <10 μm respectively, so both were excluded. Finally, based on the fluidity evaluation results, powder D was selected as the powder raw material for use in metal additive manufacturing because of its superior fluidity.

3. Optimization of additive manufacturing conditions

In metal additive manufacturing, the powder raw material is rapidly cooled down after being fused by laser. This process raises concerns about the formation of cracks in the casting material. Proper layer-by-layer building of a part using a powder raw material necessitates appropriately controlling the depth of the melt pool produced by laser beam irradiation. To determine the range of the irradiation conditions involving no cracking, a laser used in metal additive manufacturing (a Yb fiber laser, operating at a wavelength of 1060 nm with a beam diameter of 0.1 mm) was first applied to a metal plate surface. Next, the process of constructing a bed of the powder raw material followed by laser beam irradiation was repeated, and the range of irradiation conditions for the layer-by-layer building process was narrowed down. A cubic block was then manufactured under several selected conditions. Based on the filling ratio and shape of the cubic block, the appropriate additive manufacturing conditions were finally determined. The suitability of the built blocks as a turbine housing was examined according to the required tensile strength, 0.2% proof stress, and elongation.

Table 1　Comparison of powder raw materials in terms of particle morphology, size distribution and fluidity

	Powder A	Powder B	Powder C	Powder D
Electron microscopic image				
Particle size distribution				
Time required for 50g of powder to flow through a φ 3.15 orifice (s)	10.0 s	11.0 s	11.3 s	10.8 s

3.1　Irradiation testing on a metal plate surface

To determine the range of laser-beam irradiation conditions involving no cracking (in terms of laser power and scan speed), a laser beam was applied to a plate surface with combinations of four different levels of laser power and scan speed. The irradiation marks were stereo-microscopically observed to examine the presence/absence of cracks and the bead width. **Figure 2** shows the results, which were plotted with the x-axis representing the laser power and the y-axis the scan speed. Under the conditions of high laser power and low scan speed, cracking occurs. On the other hand, when the laser power is low and the scan speed is high, no cracking occurs but fusion defects become a concern because the fusion area is much smaller than the layer thickness. Considering that the intermediate range was suitable as the laser-beam irradiation conditions, we selected seven different test conditions for the additive manufacturing testing (indicated by (1) to (7) in Figure 2).

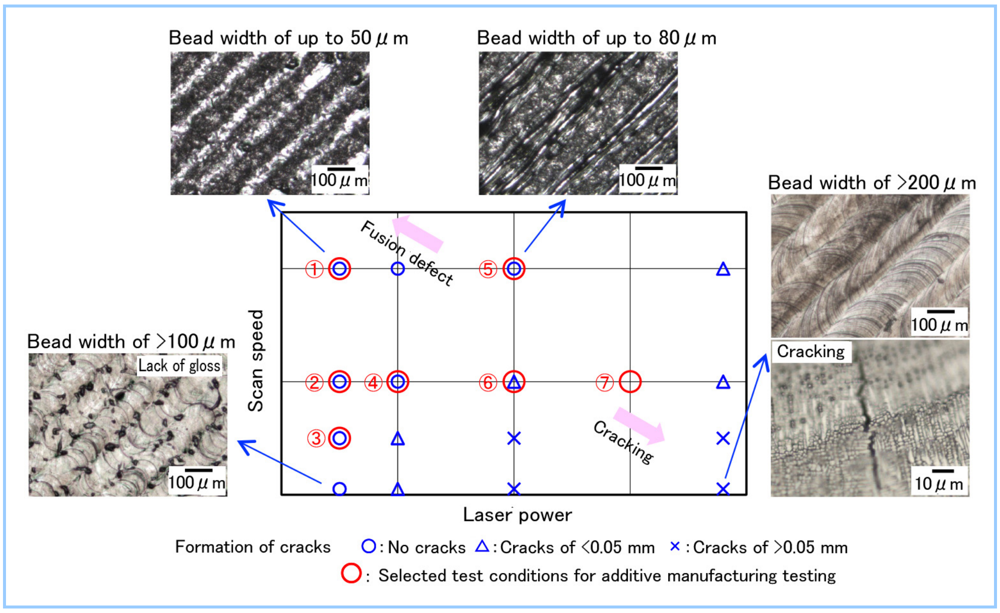


Figure 2　Surface texture after laser beam irradiation of the casting material

3.2 Additive manufacturing testing

In metal additive manufacturing, the raw material (powder) is used to construct a bed of several dozen micrometers thick, and the building process of a part progresses by applying a laser beam to the bed, allowing the powder to be fused with the substrate. In this test, we repeated the process of constructing a bed of the powder followed by laser beam irradiation 10 times, before evaluating the quality of the built part. Repetition of laser beam irradiation was conducted under each of the seven different test conditions that were selected based on the sheet-surface irradiation test results mentioned earlier. In addition to building a wall, fabrication of a 10-mm-squared slab by laser hatching was also performed. The hatching distance was set based on the bead widths resulting from the laser beam irradiation of a sheet surface.

The typical morphologies of the walls and slabs built in the tests are shown in **Figure 3**. Under condition (1), the powder raw material was not fused with the substrate, making it impossible to build a wall or slab. Regarding condition (7), the wall was fabricated but black sooty powder was formed while the slab was being built. After these two test conditions were excluded, the remaining five conditions (2) to (6), were selected for further examination.

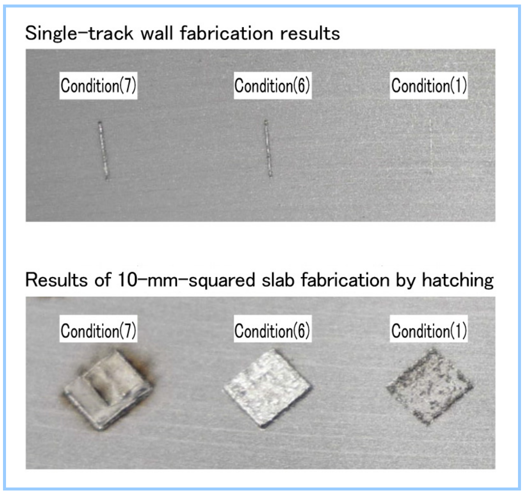


Figure 3 Additive manufacturing testing results (building-up of 10 layers)
A wall can be built but a black sooty substance is attached to the slab: condition (7)
A wall and slab with metallic glow are produced: condition (6)
No wall or slab is fabricated: condition (1)

3.3 Block fabrication

Under each of the five test conditions with different combinations of laser power and scan speed, a 10 mm cube was additively manufactured to evaluate the filling ratio. By processing the cross-sectional optical microscopic images of fabricated blocks, the void areas were estimated to obtain the filling ratios. The results are given in **Figure 4**. With low laser power (conditions (2) to (4)), the filling ratio tended to be low because of the remaining pores. On the other hand, conditions (5) and (6) indicated a filling ratio of nearly 100% in the built blocks, along with absence of tiny cracks. For the evaluation of mechanical properties, therefore, we decided to build blocks under these two test conditions.

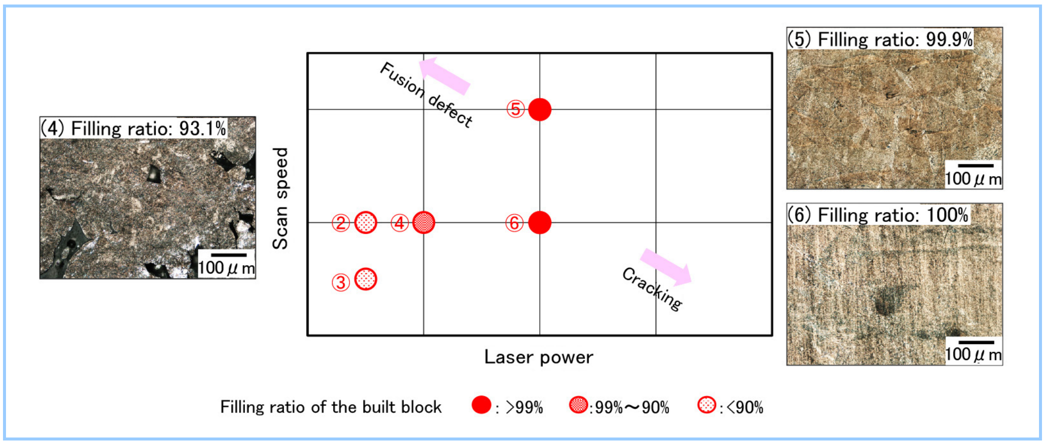


Figure 4 Relationship between the filling ratio of the built block and the build conditions

To prepare test pieces for the mechanical property evaluation, a block with dimensions of 30 mm × 30 mm × 10 mm was built under either condition (5) or (6). Electrical discharging machining was used to cut out a very small plate test piece for tensile testing in such a way that the tensile direction can be parallel to either the build direction or the layer plane. With the tensile testing machine, a strain-stress curve was obtained to estimate the tensile strength, 0.2% proof stress and elongation. **Figure 5** shows the resulting mechanical properties. The test pieces of both build conditions yielded larger tensile strength, 0.2% proof stress and elongation when force was applied in the direction parallel to the layer plane rather than in the build direction. However, it has been demonstrated that all the results satisfied the mechanical properties required for the turbine housing.

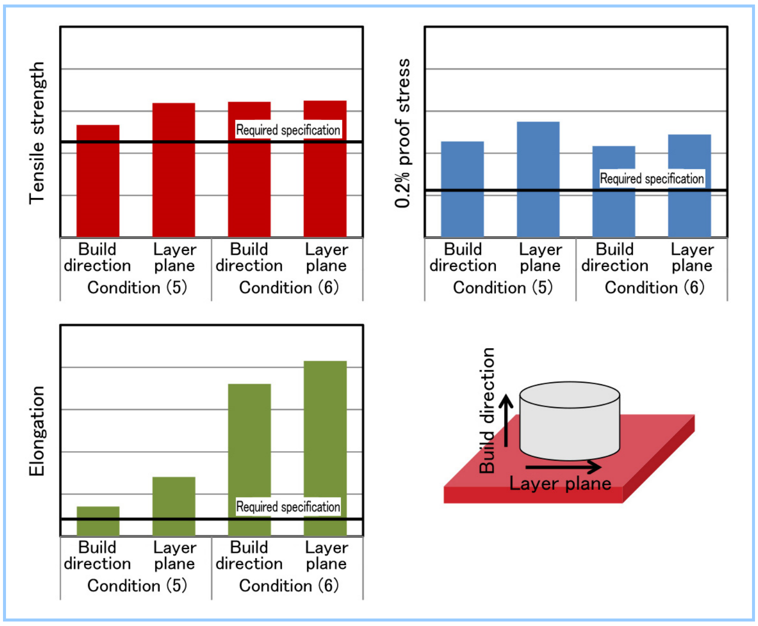


Figure 5 Mechanical properties of the blocks built under conditions (5) and (6)

4. Geometric evaluation

As the internal flow path geometry of the turbine housing or compressor cover determines the performance of turbocharger, the geometric evaluation is of importance. To realize a shorter lead time for prototyping, it is also necessary to shorten the inspection process. We therefore assessed the geometry of the internal flow path by high-power microfocus X-ray computed tomography (CT), with which non-destructive measurement becomes possible within a short period of time. One of our goals in particular was to evaluate the applicability of X-ray CT through the evaluation of the turbine housing internal path geometry. This is because, being ferrous and having a low x-ray transmission, the turbine housing is more difficult to assess than an aluminum-alloy compressor cover.

In the evaluation, a molded turbine housing was first used to measure the internal geometry by X-ray CT and the error in the internal flow path dimensions was estimated by comparing with the 3D model used for additive manufacturing. The geometry of the metal additively-manufactured turbine housing was then measured and compared with the 3D model. As shown in **Figure 6**, it has been demonstrated that the error in the dimensions of the metal additively-manufactured turbine housing was as small as that of the molded turbine housing.

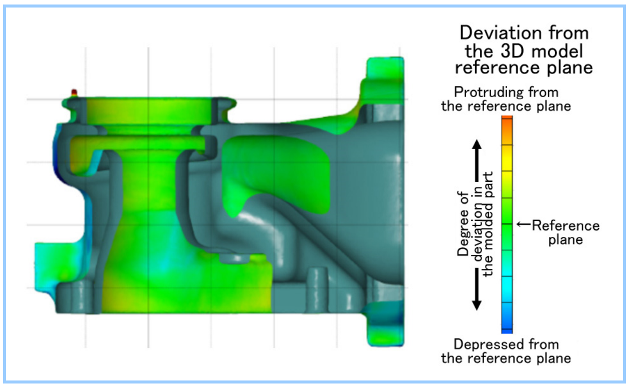


Figure 6 Internal geometry measurement of the metal additively-manufactured turbine housing using X-ray CT
Result: Color-coded based on the degree of deviation from the 3D model reference contours, illustrated in the cross section parallel to the turbine axis.

5. Conclusion

For the application of metal additive manufacturing to turbine housing prototyping, we selected the powder raw material, extracted the build conditions involving no cracking or the formation of pores in parts being built, assessed the mechanical properties of the built parts and demonstrated that metal additive manufacturing can produce parts as good as molded ones. It has also been demonstrated that the geometry of the metal additively-manufactured turbine housing can be assessed by microfocus X-ray CT, along with the error in the dimensions being as small as that of the molded turbine housing. As seen in **Figure 7**, the application of metal additive manufacturing can substantially reduce the lead time required for prototyping to one-third or less, when compared with the conventional molding method. We will further improve the metal additive manufacturing process to enable standardized quality prototypes to be produced at all our bases around the world, as well as reduce the transportation time by digitally transmitting the data for prototyping and building a prototype in proximity to the customer (“digital transportation”).

Through these efforts, we will contribute to product development in accordance with the customer’s needs by providing prototypes more promptly, and further reducing the development time.

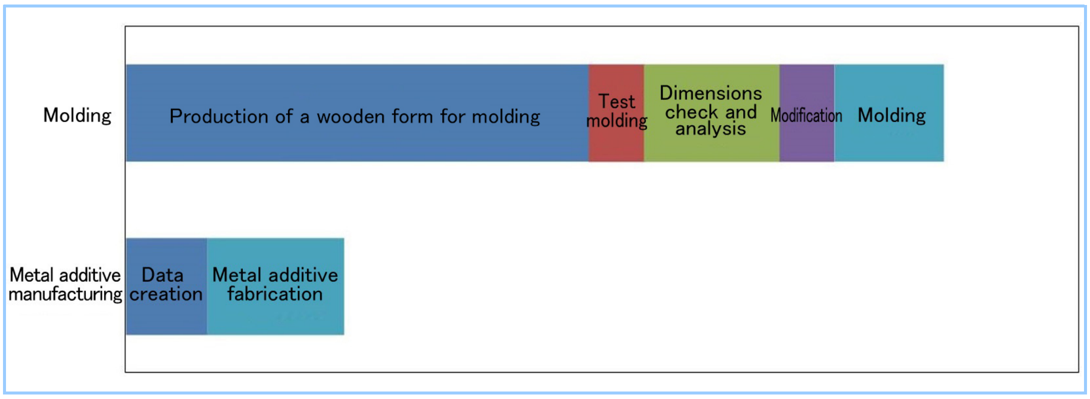


Figure 7 Comparison of the molding and metal additive manufacturing processes in terms of the lead time required for prototyping a turbine housing
The standard waiting time is included in each stage (both machining and inspection are omitted because these stages are common in the two processes).