

Introduction of Heat Exchanger Production Technique for Stirling Engine Using Additive Manufacturing

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ABSTRACT

A prototype case with thin internal fins was created in the development of a Stirling engine with performance that exceeds that of conventional compact Stirling engines. Radial grooves are cut into the pistons located inside the case in order to avoid these fins, and high accuracy is called for to help prevent contact between the pistons and fins during operation.

Since conventional manufacturing processes are unable to satisfy these specifications, precise manufacturing was realized for the first time through additive manufacturing, that is to say, the use of a 3D printer for metal materials. However, there are also many locations where the needed specifications cannot be satisfied simply by existing additive manufacturing technology, so various manufacturing process know-how was needed.

Selection of the blade used to laminate the powder, use of reinforcing rings that are removed after molding, machining of small holes to remove powder remaining inside the structure before heat treatment, and other techniques were obtained as know-how. In addition, it was found that given sufficiently short length, molding can be performed even with a plate thickness of 0.5 mm.

1. Introduction

A prototype case that has thin radial fins inside the cylinder to increase heat transfer performance was created in the development of a compact, lightweight and high-performance Stirling engine with a target power-to-weight ratio of 1 kW per 10 kg. Fine radial grooves are cut in the pistons located inside the case in order to avoid these fins, and high shape accuracy is called for to help prevent contact during operation while at the same time minimizing the clearance with the fins. In addition, to reduce both the number of parts and the weight, a multifunctional structure is used that integrates the heat exchanger parts on the high- and low-temperature sides where the working gas circulates and the cooling water channels. The heat exchanger also uses a fine shape with millimeter-size gaps in a complex arrangement to reduce the heat exchanger size while still maintaining high performance. Since conventional manufacturing processes are unable to accommodate these specifications, this manufacturing was realized for the first time through additive manufacturing (AM), that is to say, the use of a 3D printer for metal materials.

Lamination-based 3D molding technology continues

to make remarkable advances, but the main trend is typically to take shapes created with existing manufacturing processes such as casting or machining and instead use a lamination manufacturing process without modifying the shape.⁽¹⁾⁻⁽³⁾

This study first investigated the characteristics of the lamination manufacturing process, and then performed design to obtain the optimum performance using shapes able to be created only by 3D technology. However, when an attempt was made to actually manufacture these shapes, many locations were found where the needed specifications could not be accommodated simply by existing AM technology. For this reason, various manufacturing process know-how was called for.

Examples of this know-how include the use of shapes consisting entirely of thin elements with minimal variation in thickness to help prevent a reduction in shape accuracy due to thermal contraction, and reducing deformation during lamination by modifying the shape of the supports removed by machining or other processing after molding. This paper introduces specific examples of manufacturing know-how obtained as a result of trial and error.

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2. Heat Exchanger Case for Stirling Engine

2.1. Structural Features

The developed Stirling engine is called a β -type. A power piston (PP, Fig. 1) that produces power and a displacer piston (DP, Fig. 2) that moves the working gas alternately between the high- and low-temperature ends are arranged coaxially, and these pistons perform reciprocating motion with a phase difference. In addition, the DP configuration has a regenerator in the middle and pistons on both the upper and lower sides. Both the PP and DP have a bore diameter of 58 mm and a stroke of 23 mm.

Normal Stirling engines have fins that promote external heat exchange located on only the outside of the cylinder. In contrast, a characteristic of the developed Stirling engine is that radial fins are also provided inside the cylinder to promote heat exchange with the working gas at the inner wall surface. Fine radial grooves are cut into the pistons located inside the case to avoid these fins, and high shape accuracy is called for to help prevent contact during operation while at the same time minimizing the clearance with the fins.

The overall case consists of two parts: a high-temperature upper case with sheet metal fins brazed to the outside (Fig. 3) and a low-temperature lower case (Fig. 4). The upper case contains radial fins and a heat exchanger located around its inner circumference that heats the working gas as the gas moves. The lower case also contains radial fins and a heat exchanger located around its inner circumference that cools the working gas as the gas moves, and these are surrounded by a water jacket through which

cooling water flows (Fig. 5). These parts are all integrated to form a multi-functional compound case. In addition, the heat exchanger uses a fine shape with millimeter-size gaps in a complex arrangement to reduce the heat exchanger size while still maintaining the performance.

Since conventional manufacturing processes are unable to accommodate these specifications, this manufacturing was realized for the first time by AM, that is to say, the use of a 3D printer for metal materials.

2.2. Needed Accuracy

In order to reduce weight, the pressure-resistant vessel that holds the high-pressure gas is only 1 mm thick, and a machining margin of 0.2 mm is removed by finish machining. In addition, the radial fin thickness is 0.5 mm and the radial grooves cut into the pistons to avoid the fins have a width of 0.9 mm to 1.2 mm, so the groove clearance is just 0.2 mm to 0.35 mm. Therefore, strict accuracy is called for with respect to the circularity of the cylindrical case and the straightness and thickness of the fins.

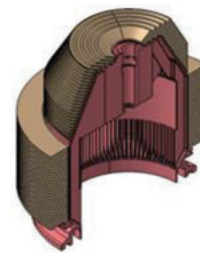


Fig. 3 Upper case

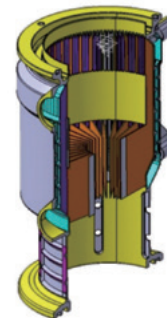


Fig. 4 Lower case



Fig. 1 Power piston

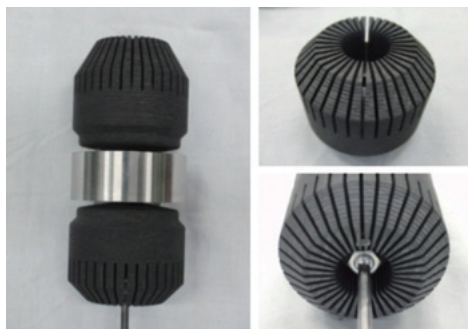


Fig. 2 Displacer piston

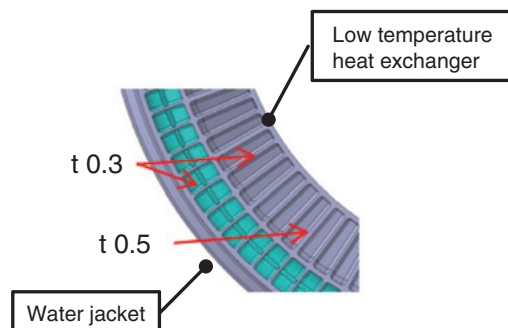


Fig. 5 Water jacket and heat exchanger of lower case

3. AM Device

3.1. AM Device

An EOSINT M270 was used for molding. Table 1 lists the device specifications. Heat-resistant alloy powder was used as the material. Figure 6 shows a photograph of the device exterior and controller screen. Molding is performed while flowing an inert gas (N_2) into the small chamber inside the device where laser irradiation is performed in order to reduce oxidation.

3.2. Prototype Model

Two sets each for a total of four upper and lower cases were manufactured simultaneously as prototype models. In addition, cutout test pieces for material verification to check the inside of those cases were also molded at the same time. The lamination molding time excluding the previously prepared base plate was 140 hours. Figure 7 shows the



Fig. 6 Additive manufacturing device

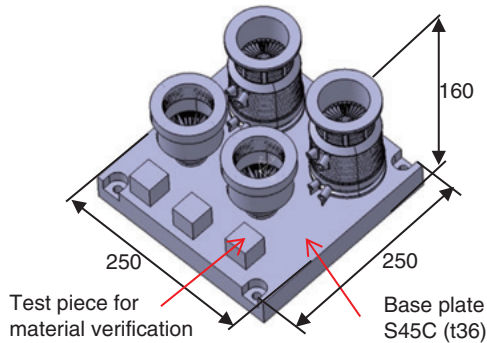


Fig. 7 Molding model

Table 1 Molding conditions

Device name	EOSINT 270
Powder materials	Co-Cr-Mo
Powder grain size [μm]	30 - 40
Laser output [W]	200
Spot diameter [mm]	0.1 (minimum)
Scan speed [mm/s]	800 (maximum)
Laminating thickness [μm]	40
Blade	Carbon brush
Building size [mm]	250X250X215

molding model.

The product was molded by repeatedly using a plate called a blade to lay a thin layer of powder material at a constant thickness while applying a load and then melting the areas to be molded with a laser to laminate from the bottom up in 40- μm increments. Figure 8 shows photographs of the molding process.

4. Prototype Manufacture

The prototype was an unprecedented shape for Honda as well as the specialized manufacturer, so trial manufacture and modification were repeated three times before finally realizing a finished product.

4.1. Radial Fin Reinforcing Ring and Carbon Brush

Maintaining the molding accuracy of thin radial fins with a plate thickness of 0.5 mm was anticipated to be challenging even before prototype manufacture. Therefore, a reinforcing ring that is removed in a subsequent process was added with the goal of increasing the strength to reduce deformation during molding (Fig. 9).

As a result, the radial fins did not deform and sufficient accuracy was secured, but the fin shape deformed in the area where the fins intersect the micro heat exchanger partitioning blade (Fig. 10). This is assumed to occur



(a) Preparation for recoating of material powder

(b) Recoating of material powder

(c) Laser irradiation

Fig. 8 Molding process

because the powder is laid while pressing strongly with a metallic or ceramic blade to increase the powder density as much as possible. Therefore, a carbon brush was used like a broom to address this issue (Fig. 11).

When a carbon brush is used with thick parts, the issue of uneven powder density arises and there is the concern of a drop in relative density. However, it was found that a drop in density is not an issue when used with a thin shape such as a fin. This was confirmed in the material inspection described hereafter.

4.2. Reinforcing Ring for Long Vertical Fins around Lower Case Periphery

Use of a carbon brush refined the radial fins, but next undulation occurred in the low-temperature fin-type heat exchanger around the periphery of the lower case (Fig. 12).

Therefore, like the radial fins of the upper case, a thin reinforcing ring covering the exposed parts of the fins was added as a countermeasure with the assumption of removal by subsequent machining. A new prototype with this

reinforcing was manufactured, and it was found that there was no undulation after reinforcing ring removal (Fig. 13).

The upper case has similar vertical fins around the periphery inside the case, but it was found that undulation did not occur over short distances of approximately 2 cm or less, such as areas hidden by the upper case and the radial fins (Fig. 14).

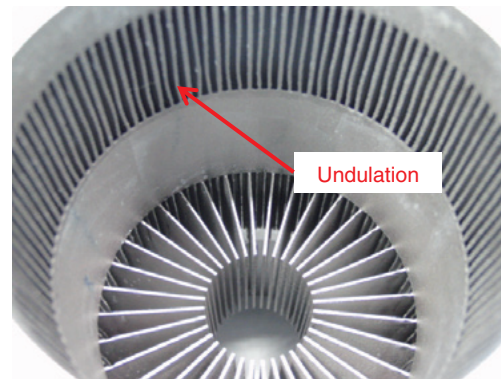


Fig. 12 Vertical fins (0.5 mm thickness) with undulation

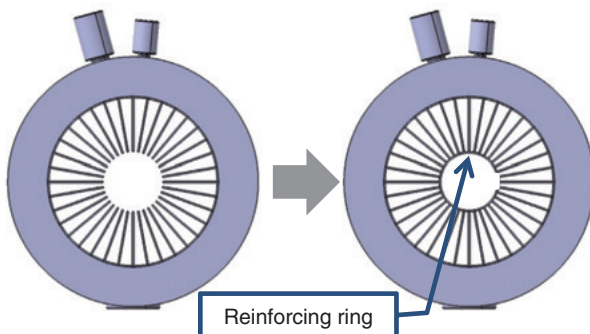


Fig. 9 Reinforcing ring

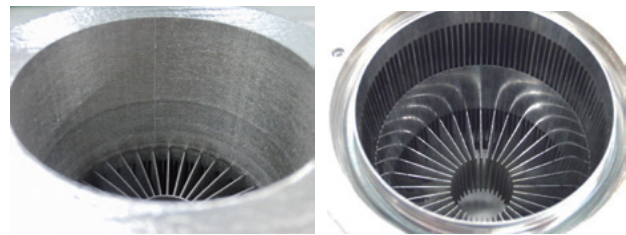


Fig. 13 Reinforcing ring before machining (left) and after machining (right)

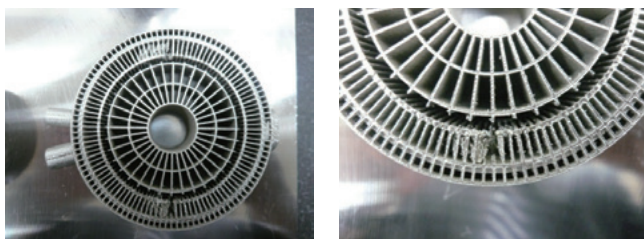


Fig. 10 Fin damage

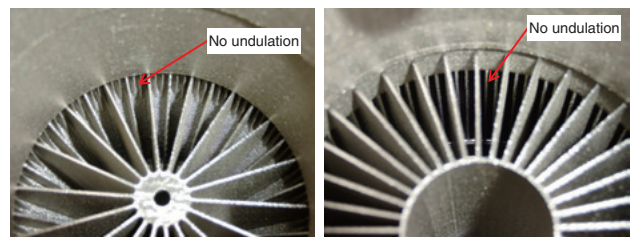


Fig. 14 Short vertical fins without undulation



Fig. 11 Conventional metal and ceramic blades and carbon blade

4.3. Holes for Removal of Residual Material

As a result of attaching a reinforcing ring as an undulation countermeasure for the low-temperature fin-type heat exchanger around the periphery of the lower case, powder remaining inside the case congealed in the heat treatment stage and became a challenge to remove (Fig. 15). The reason for this is thought to be that diffusion bonding occurred when the temperature was raised to 1050°C by heat treatment after molding.

It was found that when a fine structure has small gaps with a deep shape and no through outlet, such as those formed by attaching reinforcing rings in this manner, the sedimented material powder congeals due to diffusion bonding during heat treatment after molding. Therefore, it is important to consider ways to remove this powder in advance (Fig. 16).

As a countermeasure, small holes were opened in the reinforcing rings for powder removal, and the sedimented powder was removed before heat treatment. Small holes were opened in the three supports that are removed by machining after molding (Figs. 17 to 19).



Fig. 15 Congealed powder remaining after machining work to remove reinforcing ring

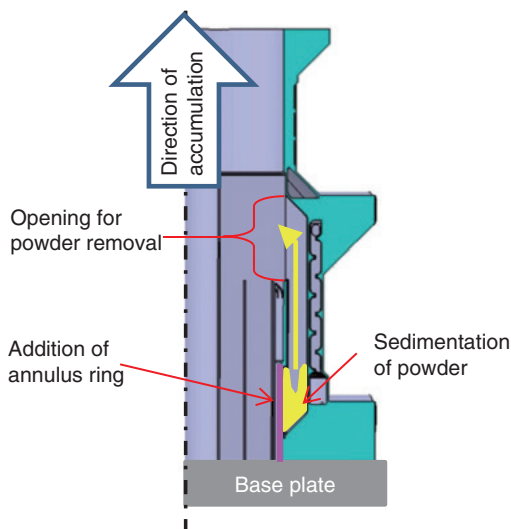


Fig. 16 Section of lower case

4.4. When Adjacent Part Thickness Differs such as Bosses

In the area around the boss where thin and thick parts are adjacent, molding resulted in a screw hole center offset of 1 mm or more. The reason for this is thought to be

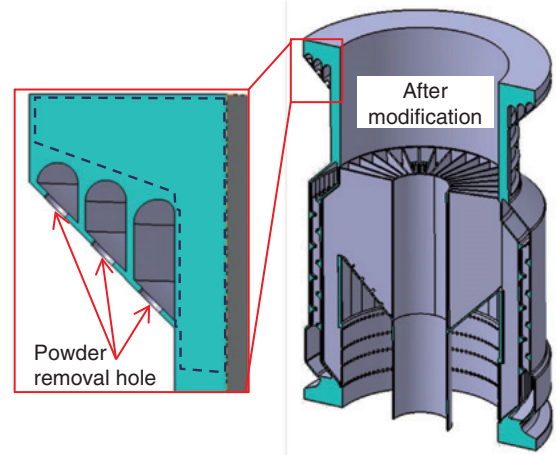


Fig. 17 Powder removal hole-1

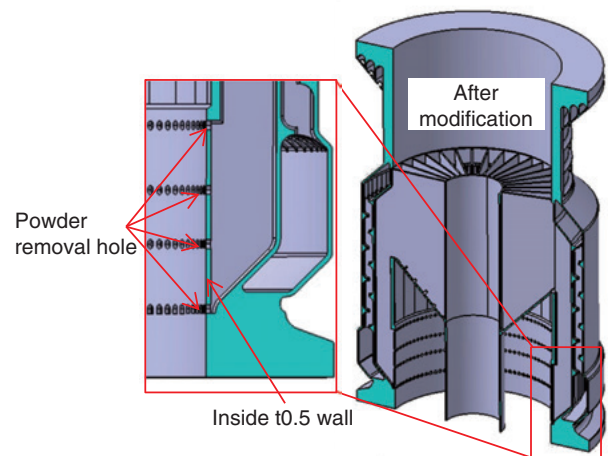


Fig. 18 Powder removal hole-2

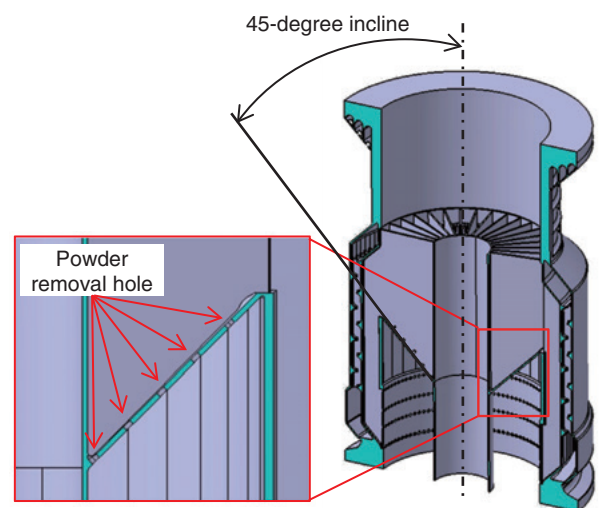


Fig. 19 Powder removal hole-3

deformation due to thermal contraction.

In cases like this it is important to modify the design so that all parts are as close to the same thickness as possible, such as by using a constricted shape at the base of the boss and opening a pilot hole beforehand (Fig. 20).

4.5. Brazed Parts and Finish Machining

The heat exchanger fins on the outside of the upper case consist of sheet metal pressed parts brazed to the case. This is because it is necessary to use a shape consisting of stacked upward facing conical shapes with an angle smaller than 45° and parallel disks, so it was determined that lamination-based molding could not be used. However, the combination of metal lamination and brazing technology enabled fabrication (Fig. 21).

Electric discharge was initially attempted as the finish machining method to remove the reinforcing ring (sleeve

inner diameter), but sufficient surface roughness could not be secured, so this was changed to grinding using a grindstone.

Grooves for mounting the neodymium magnets used to float the piston and other shapes were also machined in the lower case (Fig. 22).

5. Inspection

5.1. Confirmation of Powder Removal by X-ray Inspection

The SMX-225CT-SV3 Micro-focus X-ray CT System (tube voltage: 225 kV) made by Shimadzu Corporation was used as the inspection device. Sectional inspection measured multiple cross-sections where powder easily remains. Figures 23 and 24 show the inspection device and the sectional inspection locations.

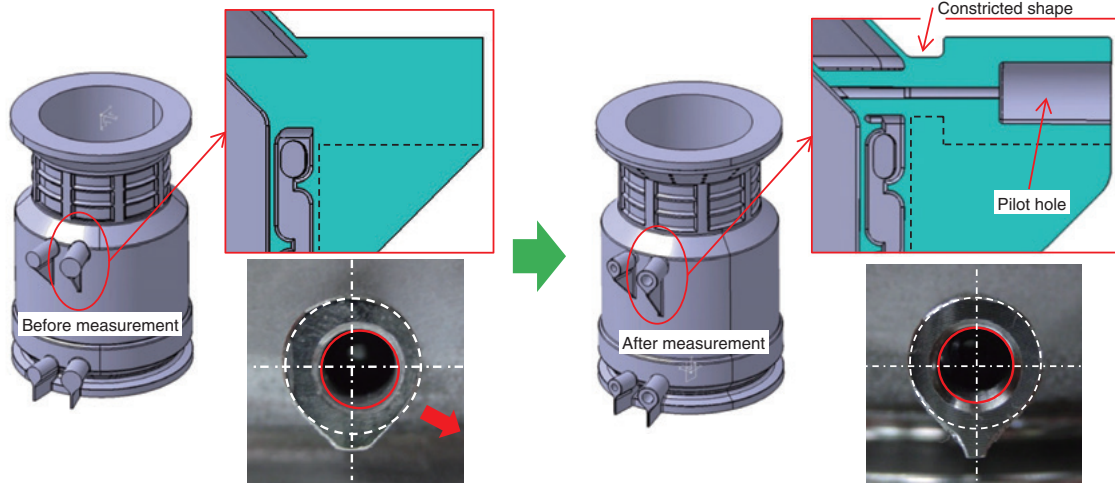


Fig. 20 Modification of boss shape

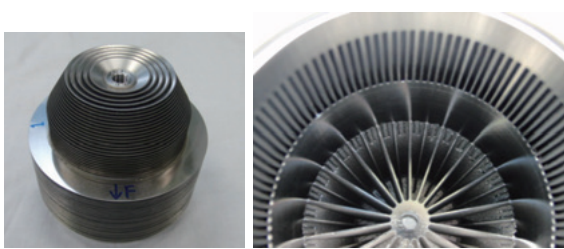


Fig. 21 Upper case



Fig. 22 Lower case



Fig. 23 Shimadzu Micro-focus X-ray CT System (SMX-225CT-SV3)

X-ray imaging enabled to confirm that the powder had been removed from all locations as a result of opening small holes in the reinforcing rings (Figs. 25 and 26).

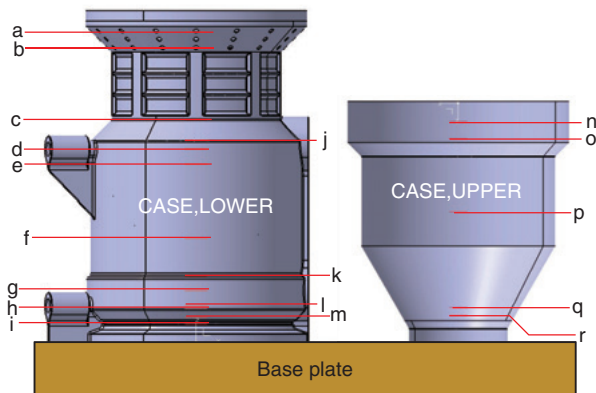


Fig. 24 X-ray measurement sections a - r

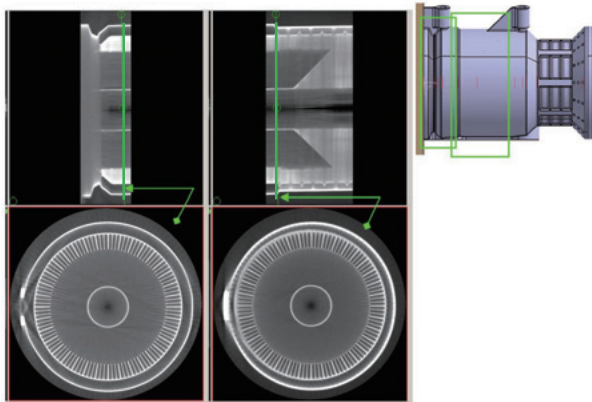


Fig. 25 Lower case sections (radial fins)

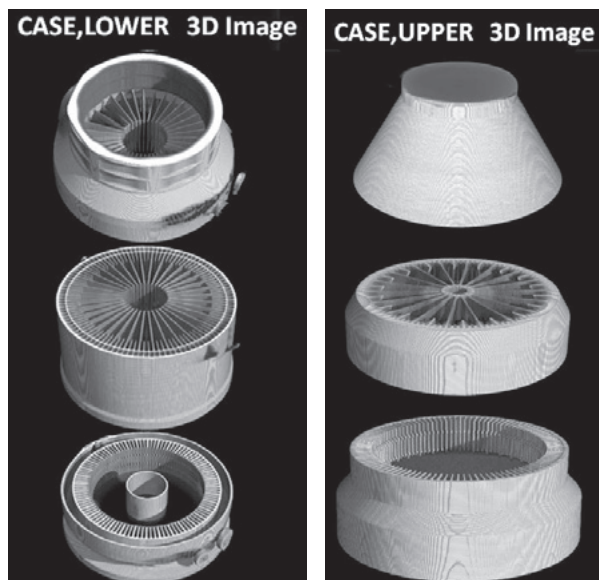


Fig. 26 Lower and upper case sections

5.2. Dimensional Inspection

High diameter accuracy and cylindricity are needed to realize a fine clearance between the case inner diameter and the pistons. Machining cannot be performed after molding in the cylinder area at the base of the fins (Fig. 27), so 3D measurement was performed during the initial molding to measure the deviation from the design value and perform calibration. As shown in Fig. 28, the product was molded with an inner radius approximately 0.2 mm smaller than the design value due to thermal contraction. In addition, the radius variation was 0.17 mm (max.), so taking into account thermal contraction provided prospects for achieving the needed tolerance of 0.2 mm.

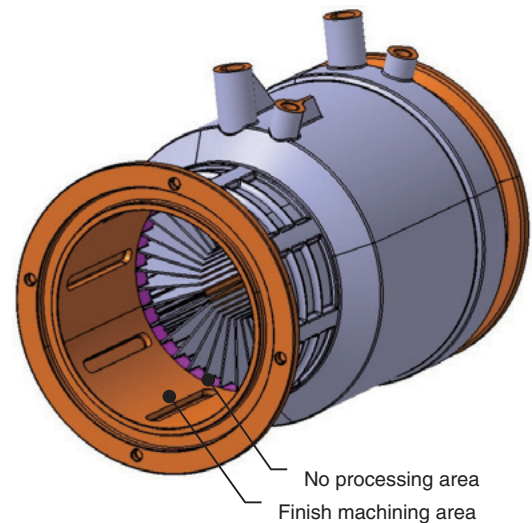


Fig. 27 Area where finish machining cannot be performed

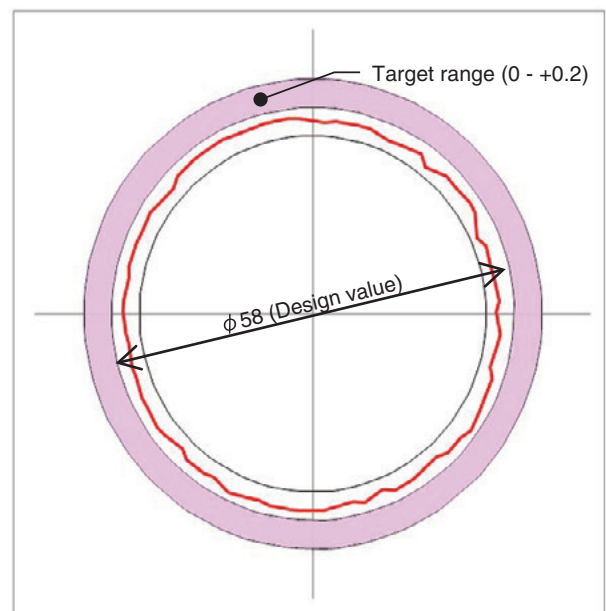


Fig. 28 Examination for dimension calibration

Table 2 Density of test pieces

Test piece	Volume [cm ³]	Mass [g]	Density [g/cm ³]
1	8.10	67.75	8.36
2	8.25	69.00	8.36
3	8.37	69.70	8.33
Average	-	-	8.35

Ultimately, the needed tolerance was secured using a diameter setting value of 58.4 mm, which is a slight increase in consideration of contraction.

5.3. Material Characteristics Inspection

It was confirmed that use of a carbon brush did not result in material imperfections.

5.3.1. Verification of density

Measurement by the water suspension (displacement) method using a digital densitometer confirmed that the density was the same level as the material data (8.3 g/cm³) (Table 2).

5.3.2. Verification of hardness

The hardness was measured using a Rockwell hardness tester. The hardness tester used a 120° diamond cone with a tip radius of 0.2 mm, and applied a load of 150 kgf.

Figure 29 shows the results of measuring the test pieces with a hardness tester. The X/Y axis indicates the planar direction and the Z axis indicates the lamination direction. The hardness in the planar direction tended to be somewhat lower than the material data (35 to 45 HRC), but was determined to be a level that does not pose issues for practical use.

5.3.3. Inspection of internal quality by optical microscope

Structural inspection of the surface layer and the interior (10 mm to 20 mm) did not find any detrimental imperfections.

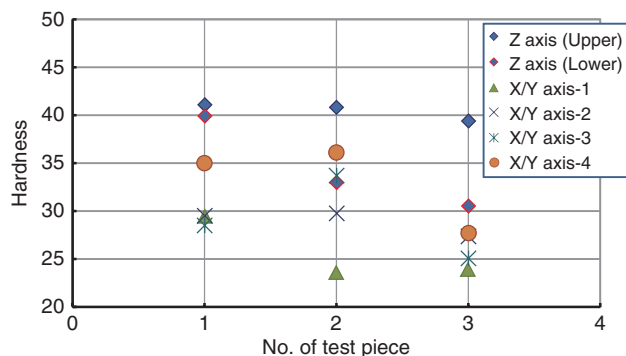


Fig. 29 Comparison of test piece hardness (HRC)

6. Summary of Design Method

6.1. Constraints

AM is a lamination molding method that stacks powder materials from the bottom up, one layer at a time. Therefore, shapes that hang down from above are supported from below by structures called supports that need to be removed after molding. In addition, even when stacking from the bottom up, there is the constraint that stacking cannot be performed at an angle of less than 45°.

Furthermore, when used for typical structures, AM is said to be unsuitable for thin plates with a thickness of 1 mm or less as deformation increases in these cases, although this also depends on the powder grain size. In fact, when structures with a fine construction such as those described in this paper are molded without any countermeasures, deformation sometimes occurs in thin locations.

6.2. Design Know-how

Changing the blade that lays the powder to a carbon brush reduces the pressing load and helps to prevent shape deformation even when molding thin plates.

Long and thin fins with a plate thickness of 0.5 mm can be molded without deformation by attaching reinforcing rings that are removed after molding. Short fins such as the heat exchanger fins with a length of 2 cm or less do not deform even when the plate thickness is 0.5 mm. Likewise, the fins inside the water jacket also have a fine structure with a plate thickness of 0.3 mm, but molding could be performed without issue over short lengths of several millimeters.

When the addition of reinforcing members creates pockets with no through outlet, it is necessary to create small holes to remove the powder remaining inside before heat treatment.

When thin plate shapes are adjacent to thick parts such as a boss or flange, deformation can be effectively reduced by opening a screw pilot hole in the boss beforehand or otherwise reducing the variation in thickness.

In locations where lamination molding cannot be used, such as the conical fins around the outside of the upper case, parts created using different forming processes (e.g., sheet metal pressed parts) can also be attached by brazing or the like.

In locations where machining cannot be performed and high material dimension accuracy after lamination is called for, the amount of dimensional change due to thermal contraction should be measured beforehand and calibration performed.

7. Conclusion

The latest AM technology was used to manufacture a prototype case with built-in heat exchanger for a Stirling engine that has high molding accuracy and a precise and complex shape. During the course of this process, it was

found that various modifications are needed in addition to conventional know-how.

These included the use of a carbon brush to effectively reduce the pressing force of the blade in the manufacturing device; modification of the support shapes that are removed by machining after molding to help prevent deformation during lamination molding; and opening holes to completely remove residual powder before heat treatment.

It was demonstrated that by introducing this new know-how from the design stage, products with precise and complex shapes that cannot easily be imitated by other manufacturing processes can be manufactured by metal lamination.

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