

Development of IH Coil Modeling Technology Using a 3D Printer

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The IH (Induction Heating) coils currently used in high-frequency heat treatment are made by processing copper material and then having a skilled worker braze it together. This method has issues such as long manufacturing lead times and short coil life due to water leakage from brazed parts. To address these issues, a novel method of producing IH coils using a metal 3D printer was developed. This reduces coil manufacturing lead time, eliminates brazing, and extends coil lifespan by optimizing the coil shape design.

Key Words: additive manufacturing, 3D printer, laser beam powder bed fusion, Induction heating coils

1. Introduction

Metal additive manufacturing (metal 3D printer) is a revolutionary next-generation technology that can efficiently manufacture parts, dies, and other items with complex shapes, and is gaining attention in a broad range of fields including aerospace, automobiles, energy, and biomaterials.

The primary system used in metal 3D printers is the PBF-LB (laser beam power bed fusion) shown in **Fig. 1**. It can produce internal structures and complex shapes which could not be created with conventional manufacturing methods, and is used in casting of automobile components, plastic molding dies, and other applications. For example, with a die produced by a 3D printer, it is possible to create internal water cooling channels with complex shapes that are not possible with drill machining. Therefore by using water cooling channels with the shape that delivers optimal cooling performance, it is possible to improve dimensional accuracy and die lifespan compared to conventional dies.

Although copper is difficult to laminate as a 3D printer material, in recent years as a result of development such as the use of green and blue high-intensity lasers, and the addition of elements such as zirconium to the material powder, cases of successful manufacture have been reported¹⁾.

This report will introduce the development details and results of induction heating (IH) coils for induction hardening through copper shaping using a metal 3D printer.

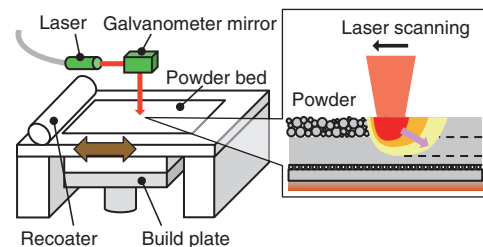


Fig. 1 PBF-LB schematic

2. Development Objectives

Induction hardening is a surface heat treatment method characterized by rapid heating using induction heating and rapid cooling primarily using jet cooling. In recent years, heat treatment methods for steel materials that used heavy oil, kerosene, gas, or other fuels have been replaced by clean electrical energy. This hardening method has gained attention as “W-Eco” (ecological and economical) heat treatment that has good energy efficiency and cost performance, and is environmentally friendly. Induction hardening has advantages such as producing high compressive residual stress by selective hardening and surface hardening, and the ability to be used in an automotive in-line process. As a result, it is widely used for automobile components, machine tool components, and other parts in order to improve wear resistance and fatigue resistance characteristics²⁾. **Figure 2** shows a schematic drawing of induction hardening. When hardening is performed, high-frequency current is applied to the IH coil, and electro-magnetic induction produces rapid heating of the metal surface due to overcurrent Joule heat produced on the surface of the workpiece. At the same time, the coil itself is heated, so an IH coil not only requires heating performance, but coil cooling performance is also important. For this reason, cooling water channels are created inside the coil.

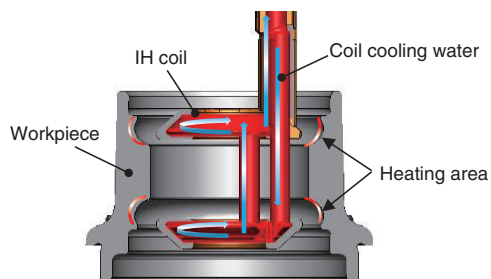


Fig. 2 Induction hardening schematic

Most IH coils have a one-of-a-kind shape that matches the shape of the heating part, and conventionally a skilled worker manually processes the copper material and brazes it together in order to produce the coil, as shown in **Fig. 3**. For this reason, there are issues such as long manufacturing lead times and water leakage from cracks in the weak brazed parts caused by thermal stress during heating, resulting in short coil lifespan.

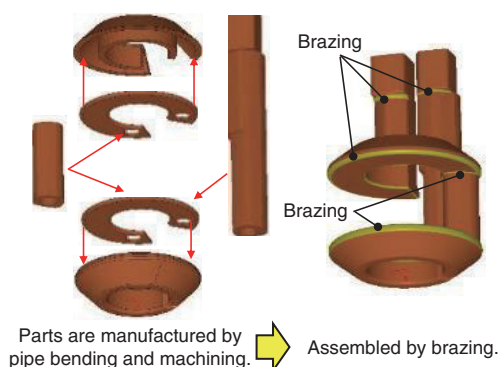


Fig. 3 Conventional coil fabrication methods

As described above, because a 3D printer can produce a single body with a complex shape, it is able to manufacture coils without the use of brazing. Therefore, manufacturing of an IH coil using a metal 3D printer (hereafter, “3D printer coil”) was investigated in order to improve lifespans by eliminating brazing and to shorten manufacturing lead times.

3. Current State of Copper Alloy Shaping

3. 1 Study of Shaping Conditions

The copper material used in an IH coil has a low absorption rate and low input heat efficiency with the Yb fiber lasers (wavelength: 1 064 nm) that are installed in an ordinary metal 3D printer. Copper itself has a high coefficient of thermal conductivity, and the heat required for melting is easily diffused into the shaped article or shaping plate. Due to these characteristics, manufacturing of high-quality copper shaped articles is considered difficult.

In order to resolve this problem, adding zirconium and other elements with a high laser absorption rate to the copper powder has been studied in order to increase the laser absorption rate of the powder itself³⁾. During this development, Cu-Zr alloy powder¹⁾ is used and applied to IH coils.

The shaping machine used was a SLM Solutions SLM280^{HL} (maximum shaping dimensions: 280 mm × 280 mm × 35 mm). **Figure 4** shows the shaping principle using PBF-LB and the primary process parameters. With PBF-LB, it has been reported that there is correlation between energy density E (J/mm³) — a comprehensive index of these process parameters — and the density of the shaped article⁴⁾. Energy density is expressed by the following formula, with P being the laser output (W), v the scan speed (mm/s), s the scan pitch (mm), and t the layer thickness (mm).

$$E = P / vst \tag{1}$$

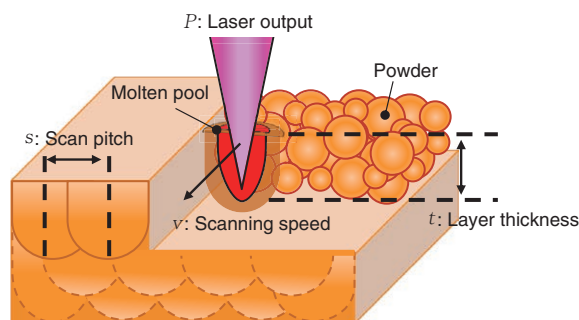


Fig. 4 Process parameters

Table 1 Fabrication conditions

Laser wavelength	1 075 nm
Beam diameter	0.08 mm
Laser output	370 ~ 400 W
Scanning speed	300 ~ 1 100 mm/s
Scan pitch	0.08 mm
Layer thickness	0.04 mm

In this development as well, the shaping results were evaluated from the relationship between energy density and the relative density of the shaped article, used as an evaluation indicator of quality. The machining conditions during shaping are shown in **Table 1**. Specimens (60 mm × 3 mm × 8 mm) were prepared by changing the process parameters on the base plate, and the relative density to the theoretical density of 7.68 g/cm³ was measured using the Archimedes principle.

3. 2 Test Results

The relationship between the measured energy density and relative density is shown in **Fig. 5**. The highest relative density of 99.3% was obtained under the condition of energy density 231 J/mm³. The reason is believed to be that when energy density is too low, the powder remains unmolten at the end of the laser irradiation time, and conversely when the energy density is too high, spatter causes melting failures and voids inside the shaped article, reducing the relative density. The results of SEM observation of the top surface of specimens are shown in **Fig. 6**. When the energy density increases, the surface asperities on the surface of the formed article become larger, showing that melting failures are occurring.

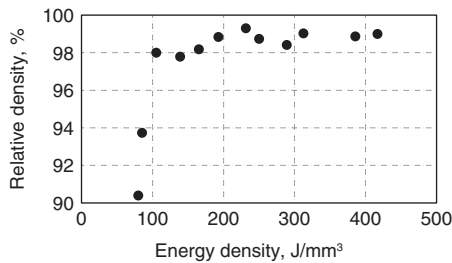


Fig. 5 Relationship between energy density and relative density

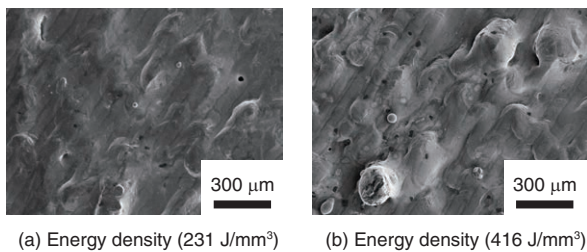


Fig. 6 SEM images of specimens

The material of an IH coil should have high conductivity from the perspective of saving energy. However, shaped articles of Cu-Zr alloy have a lower conductivity than copper because after the powder is melted by laser localized heating, it is rapidly solidified and a supersaturated solid solution of Zr forms in the Cu matrix immediately after shaping. We therefore studied improving the conductivity by precipitating the Zr in the Cu matrix using an aging process. **Figure 7** shows the conductivity measurement results after 5 hours of aging treatment at 800°C, the standard condition for Cu-Zr powder. While the conductivity before the aging process was 51.1% IACS, it improved to 88.6% IACS after the aging process. From the structures before and after the aging process and the Zr distribution results shown in **Fig. 8**, it can be seen that the Zr precipitated from within the Cu matrix.

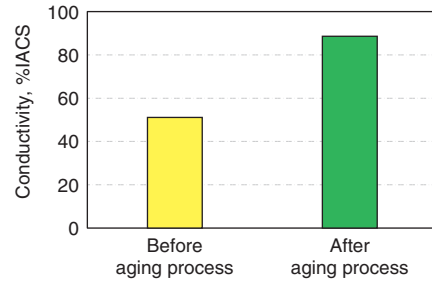


Fig. 7 Results of conductivity measurement

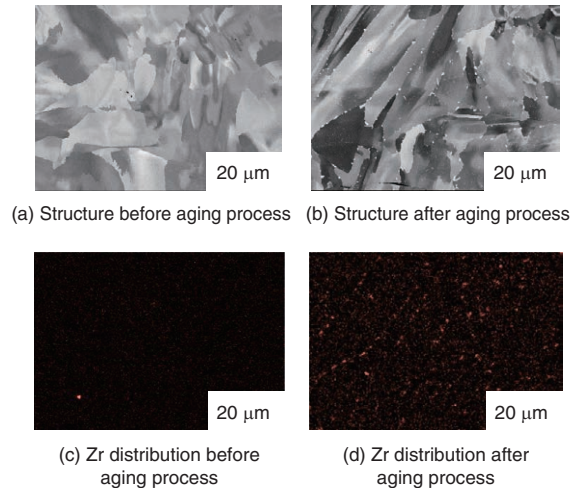


Fig. 8 Optical micrographs of specimens

3. 3 Current State of Flow Rate

Using the shaping conditions that produced high relative density, and based on the design drawing data of a conventional IH coil, an IH coil was manufactured using a metal 3D printer. When the coil cooling water flow rate is too low, the cooling water temperature rises, and the rising pressure in the coil water channels can cause damage. For this reason, the cooling water flow rate in the internal cooling water channels was focused on as the coil cooling performance and compared with a conventional product. **Figure 9** shows the coil cooling water flow rate. Despite the fact that the coils were manufactured based on the same drawing, the cooling water flow rate in the 3D printer coil was 11% lower. The reason for this is thought to be the following two points.

- Because the surface roughness of the 3D printer coil is larger, loss due to wall resistance reduced the flow rate.
- Shape collapse occurred at the top of the water channel, reducing the water channel cross section and reducing the flow rate (**Fig. 10**).

Because the cooling water flow rate was 11% lower than the conventional product, a countermeasure was considered by setting a 3D printer coil flow rate target of 8.7 L/min, 20% higher than the cooling water flow rate of the conventional coil.

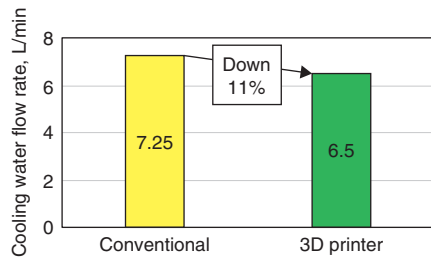


Fig. 9 Coil cooling water flow rate(L/min)

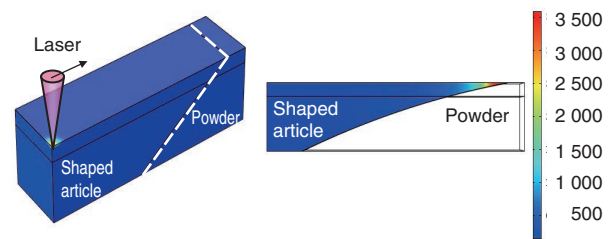


Fig. 11 Results of heat transfer analysis



Fig. 10 Water pipe collapse

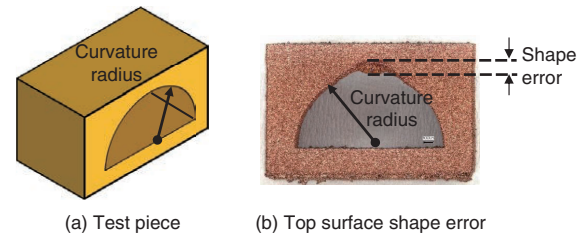


Fig. 12 Shape of test piece

4. Improving the 3D Printer Coil Quality

4.1 Establishing High-Accuracy Shaping Technology

When using PBF-LB to form shapes with voids at the bottom of the shaped article, such as the top surface of the water channel or an overhang shape, in order to prevent shape collapse, a retaining shape ordinarily known as a support is provided⁵⁾. However, in the case of a water channel inside an IH coil, it is not possible to provide supports due to concerns of reducing the cooling water flow rate, so how to prevent shape collapse without the use of supports was considered. It has been reported that with PBF-LB, when the bottom of the shaped article is a void, the heat during melting by the laser accumulates in the shaped article, causing the shape to collapse⁶⁾. Because it is thought that a similar phenomenon occurs at the top surface of the water channel, heat transfer analysis during shaping was performed. The analysis results are shown in **Fig. 11**. The temperature of the shaped article during laser irradiation was higher at the thin part at the top surface compared to other parts. As a result, it is possible that heat deformation occurs at the top surface, resulting in shape collapse. Therefore, the temperature at the top surface during shaping was reduced by controlling the laser irradiation conditions at the top surface and locally lowering the energy density.

The test piece shown in **Fig. 12** was prepared to check the effect on shape error at the top surface. **Figure 13** shows the results from comparison of shape error using test pieces with different curvature radius, and shows that the shape error was reduced in all of them.

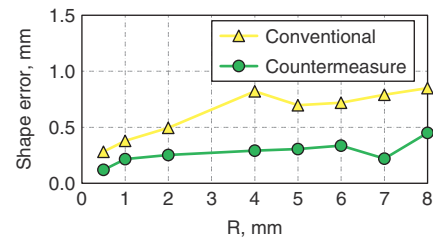


Fig. 13 Top surface shape error measurement results

4.2 Establishment of Flow Rate Improvement Technology

As described above, a metal 3D printer is able to manufacture more complex shapes than machining methods such as removal machining and plastic working, and is therefore suitable for shape optimization⁶⁾. In this development, shape optimization was applied to the cooling water channel structure of the IH coil to study the improvement of the cooling water flow rate.

Figure 14 shows a conceptual diagram of shape optimization. It is thought that pressure loss occurs at L-shaped parts of the cooling water channel, and therefore technology was used to optimize the fillet shape inside the water channel. For the optimal shape, the values of the control variables were varied, and values which minimize the target function were selected. For target function f for minimizing pressure loss, the pressure difference between cooling water channel input and output was set as the control variable. The target function is expressed using the following formula, with Ω being the design volume (mm^3), P_{in} the pressure at the cooling water channel inlet (Pa), and P_{out} the pressure at the cooling water channel outlet (Pa).

$$f = \int_{\Omega} (P_{in} - P_{out}) d\Omega \quad (2)$$

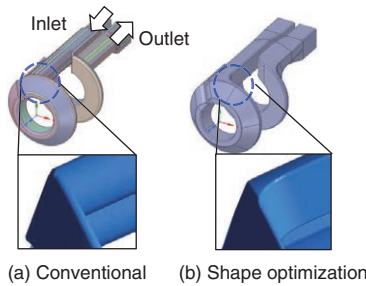


Fig. 14 Conceptual diagram of shape optimization

The fillet shape which minimized the pressure loss was derived by optimization analysis and applied to the water channel design. Figure 15 shows the results from measurement of cooling water flow rate using an IH coil where shape optimization was applied. It was confirmed that the 3D printer coil flow rate was 24% higher than a conventional brazed coil, and the target of 8.7 L/min was satisfied.

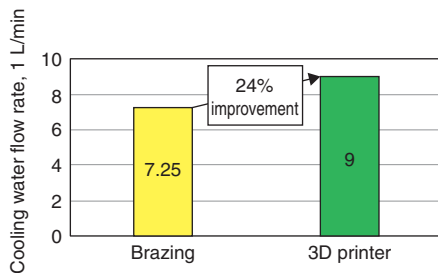


Fig. 15 Cooling water flow rate measurements results

5. Results from Application to Mass Production of Automobile Components

A heating evaluation of the metal 3D printer coil that incorporated the above countermeasures was performed. Figure 16 shows the hardening locations, and Table 2 shows the process capability Cmk for surface hardness of the heat treated component. The results of the heating evaluation showed that heating performance equivalent to a conventional coil was achieved, and that the results were within the product standards.

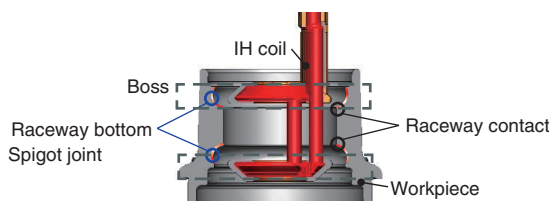


Fig. 16 HUB outer hardening point

Table 2 Heat-treated 3D printer coil Surface hardness

Item		Cm > 1.33	Cmk > 1.0	Evaluation
Boss side	Raceway bottom	1.41	1.33	○
	Raceway contact angle	1.39	1.37	○
Spigot joint side	Raceway contact angle	1.74	1.18	○
	Raceway bottom	1.91	1.15	○

Manufacturing an IH coil using a metal 3D printer reduced the coil brazing work that was previously performed by a skilled worker, and was able to reduce the coil fabrication lead time by 50% (Fig. 17).

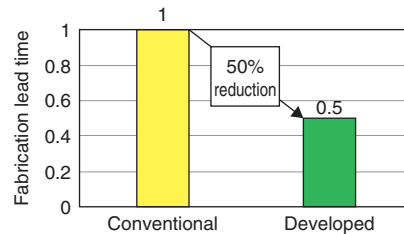


Fig. 17 Coil fabrication lead time

In a brazed coil, thermal stress during heating causes cracks to form in the weak brazed parts, resulting in water leakage and reducing the coil lifespan. However, because the use of a 3D metal printer eliminated the brazing, it improved coil strength and increased the coil lifespan from the conventional 29 000 shots to 150 000 shots. As a result, the coil intensity calculated by dividing the IH coil cost by the lifespan was reduced by approximately 90% (Fig. 18).

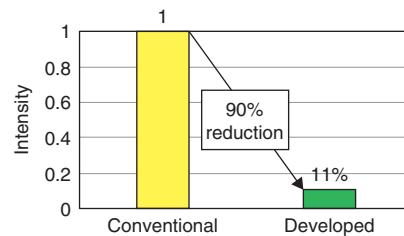


Fig. 18 The coil intensity

6. Conclusion

We developed technology for manufacturing an IH coil using a metal 3D printer, and succeeded in reducing coil manufacturing lead time by 50% and reducing coil intensity by 90%. The improved design freedom that is a feature of a 3D printer coil is expected to further improve the heating quality, extend the coil lifespan, reduce variation in coil lifespan, and reduce dependence on skilled workers for brazing.

At present, we are expanding the application to IH coils for hub units, steering components, constant velocity joints, and other automobile components. In the future, we intend to design coil shapes which can only be produced by 3D printers, and contribute to further improving added value.

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