# Deformation Properties of Induction Heating Coils Made by 3D Additive Manufacturing Using Electron Beam Melting

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Conventionally, induction heating coils, the main components of induction hardening equipment, are manufactured using many technologies such as cutting, bending, and brazing in the process to completion. To avoid this time-consuming and costly method, we have applied metal additive manufacturing, which has recently attracted attention as a new manufacturing technology, to manufacturing induction heating coils. By metal additive manufacturing equipment using electron beam melting (EB-AM, shortly), we successfully fabricated pure copper moldings equivalent to oxygen-free copper C1020. Using this molding method, we manufactured two different types of coils, one with little brazing joints, and the other with a complicated inner cooling channel that was difficult for the conventional method. Comparing the results of induction hardening experiments on those coils and the coil manufactured by the conventional method, it was confirmed that the hardening property provided by the EB-AM coils was comparable to the coil of the conventional method. In addition, it was found that the EB-AM coil with little brazing joint showed less deformation after the induction heating process than the coil of the conventional method with many brazing joints. Also, temperature measurements and simulations on the coils during the induction heating process revealed the EB-AM coil showed lower temperature, smaller deformation, and little fluctuation of the air gap between the coil and the workpiece than the coil of the conventional method.

***Keywords:*** *Additive manufacturing, Electron beam melting, Induction heating coil, Induction hardening, Simulation*

## 1. Introduction

Induction heating coils are the main components of the induction hardening equipment, and are custom designed according to customers' requests for the hardening range and the hardening depth of the workpiece[1]. Conventionally, manufacturing them needs many technologies such as cutting, bending, and brazing in the process to completion, which is time-consuming and costly. In recent years, metal additive manufacturing has been developing as a new manufacturing technology that has the potential to solve the issues of the conventional method. This technology has been expected to bring about innovations in manufacturing complex structures that were difficult to manufacture with the conventional method[2]. Therefore, we explored the possibility that metal additive manufacturing would be applied to manufacturing induction heating coils by using pure copper powder. First, we examined whether the hardening property provided by an induction heating coil manufactured by 3D metal additive manufacturing using electron beam melting (EB-AM, shortly), would be comparable to that provided by a coil manufactured using the conventional method. Second, temperature measurement during the induction heating process and a comparison of the results were conducted against the coil manufactured by the conventional method and a coil with a complicated inner cooling channel proposed by us, manufactured using EB-AM. Also, the deformation behavior of the coils during the induction heating process was investigated by simulation.

## 2. Experiment

### 2.1 Induction heating coils

We manufactured three types of coils; one using the conventional method (the conventional coil) with a brazing method, shown in Fig. 1c, and the other two using EB-AM, shown in Fig. 1a, b. These all coils are single-turn coils with an inner diameter of 34 mm and a width of 14 mm, and spray quench holes. The two EB-AM coils were fabricated by equipment named A2X, produced by Arcam AB by using pure copper powder. Both coils obtained a purity of 99.9% or higher and a filling rate of 99.8% or higher, equivalent to oxygen-free copper C1020. One of them shown in Fig. 1a was fabricated with the same design as the conventional coil shown in Fig. 1c. The other one shown in Fig. 1b has a complicated inner cooling channel designed so that the coil coolant can always directly cool the inner wall of the coil. This coil is also designed for the quenchant to be supplied through a thin pipe that crosses the channel. This unique design described above enables heat exchange with the coolant, and the coil temperature, which conventionally rises due to the joule heat generated by the eddy current in the coil, can be kept low.

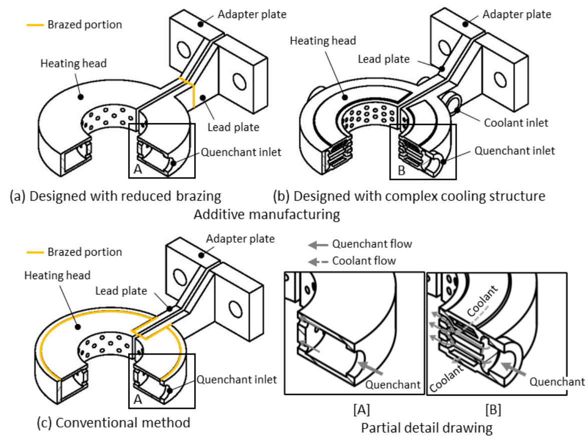


Figure 1. Overview of induction heating coils.

### 2.2 Hardening experiments

Two types of hardening experiments were conducted to observe whether induction hardening by EB-AM coils would be comparable to that by the conventional coil. In the first test, the cylindrical workpieces made of S45C were quenched using vacuum tube-type induction hardening equipment with a frequency of 200 kHz. Each workpiece has a spline shape portion on the outer circumference with a standard pitch circle diameter of 30mm and module 0.8.

The coils under test were the EB-AM coil with reduced brazing joints, shown in Fig. 1a, and the conventional coil shown in Fig. 1c, for comparison. In each of these quenched cylindrical workpieces, the quenching depths of the tips and roots at the splines were compared and evaluated by macrostructure examination. In the second test, induction hardening was performed 600 times in a row against round rod workpieces made of S45C with a diameter of 30 mm. Coil appearances were visually checked, and coil deformation of each coil was evaluated using a 3D digitizer (ATOS Triple Scan 16M, manufactured by GOM GmbH).

### 2.3 Induction heating experiments

Fig. 2 shows an overview of an induction heating experiment. Cylindrical workpieces made of S45C with an outer diameter of 32 mm, an inner diameter of 24 mm, and a length of 80 mm were heated using equipment similar to that used in the hardening experiments described above. The coils under test were the EB-AM coil with a complicated inner cooling channel, shown in Fig. 1b, and the conventional coil shown in Fig. 1c. Each coil surface temperature during induction heating was measured by using a thermal camera (CPA E60, manufactured by FIR Systems Co., Ltd.) installed at a position of 45 degrees from the coil surface, adopting the maximum temperature of five predetermined points on the coil surface. Also, the deformation behavior of each coil during the induction heating process was analyzed by conducting a coupling analysis of electromagnetic field and heat, using an induction heating simulation software (JMAG-Designer, JSOL CORPORATION).

## 3. Results and Discussion

### 3.1 Hardening properties provided by the EB-AM coils

Fig. 3 shows the macrostructures of the cylindrical workpieces quenched by induction hardening. The quenching depths at the tips and roots of splines in the workpieces are 2.55mm and 1.41mm when quenched with the EB-AM coil, and 2.48mm and 1.38mm when quenched with the conventional coil, which were almost the same. Also, it was confirmed that the martensite structure by quenching and the hardness were almost the same between the two types of coils. In addition, the EB-AM coil was observed in detail after induction hardening 600 times in a row. No defects such as water leakage or breakages were observed. Fig. 4 shows the deformations of coils after induction hardening 600 times in a row. As for the EB-AM coil, the heating head remained almost the original shape with little deformation although the lead plate and the adapter plate were deformed. As for the conventional coil, a slit portion of the heating head was deformed to open in addition to the deformations in the lead and adapter plates. The amount of deformation seemed to be affected by the total length of brazed portions. It is thought to be that the EB-AM coil showed a small amount of deformation because the coil had a few brazing joints, compared to the conventional coil.

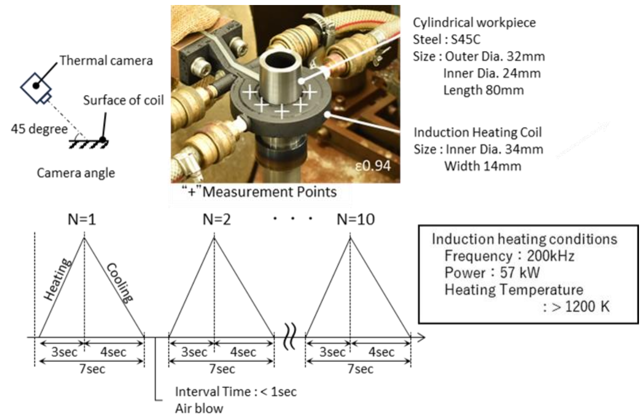


Figure 2. Overview of an induction heating experiment.

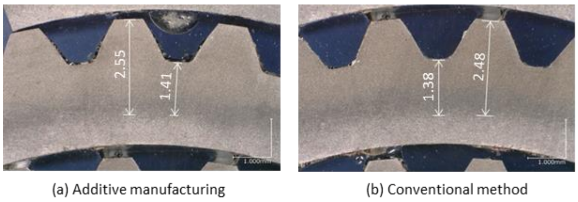


Figure 3. Hardening depth of S45C workpieces quenched using coils manufactured by electron beam melting and the conventional method, respectively.

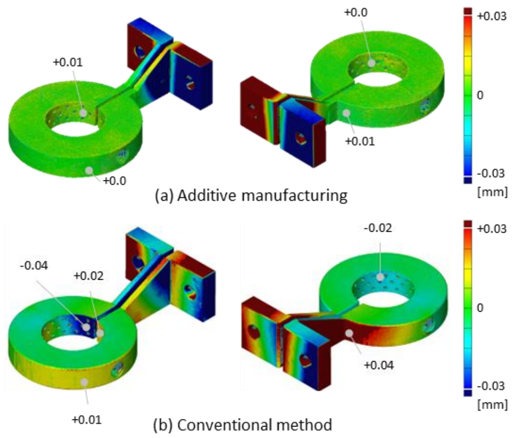


Figure 4. Deformation measured by 3D digitizer after hardening experiments on coils manufactured by additive manufacturing using electron beam melting and the conventional method, respectively.

### 3.2 Temperature distribution on the surface of the coils

We examined the results of the temperature evaluation for the EB-AM coil with the complicated inner cooling channel, during the induction heating process. Fig. 5 shows the temperature distributions of the EB-AM coil and the conventional coil, and the temperature transition of each coil during the induction heating process until repeating a cycle of the process 10 times. From the temperature distributions, the inner diameter sides of both coils show higher temperatures than other parts because the eddy current flows more intensively in the inner diameter sides of coils than other parts during the induction heating process. As for the temperature transitions, 307K was the temperature of the EB-AM coil at the 10th cycle of the process. It was 70K lower than 377K, the temperature of the conventional coil at the 10th cycle. It is considered that the unique inner cooling channel design enabled efficient heat exchange with the coolant, and it led to the large cooling performance described above.

### 3.3 Deformation properties of the coils

Fig. 6 shows the deformation behaviors of the coils during the induction heating process estimated by the induction heating simulation. As a result of thermal expansion caused by the induction heating, the coils were deformed forward with the adapter plates fixed to the high-frequency oscillator as a reference point, forming ellipse-like shapes. The deformation amounts from the position before induction heating fluctuated in the range of 0.057mm to 0.091mm for the conventional coil, and on the contrary, 0.017mm to 0.024mm for the EB-AM coil. This kept the air gap between the EB-AM coil and the workpiece almost constant during the process. It was indicated that the EB-AM coil showed less deformation during the induction heating process because the coil's temperature was kept low due to the high cooling performance.

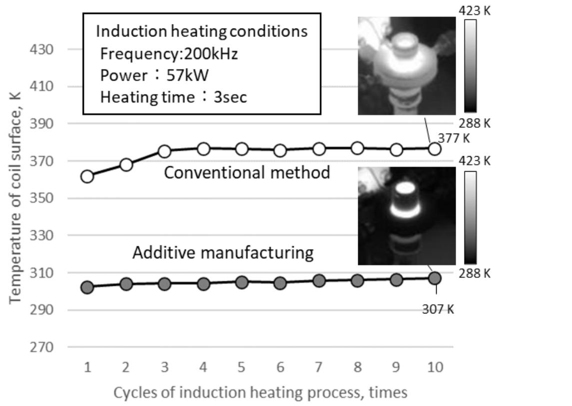


Figure 5. Temperature transition of the coils measured by the thermal camera for comparing the additive manufacturing and the conventional method, respectively in the induction heating experiments.

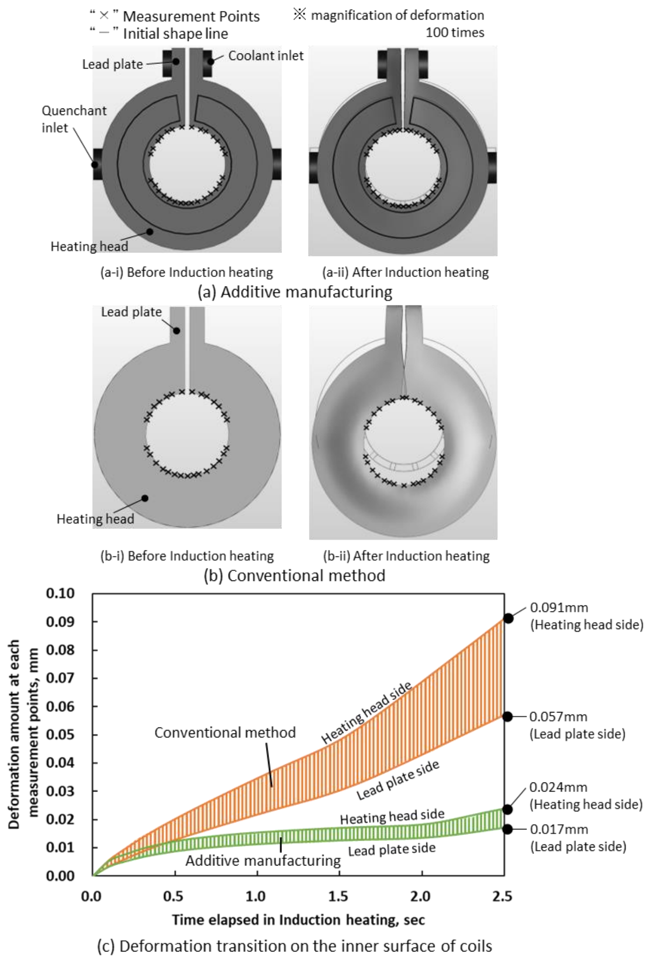


Figure 6. Simulated deformation behavior of coils using additive manufacturing and the conventional method, respectively at induction heating experiments.

## 4. Conclusions

Firstly in this report, hardening property provided by the induction heating coil made tentatively by 3D additive manufacturing method using electron beam melting, EB-AM, was investigated by quenching the workpiece made of S45C for comparing with the conventional coil made by brazing method with the same design. Secondly, the investigation was conducted on the coil temperature and deformation against the EB-AM induction heating coil with a complicated inner cooling channel devised by us compared with the conventional coil.

We found the following conclusive remarks:

Firstly, about the EB-AM induction heating coil with the same design as the conventional coil;

1) It can provide the cylindrical workpiece having a spline shape portion on the outer circumference made of S45C with the hardening range and the quenching depth evaluated by macrostructure examination at the same level as the conventional coil.
2) It can be used without problems for the induction hardening process which repeats a cycle of heating and cooling more than 600 times.
3) The deformation amount of the coil was affected by the total length of the brazed portions in each coil, and seemed not to be dependent on the difference between the additive manufacturing and the conventional method.

Secondly, about the EB-AM induction heating coil with a complicated inner cooling channel;

4) It was indicated that additive manufacturing enabled the design with a complicated inner cooling channel for the induction heating coil, which was difficult to manufacture with the conventional method using brazing.
5) The temperature fluctuation of the EB-AM coil was kept small during the induction heating process in comparison with the conventional coil.
6) The air gap between the EB-AM coil and the workpiece was kept almost constant during the induction heating process because the deformation during the process was small.

Finally, it can be expected that coils manufactured by metal additive manufacturing using electron beam melting will be widely applied to induction hardening equipment in the future.

## References


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