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Dominant Variables for Hardening of Axle Shaft through High Frequency Induction Heating

Min Hyeok Park[1, a], Jin Kyu Choi[1,b] , Kwang Sik Nam[1,c], Dong Uk Lee[1,d] and Seok Soon Lee[1, e*]

[1]School of Mechanical Engineering, ERI, GyeonSang National University, 501, Jinjudaero, Jinju Gyeongnam, Republic of Korea, 660-701

[a]mhparkorea@gmail.com, [b]minia1236@nate.com, [c]Sik.masan@gmail.com,

[d]dongdongju17@nate.com, *[e]leess@gsnu.ac.kr

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Abstract. Induction heating is being actively studied, and High frequency induction heating (HFIH) is widely used for various industrial applications. The reason for highlighting induction heating is that it has many advantages compared with previously used heating methods. The performance of HFIH is governed by a number of variables, including the applied frequency and power, shape of the coil, and duration of the process. We assumed that two of these variables are dominant. The first variable is the shape of the coil. The second variable is the frequency related to the skin effect. We found the optimal hardening conditions by changing these variables. The HFIH process was simulated using FEM and compared with results from experiments. We believe that the results of this study will be helpful for users of HFIH in the near future.

Introduction

Due to recent developments in numerical analysis, many ongoing multi-disciplinary studies are using FEA. HFIH is one of the applications being studied. However, research to date has only focused on the accuracy of the analysis and has not identified the optimal conditions for HFIH. In this paper, we determined the optimal conditions for HFIH using the following research. First, we identified the dominant variables for HFIH. The performance of HFIH is governed by a number of variables, including the applied frequency and power, shape of the coil, and duration of the process. We assumed that two of these variables are dominant. The first variable is the shape of the coil, which is one of the parameters that determine the hardening distribution. The second variable is the frequency related to the skin effect, which is one of the parameters that determine the hardening depth. Therefore, we sought to determine the best type and shape of coil and then the best frequency. This allowed us to determine the optimal hardening conditions for HFIH. These results will be useful for future applications of HFIH by industry.

Basic theory

To analyze the performance of HFIH, the electromagnetic field-induced current must be calculated. The governing equation for the electric-field distribution is expressed by Maxwell's equation:

$$\nabla \times \mathrm{E} = -\frac{\partial \mathrm{B}}{\partial \mathrm{t}} \tag{1}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t} \tag{2}$$

$$\nabla \bullet D = \rho \tag{3}$$

$$\nabla \bullet B = 0 \tag{4}$$

Where E is the electric-field intensity, H is the magnetic-field intensity, D is the charge density, B is the magnetic-flux density, and J is the current density.

$$D = \varepsilon E \tag{5}$$

$$B = \mu H \tag{6}$$

In the high-frequency range, the displacement current term of Eq. 2 is negligible. Thus, Eq. 8 is equivalent to Eq.7 after applying Ohm's law in Eq.2.

$$J = \sigma E \tag{7}$$

$$\nabla \times H - \sigma E = 0 \tag{8}$$

The magnetic vector potential A and the electric-flux density of the scalar potential V can be introduced and expressed as the intensity of the electric field.

$$B = \nabla \times A \tag{9}$$

$$E = -\frac{\partial A}{\partial t} - \nabla V \tag{10}$$

Since HFIH makes use of alternating current (AC) power, the influence of electric scalar potential V can be ignored. The following equation for the magnetic vector potential A can be obtained by substituting Eq. 9 and 10 into Eq. 8

$$\frac{1}{\mu}\nabla \times \nabla \times A - \sigma \frac{\partial A}{\partial t} = 0 \tag{11}$$

Eq. 11 is arranged for a finite-element formulation of an electromagnetic field. This gives us the eddy current induced by the heating target value, followed by the Joule heat.

Finite Element Analysis

Figure.1 shows a commonly used axle. The hardening depth must be below the values given in Fig.2. We focused on the most important part of the axle: section "A.". The required hardening depth is listed in Table.1.

Fig. 1 Rear axle shaft

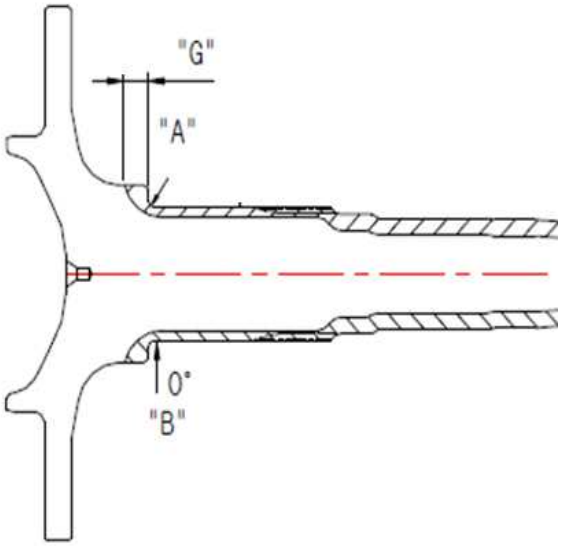

Fig. 2 Hardening section

Table. 1 Hardening depth

	Depth(mm)
“A”	6
“B”	7
“G”	10

First, the shape of the coil was varied, which affected the hardening distribution. The variables included the MTCs and STCs, as shown in Fig.3. Then, the frequency was varied, which affected the hardening depth. Commonly used frequencies of 1, 3, and 5kHz were considered.

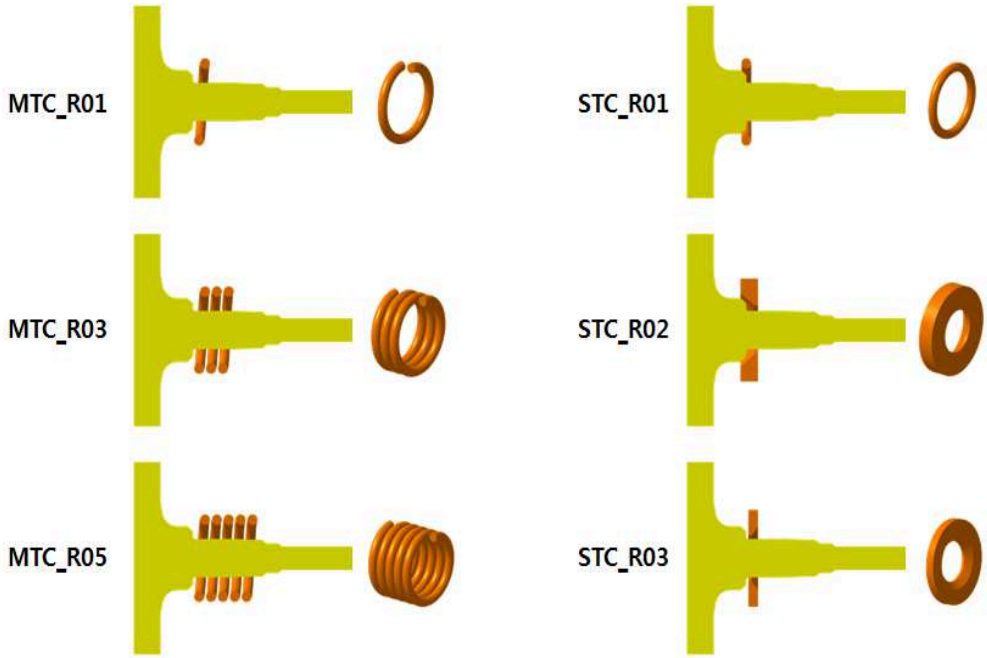

Fig. 3 Coil variables

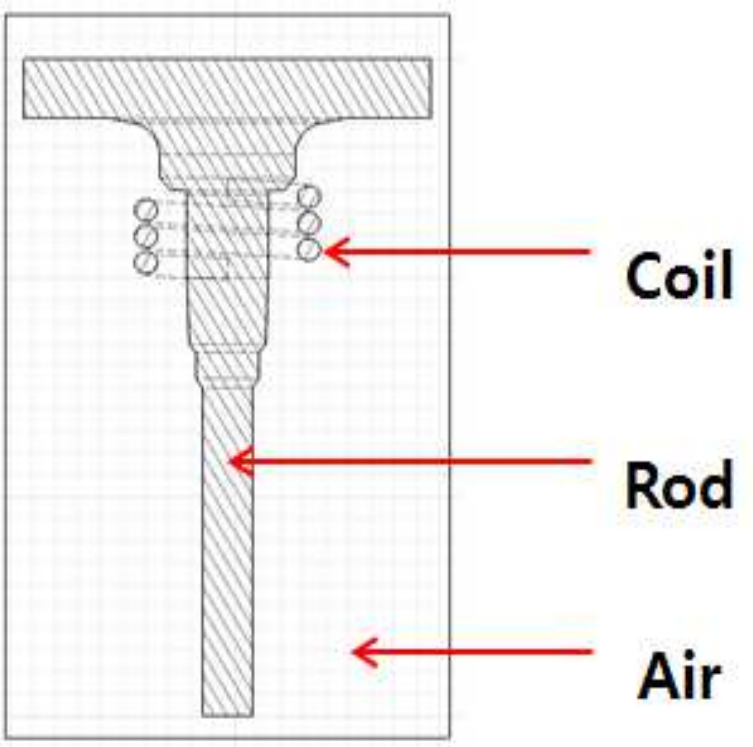

Fig. 4 Part section

Table. 2 Material property

	Property
Coil	Copper
Rod	SAE1038R
Air	atmosphere

The analysis conditions were divided into three parts, as shown in Fig.4. The coil, rod, and air environment remained constant, and are listed in the table below. The input power was also fixed.

Finite Element Analysis Result

The target boundary of hardening temperature was set to $800^{\circ}C \sim 900^{\circ}C$, Fig.5. There was a wide temperature lower than the target value. As shown in Fig.5, the temperature distribution was narrower for STC hardening, and the results indicated that the target temperature was reached. Thus, STC hardening gave the best results.

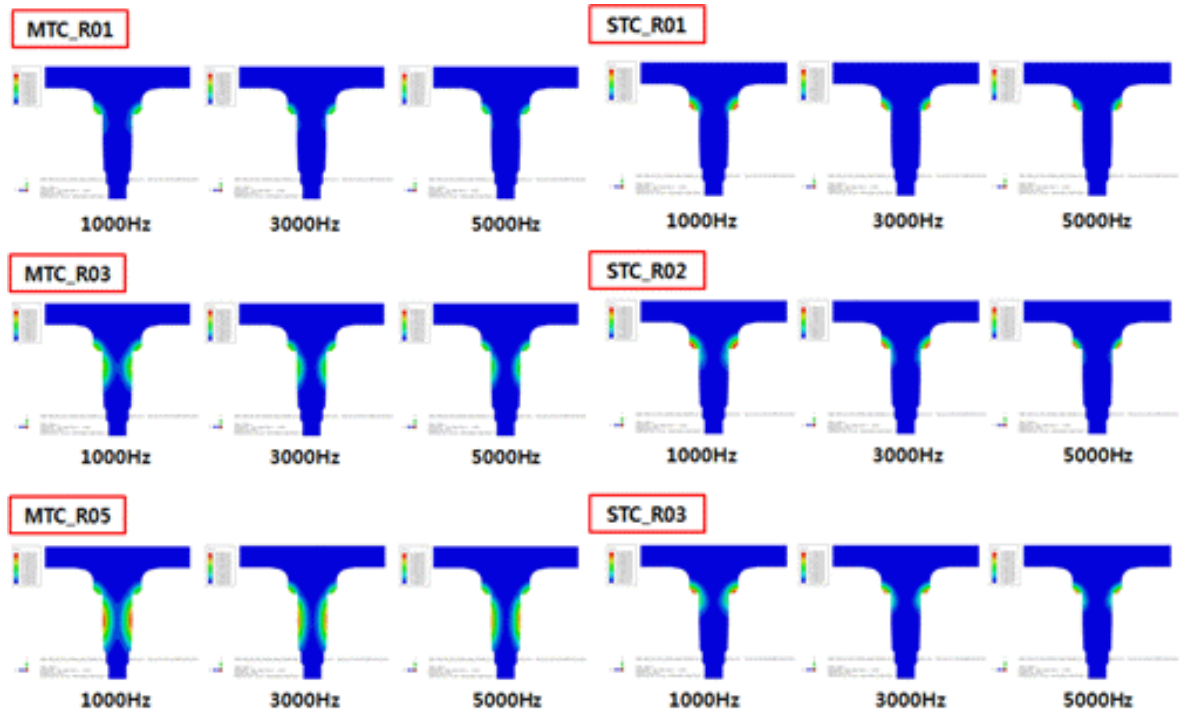

Fig. 5 Temperature distribution of MTC & STC

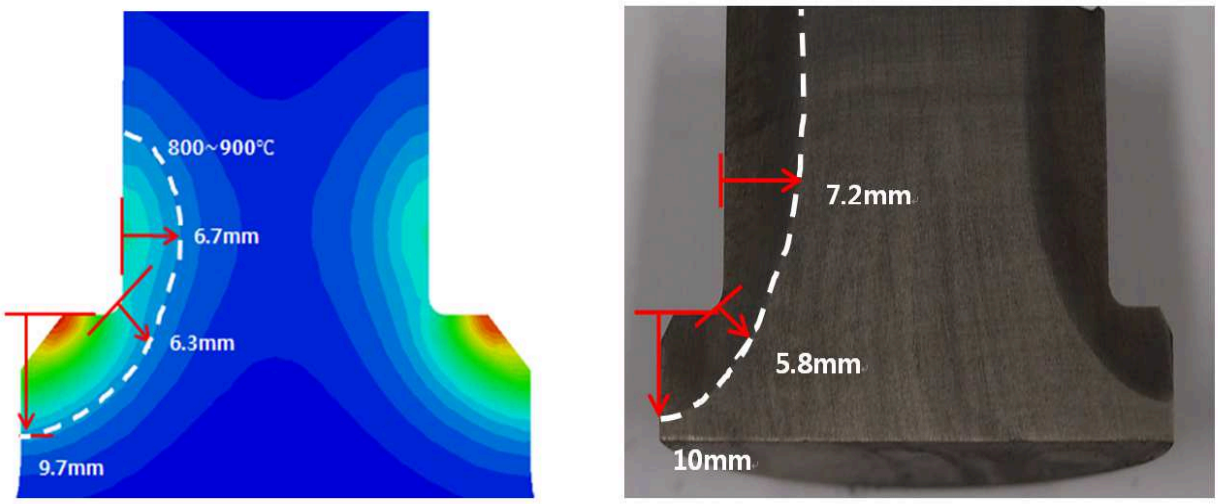

Fig. 6 Comparison of results at STC02

Table. 3 Comparison of depth

	"A"	"B"	"G"
Target hardening depth(mm)	6	7	10
Analysis temperature depth(mm)	6.3	6.7	9.7
Experiment hardening depth(mm)	5.8	7.2	10

Conclusion

We found the optimum conditions for HFIH by changing the shape of the coil and varying the applied frequency for an axial shaft. Optimum conditions are a STC_R03 shape and 3kHz frequency. Under the conditions, we can get the desired hardening depth by the FEA. Our research process is expected to be useful for HFIH and other fields.

Acknowledgements

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