Preliminary Study on Electromagnetic Thermal Coupling Numerical Simulation Technology of Static Inductor

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Abstract. In this paper, the load transfer analysis method is used. Firstly, the magnetic thermal coupling analysis model is established and the material parameters are determined in ANSYS software. Secondly, the direction of applied current is determined by studying the influence of current direction on the temperature field in the electrified wire. Then, the relationship between current frequency, current magnitude and temperature field and the change of temperature at typical points with time are studied respectively. Finally, the parameters of temperature field for high frequency induction heater to produce better plastic deformation are determined. The research content of this paper can provide a reference for the subsequent research of electromagnetic thermal structure coupling numerical simulation technology of mobile inductor.

1. Introduction
The process of welding deformation correction based on high frequency induction technology is a process of electromagnetic, thermal and stress interaction [1]. In this process, the temperature load acting on the structure is generated by the electromagnetic thermal coupling, so the electromagnetic thermal coupling process is the basis of the whole welding deformation correction analysis [2]. The research of static inductor is the basis of the research of mobile inductor, so it is necessary to study the electromagnetic thermal coupling process of static inductor.

2. Finite element model

2.1. Finite element model of electromagnetic field analysis
The finite element model of electromagnetic field adopts solid97 element in ANSYS software, and the analysis type adopts times harmonic analysis [3, 4]. As shown in Figure 1, the model is mainly composed of steel plate, wire, magnet and air region. The diameter of wire is 10 mm and the length is 40 mm. In order to improve the computational efficiency, the grid in the main sensing area is finer, and the grid in the component and air area far away from the sensing area is rougher.
2.2. Finite element model and material parameters of thermal analysis

Solid70 is used in the process of high frequency induction heating analysis [5]. Because solid70 thermal analysis element is compatible with solid97, a stable coupling relationship can be established between the two elements, which can avoid errors caused by incompatible elements in the analysis process and ensure the accuracy of the analysis results. The curves of specific heat, thermal conductivity and enthalpy with temperature are shown in Figure 2 ~ Figure 4.

![Overall model](image1)

(a) Overall model

![Inductor mesh](image2)

(b) Inductor mesh

![Front view of the mesh](image3)

(c) Front view of the mesh

**Figure 1.** Finite element model of steel plate, wire and the analytical system.

**Figure 2.** Specific heat - temperature curve.

**Figure 3.** Thermal conductivity - temperature curve.
3. Finite element model

3.1. Relationship between current direction and temperature field
When analyzing the influence of the current direction on the temperature field in two wires, it is necessary to ensure that the current size or current density is equal, and the current density applied here is 15E6A/M2, and the distribution of the magnetic field and temperature field is shown in Figure 5~Figure 6.

![Magnetic field distribution](image)

(a) Same direction of current  (b) Opposite direction of current

Figure 5. Magnetic field distribution.

![Temperature field distribution](image)

(a) Same direction of current  (b) Opposite direction of current

Figure 6. Temperature field distribution.
It can be seen from Figure 5 that the magnetic field in the same direction of current is stronger. In Figure 5(a), the magnetic field intensity in the surface area of the steel plate is large and mainly concentrated under the high-frequency inductor, and the distribution form of the electromagnetic field is strong in the middle area and decreases to both sides; in Figure 5(b), the magnetic field intensity is also mainly distributed below the high-frequency inductor, but the maximum value of the magnetic field intensity is concentrated right under the two live wires.

It can be seen from Figure 6 that the maximum temperature is 1232.21℃ when the current direction is the same, and the maximum temperature appears directly below the high-frequency inductor, with the center of the steel plate as the center of the circle, decreasing in a ring shape to the surrounding. When the current direction is opposite, the highest temperature appears just below the two wires in the high frequency inductor, which is only 201.755℃.

Figure 7 shows the distribution of the surface temperature of the steel plate on the path perpendicular to the current direction. It can be more clearly seen that the temperature field generated by the same current direction in the two wires is higher.

Through the above analysis, it can be concluded that when the current value, the high-frequency sensor model and the grid division are the same, the temperature field of the two wires with the same current direction is more uniform and the heating efficiency is higher.

3.2. Relationship between current frequency and temperature field

When the current is 1500A, the heating time is 20s and the power frequency is 5KHz, 10kHz, 20kHz, 30kHz and 40KHz respectively, the temperature distribution along the thickness direction of the steel plate is obtained as shown in Figure 8.

![Figure 7. Temperature distribution on the path.](image)

![Figure 8. Distribution of temperature along Y direction.](image)
It can be seen from the figure above that when the current frequency is constant, the closer the steel plate is to the sensor in the thickness direction, the higher the temperature is. At a fixed position in the thickness direction of the steel plate, the temperature increases with the increase of the current frequency, and the temperature difference between the lower surface and the upper surface of the steel plate also increases gradually.

The essence of induction heating is to produce uneven temperature distribution in the process of hull bending forming research or welding deformation correction, that is to say, it needs to produce obvious temperature gradient in the thickness direction of steel plate. The temperature distribution contours generated by the above five frequencies is shown in Figure 9. When using induction heating to correct welding deformation, the current frequency should be selected as high frequency, but it is not that the higher the current frequency is, the more obvious the temperature gradient is, because when the current frequency increases to a certain extent, the magnetic induction intensity generated by the magnetic field will tend to be flat, so the current frequency selected in this study is 20kHz.

3.3. Relationship between current and temperature field
Figures 10-12 show the temperature distribution along the X direction (longitudinal direction), Y direction (thickness direction) and Z direction (transverse direction) of the upper surface of the steel plate when the current frequency is 20kHz and the current is 300A, 600A, 1000A, 1200A and 1500A respectively.

**Figure 9.** Contours of temperature distribution of Y direction.
It can be seen from Figure 10 that the temperature range from 30mm to 50mm is relatively flat and in the high temperature distribution area, which is mainly because the field of vorticity generated in this area is relatively dense, resulting in the energy concentration. In the range of 0 mm to 30 mm in the front, the temperature is relatively low, and the temperature drops in a slope. This is mainly because there is no binding of the magnet in this range, so that the electromagnetic field can not produce more concentrated field of vorticity [6]. In the figure, with the increase of the current, the slope temperature change is more obvious, which indicates that with the increase of the current, the energy of the area directly below the inductor is also increasing, resulting in the increase of the temperature in the area.

It can be seen from Figure 11 that the temperature increases gradually from the lower surface to the upper surface, and the highest temperature appears in the coverage area directly below the high frequency sensor [7]. Under the same frequency and different current conditions, the temperature of the upper and lower surfaces of the steel plate will rise, but the temperature gradient in the thickness direction of the steel plate does not change obviously. That is to say, when the current frequency and high frequency induction heating time are fixed, increasing the current can not increase the temperature gradient of the upper and lower surface of the steel plate.
In Figure 12, the temperature drops in a slope similar to that in Figure 10. The range from 0 mm to 20 mm in the figure is within the coverage of the induction heater, this area is a high temperature area. However, the temperature change in the range of 0 mm to 20 mm is not as smooth as that in the range of 30 mm to 50 mm in Figure 10. This is because the magnetic field distribution is more concentrated in the central region due to the effect of the magnet, and the skin effect of the magnetic field in the magnet makes this phenomenon more obvious.

3.4. Temperature variation with time at typical points

The steel plate surface covered by the inductor can be regarded as the heat source area of induction heating. In order to make the heat source produce reasonable temperature to meet the needs of structural analysis, three typical points A, B and C as shown in Figure 13 are selected in this area to analyze the temperature change with time at these three points.

The data in Table 1 can be summarized by ANSYS analysis. Because 300A and 660A cannot meet the temperature requirements for plastic deformation, they are ignored.
Table 1. Time for each point to reach the required temperature under different current.

| Current | 1500A | 1200A | 1000A |
|---------|-------|-------|-------|
| typical points | A | B | C | A | B | C | A | B | C |
| Convex-concave point (s) | 12 | 15 | 18 | 20 | 23 | 25 | 23 | 26 | - |
| 600°C points (s) | 6 | 7 | 8 | 12 | 14 | 16 | 15 | 17 | 18 |

It can be seen that when the frequency, current and induction heating time of A, B and C on the upper surface of the steel plate are the same, the order of the highest temperature is ABC. This is mainly because point A is directly below the induction heater, where the magnetic field dissipation is weak and the energy is more concentrated, so the temperature increases fastest; there is a good magnetic material near point B, which is conducive to the magnetic field dissipation, so the energy is relatively small; point C is directly below the transverse edge of the induction heater, and the magnet can converge the magnetic field, but in the case of high frequency, the same is true in the magnet due to the skin effect, the magnetic field is concentrated on the inner side of the magnet, which weakens the magnetic field intensity at point C and leads to the lowest temperature. When point C reaches 600℃, the whole area covered by the induction heater will meet the temperature requirements for plastic deformation. However, the temperature should not exceed the time when the concave and convex points appear in the temperature curve, because when the heating time exceeds this time, the temperature will drop, and the subsequent temperature increases slowly, which will affect the temperature gradient in the thickness direction of the steel plate, and is not conducive to good plastic deformation.

4. Conclusion
In this paper, the numerical simulation of the model is carried out by using the same induction heater. The following conclusions can be drawn from different heating parameters:

1) In the high frequency induction heater, the temperature field generated by the same direction current is more uniform than that generated by the reverse current, and the heating efficiency is higher.

2) When the current and the induction heating time are constant, the temperature gradient along the thickness direction of the steel plate will also change with the increase of the current frequency. The larger the current frequency is, the greater the temperature gradient along the thickness direction of the steel plate is.

3) When the current frequency and induction heating time are fixed, the higher the current is, the higher the temperature will be. However, the temperature gradient in the thickness direction does not change obviously.

4) When the current frequency and magnitude are fixed, the temperature on the steel plate will increase with the increase of induction heating time, but when the temperature rises to a certain value, the field of vorticity generated in the steel plate begins to move towards the plate thickness direction, and the temperature curve will appear concave convex change and the temperature rise slowly.

5) In order to produce plastic deformation, the steel plate must reach the temperature required for plastic deformation, and at the same time, it needs a good temperature gradient in the thickness direction of the steel plate. Based on the above calculation results, for the steel plate to obtain better plastic deformation, the induction heating parameters are recommended as follows: when the current is 1500A, the induction heating time is 8s to 12s; when the current is 1200A, the induction heating time is 16s to 20s, the induction heating time is 18s to 23s at 1000A.

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