Numerical simulation of hull curved plate forming by electromagnetic force assisted line heating

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Abstract. Line heating is a common method in shipyards for forming of hull curved plate. The aluminum alloy plate is widely used in shipbuilding. To solve the problem of thick aluminum alloy plate forming with complex curved surface, a new technology named electromagnetic force assisted line heating (EFALH) was proposed in this paper. The FEM model of EFALH was established and the effect of electromagnetic force assisted forming was verified by self development equipment. Firstly, the solving idea of numerical simulation for EFALH was illustrated. Then, the coupled numerical simulation model of multi physical fields were established. Lastly, the reliability of the numerical simulation model was verified by comparing the experimental data. This paper lays a foundation for solving the forming problems of thick aluminum alloy curved plate in shipbuilding.

1. Introduction

Line heating is the main technique of manufacturing large hulls and complex curved plate, which has the advantages of wide ranges of application, low cost, flexible and suitable for a variety of complex curved shapes. In advanced shipbuilding countries such as Japan, Korea and so on, this technique is supported by many funds and investments to research on the deformation mechanisms of curved plate with different heat sources, deformation rules, prediction method of heating parameters and automatic machining equipment\cite{1, 2}. However, there are lots of influence factors in traditional line heating process which results in the difficulties of getting the forming regularity and controlling the process accuracy\cite{3}. In addition, high heating temperature may change the plate material even generate cracks. The weight control of hull is very important in shipbuilding. Comparing with the traditional steel plate, the aluminum alloy has advantages including lower density, higher strength, better corrosion resistance and better welding property. The aluminum alloy plate is widely used in shipbuilding. The current metal plate forming methods can be divided into cold forming methods and hot forming methods. Cold forming method including stamping forming\cite{4}, electromagnetic forming\cite{5} and laser shock peening method\cite{6}. In stamping forming, the material is extruded into specific shapes by stamping machine. However, this method can be only applied to thin plate and is not suitable for thick plate for ship manufacturing. The electromagnetic forming is wildly used in small component machining in vehicle industry. The molds of this method are very expensive. The shapes of the components in ship hulls are varied. It is not suitable for mass production, which makes the cost of application of electromagnetic forming in ship industry is really high. For the laser shock peening method, the deformation of each peening is very small. However, if the peak pressure is increased to...
get a bigger deformation, the finishing surface will be very rough and the property of the material is influenced[7].

The hot forming methods include plate warm forming technology and line heating[8]. The plate warm forming technology is mostly applied in the vehicle and aeronautics engineering. It cannot be applied in large components manufacturing in ship industry[9]. Guo, et.al[10] studied the line heat process for aluminum alloy and found that the suitable processing temperature for aluminum alloy is between 200°C and 300°C. However, under this temperature, it is very hard to get enough deformation for thick aluminum plate. To overcome these challenges, people put forward some new line heating forming technologies such as induction heating forming[11], laser heating forming[12]. However, there is no new line heating technology can well meet the requirements of aluminum alloy plate until now. Induction heating is prone to overheat on the edge of the plate and especially has low energy utilization. Laser heating need large and expensive equipment.

Both cold and hot traditional processing methods are not suitable for aluminum alloy plate forming of curved plate. This paper provides an advanced method which combines the electromagnetic forming process and line heating, which is named electromagnetic force assisted line heating (EFALH). It means that during the line heating process, the temperature is controlled in a suitable range while electromagnetic force is applied to the aluminum alloy plate to get enough deformation. In this paper, the coupled numerical simulation model of multi physics fields are established. The experiment is conducted to measure the data including the wave form of the pulse, the local deformation of the plate. The reliability of the numerical simulation model can be verified by comparing the experimental data with the numerical simulation results.

2. The solving idea of numerical simulation

In traditional line heating forming process, moving flame and cooling water are needed, as shown in Figure 1(a). The most common kinds of heating source in shipyards are acetylene and propylene. The forming theory of line heating forming was well introduced in previous researches. So this paper will only highlight on the introduction of EFALH. In this method, an external force is added to the plate forming process by line heating, as shown in Figure 1(b). The electromagnetic coil is placed above the steel plate and the coil is kept in the appropriate position to the heat source during processing. When the pulsed current flows through the electromagnetic coil, a mutative magnetic field can be generated. The magnetic field will generate a vortex which is forced by the magnetic field. Then the radial electromagnetic force that acts on the heating line by extrusion and the axial magnetic pressure that promotes angle deformation of plate are generated at the same time. This device can control the deformation of the plates by relying on the evolution of the stress and strain.

![Image](image_url)

**Figure 1** Process of line heating and EFALH

The simulation model includes the circuitry, the electromagnetic field, the temperature field and the structure field. So a suitable coupling method is very important and will determine the accuracy of the simulation result. The relationship between each fields is not linear, so finite element analysis are used to achieve the multi physical field coupling. The circuitry is used to provide the pulse current to the electromagnetic coils. The process can be achieved by circuitry- electromagnetic coupling. On the other hand, the resistivity of the plate changes with the temperature. So the influence of the temperature to the electromagnetic force is significant. The deformation of the plate can be influenced by the heat source, the electromagnetic force and structure. However, the small deformation cannot influence the temperature and electromagnetic field too much, so only thermo-structure and electromagnetic-structure one-way coupling are analyzed.
Figure 2 shows the research route of the simulation model. At first, all the elements including the aluminum plate, the line heat resource are the electromagnetic coils are built in the Three-dimensional model. The electromagnetic field, the temperature field and the structure field can be calculated. With the temperature field and the resistivity curve of the aluminum material and the electromagnetic field, the thermo-electromagnetic coupling analysis can be achieved and the electromagnetic force can be calculated. With the structure field, the final deformation of the aluminum plate can be calculated.

**Figure 2.** Flow chart of multi-physics couplings of EFALH

**Figure 3.** FEM model of EFALH

### 3. Three-dimensional finite element model of EFALH

The plate material is aluminum alloy. The temperature fields, the electromagnetic fields and the structure fields are effected by heating time and heating position. In the model, the deformation, the force and the temperature of different location and time should be simulated under the effect of the multi physical fields coupling. Two-dimensional finite element model cannot satisfy the requirement, so three-dimensional FEM are used in the simulation. The FEM model of EFALH including the whole structure is shown in Figure 3.

In the simulation model of the circuitry-electromagnetic coupling, the circuitry part includes the individual current \( I_0 \), the resistance \( R_0 \) and the coils \( P_0 \). Because the current is equal at different location in the coils, two same circuitries are used to couple the two layers of the coils. The current \( I_0 \) is defined as pulse current and is provided to the coils.

### 4. Verification of the EFALH numerical model

The propose of the verification experiment is to test the effect of EFALH and accuracy of EFALH numerical model. The plate material is aluminum alloy 5083 H116. The plate length and breadth is 2000mm \( \times \) 1000mm. The plate thickness is 8mm and 10mm, heating time is 55 seconds and 80 seconds, respectively. The heating length is 300mm. The flow rate of propylene and oxygen is determined according to forming experience[8]. The location of heating line is at the side of plate. The experimental equipment of electromagnetic force assisted line heating is shown in Figure 4. The shrinkage was measured by digital caliper. The measuring method refer to reference[8]. The local deformation is instead by the form of local shrinkage. The pulse current is measured during the EFALH process. The data of local shrinkage for EFALH and line heating process are measured and recorded before and after forming.

**Figure 4.** Equipment of electromagnetic force assisted line heating
4.1 Verification of pulse current
The pulse current in the electromagnetic coil of experiment is measured by rogowski coil and oscilloscope. The numerical and measuring results of pulse current in the electromagnetic coil are shown in Figure 5. The current rises and drops rapidly in both the numerical and measured results. It can verify the accuracy of the circuitry-electromagnetic coupling model.

![Figure 5](image)

(a) pulse current of measuring result  (b) pulse current of FEM

**Figure 5.** Numerical and measuring results of pulse current in the electromagnetic coil

4.2 Verification of deformation
The parameters of the pulse current are shown in Table 1. The distance between the aluminum plate and the electromagnetic coils is 5mm. The input data in the simulation is according to the experiment parameters under different conditions. The heating time is 55 seconds for 8mm thickness plate and 80 seconds for 10mm thickness plate.

The FEM and experiment results are shown in Figure 6. The deformation of EFALH process is bigger than the single line heating process of the same experiment condition. The electromagnetic force increases the shrinkage of the curved plate. It shows that the EFALH process has a better forming performance than the single line heating process. On the other hand, the differences between the numerical and experiment results under both experiment conditions are very small, in which the accuracy of the EFALH numerical model is proved.

![Table 1](image)

**Table 1.** The parameters of the pulse current

| No. | Parameters                                | Value  |
|-----|-------------------------------------------|--------|
| 1   | Pulse current amplitude                   | 750A   |
| 2   | Pulse current frequency                   | 10.86Hz|
| 3   | Rising time of the pulse current          | 1.2ms  |
| 4   | Dropping time of the pulse current         | 34ms   |
| 5   | Peak pulse duration                       | 0.001ms|

(a) plate with 8mm thickness (b) plate with 10mm thickness

**Figure 6.** Local shrinkage of EFALH and line heating process
5. Conclusion
A new technology named EFALH was proposed in this paper to overcome the forming difficulties of thick aluminum alloy plate. The FEM model of EFALH was established and the effect of electromagnetic force assisted forming was verified by means of self-development equipment. The electromagnetic force assisted line heating process can increase the efficiency of traditional method while it can also keep the temperature in a suitable range. The finite element analysis model with multi physical fields coupling including circuitry-electromagnetic coupling, thermo-electromagnetic one way coupling, thermo-structure and electromagnetic-structure one way coupling was established. Experiment was conducted to verify the accuracy of the FEM model of EFALH. Both the simulation and the experiment results shows that EFALH has a better forming performance than traditional line heating method. This paper lays a basis for solving the forming problems of thick aluminum alloy curved plate in shipbuilding.

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