Simulation of resistance heating process for AZ31B magnesium alloy sheet

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Abstract. Temperature is one of the key factors affecting the quality of magnesium alloy sheet products in warm rolling deformation. Inaccurate temperature control will cause defects such as difficult forming and edge cracking. This paper focuses on the temperature distribution of AZ31B magnesium alloy sheet during resistance heating based on a special warm rolling experimental mill for magnesium alloys with online heating developed by the State Key Laboratory of Rolling Technology and Automation of NorthEastern University (NEU-RAL). COMSOL finite element software was used to simulate the influence of the main parameters in heating process on temperature, and the relationship curve of steady-state and transient temperature distribution were obtained. Finally, the correctness of the simulation law was verified by resistance heating experiments. The above job provides theoretical basis for temperature control of magnesium alloy sheet during warm rolling.

1. Introduction

As close-packed hexagonal structure materials the Magnesium alloy processing performance is poor at normal temperature[1-3]. When being rolled at the recrystallization temperature, the rolling properties of the magnesium alloy get improved greatly and the organization become uniform and fine [4-6]. Therefore, most of the magnesium alloy strips are produced by means of warm rolling and temperature control becomes a key factor to ensure the quality of magnesium alloy products.

In order to better study the warm rolling process of magnesium alloy, NEU-RAL developed a set of special pilot warm rolling mill for magnesium alloy sheet with the function of rolled piece and rolls simultaneously heating on-line[7,8], as shown in figure 1. The rolled piece heating mode uses direct resistance heating [9-11] (Figure 2). The left and right clamps on the top of the hydraulic cylinders are used as electrodes, the rolled piece is clamped between the clamps, the roll gap is kept raising when heating, energize the two clamp electrodes with a low voltage and a large current to heat. The rolls heating mode uses heat transfer oil heating, which is drilling in the center of the rolls and passing hot oil into the core of the rolls. This kind of heating method can keep the roll surface temperature stable.

Based on the special warm rolling experimental mill for magnesium alloys developed by NEU-RAL, this paper focuses on studying the effect of the main parameters on the temperature of AZ31B magnesium alloy sheet during resistance heating. On one hand, heating processes were simulated by multi-physical field coupling function of COMSOL finite element software which has fast calculation speed, simple pre-processing operation and intuitive post-processing results compared with finite difference method [12, 13]. On the other hand, some heating experiments were completed corresponding to the simulation.
The purpose is to provide theoretical basis for precise temperature control of AZ31B magnesium alloy sheet in online heating process.

![Figure 1. Special pilot warm rolling mill for magnesium alloy.](image1)

**Figure 1.** Special pilot warm rolling mill for magnesium alloy.

**Figure 2.** The rolled piece heating mode of pilot warm rolling mill.

2. Simulation of resistance heating

2.1. Material parameters
The simulated experimental material is AZ31B, a typical grade of Mg-Al-Zn magnesium alloy, its chemical composition is shown in Table 1.

|       | Al  | Cu  | Ca  | Ni  | Si  | Zn  | Mg  | Others |
|-------|-----|-----|-----|-----|-----|-----|-----|--------|
|       | 3.0 | 0.01| 0.04| 0.001| 0.02| 1.0 | Bal.| ≤0.3   |

The resistivity of AZ31B magnesium alloy is $9.2 \times 10^{-5} \Omega \cdot m$ at room temperature 293K, and increases linearly with temperature rising in line with the most general rule of metal materials [14]. The above physical parameters and electrical property parameters of AZ31B magnesium alloy together are imported into the material database of COMSOL finite element simulation software for simulation.

2.2. Geometric model and boundary conditions
The sample size is $4 \times 100 \times 400$(mm) as shown in figure 3. Numbers need to be assigned for the sample’s six faces. The No. 1 surface was set as ground and the No. 6 surface was applied the current or normal potential. Other four surfaces were set as the insulated surfaces. The boundary temperature of No. 1 and No. 6 were constant 293K. The heat flux of convection heat transfer was assigned to other four surfaces. The ambient temperature was set to 293K. The mesh is automatically divided into the system's default tetrahedral mesh. The total number of tetrahedral elements are 9697. The total number of nodes are 3274.

2.3. Analysis of simulation results

2.3.1. Steady state temperature distribution. The figure 4 shows the steady-state solution results when the convection coefficient is set to 5W/(m²/K), and the current density is set to $2 \times 10^6$A/m². Figure 4(a) shows the distribution of the potential from high to low. In figure 4(b), the temperature distribution is roughly divided into three areas: the white area, the yellow area and the red area. The white area indicates the higher temperature, the red area indicates the lower temperature. The distribution of temperature is symmetrically along the length, high in the middle and low on both sides. In other words, the temperature distribution is uneven in the direction of current movement. Figure 4(c) shows the isotherm distribution that the temperature is uniform in the width direction.
Figure 3. Geometry model and grid model of AZ31B magnesium alloy sheet.

Figure 4. Steady-state simulation results of AZ31B heating process.

(a) Potential distribution  (b) Temperature distribution  (c) Isotherm distribution

2.3.2. Effect of heating rate on temperature uniformity. Simulated condition: the heating rates are respectively set to 1.5 K/s, 2K/s, 3K/s, 4K/s, 5K/s. The initial temperature is 293K, the ambient temperature is 293K and the heating target temperature is 500K. The simulation results are shown in figure 5. It can be seen from the figure 5 that with the heating rate increases the top shape changes from tip to level and gradually widens, indicating that the temperature zone of up to 500K gets widen while heating with a higher rate. The heating minimum time is 40s and the maximum time is 290s when heating to the same temperature 500K.

Figure 5. Effect of heating rate on temperature uniformity.

Figure 6. The relationship curve of thickness and temperature.
2.3.3. *Effect of samples size on heating temperature.* The design range of samples size of the magnesium alloy special pilot warm rolling mill are that the thickness is less than 5mm, the width is less than or equal to 300mm, and the length is between 400~800mm. The simulated samples size needs to be set according to these actual situation. So the parameter values of three group different dimension simulations are set as shown in table 2.

| Group No. | Thickness (mm) | Width (mm) | Length (mm) | Current density (A/m²) | Heating time (s) | Ambient temperature (K) | Convection coefficient (W/(m²/K)) |
|-----------|----------------|------------|-------------|------------------------|------------------|-------------------------|-------------------------------|
| 1         | 1~5            | 100        | 400         |                        |                  |                         |                               |
| 2         | 4              | 100~300    | 400         | 6×10⁶                 | 120              | 293                     | 5                             |
| 3         | 4              | 100        | 400~800     |                        |                  |                         |                               |

No.1 group simulation: the samples’ thickness was taken as 1~5mm and 1mm interval. The simulation results are shown in figure 6 that shows transient temperature curves at five different time. When the thickness is less than 2 mm and the heating time is the same, the temperature increases with the thickness. Only when the temperature is greater than 475K and thickness is bigger than 2mm, the temperature increases slowly with thickness. When time reaches 100s and 120s, the temperature increases with the thickness distinctly.

No.2 group simulation: the samples’ width was taken as 100~300mm and 50mm interval. Figure 7 shows the transient simulation results of heating to 120s. It can be found that the temperature rise curves of different width samples are completely same from the three-dimensional figure. Indicating that the current density does not change, the width of the samples has no theoretical effect on the heating temperature.

No.3 group simulation: the samples’ length was taken as 400~800mm and 100mm interval. The simulation results are shown in figure 8. When the length is less than 500mm, the temperature increases nonlinearly with samples length. After the length is greater than 500mm, the uniform temperature zone is getting bigger. In addition, it can be seen from figure 8 that the head and tail temperature curves of all the samples are parallel. Therefore, the lengths of the uneven temperature zones of the head and tail are equal for different length samples.
3. Heating experiment

The main parameters of the resistance heating system are as follows: heating power: 150kW; transformer output voltage: ≤24V, AC; transformer input voltage: 380V, single-phase; maximum heating temperature: 800°C. The temperature values were detected by four thermocouples, and the detection positions are fixed at 4, 5, 6, and 7 point in figure 9. The point 1, 2 and 3 are symmetrical points of 7, 6 and 5, respectively.

**Experiment 1:** The effective size of 5 samples is 2.15×240×400. Heating rate is 1.5~6.5K/s. The heating results are shown in figure 10, which are completely consistent with the simulation results of figure 5. As the heating rate increases, the temperature uniformity becomes better and better. The main reason is that under the same heating time, when the heating rate is fast, more heat is generated, and the excess heat is used to supplement low temperature zone to form a uniform temperature zone.

**Figure 9.** The location of temperature detection points.

**Figure 10.** Heating experimental results of different heating rate.

**Figure 11.** Heating experimental results of different width samples.
Experiment 2: The effective sizes of the samples are 2.15×90×400mm, 2.15×120×400mm, 2.15×240×400mm. With the same 20% control power, the heating results of different width samples are shown in figure 11. Figure 11 shows the transient temperature distribution of detection points when the heating time is 40s, 60s and 80s respectively. It can be seen from the figure that gradient distribution of temperatures along the length coordinate direction are completely the same as the simulation results and the temperature gradient tends increase with the temperature rising. The simulation result in figure 7 is that the width change has no effect on the temperature under the same current density. The experimental result in figure 11 is that under the same control power condition, the current density decreases as the sample width increases, so the smaller the width is, the faster temperature increases. It is in keeping with conservation of energy.

Experiment 3: The effective sizes of the samples are 1.2×240×400mm, 1.6×240×400mm, 2.15×240×400mm. Heating at the same 30% control power. The heating results of different thickness samples are shown in table 3. The maximum values of transient temperature are shown when the heating time is 20s, 40s and 60s respectively. Under the same control power, when the thickness of the sample becomes larger, the current density decreases, so the heating temperature decreases, which conforms to the simulation law in figure 6. The Larger volume requires more heating power.

| Heating time(s) | Max temperature of different thickness (K) |
|-----------------|------------------------------------------|
|                 | 1.2mm | 1.6mm | 2.15mm |
| 20              | 494   | 476   | 440    |
| 40              | 579   | 545   | 475    |
| 60              | 668   | 610   | 506    |

4. Conclusion
In this paper, the simulation and experimental verification of the resistance heating process of AZ31B magnesium alloy were performed and the following conclusions are drawn:

1. The steady state simulation results are that the temperature is evenly distributed along the sample width direction, unevenly distributed along the sample length, symmetrically distributed at the center of the samples length and the intermediate temperature is high but the both sides temperature are low. The simulation results are verified in experiments 2 and 3.

2. The different heating rates simulation result is that the higher the heating rate is, the longer the uniform temperature zone is in the sample length direction under the same heating target temperature. The simulation result is verified in experiments 1.

3. The simulation result of different samples size: When the current density is constant, the thickness variation of samples has little effect on samples temperature, the influence of samples width is negligible, but the influence of samples length is obvious. When the length is less than 500mm, the samples temperature increases nonlinearly with samples length. When the length is more than 500mm, the intermediate uniform zone gradually increases with the length. The simulation results are partially verified in experiments 2 and 3.

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