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Investigation on Temperature Change of Cold Magnesium Alloy Strips Rolling Process with Heated Roll

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Magnesium alloy strips are widely used in aerospace, automotive industry, etc., which are difficult to produce through cold forming process due to their poor deformation ability. In this article, we studied whether the rolling process with heated roll could be used to roll cold magnesium alloy strips. Thermal-mechanical finite element simulation of the rolling process, using heated roll and cold strips to produce the magnesium alloy strips, was carried out. Influences of roll temperature, rolling velocity, rolling reduction ratio, and initial strip thickness on the thermal field and the mean temperature of magnesium alloy strips were analyzed. Both the heated area in strips in rolling deformation zone and the mean temperature of strips at exit of rolling deformation zone increase with increasing the roll temperature and/or rolling reduction ratio, and/or with decreasing the rolling velocity and/or initial strip thickness. Finally, a formula was developed to predict the mean temperature of strips under different rolling conditions, which also could be used to calculate the critical value of parameters in rolling process.

Keywords finite element simulation, magnesium alloy strip, metal forming, rolling process

1. Introduction

The magnesium alloy strips are the lightest structural materials, which are widely used in aerospace, automotive industry, aviation, and many other fields. The magnesium alloy strips are generally produced using the twin-roll casting and the hot rolling. Kawalla et al. (Ref 1) introduced a production technology for magnesium strip based on twin-roll casting and strip rolling in Freiberg, Germany. Kang et al. (Ref 2) studied the effect of warm rolling and heat treatment on microstructure and mechanical properties in twin-roll cast ZK60 alloy sheet. Annealing treatment after warm rolling induced the decrease of strength and increase of elongation. Zhu et al. (Ref 3) studied the microstructure and mechanical properties of AZ31 magnesium alloy sheets processed by normal rolling, one-pass equal channel angular rolling, and cross equal channel angular rolling. During hot rolling process, the microstructure of strips is affected by rolling velocities, rolling temperature, reduction ratio, etc. Das et al. (Ref 4) studied the microstructures and mechanical properties of Al-Mg alloys prepared using twin-roll casting under a variety of rolling speed. The secondary dendrite arm spacing increases with increasing rolling speed. The influence of rolling speed on the microstructure and mechanical properties of AZ31 magnesium alloy sheets was studied by Xia et al. (Ref 5). The differential speed rolling did not alter the basal texture but leaded to the incline of the basal plane from the sheet surface plane to some extent.

Numerical methods have been widely used to simulate the produce process of magnesium alloy strips. The distribution of temperature and flows fields in cast-rolling zone of AZ31 magnesium alloy was obtained by the direct coupled solution of finite element method (Ref 6). Two systematical vortexes appeared in the cast-rolling zone during twin-roll casting. A CFD model for the numerical simulation of magnesium twin-roll casting process was carried out by Zeng et al. (Ref 7). A big vortex in the casting channel and a much smaller vortex between the two rolls occurred, and the mushy zone moved towards the kissing point with increasing the casting speed. A finite element model on the platform of ABAQUS was developed to predict the thermo-mechanical behavior of AZ31 magnesium alloy during hot rolling (Ref 8). The model predictions were validated for a wide range of hot rolling conditions by comparison to the experimentally measured temperature and rolling loads. Based on 3D and 2D finite element model of an AZ31 magnesium alloy strip rolling, the thermal field, equivalent plastic strain, and equivalent plastic strain rate were analyzed (Ref 9).

The deformation ability of magnesium alloy strips is poor during cold forming process. The magnesium alloys are difficult to be cold rolled (Ref 10). The magnesium alloy strips might be rolled with the heated roll for increasing their deformation. Kang et al. (Ref 11) and Zhang et al. (Ref 12) developed some kinds of equipments for uniform heating the roll to produce magnesium strips, respectively. However, we do not know whether this is the true method of the rolling process with heated roll for producing the magnesium alloy strips. For

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that, we need more reliable information about the rolling process using heated roll to cold roll magnesium alloy strips. In this article, the thermal-mechanical finite element simulations of the rolling method, using heated roll and cold strips to produce the magnesium alloy strips, were carried out. The influences of roll temperature, rolling velocity, rolling reduction ratio, and initial strip thickness on the thermal field and the mean temperature of strips were analyzed. Finally, we focused on establishing a formula to predict the mean temperature of strips during rolling process.

2. Finite Element Simulation

2.1 Basic Theories

Equation 1 (Ref. 13) shows the calculation equation of thermal distribution in an isotropic element with an internal heat source.

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}+\frac{\dot{q}}{k}=\frac{\rho c}{k}\frac{\partial T}{\partial t} \quad \text{(Eq 1)}$$

where ρ density; c specific heat; k coefficient of heat conductivity; and $\dot{q}$ internal heat source strength, which is the plastic work done of strip deformation during rolling.

$$\dot{q}=m\int_0^{\dot{\varepsilon}}\bar{\sigma}d\dot{\bar{\varepsilon}} \quad \text{(Eq 2)}$$

where m is the coefficient of heat transform by plastic work done.

During hot rolling, the thermal transfers between the strip surface and the external environment contain two ways: heat emission and convection current. When the strip is not in the deformation zone, the heat radiation is much larger than the heat convection which could be neglected. According to the Stefan-Boltzman equation,

$$Q=H_\mathrm{r}A(T-T_\infty) \quad \text{(Eq 3)}$$

where $H_\mathrm{r}=S_\mathrm{B}B_\mathrm{S}(T^2+T_\infty^2)(T+T_\infty)$; S_B coefficient of Stefan-Boltzman; B_S blackness on strip surface, T strip surface temperature; and T_∞ temperature of environment.

The heat transfers between the strip surface and the work roll is calculated by Eq 4.

$$Q=h_iA(T-T_\mathrm{R}) \quad \text{(Eq 4)}$$

where h_i coefficient of convective heat transfer between the strip and roll and T_R roll temperature.

2.2 Parameters and Models

In production, there are many methods for heating the rolls, and the temperature of roll surface also could be controlled accurately (Ref 11, 12). The thermal-mechanical finite element simulation of the AZ31 magnesium alloy strips rolling process is carried out. The roll diameter is 300 mm, and the roll is considered as elastic. The piecewise linear plasticity material model is employed for the strips. The stress-strain curve is shown in Fig. 1, where the stress for strain 1.0 is assumed in FE models, which makes the program work well. The roll and strips are assumed to be thermal isotropic. The main material parameters are listed in Table 1.

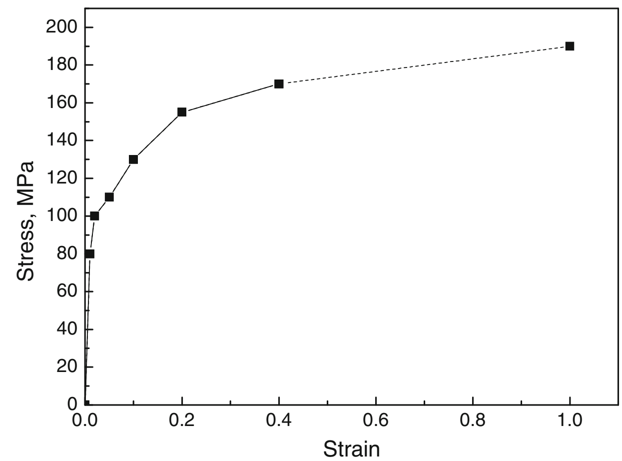

Fig. 1 Stress-strain curve in the FE model

Table 1 Material parameters

Parameters	Magnesium alloy strip	Roll
Density, kg/m^3	1740	7830
Elastic modulus, GPa	42	210
Poisson's ratio	0.36	0.3
Deformation resistance, MPa	155	-
Heat capacity, J/K	115	460
Heat transfer coefficient, W/(m °C)	95	46

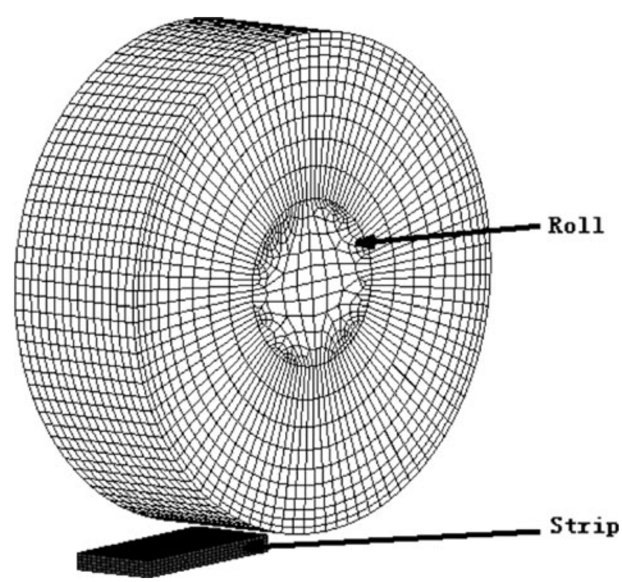

Fig. 2 Geometry model and FE meshing of rolling process

In the FE models, because of the symmetry of strip rolling processes, a half of rolling model is employed on the platform of LS-DYNA. The strip and roll are meshed with 8-noded hexahedral elements. There are 23,936 nodes and 21,135 elements in the models. The geometry model and FE meshing of rolling process is shown in Fig. 2. The friction between strip and roll is assumed to Coulomb friction model, the friction coefficient is 0.3 (Ref 9). During rolling process, 90% of

Table 2 Rolling parameters

Parameters	Value
Initial temperature of roll, °C	560
Initial temperature of magnesium alloy strip, °C	20
Rolling velocity, m/s	5
Reduction ratio, %	20
Initial strip thickness, mm	2

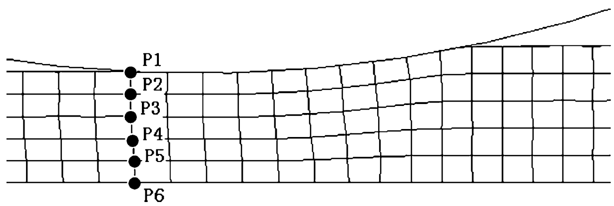

Fig. 3 Selected points in the following analysis

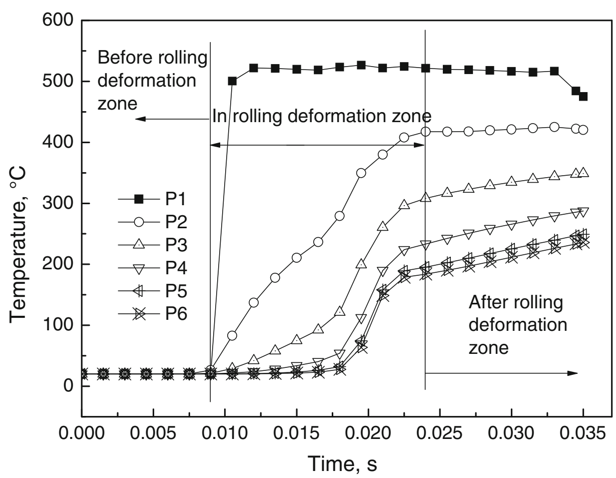

Fig. 4 Temperature at P1-P6 in rolling process

mechanical work is converted into heat. The rolling parameters are shown in Table 2. In the simulations, the influence of roll temperature (500-580 °C), rolling velocity (2-6 m/s), reduction ratio (10-25%), and the initial strip thickness (1-3 mm) on the thermal distribution of strip in the rolling deformation zone are analyzed, where only one kind of parameters is adjusted in every set of simulations.

3. Results and Discussion

During rolling process, the cold magnesium alloy strips are heated by heat transfer of heated roll and plastic mechanical work. It is expected that the strips could be heated uniformly. So the temperature change of the points (P1-P6) in Fig. 3 are analyzed. At the same time, the thermal fields of strips in the rolling deformation zone are analyzed.

Figure 4 shows the temperature change of points during the rolling process. The change of temperature could be divided into three stages. In magnesium alloy strip rolling process, we hope that they could be heated for increasing their deformation because the magnesium alloys are HCP. For that, the temperature of P1-P6 at the exit of rolling deformation zone is analyzed. Meanwhile, the mean temperature of the P1-P6 at the exit of rolling deformation zone during rolling processes is analyzed, which is considered as the mean temperature of strip in the following,

$$T_M = \sum_{i=1}^{n=6} T_{Pi}/6,$$

where T_M is mean temperature of strip, T_{Pi} is temperature of point i (i = 1-6).

3.1 Influence of Roll Temperature

Figure 5 shows the thermal field of strips in the rolling deformation zones under various roll temperatures, where the rolling velocity is 5 m/s, strip thickness 2 mm, and reduction

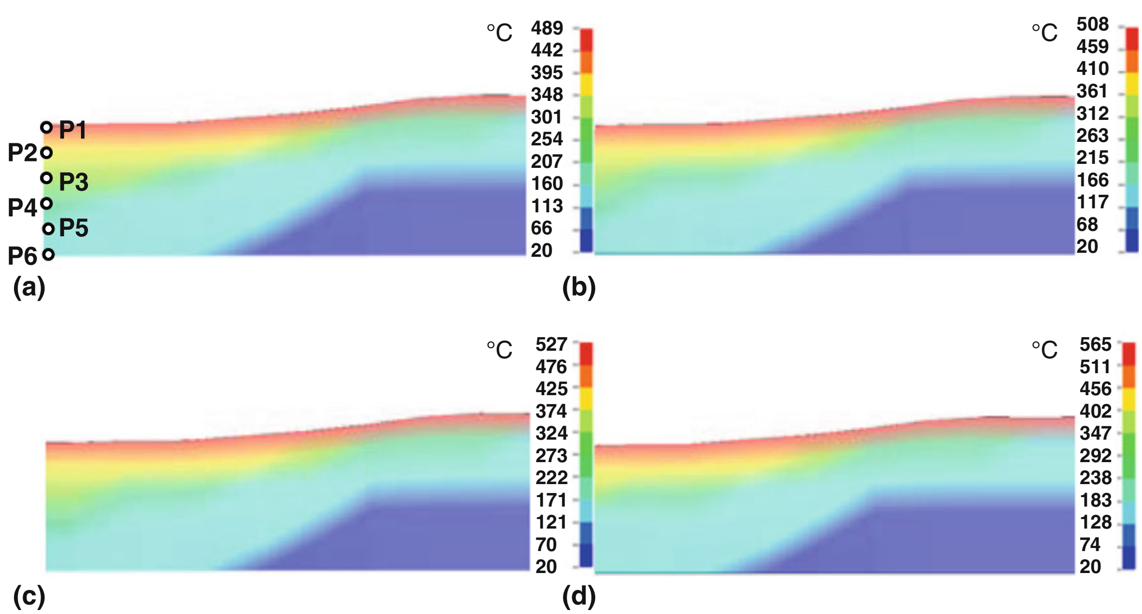

Fig. 5 Thermal field in rolling deformation zone under the roll temperature of 500 °C (a), 520 °C (b), 540 °C (c), and 580 °C (d)

ratio 20%. In the figure, with increasing the roll temperatures, the maximum temperature in rolled strips increases, and the area of low temperature in the rolling deformation zone decreases.

The temperature of the P1-P6 at the exit of rolling deformation zone under different roll temperatures is shown in Fig. 6(a). The temperature difference at certain points under a variety of roll temperatures gradually decreases with approaching to the strip central zone. The temperatures at P6 are same. Approaching to the strip surface, the temperature differences between strips are close to those between the rolls.

Figure 6(b) shows the mean temperature in strips under different roll temperatures. With increasing the roll temperature, the mean temperature in strips increases linearly. The relationship between the mean temperature (T_M) and the roll temperature (T_R) could be described by Eq 5 which is fitted by the datum in Fig. 6.

$$T_M = 104.89 + 0.4128T_R \quad \text{(Eq 5)}$$

3.2 Influence of Rolling Velocity

Figure 7 shows the thermal field of magnesium alloy strips in the rolling deformation zone under a variety of rolling velocity, where the temperature roll is 560 °C, strip thickness 2 mm, and reduction ratio 20%. In the rolling deformation zone, the heated area increases as the rolling velocity decreases. When the rolling velocity is 2 m/s, the central zone is heated at the entrance of rolling deformation zone.

Figure 8(a) shows the temperature of P1-P6 at the exit of rolling deformation zone under various rolling velocities. In the figure, the maximum temperature in strip changes slightly with variation of the rolling velocities, but the minimum temperature increases with reduction of the rolling velocity. When the rolling velocity is greater than 5 m/s, the temperatures at P4-P6 change slightly.

Figure 8(b) shows the mean temperature in magnesium alloy strips under a variety of rolling velocities. The mean temperature increases at exit of rolling deformation zone with

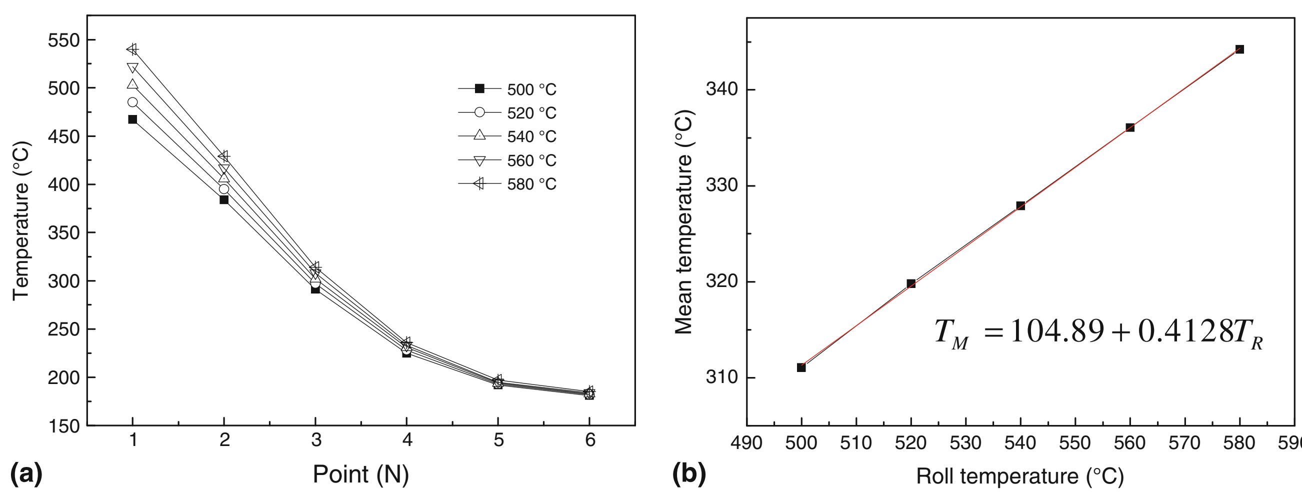

Fig. 6 Temperature at the exit of rolling deformation zone (a) and mean temperature in strips (b) under various roll temperatures

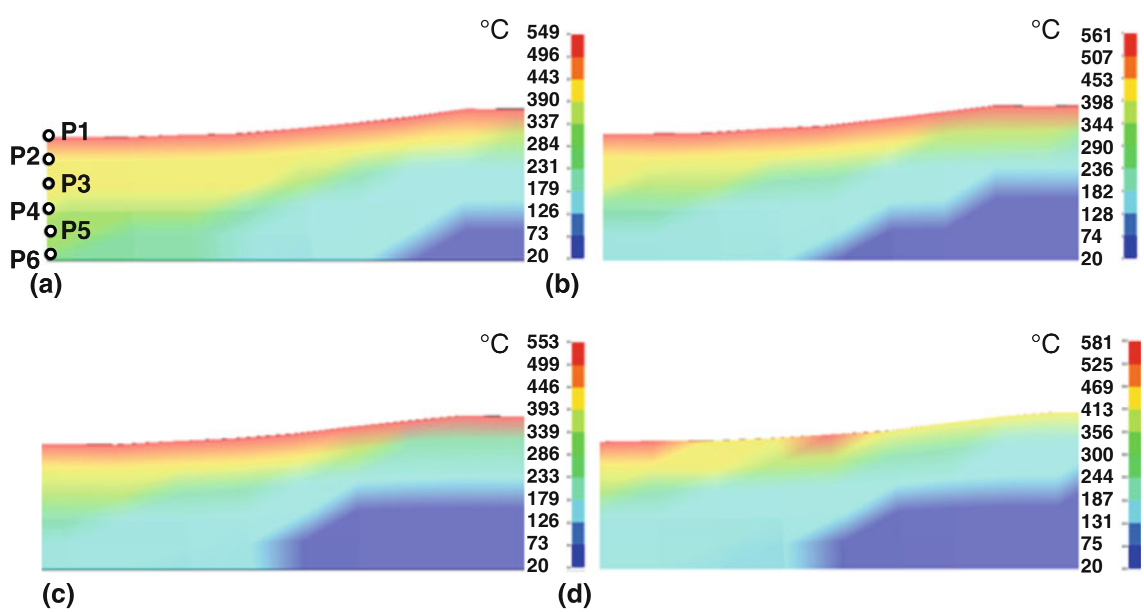

Fig. 7 Thermal field in rolling deformation zone when the rolling velocity is 2 m/s (a), 3 m/s (b), 4 m/s (c), and 6 m/s (d)

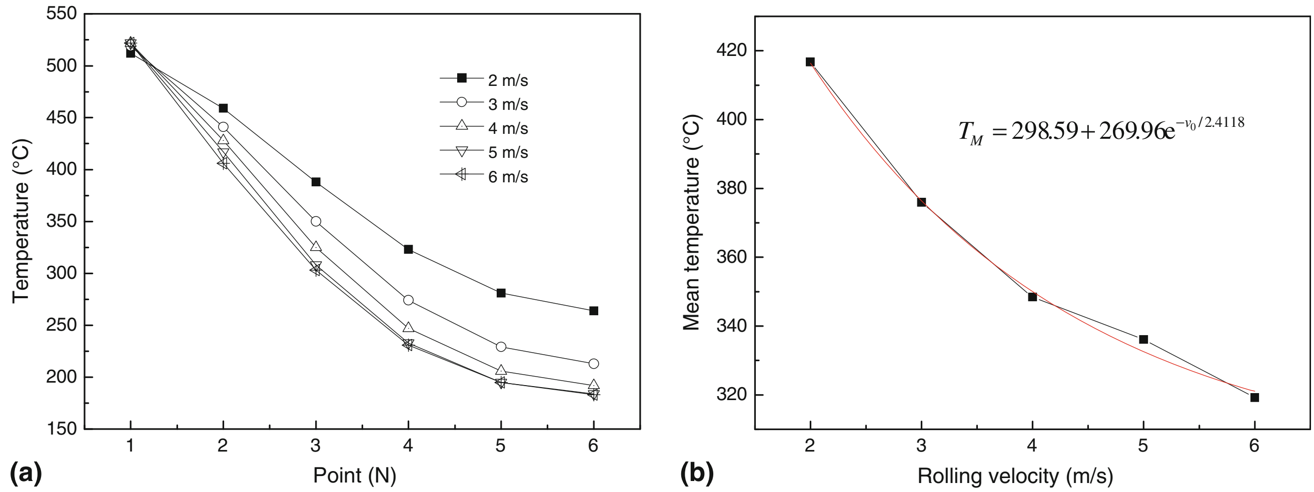

Fig. 8 Temperature at the exit of rolling deformation zone (a) and mean temperature in strips (b) under various rolling velocities

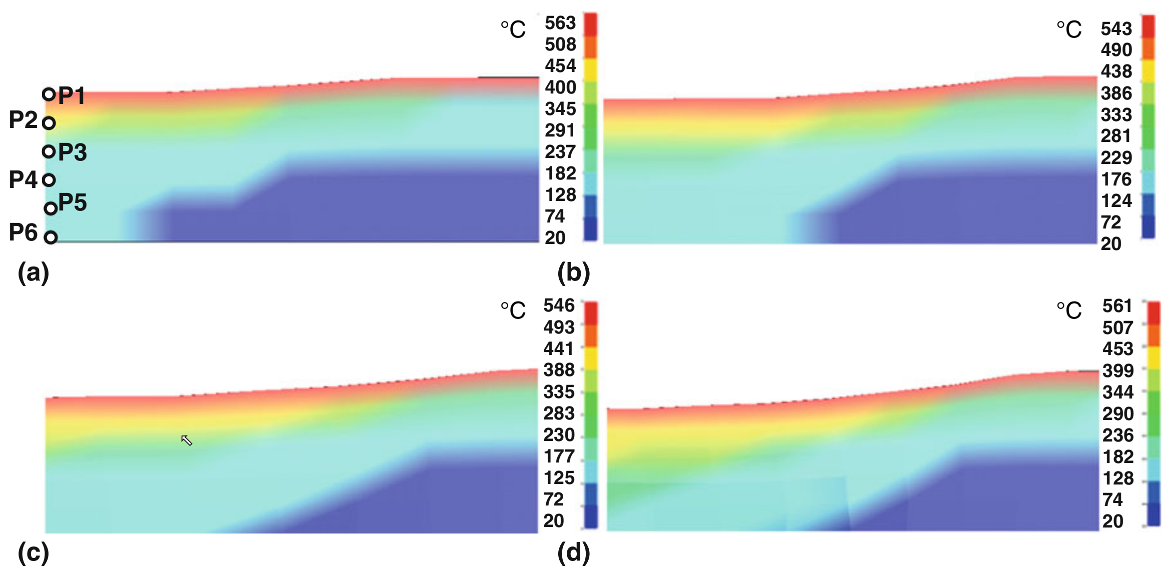

Fig. 9 Thermal field in rolling deformation zone under rolling reduction ratio 10% (a), 15% (b), 20% (c), and 25% (d)

reduction of the rolling velocity. The relationship between the mean temperature and the rolling velocity (v_0) could be described as Eq 6 fitted with the datum in Fig. 8(a).

$$T_M = 298.59 + 269.96e^{-v_0/2.4118} \quad \text{(Eq 6)}$$

3.3 Influence of Rolling Reduction Ratio

Figure 9 shows the thermal field of magnesium alloy strips in the rolling deformation zone under a variety of rolling reduction ratios, where the temperature roll is 560 °C, strip thickness 2 mm, and rolling velocity 5 m/s. With increasing the rolling reduction ratio, the heated area in strips increases.

Figure 10(a) shows the temperature of P1-P6 at the exit of rolling deformation zone under different rolling reduction ratios. In rolling process, the maximum temperature increases slightly with increasing the rolling reduction ratio, while the minimum temperature increases greatly. The temperature at P6 is about 100 °C with the 10% reduction ratio while reaches 240 °C when the reduction ratio is 25%.

Figure 10(b) shows the mean temperature in strips at the exit of rolling deformation zone under different rolling reduction ratio. The mean temperature increases with increasing the rolling reduction ratio. The polynomial fit of curve the mean temperature to the rolling reduction ratio (ε) is carried out as shown in Eq 7.

$$T_M = 211.1 + 387\varepsilon + 1157\varepsilon^2 \quad \text{(Eq 7)}$$

3.4 Influence of Initial Strip Thickness

Figure 11 shows the thermal field of magnesium alloy strips in the rolling deformation zone under a variety of initial strip thicknesses, where the temperature roll is 560 °C, reduction ratio 20%, and rolling velocity 5 m/s. The thermal field of strips in the rolling deformation zone becomes more uniform with reduction of the initial strip thickness.

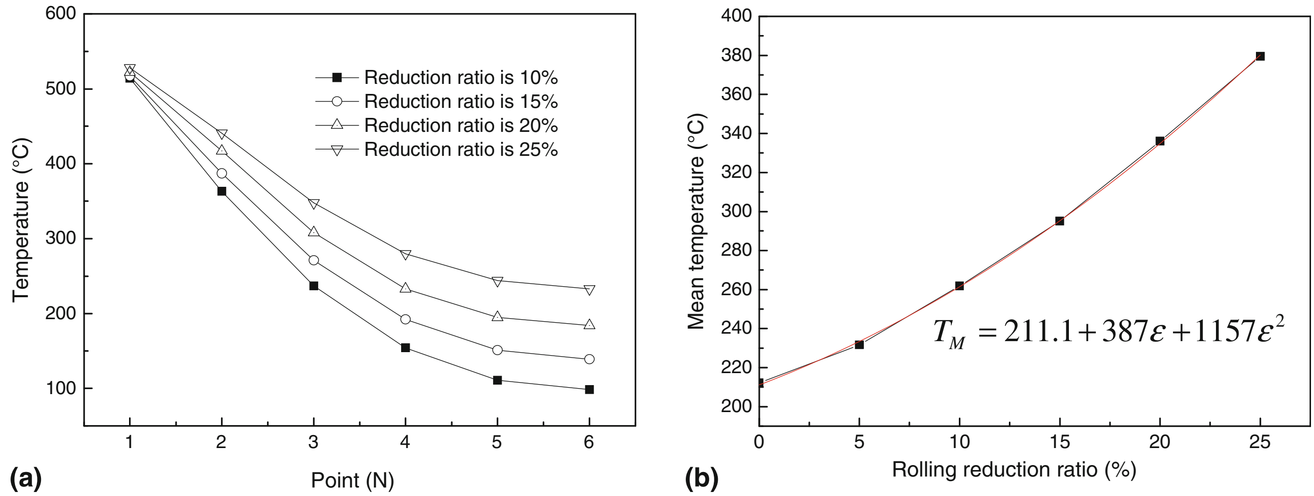

Fig. 10 Temperature at the exit of rolling deformation zone (a) and mean temperature in strips (b) under various rolling reduction ratios

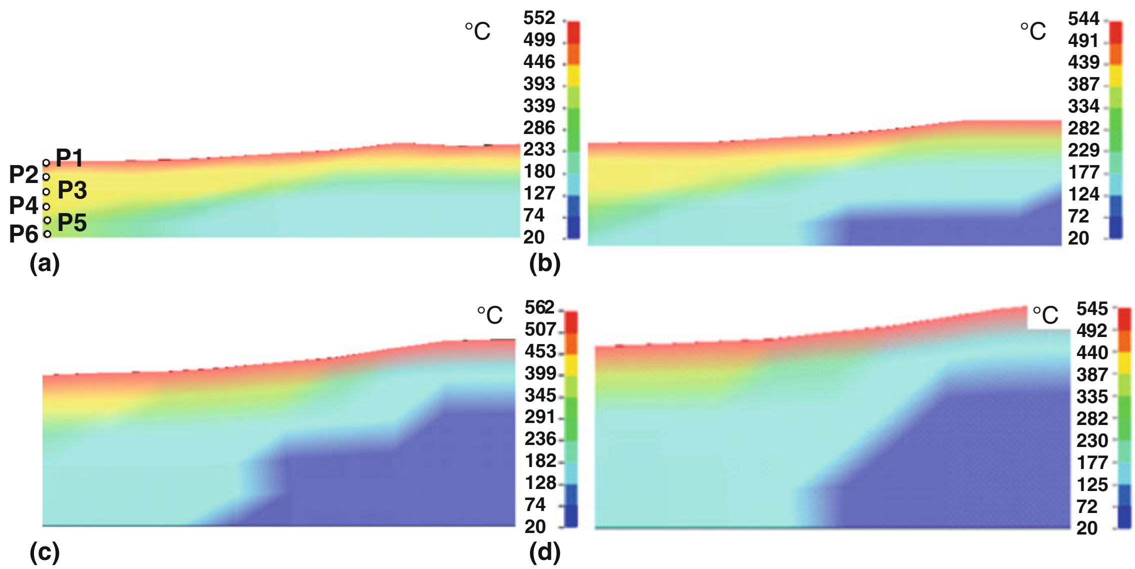

Fig. 11 Thermal field in rolling deformation zone under various initial strip thicknesses

Figure 12(a) shows the temperature of P1-P6 under various initial strip thicknesses. With reduction of the initial strip thicknesses, the temperature of P6 gradually increases. The temperature at P6 changes slightly when the initial strip thicknesses are larger than 2.5 mm.

Figure 12(b) shows the mean temperature in strips under a variety of initial strip thicknesses. In the figure, the mean temperature in strips decreases with increasing the initial strip thicknesses. The relationship between the mean temperature and the initial strip thickness (h_0) could be described by Eq 8.

$$T_M = 265.3 + 601.9e^{-h_0/0.9327} \qquad \text{(Eq 8)}$$

Equations 5-8 show the relationship between the mean temperature of strip and every factor separately. Here, we assumed that every factor above could affect the mean temperature with the same regularity when other factors are certain. Equations 5-8 should have the same value with the same parameters as shown in Table 2. Combing Eqs 5-8, the mean temperature in strips during rolling process under the above factors could be obtained as Eq 9.

$$T_M = 46.8(1 + 0.00393T_R)(1 + 0.904e^{-v_0/2.4118})(1 + 1.83\varepsilon + 5.48\varepsilon^2)(1 + 2.27e^{-h_0/0.9327}) \qquad \text{(Eq 9)}$$

Generally, it is expected that the mean temperature of strips reaches a certain value for increasing the deformation during rolling. If there are three parameters could be known, the critical value of the other parameter could be calculated. For example, under the rolling condition of roll temperature 550 °C, rolling velocity of 1 m/s, reduction ratio 15%, the critical value of initial strip thickness should be less than 1.5 mm if the ideal mean temperature of strip is of 480 °C, and curve of the ideal mean temperature to the critical value of initial strip thickness is shown in Fig. 13.

In Figs. 6, 8, 10, and 12(a), there are obvious temperature differences in strips along thickness direction. The deformation of magnesium alloy strips might also be improved for the

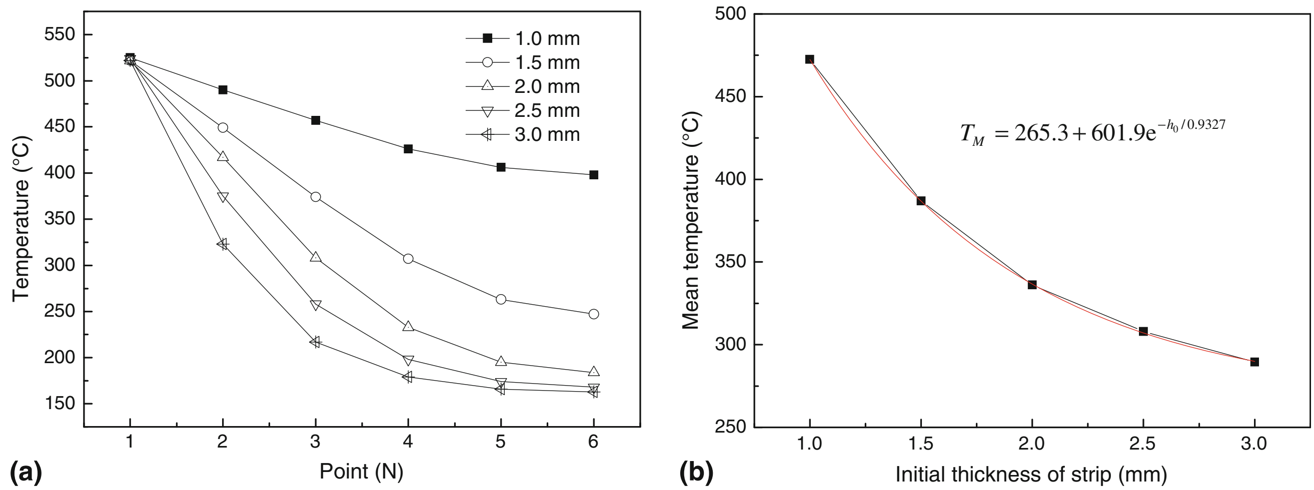

Fig. 12 Temperature in the exit of rolling deformation zone (a) and mean temperature in strips (b) under various initial strip thicknesses

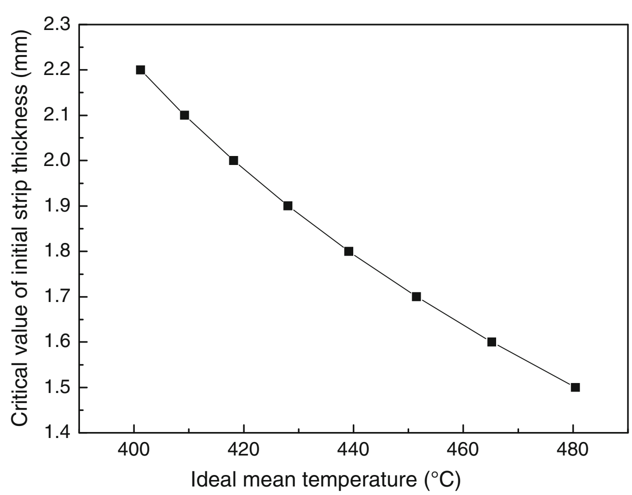

Fig. 13 Relationship between mean temperature and critical value of initial strip thickness

temperature difference along strip thickness during rolling process (Ref 10). And the temperature difference decreases greatly with reduction of rolling velocity and initial strip thickness, and with increasing the rolling reduction ratio. So the temperature difference also could be controlled through adjustment of the rolling process. From above results, when the magnesium strip thickness is thin, the ideal mean temperature and ideal temperature difference could be realized when heated roll is used. Lastly, the microstructure of materials is affected by the thermal field and strain rate, and related experiments should be further studied in future.

4. Conclusions

(1) Thermal-mechanical finite element simulation of cold magnesium alloy strips rolling process using heated roll has been carried out under a variety of roll temperature, rolling velocity, reduction ratio, and initial strip thickness. The cold magnesium alloy strips could be heated through both heat transfer and plastic work.

(2) When the heated roll is employed, the heated area of strips in the rolling deformation zone increases with increasing the roll temperature, reduction ratio, and with decreasing the rolling velocity and initial strip thickness. The temperature difference in strips decreases greatly with reduction of rolling velocity and initial strip thickness.

(3) A formula, $T_M = 46.8(1 + 0.00393T_R)(1 + 0.904e^{-v_0/2.4118})(1 + 1.83\varepsilon + 5.48\varepsilon^2)(1 + 2.27e^{-h_0/0.9327})$, is developed to predict the mean temperature of strip at the exit of rolling deformation zone considering the factors of roll temperature, rolling velocity, reduction ratio, and initial strip thickness. Meanwhile, the formula also could be used to calculate the critical value of parameters under the known rolling conditions and the ideal mean temperature of strips.

(4) The heated roll could be used to roll cold magnesium alloy strips from ideal the mean temperature and temperature difference of strips when the strip thickness is thin. And related experiments should be carried out in future.

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