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Prediction of edge cracks and plastic-damage analysis of Mg alloy sheet in rolling

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Abstract: A thermal-mechanical-damage coupled finite elements model was established to investigate temperature changes, edge cracks and rolling force during rolling of magnesium alloy sheet. A cuneal sheet was also adopted to study the influence of reduction on temperature, damage and rolling force. The results show that with increasing the reduction, the rolling force increases, and the temperature of the Mg sheet decreases. Edge cracks occur when the reduction is above 51.6%, with the damage value of above 0.49. The plastic-damage in Mg sheet rolling is a result of hole development, shearing deformation and accumulative plastic strain.
Key words: magnesium alloys; finite element analysis; rolling; damage

1 Introduction

Magnesium alloy is a promising structure material for its low density, excellent damping property, and other special properties. But it is more difficult to deform magnesium alloy than to deform aluminum and steels for magnesium alloy has hexagonal close packed (HCP) crystal structure. For instance, Mg alloy must be rolled several passes with a small reduction to get a certain thickness which can be obtained through only one pass for steel. Mg sheet also must be re-heated to prevent temperature decrease because of its higher heat conductivity and lower volume specific heat. Therefore, Mg sheet rolling is more complex than steel rolling, and is easy to appear edge crack.

Damage theories can be applied to predicting crack during Mg sheet rolling. Damage theories have been used and improved in many fields. Lots of researches were about the relationship between stress triaxiality and ductile damage[1−5]. Some studied the influence of strain paths on damage[6−7]. The interaction of damage on microstructure was also studied[7−9]. But most of the researches were about the damage under simple load, certain temperature, and certain strain rate, while the effects of temperature change were ignored. All the factors should be considered to make the model right[10]. Rolling is a complex process containing thermal changes, mechanical changes and ductile damage, and those three are interacted. So a thermal-mechanical-damage analysis is necessary to predict edge cracks in rolling.

A ductile damage model about FCC polycrystalline materials with large plasticity has been built[9]. But the ductile damage mechanism of HCP polycrystalline materials including Mg is still not clear. A damage model with finite elements (FE) software was used to study the surface cracks of extruded Mg rod[11]. This is a good way to investigate the damage caused by plastic deformation in rolling. But the model is simple and the micro-mechanism of the damage is not involved.

In this work, the temperature changes and the mechanism of edge cracks during Mg sheet rolling were investigated. A thermal-mechanical-damage coupled model was established to predict the edge cracks. Finite elements method (FEM) was adopted to study the parameters, such as flow stress, strain, strain rate and temperature, which are not easy to measure experimentally.

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2 Theories

2.1 Thermo-mechanical coupled process

Rolling is a thermo-mechanical coupled process. During rolling, the heat of the rolled sheet transfers to rollers and surroundings, while the friction and the plastic deformation generate heat. So the temperature varies during rolling. At the same time, the constitutive law of the material is dependent on temperature. Therefore, rolling is a complex process affected by both thermal and mechanical elements. The temperature change is caused by: 1) heat generated by plastic deformation and friction between roller and sheet; and 2) heat loss caused by heat transfer between sheet and roller, sheet and environment.

The heat generated by plastic deformation is considered to heat source, so the 3-dimensional heat transfer equation is

$$\rho c\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)+\Phi_{\rm V} \quad (1)$$

and the heat transfer between roller and sheet can be described as

$$\alpha=\frac{-\lambda_{\rm c}(\partial T/\partial y)}{T-T_{\rm R}} \quad (2)$$

Convection-radiation heat transfer between the sheet and the environment is defined as

$$q=h(T-T_{\rm o})=(h+h_{\rm r})(T-T_{\rm o}) \quad (3)$$

$$h_{\rm r}=\varepsilon k(T+T_{\rm o})(T^2+T_{\rm o}^2) \quad (4)$$

The heat generated by plastic deform is calculated by

$$q_{\rm p}=\eta_{\rm p}P_{\rm m}\ln(d_1/d_2) \quad (5)$$

Friction between roller and sheet also causes heat. And the heat is

$$q_{\rm fr}=MF_{\rm fr}v_{\rm r} \quad (6)$$

and heat source inside is $\Phi_V=A_1q_{\rm p}+A_2q_{\rm fr}$.

So, there is volume flux Q:

$$Q=\Phi_{\rm V}+A_3\alpha\Delta T+A_4q \quad (7)$$

The rolling process stands to the energy conservation law and force balance law, defined as Eqs.(8) and (9), respectively:

$$\int_V\rho v_i\frac{\partial v_i}{\partial t}{\rm d}V+\int_V\frac{\partial\rho}{\partial t}U{\rm d}V=\int_V\rho(Q+b_iv_i){\rm d}V+\int_S(P_iV_i-H){\rm d}S \quad (8)$$

$$\int_V\rho\left(b_i-\frac{\partial v_i}{\partial t}\right){\rm d}V=\int_S P_i{\rm d}S \quad (9)$$

in which $P_j=n_i\sigma_{ij}$.

Combining Eqs.(8) and (9) leads to thermo-mechanical energy conservation equation[12]:

$$\int_V\sigma_{ij}\frac{\partial\delta u_i}{\partial x_i}{\rm d}V=\int_V\rho b_i\delta u_i{\rm d}V-\int_V\rho\frac{\partial v_i}{\partial t}\delta u_i{\rm d}V \quad (10)$$

Those equations are the bases to FE analysis and were calculated by the MSC.Marc software to describe the rolling process.

2.2 Damage analysis

Damage mechanics proposed in 1960s has been used in many fields including plastic deformation. The Crockroft−Latham theory was built by CROCKROFT and LATHAM[13] who assumed that damage was caused by the maximum tensile principal stress. And when the energy caused by the maximum tensile principal stress and strain reached a certain value, damage took place[13], which was described by

$$\int_0^{\varepsilon_{\rm f}}\sigma_{\max}{\rm d}\bar{\varepsilon}=C\,.$$

3 Simulation and experiment

A cuneal sheet shown in Fig.1 was adopted in experiment and FEM to investigate the plastic-damage properties of the sheet with different reductions during rolling. The final thickness of the sheet after rolling is 3 mm. The sheet was rolled with different reductions ranging from 0 to 66.9%. Marks had been made every 5 mm on the edge of the cuneal sheet in order to mark initial thickness. The cuneal sheet was heated at 400 °C for 30 min before rolling. Those rollers were at room temperature of 20 °C. The diameter of the roller was 170 mm with a speed of 2.2 rad/s.

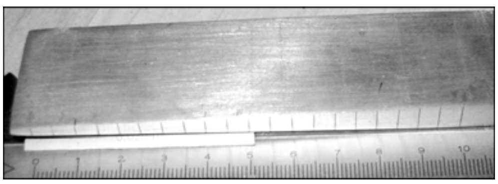

Fig.1 Photo of cuneal sheet

Thermocouples were adhered at the edge of the sheet to measure the temperature change, recording every 0.5 s. The rolling force was measured by sticking strain gages on the rolling machine. The microstructure of the cracks was investigated with SEM.

The nonlinear finite element software, MSC.Marc

& Mentat, was applied to building the 3D rolling model and analyzing the rolling process. The FE model was established according with the experiment.

The material of rolling sheet was AZ31B (Mg-3%Al-1%Zn, mass fraction) wrought Mg alloy. Some of its properties are shown in Fig.2. The cast was extruded at 400 °C, and then cut to the special shape.

The initial density of the sheet was 1 780 kg/m^3. The friction coefficient between the sheet and roller was 0.4. The thermal conductivity between sheet and environment was 0.02 W/(m·K). The ratio of q_p and plastic deformation work η_p was 0.9. The thermal conductivity between sheet and roller was 35 W/(m·K).

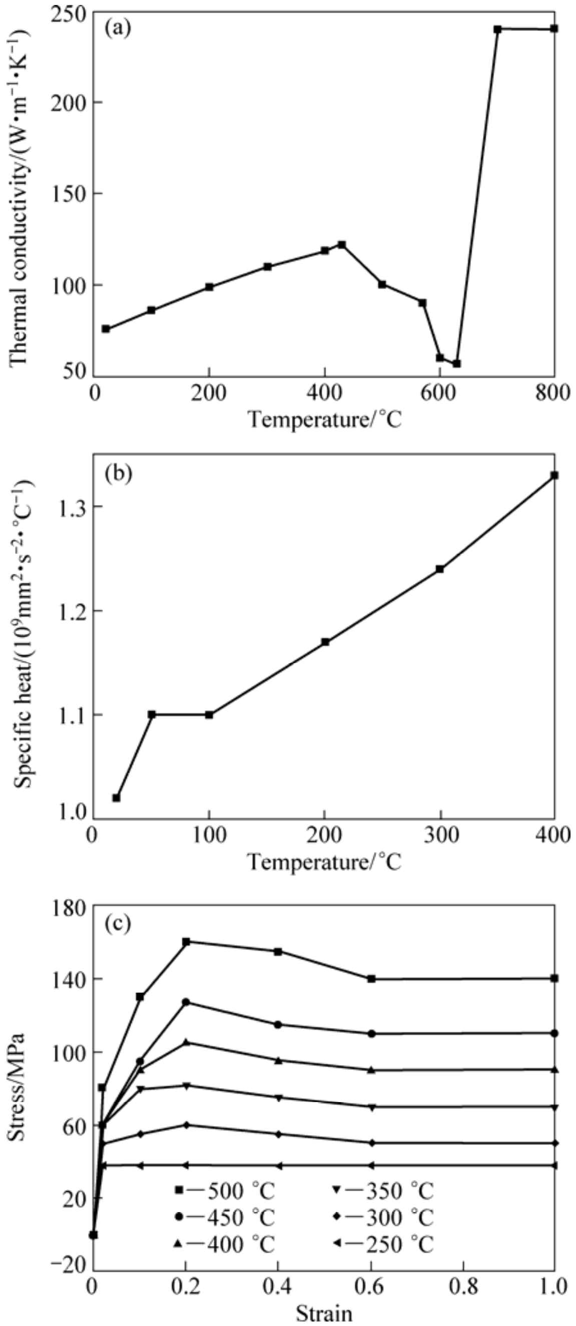

Fig.2 Properties of AZ31 alloy: (a) Thermal conductivity[14]; (b) Specific heat capacity[14]; (c) Flow stress curves at various temperatures[15]

4 Results and discussion

4.1 Thermal conductivity and temperature change

Thermal conductivity is a parameter dependent on materials, contact area, temperature difference, etc. The thermal conductivity between Mg sheet and roller was considered to be 15 W/(m·K) during rolling of AZ31 by JI and PARK[16]. To investigate the heat generation and transfer, different thermal conductivities, 0, 15 and 35 W/(m·K) were used in the finite elements model. The temperature change of one point was measured. The point was on the edge of sheet with the initial thickness of 45 mm. There was a reduction of 43% for the point. The temperature change curves of the point with different thermal conductivities investigated by FEM and the curve from experiment are presented in Fig.3.

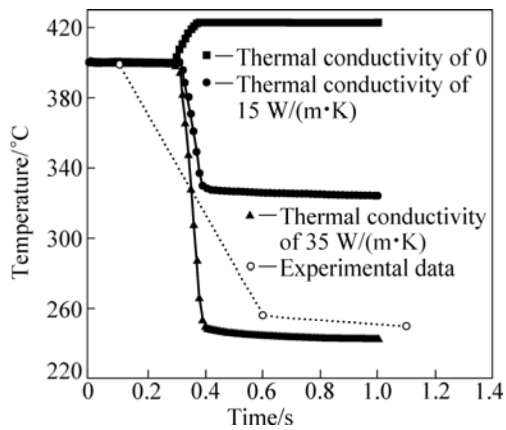

Fig.3 Temperature curves with different thermal conductivities obtained from FEM and experiment

Rolling process is a complex thermal-mechanical process and the mechanical behavior is affected by temperature. In order to get accurate temperature, the thermal conductivity must be accurate first. The temperature with the thermal conductivity of 35 W/(m·K) was the most closed to the experiment one. Therefore, 35 W/(m·K) was adopted in the FE model.

During rolling, deformation and friction generate heat, while heat transfer between sheet and roller, sheet and environment makes heat loss. At a reduction of 43%, deformation and friction make a temperature rise of 20 °C. It can be seen from the curve without heat transfer. But the heat generation is much less than heat transfer. At last, there is temperature drop of about 150 °C due to the joint action of deformation, friction, and heat transfer, especially.

It is obvious that more reduction will generate more heat. So, the part with larger initial thickness will generate more heat. But, the final temperature was not the same, as shown in Fig.4. It can be seen that as the

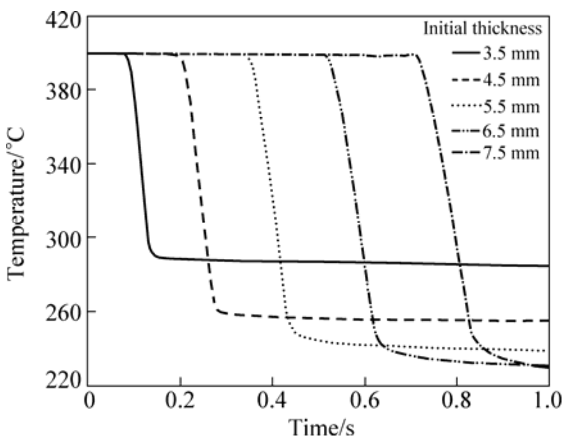

Fig.4 Temperature curves at different places of sheet with different initial thicknesses

reduction increases, the temperature decreases more. Although, the heat generation increases, the heat transfer increases as well. With continuing the cuneal sheet rolling, the contact area between the sheet and roller increases. Consequently, heat transfer that is dependent on the contact area, increases more seriously. Therefore, the temperature decreases with increasing the reduction.

4.2 Edge crack

The Crockroft−Latham theory was used to investigate the edge cracks. According to Ref.[11], the critical value to crack was set to be 0.45. The FEM damage result and the photo of rolled specimen are shown in Fig.5. From FEM result, the damage always takes place at the edge of the sheet. When the value of damage is above 0.49, crack takes place. The result was confirmed by the rolling experiment. The first cracks appear at the edge of the sheet from near the 12th mark, where the initial thickness was about 6.1 mm, and the reduction was 51.6%. Therefore, under this rolling condition, the edge cracks generated when reduction was above 51.6%.

The cracks at the edge is because of the maximum

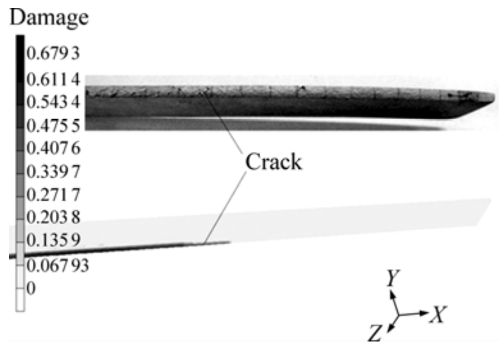

Fig.5 Edge crack results of experiment and FEM (Holes in edge of sheet are location where thermal couples inserted. They are different from the cracks.)

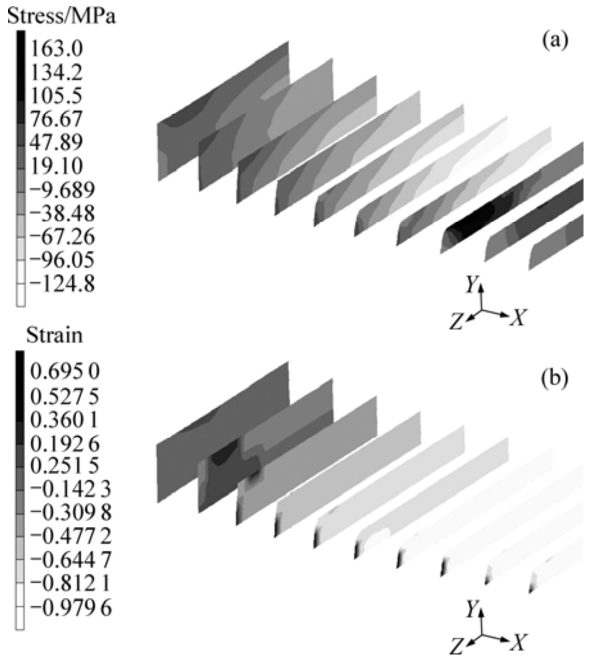

Fig.6 Map of maximum tensile principal stress (a) and map of major principal plastic strain (b)

tensile principal stress and the more principal plastic strain at the edge, which was validated by Fig.6. When the deformation was beyond the stress or strain limit, and the stress−strain energy was beyond the critical value, cracks generated.

4.3 Plastic-damage

The plastic-damage micro-mechanism was also investigated. Damage was recognized as the result of the development of holes. The Gurson theory which is acknowledged in the present damage theories was built based on the holes generation theory[17]. But, according to the SEM observation shown in Fig7, there were not only holes, smooth shear planes, but also the slipping

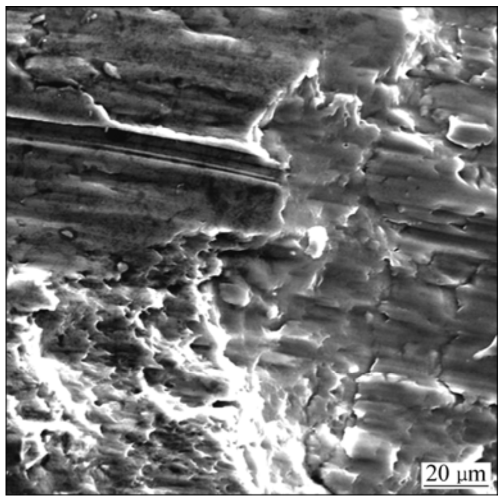

Fig.7 SEM photo of edge cracks

lines. So the plastic-damage during Mg sheet rolling is the result of holes development, shearing deformation and accumulative plastic strain.

4.4 Rolling force

With increasing the reduction, the rolling force increases, as shown in Fig.8. The deformation resistance increases with increasing the reduction. The largest rolling force is about 56 kN, while the FEM result is 52 kN. The experiment result is a little larger than the FEM result. That is attributed to the hardening of the sheet caused by rolling, especially the surface between the sheet and roller, where the temperature descends seriously.

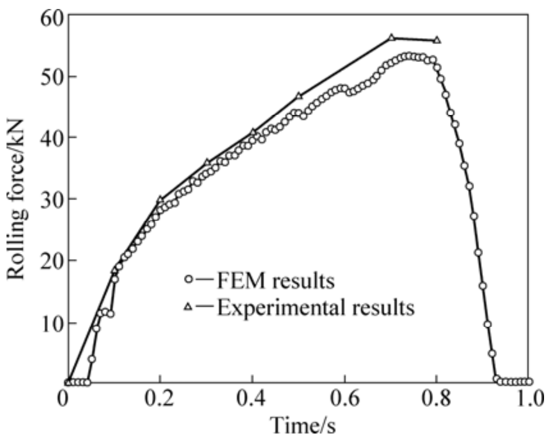

Fig.8 Rolling force curves of experimental and FEM results

5 Conclusions

1) A cuneal sheet rolling FE model was established and validated by experiments for Mg sheet rolling to predict rolling force, damage, and distribution of stress and temperature.

2) Heat transfer between rollers and sheet plays more important role than heat generation caused by friction and deformation in Mg alloy sheet rolling. So there is a large temperature decrease during Mg sheet rolling at room temperature.

3) It is successful to use Crockroft−Latham theory to predict damage including edge cracks in Mg sheet during rolling. The critical value of damage to edge cracks is above 0.49. When the reduction is above 51.6%, edge cracks appear.

4) The plastic-damage in Mg sheet rolling is a result of hole development, shearing deformation and accumulative plastic strain.

5) With increasing the reduction, the rolling force increases, and the temperature of the sheet decreases.

Nomenclature

A_i surface area
b_i volume force
c specific heat
d_1 thickness of the sheet before rolling
d_2 thickness of the sheet after rolling
F_{fr} friction force
h convective heat transfer coefficient
H flux intensity
h_r radiation heat transfer coefficient
k Boltzmann constant
M thermal conversion factor of work and heat
P_i force on the boundaries
P_m mean rolling force
Q volume flux
q_{fr} heat caused by friction
q_p heat caused by plastic deform
q Convection-radiation heat transfer between sheet and environment
S boundary length
T temperature of sheet
T_o temperature of environment
T_R temperature of roller
U energy
u_i distance
V volume
v_i velocity
v_r relative velocity of the surface contacting
α equivalent heat transfer coefficient
η_p ratio of q_p and plastic deformation work
ε emissivity
λ thermal conductivity
λ_c thermal conductivity between roller and sheet
ρ density
σ_{ij} Cauchy stress component
Φ_V heat source inside
ΔT difference of temperature

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镁合金板材轧制边裂的预测和流变−损伤分析

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摘 要：研究镁合金板材轧制过程中的温度变化、边裂和轧制力，建立热−力−损伤耦合有限元模型。采用楔形试样研究压下量对温度、损伤和轧制力的影响。结果表明：随着压下量的增加，轧制力增大，镁板的温度降低；当压下量大于 51.6%时，发生边裂，此时损伤值大于 0.49；镁板轧制中的塑性−损伤是空洞发展、剪切变形和应变积累综合作用的结果。

关键词：镁合金；有限元分析；轧制；损伤

(Edited by YANG Hua)