D. G. WANG, X. D. SHU, R. WANG, T. Z. CHEN

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INFLUENCE OF TEMPERATURE FIELD ON SURFACE QUALITY OF CROSS WEDGE ROLLING (CWR) ALUMINUM ALLOY SHAFT

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Reasonably determination of the rolling temperature of the cross wedge rolling (CWR) is the key to obtain the qualified surface of the aluminum alloy shaft parts. In this paper, the 6 082 aluminum alloy shaft parts with different section shrinkage rate between 43,75 % and 64 % are taken as examples. The thermal-deformation coupling finite element model (FEM) is established to analyze the effect of the process parameters on the temperature field. The influence law of the temperature field on the surface quality in CWR process is obtained and verified by experiment. The results provide theoretical and experimental basis for temperature selection and surface quality improvement.

Key words: cross wedge rolling, aluminum alloy, shaft, temperature field, surface quality

INTRODUCTION

CWR has been widely used in forming shafts for its advantages of low energy consumption, high efficiency, material saving and so on [1]. However, due to the particularity of aluminum alloy properties, compared with steel rolling parts, it is more likely to appear surface folding, surface indentation, surface spiral groove and other external defects [2]. The rolling temperature, including the preheating temperature of the rolled piece and the mold temperature, is one of the key factors that determine the quality of the rolled piece. The deformation mechanism is very complex which includes the material nonlinearity and the geometric nonlinearity because of the interaction of the temperature and mechanical properties of the rolling piece, and the temperature is affected by radiation, conduction, convection and deformation heat in the cross wedge rolling process [3]. Finite element simulation of elastic-plastic deformation and thermal coupling is used to discuss the influence of geometric parameters and process parameters on the temperature field by Ying Fuqiang from Zhejiang University of Technology [4]. Using micro-forming technology, H.N.Lu studied the influence of temperature on the surface quality of cross wedge rolling piece [5]. And the temperature field changes in the wedge cross-rolling expansion area has been analyzed with finite element software combined with heat transfer theory by Liu Wenke of Beijing University of Science and Technology [6]. Although the importance of temperature field to surface quality of rolled parts is emphasized above, but there are no established system-based principles. In this paper, the simulation of the 6 082 aluminum alloy shafts parts in different process parameters are carried out by finite element method. The influence law of the temperature field distribution on the surface quality of rolling parts is obtained and then verified by experiments. The results provide a new research method for further study and improvement of the surface quality of aluminum alloy.

D. G. Wang, X. D. Shu, R. Wang, T. Z. Chen: College of Mechancial Engineering and Mechanics, Ningbo University, China, E-mail: shuxuedao@nbu.edu.cn

ANALYSIS OF TEMPERATURE FIELD

In the cross wedge rolling process, the expansion of the mold in the material is spiral [7], that is, one revolution per rolling section of the rolled piece, the entire expansion zone is extended $p = \pi d \tan\beta$, where d is the diameter of the rolling completed zone and β is the spreading angle. When β is small enough, the expansion zone of rolled piece can be simplified to a frustum. The completed deformation zone can also be simplified to a frustum or a cylinder. The rolling process is shown in Figure 1.

According to Fourier's law, the heat balance equation of the micro element is as shown in formula 1.

$$dU = \Phi_{\lambda} + \Phi_{V} \quad (1)$$

Where dU is the added value of the thermodynamic energy of the microelement; Φ_{λ} is the heat flux of the

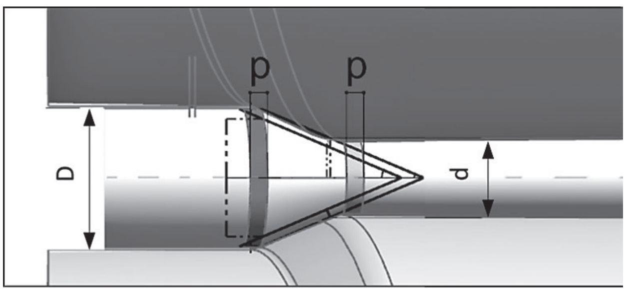


Figure 1 Expansion process of Cross wedge rolling

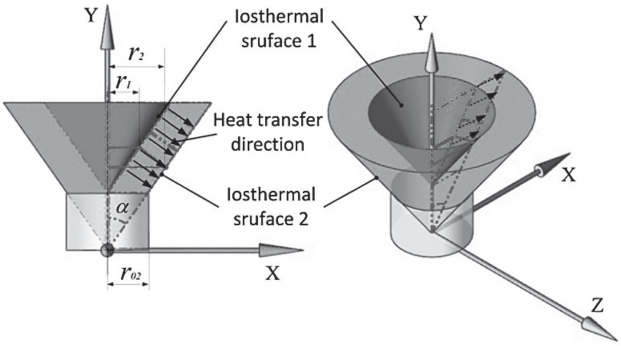


Figure 2 Isothermal surface and heat transfer

microelement; Φ_V is the heat generated by the internal heat source.

As shown in Figure 2, the spreading zone can be regarded as a frustum. The parametric equation of cylindrical coordinates is:

$$\begin{cases} x = \mathrm{r}\cos\varphi \\ y = \mathrm{r}\sin\varphi \\ z = \mathrm{r}\tan\alpha \end{cases} \tag{2}$$

$$\frac{\partial \mathrm{t}}{\partial \tau} = a\left(\frac{\partial^2 \mathrm{t}}{\partial \mathrm{r}^2} + \frac{1}{\mathrm{r}}\frac{\partial \mathrm{t}}{\partial \mathrm{r}} + \frac{1}{\mathrm{r}^2}\frac{\partial^2 \mathrm{t}}{\partial \varphi^2} + \frac{\partial^2 \mathrm{t}}{\partial z^2}\right) + \frac{\mathrm{q_v}}{\rho \mathrm{C}} \tag{3}$$

Where t and τ is temperature and time variable respectively; *x*, *y* and *z* are coordinates of a rectangular coordinate; r and φ is polar diameter and polar angle of cylindrical coordinates respectively; The temperature of rolled part can be simplified to an isothermal surface after rolled piece rotating one week, although not uniform at beginning. Assuming that the internal isothermal surface is also a frustum surface with a conical angle of 2α , the schematic diagram is shown in Figure 2. There is no internal heat source and there is no heat transfer in the circumferential direction of the cylinder for the same reason above. Formula 4 can be achieved according formula 1.

$$\frac{\partial^2 \mathrm{t}}{\partial \mathrm{r}^2} + \frac{1}{\mathrm{r}}\frac{\partial \mathrm{t}}{\partial \mathrm{r}} + \frac{1}{\tan\alpha}\frac{\partial^2 \mathrm{t}}{\partial \mathrm{r}^2} = 0 \tag{4}$$

$$\mathrm{t} = \mathrm{C_1}\left(\frac{\tan^2\alpha}{1+\tan\alpha}\right)\mathrm{r}^{\left(\frac{1+\tan\alpha}{\tan^2\alpha}\right)} + \mathrm{C_2} \tag{5}$$

Where C_1 and C_2 are pending coefficients.

Substituting boundary conditions r = r_1,t = t_1,r = r_2, t = t_2, formula 6 can be obtained.

$$\mathrm{t} = \frac{\left(\mathrm{t_2}\text{-}\mathrm{t_1}\right)\mathrm{r}^{\left(\frac{1+\tan\alpha}{\tan^2\alpha}\right)} + \mathrm{t_1 r_2}^{\left(\frac{1+\tan\alpha}{\tan^2\alpha}\right)} - \mathrm{t_2 r_1}^{\left(\frac{1+\tan\alpha}{\tan^2\alpha}\right)}}{\mathrm{r_2}^{\left(\frac{1+\tan\alpha}{\tan^2\alpha}\right)} - \mathrm{r_1}^{\left(\frac{1+\tan\alpha}{\tan^2\alpha}\right)}} \tag{6}$$

Where r_1 , t_1 is the radius and temperature of isothermal surface 1, and r_2 , t_2 the isothermal surface 2. The heat transfer can be neglected in the rolling completed zone because of line contact between the die and the rolled piece, for which the temperature distribution is determined by the heat transfer in spreading zone. Where r_2 and r_1 have great influences on the temperature field because of the large value of $(1+\tan\alpha) / \tan^2\alpha$. Especially the transition radius r_{02} from the spreading zone to the rolling completed zone determines the temperature field distribution of the rolling completed zone, whose size is determined by the section shrinkage rate. So the section shrinkage rate has great influence on the temperature field .

ESTABLISHMEN OF THERMAL-DEFORMATION COUPLING FEM OF DEFORM

The establishment of finite element model

The spreading angle β of the die is 7 ° and the forming angle α is 30 °. The FEM of CWR is obtained as shown in Figure 3. The material is 6 082 aluminum alloy, and its rheological equation is formula 7:

$$\dot{\varepsilon} = 3{,}055 \times 10^{16}\left[\sinh\left(0{,}0\ 172\sigma\right)\right]^{7{,}311}\exp\left(2{,}477 \times 10^{5}/RT\right) \tag{7}$$

The heat transfer between the rolled piece and the environment are very complex, including heat conduction between the die and the rolled piece, radiation and air convection. The direct contact heat transfer between the rolled piece and die has the greatest influence on the temperature field in the process, which can be expressed by formula 8 [8].

$$\mathrm{q} = \mathrm{h}_s\left(\mathrm{t}_s + \Delta\mathrm{t_{def}} - \mathrm{t}_w\right) + \frac{2}{3}\mathrm{q_{fr}} = -K_W \left.\frac{\partial \mathrm{t}}{\partial \mathrm{r}}\right|_{\mathrm{r}=R_W} \tag{8}$$

Where the heat transfer coefficient, the temperature of the rolled piece, the deformation temperature of the rolled piece, the temperature of the die, the friction heat flux and the thermal conductivity of the working roll are expressed as h_s, t_s, Δt_{def}, t_w, q_{fr}, K_w respectively. The general range of h_s is 25 ~ 75 k*W* / (m ^{2}. K^{-1}). Due to the characteristics of CWR, the die needs to wedge into the rolled piece, so the value of h_s is 75 k*W* / (m ^{2}. K^{-1}) because of their full contact. The relative motion between the die surface and the rolled piece is so small that Δt_{def}

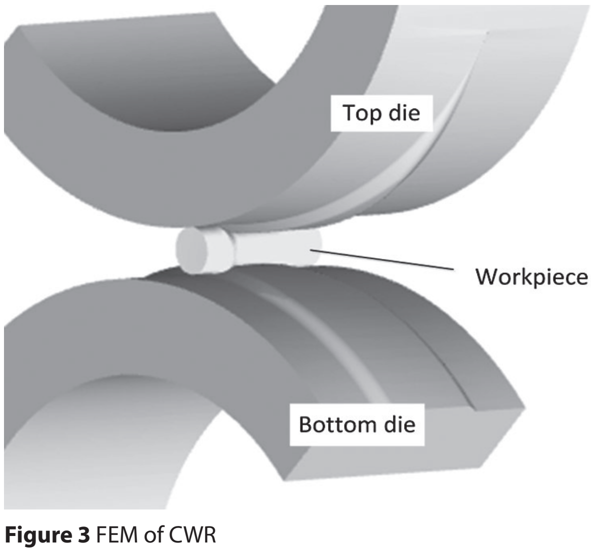
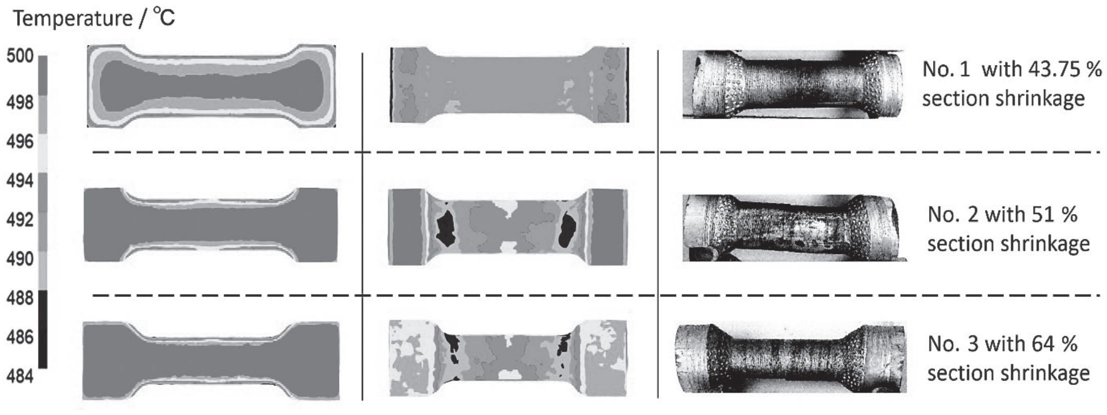


Figure 3 FEM of CWR

Table 1 **Process parameters**

Parameter / NO	Diameter of Bullet / mm	Temperature Of mould / °C	bullet Temperature / °C	Rolling speed / rad / s	f	D_{min} / mm	Section shrinkage
1	40	20	500	1	1,5	30	43,75 %
2	40	20	500	1	1,5	28	51 %
3	40	20	500	1	1,5	24	64 %
4	40	300	450	1	1,5	28	51 %
5	40	300	450	1	1,5	24	64 %



(a) (b) (c)

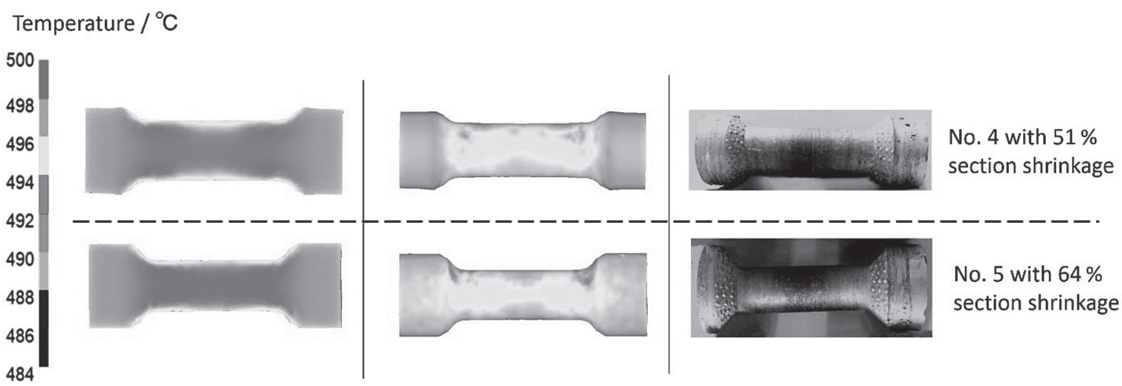
Figure 4 Temperature Field Distribution of rolled pieces with normal temperature die:(a)Internal temperature field;(b)surface temperature field;(c)rolled piece

can be neglected in cross wedge rolling process. The process parameters of CWR is shown as Table 1.

Effect of temperature field on aluminum alloy shaft in CWR process

As shown in Figure 4, the section shrinkage of a rolled piece is 43,75 %, 51 % and 64 % from left to right respectively at the rolling speed of 1 rad / s at 500 °C. The simulation and experimental figures of the temperature field of the rolled piece under the conditions are given in Table 1. With the increase of section shrinkage, the cooling degree of the rolled piece increases, but the thickness of the cooling layer on surface decreases obviously. A brittle thin layer will appear on the surface just as shown in simulation of temperature field. The surface quality problems will appear when the surface temperature field presents multi - color island distribution, surface spiral groove appears obviously when the section shrinkage rate reaches 61 %.

It is found that with the increase of section shrinkage rate the cooling layer becomes thinner due to the increase of deformation heat. While the surface temperature decreases more quickly due to the increase of the direct contact surface area with the die. As a result, surface quality issues are more likely to occur due to the brittleness and hard layer on the surface as shown in no,2 and no,3 in Figure 4. Black oxide will appear on the surface, when the preheating temperature of the rolled pieces exceeds 500 °C, for which, the preheating temperature of the rolled piece will be reduced to 450 °C. The die will be heated to 300 °C to reduce the inhomogeneity of the surface temperature of the rolled piece, and to improve the cold brittleness of the cooling layer. The simulation results and experimental verification are shown in Figure 5. After the mold is



(a) (b) (c)

Figure 5 Temperature field distribution of rolled pieces with heated die:(a)Internal temperature field;(b)surface temperature field;(c)rolled piece heated, the surface quality of the rolled parts are obviously improved.

From the microscopic point of view, aluminium alloys belong to polycrystal. When the temperature is low, the deformation of the spreading zone is more intense, and the metal is prone to anisotropy, which results in surface quality problems. With the increase of temperature, more slip systems of polycrystal are activated to compensate for surface defects caused by anisotropy during low temperature [5]. Therefore, the uniformity of temperature field on the surface of the rolled parts is greatly improved, and the thickness of the cooling layer is also increased. Thus, the surface quality problem of the rolled piece of the large section shrinkage is greatly improved.

CONCLUSIONS

Temperature field is an important parameter in cross wedge rolling process. The surface quality of the rolled piece is good if the surface temperature field of the rolled piece is uniformly distributed. When the surface temperature contour of the rolled piece is not uniformly distributed, the surface of the rolled piece will appear small brittle cracks or even spiral grooves.

The preheating temperature of the rolled piece has the greatest influence on the temperature field of the rolled piece. The higher the preheating temperature is, the higher the temperature of surface of the cooling layer.

Section shrinkage has a great influence on temperature field. The bigger the section shrinkage is, the lower the temperature of cooling layer. However, the thickness of cooling layer decreases due to deformation work. When the cooling layer is too thin, the brittle and hard layer on surface will be formed, which will cause surface quality defects or even spiral grooves.

The mold heating can improve the uniformity of the surface temperature improve the cold and brittleness of the surface, and thereby reduce the surface defects of the rolled piece.

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Note: The professional translator for the English language is Q. Q. Yan, Zhejiang, Chin