Effect of Cold Rolling Parameters on the Longitudinal Residual Stress Distribution of GH4169 Alloy Sheet

Neng-Yong Ye¹ · Ming Cheng¹ · Shi-Hong Zhang¹

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Abstract For plastic deformed parts, the dimensional accuracy is significantly affected by residual stresses and so does the performance in service. Therefore, the rolling process of GH4169 alloy sheet at room temperature was investigated by finite element method. The effects of rolling reduction, friction coefficient, rolling velocity and initial stress on the longitudinal residual stress distribution over the thickness of GH4169 alloy sheet were analyzed. The results show that the values of longitudinal residual stress can be slightly reduced by increasing the rolling reduction and velocity. The longitudinal residual stress over the thickness distributes as “V” type or weak “W” type. The initial stress mainly has an effect on the longitudinal stress in the backward slip area. But the friction coefficient has remarkable influence on longitudinal residual stress. With the friction coefficient increasing from 0.1 to 0.5, the value of longitudinal residual stress on the sheet surface is reduced by 282 MPa. Simultaneously, the tensile stress turns into compressive stress with a strong “W” type distribution.

KEY WORDS: GH4169 alloy; Cold rolling; Residual stress; Process parameters

1 Introduction

GH4169 alloy (modified Inconel 718 alloy) is a nickel-based superalloy which is extensively used in aviation components. Because of its excellent mechanical properties, good oxidation resistance and corrosion between -253 and 650 °C, the GH4169 alloy used in engineering reached 57 wt% of total superalloy consumption [1]. Recently, the technology of cold rolling forging is used in final precision forming of GH4169 alloy blades. With this technology, better mechanical properties and surface integrity can be obtained [2–4]. Besides, the deeper

distributed residual stress caused by cold rolling has better thermal and mechanical stability under the condition of high temperature or alternating loading [5, 6]. Compared with the peak value of residual stress, the residual stress distribution over the thickness direction has more significant effect on the fatigue life and crucial for precise forming of components [5, 7–10]. During the forming process, the process parameters have an important effect on the distribution of residual stress. By analyzing the rolling process of 7075-T6 aluminum alloy, Befhini et al. [11] found that the max residual compressive stress transformed from surface to the subsurface with increased rolling force. Zhao and Zhang [12] also analyzed the effect of rolling reduction on the residual stress of aluminum alloy sheet using finite element methods. The results showed that the residual stress was tensile on the surface of the aluminum alloy sheet and compressive inside when the rolling reduction was small. With increased rolling reduction, the residual stress distributed more non-uniformly. Li et al. [13] and Mao [14] analyzed the effect of rolling parameters

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✉ Ming Cheng
mcheng@imr.ac.cn

¹ Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China

on the residual stress of strip steel and SUS304 stainless steel. The results showed that the lubrication condition between the sheet and rollers has the most significant influence on the residual stress distribution over the thickness direction, while the effects of the diameters of rollers and tension were relatively smaller. As mentioned above, the process parameters had an obvious effect on the value and distribution of residual stress, but the work mostly focused on the traditional materials, such as iron and steel, and aluminum alloy. The paper investigates the residual stress of GH4169 alloy after cold rolling was not reported yet. Therefore, it is necessary to investigate the longitudinal residual stress value and variation over thickness of GH4169 alloy sheet for various process parameters. It will be beneficial to the precision forming of GH4169 alloy blades and the extended application of cold rolling technology.

The value and distribution of longitudinal residual stress under different rolling conditions are obtained by the finite element software MSC.Marc. The effect of cold rolling parameters including rolling reduction, friction coefficient, rolling velocity and initial stress state on the longitudinal residual stress of GH4169 alloy sheet is analyzed. Finally, the simulation result is verified by the rolling experiments.

2 Simulation of Cold Rolling Process

2.1 Finite Element Model

The rolling process of GH4169 alloy sheet is a complicated nonlinear subject. To ensure the accuracy and efficiency, the finite element model is simplified as follows:

The rollers are regarded as rigid bodies, and the elastic deformation during the cold rolling is ignored.

The GH4169 alloy sheet in cold rolling is modeled as isotropic, and the initial size is 70 mm × 22 mm × 2.4 mm. The finite element model is shown in Fig. 1a. The eight-node hexahedral elements with size of 0.2 mm × 0.1 mm × 0.1 mm were used in the model. In virtue of the bending stress occurred in the longitudinal direction of blades, the stress component along the rolling direction (RD) is investigated. The analytical points are shown in Fig. 1b.

2.2 Material Properties

The GH4169 alloy sheets were firstly solution treated at 980 °C for 1 h. The chemical composition of GH4169 alloy is listed in Table 1. The Young's module and Poisson's ratio of it are 203 GPa and 0.33, respectively. Figure 2 shows the true stress–true strain curve of GH4169 alloy at room temperature. It reveals that GH4169 alloy has

Fig. 1 FE model of cold rolling and analytical point of residual stress: **a** finite element model; **b** analytical points

good elongation, but it is also characterized as high resistance to deformation at room temperature.

2.3 Cold Rolling Parameters

According to the rolling parameters of blades, the rolling reductions were set between 10 and 50% and the rolling velocities were between 0.07 and 0.14 m/s. To analyze the effect of friction conditions, the friction coefficients were set between 0.1 and 0.5. And the rollers' diameters were 350 mm based on the actual rolling machine. The cold rolling parameters used in the FE analysis are given in Table 2.

3 Results and Discussion

3.1 Stress Changes Before and After Cold Rolling

The longitudinal stress distributions of GH4169 alloy sheet during and after the cold rolling are shown in Fig. 3. It can be found that the longitudinal stress σ_{11} over the thickness was symmetrically distributed all the time. During the process of cold rolling, the forward and backward slip areas were formed. In the backward slip area, the longitudinal stress was tensile on the surface and compressive in the center (A–F in Fig. 3a). However, it all became compressive when the sheet rolled into the forward slip area (G–M in Fig. 3a). When the sheet was rolled out of the exit, the

Table 1 Chemical compositions of GH4169 alloy sheet (in wt%)

C	Cr	Ni	Mo	Al	Nb	Ti	Si	P	S	Fe
0.07	18.94	52.4	2.97	0.49	5.04	1.02	0.08	0.005	0.001	Bal.

Fig. 2 True stress–true strain curve of GH4169 alloy sheet after solution treatment

stress state was changed again, and it all became tensile because of the stress equilibrium (N–P in Fig. 3a). When the process of cold rolling was finished, the longitudinal stress σ_{11} was partly released. Therefore, the residual stress on the surface was in the tensile state (A–C in Fig. 3b), but it was compressive in the center (D–E in Fig. 3b).

3.2 Influence of Rolling Reduction on the Residual Stress Value and Distribution

The longitudinal stress changes and residual stress distributions under different rolling reduction (10, 30 and 50%) are shown in Fig. 4. The rolling velocity was set at 0.11 m/s, the friction coefficient was 0.1, and the influence of initial stress was not considered. It can be seen that the rolling reduction influenced the longitudinal stress (surface) in the forward slip area more significantly than the one in the backward slip area, as indicated by the arrow in

Fig. 4a. After cold rolling, the residual stress on the surface was in the tensile state. It firstly increased and then decreased with rolling reduction increasing. But it was compressive in the center of the sheet. Besides, the residual stress distributed as weak “W” type. When the rolling reduction reached above 30%, the residual stress distributed as “V” type. Meanwhile, the area of compressive stress in the center became smaller, as shown in Fig. 4b, due to the friction resistance along the RD increases with the rolling reduction increasing. The non-uniformity of stress along over the thickness appears as a larger stress span. Accordingly, when the reduction is 30%, the residual stress distributed as “V” type, as shown in Fig. 4b. When the rolling reduction reached 50%, the residual stress on the surface decreased again, but it increased in the center. That is because the used GH4169 alloy sheet here is so thin that the middle plane of the sheet is penetrated by the normal direction force. Hence, the stress uniformity over the thickness is better than the other two situations, as shown in Fig. 5. In Fig. 5, the longitudinal stress σ_{11} distributed uniformly during the cold rolling process and kept to the end of cold rolling. At last, the longitudinal stress distributed as weaker “V” type compared to the case of $\varepsilon = 30\%$, as shown in Fig. 4b.

3.3 Influence of Rolling Velocity on the Residual Stress Value and Distribution

The longitudinal stress changes and residual stress distributions under different rolling velocities (0.07, 0.11 and 0.14 m/s) are shown in Fig. 6. The rolling reduction was 10%, and the friction coefficient was 0.1. No initial stress was considered. The result shows that the rolling velocity had no effect on the longitudinal stress on the surface on the backward slip area, as indicated by the oval in Fig. 6a. But it led to the decrease in residual stress on the surface of

Table 2 Cold rolling parameters

Rolling reduction (%)	Friction coefficient	Rolling velocity (m/s)	Initial stress	Roller diameter (mm)
10, 30, 50	0.1	0.11	Na	350
10	0.1, 0.3, 0.5	0.11	Na	
10	0.1	0.07, 0.11, 0.14	Na	
10	0.1	0.11	With

Fig. 3 Longitudinal stress σ_{11} changes in GH4169 alloy sheet ($\varepsilon = 10\%$): **a** longitudinal stress σ_{11} changes during the cold rolling; **b** residual stress distribution after the cold rolling

Fig. 4 Influence of rolling reduction on the longitudinal stress and distribution of residual stress: **a** changes in longitudinal stress on the surface; **b** distribution of residual stress along the thickness direction

Fig. 5 Longitudinal stress σ_{11} distribution during the cold rolling ($\varepsilon = 50\%$)

Fig. 6 Influence of rolling velocity on the longitudinal stress and distribution of residual stress: **a** changes in longitudinal stress on the surface; **b** distribution of residual stress over the thickness

GH4169 alloy sheet eventually, as denoted by the arrow in Fig. 6b. Under different rolling velocities, the residual stress after cold rolling distributed as “W” type. Besides, the maximum compressive stress value had the trend of transferring from the center to the surface of sheet, as shown in Fig. 6b. The reason of the residual stress on the surface decreases from 217 to 156 MPa is that the friction force is inversely proportional to the rolling velocity. The longitudinal stress at the exit becomes smaller when the rolling velocity increases. Although the longitudinal stress is partly released when the cold rolling is finished, it still presents as a decreasing trend on the surface. In the center, the residual stress increases oppositely. The “W” type distributes more strongly. On the one hand, it is because the rolling reduction is small (10%), the distribution tends to be “W” type. On the other hand, it is due to the equilibrium of stress. The residual stress in the center increased consequently when it decreased on the surface. Both these two reasons lead to the maximum compressive stress value transforming from the center to the surface. The residual stress eventually distributed as a stronger “W” type compared to case of 0.07 m/s.

3.4 Influence of Friction Coefficient on the Residual Stress Value and Distribution

The longitudinal stress changes and residual stress distributions under different friction coefficients (0.1, 0.3 and 0.5) are shown in Fig. 7. The rolling velocity and reduction were set at 0.11 m/s and 10%, respectively. The initial stress was not considered either. The results show that the friction coefficient had a significant effect on the longitudinal stress and its distribution after cold rolling, as shown in Fig. 7a. The longitudinal stress in the forward slip area

increased with friction coefficient increasing. After cold rolling, the residual stress on the surface decreased from 178 to −104 MPa, while in the center, it increased from −35 to 109 MPa. With friction coefficient increasing from 0.1 to 0.5, the residual stress distribution changed from weak “W” type to strong “W” type, as shown in Fig. 7b. The reason of these changes is that when the friction coefficient increases, the stress state at the exit of rolling deformation area is changed. Compared with Fig. 3a, the longitudinal stress at the exit is compressive on the surface and tensile in the center, as shown in Fig. 8. When the cold rolling finished, the stress is released further. The compressive stress state is preserved, as shown in Fig. 8b. So the compressive stress on the surface increased with the friction coefficient increasing.

3.5 Influence of Initial Stress State on the Residual Stress Value and Distribution

For analyzing the effect of initial stress state on the residual stress value and distribution, the initial stress after shot peening [3] was imposed along the thickness of the sheet, as shown in Fig. 9. Figure 10 shows the effect of initial stress on the longitudinal residual stress of GH4169 alloy sheet. The results show that the initial stress mainly influences the longitudinal stress at the backward slip area. For the residual stress after cold rolling, it just led to the 10 MPa decrease on the value. The distribution was not changed. That is because in the backward slip area, the longitudinal stress on the surface is tensile and compressive in the center. However, the initial stress state after shot peening is opposite. So they are neutralized to each other, as shown the oval in Fig. 10a. The longitudinal stress in the

Fig. 7 Influence of friction coefficient on the longitudinal stress and distribution of residual stress: **a** changes in longitudinal stress on the surface; **b** distribution of residual stress over the thickness

Fig. 8 Longitudinal stress σ_{11} distributions of GH4169 alloy sheet: **a** longitudinal stress distribution during cold rolling ($\mu = 0.5$); **b** longitudinal residual stress distribution after cold rolling ($\mu = 0.5$)

forward area and residual stress after cold rolling are nearly not affected, as shown in Fig. 10b.

4 Experimental Verification

Experiments of cold rolling of GH4169 alloy sheet (70 mm $\times$ 22 mm $\times$ 2.4 mm) were carried out for confirming the accuracy of the simulation results. The GH4169 alloy sheet used in the experiments is shown in Fig. 11. In

the experiment, the rolling reduction was 30%, rolling velocity was set 0.07 m/s, the roller's diameter was 350 mm, and the sheet was oil lubricated. After cold rolling, the residual stress along the RD of the sheet was tested by SWXRD-1000 (short-wave X-ray diffraction) with $W\text{K}_{\alpha 1}$ radiation ($\lambda = 0.0208992$ nm) [15, 16]. The tested result shows that the residual stress on the sheet surface was -218 MPa. It reveals that the simulation result (-239 MPa) is in good agreement with the experimental result, and the error is about 9.6%.

Fig. 9 Stress distribution along the thickness direction after shot peening [3]

5 Conclusions

- (1) With the rolling reduction increasing, the longitudinal residual stress value is slightly reduced and the distribution over the thickness is changed from weak “W” type to “V” type.
- (2) The residual stress on the surface decreases when the rolling velocity increases from 0.07 to 0.14 m/s.
- (3) Friction coefficient has a remarkable influence on longitudinal residual stress. With the friction coefficient increasing from 0.1 to 0.5, the value of longitudinal residual stress on the sheet surface is reduced by 282 MPa. Simultaneously, the tensile stress turns into compressive stress with a strong “W” type distribution.

Fig. 10 Influence of initial stress on the longitudinal stress and distribution of residual stress: **a** changes in longitudinal stress on the surface; **b** distribution of residual stress over the thickness

Fig. 11 GH4169 alloy sheet before and after cold rolling ($\varepsilon = 30\%$)

- (4) The influence of initial stress mainly locates in the backward slip area, and the value of longitudinal residual stress is also slightly reduced.

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