SIMULATION OF ROLLING TEXTURE OF ALUMINUM WITH LATH MODEL①

Chen Zhiyong, Zhang Xinming, Zhou Zhuoping, Li Saiyi and Yang Yang
Department of Materials Science and Engineering,
Central South University of Technology, Changsha 410083, P. R. China

ABSTRACT The rolling textures of pure aluminum were simulated with the modified relaxed constraints (lath) model. The minimum shear of e_{13} was introduced to solve the ambiguity of the selection of the active slip systems and thus to satisfy the strain compatibility to the maximum extent. The results of computer simulation showed a good consistence with the measured rolling textures of pure aluminum. The orientation density $f(g)$ calculated by the RC (lath) model is much closer to the measured than by the FC model.

Key words aluminum rolling texture RC lath model minimum shear principle

1 INTRODUCTION

It is well known that texture is one of the most important parameters which describe the properties of materials. The textures prediction of polycrystalline materials has been carried out for many years according to the conditions of deformation[1]. The simulation of the deformation textures of polycrystals may be mainly classified into the Sachs[2] and the Taylor[3] models, as well as the different kinds of modified (relaxed constrains) models. A lot of researches showed[1,4,5] that the Taylor model is closer to experiment results than the Sachs model. However, for the application of the FC Taylor model to the simulations of deformation textures of FCC metals, generally, there are 6 or 8 slip systems that can fulfill the yield conditions altogether when the criterion of the Bishop-Hill maximum external work or the Taylor minimum internal work is used to determine the active slip systems. Because only 5 independent active slip systems are necessary in order to complete an arbitrary shape change, so the ambiguity of the selection of the active slip systems arises. In the past investigations, the ambiguity according to the FC Taylor model has been solved usually using the following methods: Mecking took the average value of lattice rotations over all possible slip systems[6], van Houtte selected an arbitrary possible group of slip systems[7], Canova and Kocks[8] and Asaro and Needleman[9] took rate sensitivity into account, Renouard and Wintenberger[10] introduced a second order plastic work criterion. The RC models are often adopted when the deformation state of grains and the conditions of plastic deformation are considered[11,12].

In this paper, according to the shape of the deformed grains, the RC Taylor model (the lath model) is adopted. The minimum shear principle of e_{13} is introduced to approach the ambiguity of the selection of the active slip systems in order that the strain compatibility is satisfied to the maximum extent. The cold rolling textures of pure Al have been simulated and the results showed a good consistence with the measured.

2 EXPERIMENTAL

The sample with an almost random texture was obtained after the commercial Al ingot with a purity of 99.7% was properly rolled and heat

① Project 96053314, 97053316 supported by the National Doctorate Program Fund of the Education Ministry of China
Received Oct. 22, 1998; accepted Mar. 12, 1999

treated. The initial thickness of the sample was 5.6 mm, the width 32.2 mm. Using rolling steps of about 10% ~ 15% reduction and d 320 mm rolls, the sample was rolled to 0.56 mm (90% reduction). The rolling can be approximated by plane strain deformation. The initial size of grains was about d 0.25 mm. During the rolling, the grains were elongated and became lath shape gradually along the rolling direction.

The pole figures were measured on a fully automatic and computer-controlled texture goniometer in the Schulz reflection mode. Four incomplete pole figures in the range of $\alpha = 5° \sim 85°$, $\beta = 0° \sim 360°$ —{111}, {200}, {220} and {311} —were obtained with CuK_α radiation and 35 kV, 25 mA. From these pole figure data the corresponding ODFs (orientation distribution functions) were calculated after correction and symmetrization (cubic-orthogonal symmetry) using the series expansion method[13] (with $l_{max} = 22$). Because of the effects of the Fridel Law of X-ray diffraction, the calculated ODFs did not include the odd terms of the series, hence the ghost phenomenon occurs. For the elimination of ghost effects, the odd terms of the ODFs were deduced by the model ODFs consisting of a superposition of several isotropically scattering Gauss-type components, and the true ODFs (with $l$max = 23) were calculated.

3 SIMULATION

3.1 Choice of initial orientations

Considering the orthogonal symmetry of the rolling sample and the cubic symmetry of the crystals, the I subspace can represent all the orientations of the crystals, that is, the following Euler subspace is sufficient to describe the orientations distribution function of the rolling texture:

For φ_1 and φ_2: φ_1, $\varphi_2 \in [0, \frac{\pi}{2}]$;

For ϕ: $\phi \in [0, \arctan(1/\cos\varphi_2)]$, for $\varphi_2 \leqslant \frac{\pi}{4}$; $\phi \in [0, \arctan(1/\sin\varphi_2)]$, for $\varphi_2 \geqslant \frac{\pi}{4}$.

The subspace is divided into 1620 small spaces of which the central orientations g_i are their characteristic orientations and have proper weight factors. The scattering width ψ_i of the model components is assumed to be 7°. The divided orientations can approximately represent a randomly distributed texture.

3.2 Simulation method

3.2.1 Basic assumptions

(1) Slip is the only deformation mechanism, and the slip system {111}〈110〉 is assumed.

(2) All the critical resolved shear stresses on the slip systems are equal, and obey the isotropically hardening law.

(3) The slip within the grains is homogenous.

3.2.2 Simulation process

The following displacement gradient tensor in the external reference system is assumed for the simulation of the rolling texture

$$\boldsymbol{E} = \begin{bmatrix} \varepsilon & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\varepsilon \end{bmatrix} \quad (1)$$

Since the grains in the pure Al sample was rolled to lath shape gradually, the lath model has been developed, then the macroscopic displacement gradient tensor of the crystals should be

$$\boldsymbol{E}^c = \begin{bmatrix} \varepsilon & 0 & e_{13} \\ 0 & 0 & 0 \\ 0 & 0 & -\varepsilon \end{bmatrix} \quad (2)$$

The strain compatibility taken into account, the macroscopic displacement tensor of the crystals should be composed of the microscopic displacement gradient tensor due to the slip and the rotation of the crystals:

$$\boldsymbol{E}^c = \sum_s \boldsymbol{m}^s \gamma^s + \boldsymbol{R}^c \quad (3)$$

where $\boldsymbol{m}^s = \boldsymbol{b}^s \odot \boldsymbol{n}^s$, S are the activated system, γ^s is the shear amount due to slip, $\boldsymbol{R}^c$ is the crystal rotation tensor is respect to the specimen system, $\boldsymbol{b}^s$, $\boldsymbol{n}^s$ are the unit vectors of slip direction and slip plane with regard to the crystal system.

According to the Taylor[3] minimum shear principle:

$$W = \sum_s \tau_s |\gamma^s| = \min \quad (4)$$

Generally, in the case that the assumption 2 is satisfied, it can be found out that there would

be several groups of the slip system combinations that can fulfill the above relationships, then the ambiguity of the selection of the active slip systems will occur.

If the selection of the active slip systems is different, then the change of the crystal orientation is different too. So in the case that there is a multiplicity in the selection of active slip systems, another principle should be introduced. Here, the e_{13} minimum shear principle is suggested:

$$e_{13} = \min \tag{5}$$

That is, of all the groups of the slip system combinations that can satisfy the Taylor minimum shear principle, the one with the minimum e_{13} is affirmed. The above principle can solve the ambiguity problem of the selection of the active slip systems. It is obvious that although the shear deformation of crystallites is undetermined beforehand along the rolling direction, on one hand, the active slip systems can be determined according to the minimum shear principle of e_{13}, on the other hand, the strain compatibility can be satisfied to the maximum extent. While the equivalently macroscopic strain caused by the crystal deformation is minimum and the macroscopic displacement gradient tensor would be fulfilled as possible.

Once the active slip systems are determined according to the minimum shear principle of e_{13}, correspondingly, the rotation of the crystal (i e orientation change) can be calculated from the shear amounts on the corresponding slip systems. The deformation step was chosen as 0.01 in the simulations, the orientations of crystals after a large deformation were able to be predicted by means of a number of successive small deformation steps, then a series of non-randomly distributed crystal orientations were obtained (represented with the Euler angles). The ODFs were (with $l_{max} = 23$, including the odd and even terms) calculated, considering the orthogonal symmetry of the sample and the cubic symmetry of the crystals.

4 RESULTS AND DISCUSSION

The simulated and measured true ODFs are shown in Fig.1 and the skeleton line analysis of the simulated and measured textures is shown in Fig.2. In these figures, it can be seen that the calculated results show the main characteristics of the rolling textures in pure Al. In general, the rolling textures in FCC metals with high stacking fault energy are mainly accumulated around β fibre in orientation space, which principally consist of the positions $C\{112\}\langle 111\rangle$, $B\{110\}\langle 112\rangle$ and $S\{123\}\langle 634\rangle$. The application of the minimum shear principle of e_{13} can explain the C- and S-texture components well. In the case that the half width of Gauss components is 7° (close to the measured value), the simulated orientation density is very close to the measured. At the same time, though the

Fig.1 Experimental and simulated true ODFs (90 % reduction)
(a) —Experiment; (b) —Lath Model; (c) —FC Model

Fig.2 Skeleton line analysis of measured and simulated rolling textures
● —Experiment; ◆ —Lath model; ■ —FC model
(a) —Orientation density $f(g)$ along α-fibre; (b) —Orientation density $f(g)$ along γ fibre;
(c) —Orientation density $f(g)$ along β fibre; (d) —Corresponding β fibre orientations in Euler space

calculated results can demonstrate the accumulation of the crystals along β fibre, there are still some differences which display mainly in the definite orientation positions of the textures components. It can be seen clearly from the skeleton line analysis in Fig.2. First, by relaxing e_{13}, the position C can be obtained, whose Euler angles are $\{90°, 35°, 45°\}$. The single crystal rolling experiments where e_{13} was free (no constraints) showed the same results. However, in general, the measured are about $\{90°, 31°, 45°\}$ for polycrystals, i e, approximately around the position $\{225\}<554>$. Fig.2(d) shows clearly that the orientation positions of the measured β fibre lie between those of the calculation by the FC model and Lath model, in particular, in the

section of $\varphi_2 = 45°$, it can be seen that the measured positions are not located at the predicted by the RC model, but between the orientation D $\{90°, 27°, 45°\}$ (i e $\{4411\} <1\ 1\ 11\ 8>$) predicted by the FC model and $C\{90°, 35°, 45°\}$ (i e $\{112\} <111>$) predicted by the RC model. This shows that the shears of the crystallites along the rolling direction can not be realized completely as the assumption, because the interaction of adjacent grains hinders the crystals from deforming. However, it does not mean that the deformation is closer to the FC model. Fig.1 (c) shows the calculated results predicted by the FC model. It is clear that the simulated texture is much sharper under the condition of the full constrains than the measured. But the orientation density of the simulated texture by the RC model is much lower than that by the FC model, which is closer to the measured. This illustrates that the RC model adopted here is a better one. For an arbitrary orientation. It is found that the ambiguity extent of the selection of the active slip systems by the FC model (there are 4 ~ 12 groups of slip systems combinations generally) is much greater than that by the RC model (there are 1 ~ 6 groups usually). Therefore, using the modified RC (lath) model, the ambiguity problem of the slip systems selection can be solved validly, at the same time the active group of the slip systems can be determined quickly also, so the change of the crystal orientations can be calculated.

The main shortcoming of the modified model is that the grains are always considered as lath shape, which can not predict the formation and development of B texture very well. In these figures, it also can be seen that the simulated position of the B orientation $\{25°, 45°, 90°\}$ is different from the measured $\{30°, 45°, 90°\}$. In fact, on the Taylor model, by relaxing e_{12} and e_{13}, the B orientation with strong scattering around ND can be obtained, or the finally stable B orientation formed in rolling texture can be predicted by the Sachs model. However, both can not explain the formation and development of C- and S- texture components. So as to improve the simulation further, it is necessary to take into account stress equilibrium, strain compatibility, the shape changes of grains, the inhomogeneity of the macroscopic deformation and the microscopic grain deformation. It would be solved by FEM analysis method.

5 CONCLUSIONS

The effects of the grains with lath shape on deformation were taken into account while the rolling textures of pure Al were simulated. By the relaxation of e_{13} and the application of minimum shear principle of e_{13}, the ambiguity problem of the selection of the active slip systems can be solved effectively, while the strain compatibility was satisfied to the maximum extent. The results of computer simulation agree with the measured rolling textures of pure Al well.

REFERENCES

1 Hirsch J and Lücke K. Acta Metall, 1988, 36: 2883.
2 Sachs E. Z Ver dt Ing, 1928, 72: 734.
3 Taylor G I. J Inst Met, 1938, 62: 307.
4 Zhang X M and Li S Y. Bulletin of National Natural Science Foundation of China, (in Chinese), 1995, 9 (3): 26.
5 Kocks U F. Metall Trans, 1970, 1: 1121.
6 Mecking H. In: Btakaman *et al* eds. Proceedings of the 6th International Conference on Textures of Materials, Tokyo: Iron and Steel Institute of Japan, 1981: 53.
7 Van Houtte P. In: Btakaman *et al* eds. Proceedings of the 6th International Conference on Textures of Materials, Tokyo: Iron Steel Institute of Japan, 1981: 428.
8 Canova G R and Kocks U F. In: Nagashima S eds. Proceedings of the 7th International Conference on Textures of Materials, Noordwijkerhout, Netherlands Society of Materials Science, 1984: 573.
9 Asaro R J and Needleman A. Acta Metall, 1985, 33: 923.
10 Renouard M and Wintenberger. C R A S Serie B, 1981, 292: 385.
11 Kocks U F and Chandra H. Acta Metall, 1982, 30: 695.
12 Bacroix B *et al*. Acta Metall, 1986, 34: 937.
13 Bunge H J. Mathematische Methoden der Texturanalyse, Akademie - Verlag, Berlin, 1969.
14 Lücke K *et al*. Acta Metall, 1981, 29: 167.

(Edited by Huang Jinsong)