[Article ID] 1003- 6326(2001)02- 0231- 04

# Numerical simulation on microstructural evolution during multipass hot-rolling of aluminum alloys①

ZHANG Hui(张 辉), YANG Li-bin(杨立斌), PENG Da-shu(彭大暑), LIN Gao-yong(林高用)
(Department of Materials Science and Engineering,
Central South University, Changsha 410083, P. R. China)

**[Abstract]** Numerical simulation on microstructural evolution during multipass hot-rolling of aluminum alloys was performed by using DEFORM$^{TM}$ software and incorporating Zener-Hollomon parameter $Z$. The distributions of equivalent stress, equivalent strain, equivalent strain rate and temperature, as well as the distribution of recrystallization fraction through the thickness of deformed specimen during multipass hot-rolling of 5182 aluminum alloy, were all calculated. The results agree well with the metallographic examination of the deformed specimen on Gleeble 1500.

**[Key words]** 5182 aluminum alloy; multipass hot-rolling; microstructural evolution; FEM numerical simulation
**[CLC number]** TG335.11 **[Document code]** A

## 1 INTRODUCTION

In the past twenty years, great deals of quantitative relationships on microstructural evolution in hot-rolling and hot working have been established based on many experimental simulations, which provide essential mathematical model for numerical simulation on microstructural evolution. Finite element method (FEM) was widely used to simulate various physical varieties in metal forming, and today has become an acceptable valid tool for numerical simulation on microstructural evolution[1~7]. Chen et al[3,4] used the explicit dynamic relaxation method and coupled thermal analysis, as well as incorporated the quantitative relationships established by Sellars and Raghunathan et al to predicate the evolution of grain size in hot rolling of Al-5Mg and subgrain size during hot rolling of purity Al and compared with the experimental results done by Sheppard. Timothy et al[5] used two dimensional nonlinear FEM and coupled thermal stress analysis to simulate the microstructural evolution such as recrystallization fraction and grain size in single pass hot rolling of 5083 aluminum alloy and compared by plane strain compression tests. University of Leicester[6] has developed the LEFFR software to simulate the microstructural evolution during industrial thermo-mechanical processing of aluminum alloys and other metals. The physical and numerical simulation on evolution of microstructure and texture during hot rolling of aluminum alloys and prediction to three pass tandem mill as well have been successfully studied by Wells[7].

Design environment for forming DEFORM software is a general FEM software, which is widely used in the analysis of metal-forming. Kim et al[8] used DEFORM to predict the hardness distribution in cold backward extruded cups. Shen et al[9] used DEFORM to investigate the flow stress and microstructure development in non-isothermal forging of Ti-6242. Zhe et al[10] used DEFORM-2D to predict the grain size in hot forging of vanadium microalloyed steels.

In this paper, numerical simulation on microstructural evolution during multipass hot-rolling of aluminum alloys has been developed by using DEFORM$^{TM}$ software. The distribution of recrystallization through the thickness of deformed specimens during multipass hot-rolling of 5182 aluminum alloy was calculated and compared with the metallographic examination of the deformed specimens on Gleeble 1500.

## 2 COUPLED THERMAL-STRESS-MICROSTRUCTURAL EVOLUTION

### 2.1 Pre-processing

For users, the pre-processing includes inputting boundary conditions, creating geometry models and generating mesh. The automatic mesh generation system was used to generate mesh, check mesh distortion, remesh and transfer from the old mesh to the new one in the simulation of multipass hot-rolling, only the temperature change was considered during the holding period between passes.

The flow stress model was inputted on user defined flow stress routines according to the following expression[11]:

① **[Foundation item]** Project supported by Funds of Alumax Inc, USA
**[Received date]** 2000- 06- 16; **[Accepted date]** 2000- 09- 20

$$Z = \dot{\varepsilon}\exp\left[\frac{Q_{def}}{RT}\right] = A\exp(\beta\sigma) \qquad (1)$$

$$\ln A = 22.56614 - 1.68982\exp\left[\frac{(\varepsilon - 0.07503)^2}{0.11177}\right]$$

$$\beta = 0.08578 + 0.02826\exp\left[\frac{-\varepsilon}{0.04579}\right]$$

where $Z$ is Zener-Hollomon parameter, $T$ is deformation temperature, $R$ is gas constant, $Q_{def}$ is hot deformation activation energy giving a value of 174200 J/mol$^{-1}$ for 5182 aluminum alloy.

Constant shear friction between anvils and specimen was considered and the friction factor $m = 0.3$ was assumed in the analysis, the hot-rolling process parameters which included pass strain, strain rate, temperature and interpass time and other simulation controls were inputted manually on the DEFORM keyboards.

### 2.2 Post-processing

The DEFORM post-processing was used to view and extract data from the simulation results in the database. The equivalent stress, equivalent strain, equivalent strain rate and temperature at each step in deformation were viewed and stored in the database, then the variables relating to the microstructural evolution such as Zener-Hollomon parameter $Z$, the time for 50% recrystallization $t_{0.5}$ and recrystallization fraction $X$ described in Eqn. (2)[12] were defined on user defined routines:

$$X = 1 - \exp\left[-0.693\left[\frac{t_p}{t_{0.5}}\right]\right] \qquad (2)$$

$$t_{0.5} = 7.772 \times Z^{-1.267}\left[\frac{230000}{RT_p}\right]$$

where $t_p$ and $T_p$ are interpass time and holding temperature between passes respectively.

Here, two problems must be noticed. One is the treatment to strain rate after deformation, because only the temperature changes during the holding period between passes. The other is overflow in calculation of $t_{0.5}$ using Eqn. (2) because strain rate $\dot{\varepsilon} = 0$ in undeformed zones. In the study, it was assumed that $Z = 0$, $t_{0.5} = 0$ and $X = 0$ as $Z \leqslant 10^{-5}\,s^{-1}$.

### 2.3 Numerical simulation on microstructural evolution during hot-rolling

In general, there are three typical microstructures during multipass hot-rolling of aluminum alloys: as $X_i \leqslant 0.05$, a full recovered substructure; $X_i \geqslant 0.95$, a full recrystallization; and $0.05 < X_i < 0.95$, a partial recrystallization.

Numerical simulation on microstructural evolution during multipass hot-rolling of 5182 aluminum alloy has been performed by dividing multipass into a series of non-isothermal hot deformation and sequent non-isothermal annealing processes. The distributions of equivalent stress, equivalent strain, equivalent strain rate and temperature across the thickness of the specimens during hot deformation were calculated by using DEFORM-2D rigid plastic coupled thermal stress FEM analyses software. By using these results and by incorporating Zener-Hollomon parameter $Z$, the distribution of recrystallization fraction through the thickness of deformed specimens during multipass hot-rolling of 5182 aluminum alloy is calculated.

The material parameters of 5182 aluminum alloy employed in calculation include density $\rho = 2660\,kg/m^3$, thermal conductivity coefficient $k = 123\,W/mK$, specific heat $c = 904\,J/(kg\cdot K)$.

## 3 RESULTS AND DISCUSSION

The multipass hot-rolling of 5182 aluminum alloy was considered as a simple plane strain. The length of the anvils is shorter than the specimen to deep the contact length of the anvils and specimen constant during deformation. The ratio of length to width is 5. The FE (finite element) mesh generated by the automatic mesh generation system of DEFORM uses 4-nodes quadrilateral element for specimen and anvil at start of deformation, its total number of codes is 2102, the total number of elements 2013, the time increment per step 0.01 s.

Numerical simulation on microstructural evolution during multipass hot-rolling of 5182 aluminum alloy has been performed according to the typical hot-rolling schedule given by Alumax. The distributions of equivalent stress, equivalent strain and equivalent strain rate in the deformed specimen after 12th pass whose process variables are shown in Table 1, are demonstrated in Fig. 1 showing inhomogeneity through thickness of the deformed specimen.

Deformation is inhomogeneous as frictional effects between the anvil and specimen, as well as geometry shape factor $l/\bar{h}$ is the contact length of the anvil and specimen ($\bar{h}$ is the average height of the deformed specimen). The resulting gradient in equivalent strain and equivalent strain rate from the centre to the surface of the specimen decreases in the pass.

The temperature of deformation is another important parameter that affects the kinetics of recrystallization. The temperature distribution in the deformed specimen is shown in Fig. 1(d). There is a significant temperature difference of about 12 ℃ between the surface (455.19 ℃) and the centre (467.14 ℃) of the deformed specimen in the deformation zone owing to the effects of plastic deformation heat. This implies that it is necessary for industrial hot-rolling to consider the effects of plastic deformation heating.

The effect of temperature of deformation on the kinetics of recrystallization was included in the Zener-Hollomon parameter, which was determined from knowledge of the distributions of strain rate (see Fig. 1(c)) and temperature (see Fig. 1(d)). The distribution of $Z$ in the deformed specimen is shown in Fig. 2(a), varies from $Z = 0$ in undeformed zone to $Z = 2.4883 \times 10^{13}\ s^{-1}$ at centre of the deformed specimen which is found to be in reasonable agreement with the mean value of Zener-Hollomon parameter $Z$ ($9.15 \times 10^{12}\ s^{-1}$).

However, during the pass the strain rate rises rapidly to a maximum at the centre and falls to zero in undeformed zone, whereas the temperature in the centre tends to be increased by deformational heating. Thus there would be a decrease from $Z$ in the centre to zero in undeformed zone. The conditions for recrystallization ($t_{0.5}$ in Eqn. (2)) will be reached first in the centre, leading to an $X$-shape distribution (Fig. 2(b)), found to be in reasonable agreement with the mean value of recrystallization fraction $\bar{X} = 68.8\%$. Experiments show that the polarized optical microstructure fraction after 12th pass is very closed to the simulation results.

## 4 CONCLUSIONS

Numerical simulation on microstructural evolution during multipass hot-rolling of 5182 aluminum alloy has been performed by dividing multipass into a series of non-isothermal hot deformations and sequent non-isothermal annealing processes. The distributions of equivalent stress, equivalent strain, equivalent strain rate and temperature across the thickness of the specimen during hot deformation were calculated by using DEFORM™ software. By using these results and by incorporating Zener-Hollomon parameter $Z$, the distribution of recrystallization through the thickness of deformed specimens during multipass hot-

**Table 1** Process variables in 12th pass

| Starting temperature / ℃ | Finishing temperature / ℃ | Reduction / % | Strain | Strain rate / $s^{-1}$ | Holding time / s |
|---|---|---|---|---|---|
| 459 | 450 | 21.8 | 0.246 | 3.39 | 22 |

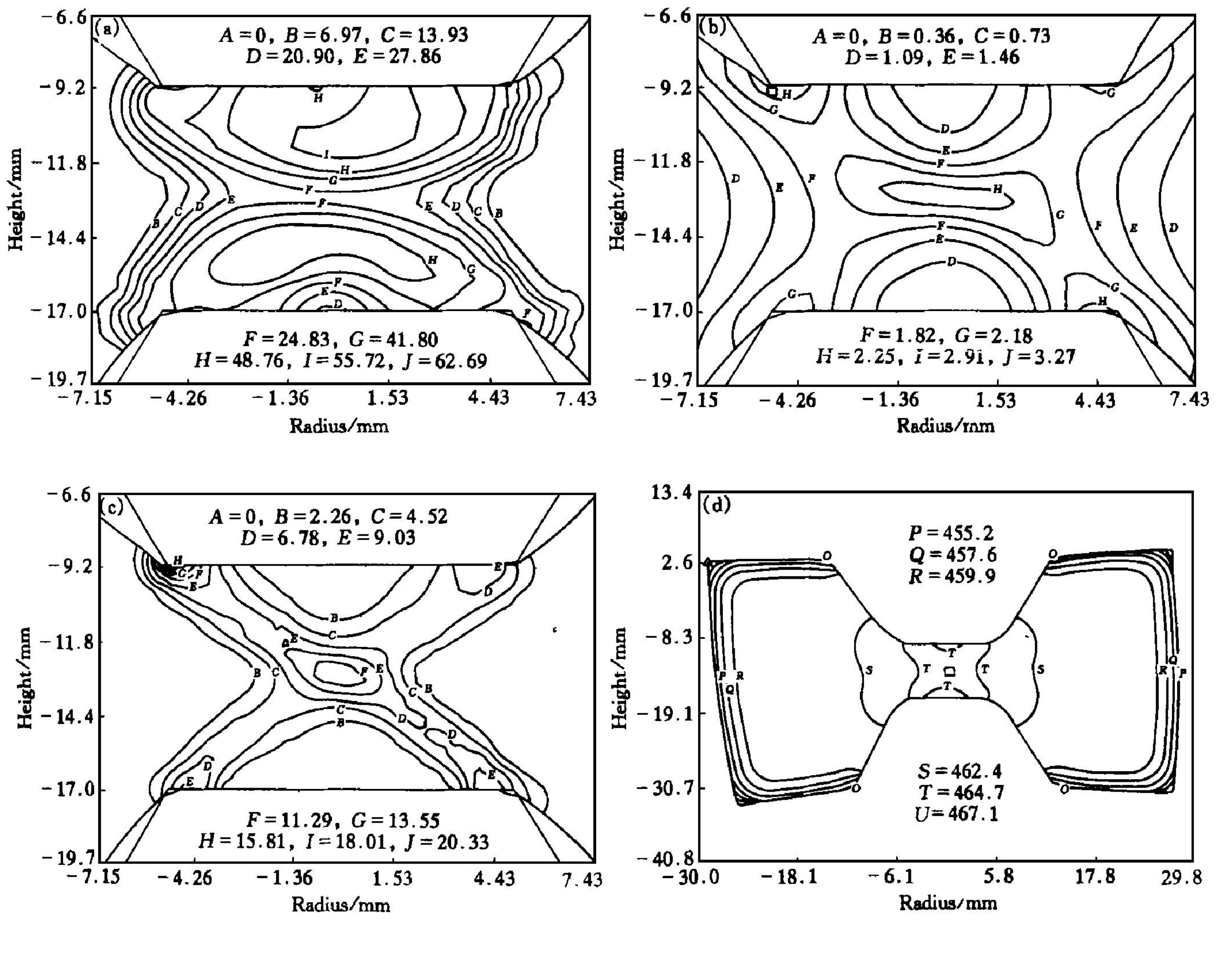


**Fig. 1** Distributions of deformation parameters in deformed specimen after 12th pass

(a) —Equivalent stress; (b) —Equivalent strain; (c) —Equivalent strain rate; (d) —Temperature rolling of 5182 aluminum alloy has been calculated, and the results agree well with the metallographic observation of the deformed specimens on Gleeble 1500.

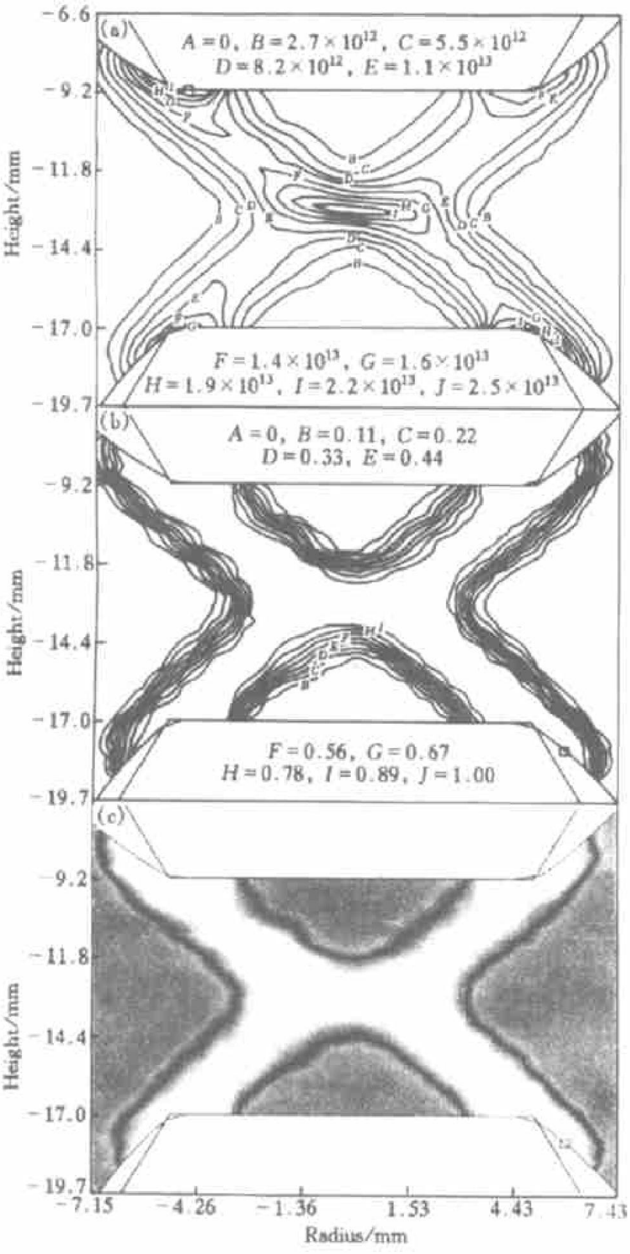


**Fig. 2** Distributions of recrystallization fraction after 12th pass

(a) —Zener-Hollomon parameter $Z$;
(b) —Contour display of recrystallization fraction;
(c) —Coloured display of recrystallization fraction

## [REFERENCES]


[1] Colas R. Computer modelling as a tool for visualizing microstructure evolution during the rolling of process [J]. J Mater Processing Technol, 1994, 45: 485- 490.

[2] McQueen H J. Metal forming: industrial, mechanical, computational and microstructural [J]. J Mater Processing Technol, 1993, 37: 3- 36.

[3] Chen B K, Thomson P F and Choi S K. Computer modelling of microstructure during hot flat rolling of aluminum [J]. Mater Sci Technol, 1992, 8(11): 72- 77.

[4] Chen B K, Choi S K and Thomson P F. Simulation of evolution of microstructure in a thermo-mechanical analysis of the hot rolling of aluminum [J]. Res Mechanics, 1991, 31: 455- 469.

[5] Timothy S P, Yiu H L, Fine J M, et al. Simulation of single pass of hot rolling deformation of aluminium alloy by plane strain compression [J]. Mater Sci Technol, 1991, 7(3): 255- 261.

[6] Puchi E S, Beynon J and Sellars C M. Simulation of hot rolling operations on commercial aluminum alloys [A]. Physical Metallurgy of Thermo-Mechanical Processing of Steels and Other Metals [C]. Tokyo: Iron and Steel Institute Japan, 1988. 572- 579.

[7] Wells M A, Lloyed D J, Samarasekera I V, et al. Modelling the microstructural changes during hot tandem rolling of AA5××× aluminum alloys: Part III. Overall model development and validation [J]. Metallurgical and Materials Transactions B, 1998, 29B(6): 709- 719.

[8] Kim H, Lee S M and Altan T. Prediction of hardness distribution in cold backward extruded cups [J]. J Mater Processing Technol, 1996, 59: 113- 120.

[9] Shen G, Semiatin S L and Altan T. Investigation of flow stress and microstructure development in non-isothermal forging of Ti-6242 [J]. J Mater Processing Technol, 1993, 36: 303- 319.

[10] Zhe W, Tingquan L, Akira K, et al. Grain size prediction in hot forging of vanadium microalloyed steels, Journal of the JSTP, (in Japanese), 1999, 40(5): 88- 92.

[11] ZHANG Hui, PENG Da-shu, YANG Li-bin, et al. Flow stress for multipass hot-rolling aluminum alloys [J]. J Cent South Univ Technol, (in Chinese), 2001, 32 (to be published).

[12] ZHANG Hui, PENG Da-shu, YANG Li-bin, et al. Recrystallization model for hot-rolling of 5182 aluminum alloy [J]. Trans Nonferrous Met Soc China, 2001, 11 (to be published).


**(Edited by LONG Huai-zhong)**