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The coupling thermal–mechanical and microstructural model for the FEM simulation of cross wedge rolling

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Abstract

The microstructural evolution models on AISI 5140 were obtained using the Gleeble-3500 thermo-mechanical simulator. Simulation on the cross wedge rolling (CWR) process has been carried out on the platform of finite element software DEFROM-3D with thermo-mechanic and microstructural evolution coupled. And distributions of the different field-variables during the whole rolling process from the knifing, guiding, stretching to sizing stage, such as effective strain, effective strain rate and temperature, were obtained. Meanwhile, three-dimensional (3D) distribution of austenite grain size of workpiece was also achieved. It is significant to understand the net-shaped mechanism and optimize CWR technology.

Keywords: CWR; Finite element method (FEM); Microstructural evolution; Grain size

1. Introduction

The CWR technique is a typical rotary forming method, whose many integrated virtues came from both forging process and metallurgical rolling technology. Owing to single continuous local large deformation for workpiece, CWR has high productivity. However, just this deformation style also leads to some product defects [1,2] and some engineering problems, such as necking, surface spiral and inner porous void and cracks, etc. So, it is helpful for CWR technique development to understand the relationships among rolling forces, deformation and inner microstructure evolution. Though many researchers made great efforts on above problems [3–11] and microstructural evolution simulations for other forming processes have been made [12,13], few literatures on two-roll CWR were reported.

Based on the software DEFROM-3D, a simulation model for the CWR process has been developed by means of 3D rigid-viscoplastic FEM in this study. In this model, many factors including thermal, mechanical and microstructural evolution are taken into account comprehensively. The microstructural evolution models on AISI 5140 were obtained using the Gleeble-3500 thermo-mechanical simulator. And distributions of the different field-variables were obtained after simulation. These results are useful to understand the net-shape mechanism and optimize CWR technology.

2. FEM and microstructure models of CWR

The CWR refers to a metal forming process in which a cylindrical billet is plastically deformed into another axisymmetrical shape by the action of wedge shape tools moving tangentially relative to each other [9]. The rounded bars are prolonged freely in the axis direction, and at the same time its cross-section area is reduced during the forming process.

FEM software DEFORM developed by Battel Columbus lab in the United States was used to establish simulation model for the CWR process. Based on rigid-viscoplastic finite element theory, a CWR model with thermo, mechanics and microstructure coupled has been developed and solved successfully. The technique of automatic remeshing in DEFORM can relieve mesh singularity during the finite element simulation process.

2.1. FEM model

The reliability of the whole simulation results is directly influenced by the accuracy of FEM model developed. And the

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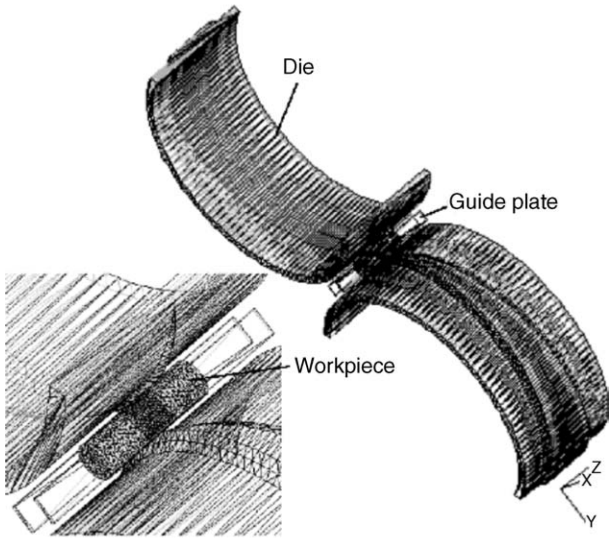

Fig. 1. CWR FEM model.

geometry precision of final product depends mainly on tools design. CWR tools are characterized by multi-segment structure and 3D higher-order surface, which make it difficult to construct solid model. In this paper, tools solid model based on features has been set up with the aid of general CAD software Pro-E. Considering high temperature deformation, a part was defined as plastic body. To decrease computer CPU time, tools were defined as rigid body. FEM model of CWR is shown in Fig. 1.

The main calculation conditions are as follows: workpiece diameter (d_0), 22 mm; workpiece length (b), 35 mm; roll diameter (D), 500 mm; rotational speed of roll (ω), 10 rpm; workpiece initial temperature (T_0), 1000 °C; surface emissivity (ξ), 0.7; area reduction (ΔA), 40%; forming angle (α), 28°; spreading angle (β), 6°; stepped tilt angle (θ), 45°.

2.2. Microstructrual evolution model

Physical simulation on AISI 5140 was carried out using the Gleeble-3500 thermo-mechanical simulator. The chemical compositions of the material tested in weight percent are described in detail in Table 1.

Based on the results from thermo-simulation experiments, dynamic recrystallization of medium carbon steel AISI 5140 for CWR process occurs under the deformation temperature from 1100 to 900 °C and strain rate 10.0–0.1 s^{-1}. The activation energy of dynamic recrystallization, which is corresponding with the peak stress, is 370.6 kJ/mol. The relationship between peak stress σ_p or peak strain ε_p and factor Z is expressed as:

$$\sigma_p = 2.626 \times 10^{-9} Z^{-6.08} \quad (1)$$

Table 1
Chemical compositions of the sample (wt.%)

	Elements					
	C	Si	Mn	P	S	Cr
Content	0.41	0.28	0.62	0.018	0.02	0.88

$$\varepsilon_p = 5.162 \times 10^{-3} Z^{0.128} \quad (2)$$

where Z is Zener Holloman parameter as follows.

$$Z = \dot{\varepsilon} \exp\left(\frac{Q_1}{RT}\right) \quad (3)$$

The exponential relational expression between dynamic recrystallization grain size d and Z is written as:

$$d = 25004.8 Z^{-0.211} \quad (4)$$

The model for recrystallization kinetics is obtained by observing the quenching microstructure of the deformed samples of AISI 5140 under the different temperature, strain and strain rate:

$$X_v = 1 - \exp[-20.691(\varepsilon - \varepsilon_0)^{3.492}] \quad (5)$$

3. Results and discussion

FEM simulation application on the CWR process can provide effective foundations for analysis on part forming process and determination of proper parameters of tool design, as well as distribution of some field-variables such as stresses, strains and temperature, etc., in the rolled part. In recent years, in accompaniment with the development of rolling theory and computer technique, the research on metal plastic process has expended into the microscopic field, for example, the simulation of austenite recrystallization and grain size distribution during the hot deformation process, even prediction on mechanical property of final products [14–16].

3.1. Strain distribution

It is a very complicated process for CWR forming. Radial reduction and axial spread of a rolled part, namely multi-axis and continuous large deformation during the rolling can be realized by CWR tool geometry feature. Nevertheless, this deformation style also increases simulation difficulty.

According to simulation results, the strain begins with contact surface between tools and workpiece and then is increasing gradually and expending to center at the knifing stage. The equivalent strain distribution of symmetrical cross-section can be seen in Fig. 2.

To be different from the strain of knifing stage, the axial strain is dominant among metal multi-directional deformations at the spreading stage. Following with the rotary rolls, surface metal is extruded spirally to the end of the rolled part, on which larger equivalent strain occurs just as shown in Fig. 3.

Due to the multi-axis deformation manner, the equivalent strain values of the CWR process are always very larger than other process only with simple deformation. The larger deformation benefits to reach the critical strain activating dynamic recrystallzation, namely easily causing dynamic recrystallization during the CWR process.

To understand the deformation mechanism from surface to center of rolled part, three points equably distributing from center to surface in cross-section away from symmetry center