Journal of University of Science and Technology Beijing
Volume 11, Number 4, August 2004, Page 343

Materials

3-D thermo-mechanical coupled FEM simulation of continuous hot rolling process of 60SiMnA spring steel bars and rods

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(Received 2003-08-12)

Abstract: The 3-D thermo-mechanical coupled elasto-plastic finite element method (FEM) was used for the simulation of the two-pass continuous hot rolling process of 60SiMnA spring steel bars and rods using MARC/AutoForge3.1 software. The simulated results visualize the metal flow and the dynamic evolutions of the strain, stress and temperature during the continuous hot rolling, especially inside the work-piece. It is shown that the non-uniform distributions of the strain, stress and temperature on the longitudinal and transverse sections are a distinct characteristic of the continuous hot rolling, which can be used as basic data for improving the tool design, predicting and controlling the micro-structural evolution of a bar and rod.

Key words: 60Si2MnA spring steel; bar; rod; elasto-plastic FEM; thermo-mechanical coupled; metal flow

1 Introduction

Round/oval roll-profiles are often alternately laid along a continuous hot rolling assembly line of a bar and rod. The continuous hot rolling of a bar or rod is a complex deformation process, which is influenced by the materials properties, deformation temperature and rate, strain, contact and friction condition, billet shape and size, roll-profile and others, so it is very difficult to find its analytical solution. Recently, with the improvement of FEM (finite element method) and the development of computer technology, numerical simulation technology based on FEM is increasingly becoming a powerful tool to analyze the continuous hot rolling process [1-6].

Actually, the continuous hot rolling of a bar or rod is a non-isothermal steady-state coupled with non-steady-state three-dimensional thermo-mechanical process. While numerically simulating the above process, it is necessary to conduct a coupled analysis, giving a consideration to the contact heat transfer between the work-piece and roll, convection and radiation between the work-piece and environment, and the heat generation due to plastic work and friction force. This study aims to get the metal flow and distributions of the strain, stress and temperature on some special sections such as longitudinal and transverse sections under some continuous hot rolling process conditions.

2 Experimental details

In order to get the flow stress of 60Si2MnA spring steel, the experimental material was taken from the same part of a square billet of 150 mm × 150 mm, and then manufactured into dozens of specimens with a diameter of 8 mm and a height of 12 mm. The chemical composition (mass fraction in %) of the experimental material is C, 0.57; Mn, 0.76; Si, 1.79; S, 0.005; P, 0.012; Cr, 0.10; and Ni, 0.08.

The hot upsetting experiments with the maximum true strain of 0.7 under various process parameters were conducted on a THERMECMASTOR-Z tester, and their flow stress curves were written down. The flow stresses at the large true strain from 0.7 to 1 can be extrapolated based on the experiment values. The whole flow stress curves are shown in **figure 1**.

3 FEM model

Figure 2 shows a 3-D elasto-plastic FEM model for two-pass continuous hot rolling. The diameters of No.1 and No.2 rolls are all 330 mm. The profile of No.1 roll is an oval one with the major axis of 65 mm and the minor axis of 32 mm; the profile of No.2 roll is a round one whose diameter is 32 mm. In order to

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shorten the computing time, the distance between No.1 and No.2 rolls along the rolling direction (–Z direction) was just set to 220 mm. The work-piece is a bar whose initial diameter and length are 42.5 and 280 mm, respectively. The compression ratio and the rolling speed of the first pass are 25.0% and 1.8 m/s, respectively, and those of the second pass are 40% and 3.5 m/s, respectively. Here, the compression ratio is the average compression ratio along the minor axis of the oval profile of No.1 roll, or that along the major axis of the work-piece deformed by No.1 roll. Due to its symmetry, just 1/4 of the work-piece was taken as the simulation object so as to shorten the computing time further.

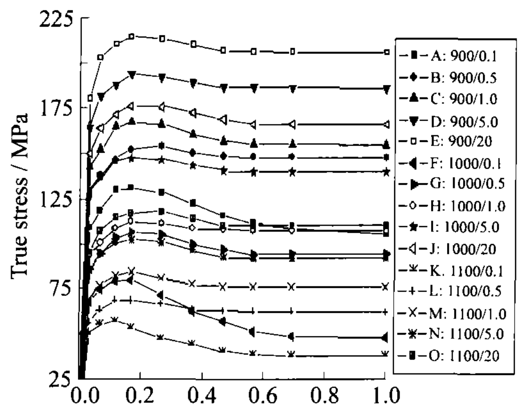


Figure 1 Flow stress (the ratio is the deformation temperature to the strain rate).

Eight-node hexahedral element type was taken and 1040 elements and 1476 nodes were obtained. The work-piece was assumed to be elasto-plastic and described by the updated Lagrange method, *i.e.*, it obeyed the Mises yield criterion and Prandtl-Reuss flow rule, and its deformation was simulated in a step-by-step manner, updating the coordinates of the material points and the property after each step. The rolls were assumed to be rigid and of heat-transfer, and they were analytically described.

On the two symmetrical planes, the displacements of all nodes perpendicular to their corresponding symmetrical planes are zero. The friction between the work-piece and roll is subject to the law of shear, and their friction coefficient was set to 0.7. The equivalent heat transfer coefficient between the free surface of the work-piece and the ambience was set to 0.17 kW/(m^2·°C). The contact heat transfer co-efficient between the work-piece and the roll was set to 20 kW/(m^2·°C). The initial temperature of the work-piece was set to 1050°C, and the ambient and roll temperatures 20 and 200°C, respectively. The conversion factor from plastic work to heat was set to 0.9 [8-11].

There is no data about 60Si2MnA spring steel in the database of AutoForge3.1 software, so its database should be set up. The thermo-physical parameters including the heat conductivity, specific heat capacity and thermal expanding coefficient at different temperatures were directly input on the software windows, and the thermo-physical parameters at high temperature can be extrapolated based on **table 1** [12]. The flow stress curves shown in figure 1 were inserted into the software. These curves constitute a multi-dimensional database, and the flow stress under some process condition can be obtained using the interpolation method, thus the error resulting from fitting the flow stress curves into the formulae can be avoided. The material mass density is 7.74×10^3 kg/m^3.

Table 1 Thermo-physical property parameters of 60Si2MnA spring steel

Temperature / °C	Young's modulus / GPa	Poisson's ratio	Conductivity / (W·m^{-1}·K^{-1})	Specific heat capacity / (J·kg^{-1}·K^{-1})	Thermal expanding coefficient / (10^{-6}/ K^{-1})
20	206	0.290	—	—	—
100	204	0.288	—	460	12.6
200	199	0.295	29.3	527	13.3
300	191	0.306	30.1	544	13.6
400	183	0.309	31.0	599	13.5
500	176	0.307	30.1	641	11.8
600	—	—	28.9	—	11.1
700	—	—	27.6	—	12.4

4 Simulation results and discussion

4.1 Metal flow and equivalent strain evolution on the work-piece surface

Figure 3 shows the metal flow and equivalent strain evolution on the work-piece surface during continuous hot rolling. From this figure, it can be seen that at increment 50, No.1 roll already bit the work-piece, and the rolling was still in a non-steady state; at increment 150, No.1 roll already rolled the work-piece steadily; at increment 200, the rolling for No.1 roll was still in a steady state, and No.2 roll began to bite the work-piece; at increment 260, No.1 roll approached the end of the work-piece, which was a non-steady-state rolling, but the rolling for No.2 roll was already in a steady state. Obviously, at increment 260, the total equivalent plastic strain at No.2 roll is generally greater than that at No.1 roll.

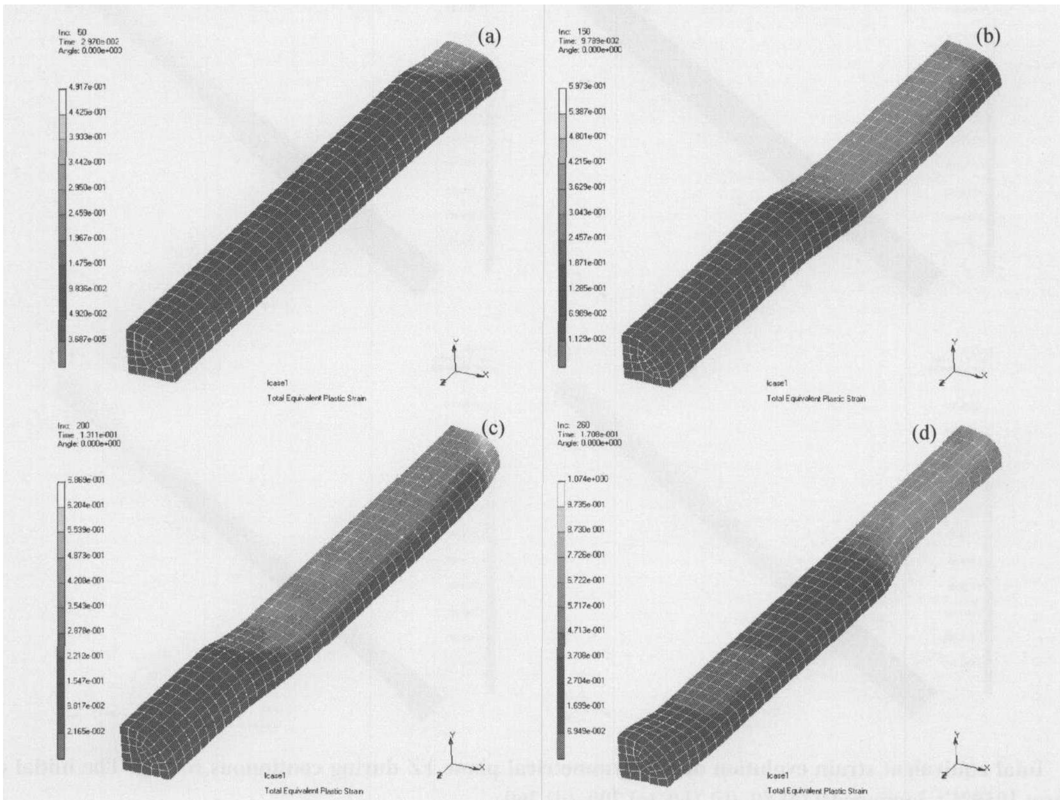


Figure 3 Metal flow and equivalent strain evolution on the work-piece surface during continuous rolling. The initial deformation temperature: 1050°C; increment: (a) 50, (b) 150, (c) 200, (d) 260.

4.2 Evolutions of the equivalent strain and temperature on the longitudinal symmetrical plane during the continuous rolling

The total equivalent strain evolution on the longitudinal symmetrical plane *YZ* is shown in **figure 4**. On the symmetrical plane *YZ*, its maximum total equivalent strain is about 0.6 after the rolling for No.1 roll is steady, and it approaches 1.1 after the rolling for No.2 roll is in a steady state.

The temperature evolution on the longitudinal symmetrical plane *YZ* is shown in **figure 5**. On the symmetrical plane *YZ*, its highest temperature is 1173°C after the rolling for No.1 roll is steady. Due to the heat generation as a result of the two-pass plastic deformation work and the friction force, its local highest temperature is 1223°C after the rolling for No.2 roll is in a steady state.

The distributions of the displacement, friction force, equivalent stress and various components of strain and stress on special sections at different rolling stages can also be presented.

4.3 Distributions of the equivalent strain, equivalent stress and temperature on typical cross sections

At increment 150, the rolling for No.1 roll is in a steady state, and **figure 6** shows the distributions of the total equivalent strain, equivalent stress and temperature on the cross section of the work-piece *via* the axis of No.1 roll. From this figure, it can be seen that they are very non-uniform, and their ranges are 0.011-0.597, 14.4-176.9 MPa and 1022-1173°C, respectively. Their non-uniform distributions attribute to their interaction. On the one hand, the distribution of the strain or the strain rate on the cross section is itself non-uniform, thus resulting in the non-uniform stress distribution, and non-uniform temperature distribution appears as a result of the plastic work and heat transfer; on the other hand, the non-uniform stress and temperature distributions have effect on the distributions of the strain and the strain rate.

At increment 260, the rolling for No.2 roll is already steady, and the distributions of the total equivalent strain, equivalent stress and temperature on the cross section of the work-piece *via* the axis of No.2 roll are shown in **figure 7**. It shows that they are also very non-uniform, and their ranges are 0.07–1.07, 7.68–174.0 MPa and 1019–1223°C, respectively.

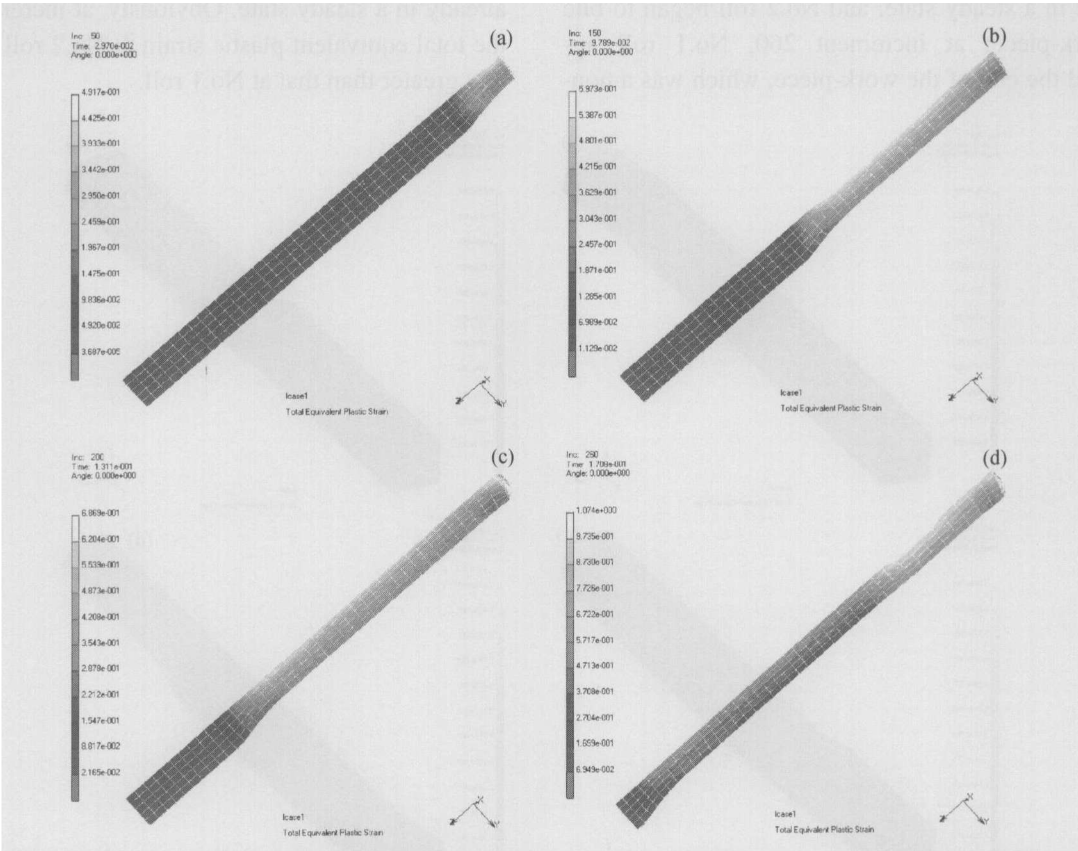


Figure 4 Total equivalent strain evolution on the symmetrical plane *YZ* during continuous rolling. The initial deformation temperature: 1050°C; increment: (a) 50, (b) 150, (c) 200, (d) 260.

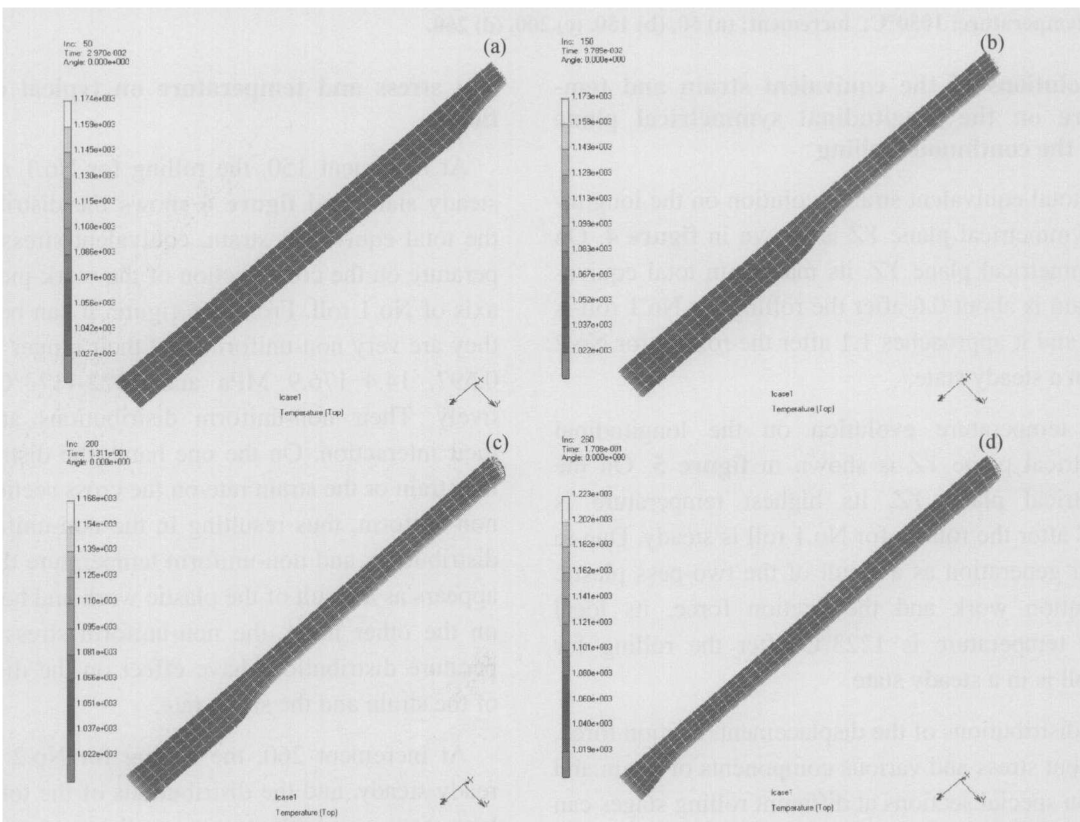
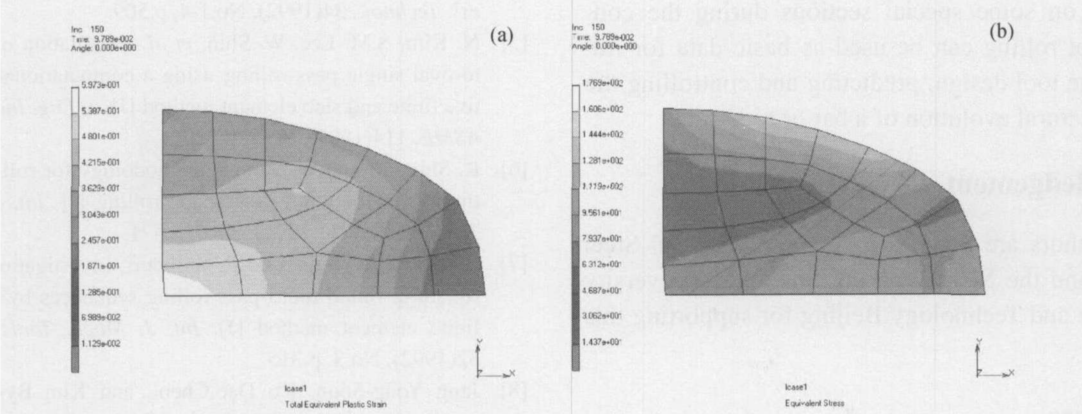


Figure 5 Temperature evolution on the symmetrical plane *YZ* during continuous rolling. The initial deformation temperature: 1050°C; increment: (a) 50, (b) 150, (c) 200, (d) 260.



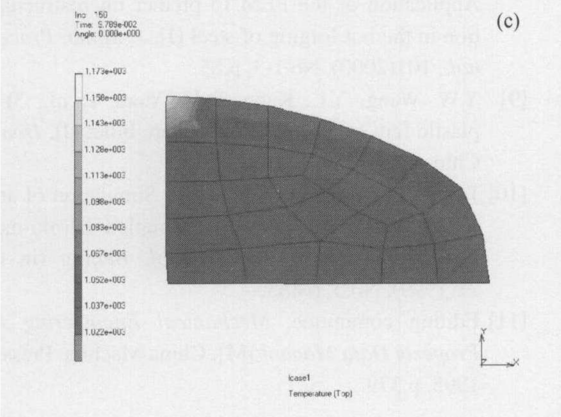
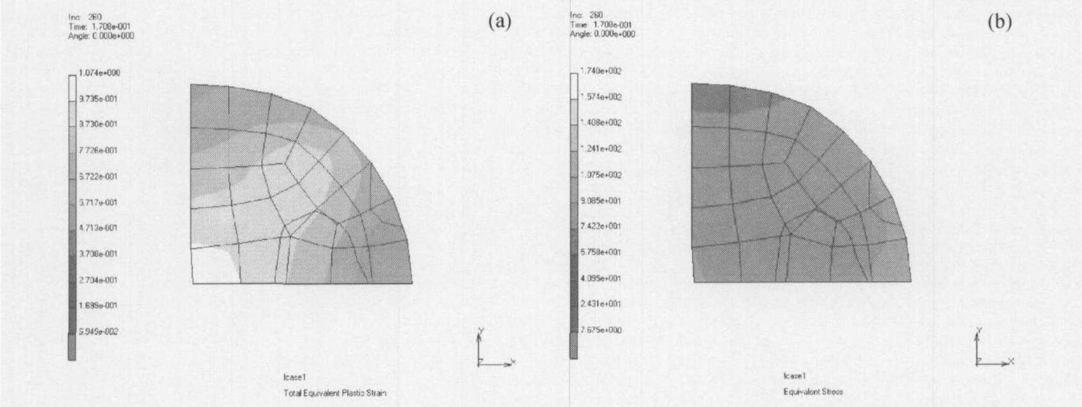


Figure 6 Distributions of the equivalent strain, equivalent stress and temperature on the cross section of the work-piece *via* the axis of No.1 roll. The initial deformation temperature: 1050°C; increment: 150. (a) total equivalent strain; (b) equivalent stress; (c) temperature.



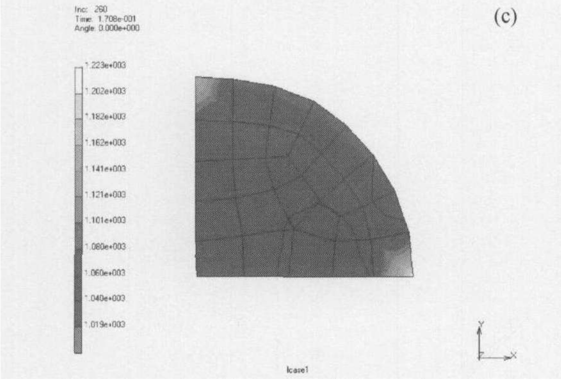


Figure 7 Distributions of the equivalent strain, equivalent stress and temperature on the cross section of the work-piece *via* the axis of No.2 roll. The initial deformation temperature: 1050°C; increment: 260. (a) total equivalent strain; (b) equivalent stress; (c) temperature.

5 Conclusions

(1) FEM simulation coupled with physical simulation vividly visualizes the metal flow and the dynamic evolutions of strain, stress and temperature during the continuous hot rolling of a 60Si2MnA spring steel bar or rod, especially inside the work-piece. The simulated results show that the non-uniform distributions of the strain, stress and temperature on the longitudinal and transverse sections are a distinct characteristic of the continuous hot rolling.

(2) The prediction of the metal flow, the evolutions of the strain, stress and temperature, and their dis-

tributions on some special sections during the continuous hot rolling can be used as basic data for improving the tool design, predicting and controlling the micro-structural evolution of a bar or rod.

Acknowledgement

The authors are grateful to Liaoning Special Steel Co. Ltd. and the Marc Working Station at University of Science and Technology Beijing for supporting this study.

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