Flow Behavior of AISI 5140 Steel in Temperature Range of Warm-Hot Forging

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Abstract
In this paper, the influence of flow stress models on FEM simulation results is discussed; the flow stress of AISI 5140 steel at different T, ε and $\dot{\varepsilon}$ in the temperature of warm-hot forging is measured by a uniaxial compression experiment with a thermomechannical simulator. The experimental results show that flow stress is very complex within the temperature range of warm-hot forging; and the traditional interpolation method adopted in FEM simulation on the basis of cold or hot flow stress models is not scientific. To improve FEM simulation precision, a flow stress mathematic model should be calibrated by experiment. Finally, the calibrated flow stress model of AISI 5140 steel is applied in the FEM simulation of the warm-hot forging process of the splined shaft of an automobile. Comparison between the results of FEM simulation and the warm-hot forging experiment indicates that the flow stress model calibrated by experiment is scientific and effective.

Key words: WARM-HOT FORGING, FLOW STRESS, FEM SIMULATION, MATHEMATIC MODEL

1. Introduction

Warm-hot forging is a new kind of precision forming process for manufacturing complex high-quality components and is presently used widely in precision forging of the automobile industry [1-3]. The process combines the precision of cold forging with the low yield stress and high forming capacity of hot-forging, and it also avoids the disadvantages of cold and hot forging. Usually the warm-hot forging temperature of steel is above and near to the recrystallization temperature. In this study, the temperature scope of warm-hot forging is 1073-1273K.

At warm-hot forging temperature, metal

flow stress is critical to process planning, die designing, selecting of die material and press capacity. In FEM simulation, the model of the flow stress determines the precision of the simulated result in a large degree. Although warm-hot forging has been used widely for its precision and efficiency in the automobile industry, the mechanism of this process has not been studied intensively. Flow stress and its FEM model within the warm-hot forging temperature range have not yet been investigated systematically.

Considerable work has been done to understand the flow behavior of austenite in carbon steels [4-6]. These research results show that the flow stress, at any time during hot working, can be seen as a function of the deformation parameters: temperature (T) , strain (ε) and strain rate ($\dot{\varepsilon}$).

In this paper, axisymmetric compression tests were carried out on AISI 5140 steel to investigate its flow behavior within the temperature range of warm-hot forging. The flow stress of AISI 5140 steel at different temperature (T), strain (ε) and strain rate ($\dot{\varepsilon}$) within the warm-hot forging temperature range is determined, then a flow stress mathematic model of AISI 5140 steel is set up and applied in an FEM simulation of the warm-hot forging process of automobile splined shaft.

2. Experimental method

2.1 The principle of the experimental method

There are three methods usually used for the determination of material flow stress, e.g., tension tests, torsion tests and compression tests. Amongst them, the method of the compression test is used mostly in bulk forming [1].

There are two main advantages with the method of the compression test:

(1) It is convenient to change and control variables such as temperature (T), strain (ε) and strain rate ($\dot{\varepsilon}$) in the tests.

(2) The deformation is usually done in a state of compressive stress, which accords well with the true stress state of most bulk forming processes.

It is useful to making the experimental results approach the real flow stress closely for the two aspects above. In an ideal compression test:

$$\sigma = L / A \tag{1}$$

$$\varepsilon = \ln(h_0 / h) = \ln(A_0 / A) \tag{2}$$

Where L is the instantaneous compressive load; h and h_0 are the instantaneous and original height of a sample; and A and A_0 are the instantaneous and original cross-sectional area.

2.2 Materials and experimental procedure

The material used in this study is a commercial AISI 5140 steel, whose chemical compositions are listed in Table 1. The solid cylindrical compressed specimen of AISI 5140 steel was machined from an annealed bar. The height to diameter ratio of 1.5 was selected for the samples to ensure homogeneous deformation. The size of the specimen is 8 mm in diameter and 12 mm in length. The axisymmetric compression deformations were conducted on a Gleeble-3500 thermo-mechanical simulator at four strain rates, i.e. 0.1 s^{-1}, 0.5 s^{-1}, 5 s^{-1} and 20s^{-1}, to a maximum strain of 0.8 at the various temperatures of 1073 K, 1123 K, 1173 K, 1223 K and 1273K. To minimizing friction, thin graphite flakes are laid between the punch head and the billet head. The schematic description of the deformation simulations is illustrated in Fig.1. The whole experimental scheme is shown in Table 2.

Table 1. Chemical composition of AISI 5140 steel used in this investigation (wt%)

Steel	C	Si	Mn	P	S	Cr	Cu
AISI 5140	0.37-0.44	0.17-0.37	0.50-0.80	≤0.04	≤0.04	0.80-1.10	≤0.30

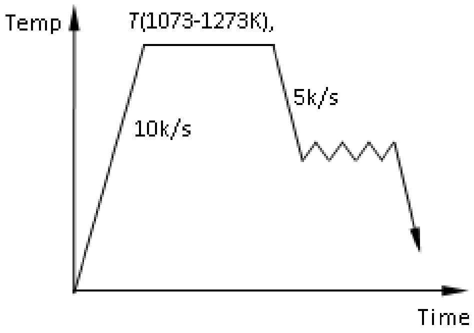


Figure 1. Schematic process of the warm-hot compression tests

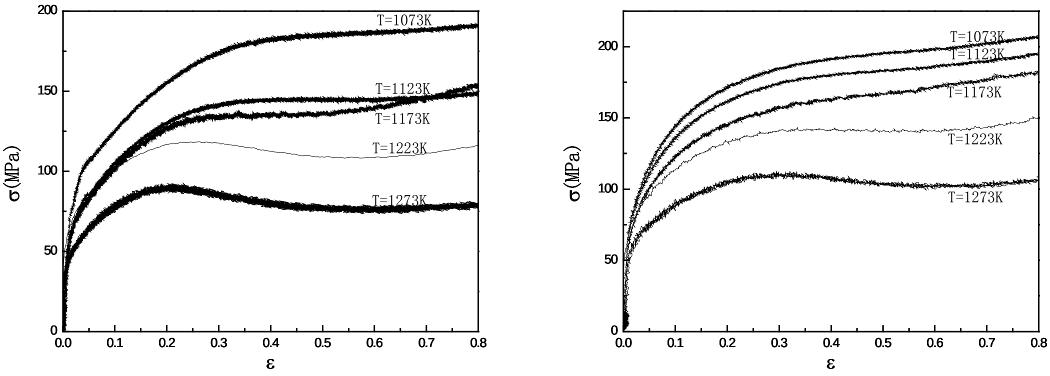
Table 2. The scheme for the determination of the flow stress of AISI 5140 steel

Temperature (K)	1073	1123	1173	1223	1273
Strain rate (s^{-1})	0.1	0.1	0.1	0.1	0.1
Strain rate (s^{-1})	0.5	0.5	0.5	0.5	0.5
Strain rate (s^{-1})	5	5	5	5	5
Strain rate	20	20	20	20	20

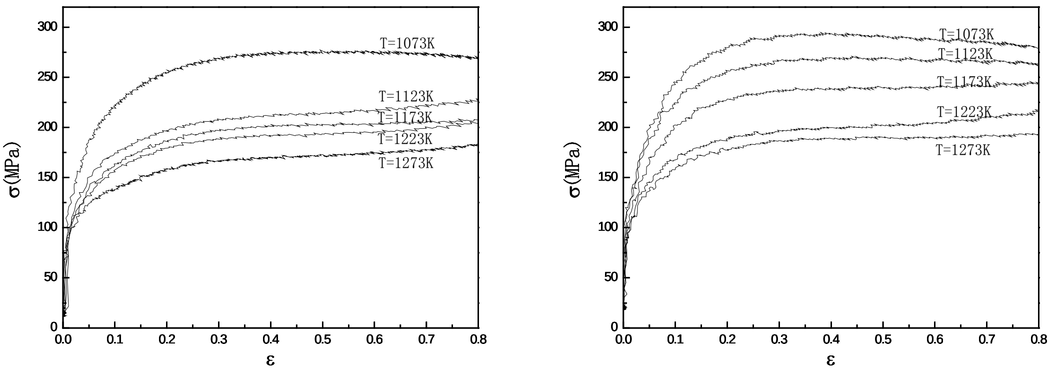
(s^{-1})						

3. Determination of AISI 5140 steel flow stress within the temperature range of warm-hot forging

3.1 True strain-stress curves



(a) $\dot{\varepsilon} = 0.1s^{-1}$ (b) $\dot{\varepsilon} = 0.5s^{-1}$



(c) $\dot{\varepsilon} = 5s^{-1}$ (d) $\dot{\varepsilon} = 20s^{-1}$

Figure 2. The true stain-stress curves of AISI 5140 steel at different strain rates

The flow stress curves of AISI 5140 steel by thermo-mechanical experiment with different temperatures and different strain rates are shown in Fig. 2. From the distribution of the flow stress curves it can be seen that all the flow stresses increase first quickly and then gradually with the increase of strain, until they reach a fixed value. It can be found that the effects of the temperature and strain rate on the flow stress are significant for all the tested conditions. The stress level decreases with increasing deformation temperature and decreasing strain rate.

It can be seen that the strain to the peak flow stress increases with decrease of the temperature and increase of the strain rate. When the temperature is high and the strain rate is low, the peak flow stress decreases slowly after a peak strain has been reached, consequently dynamic recrystallization (DRX) acts as the main softening mechanism during deformation. While in other conditions these curves are typical dynamic recovery curves, i.e. the dynamic recovery is sufficient to counteract the increase of flow stress caused by mechanical hardening and dynamic recrystallization does not occur.

It can be seen that in the range of $\dot{\varepsilon} = 0.1 - 20\ s^{-1}$, the flow stress at 1173K is 1/3 lower than that at 1073K, while the flow stress at 1273K can be 1/4 lower than that at 1173K. Thus under the premise of ensuring the precision and quality of the formed parts, high deformation temperature such as 1173-1223K is a recommended temperature for carton steel AISI 5140, which will be helpful in reducing deformation resistance and work energy.

3.2 Prediction of flow stress

It is well known that in hot deformation process the flow stress of metallic material is decided by the deformation temperature, the strain and the strain rate. The well accepted constitutive equation which can take care of the influence of the strain rate and temperature is

$$Z = \dot{\varepsilon}\exp(Q/RT) = A\sinh(\alpha\sigma)^{n} \qquad (3)$$

Where A and α are constants related to materials, Z is the Zener-Holloman parameter, n is strain rate sensitivity parameter, Q is the activation energy of deformation, R is the gas constant, $\dot{\varepsilon}$ is the strain rate , T is the absolute temperature and σ is peak stress σ_p or steady-state stress σ_s. In this paper σ is the peak flow stress σ_p, α is 0.012 [7].

Then the flow stress σ can be written as a function of Zener-Hollomon parameter, considering the definition of the hyperbolic law.

$$\sigma = \frac{1}{\alpha}\ln\left\{\left(\frac{Z}{A}\right)^{\frac{1}{n}} + \left[\left(\frac{Z}{A}\right)^{\frac{2}{n}} + 1\right]^{\frac{1}{2}}\right\} \tag{4}$$

Taking the logarithm of both sides of Eqs. (3) respectively, we have

$$\ln\dot{\varepsilon} = \ln A + n\ln\left[\sinh(\alpha\sigma)\right] - \frac{Q}{RT} \tag{5}$$

When $\dot{\varepsilon}$ value is fixed, Q can be described as Eqs. (6).

$$Q = Rn\left[\frac{\partial\ln\sinh(\alpha\sigma_p)}{\partial(1/T)}\right]_{\dot{\varepsilon}} = Rn\beta \tag{6}$$

When T is a fix value, n can be described as

$$n = \left[\frac{\partial\ln\dot{\varepsilon}}{\partial\ln\sinh(\alpha\sigma_p)}\right]_T \tag{7}$$

The value of n can be obtained from the slope of the lines in the $\ln\sinh(\alpha\sigma_p) - \ln\dot{\varepsilon}$ plots. Because the slope of the lines is approximately the same, the value of n can be obtained for different deformation temperatures by linear fitting method, and a mean value of n can be computed. β can be calculated by a similar method from the slope of the lines in the $1/T - \ln\sinh(\alpha\sigma_p)$ plots.

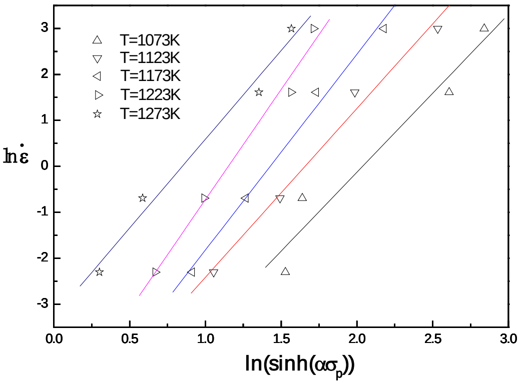


Figure 3. Peak flow stress versus strain rate for the AISI 5140 steel

According to the thermo-mechanical experiment results, the curves of the strain rate on the peak flow stress of AISI 5140 steel are shown in Fig. 3. Also Fig. 4 represents the relationship of the temperature and the peak stress of AISI 5140 steel. Based on Fig. 3 and Fig.4, the parameters calculated in this work for AISI 5140 steel are shown in Table 3. The values of ln$Z$ of AISI 5140 steel at different deformation conditions are shown in Table 4.

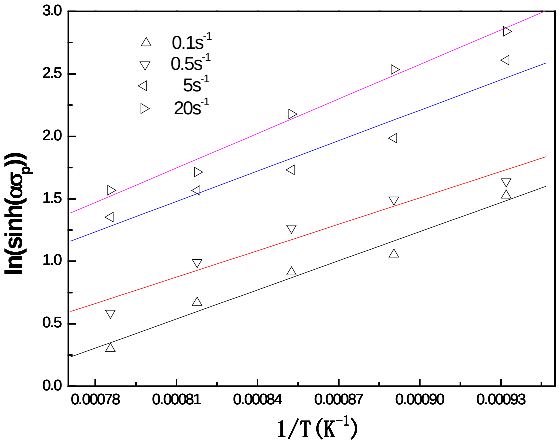


Figure 4. Effect of the temperature on the peak stress of AISI 5140 steel

Table 3. The parameters calculated for AISI 5140 steel

Parameter	Value
n	4.004 MPa^{-1}
β	8119.896 K·MPa
Q	270.321 KJ·mol^{-1}
A	5.3156×109 s^{-1}

Table 4. Values of lnZ of AISI 5140 steel at different deformation temperatures and strain rates

$\dot{\varepsilon}$ (s^{-1})	1073 K	1123 K	1173 K	1223 K	1273 K
0.1	27.998	26.648	25.414	24.281	23.237
0.5	29.607	28.257	27.023	25.890	24.846
5	31.910	30.560	29.326	28.193	27.149
20	33.296	31.946	30.712	29.579	28.535

Substituting the calculated values of Q and A into Eqs. (3) and Eqs.(4) we can get Eqs. (8) and Eqs.(9), which can be used to calculate actual peak stress in the warm-hot deformation process of AISI 5140 steel.

$$Z = \dot{\varepsilon}\exp\left(\frac{2.70321\times10^5}{RT}\right) \tag{8}$$

$$\sigma = 83.333\ln\left\{\left(\frac{Z}{5.3156\times 109}\right)^{\frac{1}{4.004}} + \left[\left(\frac{Z}{5.3156\times 109}\right)^{\frac{1}{2.002}} + 1\right]^{\frac{1}{2}}\right\} \quad (9)$$

The comparison between the measured and predicted flow stress using the above model is shown in Fig.5. The mean error *D* is calculated as

$$D = \frac{\sum_{i=1}^{n} 100 \times \frac{p_i - m_i}{m_i}}{n}\%, n = 1, 2, 3, \ldots \quad (10)$$

Where p_i is the predicted flow stress, and m_i the measured flow stress and n is the number of points. Obviously, the prediction results from the above model show high accuracy.

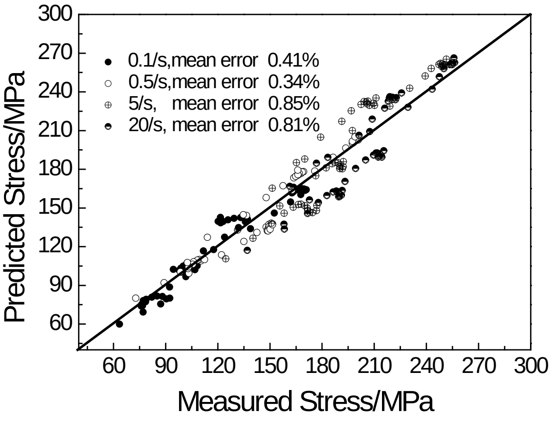


Figure 5. Comparison of the predicted and measured flow stress

4. FEM simulation of the warm-hot forging of splined shaft

Analysis of metal forming operations relies on accurate knowledge of the flow behavior of the workpiece under a variety of operating conditions [8]. This knowledge is contained in constitutive equations, which typically relate plastic flow stress to a number of variables including strain, strain-rate and temperature. Such data is usually determined using a series of stress-strain curves performed over a matrix of temperature and strain rate conditions. These equations are often used in connection with finite-element analysis to solve the equilibrium boundary-value problem numerically. It is also well known that flow stress depends not only on the current strain, strain rate and temperature but also on the history of strain rate and temperature while reaching the current strain level.

The flow stress measured in Fig. 2 has been put into a FEM simulation system, and the new flow stress model has been applied in the FEM simulation of a warm-hot forward-extrusion station of an automobile splined shaft. Fig. 6 is a comparison of load–stroke curves determined by experiment and FEM simulation. The comparison shows that the trends acquired in the different methods are similar. The reason why the experimental value is always a little larger than the FE simulation value is mainly because of the cooling process where a heated billet is put into the cavity of a cold mold.

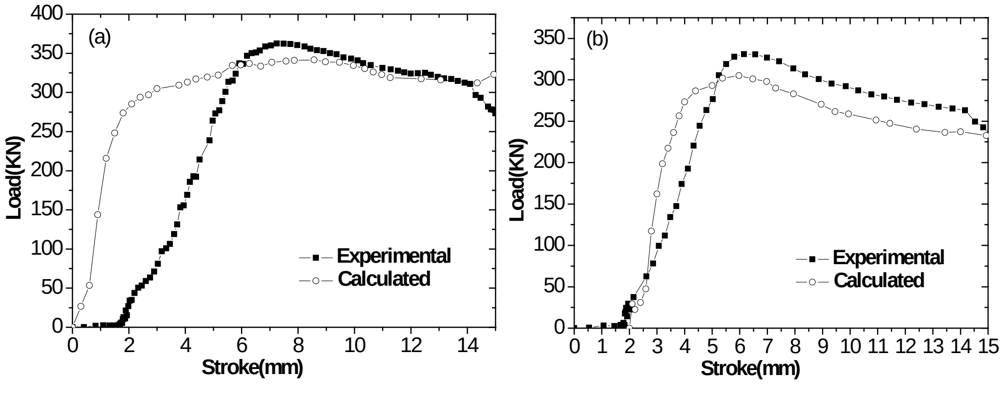


Figure 6. Load-stroke curves at different temperatures (a)T=1173K (b) T=1223K

5. Conclusions

A mathematical model has been developed for evaluation the flow stress of AISI 5140 steel at warm-hot temperatures ranges. The comparison between the theoretical and experimental confirms the validity of the model. Also, it is worth noting that the employed model is capable of utilizing in the finite element application. Among the influencing factors of *T*, ε and $\dot{\varepsilon}$, the effect of the temperature (*T*) on the flow stress is most obvious. Therefore, the strict control of the forming temperature is very important in precision warm-hot forging, which will be helpful in reducing forces and work energy, eliminating defects, and advancing the metal flow. For AISI 5140 steel, 1173-1223K is a reasonable warm-hot forging temperature range.

The systematical and accurate

determination of flow stress curves of all warm-hot forging materials is a very significant work. It will be great beneficial for improving further research on warm forging theory and process.

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References

1. B.A. Behrens, P. Suchmann, A. Schott (2008) Warm forging: new forming sequence for the manufacturing of long flat pieces. *Production Engineering*, 2(3), p.p.261-268.
2. H. Kache, R. Nickel, B.A. Behrens (2012) An innovative cross wedge rolling preforming operation for warm forging. *Enabling Manufacturing Competitiveness and Economic Sustainability*, p.p.310-315.
3. Changhyok Choi, Adam Groseclose, Taylan Altan (2012) Estimation of plastic deformation and abrasive wear in warm forging dies. *Journal of Materials Processing Technology*, 212(8), p.p.1742-1752.
4. Serajzadeh S. (2005) A mathematical model for evolution of flow stress during hot deformation. *Materials Letters*, 59(26), p.p.3319-3324.
5. Hui Yang, Zhenhong Li, Zhiliang Zhang (2007) Investigation on Zener-Hollomon parameter in the warm-hot deformation behavior of CF53. *Journal of Shanghai Jiaotong University (Science)*, 12(3), p.p.352-358
6. Hong Yan, Guohua Qian, Qiang Hu (2007) Development of flow stress of AISI H13 die steel in hard machining. *Journal of Wuhan University of Technology-Mater. Sci. Ed.*, 22(2), p.p.187-190.
7. Laasraoui A, Jonas JJ. (1991) Prediction of temperature distribution, flow stress and microstructure during the multipass hot rolling of steel plate and strip. *ISIJ International*, 31(1), p.p.95-105.
8. Qiu Ma, Zhongqin Lin, Zhongqi Yu (2009) Prediction of deformation behavior and microstructure evolution in heavy forging by FEM. *The International Journal of Advanced Manufacturing Technology*, 40(3-4), p.p.253-260.

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