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HIGH TEMPERATURE DEFORMATION CONSTITUTIVE MODEL OF GGG70L DUCTION IRON

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In order to accurately describe the high temperature deformation behavior of GGG70L ductile iron, the thermal simulation experiments with deformation rate of 0,01~10 s^{-1} were carried out at 800~1 100 °C by Gleeble-1500D thermal simulation machine. The deformation behavior of GGG70L ductile iron was studied. The temperature compensated strain rate Zener-Hollomon parameter was introduced, and the constitutive model of GGG70L ductile iron was established based on the strain compensated Arrhenius model. The results show that the theoretical value of peak stress calculated by the constitutive model is in good agreement with the experimental results, and the correlation is 97,8 %, which can accurately describe the high temperature deformation behavior of GGG70L ductile iron

Keyword: GGG70L ductile iron; high temperature deformation; stress; Zener-Hollomon parameter; constitutive model

INTRODUCTION

In recent years, with the development of automobile production industry, there are more and more requirements for the performance of automobile workpieces. GGG70L ductile iron has good mechanical properties[1], surface quenching properties and welding properties. At present, it is widely used in the drawing sequence mold of automobile covering parts, such as die, punch, blank holder and other production operations[2]. GGG70L ductile iron has good wear resistance and is a common material for large-scale, precision and long-life drawing dies. In many parts of the drawing die, due to the violent relative motion between the dies, it is easy to cause the die failure due to wear[3]. Therefore, in the manufacturing and production of large-scale drawing dies, surface strengthening processes such as laser surface quenching are often used to form a certain hardening layer in specific parts to improve the wear resistance and service life of the die.

In this paper, in order to explore the relationship between the related influencing factors and stress of GGG70L ductile iron thermal deformation, the thermal simulation experiments of different deformation temperature and strain rate were carried out by using Gleeble-1500D thermal simulator, and the constitutive model was established, which provided the basic model and data for the numerical simulation of laser surface quenching heat treatment process.

THERMAL SIMULATION EXPERIMENT OF GGG70L DUCTILE IRON

In this experiment, the GGG70L ductile iron material is processed into a cylindrical pattern. The chemical composition of the material is shown in Table 1. First, the samples were subjected to stress relief annealing, and then the samples were subjected to compression tests on a Gleeble-1500D thermal simulator at deformation temperatures of 800,900,1 000 and 1 100 °C. Each sample was heated to the strain temperature at a rate of 20 °C·s^{-1}, and then held for 3 min. After that, the sample was compressed to 50 % of its initial height at strain rates of 0,01, 0,1, 1and 10 s^{-1}, respectively, and then water quenched immediately.

Table 1 **Chemical composition of GGG70L ductile iron /wt. %**

C	Si	Mn	P	S	Cu
3,56	2,13	0,47	0,022	0,005	0,94
Ni	Mo	Mg	Cr	Fe	
0,91	0,49	0,045	0,05	residual	

Figure 1 shows the true stress-true strain curves of GGG70L ductile iron under different deformation conditions. It can be seen that under different deformation temperatures and strain rates, the true stress increases rapidly with the increase of true strain, and then increases slowly with the increase of true strain. When the strain rates are 0,01, 0,1, 1 and 10 s^{-1}, the dynamic equilibrium is achieved under the combined action of work hardening and dynamic softening caused by dynamic recrystallization. The true stress remains basically unchanged with the increase of true strain, but when the

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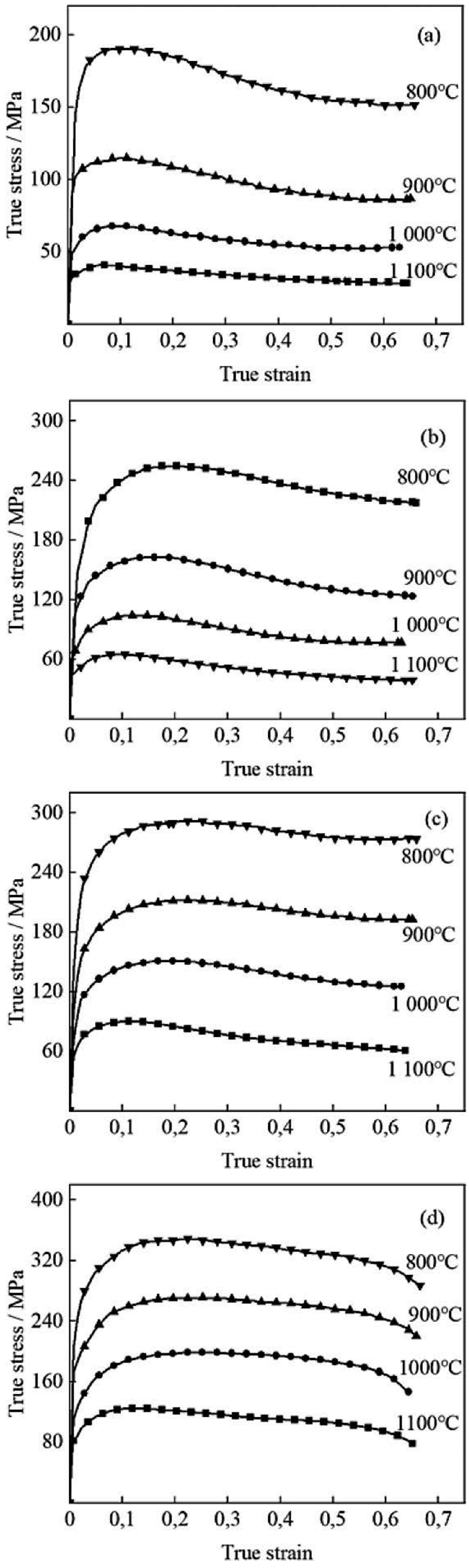

(a) 0,01 s^{-1} (b)0.1 s^{-1} (c)1 s^{-1} (d) 10 s^{-1}

Figure 1 True stress-true strain curves of GGG70L ductile iron at different strain rates

strain rate is 10 s^{-1}, there is no obvious dynamic equilibrium. It can be seen from Fig.1 that the softening effect of GGG70L ductile iron is negatively correlated with deformation temperature and strain rate. With the increase of deformation temperature or strain rate, the softening effect is weakened. At the same strain rate, the higher the deformation temperature, the lower the peak true stress, and the smaller the true strain corresponding to the peak true stress; at the same deformation temperature, the greater the strain rate, the greater the peak true stress, indicating that the work hardening effect of the material is negatively correlated with the deformation temperature and positively correlated with the strain rate.

THE ESTABLISHMENT OF CONSTITUTIVE MODEL

In order to accurately obtain the constitutive model of GGG70 L ductile iron, the numerical simulation of laser surface quenching process and the deformation analysis of heat treatment are realized. In this paper, the hyperbolic sine modified Arrhenius formula proposed by SELLARS C M and TEGART W J M is used to describe the relationship between flow stress[4], temperature and strain rate during high temperature deformation of materials, including deformation activation energy Q and thermodynamic temperature T. The relationship between temperature and strain rate under different stresses is as follows:

$$\dot{\varepsilon} = A_1\sigma^{n_1}\exp(\frac{-Q}{RT}),(\alpha\sigma \le 0,8) \tag{1}$$

$$\dot{\varepsilon} = A_2\exp(\beta\sigma)\exp(\frac{-Q}{RT}) ,(\alpha\sigma \ge 1,2) \tag{2}$$

$$\dot{\varepsilon} = A\left[\sinh(\alpha\sigma)\right]^n\exp(\frac{-Q}{RT}) \ (All\ stresses) \tag{3}$$

where: R is the molar gas constant, 8,314 J·mol^{-1}·K^{-1}; Q is the apparent activation energy of thermal deformation; T for the deformation temperature, K; $\dot{\varepsilon}$ is the strain rate, s^{-1}; σ is the true stress, MPa; A, A_1, A_2, α, β, n_1 and n are temperature independent material constants.

Taking the logarithm on both sides of Formula (1), we can get:

$$ln\dot{\varepsilon} = lnA_1 + n_1 ln\sigma - \frac{Q}{RT} \tag{4}$$

$$n_1 = \frac{\partial\ln\dot{\varepsilon}}{\partial\ln\sigma} \tag{5}$$

When the deformation temperature is fixed, $\ln\dot{\varepsilon}$ has a linear relationship with $ln\sigma$, and n_1 is the slope of the straight line.

Taking the logarithm on both sides of Formula (2), we can get:

$$In\dot{\varepsilon} = InA_2 + \beta\sigma - \frac{Q}{RT} \tag{6}$$

$$\beta = \frac{\partial\ln\dot{\varepsilon}}{\partial\sigma} \tag{7}$$

When the deformation temperature is fixed, $\ln\dot{\varepsilon}$ has a linear relationship with σ, and β is the slope of the straight line.

Substituting the peak stress of different strain rates at the same temperature into Formula (4) and Formula (6), the relationship curves of $\ln\dot{\varepsilon}$ with $ln\sigma$ and σ can be obtained. As shown in Figure 2 and Figure 3, respectively.

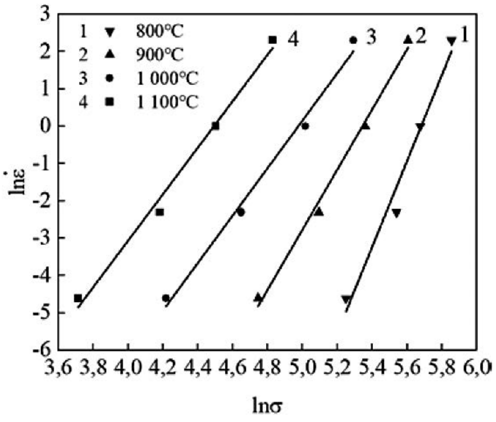

Figure 2 Relation curves of lnε̇-lnσ

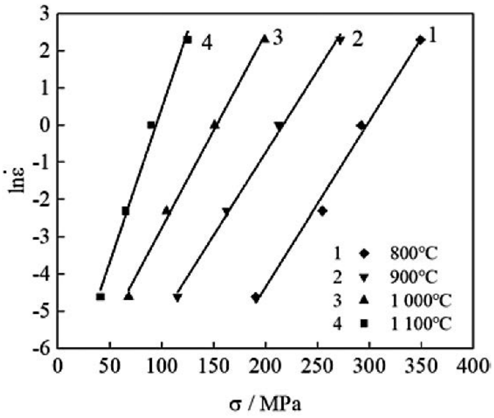

Figure 3 Relation curves of lnε̇-σ

By linear fitting, the average slope of the straight line at different temperatures is taken to obtain n_1 = 8,032 and β = 0,05589. Then $\alpha = \beta / n_1$ = 0,00696.

Taking the logarithm on both sides of Formula (3), we can get:

$$In\dot{\varepsilon} = InA + nIn\left[\sinh(\alpha\sigma)\right] - \frac{Q}{RT} \tag{8}$$

For Formula (8), the partial derivative transformation of $\dot{\varepsilon}$ and $1/T$ can be obtained respectively:

$$n = \frac{\partial In\dot{\varepsilon}}{\partial In\left[\sinh\left(\alpha\sigma\right)\right]} \tag{9}$$

$$K = \frac{Q}{nR} = \frac{\partial In\left[\sinh\left(\alpha\sigma\right)\right]}{\partial\left(1/T\right)} \tag{10}$$

In the formula: K is the material constant.

Substitute the previously obtained α values into the above formula, and make the relationship curve of $\ln[\sinh(\alpha\sigma)]$ and $\ln\dot{\varepsilon}$, $1/T$, as shown in Figure 4 and Figure 5 below.

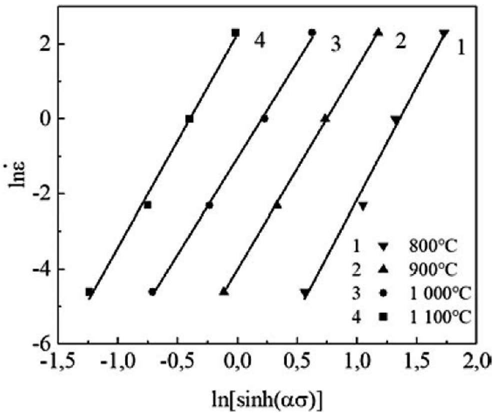

Figure 4 Relation curves of lnε̇-ln[sinh(*ασ*)]

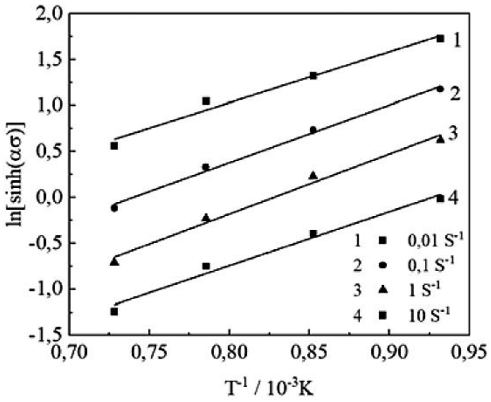

Figure 5 Relation curves of ln[sinh(*ασ*)]-1/*T*

n = 5,5619, K = 6 055,77 is obtained by linear regression method. According to $Q = nRK$, the thermal deformation activation energy of the specimen is calculated as Q =280 028,4639J / mol.

The temperature compensated strain rate Zener-Hollomon parameter is introduced to compensate the strain rate. The Z parameter is used to describe the combined effect of deformation temperature and strain rate on metal forming.

$$Z = \dot{\varepsilon}\exp\left(\frac{Q}{RT}\right) \tag{11}$$

Bring Formula (3) into Formula (11), and take the logarithm on both sides of the equal sign to obtain :

$$\ln Z = n\ln[\sinh(\alpha\sigma)] + \ln A \tag{12}$$

According to Formula (12), the relationship curves of lnZ and $\ln\ln[\sinh\sinh\left(\alpha\sigma\right)]$ are shown in Fig.6. lnA is the intercept of the lnZ-$\ln\ln[\sinh\sinh\left(\alpha\sigma\right)]$ curve, and the linear regression is carried out. Finally, the intercept lnA = 25,43032 is obtained, and the structural factor A = $1{,}10725\times10^{11}$ of the experimental alloy is obtained.

The peak stress constitutive equation of GGG70L ductile iron is obtained by introducing A, α, n and Q into Formula (3).

$$\dot{\varepsilon} = 1{,}10725\times10^{11}\left[\sinh(0{,}00696\sigma)\right]^{5{,}561895}\exp\left(\frac{-280\ 028{,}5}{8{,}314T}\right) \tag{13}$$

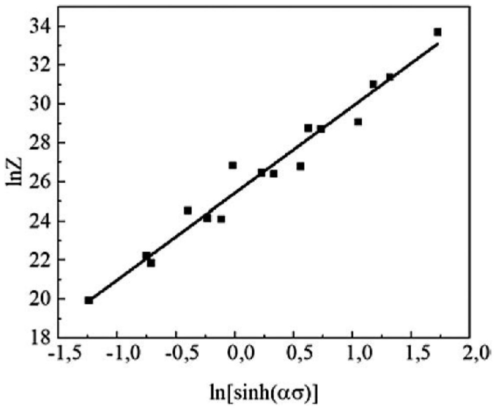

Figure 6 Relation curves of ln[sinh(*ασ*)] and ln*Z*

$$\sigma = \frac{1}{0,00696}\ln\left\{\left(\frac{Z}{1,10725\times10^{11}}\right)^{\frac{1}{5,561895}} + \right.$$
$$\left. + \left[\left(\frac{Z}{1,10725\times10^{11}}\right)^{\frac{1}{5,561895}} + 1\right]^{\frac{1}{2}}\right\} \qquad (14)$$

SIMULATION PREDICTION AND VERIFICATION OF CONSTITUTIVE MODEL

The predicted stress values of GGG70L ductile iron at different strain rates and different deformation temperatures are compared with the experimental values measured by the experiment, as shown in Figure 7. The correlation coefficient R between the calculated results of the constitutive model of GGG70L ductile iron and the experimental values is 0,97756, and the average relative error is 5,58 %. The established model can better predict the peak stress of the material.

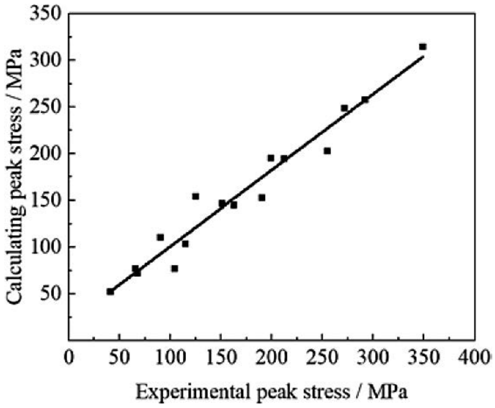

Figure 7 The peak stress calculation results are compared with the measured values

CONCLUSION

In this paper, the correlation between different deformation temperatures and strain rates of GGG70L ductile iron was studied. Based on the hyperbolic sine function Arrhenius model equation of Zener-Hollmon parameters, the constitutive model of GGG70L ductile iron in the expected strain range was established. The predicted values are in good agreement with the experimental values, and the correlation coefficient R reaches 0,978. It shows that the constitutive model established in this paper can better describe the high temperature deformation behavior of GGG70L ductile iron, and provide the basis and reference for the high temperature deformation behavior of GGG70L ductile iron.

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Note: The responsible translator for English language is W. C. LI-North China University of Science and Technology, China