The Determination of Constitutive Equations in Martensitic Heat Resistant Steels

Wenfeng Zhang[a]

School of Mechanical Engineering, Guilin University of Aerospace Technology, Guilin, Guangxi, 541004, China;

[a]wfzhang11b@alum.imr.ac.cn

Abstract

Constitutive equations were applied to analyze the deformation data of martensitic heat resistant steels in this study. Hot deformations for the experimental steels were carried out in the temperature range of 900-1200 ℃ and the strain rate range 10-3-100 s-1. In this study, the critical condition for dynamic recrystallization (DRX) was determined by a cooperation of the minimum value of –(∂θ/∂σ) and the deviation point of the linear slope of θ-σ curve. From the analysis, it was found that only one slope ratio of critical strain, εc versus critical stress, σc appeared in the 9Cr and 10Cr steels , whilst two different slopes in P92 and NS steels due to the augmentation of auxiliary softening effect of the dynamic strain-induced transformation (DSIT) .

Keywords

Hot Deformation, Dynamic Recrystallization, Martensite, Heat Resistant Steels.

References

1. Introduction

Thermomechanical processing (TMP) has become a crucial tool to advance the structure and enhance the mechanical properties of steels, including the heat resistant steels, which are mainly used as pipes or tubes extruded at high temperature. During a TMP process, recrystallization plays the main role in the associated microstructure evolution [1] which mainly determines the deformation characteristics of the steels during the hot working processes.

In analyzing the stress-strain curves, the reduced exponential function is generally used as shown in Eq. 1. In the equation, the flow stress σ is expressed as a function of ε as well as T and $\dot{\varepsilon}$ [4].

$$\sigma/\sigma_p = [(\varepsilon/\varepsilon_p)\exp(\varepsilon/\varepsilon_p)]^C \quad (1)$$

Where, the exponent parameter C can be derived for different steels. The peak strain ε_p is corresponding to the peak stress σ_p employed in the constitutive equations. This formula is superior to determine the constitutive constants, such as peak stress and peak strain, through fitting the experimental stress curve to Eq. 1. The constitutive equations used for both high stress and low stress are defined as following in the 1960s [5].

$$Z = \dot{\varepsilon}\exp(Q/RT) = A[\sinh(\alpha\sigma)]^n \quad (2)$$

Where, n=stress exponent, Q= the activation energy, α is constant for a fixed alloy, R= gas constant which equals 8.31 J / (mol•K).

The main objective of this study is to establish the constitutive equations for four types of martensitic steels and provide essential information, such as the Zener-Hollomon parameter (Z) value, the activate energy Q and the stress sensitivity coefficient n, to predict their creep behaviors in the long-term service. To calculate these coefficients, the accurate strains where different softening mechanisms take place have to precisely determined at first through calculating the original data.

2. Experiment

This study was conducted on four types of martensitic heat resistant steels. The chemical compositions of the experimental steels are listed in Table 1. Bars for the compression test, cut from the slab perpendicular to the forging direction, were machined into samples of 8 mm in diameter and 12 mm in gauge length.

The rob samples were homogenized in vacuum at 1200 ℃ for 5 min, and then cooled down to the deformation temperature of 900-1200 ℃ at a cooling rate of 10 ℃/s. After stabilizing holding for 1 min at the deforming temperature, the compression testing samples were deformed to 60% at the strain rate range of 10^{-3}-10^{0} s^{-1}. The samples were quenched to room temperature as soon as the compressions were finished.

Table 1. Chemical compositions of the experimental steels, wt%

Steel	C	Si	Mn	Cr	Mo	W	V	Nb	B	Co	N
NS	0.021	0.09	1.25	9.37	-	1.42	0.15	0.06	-	-	0.037
P92	0.11	0.37	0.46	8.77	0.42	1.73	0.17	0.057	0.0028	-	0.048
9Cr	0.089	0.31	0.50	8.58	0.40	1.65	0.18	0.060	0.0022	1.64	0.040
10Cr	0.088	0.31	0.50	10.42	0.40	2.55	0.18	0.056	0.0022	2.19	0.058

3. Results

3.1 Stress-strain curves

The stress-strain curves of the experimental steels obtained from four different strain rates labeled beside their corresponding curves are shown in Figure 1, in which the critical strain, εc, and the peak strain, εp, are marked on the curves. All the curves showed an initial work hardening but only a few out of them developed to a clear stress peak, indicating a dynamic recrystallization (DRX) taking place. It was found that the distinct peaks only appeared in the curves that obtained under high temperature and low strain rate deformation situations (low *Z* values).When the *Z* value reached a higher level, the stress curve showed a 'flat-top' shape with no peak. This phenomenon was traditionally thought to be an indication of no occurrence of DRX and implied that the dynamic recovery was the only softening mechanism operated during the deformation process [4].

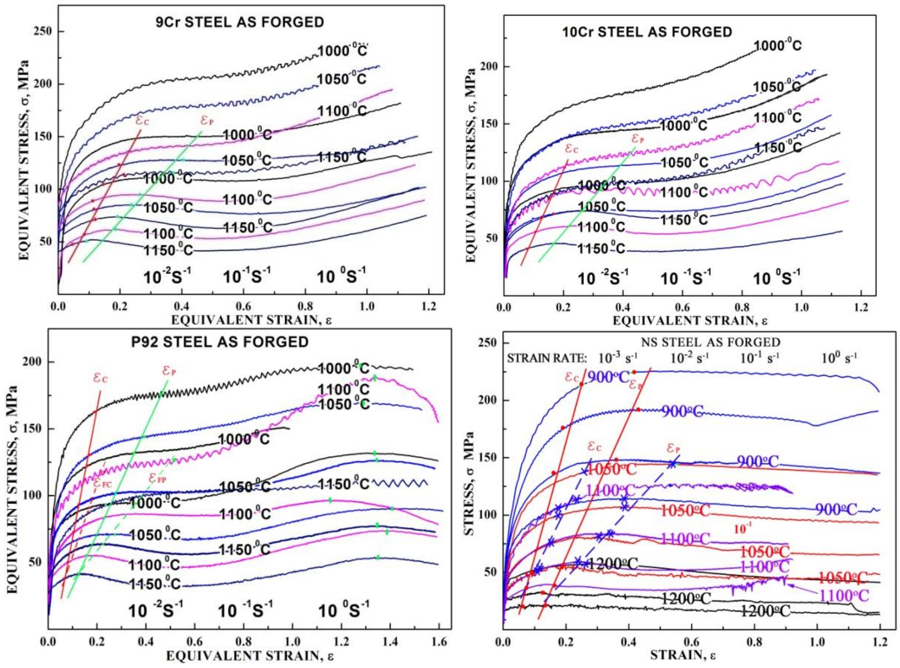

Figure 1. Equivalent stress-strain curves with indication of εc and εp of 9Cr steel, 10Cr steel, P92 steel and NS steel in sequence.

In curves of 9Cr and 10Cr steels, the critical strains kept a linear relationship with the critical stress, just like the peak strain with the peak stress. But in curves of the P92 and the NS steels, there existed two slope coefficients between the critical strain and the critical stress, as indicated in Figure 1. The appearance of two slopes might be caused by the acceleration softening of DSIT, which only took place in these two steels during hot deformation. The DSIT process slowed the accumulation of dislocation, and thus, resulted in a lower stress at the same strain.

The flow stress of NS steel was depressed a great deal comparing with the P92, 9Cr and 10Cr steels due to the small solute strengthening effect at high temperature, since the NS steel contained less content alloy elements than the other steels.

3.2 constitutive equations

In order to calculate the data under different deformation conditions, the constant coefficients in the constitutive equation were calculated through the method provided by Zhang[4]. The results, including the stress exponent, n and the activation energy, Q, were listed in Table 3.

The Q and A values could also be gained in the deformed logarithm function of the constitutive equation at a certain $\dot{\varepsilon}$, as shown in Eq. 3 and Eq. 4

$$n = \left.\frac{\partial \ln(\dot{\varepsilon})}{\partial \ln[\sinh(\alpha\sigma_p)]}\right|_{T=Const.} \tag{3}$$

$$Q_{HW} = Rn \left.\frac{\partial \ln[\sinh(\alpha\sigma_p)]}{\partial(1/T)}\right|_{T=Const.} \tag{4}$$

The value of Q for all the experimental steels were derived from the slope of the linear relationship between $\partial \ln[\sinh(\alpha\sigma_p)]$ and 103/(T+273) as shown in Figure 2.

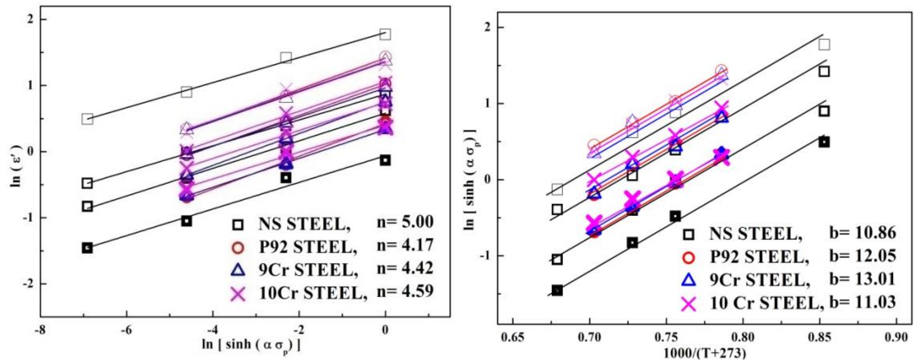

Figure 2. Linear relationships between $\ln[\sinh(\alpha\sigma_p)]$ and $\ln(\dot{\varepsilon})$ and that between $\ln[\sinh(\alpha\sigma_p)]$ and 103/(T+273) for experimental steels

Table 2. Original data for calculating α value

Strain rate, s^{-1}		0.001	0.005	0.01	0.05	0.1	1
Peak stress, MPa	1200	21.00	27.65	31.20	41.26		
	900	115.31		148.49		193.36	224.84

Finally, the coefficient values of four types of martensitic heat resistant steels were calculated, and the results are listed in Table 3.

Table 3. Coefficient values of experimental steels

steel	α, MPa^{-1}	n	Q_{HW}, kJ/mol
NS	0.012	5.00±0.22	451±24
P92	0.012	4.17±0.11	418±16
9Cr	0.012	4.42±0.18	477±39
10Cr	0.012	4.59±0.22	478±32

In the original Arrhenius theory, the activation energy Q represented the level of an energy barrier to be surmounted in some atomistic mechanism [4]. Almost universally, the activation energy increased with the alloy content. However, as in this study, the NS steel maintained a higher Q than the P92 steel although it contained less alloy content than P92 steel. Two possible reasons may be take into account: the reduction of carbon and nitrogen content and the retardation of DRX due to DSIT during deformation. With the diminution of carbon and nitrogen content, more niobium solute, which is the greatest strengthening element, was left in the matrix, leading to high stress value and consequently high activation energy. Meanwhile, as mention above, the DSIT reducing the stored energy greatly occurred before DRX, which retarded the initiation of DRX considerably.

4. Conclusion

Beneath the calculation of the hot deformation processes, there are some fundamental characteristics of four types of martensitic heat resistant steels as follows.

(1) There exhibited two different slopes in the linear relationships between εc and σc for P92 and NS steels marked in the stress-strain curves, while only one slope for 9Cr and 10 Cr steels. The change of slopes under different deformation conditions in NS steel and P92 steel were attributed to the auxiliary softening effect of DSIT.

(2) Through analyses on the flow curves of NS steel at different deformation temperatures and strain rates, the parameter α was calculated to be 0.012 MPa-1. n was set to 5.00 in NS steel, 4.17 in P92, 4.42 in 9Cr and 4.59 in 10Cr.Q to451 in NS steel, 418 in P92, 477 in 9Cr and 478 in 10Cr.

Acknowledgements

This work was financially supported by the National Science Foundation for Young Scientists of China (Grant No. 51601044), Guangxi Natural Science Foundation (NO. 2015GXNSFBA139225), Natural Science Foundation of Guilin University Aerospace of Technology (No. YJ1405) and the Dr. Start-up fund for “Study on improving the microstructure stability of the heat resistant steel by modifying the precipitates” from Guilin University Aerospace of Technology.

References

[1] A.S. Taylor, P.D. Hodgson, Materials Science and Engineering: A, 528 (2011) 3310-3320.
[2] E.I. Poliakt, J.J. Jonass, Acta mater., 44 (1996) 10.
[3] A. Bhattacharyya, D. Rittel, G. Ravichandran, Scripta Materialia, 52 (2005) 657-661.
[4] H.J. McQueen, S. Yue, N.D. Ryan, E. Fry, Journal of Materials Processing Technology, 53 (1995) 8.
[5] H.J. McQueen, N.D. Ryan, Materials Science and Engineering A, 322 (2002) 43–63.
[6] W.F. Zhang, W. Yan, W. Sha, W. Wang, Q.G. Zhou, Y.Y. Shan, K. Yang, Science China Technological Sciences, 55 (2012) 1858-1862.
[7] W.F. Zhang, P. Hu, W. Yan, W. Sha, W. Wang, Q.G. Zhou, Y.Y. Shan, K. Yang, J Iron Steel Res. Int. supplement 1-1, 18 (2011) 143-147.
[8] A. I. Fernandez, P. Uranga, B. Lopez, J. Rodriguezibabe., Materials Science and Engineering A, 361 (2003) 367-376.