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Mechanical properties and constitutive relationships of 30CrMnSiA steel heated at high rate

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Abstract

In this paper, the mechanical behavior of 30CrMnSiA steel after heating at a high rate are investigated experimentally and theoretically, including a detailed discussion of the effects of strain rate and temperature. Two constitutive models are presented to describe the mechanical response of this material after heating at a high rate, and verified by experimental results.

Keywords: Constitutive law; Heating rate; Temperature; Strain rate

1. Introduction

The determination of the mechanical behavior and constitutive laws of materials heated rapidly plays a key role in some fields, such as structural failure induced by high energy beams, etc. [1]. In general, for a steel structure irradiated by a high intensity CW laser beam, spans of heating rate and deformation velocity of materials are about 10^2 K/s to 10^3 K/s and $10^{-2}\,s^{-1}$ to $1\,s^{-1}$ [2].

As well known, a characteristic time scale exists for each process of microstructural evolution. At a given ambient temperature and loading condition, a specimen heated rapidly enough shows higher strength than another specimen heated slowly [2]. In reference [3], our group reported some experimental proofs of this phenomenon. The microstructure and strength of 30CrMnSiA steel heated with a rate of 10^3 K/s are clearly different from those the same material heated slowly at 0.1 K/s.

Many researchers have contributed to the understanding of effects of strain rate and temperature on the deformation mechanisms and properties of materials [1,4,5]. However, specimens are generally heated by resistance furnaces with a temperature rising rate not in excess of about 1 K/s in these references.

In this paper, 30CrMnSiA, a kind of widely used carbon structural steel, is selected as the material to be investigated in order to obtain its mechanical response and constitutive law under a high heating rate.

2. Experiments

The elementary constituents of 30CrMnSiA steel used in this paper are listed in Table 1. A raw rod with a diameter of 12 mm is heat treated and quenched in oil at 880 °C and subsequently tempered at 415 °C during 45 min.

All experiments are implemented in a Gleeble 1500 materials testing machine on standard specimens, as shown in Fig. 1. The temperature of specimens is detected by a fast-response thermocouple, and controlled by a feedback system, while the mechanical loading and the deformation are measured, respectively, with a force sensor and a quartz displacement sensor.

Uniform heating is achieved by a low voltage 50 Hz ac current passing directly through the specimen, and the heating rate is fixed to about 10^3 K/s while the specimen temperature varies from room temperature to about 900 °C. The specimens are elongated with different strain rates of $10^{-3}\,s^{-1}$, $10^{-1}\,s^{-1}$ and $1\,s^{-1}$.

Fig. 2 shows strain versus stress curves of 30CrMnSiA at different temperatures at strain rate of $10^{-3}\,s^{-1}$. Fig. 3 shows the same for a deformation velocity up to $1\,s^{-1}$. From Figs. 2 and 3, it is found that flow stress of 30CrMnSiA is increased with increasing strain rate from $10^{-3}\,s^{-1}$ to $10^{0}\,s^{-1}$, and that the thermal softening characteristics of this materials varies significantly with strain rate. However, at intermediate temperatures

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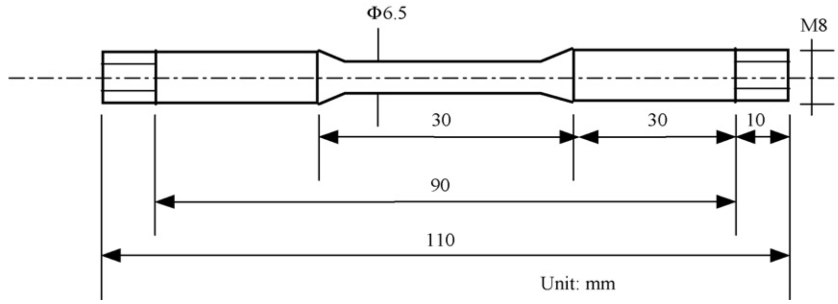

Fig. 1. Dimensions of 30CrMnSiA specimens.

Table 1
Element constituents of 30CrMnSiA (except Fe)

	Elements					
	C	Mn	Si	Cr	Ni	S
Content (%)	0.21	1.14	0.67	0.89	0.18	0.09

(400–600 °C), the flow stress drops sharply with increasing temperature in all tests.

3. Determination of constitutive law and parameters

In order to gain a widely applicable visco-plastic constitutive relationship for 30CrMnSiA steel, we focus on developing a rational model rather than an empirical equation.

Bodner and Partom [5] presented a famous constitutive law considering viscosity, work hardening and other effects in terms of the microstructural evolution of materials under thermo-mechanical loading. In particular, the Bodner–Partom model which has a reliable theoretical background, has been applied successfully in many fields.

In the present paper, the Bodner–Partom model is modified with the explicit introduction of thermal softening effect, in a simple way.

$$d_x^{\mathrm{p}} = \frac{2D_0}{\sqrt{3}}\frac{\sigma}{|\sigma|}\exp\left(-\left(\frac{1}{2}\right)\left(\frac{3A^2}{\sigma^2}\right)^n\right),$$

$$A^2 = \frac{1}{3}(Z\exp(C_1 T'^{n_1}))^2\left(\frac{n+1}{n}\right)^{1/n} \tag{1}$$

$$Z = Z_1 + (Z_0 - Z_1)\exp\left(-m\frac{W_{\mathrm{p}}}{Z_0}\right),$$

$$\dot{W}_{\mathrm{p}} = \sigma d_x^{\mathrm{p}}, \qquad T' = \frac{T - T_0}{T_{\mathrm{melt}} - T_0} \tag{2}$$

where, d_x^{p}, W_{p} and $T'$are the plastic strain rate, plastic work, and the non-dimensional temperature, respectively, and Z_0, Z_1, D_0, m, n, C_1, and n_1 are constitutive constants given in Table 2. Z denotes the deformation history of the material, and it is related to the dislocation density while n relates to dislocation velocity.

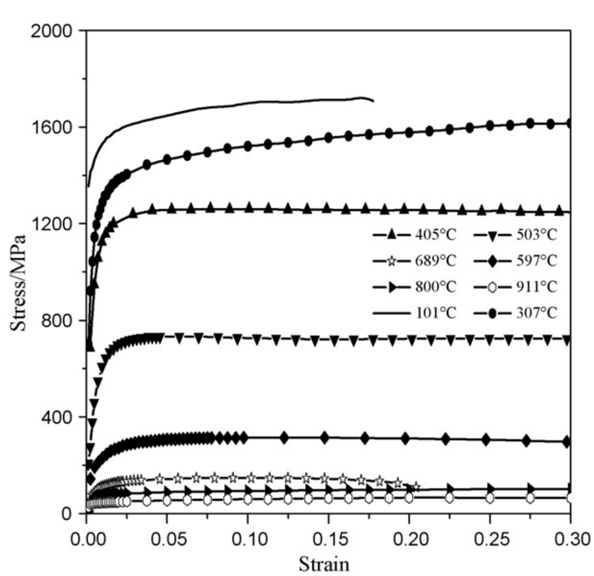

Fig. 2. Strain vs. stress curves of 30CrMnSiA steel at a strain rate of 10^{-3} s^{-1}.

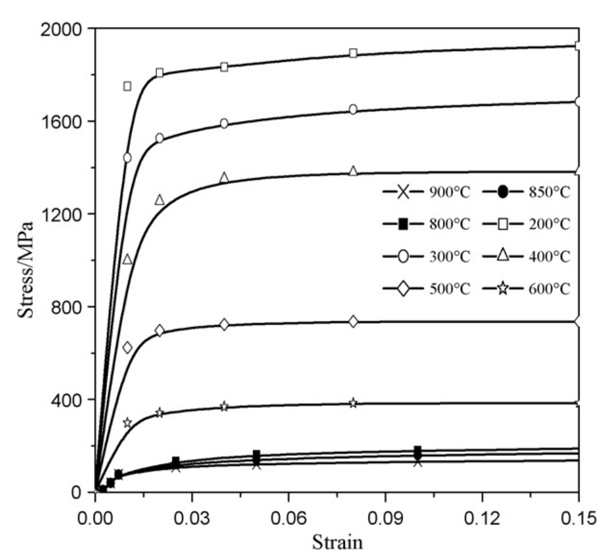

Fig. 3. Strain vs. stress curves of 30CrMnSiA at a strain rate of 1 s^{-1}.

Table 2
Constants in constitutive law depicted by Eqs. (1) and (2)

Z_0 (MPa)	Z_1 (MPa)	D_0 (s^{-1})	m	n	C_1	n_1
3378	4219	40000	398.0	1.651	−15.46	3.195

Table 3
Constants in constitutive law depicted by Eqs. (3) and (4)

σ_0 (MPa)	K_1 (MPa)	m	C_1	n_1	C (MPa)	n	A (s^{-1})	Q (J/mole)
114.6	1890	0.07	−15.88	3.184	21.0	4.51	0.27E13	0.26E6

The expression of d_x^{p} can be deduced from dislocation dynamics by introducing a specific barrier function.

However, as specimen temperature is varied from room temperature to about 900 °C, the exponent expression of the plastic deformation rate and flow stresses is inadequate to describe the complex dislocation motion mechanism. Based on the model of Anand [4], we suggest a new constitutive model where a hyperbolic sine function is adopted to depict the relationship among flow stress, strain rate and temperature. This function encompasses exponential and power law regimes, and it can be applied to a wider range of strain rates and temperatures.

$$\sigma = (\sigma_0 + K_1\varepsilon^m)\exp(C_1 T'^{n_1}) + C\sinh^{-1}[(z)^{1/n}] \quad (3)$$

$$z = \frac{\dot{\varepsilon}^{\mathrm{p}}}{A\exp(-Q/RT)} \quad (4)$$

where R is the gas constant, $R = 8.31441$ J/mole K, T absolute temperature, and Q the activation energy, σ_0, K_1, m, C_1, n_1, C, n, and A are fitting constitutive constants, listed in Table 3. Experimental data of material properties at temperatures of 20 °C, 400 °C, 600 °C, and 900 °C are introduced via a nonlinear fitting process.

In order to check these constitutive models and material constants, experimental results and theoretical predictions are compared and shown in Figs. 4 and 5, at the strain rates of 10^{-3} s^{-1} and 1 s^{-1}, respectively. It is clear that the constitutive models adopted in this paper account reasonably well for the mechanical behaviors of 30CrMnSiA in the ranges of temperature and strain rate considered here. In particular, by comparing Fig. 6 with Figs. 2 and 3, we find that the properties of 30CrMnSiA steel predicted by Eqs. (3) and (4) are rather close to the experimental data under various loading conditions.

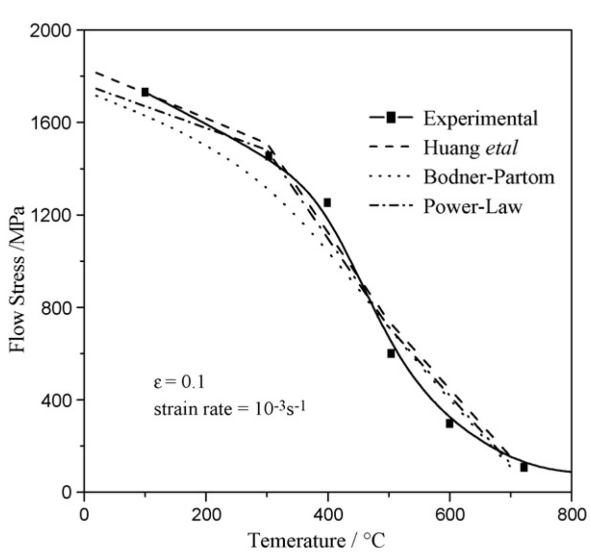

Fig. 4. Comparison of theoretical and experimental values on thermal softening of 30CrMnSiA at a strain rate of 10^{-3} s^{-1}.

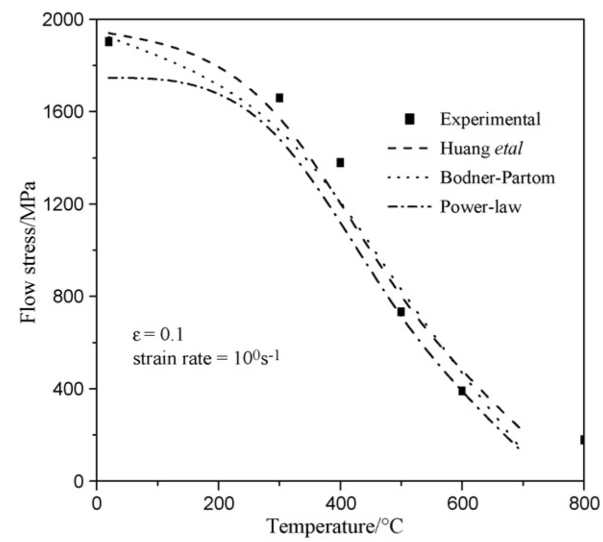

Fig. 5. Comparison of theoretical and experimental values on thermal softening of 30CrMnSiA at a strain rate of 1 s^{-1}.

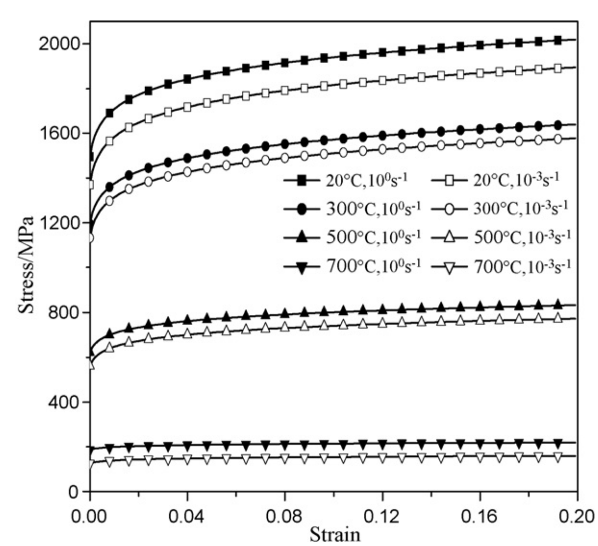

Fig. 6. Predicted mechanical behaviors of 30CrMnSiA by the new model.

4. Concluding remarks

In this paper, the macroscopic mechanical properties of 30CrMnSiA are obtained at a heating rate of 10^3 K/s. The effects of strain rate and temperature on flow stress and thermal softening are investigated.

Based on experimental results, two constitutive models are suggested to describe the mechanical behavior of 30CrMnSiA. The predominance of a modified Bodner–Partom model is the firm physical background. The predictions provided by our new model is found to be more appropriate than others to account for the experimental behavior of 30CrMnSiA steel under the thermal and mechanical conditions considered.

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