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高强钢动态力学性能本构模型研究

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摘　要：为了研究高强钢材料在动态加载过程中的力学响应，采用分离式霍普金森压杆对材料进行了不同应变率(3000 到 12000s^{-1})和不同温度(20℃到 800℃)单轴压缩实验.实验结果表明：高强钢的动态力学行为受应变率和温度的强烈影响.流动应力随着应变率的升高而增加，随着温度的升高而降低.提出了一个经验型本构模型来描述材料的加工硬化和温度软化行为.该本构模型预测的应力——应变曲线与实验结构较好吻合，表明该本构模型可进一步用于高强钢动态变形过程的数值模拟研究.

关键词：本构模型；分离式霍普金森压杆；应变率敏感性；动态力学性能；高强钢

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Constitutive model for dynamic mechanical response of high strength steel

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Abstract: It's important to understand the deformation behavior of metals in the dynamic loading process. In this study, the dynamic mechanical responses of high strength steel are investigated by uniaxial compressive experiments on the Split Hopkinson Pressure Bar (SHPB) with strain rate range from 3000 to 12000s^{-1} and temperature range from 20℃ to 800℃. The experimental results show that the mechanical responses of steel investigated are strongly affected by the strain, strain rate and deformation temperature. The flow stress increases with the increasing of strain rate while decreases with the increasing of deformation temperature. A phenomenological constitutive model is established to describe the strain rate harden and temperature soften behavior. The stress−strain relationships predicted by the phenomenological constitutive model agree well with the experimental results, which shows that the proposed constitutive model can be used to study the dynamic deformation process furthermore.

Key words: Constitutive model; SHPB; Rate sensitivity; Mechanical response; High strength steel

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1 Introduction

In the engineering application, the metals usually suffer from dynamic loading, such as high speed metal cutting, car crash, explosive-metal interaction and penetration. So it's important to understand the plastic deformation behavior of metals over a wide range of strain rates and temperatures in the design of structures[1−3]. Flow stress is the resistance to the plastic deformation of metals. With the development of computer technology, the finite element method is widely used in the analysis of metal plastic deformation. In the finite element code, the flow stress is expressed in the mathematical equations, which is also referred as constitutive model. To optimize the engineering structures, an accurate constitutive model is needed [4−5].

The constitutive model of the flow stress under different strain rates and temperature conditions has drawn a lot of attention of many researchers. Zhou et al. [6] studied the hot tensile deformation behaviors of an Al-Zn-Mg-Cu alloy under the deformation temperatures of 340 to 460℃ and strain rates of 0.01-0.001s^{-1} and proposed an Arrhenius-type constitutive model to predict the peak stress under the tested deformation condition. Tanimura et al. [7] compared the applicability of constitutive models of Cowper-Symonds (CS), Modified Cowper-Symonds (Modified CS), Johnson-Cook (JC). Samantaray et al. [8] proposed a modified constitutive model based on the Zerilli-Armstrong model considering the effects of thermal softening, strain rate hardening and isotropic hardening on flow stress to predict the elevated-temperature flow behavior of alloy D9. Park et al. [9] developed a unified constitutive model to describe the flow behaviors of pure Ta and Ta-W alloys over a wide range of strain rate and temperature.

The main objective of this study is to investigate thedynamic mechanical response of high strength steel at temperatures ranging from 20℃ to 800℃ and strain rates in the range of 3000 to 12000 s^{-1} by using the Split Hopkinson Pressure Bar (SHPB). The effect of strain rate and deformation temperature on the flow stress is analyzed according to the stress-strain relationships obtained. Then a phenomenological constitutive model is established by taking into account the combined effect of strain, strain rate and deformation temperature on the plastic deformation.

2 Experiments and results

2.1 Material

The target material in this study is a high strength steel 30Cr2Ni4MoV, which is used to manufacture the rotor of the steam turbine. The hardness is about 270HV. The chemical compositions of the studied steel are listed in Table 1. The microstructure of the material is shown in Fig. 1.

Tab. 1　Chemical composition of the studied high strength steel (wt. %)

Composition	C	Si	Mn	S	P	Cr	Ni	Mo	V	Fe
Content (wt. %)	≤0.35	≤0.03	≤0.05	≤0.004	≤0.002	1.6	3.5	0.3	0.08	Bal.

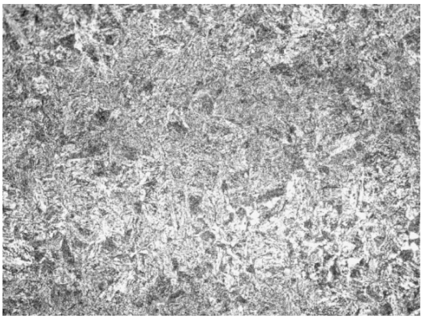


Fig. 1　Microstructure of 30Cr2Ni4MoV (500 X)

2.2 High strain rate testing

The dynamic mechanical response of the 30Cr2Ni4MoV high strength steel was tested using the Split Hopkinson Pressure Bar (SHPB) as shown in Fig. 2, which has been widely used for the determination of the dynamic mechanical properties of materials. The Split Hopkinson Pressure Bar was firstly invented by Bertram Hopkinson in 1914 and then improved by Kolsky in 1949[10]. Therefore, the Split Hopkinson Pressure Bar is also referred as Kolsky bar. As shown in Fig. 1, the primary components of SHPB system consist of three elastic bars: strike bar, incident bar and transmit bar. At the beginning of the test, a cylinder specimen is sandwiched between the incident bar and the transmit bar with lubrication for reducing the friction in the specimen/bar interface. Then the strike bar, which was driven by the compressed gas, impacts the left end of incident bar. The stress pulse induced by the impact travels along the incident bar. When the stress pulse reaches the interface between incident bar and specimen, part of the stress pulse reflects into the incident bar and rest of the stress pulse transmits into the transmit bar. At the same time, the specimen deforms uniformly. The time-dependent stress pulse in the elastic bar generates time-dependent strain, which can be measured by the strain gages at the midpoint of the incident bar and transmit bar. The signals received by strain gauges are firstly recorded by a digital oscilloscope, and then these recorded signals are transferred into a computer for further data processing.

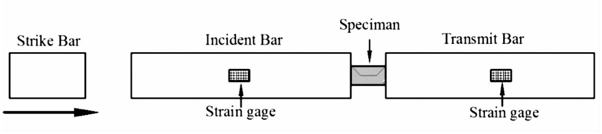


Fig. 2 Schematic illustration of Split Hopkinson Pressure Bar

Based on the one dimensional stress pulse propagation hypothesis, the average stress, strain and strain rate in the specimen can be calculated by the strain measured in the elastic bars according to following equations[10]:

$$\sigma_s = \frac{AE\varepsilon_T}{A_s} \tag{1}$$

$$\dot{\varepsilon}_s = \frac{2C_0\varepsilon_R}{L_s} \tag{2}$$

$$\varepsilon_s = \int_0^t \frac{2C_0\varepsilon_R}{L_s}dt \tag{3}$$

where E is the Young's modulus, C_0 is the wave velocity, A is the cross-sectional area of the elastic bars, A_s is cross-sectional area, L_s is the length of the cylindrical specimen. And ε_T and ε_R are elastic incident strain and elastic reflect strain caused by elastic incident stress pulse and elastic reflect stress pulse in elastic bar. And σ_s, ε_s, $\dot{\varepsilon}_s$ are, respectively, stress, strain and strain rate in the material.

In this study, the strain rates investigated range from3000 to 12000 s^{-1} and the temperature investigated range from 20℃ to 800℃. The true stress-true strain curves obtained from the experiment are shown in Fig. 3 and Fig. 4.

2.3 Results analysis

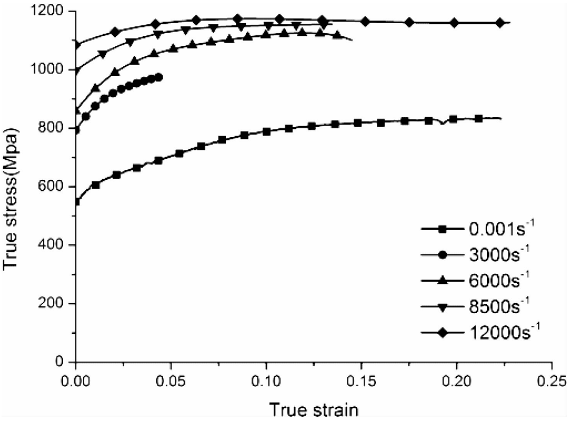


Fig. 3 True stress-true strain curves of 30Cr2Ni4MoV high strength steel under different strain rates at room temperature (20℃)

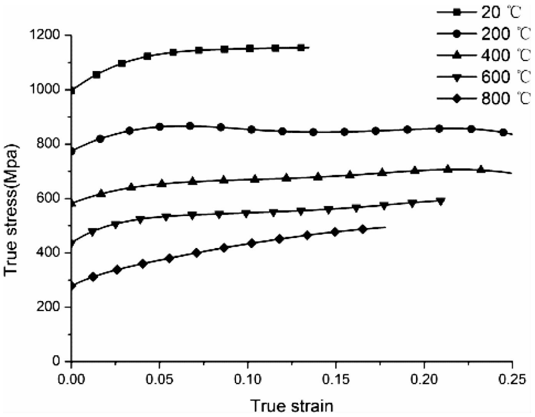


Fig. 4 True stress-true strain curves of 30Cr2Ni4MoV high strength steel under different temperatures with strain rate of 8500s^{-1}

From the experimental results, it is found that with the increasing of true strain, the flow stress increases nonlinearly, which indicates that the material is under severely plastic deformation. The work doneby the plastic deformation is irreversible. In the plastic flow stage, the increasing of flow stress, which is referred as work hardening, is a result of the slipping and propagating of dislocation[11]. The strain rate and temperature both have significant effect on the plastic flow behavior of materials. The relationship between flow stress and logarithmic strain rate at true strain of 0.03 is shown in Fig. 5, while the relationship between flow stress and temperatures at true strain of 0.02 is shown in Fig. 6.

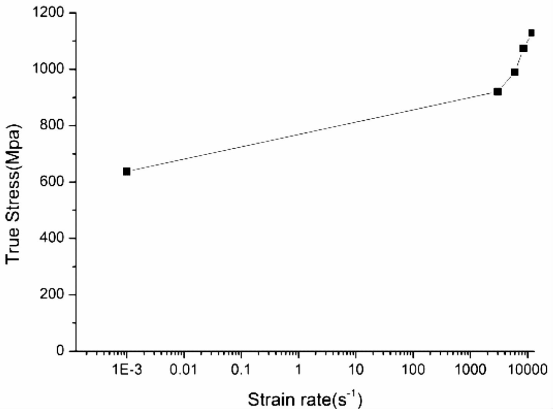


Fig. 5　Effect of strain rate on the flow stress

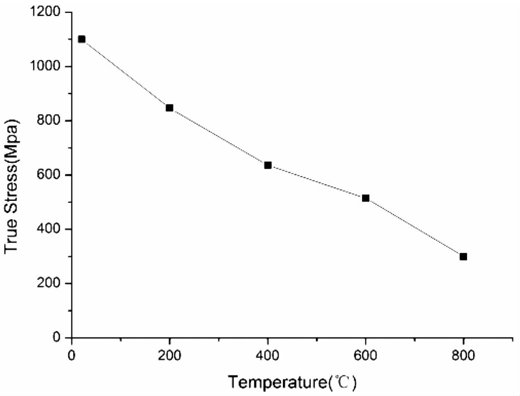


Fig. 6　Effect of temperature on the flow stress

As shown in Fig. 5, the flow stress increases with the increasing of strain rate. The strain rate sensitivity owns to the dislocation drag mechanism in the high strain rate. The temperature also has a strong effect on the flow stress. With the increasing of temperature, the thermal activation of dislocation become stronger. So the flow stress decreases with the increasing of temperature as shown in Fig. 6.

3　Establishment of constitutive models

The constitutive model proposed in the study is expressed as following:

$$\sigma_s(\varepsilon_s, \dot{\varepsilon}_s, T) = g(\varepsilon_s) * \Gamma(\dot{\varepsilon}_s) * \Theta(T) \tag{4}$$

$$g(\varepsilon_s) = \sigma_0 (1 + \frac{\varepsilon_s}{\varepsilon_0})^{1/n} \tag{5}$$

$$\Gamma(\dot{\varepsilon}_s) = (1 + \frac{\dot{\varepsilon}_s}{\dot{\varepsilon}_0})^{1/m} \tag{6}$$

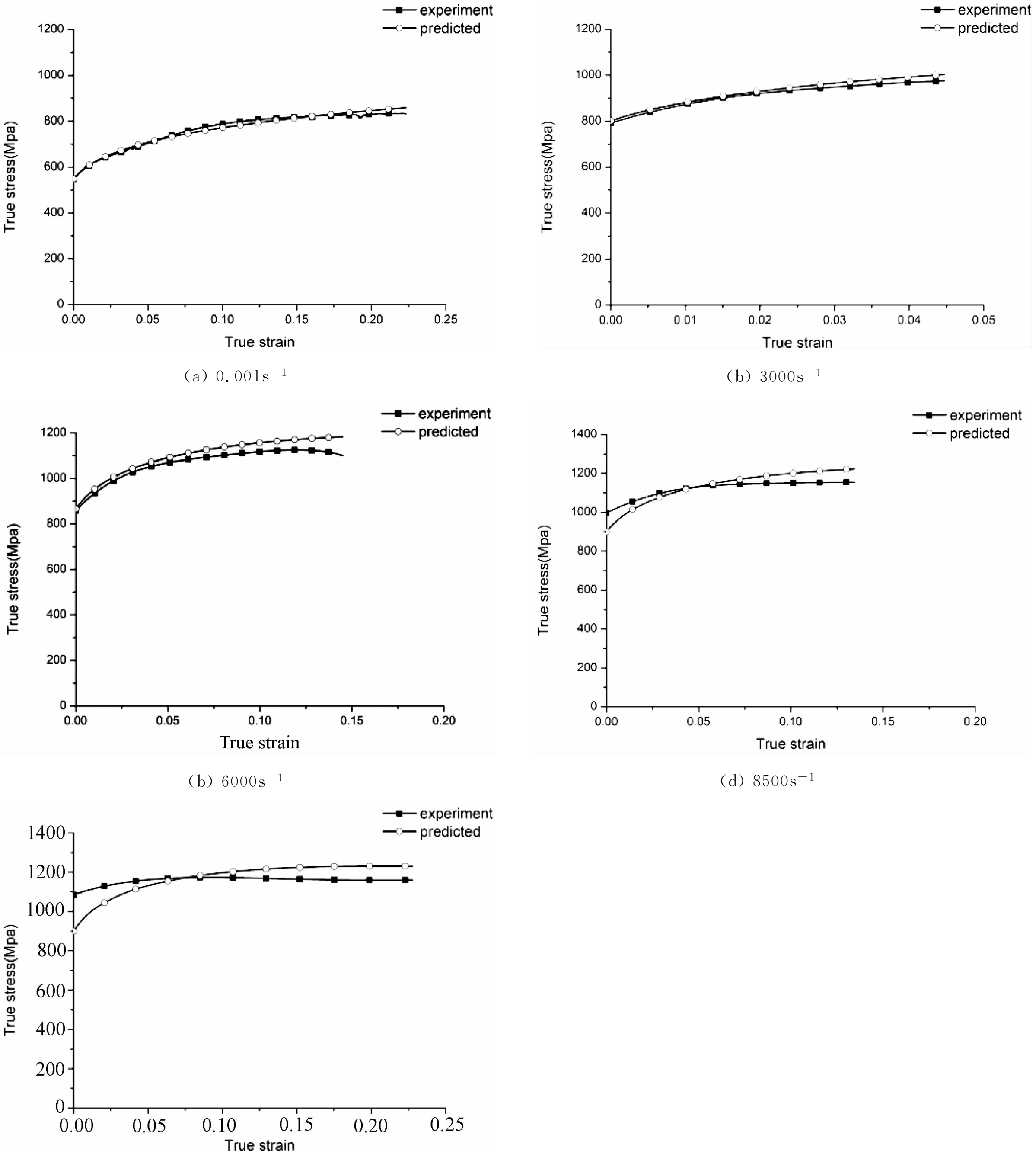
$$\Theta(T) = c_0 + c_1 T + c_2 T^2 + c_3 T^3 \tag{7}$$

where σ_0 yield stress at reference strain rate and temperature T is the deformation temperature, ε_0 is the reference strain, $\dot{\varepsilon}_0$ is the reference strain rate. m, n, c_0～ c_3 are material constants of constitutive model, respectively. $g(\varepsilon_s)$, $\Gamma(\dot{\varepsilon}_s)$ and $\Theta(T)$ in this constitutive model reflect the strain harden, strain rate harden and temperature soften behavior of metals.

By the regression analysis of the true stress-true strain curves from the experiment, the material constants of constitutive model are calibrated, as shown in table 2. The comparisons of flow stress measured in the experiment and predicted by the constitutive model at different deformation conditions are presented in Fig. 7 and Fig. 8. It is found that the flow stresses predicted by the constitutive model agree well with the experimental results.

Tab. 2 Material constants of constitutive model

σ_0	ε_0	m	$\dot{\varepsilon}_0$	n	c_0	c_1	c_2	c_3
547.92Mpa	0.01	6.9979	$100s^{-1}$	8.9047	1.0308	−1.8124e−3	2.1826e−6	−1.2745e−9

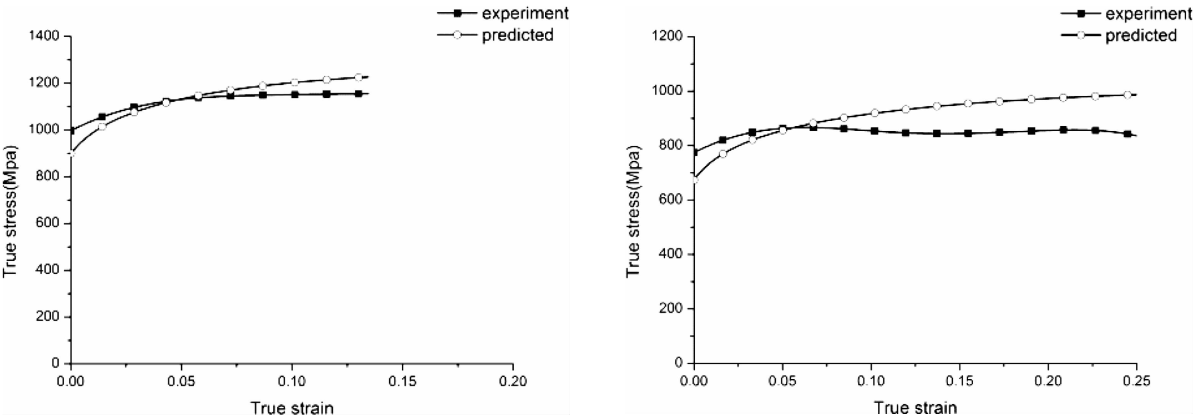


(a) $0.001s^{-1}$ (b) $3000s^{-1}$

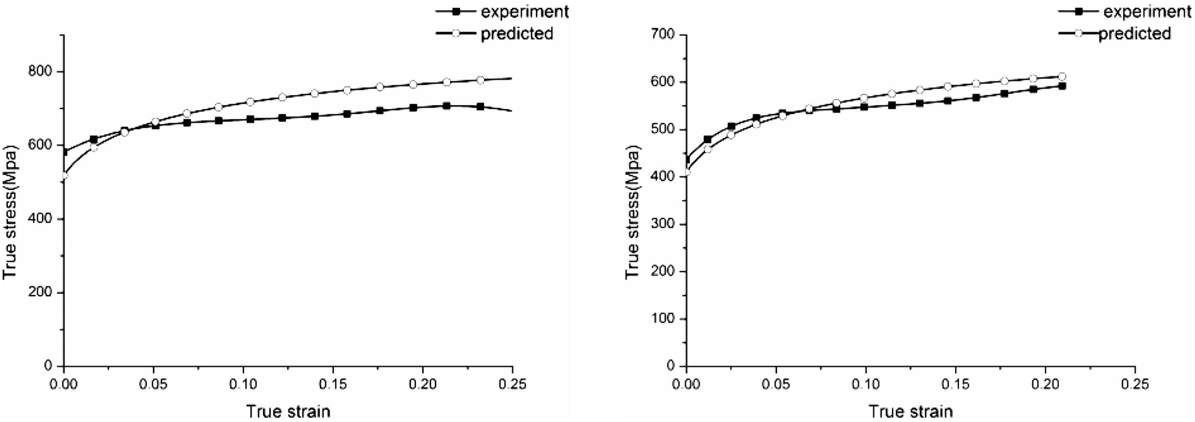
(b) $6000s^{-1}$ (d) $8500s^{-1}$

(e) $12000s^{-1}$

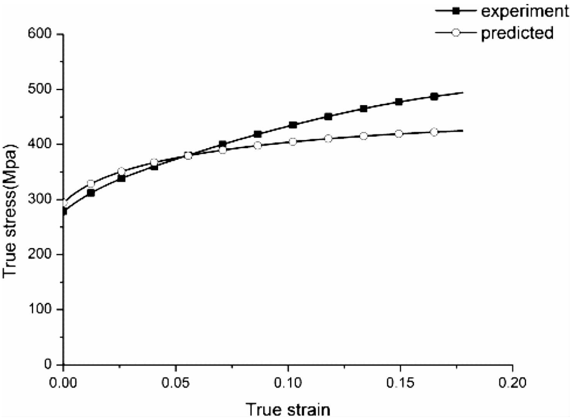
Fig. 7 Comparison of flow stress measured in the experiment and predicted by the constitutive model under different strain rates at room temperature (20℃)



(a) 20℃　　(b) 200℃



(c) 400℃　　(d) 600℃



(e) 800℃

Fig. 8　Comparison of flow stress measured in the experiment and predicted by the constitutive model under different temperature with strain rates of 8500s^{-1}

4　Conclusions

The dynamic mechanical response of 30Cr2Ni4MoV high strength steel was studied by SHPB in the present work. The strain rate and temperature sensitive of flow stress were analyzed. Based on the experimental results, a phenomenological constitutive model was proposed, which predicts the flow stress accurately in the investigated strain rate and temperature range.

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