Measurements of Shearing Property of High N Alloy Steel at Super High Strain Rates

Xiao'an Chen [1, a], Shuncheng Song [1,b] and Tinghui Wang [2,c]

[1] School of mechanics and engineering, Southwest Jiaotong University, Chengdu 610031, China

[2] Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

[a]chenxiaoan0218@163.com, [b]song_sc@163.com, [c]wangtinghui425@163.com

Abstract. In order to obtain the dynamic shearing property of high N alloy steel, the plugging test was performed by using the improved Hopkinson pressure bar system. As dynamic shearing strengths, the dynamic shearing energies during plugging process of two type high N alloy steels were determined from the shearing constitutive relationship at different super high strain rates. According to the theory of dislocation dynamics in Seeger equation, a dynamic shearing damage constitutive relationship was established and the different parameters of this material were determined by using the curve fitting method. The measured results indicated that the dynamic shearing property of high N alloy steel could be obtained effectively by the improved Hopkinson pressure bar system, and the effects of strain rate could be simulated by dynamic shearing damage constitutive relationship.

Introduction

High N alloy steels, i.e. steels which are intentionally pretreated with a certain amount of nitrogen by way of alloying process, are a comparatively late group of materials, and still in development. And they are of so many characters like unusually high strength, high fracture toughness, excellent corrosion resistance, wear resistance and nonmagnetizability and are used widely in weapon, chemistry engineering, and mechanics, etc. [1,2]. The nitrogen is in an interstitial solution. Mn, Cr, Mo and V increase its solubility while Ni and Si are decrease the solubility of nitrogen [2].

Most research of dynamic material behavior has thus far emphasized dynamic tensile behavior and compressive behavior [3-6]. However, few research focus on dynamic shearing behavior of materials. Zhiyun Zhang [7] uses the Hopkinson torsion device to obtain the dynamic behavior of ordnance steel materials at high strains and high strain rates, and shows the main causes of fracture in some materials is localized unstable shearing bands formation at high strain rates. Cunshan Fan et al. [8] test the dynamic shearing behavior of three kinds of armor materials by using SHPB technique with split punch, but they determine the shearing stress and strain as normal stress and strain which will lead to inaccuracy of the test results. A.R. Dowling et al. [9] use Kolsky bar to obtain the dynamic punching of metals while the width of shear zone is not very clearly defined, so in this case the quote shear strains and strain rates are only approximate.

In the work the dynamic shearing behavior of high N alloy steels is tested by modified Hopkinson bar system, and a dynamic shearing damage constitutive relationship is established at super high strain rates.

Experiments

The shearing property of high N alloy steel is tested by improved Hopkinson bar which is shown in figure 1. In this loading setup, a incident bar with step cross section and waveguide ring are used to obtain the plugging test, and no matter which loading configuration is adopt, the load applied on the specimen is determined by one dimensional stress-wave theory. By using this system, more accurate

results should be obtained than the split punch, and the shearing band can be defined clearly. The incident wave, reflected wave and transmitted wave, shown in figure 2, are measured by two strain gauges which are affixed on incident bar and transmission bar.
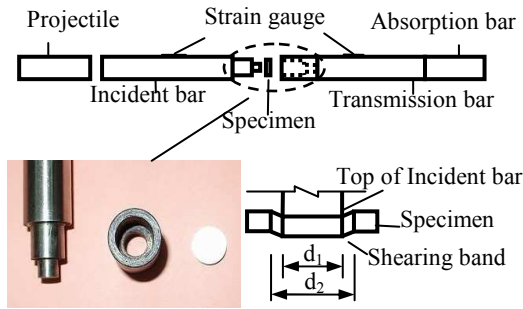
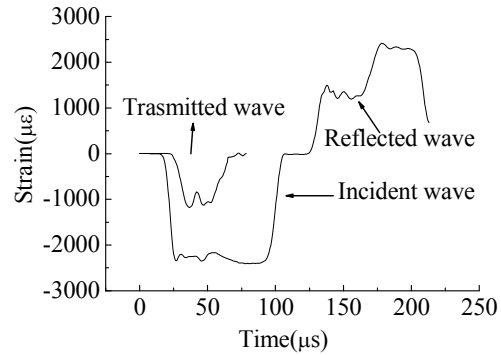Fig.1 Plugging test system sketch

Fig.2 Stress wave of plugging experiment

The specimen is a flat circular plate with different thickness. So the plugging shearing area is defined as $S=0.5\pi(d_1+d_2)H$, where H is the thickness of specimen, and d_1, d_2 are the diameter of punch and inner diameter of waveguide ring, respectively. The width of shearing band is $\delta=0.5(d_1-d_2)$. The shearing strain and stress expression are written as

$$\gamma=w/\delta=C_0\delta^{-1}\int_0^t (\varepsilon_i - \varepsilon_r - \varepsilon_t)dt , \tag{1}$$

$$\tau=EA(\varepsilon_i+\varepsilon_r+\varepsilon_t)/ \pi(d_1+d_2)H. \tag{2}$$

where w is the displacement of punch in a specified time, C_0 is the longitudinal sound speed in the Hopkinson bar, E is Young's modulus, and A is the cross-sectional area of the bar, ε_i, ε_r and ε_t are the incident strain, reflected strain and transmitted strain. The shearing stress-strain curves at different strain rates of high N alloy steel are shown in figure 3. Examination of these curves reveal three deformation stages during the punching process. The specimen is in elastic stage in a short time before the plastic follow begins, this regime is defined as Stage I almost without shearing stress. Once a certain strain is attained, the plugging begins to form with damage accumulation, denoting the Stage II deformation regime with almost shearing stress in the shearing band. This is then followed by considerably crack deformation and propagation, defining the Stage III.

The energy expenditure in the shearing process can be obtained from Equations (1) and (2) as

$$Q=qV= 0.25\pi H(d_2^2 - d_1^2)\int_0^t \tau d\gamma . \tag{3}$$

where V is the volume of shearing zone. The determind curve is shown in figure 4. It can be found that the energy expenditure is almost unchanged in the Stage I and Stage II while it is a linear development in Stage II. So the strain at beginning of Stage II provid a reference values for damage strain threshold γ_{th} and damage stress threshold τ_{th}.
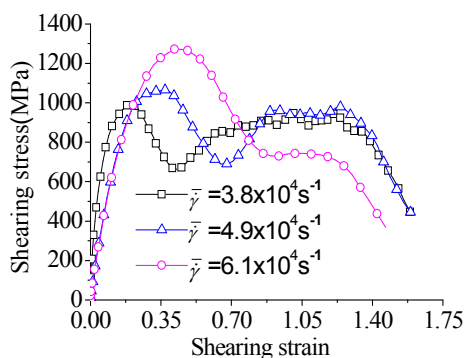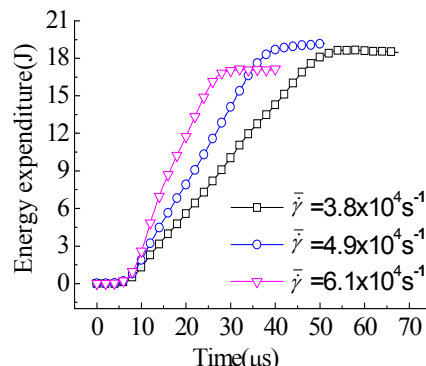
Fig.3 Shearing stress-strain curves

Fig.4 Energy expenditure during the plugging

Numerical model

Based on experiment results, the numerical model is established include damage evolution according to the theory of dislocation dynamics in Seeger equation which is based on thermally activated mechanism. In this theory the critical resolved shear stress or flow stress is written as $\tau = \tau_G + \tau^*$, where the term τ_G is depended on athermal barries, i.e. long–range barrier, determined by the structure of material. The term τ^* is due to the thermally activated barriers, that is, the barriers that can be overcome by thermal energy [10]. The thermally activated energy can be written as

$$U = U_0 - Lbd\tau^* = U_0 - v(\tau - \tau_G). \tag{4}$$

where U_0 is the activation energy at 0K, v is the activation volume, l is barrier spacing, b is dislocation Burgers vectors, d is barrier width, shown in figure 5. During the thermally activation, the activated frequency is $w = w_0 e^{-U/KT}$, where K is Boltzman's constant, T is temperature, w_0 is the natural vibrational frequency of dislocation. The time (t) taken by a dislocation to move a distance can be divided into a waiting time in front of obstacles (t_w) and a running time between obstacles (t_r). However, it seems to be the case in actuality that $t_w \gg t_r$, and thus the time expression is wrirren as

$$t = 1/w = e^{U/KT}/w_0. \tag{5}$$

According to the dislocation dynamics Orowan obtains the relationship between plastic strain rate and movement of dislocation as [10]

$$\dot{\gamma} = bAN/t = bANw_0 e^{-U/KT}$$

or

$$\tau = \tau_G + \frac{U_0}{v} + \frac{KT}{v}\ln\frac{\dot{\gamma}}{\dot{\gamma}_0} = \tau_A + \lambda_T \ln\frac{\dot{\gamma}}{\dot{\gamma}_0} \tag{6}$$

where $\lambda_T = \partial\tau/\partial\ln\dot{\gamma}$ as sensitive coefficient of strain rate.

The damage of material is obtained tend to increasing along with the increase of strain and strain rate, thus the rate-depedent micro-damage evolution is written as

$$D = D_0 + \lambda_D \ln(\dot{\gamma}/\dot{\gamma}_0) \tag{7}$$

where λ_D is sensitive coefficient of strain rate of rate-depedent micro-damage evolution. Appliying equations (6), one obtains

$$\tau = \tau_A(1 - D_0) + (\lambda_T' - \lambda_D')\ln(\dot{\gamma}/\dot{\gamma}_0) \tag{8}$$

where $\lambda_D' = \tau_A\lambda_D + \lambda_T\lambda_D\ln(\dot{\gamma}/\dot{\gamma}_0)$, $\lambda_T' = \lambda_T(1 - D_0)$. To reduce the parameters of this equation, according to Kobayashi &Dodd constitutive relationship, the equation (8) is modified on a similar way as

$$\tau - \tau_{th} = A(\gamma - \gamma_{th})^n \left(\ln\frac{\dot{\gamma}}{\dot{\gamma}_0}\right)^{-m}\ln\frac{\dot{\gamma}}{\dot{\gamma}_0} = A(\gamma - \gamma_{th})^n \left(\ln\frac{\dot{\gamma}}{\dot{\gamma}_0}\right)^{1-m} \tag{9}$$

where A, n, m and $\dot{\gamma}_0$ are the parameters of materials, the damage strain threshold γ_{th} and damage stress threshold τ_{th} are to assumed as 0.05 and $\tau_{th} = C_1\dot{\gamma}^2 + C_2\dot{\gamma} + C_3$, respectively.

Tab.1 Parameters of shearing constitutive relationship

Parameters	C_1	C_2	C_3	A(Mpa)	n	m	$\dot{\gamma}_0$
Values	-8.2e-7	0.11	-3178	260.25	0.088	0.556	156.86

The parameters of shearing constitutive relationship are shown in table 1, and the comparison between measured and calculated values at different strain rates are shown in figure 6.
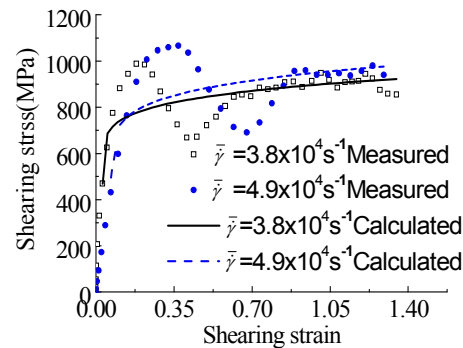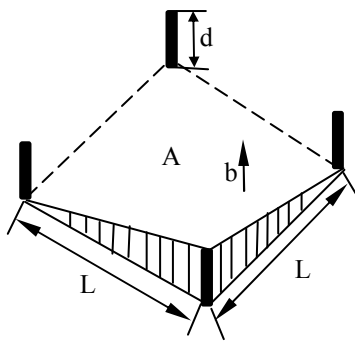

Fig.5 Dislocation overcoming a barrier   Fig.6 Comparison between measured and calculated values

Summary

The dynamic shearing properties of high N alloy steel at super high strain rate are obtained. The results indicate that the dynamic yeild shearing stress of this steel varies with shearing strain rate while the stress-strain curves reveal three deformation stages during the punching process. The dynamic shearing damage constitutive relationship is established accoding to the dislocation dynamics, and the parameters of material are determined by using the curve fitting method. This model can simulate the negative strain rate effect in Stage I and positive strain rate effect in Stage II and Stage III.

Acknowledgements

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