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Calculation of temperature distribution in adiabatic shear band based on gradient-dependent plasticity①

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Abstract: A method for calculation of temperature distribution in adiabatic shear band is proposed in terms of gradient-dependent plasticity where the characteristic length describes the interactions and interplaying among microstructures. First, the increment of the plastic shear strain distribution in adiabatic shear band is obtained based on gradient-dependent plasticity. Then, the plastic work distribution is derived according to the current flow shear stress and the obtained increment of plastic shear strain distribution. In the light of the well-known assumption that 90% of plastic work is converted into the heat resulting in increase in temperature in adiabatic shear band, the increment of the temperature distribution is presented. Next, the average temperature increment in the shear band is calculated to compute the change in flow shear stress due to the thermal softening effect. After the actual flow shear stress considering the thermal softening effect is obtained according to the Johnson-Cook constitutive relation, the increment of the plastic shear strain distribution, the plastic work and the temperature in the next time step are recalculated until the total time is consumed. Summing the temperature distribution leads to rise in the total temperature distribution. The present calculated maximum temperature in adiabatic shear band in titanium agrees with the experimental observations. Moreover, the temperature profiles for different flow shear stresses are qualitatively consistent with experimental and numerical results. Effects of some related parameters on the temperature distribution are also predicted.

Key words: nonuniform temperature; adiabatic shear band; shear strain localization; gradient-dependent plasticity; plastic shear strain distribution

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1 INTRODUCTION

It is well known that the excellent strength-to-mass ratio and fracture resistance make titanium and titanium alloys very attractive to aerospace applications. Shear localization is an important and often dominating deformation and failure mechanism for titanium and titanium alloys in dynamic loadings[1-12]. Prior to the onset of shear localization, the deformation can be approximately considered to be uniform. Once the shear localization is initiated, the intense localized shear deformation is accumulated progressively in narrow band that is called shear band or localized band. The eventual outcome of localized deformation is ductile rupture and material separation. Shear localization occurs and plays an important role in engineering applications. For example, shear bands can be observed in ballistic impact, explosive fragmentation, high speed machining, metal forming, grinding, interfacial friction, powder compaction, granular flow, and seismic event.

It is well known that intensive shear deformation is concentrated in adiabatic shear band in titanium and titanium alloys under dynamic loadings and the band thickness for Ti is approximately 10－20 μm[1,3]. For Ti-6Al-4V, the measured width of the shear bands ranges from 12 to 55 μm[13]. Besides, many experimental observations and numerical simulations show that there is a nonuniform temperature distribution in adiabatic shear band[13-18]. It is shown that the measured temperature distribution in adiabatic shear band is a function of time and position and a peak temperature of 440－550 ℃ is found in the various tests[13]. The numerical simulation shows that while most of the material in adiabatic shear band is at temperatures about 250 ℃, maximum temperature reaches over 850 ℃[14]. Measured results show that shear bands in two kinds of steels are relatively wide, that the maximum temperature rise in the band is about 450 ℃ and that the temperature distribution across the band is consistent with results of stability analyses[15]. The local temperature in the shear band is measured[16], within the shear band region, temperatures of 600 ℃ have been found. The numerical results show that there is a nonuni-

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form temperature distribution in adiabatic shear band[17]. Moreover, it is indicated that temperature distribution in the shear band has periodic patterns in both space and time[17].

Interactions and interplaying among microstructures are of very importance for Ti and Ti alloy and have been studied extensively by experiments[19-22]. For Ti and Ti alloy the texture is heterogeneous to some extent and a certain microstructure will be influenced significantly by its neighborhoods. The characteristic length in gradient-dependent plasticity, which depends on the mean grain diameter, governs the extent of long-range interaction.

According to gradient-dependent plasticity[23-25], shear localization in linear strain-softening heterogeneous material under uniform shear and static loading was investigated analytically by Wang et al[26]. Based on the same theory, analysis of localized characteristics of deformation in titanium subjected to nonuniform shear stress in the process of shear band propagation was carried out by Wang et al[27]. However, the thermal softening at high strain rates is ignored completely in previous analyses[26, 27]. Beside the shear localization of ductile metal materials, gradient-dependent plasticity has been applied into tensile localization of low-carbon steel[28, 29].

The distribution of tempreture cannot be interpreted or predicted in terms of traditional elastoplatic theory where flow stress only depends on the plastic strain rather than the plastic strain gradient. In the present paper, the nonuniformity of tempreture in adiabatic shear band in the strain-softening process is studied.

2 THEORETICAL ANALYSIS AND PROCEDURE OF CALCULATION

2.1 Mechanical model and constitutive relation

The model of shear localization that we shall consider is depicted in Fig. 1. It is a specimen with a certain height that is loaded in shear stress in the horizontal direction (i. e. x-axis) and compressive

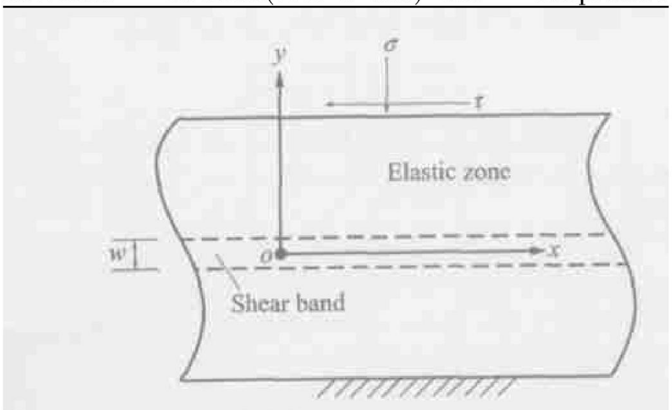

Fig. 1 Shear strain localization of specimen and well-developed adiabatic shear band

constant stress σ in vertical direction. For simplicity, the lower end of the block is fixed (i. e. the horizontal and the vertical displacements of the end are zero). An important outcome of shear localization is the decrease of the load-carrying capability of the block, so it can be supposed that localization is initiated at the peak stress and that the shear deformation only occurs in the horizontal direction.

Some experimental results show that the post-peak behavior of Ti or Ti alloy under dynamic loadings exhibits approximately linear strain-softening[6, 13], so the constitutive relation in strain-softening stage can be seen as a descending line whose absolute value of the slope is called dynamic shear softening modulus, see Fig. 2.

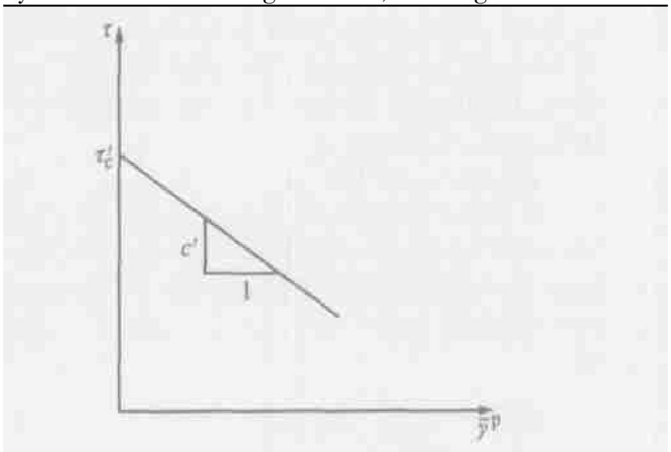

Fig. 2 Dynamic strain-softening constitutive relation

2.2 Analytical solution of plastic shear strain distribution

To consider the effects of strain softening and strain rate, herein the Johnson-Cook constitutive law[13, 30] that is semi-empirical in nature is adopted:

$$\tau = (\tau_c - c\,\bar{\gamma}^p)\cdot\left[1 + C\ln\frac{\dot{\gamma}_p}{\dot{\gamma}_0}\right] \tag{1}$$

where τ_c is the shear strength; $\bar{\gamma}^p$ is the average plastic shear strain; c is the static softening modulus; C is a material constants; $\dot{\gamma}_p$ is the average shear strain rate and $\dot{\gamma}_0$ is the average shear strain rate under quasi-static conditions.

For simplicity, let $\tau'_c = f\tau_c$, $c' = fc$ and $f = 1 + C\ln\frac{\dot{\gamma}_p}{\dot{\gamma}_0}$, then we have

$$\tau = \tau'_c - c'\,\bar{\gamma}^p \tag{2}$$

According to Wang et al[23, 27], based on gradient-dependent plasticity the plastic shear strain distribution $\gamma^p(y)$ in adiabatic shear band and the thickness w of the band can be given as, respectively

$$\gamma^p(y) = \frac{\tau'_c - \tau}{c'}\left[1 + \cos\frac{y}{l}\right] \tag{3}$$

$$w = 2\pi l \tag{4}$$

where l is the characteristic length of material and is usually concerned with average granular diameter of heterogeneous material.

2.3 Increment of temperature distribution

According to Eq. (3), increment $\Delta \gamma^{\mathrm{p}}(y)$ of the plastic shear strain distribution over any time interval $[t, t+\Delta t]$ can be expressed as

$$\Delta \gamma^{\mathrm{p}}(y)=\frac{\Delta \tau}{c'}\left[1+\cos \frac{y}{l}\right] \tag{5}$$

where $\Delta \tau=\tau_t-\tau_{t+\Delta t}$ is the increment of flow shear stress in strain-softening stage; τ_t and $\tau_{t+\Delta t}$ are the flow stresses at time t and $t+\Delta t$, respectively. For simplicity, $\Delta \tau$ can be considered to be a constant, thus $\Delta \gamma^{\mathrm{p}}(y)$ is the same for any time step.

Due to the fact that $\Delta \gamma^{\mathrm{p}}(y)$ depends on the coordinate y, the plastic work in adiabatic shear band is certainly nonuniform. The plastic work increment distribution $\Delta W(y)$ over the interval $[t, t+\Delta t]$ can be calculated as

$$\Delta W(y)=\Delta \gamma^{\mathrm{p}}(y) \cdot \tau_t \tag{6}$$

It is well known that approximately 90% plastic work is converted to heat and that the increment of temperature is dependent on the mass density ρ and the heat capacity per unit mass c_p, namely

$$\Delta T(y)=\frac{0.9}{\rho c_p} \cdot \Delta W(y) \tag{7}$$

where $\Delta T(y)$ is the increment of temperature distribution in adiabatic shear band.

It should be noted that the present expression for the increment of temperature distribution is different from that for usually average temperature expressed as

$$\Delta T=\frac{0.9}{\rho c_p} \int \tau \mathrm{d} \bar{\gamma}^{\mathrm{p}} \tag{8}$$

The main difference is that the present formulation, i. e., Eq. (7), is applicable to any position in adiabatic shear band; however, the previous expression, namely, Eq. (8), can be used to calculate the change in average temperature.

To assess the average temperature increment ΔT in adiabatic shear band over the interval $[t, t+\Delta t]$, Eq. (8) needs to be modified as

$$\Delta T=\frac{0.9}{\rho c_p} \Delta \bar{\gamma}^{\mathrm{p}} \cdot \tau_t \tag{9}$$

The increment $\Delta \bar{\gamma}^{\mathrm{p}}$ can be determined according to Eq. (2) as follows:

$$\Delta \bar{\gamma}^{\mathrm{p}}=\frac{\Delta \tau}{c'} \tag{10}$$

Substitution of Eq. (10) into Eq. (9) yields

$$\Delta T=\frac{0.9}{\rho c_p} \cdot \frac{\Delta \tau}{c'} \cdot \tau_t \tag{11}$$

At time $[t, t+\Delta t]$, the actual average temperature is

$$T_{t+\Delta t}=T_t+\Delta T \tag{12}$$

where T_t is the average temperature at time t.

Similarly, at the end of the interval, the actual average plastic shear strain is

$$\bar{\gamma}_{t+\Delta t}^{\mathrm{p}}=\bar{\gamma}_t^{\mathrm{p}}+\Delta \bar{\gamma}^{\mathrm{p}} \tag{13}$$

where $\bar{\gamma}^{\mathrm{p}}$ is the average plastic shear strain at time t.

To obtain the decrease of flow shear stress due to heat softening effect, Johnson-Cook constitutive relation is used,

$$\tau_{t+\Delta t}^m=\tau_{t+\Delta t} \cdot\left[1+C \ln \frac{\dot{\gamma}_{\mathrm{p}}}{\dot{\gamma}_0}\right] \cdot \left[1-\left[\frac{T_{t+\Delta t}-T_t}{T_{\mathrm{m}}-T_t}\right]^m\right] \tag{14}$$

where T_{m} is the melting temperature of material; T_0 is the initial temperature of material.

The shear stress $\tau_{t+\Delta t}^m$ is believed to be the actual flow shear stress caused by the heat generated by plastic shear, which wakening the load-carrying capacity of the material. Substituting $\tau_{t+\Delta t}^m$ into Eq. (6) for τ_t and using Eq. (7) to Eq. (14), then we can calculate the increment of the temperature distribution over the next time interval $[t+\Delta t, t+2 \Delta t]$. Summing the temperature distribution increments in each time step leads to change in the total temperature distribution. When shear localization just occurs, $t=0$, $T_t=T_0$, $\tau_0=\tau_c$, $\bar{\gamma}_0^{\mathrm{p}}=0$.

2.4 Process of calculation

The schematic figure for calculation process is depicted in Fig. 3.

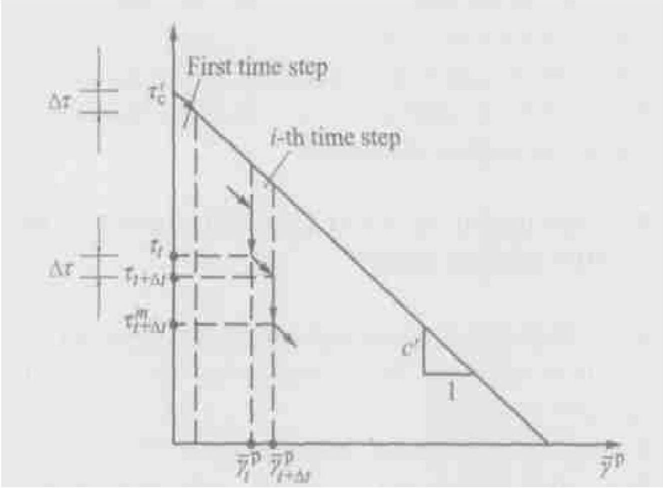

Fig. 3 Calculation of flow shear stress within any time step

The main steps for calculation of temperature distribution in adiabatic shear band are outlined as follows.

Firstly, it is assumed that the total time from occurrence of shear localization to final fracture is t_{m}. Divide t_{m} into finite time intervals n, $t_{\mathrm{m}}=n \Delta t$, for example the first interval is $[0, \Delta t]$ and any interval is $[t, t+\Delta t]$. For the sake of simplicity, decrease of flow shear stress Δt during the ith time step remains a constant. At the start of the first time step $t=0$, $T_t=T_0$, $\tau_0=\tau_c$ and

$\bar{\gamma}_0^p = 0$, where T_0 is the initial temperature of material.

Secondly, gradient-dependent plasticity is adopted to compute the increment of the plastic shear strain distribution in adiabatic shear band according to $\Delta\tau$. The flow shear stress τ_t at time t is called the old flow shear stress that is needed to calculate the nonuniform plastic work in the next step.

Thirdly, the old flow shear stress is multiplied by the obtained plastic shear strain distribution increment to calculate the change in the nonuniform plastic work. According to the well-known assumption that 90% plastic work is converted into heat, the increment of the temperature distribution in adiabatic shear band is proposed.

Next, Integrating the temperature distribution leads to the change in the average temperature. Using Johnson-Cook constitutive relation, a new flow shear stress due to thermal softening is presented. The old flow shear stress in the third step is replaced by the present new flow shear stress. Recalculate the plastic work distribution, the temperature distribution and the average temperature over the following interval. Continue the procedure above until the average plastic shear strain at failure is achieved.

Once the total time t_m is consumed, summing the increments of temperature distribution in each interval results in the total increase of temperature in adiabatic shear band.

3 EXAMPLES AND DISCUSSION

According to Ref. [13], the dynamic shear strength, the mess density, the melting temperature and the heat capacity per unit mass for Ti-6Al-4V are $\tau_c = f\tau_c$, $\rho = 4\ 428$ kJ/m^3, $T_m = 1\ 923$ K, and $c_p = 564$ J/(kg•K), respectively. The experimentally obtained shear band thickness in Ti-6Al-4V is about 12 − 55 μm[13], so we let the thickness of shear band $w = 35$ μm. Using Eq. (4), the characteristic length describing the extent of heterogeneity for Ti-6Al-4V is about $l = 5.57$ μm. The initial temperature is $T_0 = 293$ K and softening modulus $c' = 111.6$ MPa $= cf$ is selected to describe the brittleness of Ti-6Al-4V. In addition, for simplicity, we set $m = 1$.

The temperature distributions for different average plastic shear strains in adiabatic shear band in Ti-6Al-4V are shown in Fig. 4. It is found that the temperature distribution is highly nonuniform. As expected, temperature approaches to its maximum at the center of the band and decreases to zero at the two external edges. Temperature profiles become steeper when the average plastic shear strain is increased. In a word, the amount of heat generation is the highest at the sites of the highest plastic shear strain.

When the flow shear stress is decreased to 400 MPa corresponding to the average plastic shear strain of 1.8, from the peak stress, the calculated peak temperature 760 K(= 487 ℃) in the middle of the band falls into the experimentally measured range of 450 − 550 ℃[13]. The shaded region in Fig. 4 denotes the temperature range measured by an array of infrared detectors[13]. Therefore, the present prediction for the maximum temperature in adiabatic shear band is in agreement with experimental measurements.

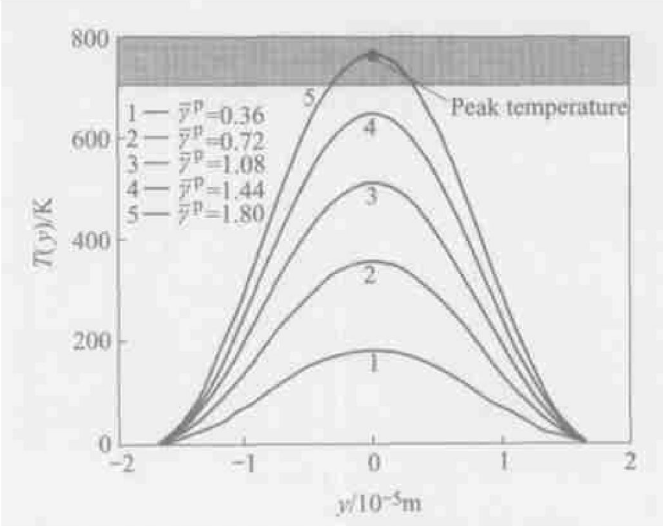

Fig. 4 Temperature distributions in adiabatic shear band for different average plastic shear strains

Fig. 5 depicts the increments of the nonuniform temperature in adiabatic shear band for different average plastic shear strains. It can be found that for the lower average plastic shear strain the temperature distribution grows more quickly than

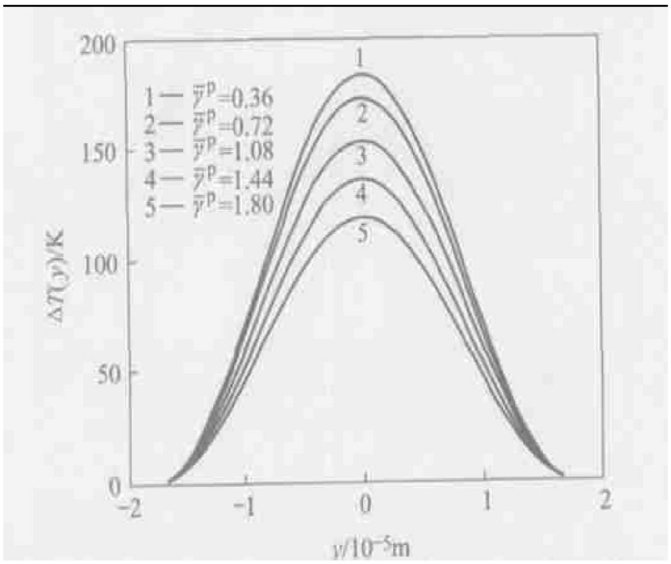

Fig. 5 Increments of temperature distribution in adiabatic shear band for different average plastic shear strains

that for the higher average plastic shear strain. This is due to the fact that the plastic work becomes low as the average plastic shear strain increases.

Effects of the dynamic softening modulus c' and the parameter $0.9(\rho c_p)^{-1}$ on the temperature profiles are shown in Figs. 6 and 7. In Fig. 6, we take $\tau'_c = 750$ MPa, $\rho = 4\,428$ kg/m^3, $T_m = 1\,923$ K, $c_p = 564$ J/(kg·K), $w = 35$ μm, $T_0 = 293$ K, $\gamma^p = 0.36$, and $m = 1$. In Fig. 7, we let $\tau_c = 750$ MPa, $T_m = 1\,923$ K, $w = 35$ μm, $T_0 = 293$ K, $\gamma^p = 0.36$, $m = 1$, and $c' = 111.6$ MPa.

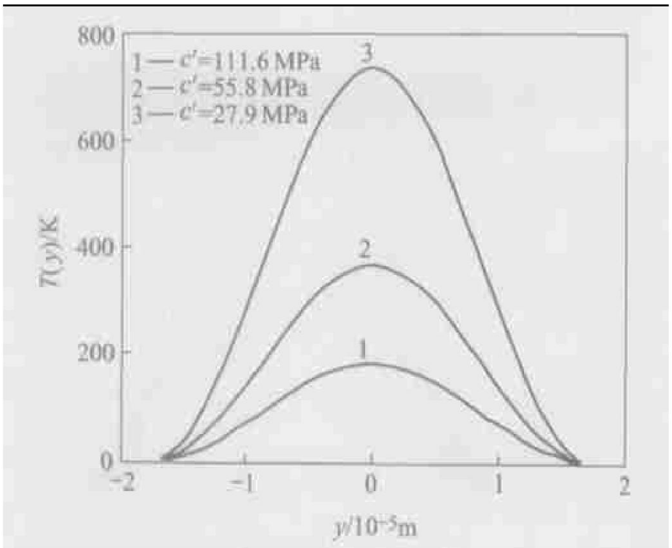

Fig. 6 Temperature distributions in adiabatic shear band for different dynamic shear softening modulus

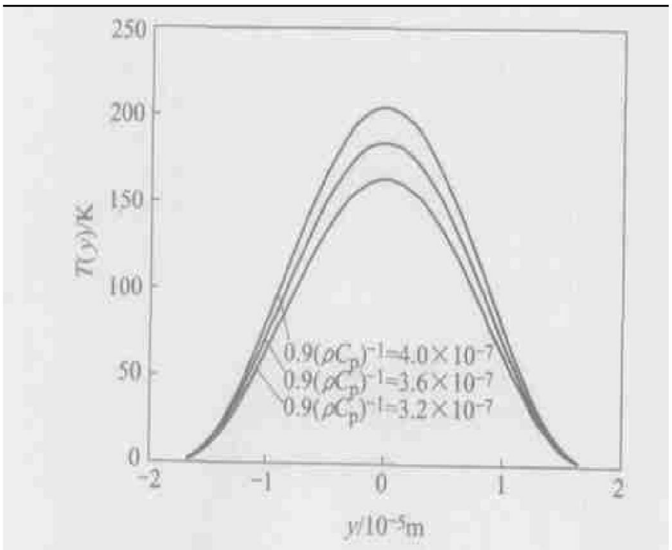

Fig. 7 Temperature distributions in adiabatic shear band for different densities of mass multiplied by heat capacities per unit mass

It is found that the lower the softening modulus is, the higher the nonuniform temperature is; the temperature is increased as ρc_p is decreased. Low heat capacity makes Ti-6Al-4V prone to increase of temperature in shear band, so that Ti-6Al-4V shows a great propensity for adiabatic shear band formation.

The present theoretical results for nonuniform temperature distributions qualitatively agree with previous numerical and experimental results showing that the temperature is a function of position and time[11, 13].

4 CONCLUSIONS

1) It is necessary to generalize or modify the traditional elastoplastic theory to investigate the characteristics of temperature distribution in adiabatic shear band, which can be observed in many experimental tests.

2) Gradient-dependent plasticity is unitized to calculate the increment of plastic strain distribution, the increment of plastic work and the increment of temperature distribution within any time step. Consequence of the increase of the average temperature in adiabatic shear band is the decrease of the load-carrying capacity, which is computed according to the Johnson-Cook constitutive relation.

3) Present calculations of the temperature distribution in adiabatic shear band show that the maximum temperature is reached at the center of the band, while at the two edges of the band there is not any temperature change. The value of the present peak temperature in adiabatic shear band in Ti-6Al-4V is consistent with experimental observations. Moreover, the obtained highly nonuniform temperature profiles agree with existing experimental measurements and numerical predictions.

4) It should be noted that the present analysis is particularly applicable to the high strain rate tests, for heat diffusion is completely neglected.

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