

Microstructure evolution mechanism in adiabatic shear band in TA2^①

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Abstract: The microstructure evolution mechanism in adiabatic shear band in commercial pure titanium (TA2) at high strain rates ($\dot{\gamma} \approx 10^5 - 10^6/s$) were studied. The nanosized recrystallized grains (about 50 nm in diameter) within the center of adiabatic shear band (ASB) were observed by means of transmission electronic microscope (TEM). A Rotational Dynamic Recrystallization (RDR) mechanism can explain the microstructure evolution (i. e. nanosized grains were formed within 5 - 10 μ s) in ASB. Kinetics calculations indicate that the recrystallized small grains are formed during the deformation and don't undergo significant growth by grain boundary migration after deformation.

Key words: adiabatic shear band; microstructure evolution; dynamic recrystallization

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1 INTRODUCTION

During the past decade, the microstructure characteristic of adiabatic shear band (ASB) was investigated by means of scan electronic microscopy (SEM), transmission electronic microscopy (TEM) and electron backscatter diffraction (EBSD). Typically, the center area of ASB is composed of equiaxed grains with a size of 50 - 300 nm in diameter. Many researchers consider it due to dynamic recrystallization (DRX)^[1-8]. Based on quantitative analysis, Andrade et al^[3] concluded that the classical recrystallization mechanisms were far too slow to account for the observed under high-strain, high-strain-rate conditions. He proposed a possibility that a new DRX mechanism exists. However, the new mechanism is not clear. Hines et al^[9] proposed a model called Progressive Subgrain Misorientation (PriSM). Perez-Prado et al^[10] found that this model is very suitable to explain the microstructure evolution in the ASBs in Ta and Ta-W alloys. Recently, Meyers et al^[8] studied the ASB in AISI 304L stainless steel quantitatively by using a model called Rotational Dynamic Recrystallization (RDR) mechanism. The result of kinetic calculation showed that the grain with diameter smaller than or equal to 200 nm can be formed at $T/T_m = 0.5$ within the deformation time. Nevertheless, they indicated that one can not exclude the possibility that the microstructural evolution continues during the cooling stage, after deformation has seized. Since the thermo-mechanical history of the shear localization regions is rather complex, one asks the obvious questions:

1) Do the observed recrystallization features occur during or after plastic deformation?

2) What is the mechanism of recrystallization?

In this paper, we address these questions for the ASBs in an explosive cladding TA2 through kinetics calculations and comparisons for existing several recrystallization mechanisms.

2 EXPERIMENTAL

The materials used in the present work were commercial purity titanium (TA2) and mild steel (A3). The TA2/A3 composite was achieved by constant stand-off explosive cladding technique. The impact velocity was equal to 608 m/s. The pressure corresponding to the velocity was approximately 8.4 GPa, the strain rate was $5 \times 10^5 - 10^6/s$ and the maximum strain was about 5^[2]. The deformation time t is simply given by the total strain divided by the strain rate, that is 5 - 10 μ s. Specimens for TEM analysis were cut from the central portion of the sheets in a plane parallel to the jetting direction and normal to the plane of the clad interface. Investigations of the microstructure in ASBs were performed with a JEOL 2010 analytical TEM (operated at 200 kV).

3 RESULTS AND DISCUSSION

3.1 Microstructure characteristic

Our previous analyses^[2] showed that many ASBs developed from the interface and disappeared in TA2 matrix but no ASB was observed on the A3 side. The

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reason was given in Ref. [2]. The shear bands have an angle of 45° across the interface direction. And the measured shear-band widths vary between 4 and 8 μm .

Fig. 1 (a) shows the recrystallized small grains within the center of ASB. The average grain size is about 50 nm in diameter. It is 2–3 orders of magnitude smaller than the matrix grain size (about 30 μm in diameter). Fig. 1 (b) shows the elongated cell structures in the transition region between ASB and the matrix. The width of these cell structures is 50–100 nm, which is a similar size of the recrystallized grains in the center of ASB. These features are similar to the ones observed in pure Cu^[3,4], Ta and its alloys^[5,10], Monel alloy^[6], 8089 AlLi alloy^[7], AISI 304L stainless steel^[8] and Ti6Al4V^[11].

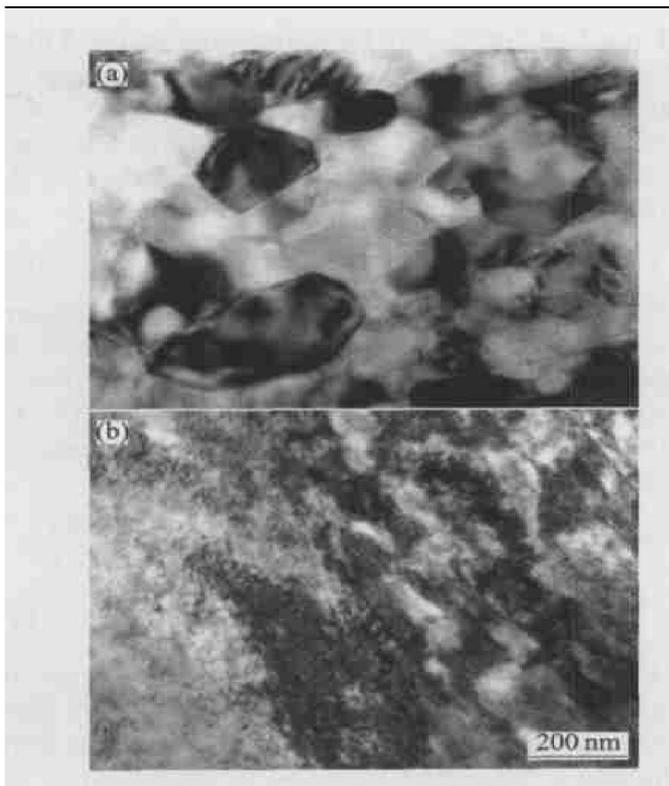


Fig. 1 TEM image showing microstructure of ASB
(a) —Recrystallized small grains within ASB;
(b) —Elongated cell structures of transition zone

3.2 Estimate temperature rise in ASB

At high strain rates ($> 10^3/\text{s}$), the deformation process is extremely short and can be considered as an adiabatic process. The following equation is used to calculate the adiabatic temperature rise in ASBs^[2,3,5-8]:

$$T - T_0 = \frac{\beta}{\rho c} \int \sigma d\varepsilon \quad (1)$$

where T_0 is the environmental temperature, β is the fraction of plastic work converted to heat, commonly $\beta = 0.9$, ρ is mass density, c is heat capacity, ε is plastic strain and σ is stress which can be calcu-

lated by constitutive equation.

Zerilli–Armstrong pointed out that HCP metals have a mechanical response falling somewhere between BCC and FCC metals. They use the following equation (Z–A equation) to describe the constitutive response of HCP metals:

$$\sigma = A_0 + B \exp[-(\beta_0 - \beta_1 \ln \varepsilon) T] + B_0 \varepsilon^n \exp[-(\alpha_0 - \alpha_1 \ln \varepsilon) T] \quad (2)$$

where A_0 , B , B_0 , C_n , α_0 , α_1 , β_0 and β_1 are experimentally determined parameters. Their values are 0, 990 MPa, $1.1 \times 10^{-4} \text{ K}^{-1}$, $7.5 \times 10^{-5} \text{ K}^{-1}$, 0.5, 700 MPa, $2.24 \times 10^{-3} \text{ K}^{-1}$ and $9.73 \times 10^{-5} \text{ K}^{-1}$ for TA2^[11], respectively.

The heat capacity of TA2 is: $C(T) = 514 + 0.1357 \times 10^{-3} T - 3.366 \times 10^3 / T^2 (\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1})$ ^[11]. Substituting it into Eqn. (1) and combining it with Eqn. (2), the relationship between temperature and effective strain will be obtained. The simple relation between true strain and engineering shear strain is^[11]: $\gamma = \sqrt{2 \exp(2\varepsilon) - 1} - 1$. The relations between temperature and the converted engineering shear strain are plotted in Fig. 2. At strain rates equal to $5 \times 10^5/\text{s}$, the temperature in ASBs will reach $0.4 T_m$ (776 K) when the strain $\gamma = 2.58$ (the corresponding time $\approx 5 \mu\text{s}$). The maximum adiabatic temperature is determined to be 1142 K when the deformation has seized. The shear band temperature as a function of engineering shear strain at different strain rates is also given in Fig. 2. Lower strain rate results in lower temperature and smaller temperature rising rate.

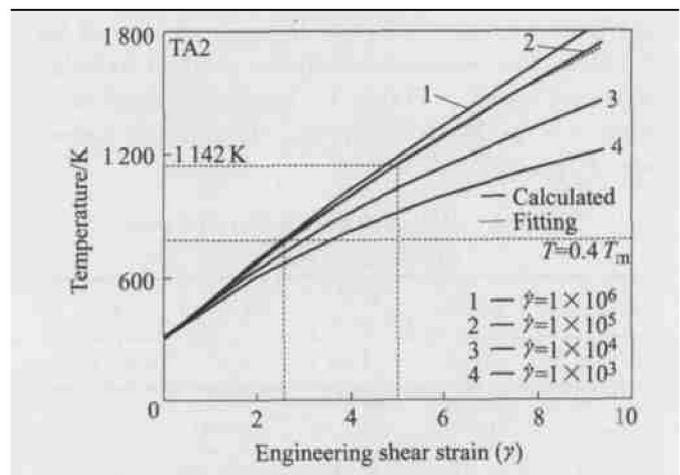


Fig. 2 Calculations predicting temperature rise within ASB in TA2 at different strain rates

In order to conveniently express the relationship between temperature and shear strain, a polynomial function is used to fit the curve when the strain rate is $5 \times 10^5/\text{s}$. The results show that the following function fits the original data well (Fig. 2):

$$T = -4.3985 \gamma^2 + 192.5605 \gamma + 293.1518 \quad (3)$$

3.3 Recrystallization mechanism

3.3.1 Recrystallization model comparisons

There are two classic static recrystallization mechanisms: high angle boundary migration mechanism and subgrain coalescence mechanism. The kinetic equation for high angle boundary migration mechanism is

$$t(T) = \frac{SLkT}{6b^2 \mu \theta \delta D_0 \exp(-Q/RT)} \quad (4)$$

where S is the recrystallized grain size, L is the average subgrain diameter, k is Boltzman's constant, T is temperature in Kelvin, b is the Burger's vector, μ is the shear modulus, θ is the subgrain boundary misorientation angle, often $\theta = 5^\circ$, δ is the width of grain boundary, D_0 is a constant related to grain boundary diffusion, Q is the activation energy, and R is the gas constant.

The kinetic equation for subgrain coalescence mechanism is

$$t(T) = \frac{L^4 kT \int_{\theta_m}^{\theta} \frac{d\theta}{\theta \ln(\theta/\theta_m)}}{6E_0 b^4 D_0 \exp(-Q^p/RT)} \quad (5)$$

where θ_m is the angle at which the boundary will have the maximum energy ($\approx 20 \sim 25^\circ$), Q^p is the activation energy for pipe diffusion, it is equal to $(0.4 - 0.6) Q^{[10]}$, E_0 is the energy of a dislocation given by $E_0 = \frac{1}{2} b^2 / 4\pi(1 - \nu)$ and ν is Poisson's ratio.

According to Eqns. (4) and (5), we can calculate the needed time for recrystallization at some certain temperatures for high angle boundary migration mechanism and subgrain coalescence mechanism, respectively. Note that the integral in Eqn. (5) is not constringent, changing the integral upper limit θ to 10^{-300} , the integral result will be 6.0619. The relevant constants used in calculations are listed in Table 1. Numerical method is used to write Matlab program. The kinetic curves are shown in Fig. 3.

Table 1 Relevant parameters of pure titanium (TA2)^[14]

$b/10^{-10}$ m	μ /GPa	$\gamma/(J \cdot m^{-2})$	$\delta/10^{-10}$ m	D_0
3.0	45.6	1.19	6.0	1.0×10^{-5}
$Q/(kJ \cdot mol^{-1})$	$K/(J \cdot K^{-1})$	$R/(J \cdot mol^{-1})$	$\rho/(kG \cdot m^{-3})$	S/Nm
204	1.38×10^{-23}	8.314	4.51×10^3	50

It is shown that the high angle boundary migration mechanism and subgrain coalescence mechanism are too slow to satisfy the deformation and cooling time, they are at least 3-4 orders of magnitude slower than the cooling curve.

3.3.2 Dynamic recrystallization

Derby^[12] classifies the dynamic recrystallization mechanisms into rotational and migrational types.

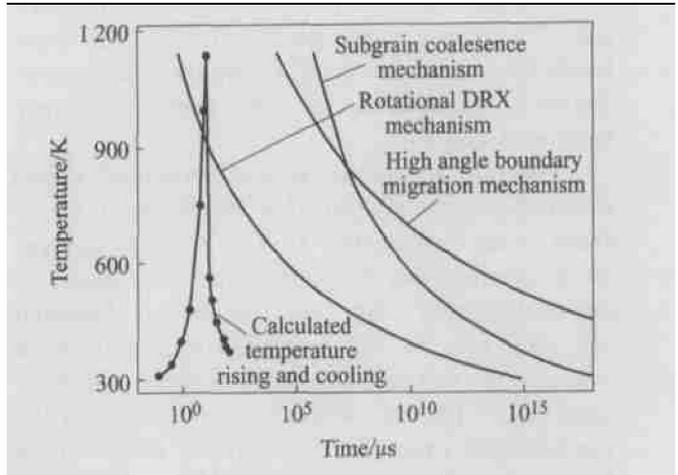


Fig. 3 Comparisons of mechanism kinetics for high angle boundary migration model and subgrain coalescence model and RDR model (The cooling curve data was from Ref. [13])

Meyers et al^[8,13] quantitatively analysed RDR mechanism model by using dislocation kinetics and energy lowest principle. The process of subgrain boundaries rotate to form high angle boundaries by the driving force of grain boundary energy and the mechanical press is described as the following equation^[8,13]:

$$t = \frac{L_1 kT f(\theta)}{4 \delta \gamma D_{b0} \exp(-Q_b/RT)} \quad (6)$$

where D_{b0} is a constant related to grain boundary diffusion, γ is the grain boundary energy, L_1 is the average subgrain diameter, and Q_b is the activation energy for grain boundary diffusion, here we choose $Q_b = (0.4 - 0.6) Q^{[10]}$, θ is the subgrain misorientation, and

$$f(\theta) = \frac{3 \tan(\theta) - 2 \cos(\theta)}{3 - 6 \sin(\theta)} + \frac{2}{3} - \frac{4\sqrt{3}}{9} \ln \frac{2 + \sqrt{3}}{2 - \sqrt{3}} + \frac{4\sqrt{3}}{9} \ln \frac{\tan(\theta/2) - 2 - \sqrt{3}}{\tan(\theta/2) - 2 + \sqrt{3}} \quad (7)$$

From Eqn. (6), the needed time for recrystallization at some certain temperatures for RDR mechanism can be calculated. According to RDR mechanism, the subgrains need to rotate about 30° to form recrystallized grains^[8,13]. However, $f(\theta)$ is a positive infinity when $\theta = 30^\circ$. Choosing $\theta = (30 - 10^{-10})^\circ$ and $L_1 = 100$ nm, the kinetic curve for RDR mechanism will be obtained as shown in Fig. 3. At the same temperature, the needed time for recrystallization for RDR mechanism is at least 4 orders of magnitude shorter than that of high angle boundary migration mechanism and subgrain coalescence mechanism. The kinetic curve intersects with the cooling curve.

The predictions of Eqn. (6) for the subgrain misorientation evolution during the deformation in ASB in TA2 are shown in Fig. 4. In Fig. 4(a), the temperature varies from $0.35T_m$ to $0.5T_m$ for a sub-

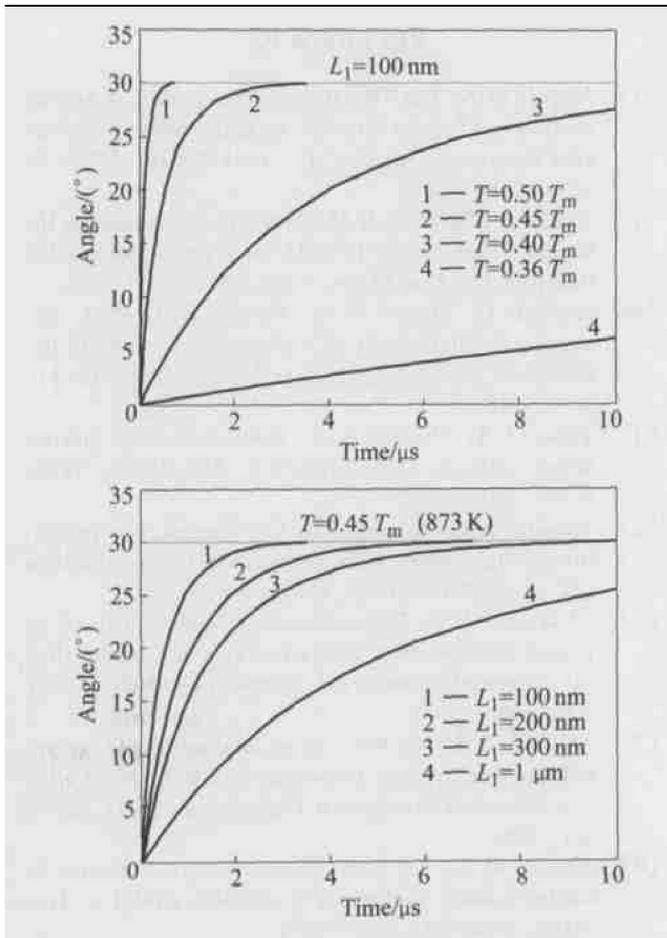


Fig. 4 Angle of rotation of subgrain boundary in TA2 as a function of needed time for (a) different temperatures for $L_1 = 100$ nm and (b) different subgrain size at $0.45T_m$

grain size of 100 nm; in Fig. 4(b), the subgrain size L_1 varies from 100 nm to 1 μm at $T = 0.45T_m$ (873 K). The rate of rotation decreases with increasing strain. The subgrain misorientation finally asymptotically approaches 30° . Larger subgrain size and lower temperature result in more needed time for recrystallization.

It is noted that in Fig. 3 and Fig. 4, we take temperature as a fixed value, which in fact is increasing continuously during the deformation (Fig. 2). Substituting Eqn. (3) into Eqn. (6), the variable T will be eliminated. The angle of subgrain rotation as a function of time for subgrain size $L_1 = 100$ nm will be obtained as shown in Fig. 5. It can be found that in the frontal about 4 μs , θ is very small. This is because in the early stage of deformation, the microstructure evolutions in severe plastic deformation zone are dislocations accumulated to form elongated cell structures and cell structures break up to form subgrains. At about 4.5 μs (the corresponding $\gamma = 2.25$, $T = 700$ K), the subgrain misorientation reached 5° and began to rotate asymptotically, approaching 30° within about 2 μs . To RDR mechanism, the subgrains rotating sharply means that DRX begins. The

critical recrystallization temperature is 700 K and it is lower than the conventional recrystallization beginning temperature ($0.4T_m$, 776 K). This is because the high dislocation density increases the driving force for recrystallization.

The needed time for subgrains (100 nm in diameter) rotating to high angle boundaries ($> 15^\circ$) is less than 3 μs (Fig. 5). The deformation time is 10 μs . So, RDR mechanism is very consistent with experiment in time. One can conclude that, according to RDR mechanism, grain with diameters smaller than or equal to 100 nm can be formed within the deformation time.

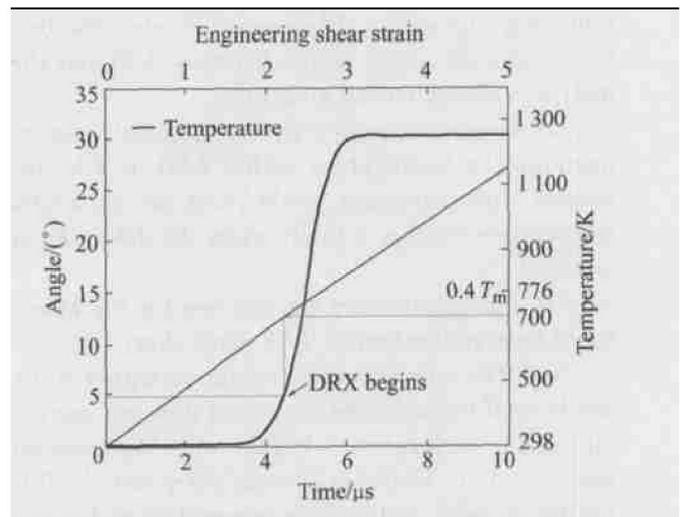


Fig. 5 Angle of subgrain rotation in TA2 as a function of time for subgrain size $L_1 = 100$ nm

As we know, migrational recrystallization mechanisms are all based on diffusion which is temperature dependent and will surely occur when the temperature is very high. For migrational recrystallization mechanisms, the following grain growth equation can be used to calculate the recrystallized grain size^[13]:

$$d \approx k_0 \sum_{i=0}^N \left| \exp\left(-\frac{Q}{2RT(t_i)}\right) \right| \Delta t^{1/n} \quad (8)$$

where k_0 and n are constants related to material, Q is activation energy for grain growth, and Δt is the change in time. For pure Ti, $k_0 = 4.3$, $n = 1$ ^[13], over the entire time, the calculated grain size d is about 0.12 nm, which is much smaller than the observed 50 nm. So, we have reason to conclude that migrational recrystallization mechanisms are too slow to account for the observed recrystallized microstructures. The influence of migrational recrystallization mechanisms is minor. During the cooling stage, the microstructure evolution must be a migrational mechanism, because of the absence of mechanical assistance. Therefore, the observed recrystallized nano-grains were formed during the deformation.

The observation by TEM shows that the recrystallized small grains in the center area of ASB have

the similar size as that near subgrains (Fig. 1). This is very consistent with RDR mechanism. If the new recrystallized grains are formed by RDR mechanism, they have not undergone significant growth by grain boundary migration.

4 CONCLUSIONS

1) Adiabatic shear bands (ASBs) are found on the pure titanium side in the TA2/A3 explosive cladding interface. The observation by TEM show that the center area of ASB is composed of recrystallized grains with a diameter of 50 nm, the feature of the transition region between ASB and the matrix is elongated cell structures.

2) Based on Zerilli-Armstrong constitutive equation, the temperature within ASB in TA2 increases with increasing strain, and the maximum temperature reaches 1 142 K when the deformation is seized.

3) The quantitative calculations for the kinetics of recrystallization of TA2 show that:

(a) The microstructure evolution within ASBs can be well explained by rotational dynamic recrystallization mechanism. Within the deformation time (5 - 10 μ s), the grains can carry out the following process: dislocations accumulate to form elongated cell structures, cell structures break up to form subgrains, subgrains rotate and finally form recrystallized grains with a diameter smaller than or equal to 100 nm.

(b) The migrational recrystallization mechanisms such as high angle boundary migration mechanism and subgrain coalescence mechanism are too slow to account for the observed fact (the calculated grain size is 2 - 3 orders of magnitude smaller than that observed). Their influence in the whole stage is minor. One has reason to conclude that the observed recrystallized nanosized grains are formed during the deformation.

REFERENCES

- [1] Meyers M A, Pak Han Ryong. Observation of an adiabatic shear band in titanium by high voltage transmission electron microscopy [J]. *Acta Metall*, 1986, 34(12): 2493 - 2499.
- [2] YANG Y, ZHANG X M. Adiabatic shear band on the titanium side in the Ti/Mild steel explosive cladding interface [J]. *Acta Mater*, 1996, 44(2): 561 - 565.
- [3] Andrade U, Meyers M A, Vecchio K S, et al. Dynamic recrystallization in high strain rate plastic deformation of copper [J]. *Acta Metall*, 1994, 42(9): 3183 - 3195.
- [4] Hines J A, Vecchio K S. Recrystallization kinetics within adiabatic shear bands [J]. *Acta Mater*, 1997, 45(2): 635 - 649.
- [5] Nemat-Nasser S, Isaacs J B, Liu Ming qi. Microstructure of high strain, high strain rate deformed tantalum [J]. *Acta Mater*, 1998, 46(4): 1307 - 1325.
- [6] LI Q, XU Y B. Dynamic recrystallization induced by plastic deformation at high strain rate in a Monel alloy [J]. *Materials Science and Engineering*, 2000, A276: 250 - 256.
- [7] XU Y B, ZHONG W L. Shear localization and recrystallization in dynamic deformation of 8089 Al-Li alloy [J]. *Materials Science and Engineering*, 2001, A238: 287 - 295.
- [8] Meyers M A, Xu Y B. Microstructural evolution in adiabatic shear localization in stainless steel [J]. *Acta Mater*, 2003, 51: 1307 - 1325.
- [9] Hines J A, Vecchio K S. A model for microstructure evolution in adiabatic shear bands [J]. *Metall Mater Trans*, 1998, 29: 191 - 203.
- [10] Perez-Prado M T, Hines J A. Microstructural evolution in adiabatic shear bands in Ta and Ta-W alloys [J]. *Acta Mater*, 2001, 49: 2905 - 2917.
- [11] Xue Q, Meyers M A, Nesterenko V F. Self-organization of shear bands in titanium and Ti-6Al-4V alloy [J]. *Acta Mater*, 2002, 50: 575 - 596.
- [12] Derby B. The dependence of grain size on stress during dynamic recrystallization [J]. *Acta Metall Mater*, 1991, 39(5): 955 - 962.
- [13] Meyers M A, Nesterenko V F. Shear localization in dynamic deformation of materials: microstructural evolution and self-organization [J]. *Materials Science and Engineering*, 2001, A317: 204 - 225.
- [14] YONG Q-long, TIAN Jian guo. Physical metallurgical data of titanium in steels [J]. *Journal of Yunnan Polytechnic University*, 1999, 15(2): 7 - 10.

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