Influence of high pulsed magnetic field on tensile properties of TC4 alloy*

Gui-Rong Li(李桂荣)†, Fang-Fang Wang(王芳芳), Hong-Ming Wang(王宏明), Rui Zheng(郑瑞), Fei Xue(薛飞), and Jiang-Feng Cheng(程江峰)

School of Materials Science and Engineering, Jiangsu University, Zhenjiang 212013, *China*

(Received 7 November 2016; revised manuscript received 31 January 2017; published online 10 March 2017)

The tensile tests of TC4 alloy are carried on electronic universal testing machine in the synchronous presence of high pulsed magnetic field (HPMF) parallel to the axial direction. The effects of magnetic induction intensity ($B = 0$, 1 T, 3 T, and 5 T) on elongation (δ) of TC4 alloy are investigated. At 3 T, the elongation arrives at a maximum value of 12.41%, which is enhanced by 23.98% in comparison with that of initial sample. The elongation curve shows that 3 T is a critical point. With B increasing, the volume fraction of α phase is enhanced from 49.7% to 55.9%, which demonstrates that the HPMF can induce the phase transformation from β phase to α phase. Furthermore, the magnetic field not only promotes the orientation preference of crystal plane along the slipping direction, but also has the effect on increasing the dislocation density. The dislocation density increases with the enhancement of magnetic induction intensity and the 3-T parameter is ascertained as a turning point from increase to decrease tendency. When B is larger than 3 T, the dislocation density decreases with the enhancement of B. The influence of magnetic field is analyzed on the basis of magneto-plasticity effect. The high magnetic field will enhance the dislocation strain energy and promote the state conversion of radical pair generated between the dislocation and obstacles from singlet into triplet state, in which is analyzed the phenomenon that the dislocation density is at an utmost with $B = 3$ T. Finally, the inevitability of optimized 3-T parameter is further discussed on a quantum scale.

Keywords: TC4 titanium alloy, tensile properties, microstructure, magneto-plasticity effect

PACS: 62.20.–x, 81.40.Lm, 61.72.Lk, 81.40.Rs **DOI:** 10.1088/1674-1056/26/4/046201

1. Introduction

Since the 1950s, as a kind of important structural material, the titanium alloy has attracted the attention of scientists. The titanium alloy exhibits a series of excellent properties such as low density, high specific strength, advanced corrosion resistance, etc. Till now, they are widely utilized in the aerospace and aviation industries, such as the structural beams of aircraft, joints, hydraulic pipes, fasteners, fan blades, compressor blades, wing structure, etc.[1] TC4 alloy with $\alpha + \beta$ structural characteristic and medium strength, together with excellent formability and walkability, is the most popular, and hence called "universal alloy". Nowadays, the development of TC4 alloy moves towards the higher performance and lower cost. Nevertheless, there are several restrictive problems restricting its further development, such as large deformation resistance, poor plasticity, high ratio of yield strength and ultimate strength.[2] Therefore, improving the plasticity and deforming capability has gradually become serious and urgent.

Over the past twenty years, more and more physical techniques have been introduced into the fields of material fabrication and processing. The diverse physical approaches including electric,[3] electromagnetic,[4] ultrasound[5] microwave techniques[6] have been utilized because of their special phenomena such as force, heat and quantum effects besides the characteristic of free-pollution. They have provided some creative approaches to improving the microstructure and properties of materials.[7] Compared with the other approaches, the high pulsed magnetic field (HPMF) technique exhibits the characteristic of low cost and high efficiency. As a result, HPMF is utilized in current experiment to process the solid TC4 alloy so as to improve the mechanical properties, especially the elongation.

In previous research work, the TC4 alloy was exposed to the high pulsed magnetic field with different values of B and N (pulses number) then its main mechanical properties were tested.[8] The experiments demonstrated that the magnetic field can increase the strength and toughness of titanium alloy. Based on magneto-plasticity effect, the current experiment is conducted in the synchronous presence of HPMF and external stress so as to test the coupled effects of them on the mechanical properties (especially the plasticity). The magnetic field parameters were optimized and the action mechanism of magnetic field was analyzed in detail. The present work aims to explore an efficient approach to improving the plasticity of titanium alloy with the double advantages of lower cost and higher efficiency.

*Project supported by the National Natural Science Foundation of China (Grant Nos. 51371091, 51174099, and 51001054) and the Industrial Center of Jiangsu University, China (Grant No. ZXJG201585).

†Corresponding author. E-mail: liguirong@ujs.edu.cn

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2. Experiment

The target material is selected as the hot rolled TC4 titanium alloy sheet (6.2%Al–4.1%V–2.3%Zr, wt%). Being different from the normal of tensile test without extra stress, the sample was exposed synchronously to the tensile stress and magnetic field generator and the sample should be ensured to be parallel to the direction of magnetic induction lines.[9] The testing machine is DNS10 electronic universal one with 10-kN maximum loading force. In order to prevent the force of HPMF, the diamagnetic clamp was commly made of carbon steel and the tailor-made calmp in the experiment was made of non-magnetic stainless steel. The tensile sample was precisely cut into a given size by precise wire-cutting technology according to Fig. 1. Before tensile test, the sample was initally annealed at 120 °C for 2 h in YFX7 / 12Q-GCd heat treatment furnace so as to relieve the machining stress.

The magnetic field generator was mainly composed of TSK-H2060 magnetizing apparatus and solenoid coil. The voltage and the electric current were adjustable at 0 kV–2 kV and 0 A–20 A separately. By changing the voltage value, the different values of magnetic induction intensity (B) of magnetic field could be obtained. The generator worked through the switch of capacitor charging and discharging, which directly connected with the magnetic coils. When the switch was on, the magnetic coils received the pulsed current and generated a high magnetic field.

The sample was cut at 10 mm far from the fracture surface to observe the microstructure and the grain orientation, which was perpendicular to the direction of magnetic induction line The X-350A x-ray stress analyzer was used to measure the parameter of full width of half maxmium (FWHM) of the fractured specimen in order to calculate the dislocation density. The sample should be grinded, polished, etched to satisfy the metallographic desirement. The sample was etched by 5-ml HF + 10-ml HNO_3 + 85-ml H_2O corrosive liquid for about 10 s then cleaned by alcohol and dried so as to observe the structure morphology by XJG-05 microscope and then measure the volume fraction of α phase by M438-110624 Metallographic analysis software. Each sample was measured at 10 positions along a straight line with a separation distance of 1mm and the measurement error should be less than 1%.

In the presence of high pulsed magnetic field, the conversion of electron spin direction has a significant effect on the property of titanium alloy. In the following deduction, on the basis of density functional theory.[10,11] the Materials Studio software (MS) was used to calculate the integrated density of states (DOS) of α titanium crystal so as to obtain the spin polarization direction of the atoms, and then analyze the effect of magnetic field on the elastic modulus.

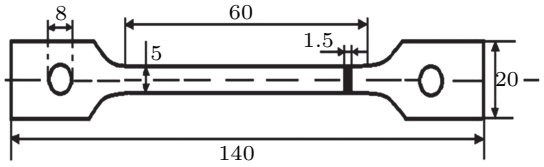


Fig. 1. Schematic diagram of tensile specimen (in unit mm).

3. Results and discussion

3.1. Tensile properties

Figure 2 shows the tensile properties of TC4 with different values of B (0, 1 T, 3 T and 5 T). Figure 2(a) shows the tensile stress–strain curve with different B values.

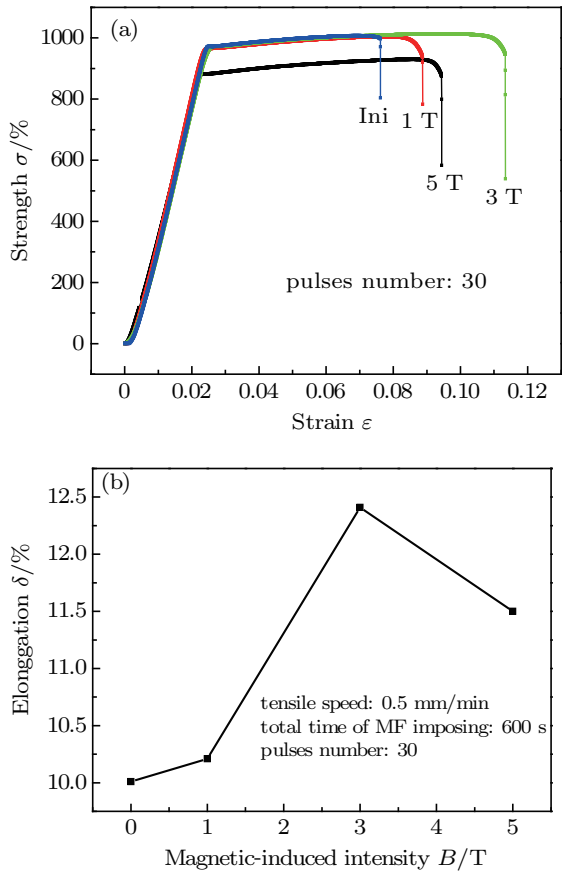


Fig. 2. (color online) Effects of B value on the tensile property of TC4 titanium alloy ($N = 30$), showing (a) stress–strain curve versus B and (b) elongation versus B.

Figure 2(b) shows the dependence of elongation (δ) on B when the number of pulses is fixed at 30. The average elongation of 1 T, 3 T, 5 T samples is 11.03% (δ), which is enhanced by 10.18% compared with the 10.01% (δ) of initial sample. The maximum value of δ is 12.41% when $B = 3$ T (marked as B^*), which is enhanced by 23.98% in comparison to the 10.01% (δ) of untreated sample. The curve tendency reveals that 3 T is a critical value. When B is less than 3 T the elongation increases gradually with B augment (0 → 1 T and 1 T→3 T); while B is larger than 3 T the elongation exhibits downtrend (3 T→5 T). It highlights that the elongation

of TC4 alloy is improved synchronously in the presence of the magnetic field.

Figure 3 shows the dependence of elastic modulus (E) on values of B (0, 1 T, 3 T, and 5 T) when $N = 30$. The relevant Evalues are 108 GPa, 105 GPa, 104 GPa, and 107 GPa. The values of elastic modulus (E) of all the magnetic field (MF) treated samples decrease by 2.5% in comparison with that of the untreated sample. At $B = 3$ T, the E of TC4 titanium alloy arrives at a minimum value which is lowered by 3.7% compared with that of the untreated sample. The data reveal that the magnetic field can reduce the elastic modulus. As is well know, the elastic modulus implies the atomic space on a micro scale. In common sense, a smaller elastic modulus corresponds to a reduced atomic distance.

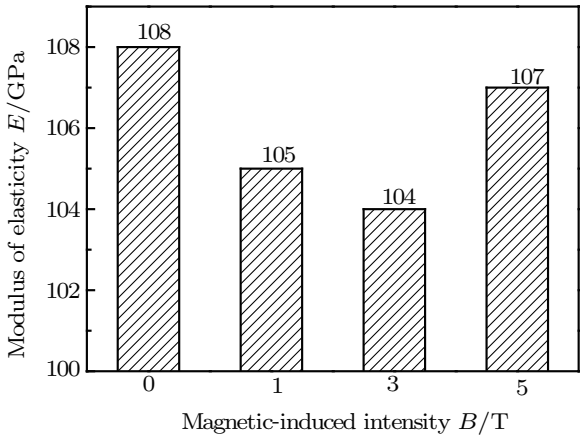


Fig. 3. Elastic moduli of TC4 titanium alloy with different magnetic induction intensities ($B = 0$, 1 T, 3 T, and 5 T).

The effects of external stress and magnetic field on TC4 alloy change not only the microstructure, but also the lattice constant, which causes the distortion, resulting in the change of atomic bond and strength, which makes the elastic recovery of the crystal material decrease

As for the magnetic properties of TC4 Titanium alloy, it is paramagnetic. On a quantum scale, the magnetic properties of material are determined by the comprehensive influences of nuclear magnetic moment, magnetic moment of the electron orbits and electron spin.

The magnetic moment of the nucleus is smaller than the electron magnetic moment, the electron orbital magnetic moment and magnetic moment of the electron spin in the opposite direction. By the virtual simulation, the atomic spin polarizations of α and β titanium crystals are studied. On the basis of the calculated integrated DOS the spin polarization direction of the atom can be determined. Due to the periodic arrangement of atoms, part of them are selected to represent the atomic configuration. Figure 4 shows an ideal array of titanic atoms.

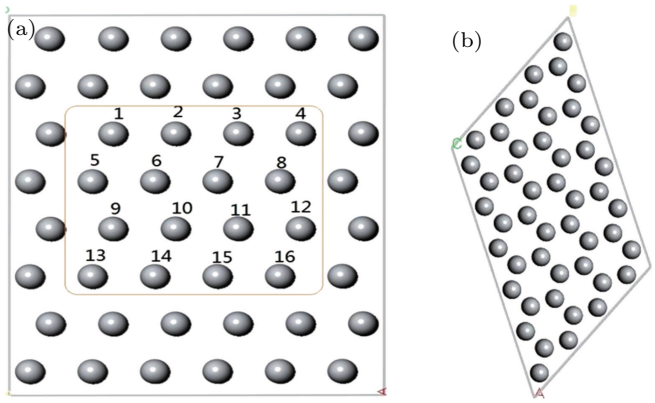


Fig. 4. Atomic arrangement and numbering in defect-free α titanium crystal: (a) the front view; and (b) the right view.

Figure 5 shows the integrated densities of spin states of Nos. 1–16 atoms in Fig. 4.

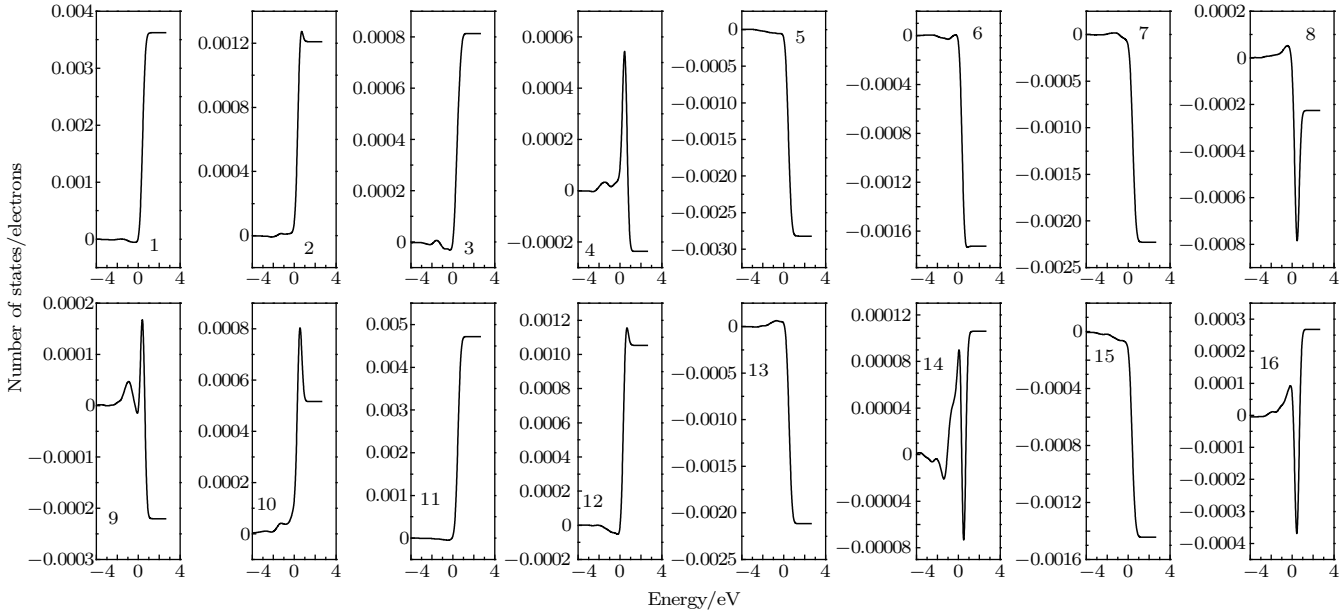


Fig. 5. Integrated DOSs of spin states of Nos. 1–16 atoms in defect-free α titanium crystal.

As can be seen from Fig. 5, the integrated densities of spin states of Nos. 1–16 below Fermi level ($E \leq 0$ eV) are almost zero. Under the condition of ground state ($T = 0$ K), the highest energy level of extra-nuclear atomic arrangement is the Fermi level, so the spin magnetic moments of these atoms are almost zero. On the contrary, the spin magnetic moments above the Fermi level change dramatically. In the case of non-ground state ($T > 0$ K), the electrons will absorb heat energy and be excited to a new level higher than the Fermi level ($E > 0$ eV). Hence, the electrons with original paired state tend to become a single electron. When exposed to a high magnetic field, in comparison with the paired electrons, these single electrons are much prone to be spin polarized.

Due to the use of material condition for the non-state ground state, it is also important to study the electronic structures above the Fermi level. Based on the spin-polarized integrated DOSs of Nos. 1–16 atoms in a range of 0 eV–2 eV, it can be found that the directions of spin polarization for any two adjacent atomic layers are opposite. Specifically, for Nos. 1–4 atoms and Nos. 9–12, the spin polarization directions are all positive; while those of Nos. 5–8 and Nos. 13–16 are all negative. For all the sixteen atoms, the integrations are preceded to 2 eV. Based on the calculated results in Fig. 5, the spin direction is confirmed and gathered to analyze the direction of spin polarization as shown by Fig. 6.

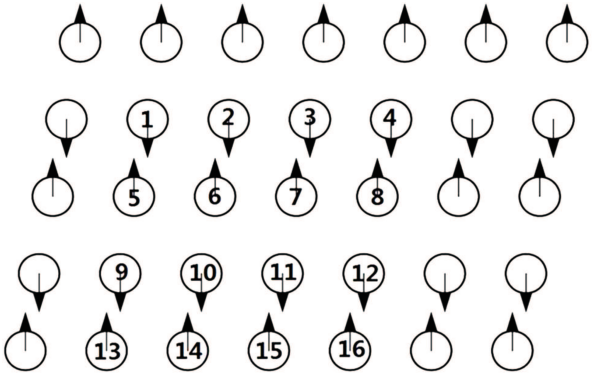


Fig. 6. Schematic diagram of spin polarization directions in defect-free α titanium crystal at non-ground state.

As can be seen from Fig. 6, in the ground state of α titanium ideal crystal, the spin polarizations of vertically adjacent two layers of atoms are in the opposite directions Under magnetic field condition, this phenomenon will lead to a repulsive force between adjacent atoms in the upper and lower layers, reducing the attractiveness of atomic layer.

During the tensile test under magnetic field, there are amounts of paramagnetic substances including dislocations and precipitates. They have the paramagnetic properties. Dislocation core region surrounding atoms under the condition of magnetic field shows stronger repulsion. TC4 titanium alloy is typical of α and β phase titanium alloy, including the elastic modulus of the lowest β titanium alloy, which is closer to the elastic modulus of human skeleton.[12] Under magnetic field condition, the spins of adjacent atomic layers are in the opposite directions, showing the performance of repulsion. The inter-atomic forces of α titanium crystal can reduce the elastic modulus of the material. The effect of magnetic field of β titanium crystal is the same as that of α titanium crystal. Therefore that stretching under pulsed magnetic field reduces the elastic modulus TC4 titanium alloy improves the biomechanical compatibility of metal materials, which is of great significance for developing the medical metal materials.

3.2. Microstructure

Figure 7 shows the metallurgical microstructures of TC4 alloy at the tensile fracture subjected to different pulsed magnetic fields. The light area corresponds to α phase, while the dark one corresponds to β phase. Figures 7(a)–7(d) correspond to the microstructures of the sample at $B = 0$ T, 1 T, 3 T, and 5 T, showing that with the gradual enhancement of magnetic induction intensity, the volume fractions of α phase in TC4 alloy are 49.7%, 53.5%, 55.9%, and 50.5% respectively. It can be seen that the amount of α phase is increased with the B enhancement. Figure 8 shows the volume fraction of α phase in TC4 titanium alloy varying with magnetic induction intensity increasing. The curve tendency shows that the 3 T is a critical value. The volume fraction of α phase in TC4 alloy shows the trend of increasing first and then reducing with the enhancement of magnetic induction intensity (0→3 T and 3 T→5 T). Therefore, it can be deduced that the high pulsed magnetic field acts as an incentive to promote the phase transformation from β phase to α phase. At $B = 3$ T, the volume fraction of α phase is increased by 12.5% over that of 0T sample. This phenomenon indicates that the magnetic field induced β matrix generates strip secondary α phase. Since

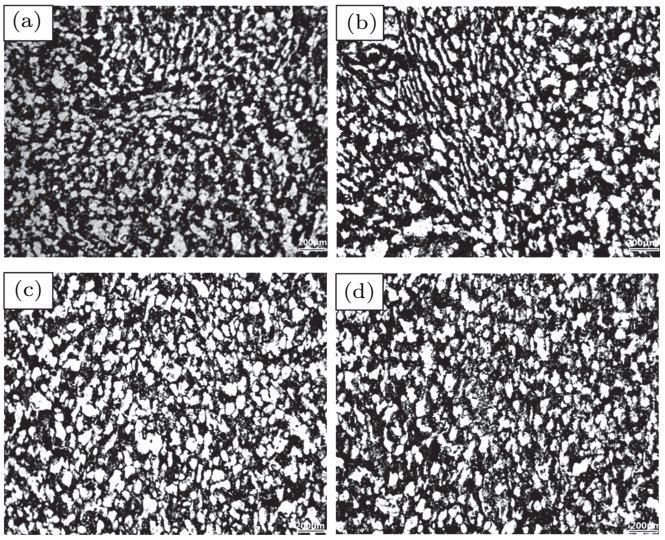


Fig. 7. Microstructures of TC4 titanium alloy with different B values: (a) $B = 0$ T, (b) $B = 1$ T, (c) $B = 3$ T, and (d) $B = 5$ T.

these secondary phases are independent, unrelated organization, the slip resistance is reduced and the shaping titanium alloy is improved.

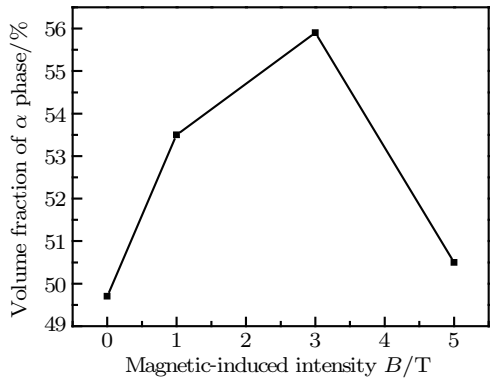


Fig. 8. Volume fraction of α phase varying with B increasing.

3.3. Texture

Figure 9 illustrates the XRD patterns of samples with different values of B ($N = 30$), showing that α and β phases are still the main components in the TC4 titanium alloy, but the heights and the widths of the diffraction peaks are changed significantly. Because of the diffraction peak intensity, the 2θ values of 35°–36°, 40°–41°, and 63°–64° are mainly taken into consideration, which are corresponding to the (100), (101), and (110) crystal plane respectively. In the cases of 0 T/3 T, the three-peak intensities are 96.58/162.68, 243.10/366.46, and 137.31/314.03 respectively. Thus, the three-peak intensities of titanium alloys are much higher than that of the initial sample when $B = 3$ T.

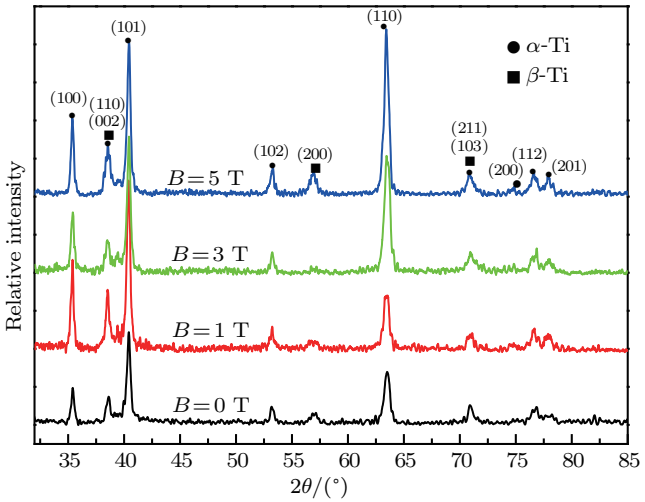


Fig. 9. (color online) XRD patterns of samples subjected to different values of B.

Particles in titanium alloys have the magnetic anisotropic property, and whose magnetic anisotropic energy is bigger than the thermal energy. When the alloy is exposed to the tensile stress and magnetic field synchronously, the particle with different crystal paralleling to the axial magnetic field has the magnetic anisotropy and different magnetization energy. The steering axis will rotate and parallel to the stretching direction because of different magnetization energies, which results in the deformation texture. Due to the influence of the texture microstructure, the mechanical property of the material demonstrates a strong anisotropy. Therefore, the elongation of the alloy is seriously affected. Figure 10 illustrates the orientations of crystal grains without and with the high pulsed magnetic field.

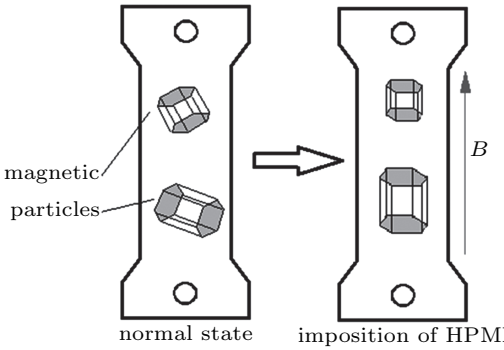


Fig. 10. Orientations of crystal grains without and with HPMF.

3.4. Dislocation characteristic

According to Dunn formula,[13,14]

$$\rho = \frac{L^2}{4.35 \times b^2}, \tag{1}$$

where is the dislocation density; L is the full width at half maximum (FWHM) in XRD test; b is the Burgers vector. It can be obviously deduced that is proportional to L^2. Therefore, the dislocation density in the sample can be characterized by the FWHM value. The L values of samples are 0.3528, 0.3728, 0.3975, and 0.3528 and the relevant values of L^2 are 0.1245, 0.1390, 0.1580, and 0.1521 respectively, which are corresponding to the magnetic induction intensities 0 T, 1 T, 3 T, and 5 T respectively. When $B = 3$ T, the dislocation density reaches a maximum value, which is 26.91 times higher than that of 0-T sample. Figure 11 shows the dependence of L^2 on B. With B increasing, the dislocation density increases rapidly first (0→1 T→3 T) and then decreases slowly (3 T→5 T). It is similar to the elongation variation indicated in Fig. 2.

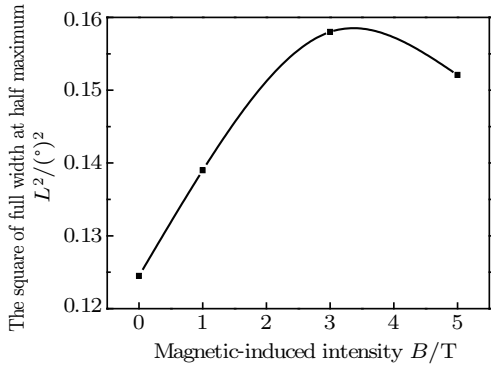


Fig. 11. Dependence of L^2 on B.

The main incentive to induce the dislocation multiplication is the principle issue to explain the effect of magnetic field. As analyzed by previous literature,[1] the reasons do not lie in the Lorentz or the magnetizing forces. In this work, the effect of the magnetic field on the dislocation multiplication will be analyzed from the angle of the dislocation strain energy and the magneto-plasticity effect.

In the surrounding areas of dislocations, the crystal will distort to some extent and store a large amount of energy that is called the dislocation strain energy. Assuming that the crystal is a uniform continuous medium without internal clearance, the dislocation strain energy E_m can be expressed as[15]

$$E_{\mathrm{m}} = \frac{Gb^2}{4\pi(1-\nu)} \ln \frac{r_1}{r_0}(1-\nu\cos^2\theta), \tag{2}$$

where G is the Lame constant, ν is the Poisson ratio, r_1 and r_0 are the inner and outer radius of the dislocation lines, θ denotes the angle between Burgers vector b and dislocation line. Only in the presence of stress, will the E_{m} be proportional to the b^2 and r_1. When only stress exists, the dislocation of strain energy is proportional to the b^2 and r_1. While in the presence of magnetic field, the dislocation core containing paramagnetic centers will be magnetized, resulting in the generation of magnetic stress. The relevant dislocation strain energy E_{H} can be further expressed as[16]

$$E_{\mathrm{H}} = \frac{bH_0h_0r_0}{8(1-\nu)}(\mu-1)(1-2\nu)(2\mu-1)\ln\frac{r_1}{r_0}, \tag{3}$$

where H_0 represents the magnetic intensity of the external magnetic field, h_0 means the magnetic intensity due to the magnetic magnetization of dislocations, and μ is the displacement vector.

In the case that the external stress and magnetic field exist spontaneously, the integrated dislocation strain energy E can be expressed as

$$\begin{aligned} E &= E_{\mathrm{m}} + E_{\mathrm{H}} \\ &= \frac{b}{4(1-\nu)}\left[\frac{bG}{\pi}(1-\nu\cos^2\theta)\right. \\ &\quad \left. + \frac{H_0h_0r_0}{2}(\mu-1)(1-2\nu)(2\mu-1)\right]\ln\frac{r_1}{r_0}. \end{aligned} \tag{4}$$

It can be deduced that the dislocation strain energy will be increased in the presence of magnetic field. However, the increased energy will not be consumed in the form of heat within the crystal.[17] It results in two changes: on one hand, it strengthens the interactions among the existed dislocations; on the other hand, it promotes the de-pinning process of dislocations from pinning center, which is attributed to the enhancement of dislocation.

It is further analyzed that the magneto-plasticity that is the effect of high magnetic field can be explained qualitatively and quantitatively. The kernel lies in the fact that the increase of elongation and plasticity are closely linked with the dislocation structural state.

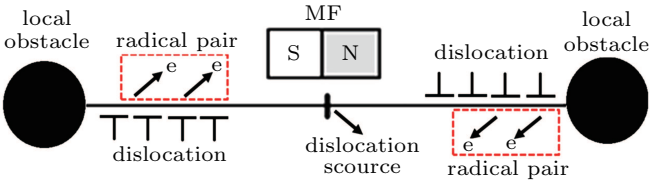


Fig. 12. (color online) Schematic diagram for free electron stimulation between the dislocation and obstacles.

In the nonmagnetic materials, such as TC4 titanium alloy, there are amounts of paramagnetic substances including dislocations and precipitates. The dislocations exhibit the paramagnetic property because of the lots of electrons in them. In TC4 alloy, the main precipitates are of α and β phases that are composed of Al and Ti intermetallic compounds, which are typical paramagnetic phases that often act as obstacles for dislocation movement. For the paramagnetic dislocation or precipitates in the absence of magnetic field, both the electron spin and the atomic intrinsic magnetic moment are in the disordered state; while in the presence of high magnetic field, their behavior will be influenced apparently. During the tensile test under magnetic field, when the active dislocations move close to the paramagnetic obstacles, the free electrons will be stimulated between paramagnetic dislocations and obstacles, which contributes to the formation of radical pairs just as shown in Fig. 12. In view of the differences in the spin combination of electron pairs, the radical pairs are divided into four states, i.e., S, T_0, T_+, and T_-,[18] which are shown in Fig. 13.

In the absence of magnetic field, the radical pair is at S state. For the S state, the spin directions of electron pair are opposite. The spin magnetic moment will be counteracted. On this condition, the demanded energy for dislocation to surmount obstacle is high.[19] The dislocation mobility and, therefore, elongation will be confined. When the sample is exposed to PHMF, the electron pairs spin will be influenced by the magnetic field and then turn into the T_0, T_+ or T_- states. For the dislocations with T structural state, the demanded energy will be lowered. Hence, it is easier for dislocations to move and surmount obstacle, which is just the essence of magneto-plasticity effect. The theory explains the plasticity enhancement of alloy subjected to both the PHMF and the tensile stress.

Magnetic field provides part of the energy for the dislocation to multiply and move, which leads to the increase of dislocation density, but the dislocation does not continue to increase with the magnetic induction intensity increasing. The dislocation pile-up effect suppresses the Frank–Read dislocation source and dislocations of multiplication.[20] This explains the trend that the dislocation density first increases and then decreases with the magnetic induction density increasing.

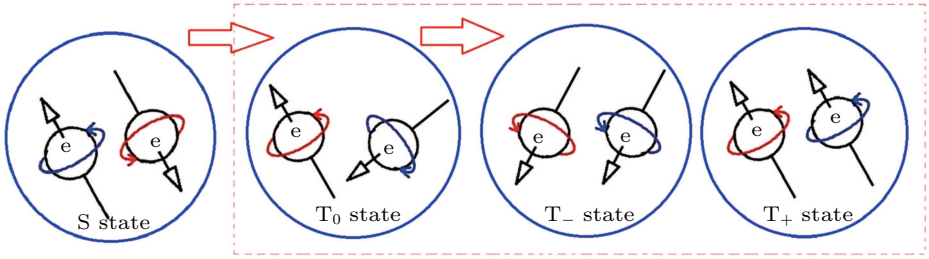


Fig. 13. (color online) Four states of radical pairs.

The density of radical pairs, D is determined by the density matrix

$$\mathrm{i}\frac{\partial D}{\partial t} = \frac{1}{h}|H_{\mathrm{a}}, D| - \mathrm{i}\frac{D}{t}, \tag{5}$$

where the $|\ |$ and i mean the matrix and its vector unit, t is the movement time of dislocation h is the Planck constant And H_{a} is the Hamiltonian function. For radical pair, the relevant energy variation E_{M} from S to T state can be expressed as[21]

$$E_{\mathrm{M}} = \Delta g \mu_{\mathrm{B}} H, \tag{6}$$

where Δg means the g factor difference for radical pair state, which is often adopted to be 10^{-3}.[22]

There are totally four kinds of irrelevant radical pair states between dislocation and obstacles, so the initial condition of density matrix can be assumed as follows:

$$D_{\mathrm{S}}(0) = D_{\mathrm{T0}}(0) = D_{\mathrm{T+}}(0) = D_{\mathrm{T-}}(0) = \frac{1}{4}. \tag{7}$$

The dislocation will move when being driven by the unordered field of internal stress. The time function can randomly distributed when it passes through the S, T resonance region. According to the Possion time distribution, in the presence of H magnetic field, the average amount at S state, that is $D_{\mathrm{S}}(H)$, can be expressed as

$$D_{\mathrm{S}}(H) = \frac{1}{t_0}\int_0^{\infty} D_{\mathrm{S}}(t)\exp\left(-\frac{t}{t_0}\right)\mathrm{d}t, \tag{8}$$

where t is the average time for radical pair to pass through S, T resonance region. It is analyzed that $D_{\mathrm{S}}(H)$ is the Laplace transition of $D_{\mathrm{S}}(t)$ whose expression in liner style is

$$D_S(H) = \frac{1}{4}\frac{\left(1+\dfrac{T_1}{t_0}\right)\left(1+\dfrac{T_2}{t_0}\right)+\dfrac{H^2}{H_{\mathrm{m}}^2}}{\left(1+\dfrac{T_1}{t_0}\right)\left(1+\dfrac{T_2}{t_0}\right)+\left(1+\dfrac{t_0}{2T_1}\right)\dfrac{H^2}{H_{\mathrm{m}}^2}}, \tag{9}$$

where T_1 and T_2 represent the spin relaxation times along longitudinal and tangential direction. As for the spin lattice relaxation in metallic material, the T_1 and T_2 are often adopted to be 2.4×10^{-9} s.[23] Furtherly, the critical magnetic field intensity H_{m} is calculated from

$$H_{\mathrm{m}} = \frac{h}{\Delta g \mu_{\mathrm{B}}\sqrt{T_1 \cdot T_2}}, \tag{10}$$

when $h = 6.63\times10^{-34}$ J·s, $\Delta g \approx 10^{-3}$, $\mu_{\mathrm{B}} = 9.27\times10^{-24}$ J/T, and $T_1 = T_2 \approx 2.4\times10^{-9}$ s are substituted into Eq. (10), the H_{m} is calculated to be 2.4×10^6 A/m corresponding to $B^* = 3$ T according to the relationship of $B = \mu H$ (μ is the magnetic susceptibility of TC4 alloy, whose magnitude is 1.26×10^6 H/m). The 3 T, a a critical value, has been ascertained through theoretical approach, which matches with the experimental phenomenon.

4. Conclusions

When TC4 alloy is investigated in the case that a high magnetic field and external stress exist synchronously, it is found that B parameter can influence the elongation of alloy positively and apparently. At a specific parameter of $B = 3$ T ($N = 30$), the elongation is increased by 23.98% individually compared with that of the initial sample. When the magnetic induction intensity is modified as $B = 0$ T, 1 T, 3 T, and 5 T with constant 30 pulses, the volume fractions of α phase in the alloy are 49.7%, 53.5%, 55.9%, and 50.5%, respectively. The magnetic field can promote the phase transformation from β to α phase. Meanwhile, the dislocation density is increased. When B is less than 3 T, the dislocation density increases with B increasing (0→1 T and 1 T→3 T); while B is larger than 3 T, the dislocation density lowers down with B increasing (3 T→5 T). Besides, the $B^* = 3$ T is the critical point when the B takes effect individually. The magneto-plasticity effect accounts for the experimental results, whose essence lies in the fact that the high magnetic field can influence the spin state of free electron, so the state of radical pair changes from S to T. The transition is beneficial to improving the dislocation structure state and increasing the dislocation mobility.

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