

MECHANICAL BEHAVIOR AND MICROSTRUCTURE EVOLUTION OF Ti-6Al-4V WIRE ROD FOR PRODUCING AEROSPACE FASTENERS

MEHANSKE LASTNOSTI IN RAZVOJ MIKROSTRUKTURE ŽICE IZ Ti-6Al-4V ZLITINE ZA IZDELAVO LETALSKIH SPONK

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The basic deformation parameters had a significant influence on the mechanical behaviour and microstructure evolution of a Ti-6Al-4V wire rod. Compression experiments were conducted to study the effect of the deformation temperatures (25–900 °C) and strain rates (0.1/s, 1/s and 10/s) on the mechanical behaviour and microstructure evolution. The microstructure observation and the quantitative metallographic of Ti-6Al-4V wire rod were investigated after the compression experiments. The results showed that the Ti-6Al-4V compressed samples tend to be cracked along a 45° angle below 300 °C, which was regarded as the critical deformation temperature. Deformation temperatures from 400 °C to 600 °C can be regarded as the warm deformation region. Deformation temperatures from 700 °C to 900 °C can be regarded as the hot deformation region. And the softening mechanism was predominated by a temperature rise and dynamic recrystallization, respectively, for the warm deformation region and the hot deformation region of the Ti-6Al-4V alloy.

Keywords: Ti-6Al-4V wire rod, mechanical behavior, microstructure evolution, deformation temperatures, deformation rates

Osnovni parametri deformacije imajo pomemben vpliv na mehansko obnašanje in razvoj mikrostrukture žice iz Ti-6Al-4V zlitine. Avtorji članka so izvedli tlačne preizkuse na vzorcih žice premera 10 mm, da bi ugotovili vpliv deformacije na mehanske lastnosti in razvoj mikrostrukture pri hitrostih deformacij 0,1 s⁻¹, 1 s⁻¹ in 10 s⁻¹ in v področju temperatur med 25 °C in 900 °C. Po tlačnih preizkusih so izvedli mikrostrukturne preiskave pri različnih pogojih deformirane Ti-6Al-4V žice in izvedli kvantitativne metalografske analize nastalih mikrostruktur. Rezultati analiz so pokazali, da imajo tlačno deformirani vzorci iz Ti-6Al-4V zlitine tendenco pokanja vzdolž kota 45° pri temperaturah pod 300 °C, ki so jo zato ocenili kot kritično temperaturo deformacije. Deformacije pri temperaturah med 400 °C in 600 °C, so avtorji ocenili kot področje tople deformacije medtem, ko lahko deformacije pri temperaturah med 700 °C in 900 °C smatramo kot področje v katerem poteka vroča deformacija. Mehanizem mehčanja materiala je bil prednostno odvisen od naraščanja temperature in dinamične rekristalizacije v področjih tople in vroče deformacije Ti-6Al-4V zlitine.

Ključne besede: žica iz Ti-6Al-4V zlitine, mehanske lastnosti, razvoj mikrostrukture, temperatura in hitrost deformacije

1 INTRODUCTION

As a kind of medium strength $\alpha+\beta$ type two-phase titanium alloy,^{1,2} the weight of Ti-6Al-4V alloy is 30 % lighter than that of steel,³ but its strength is three times higher than steel.⁴ In addition, the Ti-6Al-4V alloy has properties against corrosion, which make it an idea material to produce aerospace fasteners.^{5,6} The detailed manufacturing process parameters have great effects on the microstructure distribution of aerospace fasteners.⁷ It is necessary to investigate the effects of deformation temperatures and deformation rates on the mechanical behaviour and microstructure evolution of a Ti-6Al-4V wire rod.

Currently, the mechanical behaviour and microstructure evolution of the Ti-6Al-4V alloy have been widely reported. H. J. Mao et al.⁸ studied the microstructure and properties of Ti-6Al-4V in the range 700–900 °C. Z. Q.

Wu et al.⁹ investigated the effect of the solution temperature and wire size on the microstructure, mechanical properties and phase structure of a Ti-6Al-4V wire rod. H. J. Mao et al.¹⁰ investigated the deformation behavior of the Ti-6Al-4V alloy under different temperatures and strain rates. B. L. Luo et al.¹¹ analyzed the uniformity of the microstructure of TC4 titanium alloy bars under different heating temperatures. However, the investigation on the effect of the detailed manufacturing process parameters on the mechanical behavior and microstructure evolution of Ti-6Al-4V wire rod are rarely found.

In the present work, the effects of processing parameters, including deformation temperatures and deformation rates, on the formability, mechanical behavior and microstructure evolution were investigated based on quantitative metallography of a compressed Ti-6Al-4V wire rod. Meanwhile, the flow softening mechanism of the Ti-6Al-4V wire rod during warm compression was also analysed.

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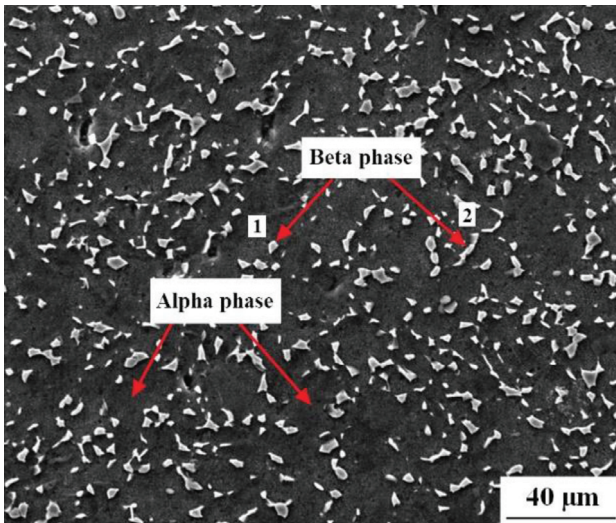


Figure 1: SEM microstructure of Ti-6Al-4V alloy wire rod in annealed state (1- granular beta phase, 2- long-strip beta phase)

2 EXPERIMENTAL PART

The as-supplied state of the Ti-6Al-4V alloy wire rod is an annealing treatment after drawing. The main chemical composition (w/%) of the Ti-6Al-4V wire rod includes: 6.20 % Al, 4.15 % V, 0.15 % O, 0.05 % Fe, 0.01 % C, 0.015 % N, 0.0016 % H and the bal. Ti. The cylindrical compression specimens were prepared with 10.0 mm diameter and 12.0 mm height. Figure 1 shows

a micrograph of Ti-6Al-4V alloy wire rod in the annealed state. It can be seen from Figure 1 that the microstructure at room temperature is composed of granular beta phase, long-strip beta phase and alpha phase as the matrix.

Compression experiments were conducted on an American DSI Gleeble-3800 Thermal Simulation Tester.¹² A layer of $\Phi 12 \text{ mm} \times 0.25 \text{ mm}$ graphite sheet was clamped between the indenter and the ends of the sample for lubrication. The test pieces were heated to a deformation temperature (25–900 °C) at a heating rate of 5 °C/s, and then compressed and deformed at a strain rate of 0.1/s, 1/s and 10/s. Water quenching was performed immediately to retain the microstructure after compression deformation.

The specimens were taken from the compressed test pieces by using a wire-cutting machine, and the specimens were embedded in cold mounting resin. The surface of the specimens was grinded first with coarse 400-grit abrasive paper to remove scratch marks caused by wire cutting, followed by finer 600-, 800-, 1000-, 1200- and 1500-grit abrasive paper.¹³ And the surfaces of the specimens were finally polished to a mirror surface using a polishing machine. After the polishing was completed, the specimens were cleaned twice. The specimen surface was wiped with a cotton ball and alcohol to remove the residual polish paste. And then the sample was put in acetone solution and shaken it to clean the impurities inside the specimens.

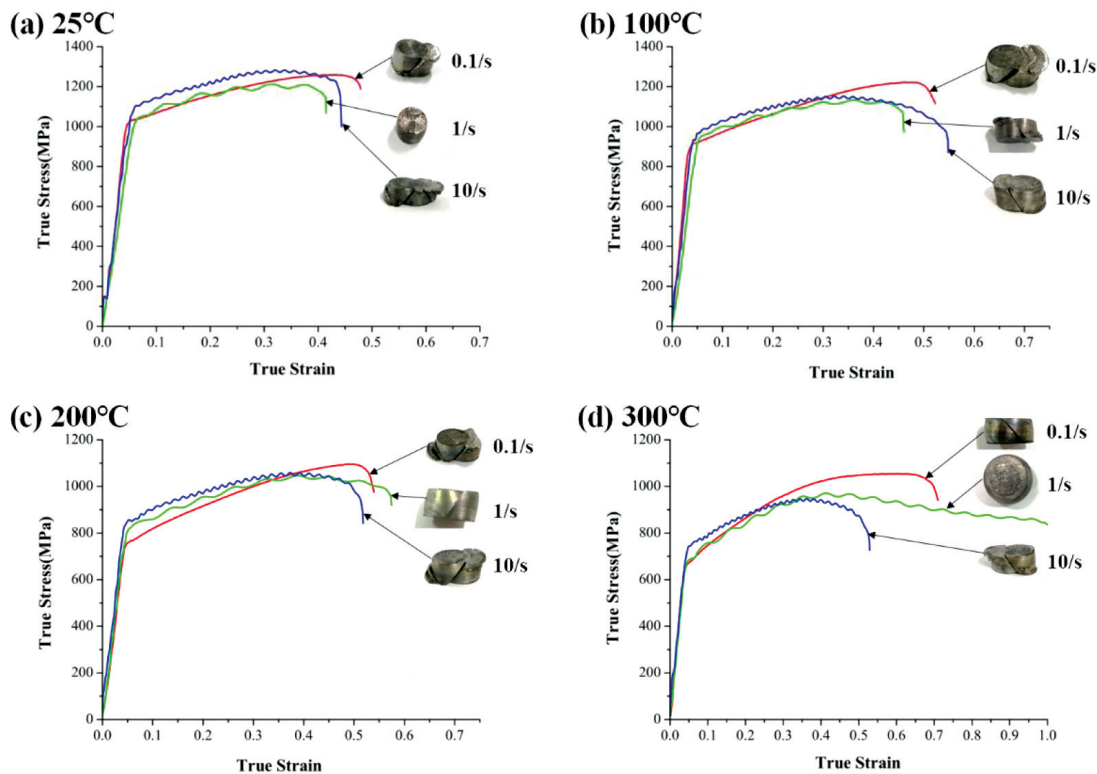


Figure 2: Compressed samples and the stress-strain relationships of Ti-6Al-4V at the deformation temperature of: a) 25 °C, b) 100 °C, c) 200 °C and d) 300 °C

After the washes were completed two times, the specimens could be etched. The etching solution consists of 2.5 mL HF, 3 mL HNO₃, 5 mL HCl and 91 mL H₂O¹⁴. The corrosion time of medium and low temperature compression specimens was 3–5 s, and the corrosion time of the high-temperature compression specimens was 8–10 s. After the corrosion, the specimen surface was rinsed with purified water, dried with a blower, and the microstructure of the Ti-6Al-4V alloy wire rod was observed with a JSM-6460 Scanning Electron Microscope (SEM).

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Effect of deformation temperatures on the formability

Figure 2 shows the compressed test pieces and its stress-strain relationships of Ti-6Al-4V at the deformation temperatures of 25 °C, 100 °C, 200 °C and 300 °C. As is seen from Figure 2, when the deformation temperature is below 300 °C, the test pieces were fractured in a direction of 45° with respect to the direction of compression. This is because the shear stress in the direction of 45° is the largest during compression. At low temperatures, the plasticity of the Ti-6Al-4V wire rod is worse and adverse to metal flow. It can be concluded that 300 °C is the critical deformation temperature of the Ti-6V-4V alloy. The Ti-6Al-4V wire rod has poor formability when the deformation temperature is below 300 °C, which should be avoided in the actual production process.¹⁵

3.2 Effect of deformation temperatures on the mechanical behavior and microstructure evolution

Figure 3 shows the stress-strain relationships of the Ti-6Al-4V wire rod at deformation temperatures of 400 °C, 500 °C, 600 °C, 700 °C, 800 °C, 900 °C with strain rates of 0.1/s, 1/s and 10/s. It can be seen from Figure 3 that during the deformation process, the flow stress rapidly rises to the peak value and then exhibits a dynamic softening characteristic. According to Figure 3,

Table 1: σ_p and its corresponding ϵ_p in the Ti-6Al-4V wire rod at the deformation temperatures of 400 °C, 500 °C, 600 °C, 700 °C, 800 °C, 900 °C

Deformation temperature/°C	Strain rate/s ⁻¹	σ_p /MPa	ϵ_p
400	0.1	928	0.64
	1	843	0.38
	10	857	0.39
500	0.1	789	0.59
	1	722	0.35
	10	735	0.29
600	0.1	600	0.29
	1	590	0.23
	10	617	0.27
700	0.1	434	0.18
	1	448	0.20
	10	513	0.22
800	0.1	275	0.30
	1	347	0.14
	10	419	0.15
900	0.1	130	0.02
	1	183	0.05
	10	232	0.13

the peak stress of each stress-strain curve and its corresponding strain are obtained, which are listed in Table 1. It can be seen from Table 1, when the deformation temperature increases from 400 °C to 900 °C at a deformation rate of 0.1/s, the stress peak of the material is reduced from 928 MPa to 130 MPa, and the strain corresponding to the stress peak is reduced from 0.64 to 0.02. In this temperature range, the stress peak decreased by 14.9 %, 23.9 %, 27.7 %, 36.6 %, and 52.7 % for every temperature rise of 100 °C. When the deformation temperature increases from 400 °C to 900 °C at the deformation rate of 1/s, the stress peak of the material is reduced from 843 MPa to 183 MPa, and the strain corresponding to the stress peak is reduced from 0.38 to 0.05. In this temperature range, the stress peak decreased by 14.4 %, 18.3 %, 24.1 %, 22.5 %, and 43.7 % for every temperature rise of 100 °C. When the deformation temperature increases from 400 °C to 900 °C at a deformation rate of 10/s, the stress peak of the material is reduced from 857 MPa to 232 MPa, and the strain corresponding to the

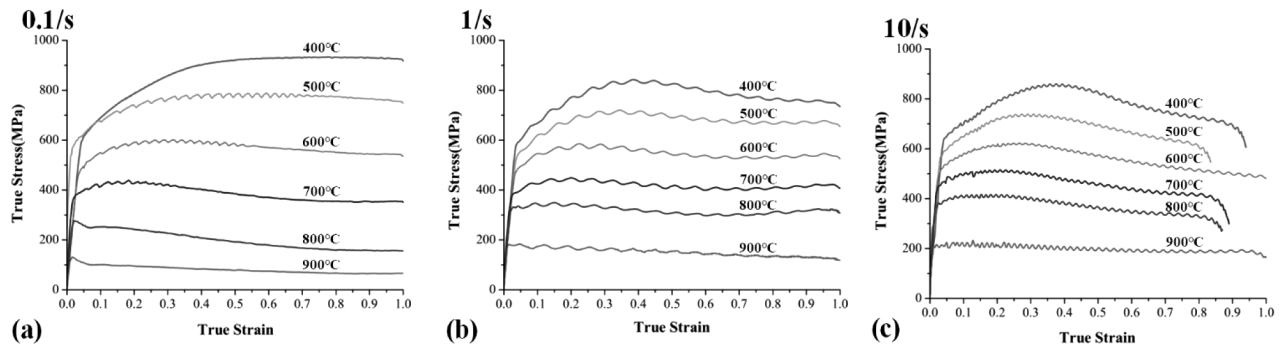


Figure 3: Stress-strain relationships of Ti-6Al-4V wire rod at deformation temperatures of 400 °C, 500 °C, 600 °C, 700 °C, 800 °C, 900 °C with strain rates of : a) 0.1/s, b) 1/s and c) 10/s

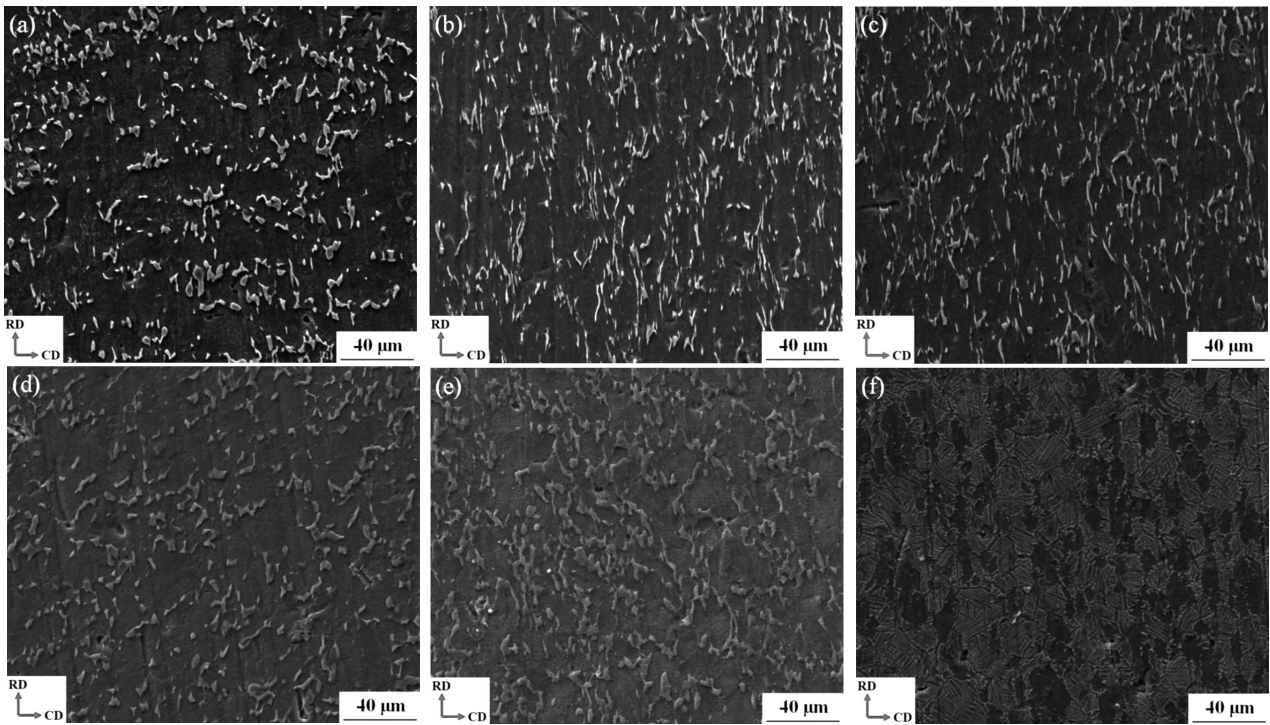


Figure 4: SEM microstructure of Ti-6Al-4V alloy wire rod at strain rate of 1/s with deformation temperatures of: a) 400 °C, b) 500 °C, c) 600 °C, d) 700 °C, e) 800 °C, f) 900 °C

stress peak is reduced from 0.39 to 0.13. In this temperature range, the stress peak decreased by 14.2 %, 16.1 %, 16.9 %, 18.3 %, and 44.6 % for every temperature rise of 100 °C. This indicates that the deformation resistance decreases as the temperature increases. And, the stress-strain curve exhibits significant sawtooth at the higher strain rate, due to the repeated competition of the

work hardening and recrystallization softening processes. In particular, the more pronounced the saw teeth takes place under the higher deformation temperature. Such curves are called non-continuous yield curves.¹⁶

Figure 4 shows the SEM microstructure of the Ti-6Al-4V alloy wire rod at strain rate of 1/s with temperatures of 400 °C, 500 °C, 600 °C, 700 °C, 800 °C

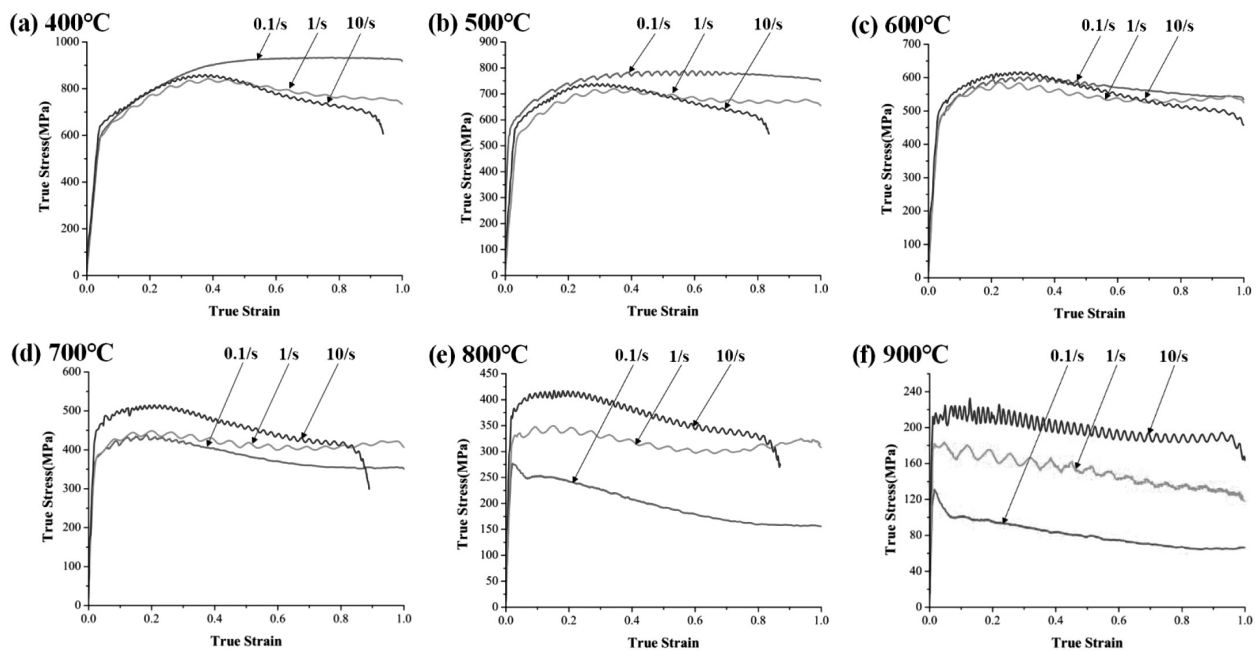


Figure 5: Stress-strain relationships of Ti-6Al-4V wire rod at strain rates of 0.1/s, 1/s, 10/s with temperatures of: a) 400 °C, b) 500 °C, c) 600 °C, d) 700 °C, e) 800 °C, f) 900 °C

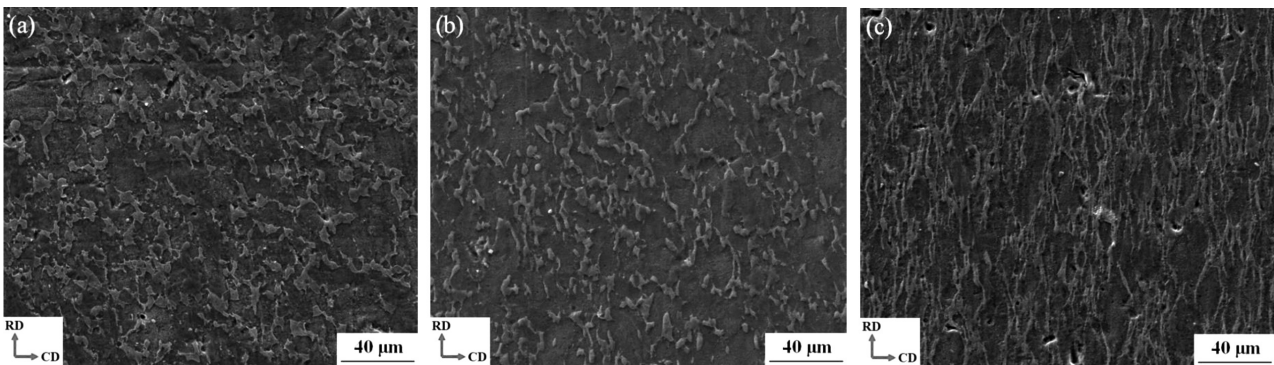


Figure 6: SEM microstructure of Ti-6Al-4V alloy wire rod at temperature of 800 °C and true strain of 1 with strain rates of: a) 0.1/s, b) 1/s, c) 10/s

and 900 °C. It can be seen from Figure 4 that the primary α phase is the black matrix, while the gray β phase particles distributes in the matrix. At the deformation temperatures of 400–600 °C, the β phase particles change into long strips along the compression direction. The sizes of β phase have little change. The shape change was caused by a local temperature rise. At the deformation temperatures of 700–900 °C, the adjacent β phase aggregates and grows with an increase of deformation temperature, and the content of β phase increases significantly. At the temperature of 900 °C, the needle-like microstructure appears obviously in the β phase.

3.3 Effect of deformation rates on the mechanical behavior and microstructure evolution

Figure 5 shows the stress-strain relationships of the Ti-6Al-4V wire rod at strain rates of 0.1/s, 1/s and 10/s with temperature of 400 °C, 500 °C, 600 °C, 700 °C, 800 °C and 900 °C. Dynamic softening is obvious in **Figure 5**. The flow stress decreases after it reaches the peak value and enters a stable stress state. It can be seen from **Figure 5** that there are differences between 400–600 °C and 700–900 °C in metal flow softening. At 400–600 °C, the stress value at the higher strain rate is lower than that at lower strain rate, which was caused by a local temperature rise. The temperature rise is directly related to the strain rate. With an increase of the strain rate, the temperature rise increases, which leads to material softening.¹⁷ When the deformation temperature is above 600 °C, the stress value at the higher strain rate is higher than that at the lower strain rate, which conforms with the normal metal flow law. At 700–900 °C, metal flow softening is predominated by the dynamic crystallization of the β phase.² Therefore, the softening mechanism is different for 400–600 °C and 700–900 °C. The deformation temperature range from 400 °C to 600 °C can be regarded as the warm deformation region, and 700–900 °C can be regarded as the hot deformation region in this work.

Figure 6 shows an SEM microstructure of the Ti-6Al-4V alloy wire rod at a temperature of 800 °C and a true strain of 1 with strain rates of 0.1/s, 1/s, and 10/s.

As can be seen from Figure 6, when the strain rate is 0.1/s, the β phase of the Ti-6Al-4V alloy undergoes a certain degree of dynamic recrystallization due to the long deformation time. The β phase is equiaxed, the grain size is larger, and nonuniformly distributes in the matrix. During the compression process, local temperature overheating is likely to occur, resulting in severe deformation. When the strain rate is 1/s, the β phase is elongated in a direction perpendicular to the compression. The grain size of the β phase is significantly reduced, and the β phase uniformly distributed in the matrix. When the strain rate is 10/s, the β phase structure is a severely deformed elongated strip structure because at a higher strain rate, the deformation time is shortened, and dynamic recovery and dynamic recrystallization cannot be sufficiently performed. Therefore, as the deformation rate increases, the β phase changed mainly in terms of morphology, and at a higher strain rate, the microstructure exhibits significant directionality.

3.4 Analysis of material flow softening during warm compression

Figure 7 shows the true stress-strain curve and strain-hardening rate at 600 °C and a strain rate of 10/s. As can be seen from Figure 8, the critical strain value is

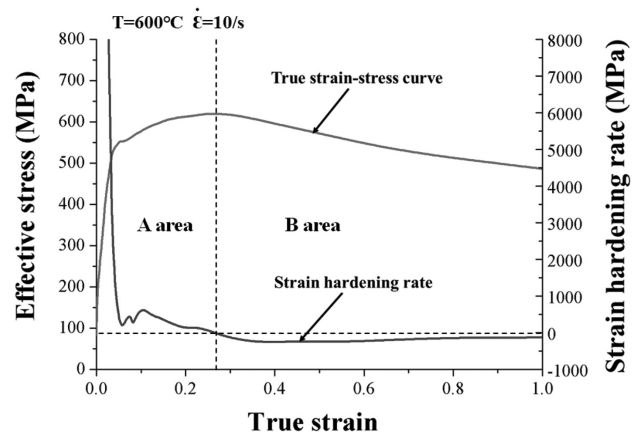


Figure 7: True stress-strain curve and strain-hardening rate at 600 °C and a strain rate of 10/s

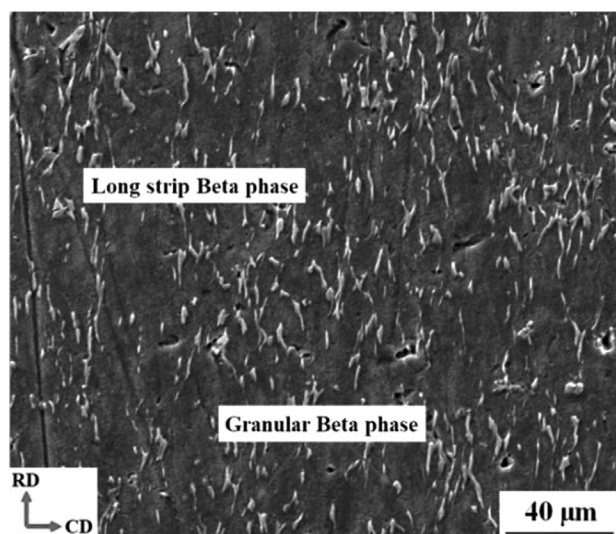


Figure 8: SEM microstructure of Ti-6Al-4V alloy wire rod at 600 °C and a strain rate of 10/s

0.27. **Figure 8** was divided into two regions: A and B. In the region A, the effective stress increases as the strain increases, and the strain hardening rate was positive. In the region B, the effective stress decreases as the strain increases, and the strain hardening rate was negative. The results show that the material flow softening of the Ti-6Al-4V wire rod occurs in region B.

Figure 8 shows the SEM microstructure of Ti-6Al-4V alloy wire rod at 600 °C and a strain rate of 10/s. It can be seen from **Figure 8** that after thermal compression deformation, there are two different forms of β phase in the matrix, i.e., the granular β phase and the long-strip β phase. The thermal conductivity of the Ti-6Al-4V alloy is low at the deformation temperature of 600 °C and a strain rate of 10/s, resulting in the heat generated by the compression deformation. The local temperature of the test piece cause adiabatic instability, which is the main reason for the flow softening during warm compression.

4 CONCLUSIONS

The Ti-6Al-4V compressed samples tend to be cracked along a 45° angle below 300 °C. The critical deformation temperature of the Ti-6Al-4V alloy is 300 °C. The Ti-6Al-4V wire rod has poor formability when the deformation temperature is below 400 °C, which should be avoided in the actual production process. Deformation temperature range from 400 °C to 600 °C can be regarded as the warm deformation region. The deformation temperature range from 700 °C to 900 °C can be regarded as the hot deformation region. And the softening mechanism was predominated by a temperature rise and dynamic recrystallization, respectively, for the warm deformation region and the hot deformation region of the Ti-6Al-4V alloy.

In the warm deformation region, the β phase particles change into long strips along the compression direction. The sizes of the β phase have little change. The shape change was caused by a local temperature rise. In the hot-deformation region, the adjacent β phase aggregates and grows with an increase in the deformation temperature, and the content of β phase increases significantly. In the hot deformation region, dynamic crystallization takes places at a lower strain rate for a given deformation temperature. However, insufficient crystallization appears at the higher strain rate, the β phase becomes long strips in the matrix, and the microstructure exhibits significant directionality.

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