

Deformation Behavior in the Isothermal Compression of Hydrogenated Ti–5.6Al–4.8Sn–2.0Zr–1.0Mo Alloy

Yingying Lin, Miaoquan Li, Weifu Zhang, and Yong Niu

(Submitted November 29, 2005; in revised form April 22, 2006)

The isothermal compression of hydrogenated Ti–5.6Al–4.8Sn–2.0Zr–1.0Mo alloy has been carried out. The experimental result shows that the additional hydrogen significantly decreases the flow stress of Ti–5.6Al–4.8Sn–2.0Zr–1.0Mo alloy. The minimum peak stress at deformation temperature of 830–900 °C corresponds to the hydrogen content of 0.4 wt.%, alternatively the appropriate hydrogen content raises the true strain rate up to one order of magnitude in comparison with the received Ti–5.6Al–4.8Sn–2.0Zr–1.0Mo alloy. X-ray diffraction examination shows the appropriate hydrogen content accelerates the β phase transformation so as to improve the workability of this alloy. However, the hydride phase appears when the hydrogen content is about 0.734 wt.%, which increases of the flow stress in comparison to the flow stress of this alloy with hydrogen content of 0.4 wt.%.

Keywords activation energy for deformation, high temperature titanium alloy, hydrogenation, isothermal compression

effect of the hydrogen content on the deformation behavior has been discussed.

1. Introduction

The Ti–5.6Al–4.8Sn–2.0Zr–1.0Mo alloy is a novel high temperature titanium alloy, which has good properties at the service temperature of 600 °C. However, the Ti–5.6Al–4.8Sn–2.0Zr–1.0Mo alloy is hard to deform due to a near-alpha titanium alloy, which limits its application in the aviation and aerospace industries. Therefore, it is important to investigate the deformation behavior and to explore new forming technique of the Ti–5.6Al–4.8Sn–2.0Zr–1.0Mo alloy.

A few researchers (Ref 1–8) had pointed out that the hydrogen could improve mechanical and service properties of titanium alloys resulting from refinement of microstructure. Keer (Ref 9) reported that appropriate hydrogen content in the Ti–6Al–4V alloy could stabilize the β phase and reduce the flow stress by 30.0%; alternatively hydrogen could lower the deformation temperature by 80 °C. Meanwhile, Zhang (Ref 10) had found that the peak stress of the Ti–25Al–10Nb–3V–1Mo alloy with the hydrogen content of 0.2 wt.% decreases by 21.0–31.0% in comparison with that prior to hydrogenation. Hou et al. (Ref 6) reported that the hydrogen significantly affected the deformation behavior of α -type titanium alloy but had almost no effect on those of β -type titanium alloy (Ref 6). Certainly, the vacuum annealing was conducted for all the hydrogenated alloys to remove the hydrogen after deformation. In this paper, the isothermal compression of hydrogenated Ti–5.6Al–4.8Sn–2.0Zr–1.0Mo alloy has been carried out, and the

2. Experimental Procedures

The nominal chemical composition (wt.%) of Ti–5.6Al–4.8Sn–2.0Zr–1.0Mo alloy is 5.6Al, 4.8Sn, 2.0Zr, 1.0Mo, 0.35Si, 0.05C and balance Ti. The original microstructure is composed of the equiaxed α phase and β phase, which is shown in Fig. 1.

The alloy samples were hydrogenated in a quartz tube furnace at the temperature of 700 °C with high purity hydrogen gas. Hydrogen content of the alloys was controlled by the quantities of the hydrogen gas and calculated by the reduction of hydrogen pressures while hydrogenating. Once the hydrogen pressure reached the setting value, the samples were separated in the little quartz tube immediately. To ensure homogeneous

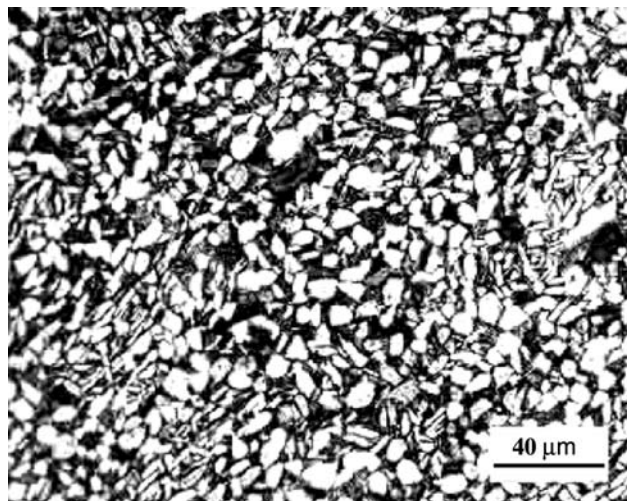


Fig. 1 The microstructure of the as-received alloy

Yingying Lin, Miaoquan Li, Weifu Zhang, and Yong Niu, School of Materials Science and Engineering, Northwestern Polytechnical University, Xian 710072, P.R. China. Contact e-mail: honeyml@nwpu.edu.cn.

distribution of the hydrogen in this alloy, the samples were held for 30 min after hydrogenation and then cooled to room temperature. According to the report that most titanium alloys with hydrogen below to 0.8 wt.% are benefit for plastic deformation, so the samples were hydrogenated in this range and selected three levels: 0.2 wt.%, 0.4 wt.% and 0.8 wt.% approximately (Ref 6). In additional the actual experimental value is slight different from the idealized ones, because it is too difficult to control the hydrogenation content accurately. The hydrogenated samples for the isothermal compression are 8.0 mm in diameter and 12.0 mm in height, and the longitudinal direction was parallel to the compression direction.

The experimental schedules for isothermal compression was arranged at the temperature of 830–900 °C and the true strain rate of 0.1–50.0 s⁻¹. The isothermal compression was carried out in the Thermecmaster-Z simulator. The samples were pre-heated up to the temperature and homogenized for 300 s prior to compression. In the compression process, a glass lubricant was coated on the sample surface against oxidation at high temperature, and the argon gas was put into the chamber to avoid the hydrogen escaping from the hydrogenation samples. All of the samples were compressed by height reduction of 50.0% and then air cooled immediately after the compression. X-ray diffraction was conducted on a PANALYTICAL X'Pert Pro X-ray diffraction analyzer.

3. Experimental Results and Discussion

3.1 Flow Stress

The flow stress–true strain curves of hydrogenated Ti–5.6Al–4.8Sn–2.0Zr–1.0Mo alloy in the isothermal compression

at the different temperatures, hydrogen contents and true strain rates are shown in Fig. 2. From Fig. 2, it can be found that all of flow stress of the hydrogenated alloy is lower than that of the received alloy at the same deformation condition. The flow stress increases with the increasing of true strain after a drop at three hydrogen contents levels. Mechanism of work-hardening effect is dominant prior to occurrence of the peak stress while mechanism of flow softening effect playing an important role in the succeeding deformation process. Especially, the stress–true strain curve of this alloy with the hydrogen content of 0.4 wt.% is different from that of the others, which has a characteristic of the steady flow in the β phase region except for the isothermal compression at deformation temperature of 850 °C and true strain rate of 50.0 s⁻¹.

Figure 3 shows the dependence of peak stress on the hydrogen content at different deformation temperatures and true strain rates. From Fig. 3, it can be seen that all of peak stresses of the hydrogenated Ti–5.6Al–4.8Sn–2.0Zr–1.0Mo alloy are lower than those of the received alloy at the same temperature and true strain rate. The peak stress increases with increasing hydrogen content of 0.4–0.8 wt.% after a drop in hydrogen content of 0–0.4 wt.%. The lowest peak stress corresponds to the hydrogen content of 0.4 wt.%. The peak stress of the hydrogenated Ti–5.6Al–4.8Sn–2.0Zr–1.0Mo alloy decreases with decreasing true strain rate at deformation temperature of 850 °C as expected, and is concordance with those of the received alloy. From the Fig. 3, it is obviously acquired that the peak flow stress of the alloy with 0.4 wt.% hydrogen at the deformation of 850 °C is much lower than that of the hydrogen-free alloy at the deformation of 900 °C on the same true strain rate of 0.1 s⁻¹. Also, the flow stress of Ti–5.6Al–4.8Sn–2.0Zr–1.0Mo hydrogen free alloy in isothermal compression at the deformation temperature of 960–1060 °C and true strain rate of 0.001–50.0 s⁻¹ were obtained. According

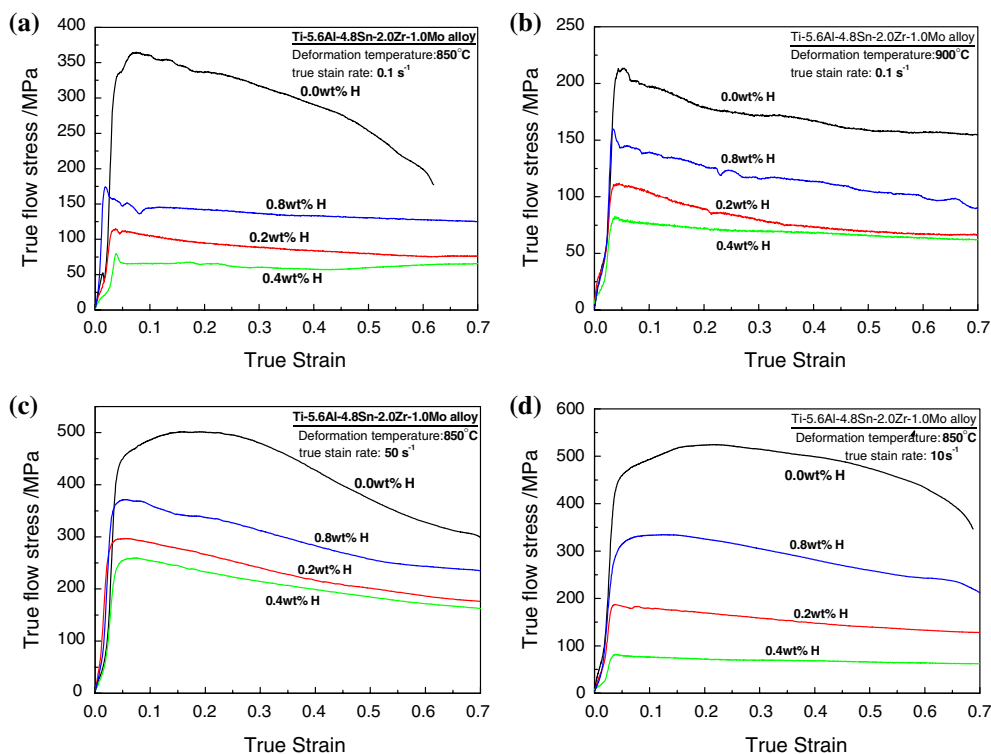


Fig. 2 Stress–true strain curve of the Ti–5.6Al–4.8Sn–2.0Zr–1.0Mo alloy

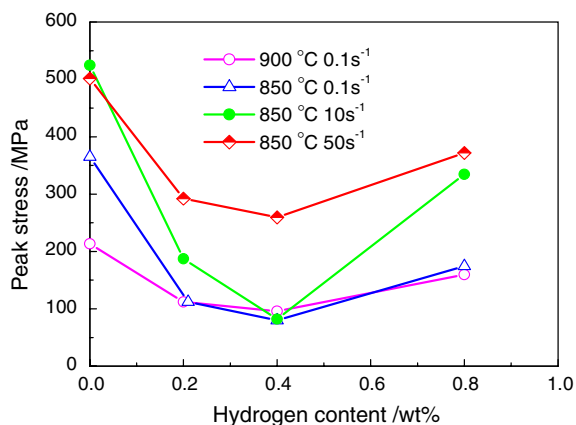


Fig. 3 Variation of the peak stress with the hydrogen content of Ti-5.6Al-4.8Sn-2.0Zr-1.0Mo alloy

to the experimental results, the peak stress of the received Ti-5.6Al-4.8Sn-2.0Zr-1.0Mo alloy is 86.2 MPa at the deformation temperature of 960 °C, which is similar to that of hydrogenated with 0.4 wt.% alloys at deformation temperature of 900 °C and true strain rate of 0.1 s⁻¹. The experimental results indicate that the hydrogen content of 0.4 wt.% can decrease the deformation temperature approximately by 60 °C. Besides those experimental phenomenon, hydrogenating on the alloy make it possible for deformation at higher true strain rate at the same deformation temperature. For example, when deformation on the temperature of 850 °C, the flow stress of the alloy with 0.4 wt.% on the rate of 10 s⁻¹ is lower than that of hydrogen-free alloy on the rate of 0.01 s⁻¹, and the alloy with 0.4 wt.% on the rate of 50 s⁻¹ as well. That is the 0.4 wt.% hydrogen on the alloy raise the true strain rate by more than one order of magnitude at deformation temperature of 850 °C.

Effect of the hydrogen content on the deformation behavior of titanium alloy has been reported (Ref 9-11). All of the experiments showed a similar dependence of the flow stress on the hydrogen content, in which a critical value of the hydrogen content can result in the lowest flow stress. Kerr (Ref 9) had obtained the lowest flow stress of hydrogenated Ti-6Al-4V alloy charged with the hydrogen content of 0.4 wt.%. This was explained by noting that the β phase (easy to deform) would increase with increasing hydrogen content up to 0.4 wt.%, while the formation of hydride precipitates would be expected to increase the flow stress at hydrogenation levels of 0.6 wt.% or higher and deformation temperature less than the eutectoid temperature. Zhang (Ref 10) insisted that the lower transition temperature of the β phase and a greater quantity of β phase resulted in a decrease of flow stress during the isothermal compression of Ti-25Al-10Nb-3V-1Mo alloy. However, the dissolution of hydrogen in β phase can result in the lattice distortion of the β phase and consequently the strengthening effect on the hydrogenated alloy with high hydrogen content is such as to increase the flow stress again in comparison with the appropriate hydrogen content of 0.2 wt.%. Kerr (Ref 9) indicated that the effect of hydrogen content on the deformation behavior greatly depends on the alloying elements, resulting in the appropriate hydrogen content to be related to the chemical compositions of titanium alloys.

3.2 X-ray Diffraction Examination

X-ray diffraction of the Ti-5.6Al-4.8Sn-2.0Zr-1.0Mo alloy with the hydrogen content of 0.734 wt.%, 0.356 wt.%,

0.193 wt.% and the hydrogen-free alloy is shown in Fig. 4. The experimental result shows that the received alloy consists of the α phase and β phase, and the α phase is the dominant phase. The intensity of diffraction peak of the β phase is enhanced with increasing hydrogen content in Ti-5.6Al-4.8Sn-2.0Zr-1.0Mo alloy, which implies that the β phase increases with the increasing hydrogen content at the same temperature. Both the larger quantity of β phase and the lower β -phase transition temperature are beneficial for the high temperature deformation. The experimental results are in agreement with the variation of flow stress presented in Section 3.2. The hydride phase in Ti-5.6Al-4.8Sn-2.0Zr-1.0Mo alloy appears when the hydrogen content reached 0.734 wt.%. However, the hydride phase is not beneficial for the high temperature deformation. Then, the appearance of the hydride phase results in an increasing in flow stress.

3.3 Variation of the Activation Energy for Deformation

The relationship between $\ln \sigma$, $1/T$ and $\ln \dot{\epsilon}$ is shown in Fig. 5. The relationship between the steady flow stress, true strain rate and deformation temperature is subjected to the following equation (Ref 11):

$$\dot{\epsilon} \exp[Q/(RT)] = A\sigma^n \quad (\text{Eq 1})$$

Where $\dot{\epsilon}$ is the true strain rate (s⁻¹); Q is the activation energy for deformation (KJ/mol); R is the gas constant (8.3154 KJ/mol); σ is the flow stress (MPa); T is the deformation temperature (K); and A and n are the material constants. The Q -value can be derived from Eq. (1), that is

$$Q = nR \cdot \partial \ln \sigma / \partial (1/T) \quad (\text{Eq 2})$$

The value of n can be calculated as

$$n = \ln(\dot{\epsilon}_2/\dot{\epsilon}_1) / \ln(\sigma_2/\sigma_1) \quad (\text{Eq 3})$$

The activation energy for deformation of Ti-5.6Al-4.8Sn-2.0Zr-1.0Mo alloy with hydrogen content of 0.2 wt.% is calculated to be 627.27 KJ/mol. The activation energy for

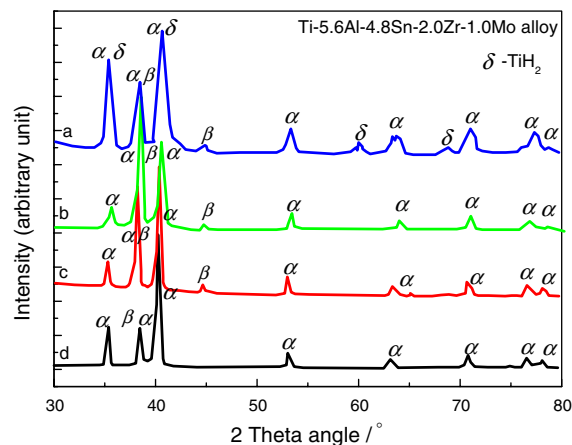


Fig. 4 X-ray diffraction of the Ti-5.6Al-4.8Sn-2.0Zr-1.0Mo alloy with the hydrogen content of (a) 0.734 wt.%; (b) 0.356 wt.%; (c) 0.193 wt.%; (d) hydrogen-free alloy

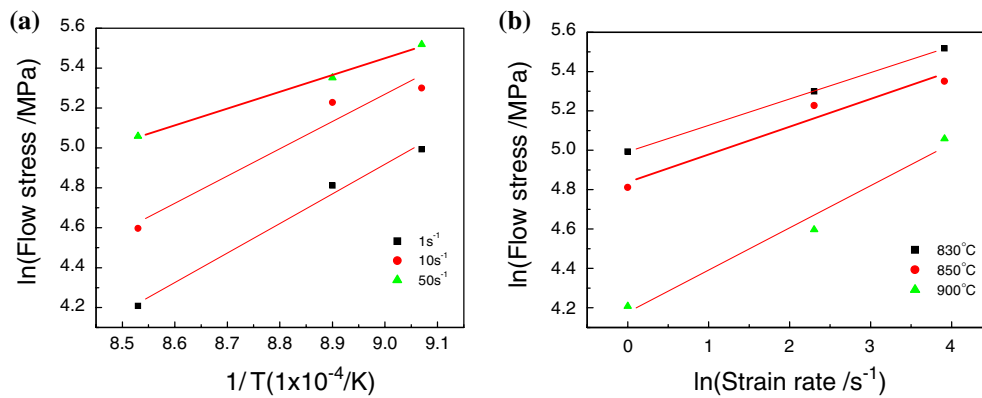


Fig. 5 Relationship between the flow stress, the deformation temperature and the true strain rate ($\epsilon = 0.6$)

deformation was decreased by 455.18 KJ/mol in comparison with that of the as received Ti-5.6Al-4.8Sn-2.0Zr-1.0Mo alloy in the two-phase region, which indicates to improve the workability of Ti-5.6Al-4.8Sn-2.0Zr-1.0Mo alloy. Zhang (Ref 11) also reported that the activation energy of hydrogenated Ti-14Al-19Nb-3V-2Mo alloy with 0.2 wt.% decreased from 692.0 KJ/mol to 571.0 KJ/mol. This implies that the hydrogenation decreased the activation energy for deformation of the Ti₃Al alloy.

4. Conclusions

The isothermal compression of Ti-5.6Al-4.8Sn-2.0Zr-1.0Mo alloy with hydrogen content of 0.0-0.8 wt.% at the deformation temperature of 830-900 °C and the true strain rate of 0.1-50.0 s⁻¹ was performed. The conclusions are as follows.

- (1) Hydrogenation can significantly decrease the flow stress in the isothermal compression of the Ti-5.6Al-4.8Sn-2.0Zr-1.0Mo alloy.
- (2) The decrease of flow stress is related to the hydrogen content of Ti-5.6Al-4.8Sn-2.0Zr-1.0Mo alloy. The peak stress increases with the increasing of hydrogen content from 0.4 to 0.8 wt.% after a drop in the peak stress over the hydrogen content of 0.0-0.4 wt.%.
- (3) The deformation temperature of Ti-5.6Al-4.8Sn-2.0Zr-1.0Mo alloy charged with the hydrogen content of 0.4 wt.% decreased by approximately 60 °C at the same true strain rate. Conversely, the true strain rate may rise by one order of magnitude at the same deformation temperature.
- (4) The more the hydrogen content, the greater is the quantity of the β phase in the Ti-5.6Al-4.8Sn-2.0Zr-1.0Mo alloy.
- (5) When the hydrogen content reached 0.734 wt.%, the hydride phase appeared and degraded the workability of the Ti-5.6Al-4.8Sn-2.0Zr-1.0Mo alloy.
- (6) Hydrogen can lower the activation energy for deformation of Ti-5.6Al-4.8Sn-2.0Zr-1.0Mo alloy in the two-phase

region. The hydrogen content of 0.2 wt.% decreased the activation energy by 455.18 KJ/mol in comparison with that of the hydrogen-free alloy.

Acknowledgments

The authors acknowledge the financial support from the Natural Science Foundation of China with Grant No. 50371068, and the Aeronautic Science Foundation of AVIC with Grant No. 04H53058 of China.

References

1. N. Eliaz, D. Eliezer, and D.L. Olson, Hydrogen-Assisted Processing of Materials, *Mater. Sci. Eng.*, 2000, **A289**, p 41
2. D. Eliezer, N. Eliaz, N.O. Senkov, and FH Froes, Positive Effects of Hydrogen in Metals, *Mater. Sci. Eng.*, 2000, **A280**, p 220, in Chinese
3. M.C. Han, Thermohydrogen Treatment of Titanium Alloys, *Aerospace Mater. Technol.*, 1999, **1**, p 23, in Chinese
4. J.C. Liao, The Application Range of Thermohydrogen Technology of Titanium and Its Prospects, *Prog. Titanium Industry*, 2002, **6**, p 18, in Chinese
5. X.L. Ning, Revisable Alloying of Titanium Alloys, *Prog. Titanium Industry*, 1995, **1**, p 19, in Chinese
6. H.L. Hou, Z.Q. Li, Y.J. Wang, and Q. Guan, Technology of Hydrogen Treatment for Titanium Alloy and Its Application Prospect, *Chin. J. Nonferrous Metals*, 2003, **3**, p 533, in Chinese
7. O.N. Senkov and F.H. Fronces, Thermohydrogen Processing of Titanium Alloys, *Int. J. Hydrogen Energy*, 1999, **24**, p 565
8. O.N. Senkov and J.J. Jones, Effect of Phase Composition and Hydrogen Level on the Deformation Behavior of Titanium-Hydrogen Alloys, *Metall. Mater. Trans.*, 1996, **27**, p 1869
9. K. Kerr, P.R. Smith, Hydrogen as Alloying Element in Titanium, *Proceedings of the 4th International Conference on Titanium*, Kyoto, Japan, May 19-22, 1980
10. Y. Zhang, S.Q. Zhang, and C. Tao, Hydrogenation Behavior of Ti-25Al-10Nb-3V-1Mo Alloy and Effect of Hydrogen on its Microstructure and Hot Deformability, *J. Hydrogen Energy*, 1997, **22**, p 125
11. Y. Zhang and S.Q. Zhang, Hydrogen Effects on the High Temperature Deformation Characteristics of a Cast Ti-14Al-19Nb-3V-2Mo alloy, *Scripta Materialia*, 1999, **27**, p 1315