JMEPEG (2010) 19:59–63
DOI: 10.1007/s11665-009-9427-5

1059-9495/$19.00

High-Temperature Deformation Behavior of Ti-6Al-4V Alloy without and with Hydrogenation Content of 0.27 wt.%

Yong Niu, Miaoquan Li, Hongliang Hou, Yaoqi Wang, and Yingying Lin

(Submitted September 25, 2008; in revised form March 3, 2009)

Isothermal compression of Ti-6Al-4V alloy without and with hydrogenation content of 0.27 wt.% was carried out on Gleeble-1500D thermal simulation machine at deformation temperature between 760 and 1000 °C and strain rate from 0.001 to 1 s^{-1}. The experimental results show that hydrogenation can decrease the deformation temperature or increase the strain rate of Ti-6Al-4V alloy. The apparent activation energy was determined to be 667 kJ mol^{-1} for isothermal compression of the Ti-6Al-4V alloy without hydrogenation content of 0.27 wt.% in the α + β phase region (760-960 °C), and this value was about 655 and 199 kJ mol^{-1} for the alloy with 0.27 wt.% of hydrogenation content in the α + β phase region (760-840 °C) and β phase region (840-960 °C), respectively. Constitutive equation was developed for the high-temperature deformation of Ti-6Al-4V alloy both without and with hydrogenation content of 0.27 wt.%.

Keywords high-temperature deformation, hydrogenation, Ti-6Al-4V alloy

1. Introduction

Titanium alloys have a high affinity for hydrogen. An increased understanding of titanium metallurgy has demonstrated that hydrogen as a temporary alloying element can be used to improve the processing and microstructure/mechanical properties of the titanium alloys through hydrogenation properly, which is called the thermal hydrogenation processing (THP) (Ref 1-6). Numerous investigations have been performed to study the effect of hydrogenation on the deformation behavior and microstructure of titanium alloys (Ref 2, 7-12). The Ti-6Al-4V alloy is most often produced by an ingot-metallurgy route and one of the key steps in such processing is the breakdown of the transformed structure produced by initial β phase field hot working and heat treatment (Ref 13). Deformation behavior and microstructure of the Ti-6Al-4V alloy with lamellar starting structure had been investigated (Ref 13-15). THP can be used to decrease the flow stress and the deformation temperature greatly and may also be used to improve the final microstructure of the titanium alloys.

In this paper, isothermal compression of Ti-6Al-4V alloy with lamellar starting structure both without and with hydrogenation content of 0.27 wt.% has been conducted, so as to study the effect of hydrogenation on the deformation mechanisms in high-temperature deformation Ti-6Al-4V alloy.

Yong Niu, Miaoquan Li, and **Yingying Lin**, Northwestern Polytechnical University, Xi'an 710072, P.R. China; and **Hongliang Hou** and **Yaoqi Wang**, Beijing Aeronautical Manufacturing Technology Research Institute, Beijing 100024, P.R. China. Contact e-mails: yong4102@163.com and honeymli@nwpu.edu.cn.

2. Experimental Procedures

Ti-6Al-4V alloy is consisted of 6.23 Al, 4.09 V, 0.05 Fe, 0.008 C, 0.03 N, 0.004 H, 0.13 O and balance Ti. The received bars of Ti-6Al-4V alloy with 10.0 mm in diameter were heat-treated in the following procedure: (1) heated to 1030 °C and hold for 1 h, (2) cooled in furnace to room temperature so as to obtain lamellar structure illustrated in Fig. 1. Specimens with 12.0 mm in height and 8.0 mm in diameter were machined from the heat-treated bars.

Hydrogenation treatment was performed in high-purity hydrogen atmosphere at 750 °C hold 2 h and furnace-cooled to room temperature with a cooling rate of about 10 °C/min. The obtained hydrogenation content of 0.27 wt.% was controlled by hydrogen pressure, which is 5 kPa, and determined by weighing the specimens before and after hydrogenation to the nearest 0.01 mg.

High-temperature deformation behavior of titanium alloys is significantly different when the deformation is performed whether in the α + β phase region or in the β phase region. So the β transus temperature is a very important parameter for the high-temperature deformation study of titanium alloys. Hydrogen element is one of the β phase stabilizers for titanium alloys, and hydrogen element addition will decrease the β transus temperature of titanium alloys. Metallographic techniques were used to measure the β transus temperature. The β transus temperature of the Ti-6Al-4V alloy with hydrogenation content of 0.27 wt.% was identified as 840 °C. There is about 135 °C decrease in β transus temperature compared to that of the Ti-6Al-4V alloy without hydrogenation content of 0.27 wt.% (β transus temperature is about 975 °C). The present

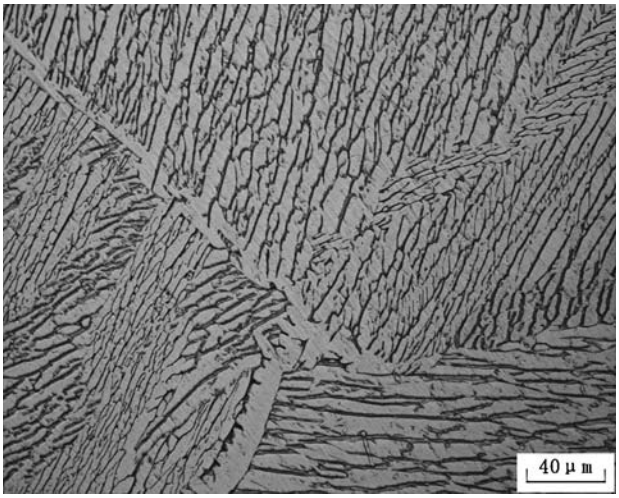

Fig. 1 Optical micrograph of the heat-treated Ti-6Al-4V alloy with lamellar structure

result is compared well with the reports of Kerr et al. (Ref 2) and Qazi et al. (Ref 16). After isothermal compression Ti-6Al-4V alloy, dehydrogenation in vacuum was carried out at 750 °C hold 2 h. The hydrogenation contents of some specimens were reconfirmed by weighing the specimens before and after dehydrogenation to make sure that no significant amount of hydrogen was lost during isothermal compression.

Isothermal compression of Ti-6Al-4V alloy with lamellar starting structure both without and with hydrogenation content of 0.27 wt.% at a constant strain rate was conducted on a Gleeble-1500D at deformation temperatures ranging from 760 to 960 °C with 40 °C intervals and strain rates ranging from 0.001 to 1.0 s^{-1}. The specimens were heated with a heating rate of 10 °C/s and hold 3 min at the deformation temperature prior to isothermal compression. The specimens were compressed to 50% in height and were cooled in air to room temperature. In the isothermal compression process, a glass lubricant was coated on the specimen's surface to avoid the oxidation of the specimen and the escape of hydrogen from the specimens with hydrogenation content of 0.27 wt.% (Ref 2). During isothermal compression, the flow stress was recorded as a function of strain for each deformation temperature and strain rate. Optical microscopy specimens were ground and polished using conventional techniques and etched with a solution of 10 mL HNO_3, 5 mL HF and 85 mL H_2O and microstructural examination was conducted on an OLYMPUS BX41M optical microscope.

3. Experimental Results and Discussion

Typical flow stress-strain curves are illustrated in Fig. 2. If isothermal compression was carried out in the α + β phase region (760, 800, 840, 880 and 920 °C for the Ti-6Al-4V alloy without hydrogenation content of 0.27 wt.% and 760 and 800 °C for the alloy with hydrogenation content of 0.27 wt.%), the flow stress-strain curves exhibited a sharp increase of flow stress at the beginning of compression, eventually culminating in a peak stress. Beyond the peak stress, the curves dropped continuously and kept a near steady flow at large strains of 0.7.

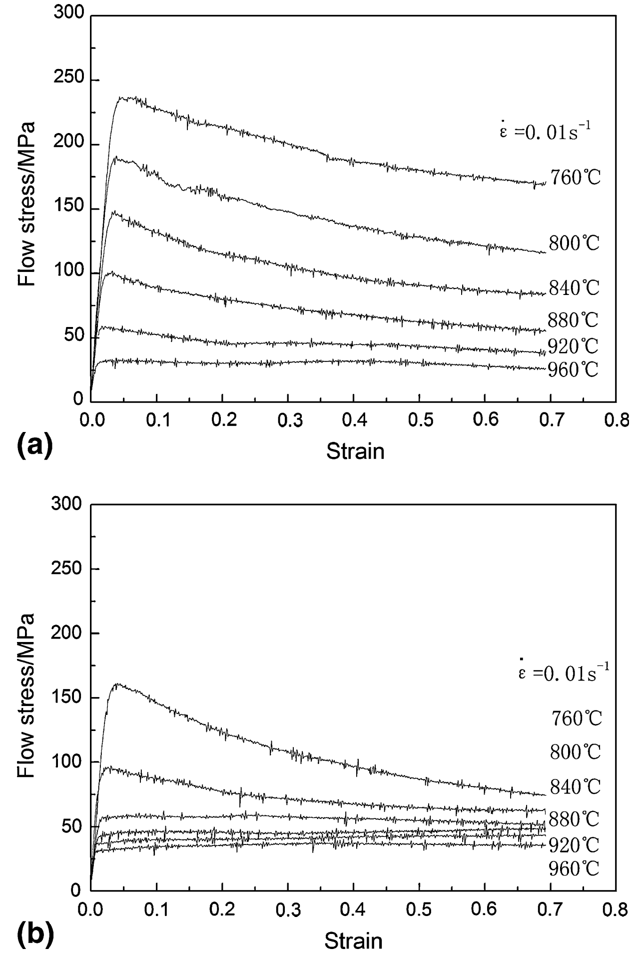

Fig. 2 Flow stress-strain curves of the Ti-6Al-4V alloy (a) without and (b) with hydrogenation content of 0.27 wt.%

When the isothermal compression was carried out near or above the β transus temperature (960 °C for the alloy without hydrogenation content of 0.27 wt.% and 840, 880, 920 and 960 °C for the alloy with hydrogenation content of 0.27 wt.%), the curves were characterized by an initial sharp increase of flow stress to a maximum value, followed by a very limited softening effect.

Effect of the deformation temperature on the peak flow stress at different strain rates is shown in Fig. 3. The peak flow stress of the Ti-6Al-4V alloy without and with hydrogenation was observed to decrease with an increase of deformation temperature. However, for the Ti-6Al-4V alloy with hydrogenation content of 0.27 wt.% deformed at more than 800 °C of deformation temperature, there was a small increase. The flow stress in the high-temperature deformation of titanium alloys is dependent on the deformation temperature in β region slightly, but there is a strong dependence on the deformation temperature in α region or α + β region (Ref 17). For the Ti-6Al-4V alloy with hydrogenation content of 0.27 wt.%, the β transus temperature is 840 °C. Thus, the peak flow stress of Ti-6Al-4V alloy with hydrogenation content of 0.27 wt.% during isothermal compression at more than 800 °C of deformation temperature has been observed to show slight dependence on temperature and to reflect the deformation characteristics of β phase. For all of the experimental strain rates, the peak flow stress of Ti-6Al-4V alloy with hydrogenation content of

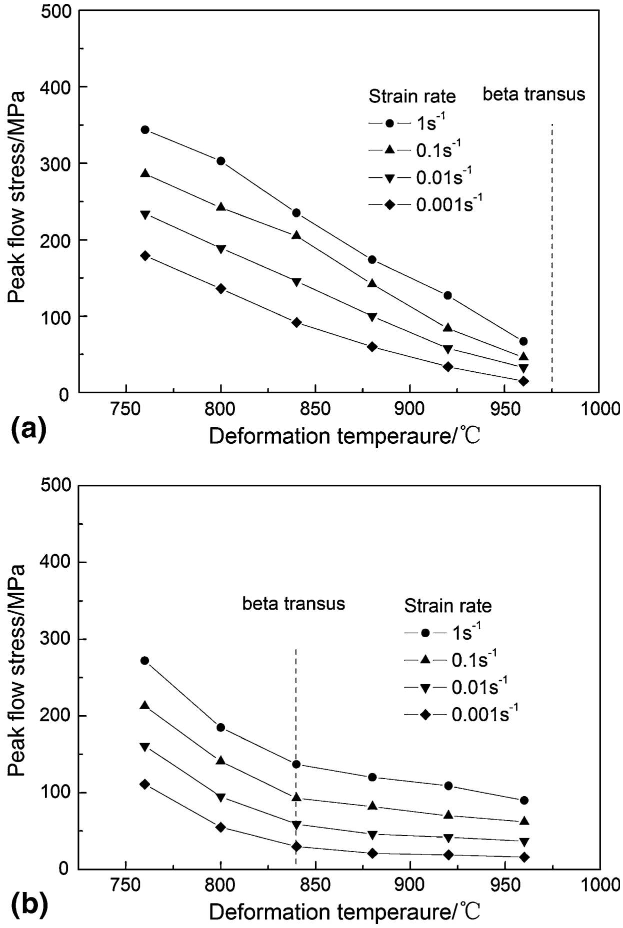

Fig. 3 Peak flow stress of the Ti-6Al-4V alloy (a) without and (b) with hydrogenation content of 0.27 wt.%

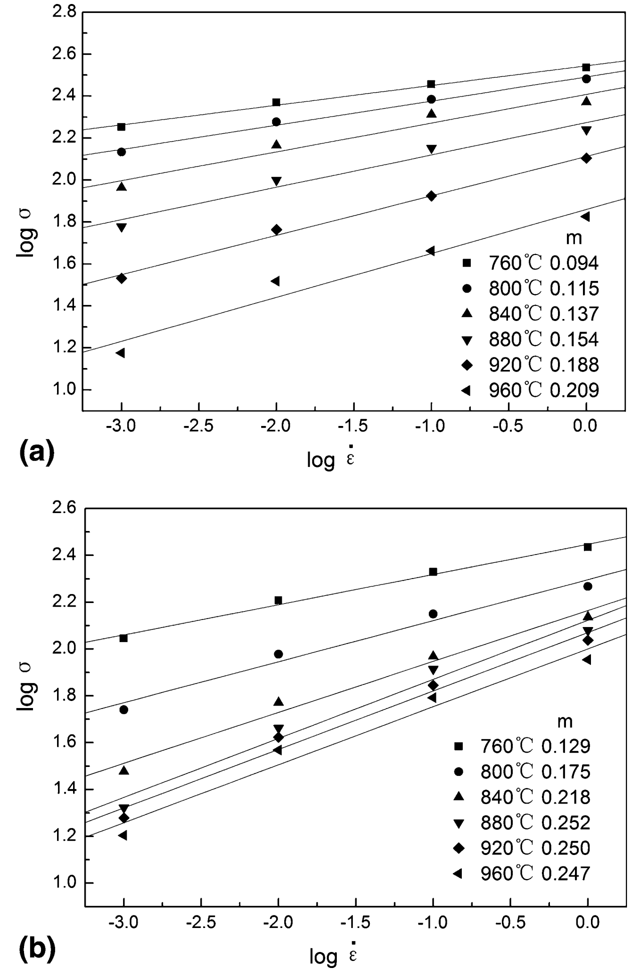

Fig. 4 Variation of the peak flow stress with strain rate of the Ti-6Al-4V alloy (a) without and (b) with hydrogenation content of 0.27 wt.%

0.27 wt.% deformed at 760, 800, 840 and 880 °C of deformation temperatures is less than those of the Ti-6Al-4V alloy without hydrogenation content of 0.27 wt.% deformed at 800, 840, 880 and 920 °C of deformation temperatures, respectively. At less than 920 °C of deformation temperature, the peak flow stress of the alloy with hydrogenation content of 0.27 wt.% deformed at strain rates of 1.0, 0.1 and 0.01 s^{-1} is not more than that of the Ti-6Al-4V alloy without hydrogenation content of 0.27 wt.% deformed at 0.1, 0.01 and 0.001 s^{-1} of strain rate, respectively. Hence, hydrogenation can decrease the deformation temperature by about 40 °C or increase the strain rate by about one order of magnitude at deformation temperature from 760 to 920 °C and strain rates from 0.001 to 1.0 s^{-1}.

Effect of the strain rate on the peak flow stress at various deformation temperatures is shown in Fig. 4. The peak flow stress was observed to increase with an increase of the strain rate for deformation temperatures between 760 and 960 °C. Specifically, the logarithmic peak flow stress-logarithmic strain rate could be fitted linear for strain rates between 0.001 and 1.0 s^{-1} and the strain rate sensitivity (m) was calculated. The m values increased from 0.094 to 0.21 with an increase of deformation temperature from 760 to 960 °C for high-temperature deformation of the Ti-6Al-4V alloy without hydrogenation content of 0.27 wt.% and these values were calculated to be between 0.129 and 0.218 for high-temperature deformation of alloy with hydrogenation content of 0.27 wt.% in the α + β phase region and about 0.25 in the β phase region. These results are compared well with the values reported in previous work (Ref 13, 17). Hydrogenation can increase the m value for high-temperature deformation of Ti-6Al-4V titanium alloy. This result is in agreement with the results of Zhang et al. obtained from a Ti-14Al-19Nb-3V-2Mo alloy (Ref 11).

The relationship between peak flow stress, strain rate and deformation temperature was obtained using a phenomenological approach comprising the equation proposed by Sellars and Tegart (Ref 18):

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

where σ is the peak flow stress (MPa), $\dot{\varepsilon}$ is the strain rate (s^{-1}), Q is the apparent activation energy of deformation (kJ mol^{-1}), R is the gas constant (kJ mol^{-1} K^{-1}), T is the absolute deformation temperature (K), and α, A and n are the material variations. Specifically, the logarithmic plots of the peak flow stress as a function of the strain rate that gave the best possible linear fits at α values of 0.009 and 0.01 for the isothermal compression of Ti-6Al-4V alloy without and with hydrogenation content of 0.27 wt.% are shown in Fig. 5. Figure 6 shows the variation of the peak flow stress with deformation temperature during isothermal compression of Ti-6Al-4V alloy. By analyzing the experimental data in

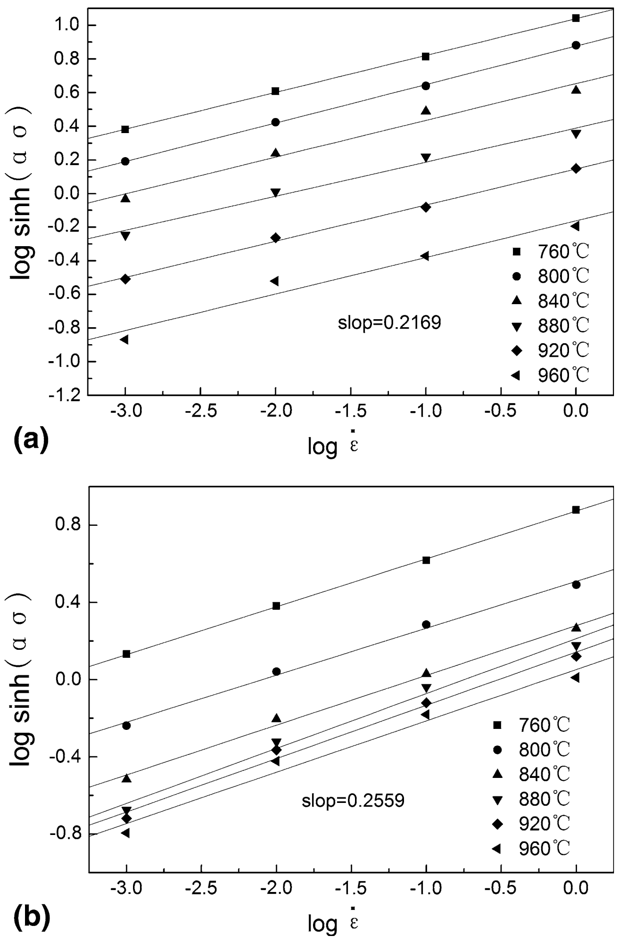

Fig. 5 Logarithm plots of the peak flow stress as a function of the strain rate for the Ti-6Al-4V alloy (a) without and (b) with hydrogenation content of 0.27 wt.%

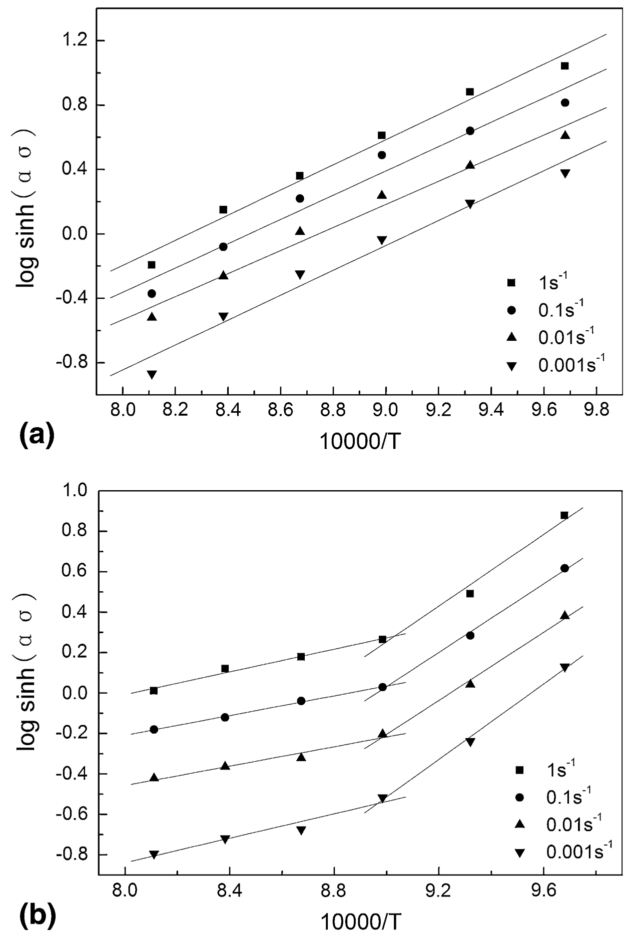

Fig. 6 Variation of the peak flow stress with deformation temperature of the Ti-6Al-4V alloy (a) without and (b) with hydrogenation content of 0.27 wt.%

Fig. 5 and 6, the apparent activation energy was determined to be 667 kJ mol^{-1} for isothermal compression of the Ti-6Al-4V alloy without hydrogenation content of 0.27 wt.% in the $\alpha + \beta$ phase region (760-960 °C), and this value was about 655 and 199 kJ mol^{-1} for the Ti-6Al-4V alloy with 0.27 wt.% of hydrogenation content in the $\alpha + \beta$ phase region (760-840 °C) and β phase region (840-960 °C), respectively. Deformed in the $\alpha + \beta$ phase region, apparent activation energies reported for titanium alloys (310-720 kJ mol^{-1}) are usually much higher than that for α-Ti self-diffusion ($\sim$150 kJ mol^{-1}) presented in Ref 14, 17, 19. For high-temperature deformation of the Ti-6Al-4V alloy with hydrogenation content of 0.27 wt.% in the β phase region, the apparent activation energy is close to the apparent activation energy reported for self-diffusion in β titanium (Ref 17). Figure 7 shows the variation of strain rate temperature parameter Z (Zener-Hollomon variation) with the peak flow stress with a correlation coefficient of 0.99. Based on the experimental results, a novel constitutive equation for high-temperature deformation of Ti-6Al-4V alloy both without and with hydrogenation content of 0.27 wt.% may be written in the following.

For the Ti-6Al-4V alloy without hydrogenation content of 0.27 wt.% in the $\alpha + \beta$ phase region:

$$\dot{\varepsilon}\exp(667000/RT) = 4.126 \times 10^{28}[\sinh(0.009\sigma)]^{4.51} \qquad \text{(Eq 2)}$$

For the Ti-6Al-4V alloy with hydrogenation content of 0.27 wt.% in the $\alpha + \beta$ phase region:

$$\dot{\varepsilon}\exp(655000/RT) = 5.665 \times 10^{29}[\sinh(0.01\sigma)]^{3.94} \qquad \text{(Eq 3)}$$

For the Ti-6Al-4V alloy with hydrogenation content of 0.27 wt.% in the β phase region:

$$\dot{\varepsilon}\exp(199000/RT) = 4.43 \times 10^{8}[\sinh(0.01\sigma)]^{3.60}. \qquad \text{(Eq 4)}$$

4. Conclusions

1. The peak flow stress of the Ti-6Al-4V alloy without and with hydrogenation decreases with an increase of the deformation temperature and a decrease of the strain rate. Hydrogenation can decrease the deformation temperature by about 40 °C or increase the strain rate by about one order of magnitude at deformation temperature from 760 to 920 °C and strain rate from 0.001 to 1.0 s^{-1}.
2. The apparent activation energy was determined to be 667 kJ mol^{-1} for isothermal compression of the

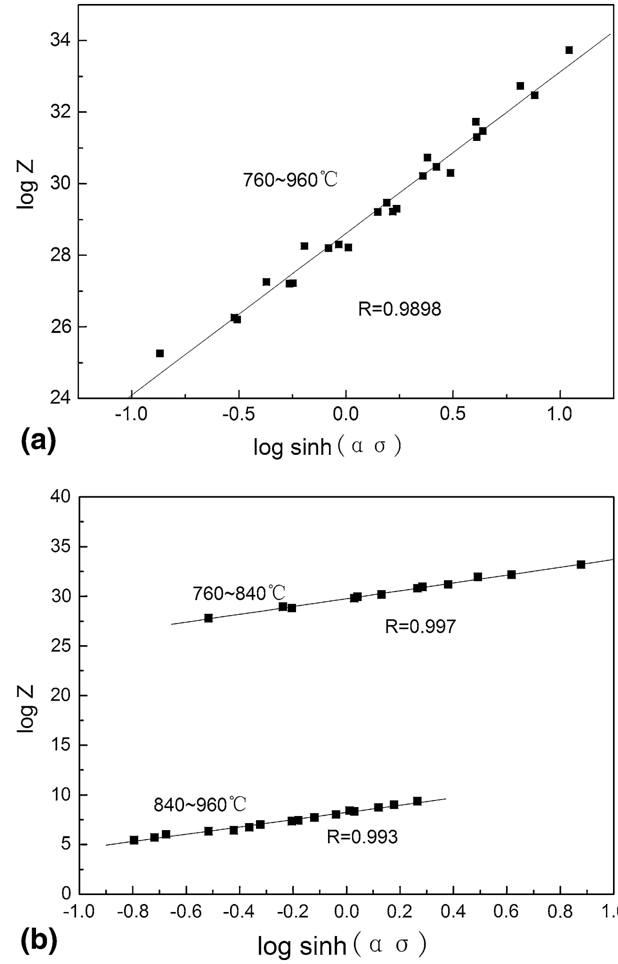

Fig. 7 Variation of the Zener-Hollomon parameters with the peak flow stresses for the Ti-6Al-4V alloy (a) without and (b) with hydrogenation content of 0.27 wt.%

Ti-6Al-4V alloy without hydrogenation content of 0.27 wt.% in the $\alpha + \beta$ phase region (760-960 °C), and this value was about 655 and 199 kJ mol^{-1} for the Ti-6Al-4V alloy with 0.27 wt.% of hydrogenation content in the $\alpha + \beta$ phase (760-840 °C) and β phase regions (840-960 °C), respectively.

3. A novel constitutive equation was proposed for high-temperature deformation of Ti-6Al-4V titanium alloy both without and with hydrogenation content of 0.27 wt.% over a wide range of deformation temperature and strain rate.

Acknowledgments

The authors thank the financial supports from the National Natural Science Foundation of China with Grant No. 50371068, and the Aviation Scientific Foundation of AVIC with Grant No. 05H53058.

References

1. F.H. Froes, O.N. Senkov, and J.I. Qazi, Hydrogen as a Temporary Alloying Element in Titanium Alloys: Thermohydrogen Processing, *Int. Mater. Rev.*, 2004, **49**, p 227–245
2. W.R. Kerr, R.R. Smith, M.E. Rosenblum, F.J. Gurney, Y.R. Mahajan, and L.R. Bidwell, Hydrogen as an Alloying Element in Titanium (HYDROVAC), *Titanium 80: Science and Technology* (Warrendale, PA), TMS, 1980, **4**, p 2477–2486
3. N. Eliaz, D. Eliezer, and D.L. Olson, Hydrogen-Assisted Processing of Materials, *Mater. Sci. Eng. A*, 2000, **289**, p 41–53
4. V.A. Goltsov, Hydrogen Treatment (Processing) of Materials: Current Status and Prospects, *J. Alloys Compd.*, 1999, **293–295**, p 844–857
5. A.A. Ilyin, I.S. Polkin, A.M. Momonov, and V.K. Nosov, Thermohydrogen Treatment—The Base of Hydrogen Technology of Titanium Alloys, *Titanium 95: Science and Technology* (London), The Institute of Materials, 1995, **4**, p 2462–2469
6. D. Elieaer, N. Eliaz, O.N. Senkov, and F.H Fores, Positive Effects of Hydrogen in Metals, *Mater. Sci. Eng. A*, 2000, **280**, p 220–224
7. S.Q. Zhang and L.R. Zhao, Effect of Hydrogen on the Superplasticity and Microstructure of Ti-6Al-4V Alloy, *J. Alloys Compd.*, 1995, **218**, p 233–236
8. O.N. Senkov and J.J. Jonas, Effect of Phase Composition and Hydrogen Level on the Deformation Behavior of Titanium-Hydrogen Alloys, *Metall. Mater. Trans.*, 1996, **27A**, p 1869–1876
9. Y.Y. Lin, M.Q. Li, Y. Niu, and W.F. Zhang, Effect of Hydrogenation on the Microstructure During the Isothermal Compression of Ti-5.6Al-4.8Sn-2.0Zr-1.0Mo Alloy, *Mater. Sci. Forum*, 2007, **551–552**, p 417–420
10. Y.Y. Lin, M.Q. Li, W.F. Zhang, and Y. Niu, Deformation Behavior in the Isothermal Compression of Hydrogenated Ti-5.6Al-4.8Sn-2.0Zr-1.0Mo Alloy, *J. Mater. Eng. Perform.*, 2007, **16**, p 93–96
11. Y. Zhang and S.Q. Zhang, Hydrogen Effects on High Temperature Deformation Characteristics of a Cast Ti-14Al-19Nb-3V-2Mo Alloy, *Scr. Mater.*, 1997, **l37**, p 1315–1321
12. Y.X. Chen, X.J. Wan, F. Li, and Q.J.W.Y.Y. Liu, The Behavior of Hydrogen in High Temperature Titanium Alloy Ti-60, *Mater. Sci. Eng. A*, 2007, **466**, p 156–159
13. S.L. Semiantin and T.R. Bieler, The Effect of Alpha Platelet Thickness on Plastic Flow During Hot Working of Ti-6Al-4V with a Transformed Miscrostructure, *Acta Mater.*, 2001, **49**, p 3565–3573
14. T. Seshacharyulu, S.C. Medeiros, W.G. Frazier, and P.V.R.K. Prasad, Microstructural Mechanisms During Hot Working of Commercial Grade Ti-6Al-4V with Lamellar Starting Structure, *Mater. Sci. Eng. A*, 2002, **325**, p 112–125
15. S. Tamirisakandala, B.V. Vedam, and R.B. Bhat, Recant Advances in the Deformation Processing of Titanium Alloys, *J. Mater. Eng. Perform.*, 2003, **6**, p 661–673
16. J.I. Qazi, O.N. Senkov, J. Rahim, A. Genc, and F.H. Fores, Phase Transformations in Ti-6Al-4V-xH Alloys, *Metall. Mater. Trans.*, 2001, **32A**, p 2453–2463
17. P. Wanjara, M. JaHazi, H. Monajati, S. Yue, and J.P. Immarigeon, Hot Working Behavior of Near-Alpha Alloy IMI834, *Mater. Sci. Eng. A*, 2005, **396**, p 50–60
18. C.M. Sellars and W.J. Tegart, *Acta Metall.*, 1966, **14**, p 1136–1138
19. R. Ding, Z.X. Guo, and A. Wilson, Microstructural Evolution of a Ti-6Al-4V Alloy During Thermomechanical Processing, *Mater. Sci. Eng. A*, 2002, **327**, p 233–245