Effect of Carbon Element on Mechanical Properties of *In Situ* 5 vol% TiC/Ti-1100 Composite

Feng-cang Ma, Wei-jie Lu, Ji-ning Qin and Di Zhang*

State Key Laboratory of Metal Matrix Composites, Shanghai Jiao Tong University, Shanghai 200030, P.R. China

In the present work, samples which were added various contents of C into Ti-1100 alloy were prepared, and *in situ* 5 vol% TiC/Ti-1100 composite was prepared. The microstructure of samples after hot-forging was examined using optical microscopy (OM). Mechanical properties of the samples were tested by tensile tests at ambient temperature and 873 K, respectively. Fractography of the composite was performed by scanning electron microscope (SEM). It was found that C element increases strength of Ti-1100 alloy obviously. But the strengthening mechanism of C in the composite was different at ambient temperature and 873 K. Compared to monolithic Ti-1100 alloy, the increase in strength at ambient temperature mainly results from solute C element in matrix, but at 873 K, the increase in strength also results from TiC particles.

(Received November 28, 2005; Accepted February 1, 2006; Published April 15, 2006)

Keywords: *in situ* titanium matrix composites, mechanical properties, strengthening mechanism

1. Introduction

The incorporation of low density, high modulus and high strength reinforcements into titanium, which by itself possesses a high specific strength at room and moderately elevated temperatures, significantly improves its specific modulus, specific strength and creep resistance.¹⁾ Compared with continuous-reinforced titanium matrix composites (TMCs), whisker or particle reinforced TMCs possess isotropic behavior, ease of fabrication and low cost. This has stimulated recent interest in the study of TMCs.²⁻⁵⁾ The TMCs reinforced with whisker or particles are conventionally prepared by powder technology^{6,7)} or liquid metallurgy.^{8,9)} However, TMCs reinforced with ceramic particles formed *in situ* techniques are an emerging group of discontinuous-reinforced composites that have distinct advantages over the conventional TMCs. This process eliminates the interface incompatibility between matrix and reinforcement by creating more thermodynamically stable reinforcements based on their nucleation and growth from parent matrix phase. These composites produced via *in situ* techniques exhibit high specific strength and modulus, as well as excellent oxidation and creep resistance.¹⁰⁾ On the other hand, Ti-1100 is a very popular commercial Ti alloy used at elevated temperature, so it is a very useful study to improve the properties of Ti-1100 alloy by *in situ* techniques.

In this paper, C element was added to Ti-1100 alloy to prepare TiC/Ti-1100 composites utilizing self-propagation high-temperature synthesis (SHS) reaction, and TiC ceramic particles were synthesized through the following reactions:

In another work by these authors to measure the β transus temperature of *in situ* TiC/Ti-1100 composites, it was found that the max solubility of C in a Ti is about 0.28 mass%.¹¹⁾ In order to investigate the effect of C in the *in situ* TiC/Ti-1100 composites, the sample with 0.28 mass% C content and monolithic Ti-1100 alloy were also prepared in this paper.

Table 1 Composition of samples.

Samples number	C content (mass%)	Volume fraction of TiC (%)	Ti-1100
N ₁	0	0	Balance
N ₂	0.28	0	Balance
N ₃	2	5	Balance

2. Experimental Procedure

Compositions of the samples prepared in this paper are listed in Table 1. The nominal alloy composition of Ti-1100 is Ti-6Al-2.75Sn-4Zr-0.4Mo-0.45Si. Ingots of the samples were prepared in a vacuum arc remelting (VAR) furnace. In order to ensure the chemical homogeneity of the samples, the ingots were remelted at least three times. After casting, the ingot was forged into rods. Phase identification of the composites was performed by a D-max IV A X-ray diffractometer (XRD). The tensile samples were a plate with a gauge thickness of 1.5 mm and length of 40 mm. They were machined from hot-forging rods with the specimen axis parallel to the hot-forging direction. The tensile tests were performed using a SHMADZU AG-100KNA servohydraulic structural test machine. The average strain rate was $5.0 \times 10^{-3} \text{ s}^{-1}$. Load-elongation curves were obtained on an X-Y plotting table that was linked to the load cell of the machine and to an extensometer clamped to test samples. Samples for optical microscopy (OM) were cut from the specimens after forging. Then the samples were prepared using conventional techniques of grinding and mechanical polishing. The samples were etched in Kroll's reagent (composition: 1-3 ml HF, 2-6 ml HNO₃, 100 ml water). The microstructures of samples were characterized using a LECO2000 optical microscopy. Fractography of the composites in tensile tests also was investigated by scanning electron microscopy (SEM) Philips SEM 515.

3. Experimental Results and Discussion

3.1 Phase identification and microstructure

Figure 1 shows XRD patterns of the specimen. It indicates

*Corresponding author, E-mail: zhangdi@sjtu.edu.cn

Fig. 1 X-ray diffraction patterns for 5 vol% TiC/Ti-1100 composite.

Fig. 2 The distribution of TiC particles in composite after ingot breakdown (unetched).

Fig. 3 Optical micrograph of samples after hot-forging: (a) N_1 (monolithic Ti-1100 alloy), (b) N_3 (*in situ* 5 vol% TiC/Ti-1100 composite).

Fig. 4 Stress-strain curves of samples during tensile tests at ambient temperature.

Fig. 5 Stress-strain curves of samples during tensile tests at 873 K.

that the present phases in the composites are titanium, TiC. The result of the XRD analysis confirms that titanium matrix composites reinforced with TiC can be fabricated by this method utilizing the reaction between Ti and C. The distribution of TiC particles in the composite is shown in Fig. 2. It can be seen that reinforcements are distributed

uniformly in the titanium matrix, and the size of TiC particles is about 5–10 μm . The microstructures of the samples after forging are presented in Fig. 3. The size of a grains is about 10–20 μm , and size of a grains in N_2 is almost same as that in N_1 . But from Fig. 3, it also can be seen that the size of a phase in N_3 is smaller than that in N_1 , which may result from the formation of TiC particles during solidification process.

Fig. 6 SEM micrographs showing the fracture surfaces: (a) monolithic Ti-1100 alloys at ambient temperature, (b) Ti-1100 alloys with 0.28 mass% C at ambient temperature, (c) 5 vol% TiC/Ti-1100 composite at ambient temperature, (d) 5 vol% TiC/Ti-1100 composite at 873 K.

Because the melting point of TiC is higher than that of matrix alloy, TiC form firstly in the liquid phase with decreasing of temperature. Many fine TiC particles act as crystallization nucleation for matrix alloy during solidification process.¹²⁾ It is well known that finer grain is favorable in high strength during tensile tests.

3.2 Tensile properties

The tensile results of various samples at ambient temperature and 873 K are presented in Fig. 4 and Fig. 5 respectively. From Fig. 4 and Fig. 5, it can be seen that addition of C element can increase the strength of Ti-1100 obviously. It is well understood that the strengthening effect of C in the composite comes from two ways, i.e. one is the solid solution in matrix, and the other is the formation of TiC particles. From Fig. 4, the tensile strength of sample N₃ is almost equal to that of N₂ sample, which indicate that the strength increase for the composite compared to monolithic Ti-1100 alloy mainly comes from the solid solution of C in matrix, but it also can be seen that solid solution C in matrix

decrease the ductility of Ti-1100 alloy rapidly. But at 873 K, there is an about 100 MPa increase in tensile strength for sample N₃ compared to sample N₂. It is obvious that compared to sample N₁ the increase (about 220 MPa) in strength for sample N₃ results from not only solid solution C in matrix but also TiC particles. In order to investigate the different strengthening effect of C in the composite at different temperatures, fractography of the composite was performed.

3.3 Fractography

The typical SEM micrographs of the fracture surfaces of 5 vol% TiC/Ti-1100 composite at ambient temperatures and 873 K are showed in Fig. 6. These indicate that the tensile fracture surfaces are different at ambient temperature and 873 K. As Fig. 6(a) presented, at ambient temperature a ductile fracture mode was observed in sample N₁ (monolithic Ti-1100 alloy), but a brittle cleavage fracture mode was observed at ambient temperature in sample N₂ and N₃ (Fig. 6(b) and Fig. 6(c)) and no cracked TiC particles were

Fig. 7 SEM micrographs of longitudinal sections of different deformed areas in the fractured composite at 873 K: (a) minute deformed area, (b) moderate deformed area, (c) heavy deformed area.

observed in sample N₃. The results indicate that solid solute C in matrix has obvious effect on the fracture of the composite during tensile tests at ambient temperature. Solid solute C in matrix decreases the ductility of the sample N₂ and N₃ rapidly. During tensile tests, the titanium matrix experienced cleavage fracture at ambient temperature. At 873 K, it can be seen from Fig. 6(d) that the fracture surface consisted of the fine dimples. It shows a typical character of ductile fracture. Many cracked reinforcements can be found on the fracture surface. In order to understand the fracture process of the composites at 873 K, the longitudinal sections of the fractured tensile specimens were examined. Three parts in the longitudinal sections were examined (Fig. 7). It is clear that the deformation of the composites is heavy at one end of fracture surface and minute at another end. The fractured test samples were divided into three parts: minute deformed area (Fig. 7(a)), moderate deformed area (Fig. 7(b)) and heavy deformed area (Fig. 7(c)). With deformation increasing, some TiC reinforcements crack, as presented in Fig. 7(b) and Fig. 7(c). Because of the cracking of TiC reinforcements, the effect of its load bearing vanished, and many cracks formed in matrix (Fig. 7(c)). From the fracture process of the composite at 873 K, it can be seen that TiC particles bear large stress during tensile process.

3.4 Strengthening mechanism of TiC in the composite

In order to understand the obtained tensile results, it is necessary to analyze stress distribution in the composite during tensile process. Due to the difference in stiffness between reinforcements and matrix, the distribution of stress in the composite is very complex during deformation. A simulated method suggested by Eshelby presented the average stress in matrix and reinforcements of composite during elastic deformation process by following formulas:¹³⁾

$$\langle \sigma \rangle_M = -f C_M (S - I) \varepsilon^T \quad (2)$$

$$\langle \sigma \rangle_I = (1 - f) C_M (S - I) \varepsilon^T \quad (3)$$

in above formulas, $\langle \sigma \rangle_M$, $\langle \sigma \rangle_I$, f , C_M , S , I and ε^T are average stress in matrix, average stress in reinforcements, volume fraction of reinforcements, stiffness constant of matrix, tensor depended on the shape of reinforcement, unit matrix and equivalent strain of reinforcements. And these formulas can be used to evaluate strength of composites.

At ambient temperature, due to the poor ductility of matrix caused by C solid solution, when the composite failed the value of ε^T was very small, and the value of $\langle \sigma \rangle_I$ was small too. Load transferring effect of matrix to TiC particles is not obvious, and the increase in strength for the composite compared to Ti-1100 alloy mainly came from solid solution C in matrix. But at 873 K, due to higher ductility of matrix, the value of ε^T became larger, and the value of $\langle \sigma \rangle_I$ became larger too. Load transferring effect of matrix to TiC particles became obvious, so the increase in strength for the composite compared to monolithic Ti-1100 alloy also came from TiC particles. From formula (2) and (3), values of $\langle \sigma \rangle_M$ and $\langle \sigma \rangle_I$ for this composite are calculated to be $0.05 C_M (S - I) \varepsilon^T$ and $0.95 C_M (S - I) \varepsilon^T$, respectively. This result shows that the average stress in reinforcements is larger than that in matrix for the *in situ* 5 vol% TiC/Ti-1100 composite during tensile process. When the value of $\langle \sigma \rangle_I$ was larger than the strength limit of TiC particles during tensile tests at 873 K, TiC particles cracked.

Besides load transferring effect of matrix, there are other ways for TiC particles to strengthen the composite. As mentioned above, the formation of TiC particles in liquid phase refined grains of matrix. Due to the difference in coefficient of thermal expansion between TiC particles and matrix, TiC increase the dislocation density in matrix during cooling process of the composite.

4. Conclusions

The following generalized conclusions can be drawn from this work:

- (1) C element can increase the strength of Ti-1100 alloy obviously at ambient temperature or at 873 K.
- (2) At ambient temperature, *in situ* 5 vol% TiC/Ti-1100 composite experiences cleavage fracture during tensile tests. Compared to Ti-1100 alloy, the tensile strength increase about 300 MPa and ductility decrease greatly, which mainly results from the solid solution C in matrix.
- (3) At 873 K, *in situ* 5 vol% TiC/Ti-1100 composite experiences ductile fracture, and many TiC particles crack during tensile process. Compared to Ti-1100 alloy, the tensile strength increases about 220 MPa, which results from not only solid solution C in matrix but also TiC particles.

Acknowledgments

We would like to acknowledge a financial support provided by A Foundation for the Author of National Excellent Doctoral Dissertation of P R China under Grant No: 200332, the Research Fund of Science and Technology Commission of Shanghai Municipality under Grant No:

04DZ14002, 0452nm045, 03ZR14063, and the ItoYama Foundation.

REFERENCES

- 1) S. Ranganath: J. Mat. Sci. **32** (1997) 1–16.
- 2) D. G. Konitzer and M. H. Loretto: Acta Metall. Mater. **37** (1989) 397–403.
- 3) S. Rangarajan, P. B. Aswath and W. O. Soboyejo: Scr. Metall. Mater. **35** (1996) 239–243.
- 4) S. Gorsse, J. P. Chaminade and Y. LePetitcorps: Composites Part **A29** (1998) 1229–1233.
- 5) H. Hofmann, G. Frommeyer and C. Derder: Mater. Sci. Eng. **A245** (1998) 127–132.
- 6) P. Wanjara, S. Yue, R. A. L. Drew, J. Root and R. Donaberger: Key Eng. Mater. **127–131** (1997) 415–421.
- 7) S. Abkowitz and S. M. Abkowitz: Ind. Heating **60** (1993) 32–37.
- 8) Y. Lin, R. H. Zee and A. Chin: Metall. Trans. **A22** (1991) 859–863.
- 9) R. Zee, C. Yang, Y. X. Lin and B. Chin: J. Mater. Sci. **26** (1991) 3853–3859.
- 10) B. G. Velasco and P. B. Aswath: J. Mater. Sci. **33** (1998) 2203–2208.
- 11) F. C. Ma, W. J. Lu, J. N. Qin and D. Zhang: Mater. Lett. **60** (2006) 400–405.
- 12) W. J. Lu, D. Zhang, R. J. Wu and H. Mori: Metall. Trans. **A33** (2002) 3055–3063.
- 13) T. W. Clyne and P. J. Withers: *an introduction to metal matrix composites* (in chinese). (Metallurgy industry press, Beijing, 1996), pp. 41–65.