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LETTER

Strengthening mechanisms of carbon element in in situ TiC/Ti-1100 composites

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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].

In this paper, C element was added to Ti-1100 alloy to prepare TiC/Ti-1100 composites utilizing SHS technique, TiC ceramic particles are synthesized through the following reactions:

$$Ti + C \rightarrow TiC \quad (1)$$

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In another work by author to measure the β transus temperature of in situ TiC/Ti-1100 composites, it was found that the solubility of C in α Ti is about 0.28 wt % [11]. In order to investigate the effect of C in the in situ TiC/Ti-1100 composites, the sample with 0.28 wt% C content and monolithic Ti-1100 alloy were also prepared in this paper.

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 melted 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 $5.0\times10^{-3}s^{-1}$. 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 OM. Fractography of the composites in tensile tests also was investigated by scanning electron microscopy (SEM) Philips SEM 515.

Fig. 1 shows XRD patterns of the specimen. It indicates that the present phases in the composites are titanium, TiC. The result of the XRD analysis confirms that TMCs reinforced with TiC can be fabricated by this method

Table 1 Composition of samples

Samples number	C content (wt.%)	Volume fraction of TiC (%)	Ti-1100
N_1	0	0	Balance
N_2	0.28	0	Balance
N_3	2	5	Balance
N_4	3.7	10	Balance

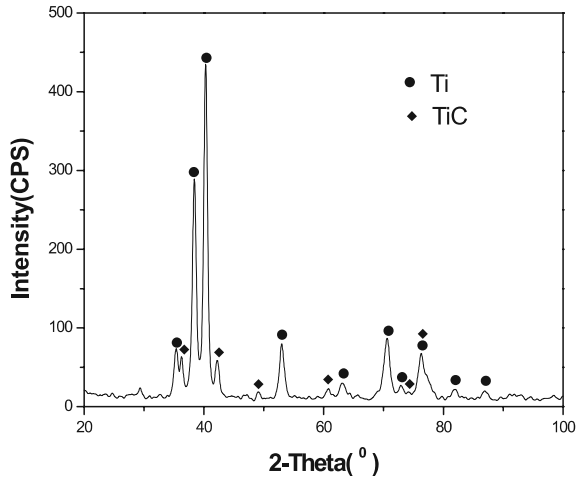

Fig. 1 X-ray diffraction patterns of TiC/Ti-1100 composite

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 um. The microstructures of the samples after forging are presented in Fig. 3, and the size of α grains is about 10–20 μm.

The tensile results of various samples at ambient temperature and 873 K are presented in Figs. 4 and 5, respectively. From Figs. 4 and 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 the other is formed TiC particles. From Fig. 4, the tensile strength of sample N_4 and N_3 is almost equal to that of N_2 sample, which indicate that the increase in strength for this composite compared to monolithic Ti-1100 alloy mainly come 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 greatly. But at 873 K, there is an obvious increase in tensile strength for sample N_3 and N_4 compared to N_2 and the tensile strength of sample N_2 is lager than that of N_1. It is obvious that compared to sample N_1 the increase in strength for composite 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. The typical SEM micrographs of the fracture surfaces of 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, a brittle cleavage fracture mode was observed at ambient temperature and no cracked TiC particles were observed, which indicate that the fracture of the composite was caused by matrix. Because solid solution C in matrix decrease ductility of matrix greatly, the ductility of matrix is fairly low at ambient temperature, before the composites have a large deformation, the titanium matrix experienced cleavage fracture. At 873 K, it can be seen from Fig. 6(b) 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 near the fracture surface were examined, and the result was presented in Fig. 7. From Fig. 7, it can be seen that many TiC cracked before composites failure during tensile tests. From the fractured process of the composite at 873 K, it can be that TiC particles bear large stress during tensile process.

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

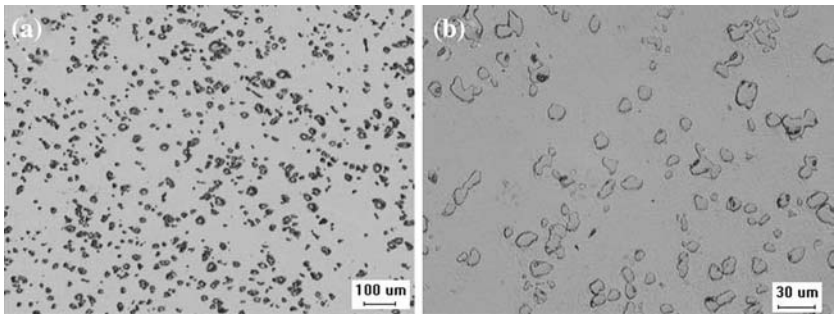

Fig. 2 Distribution and optical micrograph of TiC particles in composite after ingot breakdown (unetched): (a) N_3 (5 vol.% TiC/Ti-1100 composite); (b) N_4 (10 vol.% TiC/Ti-1100 composite)

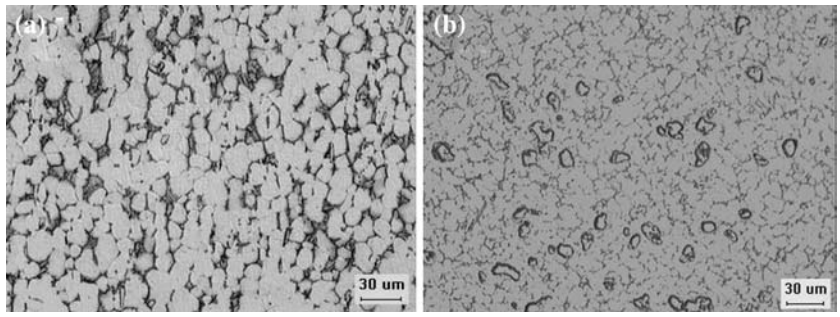

Fig. 3 Optical micrograph of samples after hot-forging: (a) N_1 (monolithic Ti-1100 alloy); (b) N_3 (in situ 5 vol.% TiC/Ti-1100 composite)

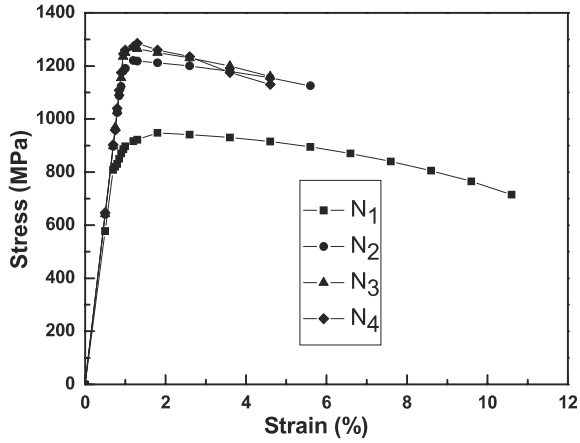

Fig. 4 Stress–strain curves of samples during tensile tests at ambient temperature

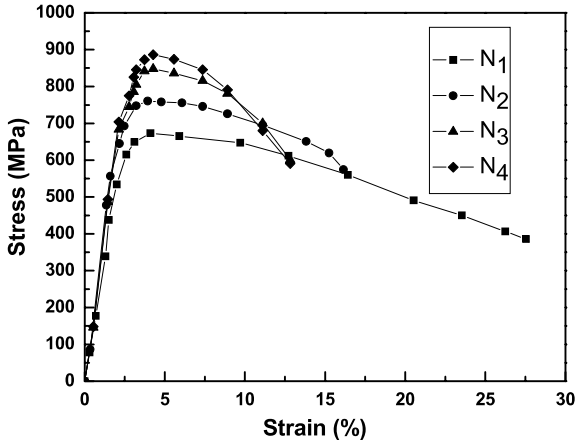

Fig. 5 Stress–strain curves of samples during tensile tests at 873 K

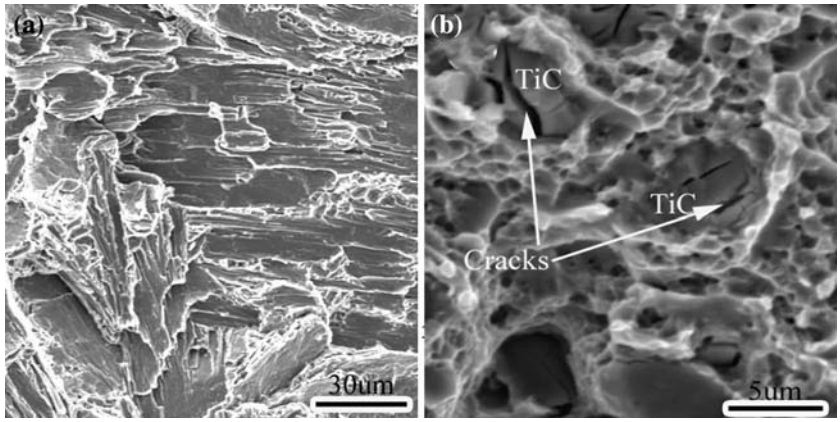

Fig. 6 SEM micrographs of the fracture surfaces for 10 vol.% TiC/Ti-1100 composite: (a) ambient temperature, (b) 873 K

the average stress in matrix and reinforcements of composite by following formulas [12]:

$$\langle\sigma\rangle_M = -fC_M(S-I)\varepsilon^T \tag{2}$$

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

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, before failure of the composite the value of ε^T is very small, and the value of $\langle\sigma\rangle_I$ is small too. Load transferring effect of matrix to TiC particles is small, and the increase in strength for the composite mainly comes from solid solution C in matrix.

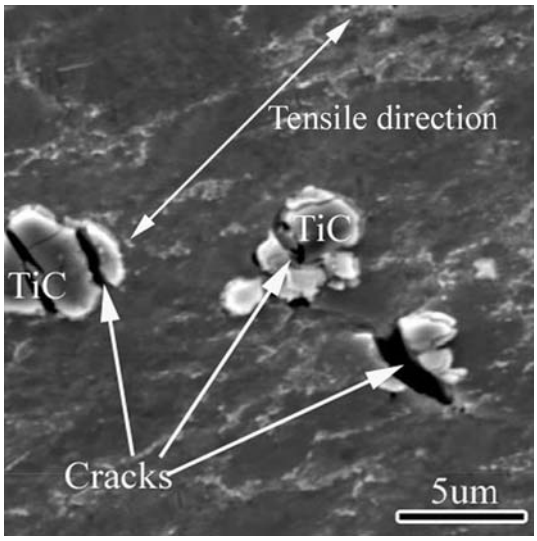

Fig. 7 SEM micrographs of longitudinal sections of the fractured composite at 873 K (10 vol.% TiC/Ti-1100 composite)

But at 873 K, due to higher ductility of matrix, the value of ε^T before failure of the composite become larger, and the value of $\langle\sigma\rangle_I$ is larger too. Load transferring effect of matrix to TiC particles becomes obvious, so the increase in strength for the composite also comes from TiC particles. From formulas (2) and (3), it also can be seen that the average stress in reinforcements is larger than that in matrix for these TiC/Ti-1100 composites during tensile process. When the value of $\langle\sigma\rangle_I$ is larger than the strength limit of TiC particles during tensile tests at 873 K, TiC particles will crack.

From above discussions, it can be summarized that C element can increase the strength of Ti-1100 alloy obviously at ambient temperature or at 800 K. But the strengthening mechanism is different at different temperatures. At ambient temperature, compared to Ti-1100 alloy the tensile strength increases mainly results from the solid solution C in matrix. At 873 K, compared to Ti-1100 alloy the tensile strength increases results from not only solid solution C in matrix but also formed TiC particles.

References

1. Ranganath S (1997) J Mat Sci 32:1
2. Konitzer DG, Loretto MH (1989) Acta Metall Mater 37:397
3. Rangarajan S, Aswath PB, Soboyejo WO (1996) Scr Metall Mater 35:239
4. Gorsse S, Chaminade JP, LePetitcorps Y (1998) Composites Part A 29:1229
5. Hofmann H, Frommeyer G, Derder C (1998) Mater Sci Eng A 245:127
6. Wanjara P, Yue S, Drew RAL, Root J, Donaberger R, Key Eng Mater 127–131 (1997) 415
7. Abkowitz S, Abkowitz SM (1993) Ind Heating 60(9): 32
8. Lin Y, Zee RH, Chin A (1991) Metall Trans A22: 859
9. Zee R, Yang C, Lin YX, Chin B (1991) J Mater Sci 26: 3853
10. Velasco BG, Aswath PB (1998) J Mater Sci 33: 2203
11. Ma FC, Lu WJ, Qin JN, Zhang D (2006) Mater Lett 60: 400
12. Clyne TW, Withers PJ (1996) An introduction to metal matrix composites (in chinese). Metallurgy industry press, Beijing, pp 41–65