EFFECTS OF HOT EXTRUSION AND HEAT TREATMENT ON THE MICROSTRUCTURE AND TENSILE PROPERTIES OF TIB_W/TI6AL4V COMPOSITES WITH A NOVEL NETWORK MICROSTRUCTURE

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Abstract

TiB whisker reinforced Ti6Al4V matrix (TiBw/Ti64) composite with a network microstructure has been extruded in order to further improve the mechanical properties. By microstructure observation, the equiaxed network microstructure has been deformed to a column network, and the whiskers are directionally distributed along the extruded direction. The tensile test results show that not only the strength but also the ductility is remarkablly improved by extrusion deformation. The improvement of the strength can be mainly attributed to the matrix strain hardening effect, however, that of the ductility to the decreased local volume fraction of TiBw reinforcement in the network boundary region. Moreover, the tensile properties can be further improved by the subsequent heat treatment.

1. Introduction

In the past decades, numerous researches in the field of titanium matrix composites (TMCs) including continuously SiC fibers (SiC_f) reinforced titanium matrix composites (CRTMCs) fabricated by conventional *ex-situ* method and discontinuous whiskers or particles reinforced titanium matrix composites (DRTMCs) fabricated mainly by novel *in situ* methods had been conducted [1-5]. In particular, TiB whiskers (TiBw) reinforced Ti matrix composites as a typical representation of DRTMCs have been unanimously commended to be the optimal candidate materials for commercial automotive, aerospace and military applications due to their superior and isotropic properties [1-4]. However, the researchers have always pursued a homogeneous distribution of the TiBw reinforcement. In reality, the experimental results in the past 40 years have adequately demonstrated that the composites with a homogeneous reinforcement distribution just can exhibit a limited improvement of mechanical property, even inferior mechanical property such as extreme brittleness for the TMCs fabricated by the conventional powder metallurgy (PM) process [6, 7]. Fortunately, in our previous work [1, 2], a quasi-continuous network reinforcement distribution which can exploit a superior ductility of the matrix and the strengthening effect of the reinforcement have been successfully designed and fabricated by a simplified PM process and selecting the large Ti64 powder.

Additionally, plastic deformation and heat treatment can play a very important role in improving the mechanical properties of metal matrix composites (MMCs) [8, 9]. The processing parameters significantly affects the microstructure and mechanical properties of MMCs. Therefore, the present work focuses on the hot extrusion, one of plastic deformation techniques, and heat treatment to the novel TiBw/Ti64 composite with a novel quasi-continuous network microstructure, in order to further improve the mechanical properties.

2. Experimental procedures

As reported in our previous work [1, 2], TiBw/Ti64 composites with a novel network reinforcement microstructure were sucessfully fabricated by selecting the raw maerials of the large

Ti64 powders and fine TiB_2 powders, the processes of low-energy milling and reaction hot pressing. Fig. 1 shows the network microstructure of the typical 5vol.%TiBw/Ti64 (200μm) composite. The synthesized TiB whisker reinforcements are distributed around Ti64 matrix particles and formed a 3D equiaxed network microstructure. The overall network unit can be divided into a network TiBw-rich boundary region and a TiBw-lean matrix region due to the well defined boundary width as shown in Fig. 1 [1, 2].

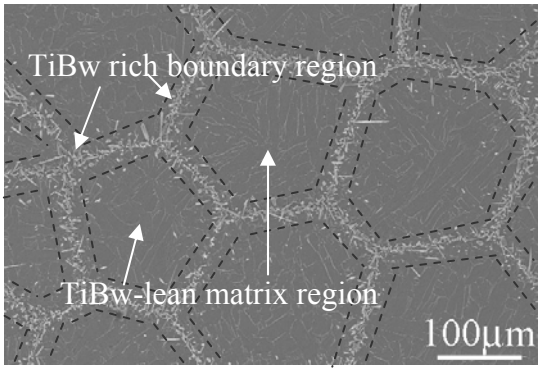

Fig. 1. SEM micrograph of *in situ* TiBw/Ti64 composite with a quasi-continuous network microstructure.

In order to further investigate the effects of subsequent deformation and heat treatment on the microstructure and mechanical properties of the composites with a novel network microstructure, hot extrusion deformation was performed to the typical 5vol.%TiBw/Ti64 (200μm) composite by a extrusion ratio of 16:1 at 1100°C. Then, the as-extruded composite was, respctively, heat treated by two different parameters: the complete annealing (1200°C for 40min and then furnace cooling); the solid solution and aging (900°C for 40min and then water quenching followed by 500°C for 6h by air cooling).

Room temperature tensile tests were carried out using an Instron-1186 universal testing machine at a constant crosshead speed of 0.5 mm/min (approximate strain rate is 5.5×10^{-4}/s). A total of three tensile samples with dimensions of 15mm×5mm×2mm along the extruded direction were tested for each sample. Microstructural and fracture characterizations were performed using a scanning electron microscope (SEM, Hitachi S-4700). The samples of microstructure observation were etched using the Kroll's solution (5vol%HF+10vol.%HNO_3+ 85vol.%H_2O) for 10s after mechanical polishing. One profile surface of the tensile sample before test was also mechanically polished in order to observe the fracture characteristics of the composite.

3. Results and discussions

Figure 2 shows the SEM micrographs of the as-extruded TiBw/Ti64 composite along the longitudinal and the cross sections. As shown in Fig. 2(a), the equiaxed network is extended by extrusion deformation. Thereby, the network boundary surface is increased, which leads to decrease the local volume fraction of reinforcement in the network boundary. It is certain that the decrease of the local reinforcement volume fraction is benificial to the ductility but harm to the strength of the composite along the extruded direction [2]. In the boundary region, TiB whiskers are distributed along the extruded direction due to the extrusion deformation as shown in Fig. 2(b). A part of them are broken to alignment distribution due to the previous 3D distribution. The alignment distribution of reinforcement is benificial to the strengthening effect.

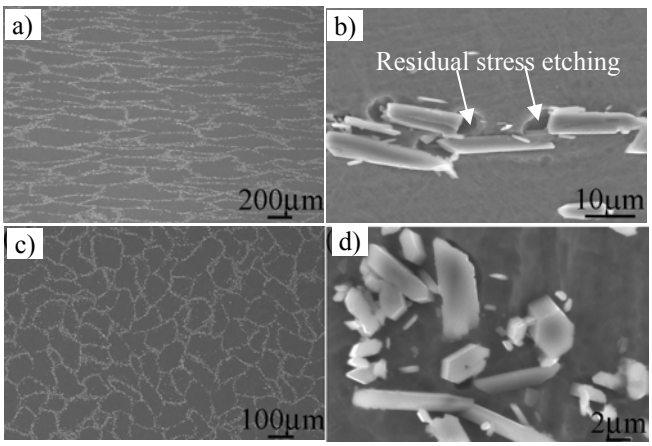

Fig. 2. SEM micrographs of the longitudinal (a, b) and cross (c, d) sections of the as-extruded 5vol.%TiBw/Ti64 (200μm) composite at different magnifications; a), c) at low magnifications, b), d) at high magnifications

A serious residual stress is generated due to the mismatched deformation of the matrix and the whiskers. Additionally, the Ti64 matrix of the as-sintered TiBw/Ti64 composites exhibits the quasi-equiaxed α+β microstructure as reported in the

previous work [1], however, which is insteaded by martensite due to the deformation above the β transus temperature of 1100°C followed by air cooling. This deformed martensite can exploit a superior strength of the Ti64 matrix and thereby the composite [10].

As shown in Fig. 2(c), the cross section of the network microstructure of the composites also retain a quasi-equiaxed morphology. Therefore, the previous 3D equaixed network is become to a 3D column network along the extruded direction combining with the Fig. 2(a), which is also benificial to the combination of strenth and ductility of the composite. Fig. 2(d) further shows the alignment distribution and the hexagon cross section of TiB whiskers.

Fig. 3 shows the SEM micrographs of the composites after heat treatments following the hot extrusion deformation. As shown in the Fig. 3(a), the matrix exhibits a transformed β microstructure including residual martensite and fine α+β phases transformed from the quenching martensite, which is benificial to the strength of the composite. However, after the complete annealing, the matrix exhibits a quais-equiaxed α+β microstructure similar with that of the as-sintered composites [1] as shown in the Fig. 3(b). This equiaxed microstructure can exploit a higher ductility but a lower strength than the transformed β microstructure. Comparing with Figs. 2(b), 3(a) and 3(b), the stress etching seriousness decreases with increasing the temperatures of heat treatment, which demonstrates that the residual stress was generated due to the mismatched deformation of reinforcement and matrix during extrusion.

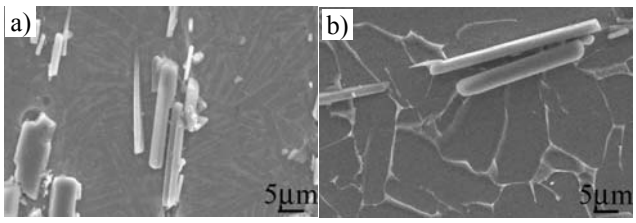

Fig. 3. SEM micrographs of 5vol.%TiBw/Ti64 composite (200μm) heat treated by (a) 900°C/30min/QC and (b) 1200°C/30min/FC

Fig. 4 shows the tensile stress-strain curves of 5vol.%TiBw/Ti64 composites on different conditions. Firstly, by comparing with curve 1 and curve 2, not only the strength but also the elongation of the 5vol.%TiBw/Ti64 composite is remarkably improved by extrusion deformaton. The tensile strength and the tensile elongation are increased from 1090MPa and 3.5% to 1230MPa and 6.5%, respectively, along the extruded direction. That is to say, the tensile strength and the tensile elongation are increased by 13% and 86%, by etrusion deformation. The main reason for the significant imrovement of the ductility of the composite is the decrease of the local volume fraction of reinforcement on the network boundary and the deformed column matrix distributed along the extruded direction [2]. The increment of strength is mainly due to the strain hardening of matrix and the alignment distribution of TiB whisker reinforcement. Morerover, the strength can be further increased from 1230MPa to 1388MPa by the heat treatment of 900°C/WQ+500°C/AC due to the solution and aging strengthening as shown in Fig. 4. However, the elongation decreases to 2%. It is certain that the strength would further increase with increasing the solution temperature or decreasing the aging temperature. In orther words, the ductility of the as-heat treated composites can be further improved by decreasing the solution temperature or increasing the aging temperature.

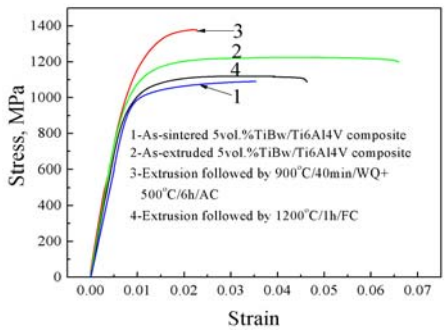

Fig. 4. Tensile stress-strain curves of the as-sintered, as-extruded and as-heat treated 5vol.%TiBw/Ti64 composite (200μm).

After annealing treatment at 1200°C, both the strength and the elongation of the composite decrease as shown in Fig.4. The reason for the decrease of the strength is that the strain hardening generated by extrusion deformation is completely eliminated by the complete annealing. The decrease of the ductility is due to the elimination of the defomed microstructure and the growth of α+β phases. It is certain that the decreasing degree of the strength and the ductility of the composite can be

decreased by decreasing the annealing temperature. It is worth pointing out that both the strength and the ductility along the extruded direction of the composite undergoing the extrusion deformation followed by the complete annealing treatment are higher than those of the as-sintered composite. This phenomenon indicates two truths: the strengthening effect of TiB whisker with a alignment distribution is slightly higher than that with a network distribution. The ductility of the composites with a network microstructure can be increased by decreasing the local volume fraction of reinforcement. However, it is certain that both the strength and the ductility along the traverse direction are lower than those of the as-sintered composite with isotropic properties.

Fig. 5 shows the fracture profile surface and fracture surface of the polished tensile sample. As shown in Fig. 5(a), the matrix columns exhibit so much plastic deformation generated during tensile deformation, which indicates a superior capability bearing strain compared with the network microstructure[2]. TiBw even far away from fracture surface are multi-broken due to its higher modulus, therefore, TiBw throughout play its strengthening effect. These are consistent with the increase of the strength and the ductility of the composites by the subsequent extrusion deformation.

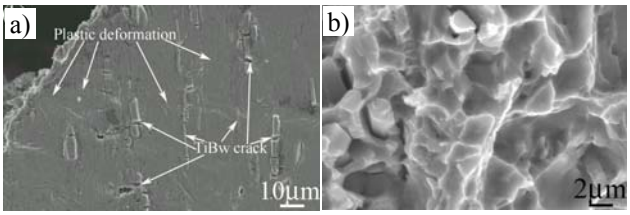

Fig. 5 The SEM profile surface (a) and fractographs (b) of the tensile sample of the as-extruded 5vol.%TiBw/Ti64 composite

TiB whiskers are not pulled out but broken as shown in Fig. 5(b). This corresponds to the fracture of TiBw shown in Fig. 5(a), and indicates a superior bonding between matrix and TiB whisker. So many dimples and matrix tearng lines corresponds to the superior ductility of the as-extruded composite due to the refinement of matrix microstructure and the decreased local volume fraction of reinforcement on the network boundary.

4. Conclusions

The microstructure and the mechanical properties of the TiBw/Ti64 composite with a network microstructure have been significantly affected by the subsequent deforamtion and heat treatment. The present work has led to the following findings:

(1) Not only the strength but also the ductility of the TiBw/Ti64 composites with a network microstructure can be significantly increased along the extruded direction by the hot extrusion deoformation.

(2) The strength improvement can be attributed to the matrix strain hardening and the reinforcment alignment distribution, howeve the ductility improvement to the decreased local volume fraction and the refinement of the matrix microstructure.

(3) The subsequent heat treatment of solution and aging can further increase the strength but decrease the ductility of the as-extruded composite, however, the annealing can futher decrease both the strength and the ductility.

(4) The residual stress generated during the deformation decreases with increasing the temperature of the subsequent heat treatment.

Acknowledgements

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