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Effects of rolling deformation on microstructure and mechanical properties of network structured TiB_w/Ti composites

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Abstract: TiB whiskers reinforced pure Ti (TiB_w/Ti) composites with a novel network microstructure were successfully fabricated by reaction hot pressing (RHP). TiB whiskers are in situ synthesized around the large pure Ti matrix particles, and subsequently formed into TiB_w network structure. The novel TiB_w/Ti composites with a network microstructure exhibit a superior combination of mechanical properties. In order to further improve the mechanical properties and guide the subsequent plastic forming, the rolling deformation behavior of the novel composites was investigated. The results show that the strength of the novel TiB_w/Ti composites can be effectively enhanced by rolling deformation due to the matrix deformation strengthening effect, and increased with increasing the rolling reduction. The strength of 8.5%TiB_w/Ti (volume fraction) composite is significantly increased from 842 MPa to 1030 MPa by rolling deformation. It is certain that the TiB whiskers are gradually broken with increasing the rolling reduction, which is harmful to the mechanical properties of the composites.

Key words: titanium matrix composites (TMCs); rolling deformation; reaction hot pressing (RHP); network microstructure; tensile properties

1 Introduction

As a typical member of metal matrix composites (MMCs) family, titanium matrix composites (TMCs) offer a combination of good mechanical properties and high temperature durability that render them attractive materials for automotive, aerospace and military applications [1−6]. In particular, discontinuously reinforced titanium matrix composites (DRTMCs) fabricated by in situ methods such as reaction hot pressing (RHP) and melting technique are sought-after due to their superior and isotropic properties and low cost [5−8].

However, irrespective of which processing method used, the aim is always to achieve a homogeneous microstructure where the reinforcements are uniformly distributed [5−8]. The reality is that many TMCs with a homogeneous microstructure exhibit a limited improvement or inferior mechanical properties particularly for DRTMCs fabricated by the conventional RHP technique, exhibiting extreme brittleness [6−10].

It is encouraging that the ductility of the TiB_w/Ti composites is significantly improved by tailoring the TiB_w distribution to a novel network microstructure. The network boundary region can exploit a superior strengthening effect of TiB_w reinforcement, while the relatively large matrix (TiB_w-lean) region contributes positively to the ductility of the composites [11,12]. This work echoes a recent proposal by LU [13] that the overall properties of composites can be further enhanced by assembling metals with other components in a controlled way to form novel multiscale hierarchical structures, compared with a conventional or homogeneous composite structure. It is certain that the subsequent hot deformation can further improve mechanical properties of the composites fabricated by RHP [14]. Therefore, it is significant to investigate the rolling deformation behavior of the novel network structured TiB_w/Ti composites in order to further improve their mechanical properties and guide the subsequent plastic forming.

2 Experimental

The TiB_w/Ti composites with a novel network

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microstructure were fabricated by RHP based on the system of large spherical Ti powders and fine prismatic TiB_2 powders. Firstly, the spherical Ti powders with a large particle size of 45−125 μm (Fig. 1(a)) and the prismatic TiB_2 powders with a fine size of 1−8 μm (Fig. 1(b)) are selected. Secondly, the selected two raw material powders are blended at the speed of 150 r/min for 5 h using a planetary blender. The size of large Ti powders is retained by using the low-energy blending. Finally, the blended powder mixtures (Figs. 1(c) and (d)) are reaction hot pressed at 1 200 °C under a pressure of 20 MPa for 1 h. As shown in Figs. 1(e) and (f), TiB_w can be in situ synthesized around the large Ti matrix particles according to the following reaction equation (1) [7]:

$$Ti(s)+TiB_2=2TiB(s) \quad (1)$$

In general, the TiB phase is thermodynamically more stable than TiB_2 phase with excess Ti [15]. According to the above reaction equation, 8.5% and 12% TiB_w/Ti volume fraction composites are prepared. For comparison, the pure Ti sample is also fabricated using the same processing parameters.

Tensile tests are carried out using an Instron−5569 universal testing machine at a constant crosshead speed of 0.5 mm/min. The tensile specimens have gauge dimensions of 20 mm×5 mm×2 mm and a total of five specimens are tested for each material. Microstructural examination is performed by scanning electron microscopy (SEM, Hitachi S−4700).

3 Results and discussion

3.1 Microstructure of as-sintered composites

Figure 2 shows the micrographs of the 8.5% and 12%TiB_w/Ti composites with a network microstructure. It can be seen from Fig. 2 that the TiB_w whiskers are in situ synthesized by network distribution around Ti particles and form a novel network microstructure. Additionally, many TiB whiskers grow into the inside of Ti particles like dowel connectors linking the neighboring Ti particles, which can effectively improve the strength and fracture toughness of TMCs as shown in Fig. 2. Moreover, the local volume fraction of TiB_w reinforcement in the network boundary increases with increasing the overall volume fraction. This is positive to improve the strength of the network structured composites. By comparison, many agglomerations are formed in the 12%TiB_w/Ti composite, which is possibly positive to strength but certainly negative to the ductility of the composite. The agglomerations are similar to the TiB whisker cluster formed due to the large B_4C raw material reported by NI et al [16]. Therefore, the formation of the TiB whisker agglomerations can be attributed to the much high local volume fraction of reinforcement in the network boundary.

3.2 Tensile properties of as-sintered composites

Table 1 shows the tensile properties of the as-sintered pure Ti and TiB_w/Ti composites with a network microstructure. The strength of the network structured TiB_w/Ti composites is remarkably increased compared with that of pure Ti fabricated using the same parameters, and the strength increases with increasing the volume fraction of TiB_w reinforcement. In particular, the ultimate strength (σ_b) of 12% TiB_w/Ti composite is increased by 88%, from about 482 MPa to 908 MPa. The σ_b of 8.5% TiB_w/Ti composite is increased to about 842 MPa or by 75%. The remarkable improvement of strength appears to reveal the most effective strengthening effect for the DRTMCs to date. For the present composites, the remarkable improvement of the strength can be attributed

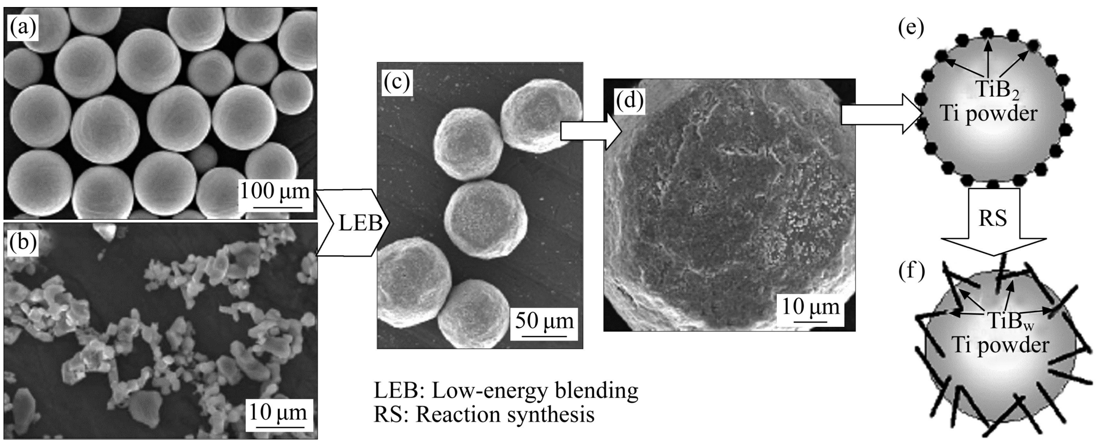

Fig. 1 Flow chart showing processing route together with morphologies of raw materials and schematic illustrations of network distribution: (a) Pure Ti powders (45−125 μm); (b) TiB_2 powders (1−8 μm); (c) Blended mixture at lower magnification; (d) Blended mixture at higher magnification; (e) Schematic illustration of network distribution before reaction synthesis; (f) Schematic illustration network distribution after reaction synthesis

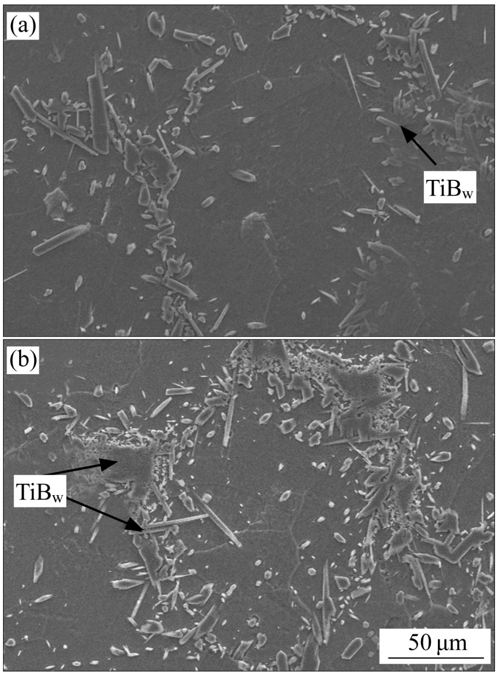

Fig. 2 SEM micrographs of TiB$_w$/Ti composites with network microstructure: (a) 8.5% TiB$_w$/Ti; (b) 12% TiB$_w$/Ti

Table 1 Tensile properties of as-sintered pure Ti and TiB$_w$/Ti composites with novel network microstructure

Sample	Ultimate strength/MPa	Elongation/%
Ti	482.4±7	18.4±0.7
8.5%TiB$_w$/Ti	842.3±6	11.5±0.3
12%TiB$_w$/Ti	908.6±7	4.0±0.2

to the tailored network microstructure and the dowel like structures of TiB whiskers. Therefore, the strengthening effect of TiB$_w$ reinforcement can be significantly improved by tailoring the network distribution.

Additionally, Table 1 also reveals the tensile ductility of the novel composites. For the 8.5% TiB$_w$/Ti composite with a network microstructure, the superior elongation of about 11.5% appears to be the most effective improvement to date, giving the remarkable σ_b increment of 75%. The superior ductility of the present composites can also be attributed to the tailored network reinforcement microstructure and the dowel-like TiB$_w$ structure. On one hand, the large matrix region can effectively restrict the crack propagation, and effectively reduce the crack propagation speed; On the other hand, the large matrix region can effectively bear tensile strain during tensile deformation.

Figure 3 shows the macro images of the composites after rolling deformation. It can be seen that no crack forms before 55% rolling reduction, and just small cracks occur around the edge till 80% rolling reduction. This phenomenon indicates that the prepared composite possesses a good plastic forming ability.

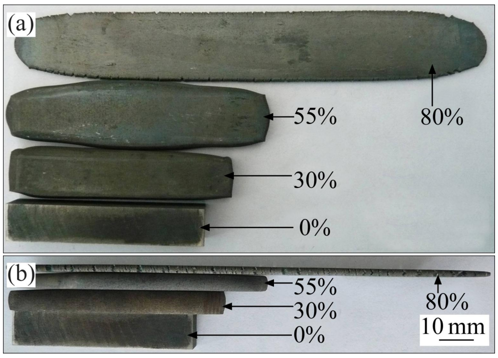

Fig. 3 Macro images of network structured TiB$_w$/Ti composites with different rolling reductions: (a) Top view; (b) Side view

3.3 Microstructure of as-rolled composites

Figure 4 shows the SEM micrographs of the as-rolled 8.5% TiB$_w$/Ti composite with different rolling

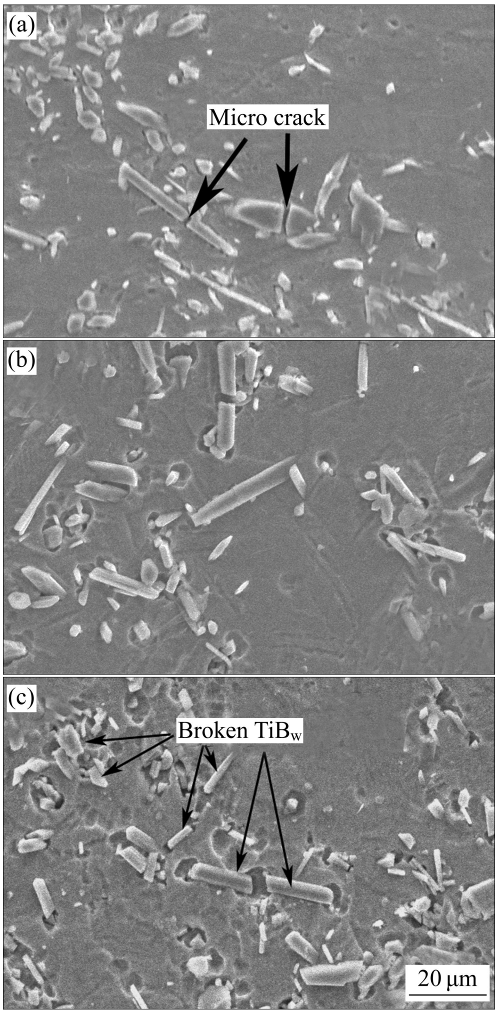

Fig. 4 SEM micrographs of as-rolled 8.5%TiB$_w$/Ti composites with different reductions: (a) 30%; (b) 55%; (c) 80%

reductions. The partial TiB_w particles undergoing a little deformation are broken, leading to some micro cracks which will serve as the origin of crack during subsequent tensile deformation. However, the distance of the broken segments of TiB_w increases with increasing the rolling reduction, which will make the previous micro crack open and be filled by deformed matrix. This can be demonstrated by the remote two broken segments of TiB_w and the increasing etched holes caused by residual stress etching around the broken TiB_w, as shown in Fig. 4. Therefore, the aspect ratio of TiB_w decreases with increasing the rolling reduction, which is beneficial to the toughness or ductility of the composites. The deformation strengthening effect of Ti matrix increases with increasing the rolling reduction, which positively improves the strength of the composites.

3.4 Tensile properties of as-rolled composites

Figure 5 shows the variations of tensile properties of 8.5% TiB_w/Ti and 12%TiB_w/Ti composites with increasing the rolling reductions from 0% to 80%. As predicted above, the low rolling reduction weakens the ductility of TMCs due to the formation of TiB_w micro crack and deformation strengthening effect of the Ti matrix. Further increasing the rolling reduction improves the ductility of TMCs due to the further dispersing TiB_w and reducing aspect ratio of TiB_w. The strength of 8.5% TiB_w/Ti composite is increased from about 842 MPa to about 1030 MPa after 80% rolling reduction. However, the ductility of 8.5%TiB_w/Ti composite reduces after rolled deformation (Fig. 5(a)), which is mainly due to the deformation strengthening effect of Ti matrix. The strength of 12%TiB_w/Ti composite is increased from about 908 MPa to about 1068 MPa. Moreover, the ductility of 12%TiB_w/Ti composite is effectively improved from 4% to 6.3% mainly due to the significant dispersing role of TiB_w reinforcement for higher volume fraction. The strength of the composites always increases with increasing the rolling reduction mainly due to the deformation strengthening effect of Ti matrix. In addition, it is reasonable that the strength of the as-rolled 12%TiB_w/Ti composite is always higher and the ductility is lower than those of the as-rolled 8.5%TiB_w/Ti composite with the same rolling reduction due to the higher volume fraction of TiB_w reinforcement.

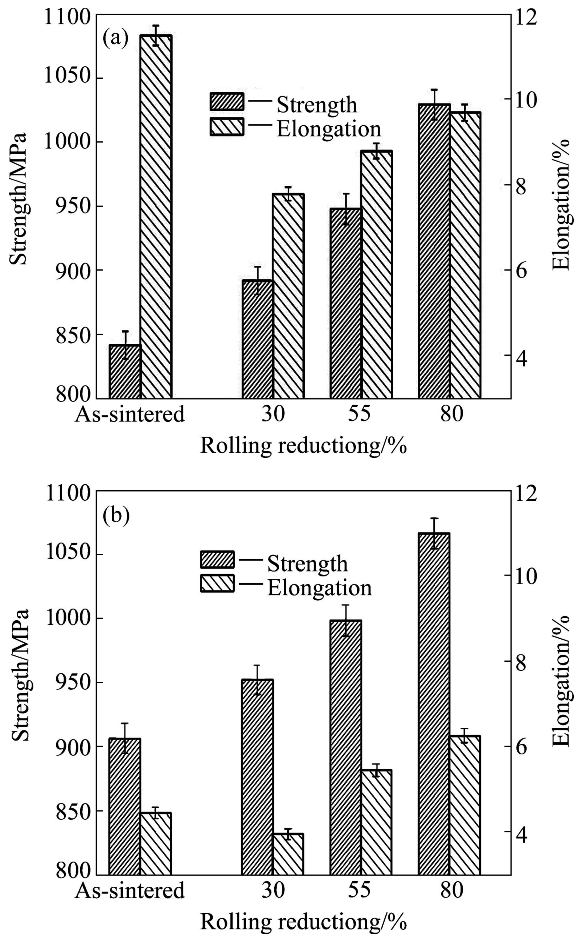

Fig. 5 Comparison of tensile properties of composites rolled by different reductions: (a) 8.5% TiB_w/Ti; (b) 12%TiB_w/Ti

4 Conclusions

1) The novel TiB_w/Ti composites with a network microstructure can be successfully fabricated by selecting large Ti powders and low-energy milling process. The novel composites exhibit a superior combination of mechanical properties and a superior forming ability.

2) The strength of the novel TiB_w/Ti composites can be effectively enhanced by rolling deformation due to the matrix deformation strengthening effect, and increase with increasing the rolling reduction. The strength of 8.5% TiB_w/Ti composite is increased from about 842 MPa to about 1030 MPa by rolling deformation.

3) The TiB whiskers are gradually broken with increasing the rolling reduction, which is harmful to the mechanical properties of the composites.

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轧制变形对网状结构 TiB_w/Ti 复合材料组织与力学性能的影响

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摘 要：通过反应热压技术成功制备出网状结构 TiB 晶须增强纯钛(TiB_w/Ti)复合材料。原位合成的 TiB 晶须分布在大尺寸 Ti 基体颗粒周围形成网状结构。这种新型的网状结构 TiB_w/Ti 复合材料表现出优异的综合力学性能。为了进一步改善力学性能及指导后续塑形变形加工，研究这种新型复合材料的轧制变形行为。结果表明：由于基体的形变强化，这种新型 TiB_w/Ti 复合材料的强度可以通过轧制变形得到有效的提高，并且强度水平随着变形量的增加而增加。其中，通过轧制变形，可以使 8.5%TiB_w/Ti 复合材料的强度从 842 MPa 提高到 1030 MPa。需要指出的是，随着变形量的增加，TiB 晶须的断裂程度也增加，这一点对复合材料的力学性能是不利的。

关键词：钛基复合材料；轧制变形；反应热压；网状结构；拉伸性能

(Edited by HE Xue-feng)