Experimental study on dynamic mechanical properties of TiB-whisker-reinforced Ti-6Al-4V Alloy

WANG Hao1,a, ZHANG Zhaohui1,2,b,*, SONG Qi1,c, YIN Shipan1,d, HU Zhengyang1,e and Li Xianyu1,3,f

1 School of Materials Science and Engineering, Beijing Institute of Technology, Beijing 100081, China
2 National Key Laboratory of Science and Technology on Materials under Shock and Impact, Beijing 100081, China
3 School of Physics and Electronic Information, Yan’an University, Yan’an 716000, China
a18810791981@163.com, bzhang@bit.edu.cn, csongqi0119@163.com, dpanpanyin@outlook.com, e Huzy_job@163.com, f lyissp@126.com

Abstract: In this study, the titanium matrix composites (TMCs) reinforced by TiB whiskers (TiBw) were fabricated by spark plasma sintering (SPS) technique. The dynamic compression test was carried out to study the effect of TiBw content on dynamic mechanical properties of TiBw/TMCs. Results showed that the TiBw content (0.76vol%~6.84vol%) correspond to specific microstructure which affect the dynamic mechanical properties of the composites. Under high strain-rate (3100s⁻¹), the 4.56 vol.% TiBw/TMCs showed the highest flow stress (~1968MPa) and strain (~15%). The absorbed energy increased first and then decreased with increase of TiB2 content, and the highest absorbed energy of 275.8 MJ.m⁻³ was achieve by TMC2. Besides, the analysis of fracture appearance indicated that TiBw dominates the failure of the TMCs, fractography of composites varies by the TiBw content of TMCs.

1. Introduction
Due to their superior mechanical properties, excellent thermal/corrosion resistance and good biocompatibility, titanium alloys have been widely used in the aerospace, power generation, chemical, and biomedical industries [1-3]. The application of titanium alloys is often restricted because of their relatively low specific stiffness and wear resistance. In recent decades, the titanium matrix composites (TMCs) reinforced with particles or whiskers have been of great interest owing to their better mechanical properties as well as good wear resistance. In recent decades, the titanium matrix composites (TMCs) reinforced with particles or whiskers have been of great interest owing to their better mechanical properties as well as good wear resistance. TiB2, SiC, B4C, Ti5Si3, and TiB have been used to produce TMCs. Among the great magnitude of TMCs reinforcement, TiB is considered as the ideal candidate due to its high thermodynamic stability, similar thermal expansion coefficients with the titanium matrix, excellent interface bonding with Ti [4].

Ti alloys and composites are widely used as engineering structure which are often subjected to dynamic loads such as impact and blast. It is generally believed that mechanical responses and failure mechanisms of materials under dynamic load are different from that of quasi-static. Many researches have reported that dynamic mechanical behavior of compression has distinguishable strain rate effect. Biswas et al. [5] had observed that both deformation and fracture of TC4 alloy exhibited appreciable rate sensitivity, however, the strength and ductility exhibited opposite trends as strain rate increased.
Rodriguez et al. [6] found that thermal softening rate was greater than strain hardening during plastic deformation in additive manufactured (AM) TC4 alloy, thus it shows great plasticity ultimately. However, these researches are mainly focus on the dynamic mechanical properties of TC4 alloy which is homogeneous material. The research on dynamic mechanical properties and failure mechanisms of TiB-whisker-reinforced TMCs had not previously been reported.

In our work, TMCs reinforced with four different contents TiB whiskers (TiBw) were synthesized by spark plasma sintering (SPS) technique. As for a new sintering, it is known as the fast sintering and low temperature sintering because of the electrical discharge effect and the use of electric-pulsed current on the electrodes. The effect of TiB2 content on dynamic compressive mechanical properties of TMCs and the failure modes of the samples were carefully investigated.

2. Experimental

Ti-6Al-4V (TC4) (~25 μm, Mengtai Powder Business Department) powders and TiB2 (~50 nm, Ningxia Machinery Research Institute) powders were used in this study. The powders were weighed in appropriate proportions to prepare the monolithic Ti–TiB2 composite samples. Solution ball milling (SBM) method is used in this study to mix two kinds of powders evenly at a speed of 350 rpm for a period of 60 min. The weight percentage of reactants and theoretical volume percentage of products were listed in Table 1. Thereafter, the experimental composites TC4-0.45 wt % TiB2, TC4-1.35 wt % TiB2, TC4-2.7 wt % and TC4-4.05 wt % TiB2 mentioned below are designated as TMC1, TMC 2, TMC 3 and TMC 4, respectively.

The powder mixture were loaded into a cylindrical graphite die with an internal diameter of 40 mm and an external diameter of 55 mm. Then the samples were sintered (SPS equipment: SPS-3.20MK-IV, Sojitz Machinery Corporation, Tokyo, Japan, with a pulse duration of 3.3 ms and a current on-off ratio of 12:2) at 1050 °C for 10 min under an external pressure of 40 MPa in a vacuum of <1 Pa. Four billets with a diameter of ~40 mm and thickness of ~10 mm were prepared for each composition.

In order to investigate the dynamic mechanical properties of samples under higher strain rates, the dynamic loading was performed at room temperature on a Split Hopkinson Pressure Bar (SHPB) system. The SHPB system is used for testing the dynamic behavior of materials at the strain rates ranging from $10^2$–$10^4$s-1. In our work, dynamic compression tests were carried out at the strain rate of about 3100s-1. The SHPB (Fig. 1) is considered as an efficient equipment for testing the mechanical response of composite materials, such as rocks and concrete, with high strain rate [7]. As shown in Fig.1, the SHPB device consists of a striker, an incident bar and a transmission bar. The cylindrical specimens with a dimension of φ5 mm×5 mm were machined from the sinters.

According to one-dimensional elastic wave propagation theory. The strain rate $\dot{\varepsilon}$, strain $\varepsilon$, and stress $\sigma$ can be determined as follows [8]:

\[
\dot{\varepsilon} = \frac{2C_b}{L_g} (\varepsilon_i - \varepsilon_t) \quad (1)
\]

\[
\varepsilon = \int_{t_0}^{t} \dot{\varepsilon} dt \quad (2)
\]

\[
\sigma = \frac{A_s}{A_t} E \varepsilon_t \quad (3)
\]

Where $C_b$ is the longitudinal-wave velocity in the incident and transmitted bars, $L_g$ is the effective gauge length of the samples, $E$ is the Young’s modulus of the incident and transmitted bars, and $A$ and $A_t$ are the cross-sectional areas of the bars and the specimen, respectively [9]. The strain rates can be calculated by Eq (1) and determined as the average value during the plastic deformation process.
3. Results
The dynamic true stress-strain curves of TMC1, TMC2, TMC3 and TMC4 are shown in Fig. 2. The results indicate that the uniform dynamic plastic strain decrease with the increasing TiB$_2$ content. The uniform dynamic plastic strain of TMC1 is 17%, while TMC2 is 15%. It is obviously that 0.45% TiB$_2$ addition gets the optimal plastic properties and the strain decreases with the ceramic phase content increasing due to inharmonic deformation.

Fig. 2(b) shows that the yield strength increases continuously as increasing TiB$_2$ content from 0.45% to 2.7%, and gets a maximum value of 1968 MPa belonged to TMC3. The growing yield strength could be attributed to the presence of ceramic reinforcement phases with specific morphologies in the as-sintered structure. The strengthening effects of TiBw/TC4 composites are principally attributed to two aspects: Firstly, during dynamic loading process, the in-situ TiB whiskers enable transfer a load from a soft matrix to hard reinforcements directly. Secondly, the matrix properties are improved due to the in-situ formation of TiB whiskers, such as grain refinement, solid solution strengthening, geometrically increased density of dislocations and strengthening due to thermal incompatibilities of the matrix and reinforcements [10]. However, a slightly drop in the yield strength occurred when the TiB$_2$ content exceeded 2.7%, the strength decreased to 1890 MPa for TMC4. Yan et al. [11] have reported that when the in situ TiB content exceeded 10%, the homogeneity of composites deteriorates obviously. It would weaken the reinforcement effect of TiB partly and lead to a reduction of yield strength finally.
The absorbed energy during deformation is one of the most important indicators to identify dynamic mechanical property. The energy absorbed by materials can be calculated as follows:

\[ E = \int_{\varepsilon_s}^{\varepsilon_f} \sigma d\varepsilon \]  

Where \( \varepsilon_s \) and \( \varepsilon_f \) are the start and end point of the plastic deformation, respectively. The absorbed energy of different microstructures is shown in Fig. 3.

Fig. 3 shows the absorbed energy of different content TiBw/TMCs. The variation of TiB2 content induced major changes in the dynamic mechanics performance of the composites. The experimental results show that the absorbed energy increases first and then decreases with increase of TiB2 content. The highest absorbed energy of 275.8 MJ.m\(^{-3}\) was achieved by TMC2, and the value dramatically degrade by TMC4. It is similar to that the flow stress and absorb energy change trend with TiB2 content. However, the TiB2 contents corresponding to maximum values of flow stress and absorbed energy are different, and the extent of the declines in flow stress and absorbed energy of TMC4 are not the same. The main reason for this may be attribute to the reduction of the plastic properties of TMCs.

The fracture characteristics and mechanisms of the TMCs are identified by SEM observations on the impact specimens. Fig. 4a-d shows the fracture surfaces of TMC1, TMC2, TMC3 and TMC4, respectively. According to maximum shear stress theory, the shearing stress of oblique section with a 45 degrees angle to the cross section reaches the maximum and fracture usually occur on this section. It can be seen in TMC1 that many big and deep dimples were spread over in the central area as well as small dimples were observed on the edge, indicating that the fracture type is plastic fracture. As shown in Fig. 4(b), the sizes and number of dimples in TMC2 were much smaller than that in TMC1. Besides, no obvious dimples were observed in TMC3 and TMC4, which indicates poor plastic properties of TMC3 and TMC4.
Fig. 4 Dynamic compression fracture morphology of specimens: (a) TMC1, (b) TMC2, (c) TMC3 and (d) TMC4

4. Conclusions
In this study, the SPS was used to fabricate TiBw/TMC successfully. The dynamic compressive behavior of TMCs and its fracture mechanism were characterized and discussed. Following conclusions can be drawn.

1) The flow stress increases with TiB2 content and then decreases, the highest yield stress of 1968MPa was achieved by TMC3.
2) The absorbed energy increases first and then decreases with increase of TiB2 content, and TMC2 owns the highest absorbed energy of 275.8 MJ.m⁻³.
3) The fracture mechanism of TiBw/TMCs was characterized by from ductile fracture to brittle fracture with the increasing TiB2 content.

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