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Improving the tensile ductility of metal matrix composites by laminated structure: A coupled X-ray tomography and digital image correlation study

Guohua Fan [a,*], Lin Geng [a], Hao Wu [b,*], Kesong Miao [a], Xiping Cui [a], Huijun Kang [c], Tongmin Wang [c], Honglan Xie [d], Tiqiao Xiao [d]

[a] *School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, PR China*
[b] *School of Materials Science and Engineering, University of Jinan, Jinan 250022, PR China*
[c] *School of Materials Science and Engineering, Dalian University of Technology, Dalian 116000, PR China*
[d] *Shanghai Synchrotron Radiation Facility, Shanghai 201204, PR China*

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ABSTRACT

The microstructure design strategy of laminated structure was applied to improve the mechanical properties of metal matrix composites (MMCs). The laminated composites were prepared by hot pressing and rolling of alternately stacked Ti foils and SiC_p/Al composite foils, and exhibited a superior strength-ductility synergy compared to SiC_p/Al bulk MMCs. Coupling X-ray tomography and digital image correlation (DIC) revealed that the enhanced mechanical properties originated from the contribution of the interface on local stress/strain transfer behaviors, thus delaying the crack initiation and propagation within SiC_p/Al layers.

The addition of reinforcements makes metals strong but brittle. The well-known strength-ductility trade-off dilemma of metal matrix composites (MMCs) originates from (i) the easy crack initiation caused by the deformation incompatibility between the matrix and the reinforcements, and (ii) the weak resistance to crack propagation [1,2]. Therefore, how to suppress the crack initiation and propagation of MMCs is a key route to improve their mechanical properties, in particular for the tensile ductility; in essence, the scientific problem is how to artificially control the strain distribution by microstructure design [3–5]. Recent investigations have demonstrated that laminated structure can effectively inhibit the strain localization during the plastic deformation, thus exhibiting a superior strength-ductility combination [6–8]. However, the vast majority of research work focus on the metal-metal laminated composites [9,10]. The potential of MMCs serving as one of laminated components, as well as whether the strategy of laminated structure can be applied in improving the mechanical properties of MMCs or not, remains unclear.

In the past few years, the understanding of strain localization mainly depends on the post-mortem examination of deformed microstructures [11,12], lacking direct visualization of strain evolution process. For this purpose, the technologies of digital image correlation (DIC) and X-ray tomography were recently developed [10,13]. However, both technologies are primarily applied in bulk homogeneous materials [1,2], marginally in the laminated composites. Additionally, coupling DIC and X-ray tomography is very useful to correlate the deformation and fracture behaviors of the composite, but the application of the coupled technology is rarely reported.

In this work, the classical SiC_p/Al composite was selected as referenced MMCs. The microstructure design strategy of laminated structure was used to improve the mechanical properties of SiC_p/Al MMCs. The laminated composite was fabricated by hot pressing and rolling of alternately stacked Ti foils and SiC_p/Al composite foils, and room temperature tensile tests were performed to compare the mechanical properties of SiC_p/Al, Ti, and Ti-(SiC_p/Al) laminated composites. The deformation and fracture behaviors of laminated composites were characterized by coupling DIC and X-ray tomography, and the mechanisms behind the enhanced mechanical properties of laminated composites were elucidated.

Commercially pure Ti foils and in-house fabricated 10 vol% SiC_p/Al composite foils were cut into several rectangles with dimensions of 30 mm width by 50 mm length, chemically etched to a final thickness of 160 μm and 150 μm, respectively, alternately stacked, and then hot pressed at 515 °C under 75 MPa for 1.5 h, followed by hot rolling through 6 passes to a total thickness reduction of 30%. The rolling temperature was selected as 500 °C, and before every rolling pass, the

* Corresponding authors.
E-mail addresses: ghfan@hit.edu.cn (G. Fan), mse_wuh@ujn.edu.cn (H. Wu).

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sample was annealed at 500 °C for 10 min. The details of sample preparation can be referred to our previous work [10].

An Olympus optical microscope (OM), and a FEI Tecnai F30 transmission electron microscope (TEM) were employed for microstructure observation. The mechanical properties of laminated composites and SiC_p/Al bulk MMCs were evaluated by room temperature tensile tests. The gauge dimensions of tensile specimens were 5 mm width by 18 mm length by 2 mm thickness, and the tensile tests were performed using an Instron-1186 universal testing machine at a strain rate of $1 \times 10^{-4}\,s^{-1}$. The tensile fractured specimen was then examined by X-ray tomography (Shanghai Synchrotron Radiation Facility, SSRF) for direct visualization of the spatial distribution of cracks [13]. The X-ray beam energy was 28 keV, and the spatial resolution of X-ray tomography was 0.65 μm. The VGStudioMax software was used for data post-processing.

The laminated composite was deformed with in situ OM imaging (the latter provided a large field-of-view with representative statistics). The deformation was carried out by uniaxial tensile loading to different strain levels at a displacement rate of 2 μm/s through a screw-driven Kammrath & Weiss GmbH tensile stage (Dortmund, Germany), and the specimen geometries were 2 mm thickness by 2 mm width by 18 mm length. A commercial VIC-2D software was utilized for DIC analysis and the calculation of local strain fields.

The laminated composites, composed of alternating layers of Ti and SiC_p/Al as shown in the inset of Fig. 1b, were successfully prepared in the present work, and the thicknesses of both components were measured as 110 ± 10 μm (Ti layers) and 100 ± 9 μm (SiC_p/Al layers), respectively. In between both layers, there exists a 25 nm-thickness $TiAl_3$ layer (Supplementary Fig. S1), probably due to the process of hot pressing and rolling during the sample preparation. Despite the presence of nano-sized $TiAl_3$ layers, the mechanical properties of laminated composites were still higher than those of SiC_p/Al bulk MMCs (Fig. 1a and Table 1). Additionally, the volume fraction of SiC_p also plays a very important role on the mechanical properties of Ti-(SiC_p/Al) laminated composites as shown in Fig. 1b and Table 1.

Taking 10 vol% SiC_p/Al bulk MMCs for example, the ultimate tensile strength of Ti-(10 vol.% SiC_p/Al) laminated composite increased up to 363 MPa, while the elongation of laminated composite is double that of bulk MMCs (Table 1). In order to explain the underlying mechanism of such improved mechanical properties, we firstly compared the three-dimensional fracture characteristics of both samples, and several of important results were summarized as follows: (i) The large flake-like cracks in SiC_p/Al MMCs (Fig. 2c) were in sharp contrast to many small cracks with globular morphology in laminated composites (Fig. 2a), and the latter was more clearly observed in reconstructed slices as shown in Supplementary Fig. S3. (ii) In the case of bulk MMCs, the plastic deformation was highly localized [2]. For example, the reduction of area in 20 vol% SiC_p/6061Al was only 3% nearby the fracture surface, and almost zero at 5 mm-away from the fracture surface [14]. However, a wide crack distribution was observed in laminated composites (Fig. 2b), indicative of a more homogeneous deformation mode and implying that the grains far away from the fracture surface sufficiently participated into the plastic deformation [7,11]. (iii) No crack was found in the Ti layers of laminated composites, and the laminated composite was fractured by SiC_p/Al cracking and interfacial decohesion (Fig. 2d and Supplementary Fig. S3). The fundamental mechanism behind the observed interfacial delamination will be discussed later. Additionally, it seems plausible from Supplementary Fig. S3 that the presence of Ti layers restricted the crack propagation behavior within the SiC_p/Al layers, and that cracks penetrating into the Ti layers were strictly inhibited.

Table 1
Mechanical properties of SiC_p/Al, Ti, and laminated composites.

Material systems	Ultimate tensile strength (MPa)	Elongation (%)
10 vol.% SiC_p/Al MMCs	156 ± 11	11.8 ± 1.2
As-rolled Ti	571 ± 29	21.6 ± 1.7
Ti-(0 vol.% SiC_p/Al) laminates	276 ± 18	34.5 ± 2.3
Ti-(3 vol.% SiC_p/Al) laminates	341 ± 22	31.4 ± 2.1
Ti-(5 vol.% SiC_p/Al) laminates	351 ± 23	30.6 ± 1.8
Ti-(10 vol.% SiC_p/Al) laminates	363 ± 25	24.5 ± 1.5

Fig. 3 shows real-time visualization of strain evolution process of laminated composites during the tensile deformation. The strain tensor component used for DIC analysis was selected as *xx* normal strain (ε_{xx}, along the horizontal direction). The region of interest (ROI) was labeled by black dotted ellipse, which vividly describes how localized strains within SiC_p/Al layers transferred into the neighboring Ti layers, and finally back to the SiC_p/Al layers with increasing tensile strains (Fig. 3). This "reversed" strain transfer path seems impossible for SiC_p/Al MMCs (Supplementary Fig. S4) or as-rolled Ti (Supplementary Fig. S5), and also indicates the stress partitioning nearby the interface between SiC_p/Al layers and Ti layers [12,15]. At the same time, the positive ε_{xx} strain at the ROI was gradually changed to the negative ε_{xx} strain when the macroscopically true strains increased from 0.3% to 4.0% (Supplementary movie 1). Additionally, the contribution of the interface on local stress/strain transfer was intuitively apparent: (i) As the tensile deformation progressed, several of regions in SiC_p/Al layers nearby the ROI, with a local strain level of nearly zero at the early deformation stage, started to participate into the plastic deformation, and the loads were not transmitted by themselves, but by the interface and the shear stress that the adjacent Ti layer exerted [15,16]; (ii) Deformation was no longer localized within the SiC_p/Al layers, and strong strain transfer effect was observed, which may reduce the local stress concentration of SiC_p/Al layers and effectively suppress the crack initiation and propagation within SiC_p/Al layers [17]; (iii) The localized deformation, especially along crystallographic ⟨c⟩ direction, of as-rolled Ti (caused by strong basal texture, Supplementary Fig. S2) was stabilized by laminated structure, thus leading to a larger tensile ductility as shown in Fig. 1a.

Quantitative measurements of ε_{xx} strain tensor component as a function of tensile strains indicate the change in deformation mechanisms of

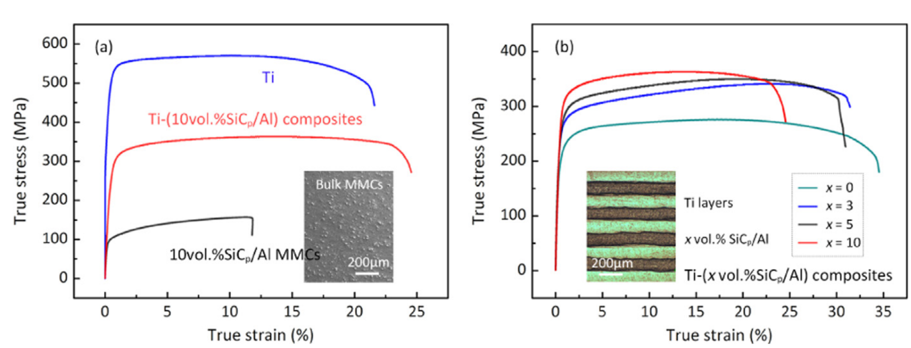

Fig. 1. Tensile stress-strain curves of (a) bulk MMCs, Ti, and laminated composites with the same processing route, and (b) Ti-(*x*vol.% SiC_p/Al) laminated composites ($x = 0, 3, 5, 10$).