

Strengthening and toughening of layered Ti-Al metal composites by controlling local strain contribution

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Abstract. Layered Ti-Al metal composites (LMCs) with different thickness ratios of the Ti and Al layers were fabricated by hot-rolling and annealing. To study the effect of layer thickness on the mechanical properties of LMCs from the viewpoint of local strain distribution, the strain evolution of LMCs was investigated via in-situ tensile testing. It is found that the mechanical properties of LMCs are correlated with the degree of strain localization. Suppressing strain localization during plastic deformation is crucial to achieve the goal of both strengthening and toughening in LMCs. Additionally, the layered structure can facilitate the redistribution of strain localization, and the transfer of strain localization can be effectively controlled by changing the thickness ratio of the Ti and Al layers.

1. Introduction

Considering the increasing demands of industrial technology application, such as energy reduction and in-service security, a new challenge for the combined strengthening and toughening of metal matrix composites (MMCs) has been recognized. However, the traditional trade-off between strength and ductility is difficult to overcome. Nevertheless, in recent years, researchers have found that a combination of strength and ductility may be accomplished by modifying the distributions of microstructures and components, such as layered, bi-continuous and gradient structures [1-8]. This research has indicated that one feasible strategy is that a combination of strengthening and toughening achieved by configuration design [9-11].

It is well known that damage of a metal may be attributed to strain localization and the following crack nucleation [12]. Recently, an effect of localized strain on the strengthening and toughening of nano-metals and amorphous alloys has been investigated [13]. Control of the strain capacity by preventing strain localization is thus crucial to enhance plastic deformability. A direct visualization of local strain by digital image correlation (DIC) is useful to understand strengthening and toughening mechanisms in MMCs with different configuration designs. In this paper, we show by following the strain evolution it is possible to understand how the design of the microstructural configuration can be used to achieve a combination of strength and ductility.

In this study, layered Ti-Al metal composites (LMCs) were selected to characterize the correlation between configuration design and strengthening/toughening mechanism via localized strain distribution analysis. The deformation behavior was investigated by DIC during in-situ tensile testing to reveal the effect of local strain distribution on mechanical properties.



2. Experimental methods

2.1 Sample preparation

Commercially pure Ti sheets (TA1) with an original thickness of 100 μm and pure Al sheets (1060) with an original thickness of 100 μm and 50 μm , were selected as raw materials. They were cut into several squares with surface areas of 100 mm width by 100 mm length, and then chemically eroded using 10 vol.% HF solution and 10 wt.% NaOH solution, respectively, in order to remove the surface oxide layer. The as-prepared sheets were alternately stacked, hot-pressed in vacuum under 40 MPa at 500 °C for 1 h, then hot-rolled at 500 °C to a total thickness reduction of 30%, and then finally annealed at 500 °C for 1 h.

2.2 Microstructure characterization and tensile tests

The microstructure of the layered composites was examined by a FEI HELIOS Nanolab600i scanning electron microscope (SEM). The sample surface used for SEM observation was the transverse-normal direction plane (TD-ND), prepared by mechanical grinding and polishing.

The tensile tests were performed on an Instron-1186 Universal Testing Machine at room temperature (RT) at a strain rate of $5 \times 10^{-4} \text{ s}^{-1}$. Flat dog-bone shape tensile specimens with a gauge dimension of 5 mm $\times$ 18 mm $\times$ 2 mm were prepared by electrical discharge machining and mechanical grinding. A total of three specimens for each condition were used to achieve representative statistics.

2.3 Strain evolution process

Dog-bone shape tensile specimens, 2mm in thickness, 1.5mm in width, and 10mm in gauge length, were prepared and loaded in-situ using Kammrath-Weiss micro-tensile stage mounted in a FEI HELIOS Nanolab600i SEM. The tensile displacement rate was 5 $\mu\text{m/s}$, corresponding to a strain rate of $5 \times 10^{-4} \text{ s}^{-1}$. High resolution micrographs covering 900×800 pixels were captured at different tensile strains. The VIC-2D software was utilized for data post-processing and for the calculation of the local strain distribution.

3. Results

3.1 Microstructure and mechanical properties

Two kinds of layered Ti/Al composites were successfully prepared by hot pressing and hot rolling of alternately stacked Ti and Al foils. In each case, the thicknesses of the Ti foils after rolling was 70 μm , while the Al foils were 70 μm or 35 μm in thickness, respectively, referred to in the following as samples R70 and R35. The microstructures of these two composites are shown in figure 1, indicating also the uniform deformation behavior of the Ti and Al foils during the multi-pass hot rolling (without local necking). Additionally, the high-magnification backscatter electron (BSE) micrographs in figure 1b and d, show a well-bonded interface and that no cracking or debonding was found at the interface between the Ti and Al layers.

Figure 2 shows the engineering stress-strain curves of samples R35 and R70, both exhibiting a superior strength-ductility synergy imparted by layered structure. The improved yield strength and ultimate tensile strength of the R35 sample can be easily understood based on a rule of mixtures strengthening. However, its tensile elongation to fracture is 46%, compared to 38% for the R70 sample. This finding is counterintuitive, and also implies that the thickness of the Al layers can significantly change the mechanical behavior of LMCs. To further investigate this, we applied the DIC method for direct visualization of full-field strain distribution, to determine how the strain evolution process was affected by the Al layer thickness.

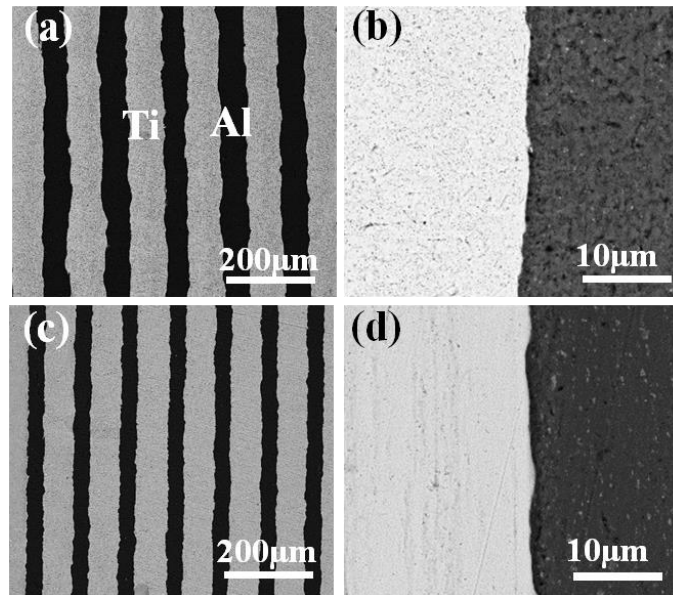


Figure 1. The microstructures of LMCs with the same Ti layer thicknesses of 70 μm and different Al layer thicknesses of 70 μm and 35 μm (R70 and R35). The low magnification image: (a) R70 and (c) R35; The high magnification image: (b) R70 and (d) R35.

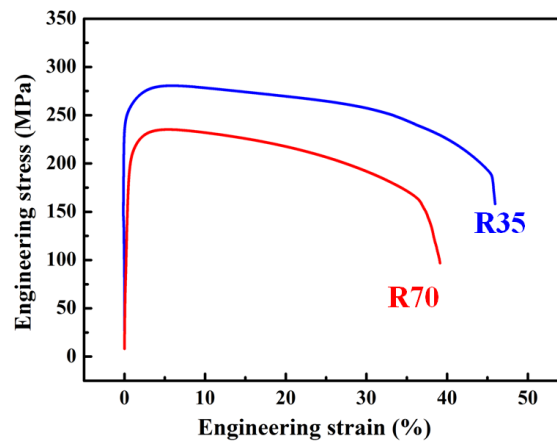


Figure 2. The engineering stress-strain curves of LMCs with different Al layer thicknesses. The loading direction is parallel to TD.

3.2 Strain evolution process

Combining in-situ loading and DIC analysis was used to reveal the dependence of the Al layer thickness on the strain evolution process during tensile deformation. The engineering stress-strain curves of the R35 and R70 samples are shown in figure 3a, where the up-and-down serrations are due to the interrupted loading mode necessary for capturing images for DIC analysis at different tensile macro-strains of 4.0%, 6.0%, 9.0%, and 15.0%.

For layered Ti/Al composites, the soft Al layer should yield first compared to the adjacent hard Ti layer. The non-synchronous deformation behaviors of Ti and Al layers produce the stress/strain partitioning, which may explain the generation of compressive strains within the Al layer or at the interface between the Ti and Al layers at a tensile macro-strain of 4.0% as shown in figure 3b. As the plastic deformation progresses, the initial compressive strains gradually disappear and are replaced by severe strain localization occurring at the Ti layer or at the interface (figure 3c and d). However, the

early strain localization of Ti layer is effectively relieved by deformation in the adjacent Al layer via stress-transfer, presenting a strain non-localization trend even as the tensile macro-strain is increased up to 15% (figure 3e). In other words, in the R35 sample localized strains present during the plastic deformation can be efficiently transferred to other deformation regions, thus allowing the R35 sample to plastically deform over wider deformation region. For comparison, we examined the ε_{xx} local strain evolution of the R70 sample under otherwise identical conditions, and found that the premature strain localization occurred and quickly developed in the R70 sample even at a very low strain level of 6.0% (figure 3g). Careful examination of strain evolution process of the R35 and R70 samples indicates that the thin Al layer obviously alleviated the degree of strain localization of the Ti layer at the same strain levels.

Figure 4 shows the quantitative measurements of ε_{xx} local strain with increasing tensile macro-strain. Two scalar indicators were introduced to evaluate the degree of strain localization during the tensile deformation. The first is the average ε_{xx} local strain of the Ti layer (figure 4a), and the other is the average ε_{xx} local strain at the region of interest (ROI) normalized by the macroscopic engineering strain (figure 4b). It is found that the R70 sample sustains a higher average/macroscopic strain ratio compared to the R35 sample (figure 4b). Therefore, the plastic deformation of the R70 sample may take place at a very limited region, and the decrease in the Al layer thickness significantly alleviates the degree of strain localization. Additionally, an inflection point appeared at a macroscopic strain of $\sim 15.0\%$, corresponding to the start of severe strain localization (figure 3i). It is thus concluded that strain localization leads to deformation instability of layered composites, which is experimentally supported by the sharply increased magnitude of the average/macroscopic strain ratio in figure 4b.

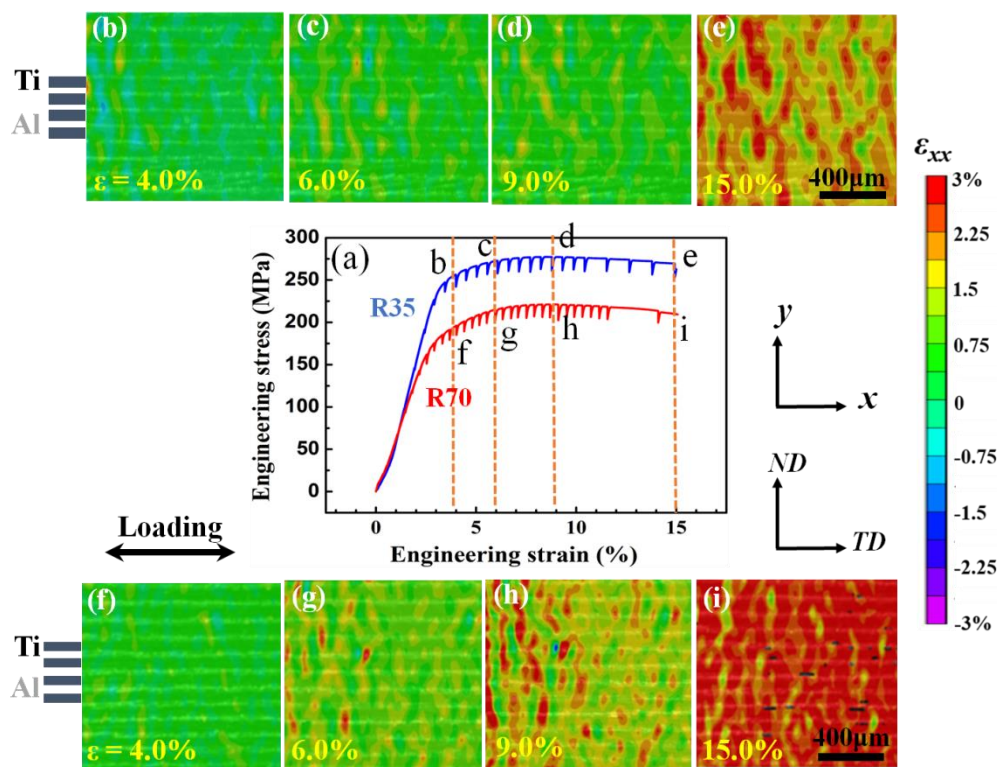


Figure 3. The evolution of ε_{xx} local strain for LMCs with different Al layer thicknesses along the loading direction at different tensile strains. (a) Engineering stress-strain curves; (b-i) Strain evolution mapping of (b-e) R35 and (f-i) R70 samples. The tensile macro-strains at which the SEM images were captured (used for strain analysis) are labeled by yellow font in (b-i).

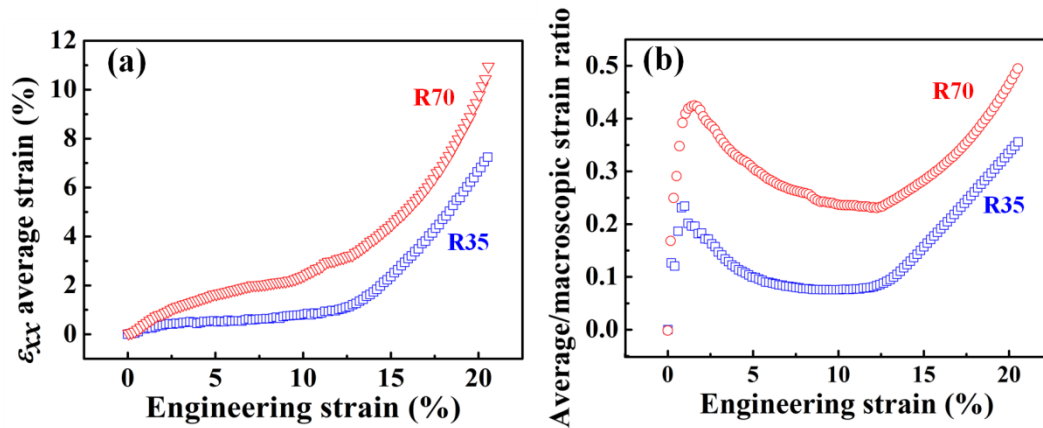


Figure 4. Quantitative statistics of ϵ_{xx} local strains with increasing tensile strains. Two scalar indicators were introduced to represent the degree of strain localization during the deformation: (a) the average ϵ_{xx} local strains of component Ti layer; (b) the ratio of average ϵ_{xx} local strains to macroscopically engineering strains.

4. Discussion

The confined strain evolution process of the layered Ti/Al composites, as shown in figure 3 and 4, is intimately correlated with their microstructure. After hot rolling, the hard Ti layer has a strong $\langle 0001 \rangle$ //ND basal texture compared to the typical recrystallized condition of the Al layer, as shown in figure 5. Our recent work has demonstrated that the plastic deformation of LMCs is actually dominated by the hard Ti layer [14], and easy prismatic slip is expected under such a crystallographic characteristic of a strong basal texture. During tensile deformation, strain localization of the Ti layer may occur when prismatic slip in the Ti can no longer accommodate the imposed strain. Generally, the onset of strain localization should induce the start of necking. However, the latter is delayed by the layered structure via the strain-transfer behavior, as shown in figure 3. Our work also indicates that the degree of strain-transfer can be controlled by adjusting the thickness of the soft Al layer.

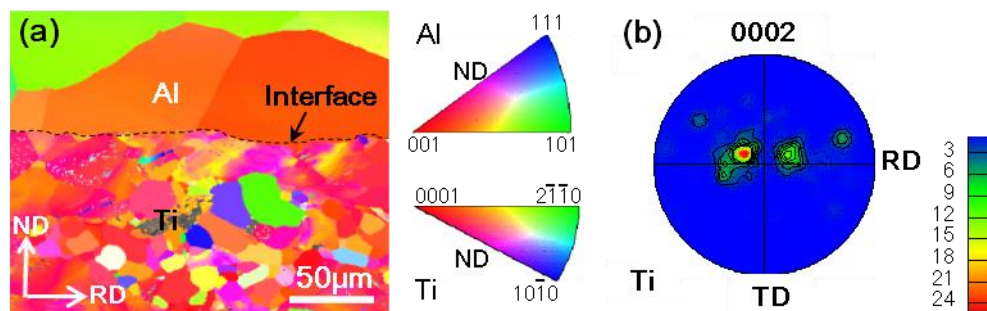


Figure 5. Crystal orientation maps of LMC obtained by electron backscatter diffraction (EBSD): (a) inverse pole figure for normal direction (ND); (b) (0001) pole figure for Ti in LMC. The Image was reproduced with permission from Ref. [14].

The two-dimensional DIC mapping provides insights in understanding the relationship between microstructure design and in-plane strain evolution during tensile deformation. The different layered structures (therefore thickness ratio) change the deformation behavior of the LMCs. For example, localized strains within the Ti layer can be effectively transferred to a wider deformation region as a consequence of the adjacent Al layers. In addition, the mechanical properties and textures of layered components should be taken into consideration for the strain-transfer behavior [14, 15]. Firstly, LMCs with different Al layer thicknesses have similar crystallographic textures due to the similar processing

parameters during the sample preparation. Therefore the influence of crystal orientation is negligible. Secondly, the difference in the elastic modulus and yield strength between Ti and Al results in a deformation incompatibility of the layered composites and the formation of compressive stresses in the Al layer. Finally, the plastic deformation of LMCs is essentially a stress-mediated strain evolution process, and the layered structure has a significant influence on the redistribution of local strain [4]. The strain localization of the Ti layer will be aggravated if the accumulated stresses cannot be relaxed by local plastic deformation. To some extent, the thickness reduction of the Al layer facilitates an effective transfer of any accumulated stresses in the Ti layer to adjacent Ti layers across the thin Al layer [4, 16]. As a result, the strain localization of Ti can be effectively relieved by a thinner Al layer.

Similarly, the mechanical properties of MMCs are influenced by the spatial distribution of the component phases, the grain size, the chemical constituents and the morphology of the reinforcements [15]. In the past few years, integrating these factors has been constantly investigated for performance optimization. For example, the layered configuration design of component phase significantly enhances the capability of strain transfer [14]. Based on the layered configuration design of MMCs, we conclude that (i) suppressing strain localization during the plastic deformation is crucial to achieve the strategy of strengthening and toughening for MMCs, and (ii) the mechanical properties of MMCs depend on the degree of strain localization. Good deformation stability can be obtained if strain localization or stress concentration in one area can be effectively transferred to another area. In MMCs the transfer of local strain can be achieved by microstructural configuration design, especially layered configuration design.

5. Conclusions

To study the effect of configuration design on the mechanical properties of MMCs from the viewpoint of local strain distribution, LMCs have been designed and prepared using pure Ti and Al sheets. From in-situ tensile testing combined with DIC analysis, it is found that the mechanical properties of the LMCs are essentially governed by the degree of strain localization. Suppressing strain localization during the plastic deformation is crucial to achieve the goal of combined strengthening and toughening in LMCs. Moreover, a transfer of strain localization can be achieved by the use of a layered configuration design, where the strain transfer is found to be more effective with decreasing Al layer thickness. This finding may provide new insights in guiding the design of high-performance MMCs.

Acknowledgements

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