Microstructure Characteristic of Adiabatic Shear Bands for Aluminum Matrix Composites Compressed With High Strain Rates

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Abstract. In this paper, the novel transformed bands in adiabatic shear bands (ASBs) were researched which was characterized as melting or solid to liquid phase transformation. By split Hopkinson pressure bar (SHPB), optical microscope (OM) and scanning electron microscope (SEM), microstructure characteristic in the transformed bands at varied strain rates were observed. From the experimental results, it was found that molten aluminum bands and aluminum balls agglomeration, which called transformed bands, were found on the shearing surface for 55%TiB₂/Al composites compressed at strain rates of 1~2×10³ s⁻¹. It was concluded that there were the molten aluminum alloy and the molten aluminum particles on the shear flat surface oriented at an angle approximately 45° to the compression axis, which was transformed band. It was formed due to aluminium alloy melt at high temperature and solidified sharply by analysis. The formation of transformed bands was ascribed to adiabatic temperature rise, which caused aluminum alloy matrix softened and molten. The adiabatic temperature rise was 800-900K by calculation. The local high temperature led to the formation of the molten aluminium particles whose diameter was 1-3µm on the adiabatic shear flat surface. With the rapid convergence of molten aluminium particles and growing up, the adiabatic shear band was finally formed.

Introduction

Metal matrix composites (MMCs) have rapidly developed due to the urgent need for the lightweight and high-performance materials in aerospace, defense industries and automobile industries. However, MMCs was inevitably suffered the effect of impact load during their application environments. Micro-cracks, micro-holes and adiabatic shear were part of the failure form in which the adiabatic shearing became one of the attention focuses in recent years. Currently, several obvious characteristics of adiabatic shear band were found. One of the most common characteristic was dark gray narrow band [1, 2], which was found after the dynamic compression in 5-25 vol. % of aluminum matrix composites. This kind of dark gray shear zone was similar as metal materials such as steel, aluminum and titanium alloy phase transition [3-6] in the appearance and structure. Dynamic recrystallization of phase transformation was preliminary thought to be present. Recently, two kinds of adiabatic shear band with different morphology characteristics were found in particles reinforced metal matrix composites (PRMMCs) after the dynamic compression. One of adiabatic shear band was bright white and composed of the flowing molten aluminum group which was found in aluminum matrix composites with 40-55vol% reinforcements. The other was the bright white narrow band which was formed in aluminum matrix composites with 60-65vol% reinforcement phase. And the microstructure characteristics of phase transformation band at different strain rate compression were researched. The surface morphology of two kinds of adiabatic shear band (ASB) is similar to that of ASB formed in metal glass or Zr matrix amorphous composites [7, 8]. According to the above observation, the preliminary estimated local adiabatic temperature rise was even more than the matrix alloy melting point. No much deeper research was reported at present. In this paper, the transformed band was researched whose feature was newly
found the molten aluminum including solid and liquid phase in aluminum matrix composites.

Experimental

An Al-Cu-Mg alloy (2024Al) was selected as the matrix. The composites were produced by pressure infiltration method which was reinforced with 55vol% TiB$_2$ particles. And TiB$_2$ ceramic particles with an average size of 8μm were chosen as the reinforcement. The specimens were machined to short cylindrical bar with 8mm in diameter and the length-diameter ratio was respective 2 and 1.5. The quasi-static compression tests were conducted on Instron machine with a strain rate of 7×10$^{-4}$ s$^{-1}$. A conventional split Hopkinson pressure bar (SHPB) was used to obtain high strain rate compression response of the materials over a strain rate range of 1×10$^3$-2×10$^5$ s$^{-1}$. At the same time, the interfaces between the specimens and the compression platens were lubricated in order to reduce friction. All fracture morphologies of the composites specimens were observed by S-570 scanning electron microscope.

Result

Dynamic Compression Stress-Strain Curves

![Figure 1. Dynamic compression Stress-strain curves of TiB2/Al composite.](image)

Figure 1. Dynamic compression Stress-strain curves of TiB2/Al composite.

Figure 2. Fractural features of 55vol%TiB2/Al composite at different strain rate.

The stress-strain curves of the 55 vol% TiB2/Al composite under dynamic and static load were shown in Fig.1. From Fig.1, the compression strength of TiB2/Al composite was 870MPa under static load. The plastic deformation of compressed specimen was small. When the flow stress was 950MPa under 1.3×10$^3$s$^{-1}$ compress strain rate, and with increasement of strain rate, the flow stress of composite increased. When compress strain rate was 1.5×10$^3$s$^{-1}$, the flow stress was 1090MPa. While the dynamic compress took place at the higher strain rate (1.8×10$^3$s$^{-1}$), obvious stress softening stage was observed on the corresponding stress-strain curve during plastic deformation of composite. And the better plastic deformability was obtained at high strain rate suffered dynamic compression for composite and the elongation was 4-5%. Comparing with the failure of composite at dynamic and static load, the plastic strain of specimen under high strain rate was 3 to 5 times higher than that under quasi static compression.

Macroscopic Fracture Characteristic

The macroscopic fracture appearance of 55 vol% TiB$_2$/Al composite was shown in fig.2 under quasi-static and dynamic compression. From fig.2, it was seen that 55vol% TiB$_2$/Al composite was
fractured in typical shearing mode with a single plane oriented at an angle approximately 45° to the compression axis under quasi-static compression, which was obvious brittle fracture characteristics. Although there was similar dynamic deformation and macroscopic failure rule at different compression strain rate for the composite, there was some subtle difference. At high strain rate, the plastic deformation ability of 55 vol% TiB₂/Al composite was certain. However, with increase of the strain rate, the trend of brittle fracture was obviously accelerated.

Discussion

Formation and Morphologies Characteristic of Transformed Band

SEM morphologies for 55vol% TiB₂/Al composites specimen at 1.3~1.8×10³ s⁻¹ strain rate are shown in Fig. 3. It was found in Fig. 3 that there was fluid-like molten aluminum agglomeration on the shear plane oriented at an angle approximately 45° to the compression axis. Moreover, it was transformed band formed due to the sharp condensation of the molten aluminum alloy at high temperature. Usually, the deform band was main feature in ASB for the low volume fraction of aluminum matrix composites, while the transformed band was seldom reported [9-12]. The reason was that reversion and recrystallization was more possibly present during SHPB compression, adiabatic temperature rise was not high so that the transformed band was not subsistent. But it was found in literature [7] that even in suffered static load, the transformed band was present in Tungsten particles reinforced amorphous materials and Tungsten wire enhanced amorphous block which was normally called as “phenomenon of matrix materials melt”.

![Figure 3](image1)

(a) transformed band; (b) molten aluminum band.

ASB is the sign of materials macroscopic failure in that the microcracks, microhole in ASB eventually led to material failure. ASB was the result of competition between thermal softening and work hardening. It was a serial of course related to velocity resulting which included such as the generation and development of deformed band, the transformation of deformed band, the development of transformed band, the crack propagation along the shear zone. The formation of transformed ASB was a similar course like the generation, development and growing of deformed band.

![Figure 4](image2)

(a) the accumulation area of aluminium cells on adiabatic shear surfaces (b) SEM morphologies of molten aluminum cells.
For the function of adiabatic shear localization, it was local high temperature on the adiabatic shear plane. The temperature at local region of ASB was above 900℃, which may cause the local region of aluminium alloy matrix molten. The volume of aluminium alloy matrix was swelled when it was melt which led to the molten aluminium alloy on the shear plane flowing from the gap of the reinforcement phase then the different particles were formed on the shear plane whose diameter was no more than 5 μm. All this molten aluminium particles was scattered on the local region and the size of them was nonuniform and irregularly arranged as shown in Fig.4a. As shown in box A of Fig.4a, the different size of melt aluminium particles got together. One part of aluminum matrix swelled and formed alone, the other part of aluminum matrix formed by attaching on the small size ceramic particles. While in box B region, only discontinuous small molten aluminium particles was present as arrowhead, the quantity of prominent samll particles was few and the big accumulation area was not formed, whose subtle morphology was shown in Fig.4b.

It was further analyzed that the adiabatic shear failure of 55vol% TiB2/Al composites was affected by thermal softened effect. Once the matrix materials were suffered the inelastic plastic deformation and inhomogeneous plastic deformation, the local region of high volume fraction particles reinforced aluminum matrix composites were thermally softened due to rapidly heat. And thermal soften can decrease the strain rate sensitivity of matrix alloy and weaken the stain hardening effective. Once the thermal soften is the dominant, deformation of the composites will develop along two directions. One is the slip among the reinforcement particles and the formation of slip groove. The second is the formation of local adiabatic shear band caused by thermal soften. At high strain deformation, the thermal soften control the strain and strain hardening, and then the local adiabatic shear band is generated. Inside the shear bands, a large plastic deformation is happened in matrix alloy, even with the melting, which is the source of the melted aluminum alloy. Out of the shear bands, the plastic deformation ability of the matrix alloy is similar to that at quasi-static load, and the soften trend is not obvious. Because of local adiabatic shearing, some micro-cracks are formed inside the TiB2 particles and aluminum alloy. And the cracks are propagated along the TiB2-Al interfaces, which causes the unstable fracture.

Therefore, the failure mechanism of TiB2/Al composite material was assumed that thermal softening induced the dynamic bucking failure. With increase of the enhanced phase volume fraction, the function of bearing deformation and load transmission which was in the charge of matrix material was changed to impose on reticular structure formed by the contacting particles. The increase of strain rate contributed to damage of enhanced phase particles, and with thermal softening effect, adiabatic shear failure of composite materials was inclined to take place.

**Calculation for Temperature Rise and Analysis for Dynamic Failure of AMC**

Due to dynamic recrystallization of phase transformation, the temperature was a key parameter for analyzing the formation course of ASB. The temperature rise in the shear band can be calculated by [14]

\[
\Delta T = T - T_0 = \int_0^{\varepsilon_f} \frac{\beta \sigma}{\rho C_m} d\varepsilon
\]

where \(\varepsilon_f\) is the final plastic strain; \(\beta\) was the fraction of plastic work converted into heat; \(\rho\) is the density and \(C_m\) was the specific heat. The heat capacity for Aluminium was 960 J(kgK)\(^{-1}\). For AMC, formula (1) can be written as follow:

\[
\Delta T = T - T_0 = \frac{\beta}{\rho C_m} \frac{h_1}{h_2} \cos \theta \int_0^{\varepsilon_f} \sigma d\varepsilon \approx \frac{\beta}{\rho C_m} \frac{h_1}{h_2} \sum S_i
\]

where \(\theta\) is the angle between the shear layers to the applied force axis, \(h_1\) the height of the specimen and \(h_2\) the layer thickness of the transformed bands (0.03–0.12mm). \(S_i\) is the deformation energy per unit area. Separating the area surrounded by the dynamic compression
curves and the axis to a series of unit area as $\Delta \epsilon_i$, $S_i$ is calculated as:

$$S_i = \frac{\Delta \epsilon_i \times (\sigma_i + \sigma_{i+1})}{2} (i = 1, 2, 3, \ldots)$$

According to the above formula, a $\Delta T$ of 800-900K was obtained inside the transformed band for TiB$_2$/Al composites. It is much higher than those of the adjacent colder matrix and particles. When compressed, the whole failure process has a duration of about 3 $\mu$s, and the formation time for the transformed band was only 0.1 $\mu$s or even shorter.

As the loading duration was very short, the dissipation of the mechanical energy into heat generates strong temperature heterogeneities. According to the calculations, local cooling rate for the transformed band during the whole cooling process will achieve $10^6$ K/s or even high and the amorphous inside the transformed band during adiabatic shearing failure was found. However, the formation course of the amorphous and its affect factors was still unknown. In future research, the advanced temperature measure system will be used to obtain the temperature rise inside the specimen during dynamic compression in order to verify the dominant factor which can control the formation of the transformed band and its microstructure.

Based on the above analysis, it was deduced that the failure mode for AMC was a hybrid fracture with particle cracking and matrix softening.

The diagram of ASB formation was shown in Fig. 5. From it, it was known that the dynamic failure was changed from thermal softening instability to brittle fracture. The specimen deformed elastically first due to suffering the applied force during the formation of ASB (in Fig. 5a). Moreover, from Fig. 6b and c, it was shown that the formation of an intense thermal softening region and the propagation of micro-cracks were present which implied shearing and splitting failure. Because the effects of strain hardening and strain rate hardening for the aluminum alloy matrix were weakened by thermal softening. On the one hand, it resulted in the rapid loss of stress carrying capability on the aluminum alloy matrix, which causes the shearing failure of the composite specimen. The whole failure process was shown in Fig. 6b, c and d. On the other hand, the interfacial bonding of reinforcement and matrix was deteriorated by thermal softening, which was the reason of the initiation and growth of void sand cracks. Finally the composite specimen’s failure in splitting was present, and the failure process was shown in Fig. 6c and d.

**Conclusion**

In this paper, based on such as SHPB, OM and SEM, microstructure feature of transformed band for aluminum matrix composite was observed during dynamic load. It was found the molten aluminum group was the main characteristic in transformed band, and the conclusion was obtained:

1) It was seen that there were the molten aluminium alloy and the molten aluminium particles on the shear flat surface oriented at an angle approximately 45° to the compression axis, which was transformed band. It was formed due to aluminium alloy melt at high temperature and solidified sharply by analysis.
2) The formation of transformed band was related to adiabatic temperature rise. The adiabatic temperature rise was 800-900K by calculation. The local high temperature led to the formation of the melt aluminium pariticles whose diameter was 1-3µm on the adiabatic shear flat surface. With the rapid convergence of molten aluminium pariticles and growing up, the adiabatic shear band was finally formed.

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