Dislocation arrangements in magnesium matrix composites

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Abstract. Magnesium matrix composites reinforced with TiC particulates was successful synthesized by in-situ synthesis method. The dislocation arrangements in the composites have been investigated. Compared to magnesium alloy, there is high dislocation density in the composites. Besides dislocation network, dislocation pile-ups have been found in α-Mg and β-Mg$_{17}$Al$_{12}$ phases. They are confined in the slip planes, and some of them pile up against the grain boundaries. The dislocation arrangements in the composites are due to the addition of TiC particulates. Moreover, the compound twin reveal in the casting composites, which is beneficial to the deformation behavior of the composites.

1. Introduction
Magnesium matrix composites (Mg-MMCs), as the lightest structural materials, are very attractive in large amount of technical applications [1, 2], such as automobile, aeronautical and aerospace, electronic industries, etc. However, Mg-MMCs possess poor ductility and low cold forming capability, which is due to its hexagonal close packed (hcp) structure. In order to improve plasticity of Mg-MMCs, it is important to understand their deformation behaviors. Dislocation plays an important role on deformation behaviors of materials. But there are littler investigations of mechanical properties, especially concerning the dislocation structure of Mg-MMCs. Some researchers have been focused on the dislocation arrangements in magnesium alloys or magnesium matrix composites [3–5]. Congyang Zhang et al [3] indicated the dislocations pile-ups in the AZ91D magnesium alloy are found to be beneficial to the resistance to stress corrosion cracking of the alloy, and thereby beneficial to the mechanical properties of the alloy. Dislocation networks are found to increase with deformation in all cases. In research of Levente Balogh et al [4], a ZK60 magnesium alloy was processed by equal-channel angular pressing (ECAP). The results show the subgrain size and twin boundary density increase between 1 and 2 passes and then decrease, the dislocation density continuously decreases up to 8 passes and the measured microhardness remains reasonably constant between 1 and 8 passes of ECAP. K. Máthis et al [5] investigated the deformation in pure magnesium at various temperatures. The evolution of the dislocation density and the Burgers vector types with the temperature of deformation is discussed on the basis of dislocation reactions and dynamic recovery in magnesium. Compared to magnesium alloy, Mg-MMCs possess high dislocation density due to the addition of reinforcement particulates [6]. The micron particles lead to inhomogeneous deformation of magnesium matrix, thus causes dislocation pile-up near particles and the formation of twinning away from particles. Larger stress concentration occurs at the end of some micron particles, which results in the appearance of microcracks. In the course
of subsequent deformation, the composite fractures due to rapid extension of microcracks [7]. So, the
dislocation arrangements of Mg-MMCs may be more complex than that of magnesium alloy. The
research of dislocation arrangements in Mg-MMCs is beneficial to understanding the deformation
behavior, farther, the mechanical properties of Mg-MMCs.

The aim of the present paper is to synthesize TiC/AZ91 composites using in-situ synthesis method,
and to determine the dislocation arrangements in the composites.

2. Experimental procedures
The 8wt.%TiC/AZ91 composites were prepared by remelting and dilution technique that is an in-situ
synthesis method. Specimens for TEM analyses were prepared as follows. First, slices with dimensions
10×4×0.2mm were cut from the TiC/AZ91 composites. Then they were mechanical polished and cut
into Φ3mm disks, and dimpled to about 10μm in the center. Final preparation of the specimens was ion
milling on a Gatan precision ion polishing system 691 under conditions of 5.0 kV and incident angle of
6-4℃. TEM analysis was conducted on a Hitachi H-800 transmission electron microscopy.

3. Results and discussions
Fig.1 shows typical TEM images of the dislocation arrangements in the AZ91 alloy and TiC/AZ91
composites.

![Fig 1. The dislocation arrangements in magnesium materials ((a) AZ91 alloy; (b) TiC/AZ91 composites).](image)

According to Fig.1, the dislocation density of TiC/AZ91 composites is higher than that of AZ91 alloy.
In TiC/AZ91 composites, thermal stress generates during cooling process from molten temperature
to room temperature because of the mismatch of thermal expansion coefficients between magnesium
matrix and TiC particulates. The relaxations of thermal stress go through stress diffusion and nucleation
of dislocation. So, the improvements of dislocation density that gain from the relaxations of thermal
stress are described as [8]:

\[
\Delta \rho = \frac{12 \Delta \alpha \Delta T V_p}{bd}
\]

(1)

Where \(d\) is the average diameter of TiC particulates, \(\Delta \alpha\) is the difference of thermal expansion
coefficients between Mg and TiC, \(\Delta T\) is the difference of temperature, \(V_p\) is the volume fractions of
TiC particulates, and \(b\) is the Burger’s vector. In our research, \(d\) is average 500nm, \(\Delta \alpha\) is 19.48×10⁻⁶K⁻¹,
and \(\Delta T\) is 180K, \(V_p\) is 3.1%, and \(b\) is 0.32094nm. According to the above equation, the
improvements value of dislocation density in magnesium matrix composites is $8.128 \times 10^{15} \text{m}^{-2}$. So, the dislocation density of TiC/AZ91 composites is higher than that of AZ91 alloy due to the addition of TiC particulates in magnesium matrix.

The dislocation arrangements in the TiC/AZ91 become more complex (as shown in Fig.2).

![Fig 2. The dislocation arrangements in 8wt.%TiC/AZ91 composites (a), (c)network dislocation; (b)dislocation around TiC particulates; (d) parallel dislocation; (e) (f) dislocation pile-up.]

In TiC/AZ91 composites, there is high dislocation density around TiC particulates (as shown in Fig.2 (b)), which is due to the larger thermal stress in the interface of magnesium matrix and TiC particulates. It is discovered the presents of dislocation networks in TiC/AZ91 composites. The average dislocation spacing of the dislocation networks is measured to be about 20-80nm (as shown in Fig. 2(a)). Parallel dislocation is also been discovered in TiC/AZ91 composites (as shown in Fig.2(c), (d)). The average dislocation spacing of the parallel dislocation is measured to be about 15-20nm. Moreover, dislocation


pile-ups have also been found (as shown in Fig. 2 (e), (f)). Each dislocation pile-ups consists of several very short dislocations of about 10-20 nm in length. The dislocation pile-ups are confined in various slip planes. The spacing between each parallel dislocation in the pile-ups is measured to be only several nanometers. Speidel M.O. et al. [9] have studied the relationship between the susceptibility to stress corrosion cracking and the dislocation pile-ups against the grain boundaries in the bands in aluminum alloys and found that dislocations pile-ups are resistant to stress corrosion cracking in aluminum alloys. As shown in Table 1, the mechanical properties of the TiC/AZ91 composites are apparently higher than that of AZ91 alloy, which is probably contributed to the abundant amount of dislocation pile-ups.

Dislocations have also been found in the $\beta$-$\text{Mg}_{17}\text{Al}_{12}$ phase in the TiC/AZ91 composites. Fig. 3 gives TEM image of the $\beta$-$\text{Mg}_{17}\text{Al}_{12}$ precipitation in the TiC/AZ91 composites.

![Fig 3. TEM images of the $\beta$-$\text{Mg}_{17}\text{Al}_{12}$ precipitation and its dislocation (a) $\beta$-$\text{Mg}_{17}\text{Al}_{12}$ precipitation; (b) dislocation in $\beta$-$\text{Mg}_{17}\text{Al}_{12}$ phase)](image)

The Fig. 3 shows the presence of numerous dislocations in $\beta$-$\text{Mg}_{17}\text{Al}_{12}$ phase. The thermal stress also remains in $\beta$-$\text{Mg}_{17}\text{Al}_{12}$ phase during cooling process. In order to relax thermal stress, the dislocations in the $\beta$-$\text{Mg}_{17}\text{Al}_{12}$ phase form as networks and confine within the phase. The $\beta$-$\text{Mg}_{17}\text{Al}_{12}$ phase in TiC/AZ91 composites is smaller than that in AZ91 alloy for the addition of TiC particulates in magnesium matrix. The relaxations of thermal stress in $\beta$-$\text{Mg}_{17}\text{Al}_{12}$ phase go through in a confined slip plane. So, the spacing between each parallel dislocation in $\beta$-$\text{Mg}_{17}\text{Al}_{12}$ phase is found to be about several nanometers only. Thereby, it can be considered as dislocations pile-ups in the TiC/AZ91 composites, which are beneficial to the resistance to stress corrosion cracking, and thus beneficial to the mechanical properties of the TiC/AZ91 composites (as shown in Table 1).

| Materials | Heat-treatment | Mechanical properties |
|-----------|----------------|-----------------------|
| AZ91      | F              | $\sigma_b/\text{MPa}$ | $\sigma_{0.2}/\text{MPa}$ | $\delta/%$ | $E/\text{GPa}$ |
|           | 165            | 97                    | 2.5                   | 45         |
|           | T4             | 275                   | 90                    | 15         | 45         |
|           | T6             | 275                   | 145                   | 6          | 45         |
| TiC/AZ91  | F              | 197                   | 106                   | 1.9        | 47.5       |
|           | T4             | 298                   | 109                   | 4.5        | 47.5       |
|           | T6             | 297                   | 162                   | 1.8        | 47.5       |
Beside the presence of complex dislocation arrangements, compound twin is also discovered in the casting TiC/AZ91 composites (as shown in Fig.4).

![Fig 4. TEM images of compound twin in TiC/AZ91 composites ((a) compound twin; (b) Compound twin around TiC particulates).](image)

The width of compound twin is about 20-150nm. And the twinning will be ceased in front of TiC particulates. In metal materials, the critical shear stress to twinning is far larger than that of slip deformation. So twin deformation form in the place where thermal stress is very high, such as grain boundaries, interface and dislocation. Compared to slip deformation, the twinning has a little contribution to deformation behavior. But the twinning can change the grain direction, which moves the direction of slipping system. So, the compound twin is also advantageous of deformations in TiC/AZ91 composites.

4. Conclusions
There are high-density dislocations in the TiC/AZ91 composites due to the addition of TiC particulates. For the addition of TiC particulates, the complex dislocation arranges such as dislocation networks, dislocation pile-ups and parallel dislocation is revealed in the cast TiC/AZ91 composites. Dislocation pile-ups are confined in the slip planes and piled up against the grain boundary. Compound twin is discovered in the cast TiC/AZ91 composites. High-density dislocations pile-ups and compound twin in the TiC/AZ91 composites are beneficial to the resistance to stress corrosion cracking.

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