The Microstructures for Hot Compressive Deformation of MB15 Magnesium Alloy and Al$_{18}$B$_4$O$_{33}$w/MB15 Magnesium Matrix Composites

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Abstract. The hot compressive deformation behaviors of MB15 and Al$_{18}$B$_4$O$_{33}$w/MB15 have been researched on with hot compression tests. The flow behaviors of the deformed materials have been analyzed. The microstructure observation tests were carried out by means of OM and TEM. The results of the study indicate that working hardening is more obvious at low temperature than that at high temperature, and the materials exhibit significant instability phenomenon at high strain rate (1-10s$^{-1}$). The optimal process parameters for the deformed materials are higher temperature (623-673K) and lower strain rate (0.001-0.01s$^{-1}$). Dislocation slip, dynamic recrystallization and mechanical twinning have been observed for the deformed materials. Dynamic recrystallization is the main deformation mechanism of the deformed materials at higher temperature and lower strain rate. Twinning is the main deformation mechanism of the deformed materials at lower temperature and medium strain rate, and that appears at earlier deformation stage in the material’s deformation process.

1. Introduction
Magnesium alloys are the lightest ones among the structural metals. They have great current applications and potential applications in automotive and aerospace component manufactures for their light-weighting and high damping capacity [1]. But magnesium alloys have limited ductility at room temperature. Elevating temperature can active prismatic slip, thus to increase basal slip which is the most favorable slip system [2]. The formation of new grain in hot deformed magnesium alloy appears by dynamic recrystallization, while nucleation appears by sub-grain rotation, bulging and twinning [3]. In the past, there were many studies about DRX mechanisms, but few studies have paid attention to the relationships between the dynamic recrystallization mechanisms and deformation conditions [4]. In this research, the performances of MB15 alloy in hot compressive deformation tests have been studied under several deformation conditions.

Because Al$_{18}$B$_4$O$_{33}$ whiskers have many excellent performances, they have been widely used as reinforcements in aluminum matrix composites, and many Al$_{18}$B$_4$O$_{33}$w/Al composite components have also been used [5-6]. In recent years, Al$_{18}$B$_4$O$_{33}$ whiskers as reinforcements in magnesium matrix composites have a wide range of development and application. Many studies on hot deformation processing of magnesium alloys have been carried out, and the hot deformation of magnesium alloys have been used in industrial manufactures [7]. In order to study the relationships between the microstructures and the deformation properties of magnesium matrix composites, the hot compressive deformation behaviors of Al$_{18}$B$_4$O$_{33}$w/MB15 composites have been studied.
2. Experiment

In this research, MB15 magnesium alloy and Al18B4O33/MB15 (20vol.%) magnesium matrix composites were used as the test materials. The chemical composition (wt.%) of MB15 magnesium alloy was shown in Table 1. Al18B4O33 whiskers (diameter 0.5-1.0μm, length 10-30μm) were used as reinforcements of MB15 magnesium alloy. The materials were fabricated by squeeze casting technique.

| Element | Mg  | Zn | Zr | Si  | Mn | Al | Fe | Cu | Ni |
|---------|-----|----|----|-----|----|----|----|----|----|
| Content | balance | 5.50 | 0.60 | 0.009 | 0.015 | 0.007 | 0.012 | 0.002 | 0.0009 |

The hot compressive deformation experiments were carried out at the temperature of 523-723K, the strain rate of 0.001-10s\(^{-1}\) and the true strain of \(\varepsilon=0.6\). The experimental temperatures were determined by the dynamic recrystallization temperature range of the materials. The strain rates and the true strain were determined according to the processing conditions. Cylindrical samples with the diameter of 8 mm and the height of 12 mm were used for the tests. The samples were heated to experimental temperature and remained the heat for 3-5min before compressive deformation tests began. Fluctuation of temperature was controlled within ±1°C. The samples were quenched in water after hot compression was finished. The compression direction was parallel to the axis direction of the samples. The microstructures of the hot compression sample’s surfaces were analyzed by means of optical microscopy (OM) and transmission electron microscopy (TEM).

3. Results and Discussion

3.1. Compressive True Stress-Strain Curves

The compressive true stress-true strain curves of hot compression deformed MB15 alloy at the temperature of 648K and the strain rate of 0.001-10s\(^{-1}\) are indicated in figure 1(a). The results shows that the flow stress reduces with decreasing of the strain rate. The materials exhibit significant instability phenomenon at high strain rate (1-10s\(^{-1}\)). Besides, the flow stress increases first and then reaches a stable state at low strain rates. Such flow behavior is the typical feature of dynamic recrystallization in the hot working process. The similar results have been obtained at other higher temperatures.

![Figure 1](image-url)
strain rate of 0.01s\(^{-1}\) and the temperature of 523-723K are obtained in figure 1(b). The results shows that flow stress increases with decreasing of the deformation temperature. The phenomenon of working hardening is more obvious at low temperature than that at high temperature. In addition, softening behaviors of the samples occur at the temperature of 523-573K, but there is little variety at the temperature of 623-723K. The similar results have been obtained at other lower strain rates.

The compressive true stress–true strain curves of hot compression deformed Al\(_{18}\)B\(_4\)O\(_{33}\)w/MB15 magnesium composites at the temperature of 623K and the strain rate of 0.001-10s\(^{-1}\) are indicated in figure 2(a). As everyone knows that the flow stress is closely related to the strain rate and the temperature on the condition that the strain is constant. Figure 2(a) shows that flow stress is released by appearing fractures in the samples at the strain rate of 1-10s\(^{-1}\). With increasing of the strain rate, whisker appears rotation and fracture because it is non-deformed ceramic reinforcement. Therefore, the flow stress decreases significantly after reaching the peak value. In addition, the flow stress decreases significantly because of dynamic recrystallization and dynamic recovery at medium strain rates and higher temperatures.

The compressive true stress–true strain curves of hot compression deformed Al\(_{18}\)B\(_4\)O\(_{33}\)w/MB15 magnesium composites at the strain rate of 0.1s\(^{-1}\) and the temperature of 523-723K are indicated in figure 2(b). It shows that the strain hardening decreases with increasing of the temperature. Moreover, the strengthening effect of Al\(_{18}\)B\(_4\)O\(_{33}\) whisker is gradually weakening with increasing of the temperature. Therefore, the sample exhibits significant softening phenomenon at higher temperature. The similar results have been obtained at other lower strain rates.

**Figure 2.** Compressive true stress–true strain curves of hot compression deformed Al\(_{18}\)B\(_4\)O\(_{33}\)w/ MB15 composites at (ε=0.6) (a) T=623K and ε =0.001-10s\(^{-1}\) (b) ε = 0.1s\(^{-1}\) and T=523-723K

### 3.2. Microstructures

At the strain rate of 0.001s\(^{-1}\) and the temperature of 573-723K, the compression deformed MB15 alloy appears dynamic recrystallization (DRX) microstructure which is shown in figure 3. Because the dynamic recrystallization transformation is incomplete at lower temperature, it can be seen that the number of DRX grains is larger at higher temperature than that at lower temperature, and it is shown in figure 3(a) and (b). But the dynamic recrystallization grain appears growth phenomenon at 673-723K, which is shown in figure 3(c) and (d). At the same time, figure 3(a) and (b) also indicate that the formation of new grain is accompanied by the slip of original grain boundaries at a large number of formed slip zones at the temperature of 573-723K. Moreover, the migration of grain boundary occurs simultaneously with the formation of low-angle boundaries. In summary, the formation of new grain is achieved by the formation of new grain boundaries. The formation of new boundary is usually located in the initial grain boundaries and inside initial grains.

In figure 4, it shows the compression deformed MB15 alloy appears dynamic recrystallization, twinning and dislocation slip. High-density dislocations near the original grain boundaries are shown in figure 4(a) (673K-0.01s\(^{-1}\)). Moreover, dislocation structures in the subgrains are shown in figure 4(b)
and a large number of dislocations in the twins can be seen in figure 4(c) (673K-0.01s$^{-1}$). These microstructures show that twinning dynamic recrystallization (TDRX) is an important aspect of dynamic recrystallization (DRX) mechanisms. In summary, subgrains begin to appear at the serrated grain boundaries. With the deformation proceeding, subgrains develop to the all grains by dislocation cell wall transforming into subgrain boundaries. The above results show that the formation of subgrain depends on the formation of dislocation substructures in the deformation process of hot compressed materials.

Dislocation slip, dynamic recrystallization and mechanical twinning are typical microstructural features of hot compression deformed MB15 alloy. At higher temperature and moderate strain rate, the plasticity of the material increases due to occurring dynamic recrystallization. While twins occur at lower temperature and earlier deformation stage.

![Figure 3](image_url)

**Figure 3.** OM microstructures of hot compression deformed MB15 alloy at $\varepsilon =0.001s^{-1}$ and (a) 573K (b) 623K (c) 673K (d) 723K

![Figure 4](image_url)

**Figure 4.** TEM microstructures of hot compression deformed MB15 alloy (a) dislocation (b) DRX (c) twinning

TEM microstructures of hot compression deformed Al$_{18}$B$_3$O$_{33w}$/MB15 composites are shown in figure 5. Figure 5(a) (573K-0.001s$^{-1}$) shows that there are a lot of dislocations near the whiskers. Whiskers as non-deforming ceramic reinforcements are the preferred sites for recrystallization nucleation formation. It’s because Al$_{18}$B$_3$O$_{33}$ whiskers can increase nucleation rate of dynamic recrystallization by increasing dislocation density in the matrix of composites. A large number of equiaxed recrystallization grains appear at the temperature of 623-673K and the strain rate of 0.001-0.01s$^{-1}$. It indicates that dynamic recrystallization is the main deformation mechanism of the materials under such deformation conditions. It is also the reason for the decrease of flow stress in the deformation process.

As shown in figure 5(b) (673K-0.01s$^{-1}$), there are many fine dynamic recrystallization grains near the aluminum borate whiskers. Moreover, there are no obvious dislocations inside the recrystallized grains. In addition, plenty of banded twins appear at lower temperature of 523-573K. It indicates that
mechanical twinning is the main deformation mechanism of the materials at lower temperature. As shown in the figure 5(c) (623K-0.001s⁻¹), many twins have been observed in the deformed materials. Therefore, twinning is the main reason for the high strain hardening rate of the materials at lower temperature.

Figure 5. TEM microstructures of hot compression deformed Al₁₈B₄O₃₃w/MB15 composites
(a) dislocation (b) DRX (c) twinning

4. Conclusions
For MB15 alloy and Al₁₈B₄O₃₃w/MB15 composites, flow stress of the materials decreases with increasing of the temperature at fixed strain rate. Working hardening is more obvious at low temperature than that at high temperature. The materials exhibit significant instability phenomenon at high strain rate. The strengthening effect of Al₁₈B₄O₃₃ whisker is gradually weakening with increasing of the temperature. The optimal process parameters for the deformed materials are higher temperature (623-673K) and lower strain rate (0.001-0.01s⁻¹).

Dislocation slip, dynamic recrystallization and mechanical twinning are typical microstructural features of hot compression deformed MB15 alloy. At the strain rate of 0.001-0.01s⁻¹ and the temperature of 573-723K, the compression deformed MB15 alloy appears dynamic recrystallization microstructures. The formation of subgrain depends on the formation of dislocation substructures in the deformation process. The formation of new grain is achieved by the formation of new grain boundaries.

For hot compression deformed Al₁₈B₄O₃₃w/MB15 composites, dynamic recrystallization is the main deformation mechanism at higher temperature and lower strain rate. A large number of equiaxed recrystallization grains appear at the temperature of 623-723K and the strain rate of 0.001-0.1s⁻¹. Twinning is the main deformation mechanism of the materials at lower temperature and medium strain rate. It is the main reason for high strain hardening rate of the materials under such deformation conditions.

5. References
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