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Microstructural evolution of 2026 aluminum alloy during hot compression and subsequent heat treatment

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Abstract: 2026 aluminum alloy was compressed in a temperature range of 300-450 °C and strain rate range of 0.01-10 s⁻¹. The correlation between compression conditions and microstructural evolution after solution and aging heat treatment was investigated. It is found that the recrystallization and precipitation behavior after heat treatment are associated with the temperature compensated strain rate *Z* value during hot deformation. Under low *Z* parameter condition, a small quantity of fine recrystallized grains are formed, and the well formed subgrains with clean high-angle boundaries and coarse precipitates seem to be remained during heat treatment. Under high *Z* parameter condition, a large number of fine equiaxed recrystallized grains are produced, and a high dislocation density with poorly developed cellularity and considerable fine dynamic precipitates are replaced by the well formed subgrains and relatively coarse precipitates after heat treatment. The average recrystallized grain size after heat treatment decreases with increasing *Z* value and a quantitative relation between the average grain size and the *Z* value is obtained.

Key words: 2026 aluminum alloy; hot deformation; heat treatment; recrystallization; precipitation

1 Introduction

Hot working and subsequent heat treatment are the main manufacturing procedures of heat-treatable aluminum alloys. The hot deformation results in a number of different complicated dynamic microstructure evolution that may significantly influence the static microstructure change during heat treatment and therefore final mechanical properties of the alloys. The properties of 2025 aluminum alloy were found to exhibit a dependence on its microstructure developed during hot forming and heat treatment. Higher forming temperatures resulted in coarser recrystallized microstructures, which tended to reduce the susceptibility to exfoliation corrosion, but adversely affected tensile properties[1-2]. The microstructure consisted of recovered elongated grains and the main restoration processes recovered during post heat treatment for AA7075 alloy and the alloy containing 0.1% Sc with relatively higher Zn and Cu content, but recrystallization proceeded during post heat treatment latter[3]. When the hot-deformed Al-Zn-Mg-Cu-Cr alloy was subjected to recrystallization treatments, the recrystallized grain size decreased with the increase of the temperature compensated strain rate Z[4]. Precipitations were observed in the hot deformation of P/M Al-Cu composites, but the grain size decreased after heat treatment[5].

2026 aluminum alloy is a modified version of 2024 aluminum alloy, which contains low levels of Fe and Si, and minor addition of Zr to inhibit recrystallization during thermo-mechanical processing. At present, hot compression tests of 2026 aluminum alloy were performed at temperatures ranging from 300 to 450 °C and strain rates from 0.01 to 10 s⁻¹, and then the deformed samples were subsequently solution treated at 500 °C and aged at 185 °C for 12 h. The purpose of this work is to investigate the effects of hot deformation processing parameters on microstructural evolution of 2026 aluminum alloy during subsequent heat treatment.

2 Experimental

The main chemical composition of 2026 aluminum alloy was 4.39% Cu, 1.15% Mg, 0.51% Mn, 0.12% Zr and balance Al (mass fraction). Cylindrical samples with size of $d10 \text{ mm} \times 15 \text{ mm}$ were machined from commercial semi-continuous casting ingots and subsequently homogenized at 500 °C for 24 h, followed by water quenching. Convex depressions of 0.2 mm deep

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were machined on both ends of the samples in order to maintain the lubricant of graphite mixed with machine oil during compression tests. Compression tests were carried out on a computer servo-controlled Gleeble 1500 system at strain rates of $0.01-10 \text{ s}^{-1}$ and deformation temperatures of 300-450 °C. The sample was resistance heated at a heating rate of 10 °C/s to deformation temperature and held for 180 s by thermocoupledfeedback-controlled AC current before compression. The samples were deformed to half of their original height and water quenched immediately. Subsequently, the deformed samples were split parallelly to the compression axis along the direction of centerline, and half of the sample was solution treated at 500 °C for 2 h, then water quenched and followed by artificial aging at 185 °C for 12 h. Both the hot compressed and the heat treated specimens were prepared by the conventional methods. The microstructure was observed on MM-6 metallographic microscope and H-800 transmission electron microscope (TEM), respectively.

3 Results and discussion

3.1 Recrystallization behavior

Figure 1 shows the optical micrographs of 2026 aluminum alloy deformed at different temperatures and strain rates. The structure consists of fine grains and elongated grains, which indicates that dynamic recrystallization (DRX) occurs in evidence during hot compression deformation. The DRX grain size is dependent sensitively on deformation temperature, strain rate and temperature compensated strain rate Z [6]:

$$Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) \tag{1}$$

where Z is the Zener-Hollomon parameter; R is the gas constant and Q is the activation energy for hot deformation, which is 340.98 kJ/mol[7]. Decreasing Z value, which is equal to increasing deformation temperature or decreasing strain rate, leads to more adequate proceeding of DRX because of high driving force and sufficient time for recrystallization. Hence, coarser recrystallized grains can be observed in the specimen deformed at 450 °C and strain rate of 0.01 s⁻¹ $(Z=4.32\times10^{22})$ compared with that at 300 °C and strain rate of 10 s⁻¹ (Z=1.22×10³²). During hot deformation of aluminum alloys, a large number of migration of atoms and dislocations cause the merging of some grains, and low-angle grain boundaries transform into high-angle grain boundaries through absorbing dislocations. Subsequently, the recrystallized grains grow greatly through the migration of dislocations and high-angle grain boundaries. The grain refinement is induced by a deformation-induced continuous reaction which is essentially similar continuous to dynamic recrystallization (CDRX)[7-9]. Continuous dynamic recrystallization usually caused by gradual subgrain growth leads to the formation of high-angle boundary migration. Typically, the mechanisms of continuous dynamic recrystallization nucleation may be that some



Fig.1 Optical microstructures of 2026 aluminum alloy deformed at: (a) 450 °C, 0.01 s⁻¹; (b) 400 °C, 0.1 s⁻¹; (c) 350 °C, 1 s⁻¹; (d) 300 °C, 10 s⁻¹

subgrains coarsen through mergering other adjacent subgrains to produce high-angle boundaries. Subgrain boundary migration occurs when particle coarsening leaves some subgrain boundaries weakly restrained. Alternatively, elevated temperature straining may provide added driving pressure for boundary migration, accelerating the continuous dynamic recrystallization [7-9]. Indeed, it has been well known that aluminum alloys containing high density of Al₃Zr dispersoids or alloys containing high density of several types of fine particles provide sufficient boundary drag pressure to prevent the nucleation of discontinuous recrystallization and hence accelerate the continuous dynamic recrystallization[8-9]. For these reasons, it can be concluded that the grain refinement during hot deformation of 2026 aluminum alloy occurs with the main type of the CDRX.

In order to examine the effect of deformation process parameters on the heat treatment sequence, specimens were prepared from the material deformed over a wide range of temperatures and strain rates. Figure 2 shows the optical micrographs of 2026 aluminum alloy solution treated at 500 °C and then aged at 185 °C for 12 h (typical T6 temper) after hot deformation at different temperatures and strain rates. Figure 2(a) shows the heat treated microstructure of a sample deformed at temperature of 450 °C and strain rate of 0.01 s⁻¹, which is typical microstructure of this alloy with low *Z* values. Figure 2(b) shows the heat treated microstructure of a sample deformed at temperature of the sample deformed at temperature of a sample

300 °C and strain rate of 10 s⁻¹, which is typical microstructure of this alloy with high Z values.

It can be seen that the deformed structure (Fig.1) is replaced by relative coarse grains (Fig.2). Clearly, static recrystallization occurs during solution treatment, and the degree depends on the prior hot deformation conditions. It could be explained by stored deformation energy evaluation. Low Z value could get low stored strain with fine grains which are stable during heat treatment. High Z could get high stored strain, thus a lot of fine recrystallized grains are formed after heat treatment. These two effects of deformation parameters, the deformation temperature and the strain rate on the recrystallization process equalize mutually. Both the nucleation and growth of recrystallized grains are thermally activated progresses. The deformation under the condition of low temperature and high strain rate leads to acute distortion of crystal lattice and high dislocation density. When the samples are subjected to solution heating after deformation, the distortion energy becomes the main driving force and therefore accelerates recrystallization. It is suggested that there is very little driving force for static recrystallization during heat treatment at higher deformation temperatures. As long as the recovered elongated grains remain, the locally recrystallized grains which are evolved during the hot deformation grow rapidly by consuming the recovered elongated grains during post heat treatment[4-5, 10]. The average recrystallized grain size is measured through quantitative metallographic analysis and the curves of



Fig.2 Optical microstructures of heat treated 2026 aluminum alloy after deformation at: (a) 450 °C, 0.01 s⁻¹; (b) 400 °C, 0.1 s⁻¹; (c) 350 °C, 1 s⁻¹; (d) 300 °C, 10 s⁻¹

The average recrystallized grain sizes varied with Zener-Hollomon parameters are shown in Fig.3. It is obvious that the average recrystallized grain size D_r decreases with increasing Z parameter. The quantitative relation of the average recrystallized grain size and Z parameter is obtained by the analysis of curve fitting:

$$D_{\rm r} = 11.16 + 25.98 / \left[1 + \exp\left(\frac{\ln Z - 61.68}{4.18}\right) \right]$$
(2)



Fig.3 Relation of average recrystallized grain size and Z value

which can be used to predict and control the recrystallized grain size of the alloy during hot deformation and subsequent heat treatment.

3.2 Substructure evolution and precipitation behavior

Figure 4 shows the Tem images micrographs of specimen deformed at different temperatures and strain rates. The most important structural feature directly related to the deformation processing is the substructure, as shown in Fig.4(a). The subgrains are well formed with clean high-angle boundaries and coarse precipitates are distributed in the interior grain, which is extremely similar to that produced by solution-treatment followed by cold-working aging[11-13]. For the specimen deformed at low Z value, there are some static precipitations during preheating and stabilization at relatively high deformation temperature. Because of this and the short range to the solvus, there is little solute for dynamic precipitation (DPN). As a consequence, the particles are sufficiently large to cause only limited interference to dynamic recovery (DRV), so that the subgrains are equiaxed and well recovered. Moreover, the strain rate has other influences. At a low strain rate of 0.01 s^{-1} , there is enough time for precipitate coalescence



Fig.4 TEM images of 2026 aluminum alloy deformed at: (a) 450 °C, 0.01 s^{-1} ; (b) 400 °C, 0.1 s^{-1} ; (c) 350 °C, 1 s^{-1} ; (d) 300 °C, 10 s^{-1}

during deformation stage.

On the contrary, the specimen deformed at high Z, typically at temperature of 300 °C and strain rate of 10 s^{-1} , exhibits a high dislocation density with poorly developed cellularity as shown in Fig.4(d). It is considered fine DPN with dimensions of less than 0.01 µm and the precipitates give rise to bands of fine elongated cells between deformation bands. Hence, the sub-boundary definitions become more indistinct with decreasing deformation temperature or increasing strain rate, owing to the dislocation tangles. The soluble atoms and a uniform dispersion of fine particles, such as Al₃Zr, interact with the dislocations, which reduces dynamic recovery and recrystallization, and hence the higher strain energy may speed up dynamic precipitation during hot deformation of Al-Cu alloys[14-15]. At a strain rate of 10 s⁻¹, there is enhanced DPN due to higher dislocation density, but there is less coalescence because the time to finish strain is shortened.

Figure 5 shows the TEM images of the alloy solution treated at 500 °C and then aged at 185 °C for 12 h after deformation at different temperatures and strain

rates. The most distinct structural change compared with the deformed microstructure is the retained substructure. The subgrains remain well formed with clean boundaries and very low dislocation density. A large number of fine dispersion particles and considerable coarse precipitates are also evident. The precipitate size is found to decrease with increasing Z, and is even like under-aged state, but it has been relatively coarsened by heat treatment.

At lower values of Z, for a hot compression at temperature of 450 °C and strain rate of 0.01 s⁻¹, the typical substructure of the heat treated specimen is shown in Fig.5(a). In the solution treated and aged condition, subgrains may be retained throughout the solution treatment. The retained substructure is found to increase with increasing Z, as shown in Fig.5(d), for a heat treated material after compression at temperature of 300 °C and strain rate of 10 s⁻¹. Besides, the substructure of recovered state is thought to be responsible for offering heterogeneous nucleation site for fine and uniform precipitation of second-phase particle[15], as shown in Fig.5(a)–(d), which reveals that the precipitation formed throughout the structure and



Fig.5 TEM images of heat treated 2026 aluminum alloy after deformation at: (a) 450 °C, 0.01 s⁻¹; (b) 400 °C, 0.1 s⁻¹; (c) 350 °C, 1 s⁻¹; (d) 300 °C, 10 s⁻¹

preferential precipitation occurs at the subgrain boundary and interior.

X-ray diffraction (XRD) analysis demonstrates that the precipitates consist of bar-shaped Al₂CuMg (*S* phase) and Al₃Zr phases with a small amount of θ phase, which appear in the heat treated Al-Cu-Mg alloys[11–13], as shown in Fig.6, indicating that the compositions of precipitating phases do not exhibit any noticeable difference between the hot deformed and the heat treated samples, even though the precipitates have grown up in heat treatment sequence.



Fig.6 XRD patterns of 2026 aluminum alloy: (a) Hot deformed; (b) Heat treated

4 Conclusions

1) Recrystallization and precipitation behavior are associated with the temperature compensated strain rate Z value after heat treatment. Under low Z parameter condition, a small quantity of fine recrystallized grains is formed, and the well formed subgrains with clean high-angle boundaries and coarse precipitates seem to be remained during heat treatment. Under high Z parameter

condition, a large number of fine equiaxed recrystallized grains are formed, and the high dislocation density with poorly developed cellularity and considerable fine dynamic precipitates are replaced by the well formed subgrains and relatively coarsen precipitates after heat treatment.

2) The average recrystallized grain size after heat treatment decreases with increasing Z value and a quantitative relation between the average grain size and the value of Z is obtained.

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2026 铝合金热变形及热处理过程中的微观组织演变

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摘 要:研究 2026 铝合金在温度为 300-450 °C 和应变速率为 0.01-10 s⁻¹ 的变形条件与固溶时效热处理后微观组 织之间的关系。结果表明: 热处理后的再结晶和析出特性与热变形时的温度补偿应变速率 Z 有关。在低 Z 条件下, 热处理后会形成少量细小的再结晶晶粒, 热变形过程产生的高角度亚晶粒和粗大析出物被保留下来; 高 Z 条件下, 热处理后会产生大量细小等轴晶再结晶晶粒, 热变形过程产生的高密度晶胞和相对细小的动态析出物被热处理后 完整的亚晶粒和相对粗化的析出物所替代。热处理后的平均再结晶晶粒尺寸随着 Z 值的增加而减小。建立两者的 定量关系式。

关键词: 2026 铝合金; 热变形; 热处理; 再结晶; 析出

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