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Effect of deformation temperature on microstructure and mechanical properties of 7055 aluminum alloy after heat treatment

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Abstract: The multi-pass hot compression test of 7055 aluminum alloy was performed at different temperatures and then the samples were heat treated by T6 heat treatment. The compressed samples were analyzed by OM and TEM. The results reveal that the average aspect ratio of the grains in the specimens compressed first decreases and then increases, the dislocation density decreases and subgrain diameter increases with the increase of deformation temperature. The effects of deformation temperature on the microstructure and mechanical properties of 7055 aluminum alloy after heat treatment were investigated by means of OM and mechanical property test. The results indicate that the deformation temperature significantly influences microstructure and mechanical property of 7055 aluminum alloy. The volume fraction of recrystallization grains presents a "fall−rise" pattern with the deformation temperature rising. The mechanical properties get better when the volume fraction of recrystallization grains decreases. Moreover, the volume fraction of recrystallization grain has a minimum value, appropriately 45%, and the sample exhibits the highest strength and elongation at the deformation temperature of 400 °C.

Key words: 7055 aluminum alloy; hot deformation temperature; hot compression; recrystallization

1 Introduction

The age-hardenable Al−Zn−Mg−Cu alloys have a desired combination of high specific strength and hardness, good resistance to stress corrosion cracking and high fracture toughness, which renders them very useful in aerospace applications [1,2]. The Al−Zn−Mg−Cu−Zr(7055 alloy) contains a higher Zn/Mg ratio relative to 7150 alloy and a less content of the impurity of Fe, Si and Mn. This high solute alloy evokes high resistance to stress corrosion cracking and strength by the T77 heat treatment and is applied as upper wing structural material in the Boeing 777 aircraft [3]. At the present, researchs on the 7055 alloy, composition optimization and microstructures after heat treatment, such as second phases and precipitates, and their influences on the properties have been widely reported. Meanwhile, some innovative heat treatments have been developed [3−5]. In recent articles [6], the microstructure evolution of 7055 alloy during hot deformation was shown. However, the detailed influence of deformation temperature on heat-treated microstructure and mechanical properties are still less reported.

The deformation temperature significantly affects the final mechanical properties of the product [7,8]. For 7055 alloy, the temperature significantly influences dynamic recovery and recrystalization during hot deformation, and affects static recovery and recrystalization during heat treatment, which decides the final microstructure and mechanial properties. In this work, the influence of hot deformation temperature on microstructure and mechanial properties after heat treatment is investigated. This result is benifical to select a reasonable deforamtion temparature, controll the microstructure and mechanical properties and produce satisfactory product.

2 Experimental

The 7055 aluminum alloy with the composition (mass fraction) of Zn 7.87%, Mg 2.16%, Cu 2.05%, Zr

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0.12%, Fe 0.06%, Si 0.04% was manufactured by semi-continuous casting. The as-cast ingot with a lot of dendrites and coarse second phase (Fig. 1(a)) was homogenized at 470 °C for 24 h. Most of the coarse second phase re-solves in Al matrix, the dendritic segregation in as-cast ingot is effectively decreased and the mean grain size is about 80 μm after homogenization treatment (Fig. 1(b)).

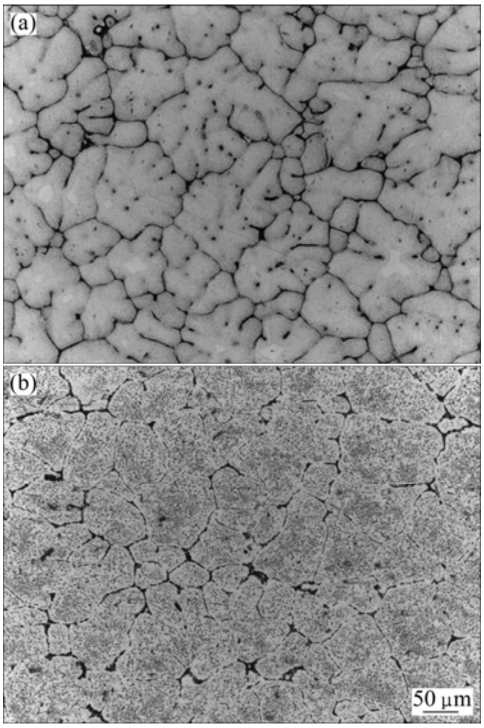

Fig. 1 Optical microstructures of as-cast (a) and as-homogenized (b) 7055 alloy

The samples (Fig. 2(a)) for multi-pass compression were machined from as-homogenized ingot. The flat ends of the sample were recessed to a depth of 0.2 mm to entrap the lubricant of graphite mixed with machine oil so that friction at the sample/die interface could be minimized during deformation. Seven-pass compression tests were carried out at a strain rate of 1 s^{-1} and deformation temperatures of 300, 350, 400 and 450 °C respectively using a computer servo-controlled Gleeble−1500 system. The interpass time was held constantly for 5 s, and the total strain was 1.6. The sample was resistance-heated to deformation temperature at a heating rate of 2 °C/s by thermocoupled feedback-controlled AC current and the temperature was held for 3 s before deformation. Solution treatment of compressed and air-cooled samples was as follows: firstly, samples were held at 475 °C for 1 h, and then the soluble samples were quenched in ambient temperature water. Samples were held at 120 °C for 24 h during artificial ageing treatment. Some samples in artificial ageing treatment condition were sectioned parallel to the compression axis and prepared by the conventional methods for the microstructure observation by means of OM and TEM. Samples for OM observations were corroded by 1% HF+16% HNO_3+ 83% H_2O (volume fraction)+3 g CrO_3 [9]. The samples (Fig. 2(b)) for tensile tests were machined from the sample heat-treated by T6. Tensile properties were determined on the average value of three samples by a Reger−3010 mechanical testing machine.

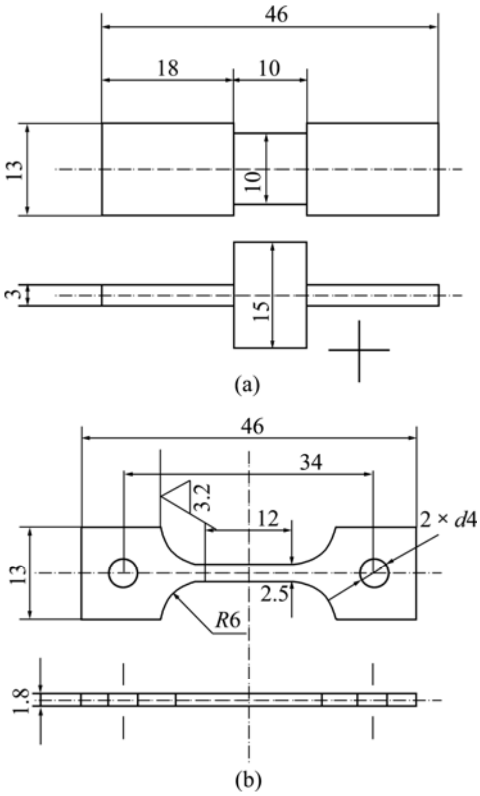

Fig. 2 Schematic diagrams of hot-compressed sample (a) and tensile sample (b) (unit: mm)

3 Result and discussion

3.1 Influence of deformation temperature on microstructure of compressed samples

Figure 3 shows the grains of samples compressed at 1 s^{-1} and different temperatures. As depicted, the grains of the billet compressed at each temperature become flat relative to the as-homogenized ones. The structure consists of elongated grains and fine grains which indicate that recrystallization occurs in evidence during multi-pass hot compassion. Furthermore, the average aspect ratio of the grains in the compressed specimens first decreases with the temperature increasing then increases. There are some recrystallized grains with the size ranging from 5 μm to 10 μm.

Due to the difficulty of distinguishing the microstructures of samples deformed at different temperatures through optical microscope, they were

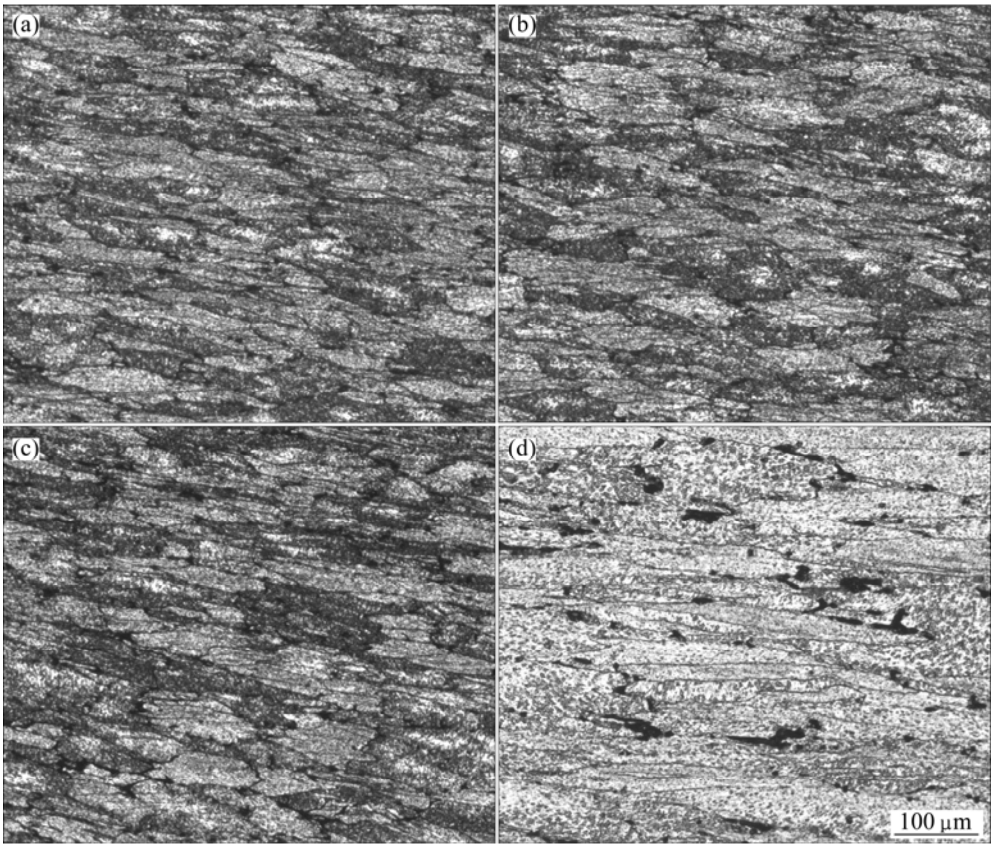

Fig. 3 OM microstructures of samples deformed at different temperatures: (a) 300 °C; (b) 350 °C; (c) 400 °C; (d) 450 °C

observed by a transmission electron microscope (TEM). The microstructures of the sample compressed at 1 s^{-1} and different deformation temperatures are shown in Fig. 4. At the deformation temperature of 300 °C, there is a lot of tangled dislocation and elongated subgrains with a high-dislocation-density and an average diameter of 0.8 μm (shown in Fig. 4 (a)). With the increase of the deformation temperature, the dislocation density decreases in the subgrain interior and boundary, and the subgrains begin to change from elongated shape to equiaxed shape (shown in Figs. 4(b) and (c)). When the deformation temperature is 450 °C, the equiaxed subgrains with a size of about 2 μm contain low-dislocation-density. The dislocation density is also very low, and subgrain boundary becomes plain (shown in Fig. 4(d)). Subgrain diameter increases with the increase of deformation temperature.

The microstructures of the samples compressed at different temperatures and then heat-treated under the same condition are shown in Fig. 5, displaying the elongation grains perpendicular to the compression direction. According to Refs. [9] and [10], the white area is recrystallization grains and the gray and the black areas include subgrains. The volume fraction of recrystallization grains in Fig. 5 was evaluated by an image processing software, and the result was shown by a "fall−rise" pattern in Fig. 6. It can be seen from Fig. 5 and Fig. 6 that the sample deformed at 300 °C and heat-treated by T6 has a lot of recrystallization grains and the volume fraction of recrystallization grains is about 67%. At the deformation temperature of 400 °C, the volume fraction of recrystallization grains is reduced to 45% and more subgrains are reserved. At the deformation temperature of 450 °C, the sample after heat treatment includes a little subgrains and the microstructure mainly includes large diameter recrystallization grains and equiaxed recrystallized grains.

From Figs. 5(a) and 5(b), it can be seen that a lot of recrystallization grains appear in the heat-treated samples. When 7000 serial aluminum alloy is deformed at a relatively low temperature, it partly recovers and a lot of subgrains form. The lower the deformation temperature is, the higher the deformation energy will be (in Fig. 4). Deformation energy is the driving force for static recrystallization during heat treatment [11−13]. Therefore, a lot of recrystallization grains form in the sample deformed at 300 °C and then heat-treated (shown in Fig. 5(a)). At a relatively high deformation temperature, the dynamic recovery degree increases, consuming a large amount of deformation energy. Some large size subgrains form, and maybe partly transform into recrystallization grains during of large size heat

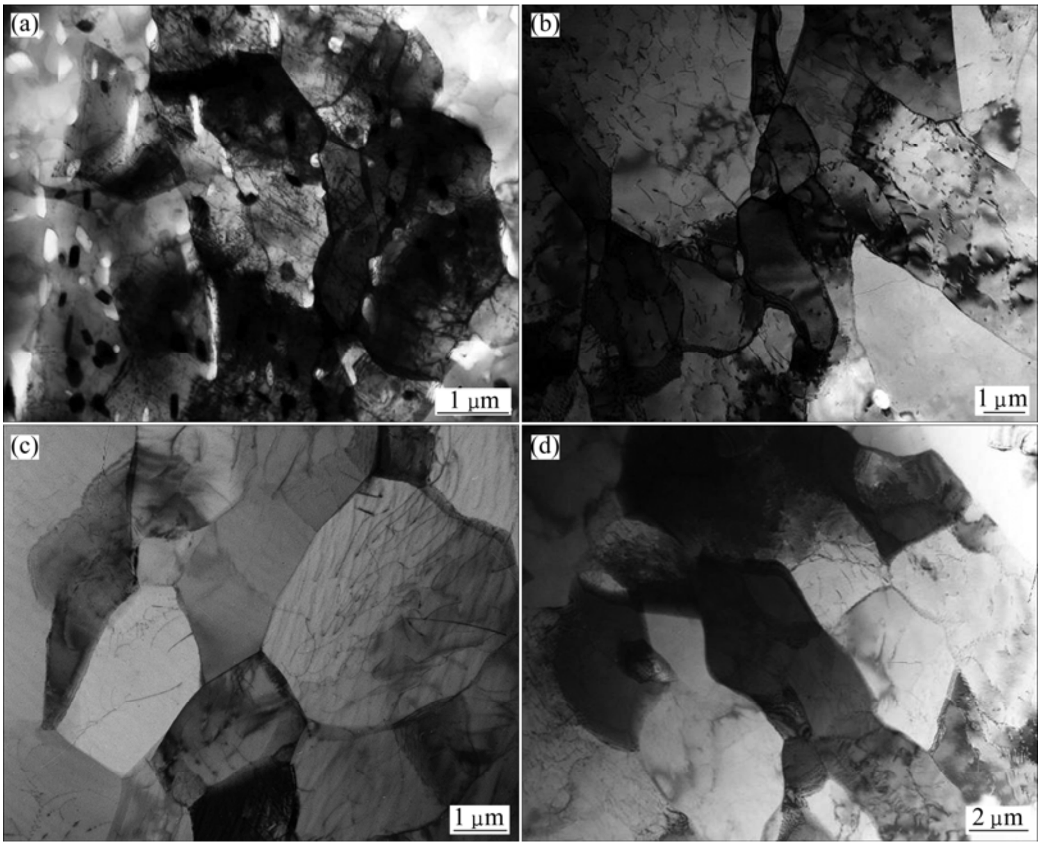

Fig. 4 TEM images of samples deformed at different temperatures: (a) 300 °C; (b) 350 °C; (c) 400 °C; (d) 450 °C

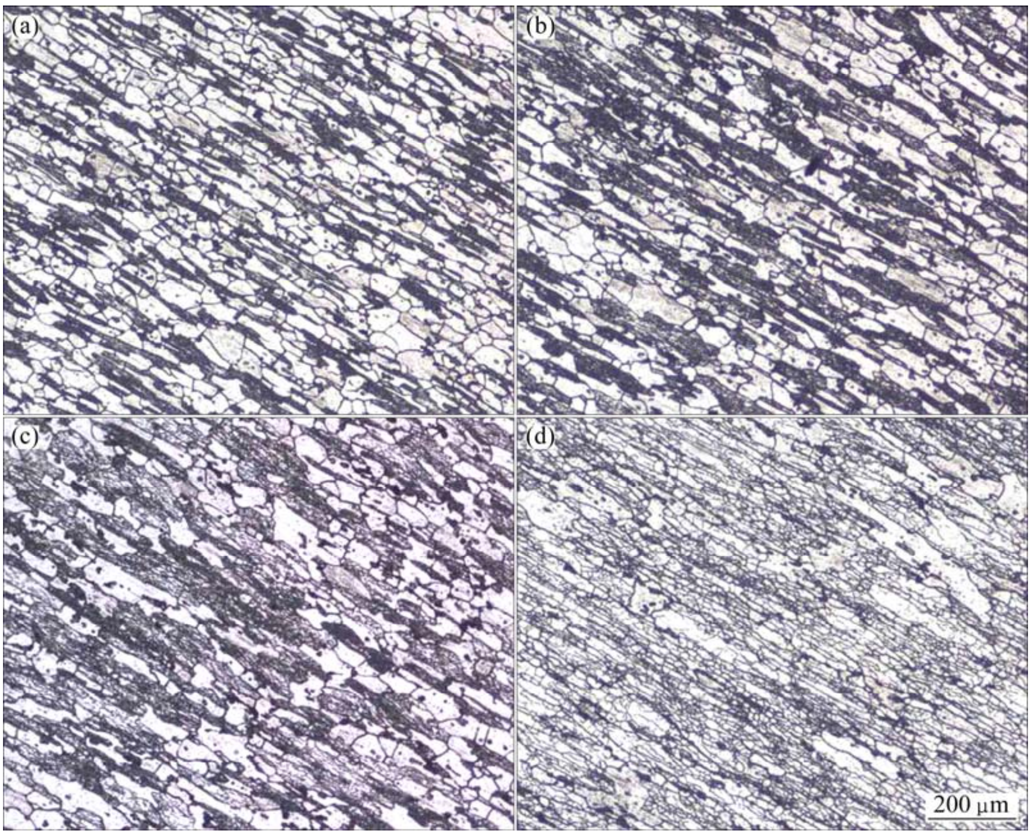

Fig. 5 OM images of 7055 alloy deformed at various temperatures and same heat-treatment condition: (a) 300 °C; (b) 350 °C; (c) 400 °C; (d) 450 °C

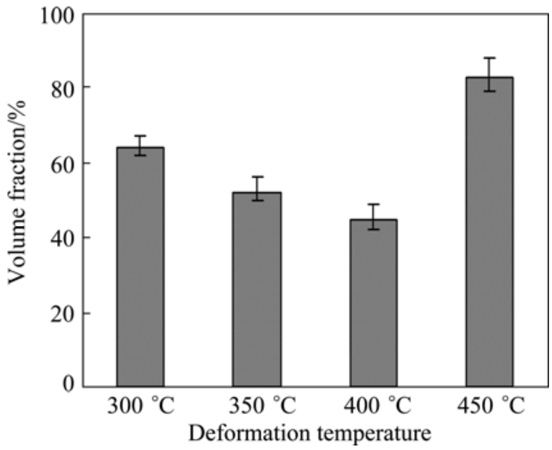

Fig. 6 Recrystallization volume fraction of heat-treated 7055 alloy

treatment. When the alloy is deformed at the temperature of 450 °C (Fig. 4(d)), some coarse subgrains grow up through mergence and torsion of subgrains, and then are transformed into recrystallized grains. Due to the relatively high deformation temperature, complex dynamic recovery and recrystallization take place, and static recovery and recrystallization continue after deformation, which leads to a number of recrystallized grains and new grain nucleus [14]. They grow up without incubation period during heat treatment. The final microstructure contains coarse recrystallization grains, small equiaxed recrystallization grains and deformation grains after heat treatment.

3.2 Influence of deformation temperature on mechanical properties

Heat-treatment process of the sample compressed at different temperatures is as follows: firstly, samples were held at 475 °C for 1 h, then the soluble samples were quenched in ambient temperature water and finally artificial ageing treatment processed at 120 °C for 24 h. Their mechanical properties are shown in Fig. 7. The ultimate tensile strengths of the samples compressed at 300 °C and 350 °C are 585 MPa and 570 MPa respectively. The sample compressed at 400 °C has the maximum ultimate tensile strength of 608 MPa. The sample compressed at 450 °C has the minimum ultimate tensile strength of 558 MPa.

When the alloy was compressed at 300 °C, due to the relatively low deformation temperature a lot of subgrains with tangled dislocation formed (shown in Fig. 3(a)). High deformation energy caused a multitude of small recrystallized grains to form during heat treatment. Meanwhile, high dislocation density accelerates the solute atom to diffuse and improve the solid solution, which provide the driving force for the new precipitation phase during ageing treatment [15]. In contrast, the ultimate tensile strength of the sample deformed at 300 °C is slightly higher than that of the sample deformed at 350 °C, due to the small recrystallized grains and a lot of second phase.

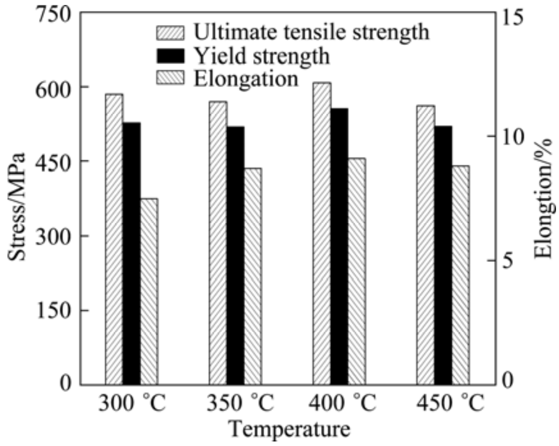

Fig. 7 Mechanical properties of 7055 alloy deformed at various temperatures after heat treatment

From Fig. 7, it can be seen that the ultimate tensile strengths of the samples deformed at the temperature from 350 °C to 450 °C are increased due to a lot of sub-microstructures. These sub-microstructures are beneficial to the solute atom diffusion and the second phase precipitation. When the samples are compressed at the same strain rate, the degree of dynamic recovery is increased with raising deformation temperature. The sample with a multitude of sub-microstructure has a relatively small fraction of recrystallized grains after heat treatment. The sample deformed at 400 °C has the lowest volume fraction of recrystallized grain, so it obtains the highest strength and a relatively high elongation. It is worth to note that these results are in good agreement with a number of previous investigations on Al−Zn−Mg−Cu alloy which have reported that the strength increases with the volume fraction of recrystallization grain decreasing [16].

At a relatively high deformation temperature (450 °C), a lot of recrystallization grains with a small diameter form due to the dynamic and static recrystallization. They grow up and form recrystallization grain with large diameter during heat treatment (shown in Fig. 5(d)). A lot of high angle boundaries lead a multitude of the coarse second phase to precipitate, which consumes a lot of solute atom and decreases the strength.

4 Conclusions

1) The average aspect ratio of the grains in the specimens compressed first decreases with the temperature increasing then increases, and recrystallization happens during compression.

2) The microstructure of samples subjected to multi-pass hot compression is dependent on the deformation temperature. The dislocation density decreases and the average subgrain diameter increases from 0.8 μm to 2 μm with increasing the deformation temperature.

3) The deformation temperature significantly influences microstructure and mechanical properties of the compressed and then heat-treated samples. The volume fraction of recrystallization grains presents a “fall−rise” pattern with increasing the deformation temperature, and reaches the minimum value, appropriately 45%, at deformation temperature of 400 °C. Moreover, the ultimate tensile strength and elongation have the maximum values at this temperature.

4) The volume fraction of sub-microstructure in the heat-treated sample influences the mechanical properties. Under the experimental condition, when the volume fraction of recrystallization grains is the minimum value, the strength obtains the maximum value.

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热变形温度对 7055 铝合金热处理组织和力学性能的影响

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摘 要：采用 Gleeble−1500D 热模拟试验机对 7055 铝合金进行多道次热压缩试验，并对热压缩试样进行 T6 热处理。采用 TEM、OM 观察热压缩试样与热处理试样的组织形貌，并对热处理 7055−T6 试样进行拉伸试验，研究变形温度对 7055 铝合金多道次热压缩后组织、热处理后的显微组织与力学性能的影响。结果表明：热变形温度不仅影响多道次热压缩后试样的组织，而且显著影响该合金热处理后的组织和力学性能。在本试验条件范围内，随着温度的升高，经多道次热压缩后试样的晶粒长宽比先减小然后增加，位错密度降低，亚晶尺寸增加，热压缩过程中发生再结晶；热处理后合金中再结晶晶粒体积分数先降低后增加。再结晶体积分数越小，合金的强度越高。当温度为 400 °C 时，再结晶体积分数最小，约为 45%，并且合金的抗拉强度和伸长率达到最大值。

关键词：7055 铝合金；变形温度；热压缩；再结晶

(Edited by Hua YANG)