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Effect of pre-deformation on microstructure and mechanical properties of 2219 aluminum alloy sheet by thermomechanical treatment

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Abstract: Thermomechanical treatment is usually used to achieve good mechanical properties and microstructure of metal materials. The effect of pre-deformation on the microstructure and mechanical properties of 2219 aluminum alloy sheet by TMT process was investigated. The studies show that the yield strength and tensile strength increase firstly and decrease with the increase of pre-deformation under a certain heat treatment condition and total deformation. The tensile strength of 2219 aluminum alloy sheet reaches the maximum value when the pre-deformation is about 2%. It is also found that the very fine Al_2Cu appears inside the grain, which is the precipitated phase for the strengthening of the 2219 aluminium alloy.

Key words: 2219 aluminum alloy; thermomechanical treatment (TMT); pre-deformation; precipitation strengthening; mechanical properties

1 Introduction

High performance aluminum alloy is widely used in the fields of aviation and aerospace to manufacture some main structures and key components of airplane or aircraft for its characteristics of low density and high strength. Generally, the high performance mechanical properties of this kind of aluminium alloy can be achieved by thermomechanical treatment (TMT) process, which includes three main procedures of solid solution-quenching, plastic deformation and aging [1]. TMT process can give the excellent performance of material by taking advantage of its deformation strengthening during plastic deformation and the transformation strengthening during heat treatment [2]. For example, TMT process can refine the precipitated phase significantly [3], and produce mesh substructure by the intertwined dislocation with precipitated phase, which can improve the mechanical properties of the 2014 aluminum alloy greatly [4]. Plastic deformation process may be useful in the effect of aging process, which is helpful to improve the mechanical properties of 2519A aluminium alloy and refine the precipitated phase of alloys notably [5,6].

The mechanism of TMT process has been revealed by some studies that the plastic deformation in the phase of heat transition can increase the lattice defects, which has an great effect on the kinetics of the precipitated phase transition [7,8]. The typical lattice defects include dislocation, vacancy, stacking fault, small angle grain boundary, and high angle grain boundary, etc. So, as the results, plastic deformation can form greater area of dislocation networks, make the grain boundary distribution more uniform, and achieve best microstructure and properties of aluminum alloy. What's more, some studies also show that the pre-deformation before heat treatment is crucial for TMT process [9−14]. However, there are few study results available concerning the effect of the pre-deformation degree and the strengthening rule of pre-deformation on the phase transition and microstructure.

Therefore, the effect of pre-deformation on microstructure and mechanical properties of 2219 aluminum alloy sheet in TMT process was investigated in this work. The flat rectangular blank was stretched at

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different degrees of pre-deformation with a specially designed setup and the tested specimens were cut off from the pre-deformed blank and the strain of the tested specimens was measured by grid analysis method. Then, the mechanical properties of the test specimen were determined by using uniaxial tensile test. The fracture morphology was observed with scanning electron microscope (SEM), and substructure was analyzed with transmission electron microscope (TEM).

2 Experimental

2.1 Material

The material used in this experiment is 2219 aluminum alloy sheet under annealed condition with 6.5 mm in thickness. The main chemical constituent is listed in Table 1.

Table 1 Chemical composition of 2219 Al alloy sheet (mass fraction, %)

Cu	Mn	Si	Fe	Mg
5.80−6.80	0.20−0.40	0.20−0.40	0.30	0.02
Zn	Zr	Ti	V	Impurities
0.10	0.10−0.25	0.02−0.10	0.05−0.25	≤0.05

2.2 TMT process with pre-deformation

Figure 1 shows the main procedures of pre-deformation TMT process. A pre-deformation procedure was added before the heat treatment of traditional TMT process. The degree of pre-deformation was controlled from 0 to 12% and the total deformation of the whole process was kept at 12% in order to investigate the effect of deformation on mechanical properties. Furthermore, the same heat treatment condition was followed during each test, as listed in Table 2. The interval time between solution and artificial aging did not exceed 60 min.

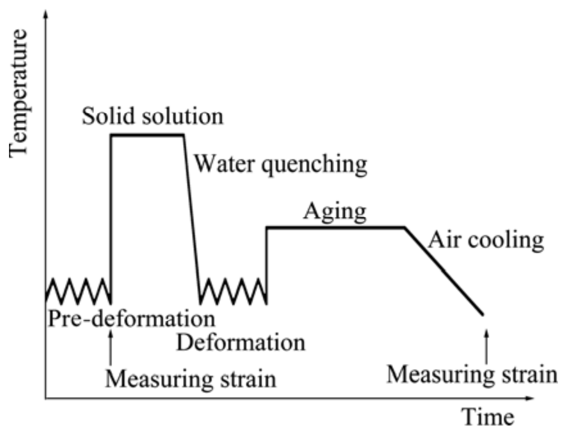

Fig. 1 Schematic diagram of TMT process with pre-deformation

Table 2 Parameters of TMT process of 2219 aluminum alloy

Process	Temperature	Time
Solution	535 °C	55 min
Quenching	Room temperature, Water quenching	Less than 10 s
Aging	175 °C	18 h

2.3 Deformation method

In order to study the pre-deformation (P_d) before heat treatment and the total deformation (T_d) of TMT process, a special experimental setup was developed to produce uniaxial tensile test specimens with different plastic deformations, as shown in Fig. 2. To begin with, the blank was held closely by the upper and lower blank holders without any material flow-in. Then, the blank was stretched by the drawing of a cylindrical surface punch. By this method, the value and distribution of plastic deformation on blank can be controlled by the drawing height and the shape of the punch.

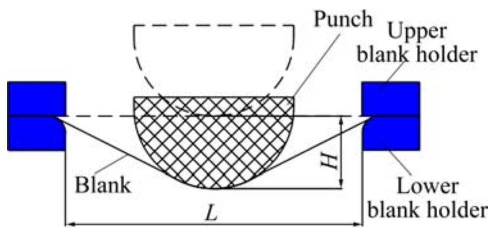

Fig. 2 Diagram of deformation experimental setup

In this work, a rectangular blank with length of 360 mm and width of 160 mm was used in the experiments, and the circular grid with 5 mm in diameter was printed on both sides of the blank by electric corrosion method, then after the TMT process the test specimens for uniaxial tensile test were cut off from the deformed blank, as shown in Fig. 3.

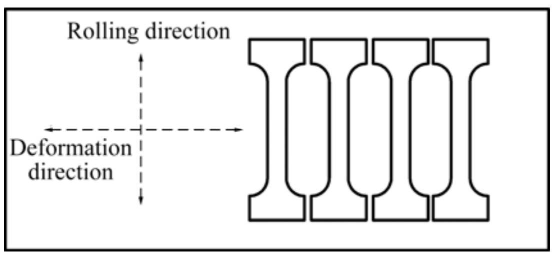

Fig. 3 Diagram of test specimen after pre-deformation

2.4 Test methods

Grid strain test was carried out to measure and analyze the deformation of test specimen after pre-deformation and artificial aging, respectively. The photos of the deformed grids were captured by a digital camera and distinguished through the ASAME software. The final strain results were output by ASAME software.

Uniaxial tensile test was carried out to determine the mechanical properties of tested specimen after TMT process. Tensile specimen was cut along the rolling direction, as shown in Fig. 3, which is perpendicular to the deformation direction. The specimen geometry was designed according to the standard GB/T 228—2002. Instron-1186 electronic universal testing machine was used for tensile test with drawing speed of 5 mm/min.

Finally, fracture morphology was observed with scanning electron microscope, and substructure was analyzed with transmission electron microscope.

3 Results

3.1 Mechanical properties

The results of mechanical properties by uniaxial tensile test are given in Table 3.

Table 3 Mechanical properties of tensile tested samples

Pre-deformation, P_d/%	Total deformation, T_d/%	Yield strength/MPa	Tensile strength/MPa	Elongation/%
0.69	11.27	269.75	365.72	19.83
1.63	11.67	288.62	387.96	16.83
3.31	11.98	267.09	353.83	15.90
6.63	11.48	260.81	355.57	15.90
9.12	11.45	256.33	357.34	15.22

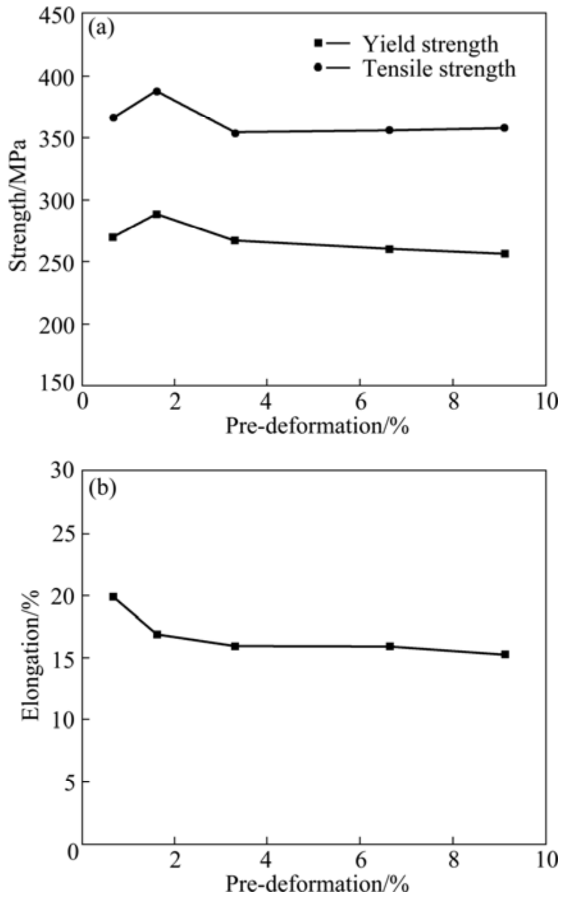

Fig. 4 Effect of pre-deformation on mechanical properties: (a) Strength; (b) Elongation

Figure 4 shows the effect of pre-deformation on the final mechanical properties of test specimen after TMT process in the case of equal total deformation for 2219 aluminum alloy blank. The tensile strength and yield strength increase firstly and then decrease with the increase of pre-deformation. The tensile strength and yield strength increase significantly when the pre-deformation is lower than 2%. The maximum tensile strength is 387.96 MPa, and yield strength is 288.62 MPa, when the pre-deformation degree is 1.63%. The elongation decreases obviously and then changes very little when the pre-deformation exceeds 2%, and the minimum elongation is about 16%.

3.2 Tensile fracture morphology

Figure 5 shows the SEM images of tensile fracture morphology of 2219 aluminum alloy after TMT process. It can be seen that fracture surfaces were full of dimples in different deformation conditions. The fracture mechanism is the fracture mode by congregation of micro-cavity. It is easy to find that a little pre-deformation can make the tensile fracture morphology change obviously when the total deformation is about 6.5%, as shown in Fig. 5(a) and Fig. 5(b). In comparison, the size of dimple shown in Fig. 5(b) is smaller than that in Fig. 5(a), the depth of dimple is much shallower and its distribution is more uniform. When the total deformation is about 11.5%, the similar observation is found from Fig. 5(c) and Fig. 5(d). The reason is that smaller second-phase particles are brought by pre-deformation during TMT process.

3.3 Microstructure

Figure 6 shows the TEM images of the grains for test specimen after TMT process. Figure 6(a) shows a TEM image of sheet inside the grains when the pre-deformation is 0 and total deformation is 9.76%. Figure 6(b) shows a TEM image of sheet inside the grains when the pre-deformation is 1.13% and total deformation is 9.41%. It can be found that there are many orthogonal flaky precipitated phases inside the grains for the 2219 aluminum alloy after TMT which mainly act as the obstacles for deforming easily. These dense precipitated phases growing orthogonally in the α-matrix make the dislocation motion become difficult, which leads to further deformation conducting hardly. The direct result is that sheet gets to be strengthened. Through observing the density of precipitated phases in two TEM images, it can be seen that the precipitated

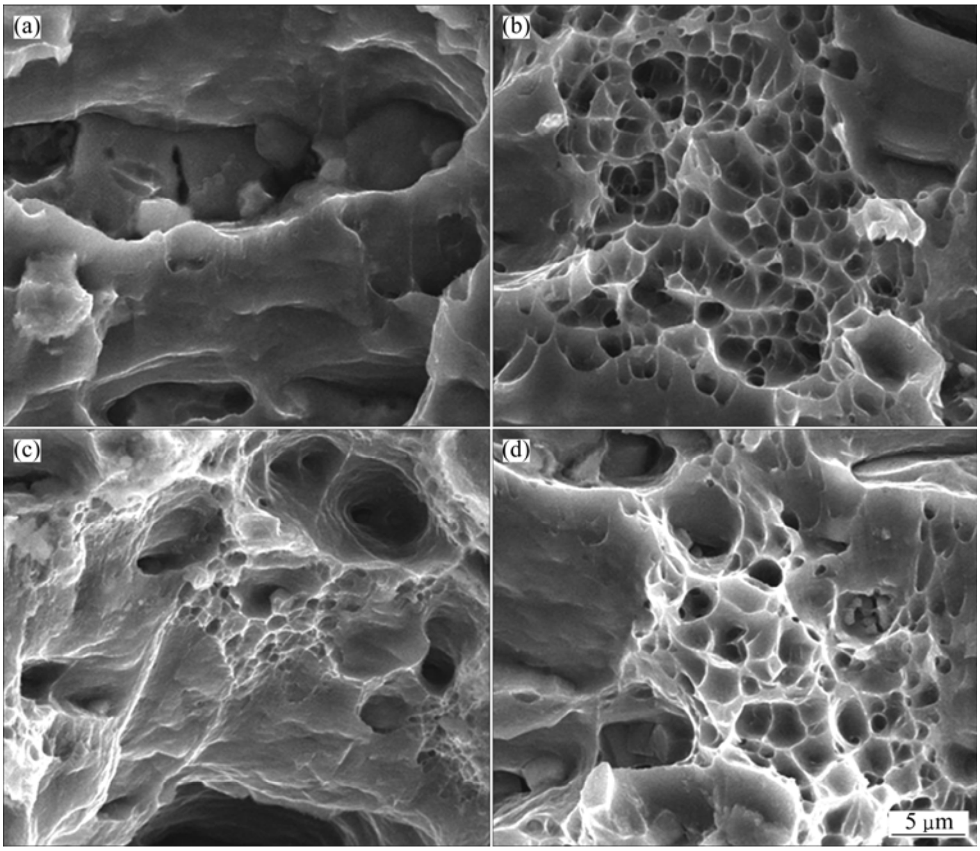

Fig. 5 Tensile fracture morphologies in different conditions: (a) P_d=0, T_d=6.76%; (b) P_d=1.3%, T_d=6.26%; (c) P_d=1%, T_d=11.12%; (d) P_d=1.63%, T_d=11.67%

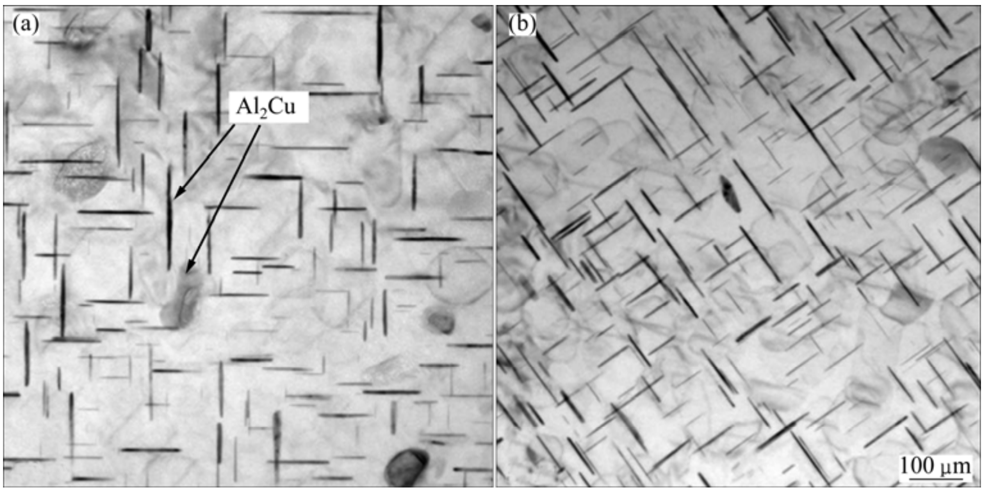

Fig. 6 TEM images of grains: (a) P_d=0, T_d=9.76%; (b) P_d=1.13%, T_d=9.41%

phase becomes dense. The results reflect that the pre-deformation promotes the precipitated phase to precipitate after the TMT process, so it has a better strengthening effect.

The reason for the pre-deformation promoting the precipitated phase to precipitate after the TMT process is that extensive dislocation inside the sheet is produced during pre-deformation process before solution, which leads to the density of vacancy increasing. The increasing density of vacancy makes activation energy of the precipitated phase formation decrease, which leads to the solute atoms spreading easier, and the θ' nucleation sites increasing, so that the substructure in the crystal becomes refined.

Figure 7(a) shows the TEM image at the grain boundary when the pre-deformation is 0 and the total deformation is 9.76%. Figure 7(b) shows the TEM image at the grain boundary when the pre-deformation is 1.13% and the total deformation is 9.41%. A new different granular precipitated phase can be found at the grain boundary of 2219 aluminum alloy sheet after TMT process, the size is bigger and quantity is less compared with precipitated phase inside grain. The diffraction pattern illustrates that the strength phase is Al_2Cu. From the two TEM images, it can be known that the quantity of precipitated phase at the grain boundaries is greater, whose grain boundaries are effective to impede the dislocation to move. Generally, the relationship is positively proportional between the quantity of precipitation phase at grain boundary and the ability to impede dislocation motion. That's why the strength is higher, which is in line with the mechanical properties. Therefore, pre-deformation makes 2219 aluminum alloy strengthened during TMT.

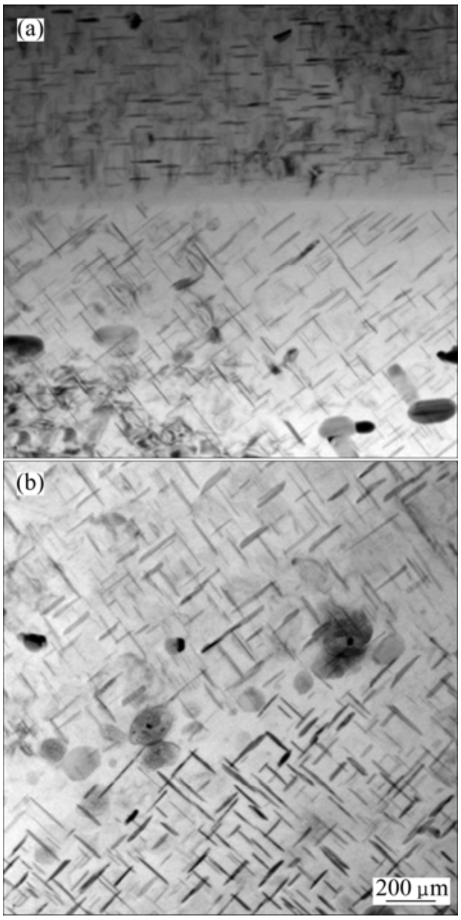

Fig. 7 TEM images at grain boundaries: (a) P_d=0, T_d=9.76%; (b) P_d=1.13%, T_d=9.41%

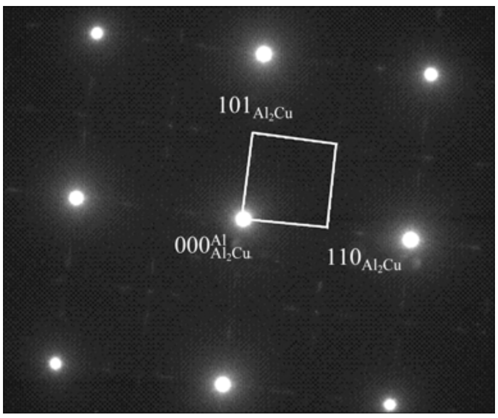

Fig. 8 Diffraction patterns of θ' phase

In addition, it can be found from two TEM images that clear free zones of the precipitation occur when the pre-deformation is 0 and the total deformation is 9.76%. However, precipitation free zones shown in Fig. 7(b) are thinner or not obvious. Generally, the reason for the appearance of precipitation free zones is that the supersaturated vacancy by water quenching is easy to slide into the grain boundary, so that solute concentration is very low at the grain boundary, which is bad for the precipitation of the phase, and then precipitation free zones appear. WAGN et al [15] pointed out that the solute atoms dissolve faster at the grain boundaries, and dissolution phase absorbs solute atoms at the grain boundaries, which produces the precipitate-free zones at the grain boundaries. In the precipitate-free zones, the more the quantity of precipitation phase on the grain boundaries, the fewer the degree of transgranular fracture and the worse the plasticity of the alloy. This conclusion is consistent with the mechanical property testing that pre-deformation makes plasticity of 2219 aluminum become poor.

4 Conclusions

1) The strength of test specimen increases firstly and then decreases with the increase of pre-deformation, when the total deformation is kept at about 12%. The maximum tensile strength and yield strength are obtained when the pre-deformation is about 2%.

2) The strength phase is Al_2Cu which precipitates inside the grains, and grows orthogonally and distributes dispersively.

3) Pre-deformation can make the distribution of precipitated phase more dispersive. The reason is that the pre-deformation can promote more nucleation sites in solution, and more second phases precipitate in aging. Therefore, motion of dislocation is pinned and the strength of the sheet increases.

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2219 铝合金板材形变热处理中预变形对微观组织和力学性能的影响

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摘 要：形变热处理(TMT)是一种能够使金属材料获得最终优良性能和微观结构的工艺方法。研究 2219 铝合金板材在两次形变热处理工艺中预变形量对其力学性能及组织的影响。研究表明，经过两次形变热处理的铝合金板材的屈服强度和抗拉强度随着第一次变形的变形量先增大后减小；第一次变形量为 2%左右时，强度达到最高值。通过微观组织观察，发现经过形变热处理的 2219 铝合金板材内部有 Al_2Cu 相析出，在经过第一次变形量为 2%的两次形变热处理时，板材中的析出相最细密，因此，2219 铝合金得以强化。

关键词：2219 铝合金；形变热处理(TMT)；预变形；析出强化；力学性能

(Edited by YANG Bing)