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Influence of sequence of cold working and aging treatment on mechanical behaviour of 6061 aluminum alloy

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Abstract: The influence of combination of different designated precipitation hardening and cold working on the tensile properties of 6061 aluminum alloy was investigated. The results indicate that applying single aging at 180 °C for 4 h in different thermal-mechanical treatments improves both the strength and elongation. However, double aging does not improve the mechanical properties. In addition, pre-aging shows a negative effect on the subsequent precipitation hardening of material. The changes in mechanical properties were discussed by explanation of microstructural evolution due to the competition of precipitation hardening, strain hardening and work softening processes.
Key words: 6061 aluminum alloy; age hardening; hardening; mechanical properties

1 Introduction

Aluminum alloys are widely used for high-strength and light mass structures in aerospace and automotive applications. Aluminum−magnesium−silicon (Al−Mg−Si) denoted as 6xxx series alloys are medium strength heat treatable alloys and have good formability [1].

Work hardening and precipitation hardening are common strengthening mechanisms of 6xxx series of aluminum alloys [2]. When cold working is combined with age treatment, two main microstructural processes are competing with each other. Work softening due to dislocation annihilation during age treatment improves ductility and decreases strength of alloy. On the other hand, work hardening as a result of increase of dislocation density over cold working and dislocation pinning by precipitates formed during age treatment increases strength of material and reduces its elongation.

The microstructural evolution and the effect of various designated heat treatments on mechanical behavior of Al−Mg−Si alloys have been investigated [3−12]. In some previous studies [13−15], the process-model approaches have been used to predict the mechanical properties of 6xxx series alloys as well. RISANTI et al [3] used interrupted aging to investigate the strength and toughness of extrusion grade AA6061. They compared the experimental results with those by conventional T6 treatment. The tensile properties of AA6061 subjected to various degrees of precipitation hardening were examined by OZTURK et al [4]. DEMIR and GUNDUZ [5] investigated the impact of artificial aging on the machinability of AA6061 in as-received, solution heat treated and aged conditions. KIM et al [6] investigated the mechanical and tribological properties of rheo-formed wrought AA6061 alloy. The influences of interrupted age treatments on precipitation process, microstructural development and mechanical properties of 6061 alloy were studied by BUHA et al [7]. They focused on secondary precipitation using transmission electron microscopy (TEM) and differential scanning calorimetry (DSC). CHANG et al [8] showed that natural pre-aging has a positive effect on artificial aged Al−Mg−Si alloys. They explained that natural aging increases the volume fraction of fine precipitates and significantly improves the mechanical properties. The positive effect of pre-aging at 170 °C for 5 min on Vickers hardness, mechanical property and formability of 6000 series of aluminum alloy was illustrated by LIU et al [9]. However, some authors indicated the negative result of pre-natural aging on peak hardness of material subjected to artificial aging [10−12]. SONG [13]

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developed a strengthening model to relate microstructure features of Al−Mg−Si alloys during aging treatment with yield strength and hardness. WEAKLEY-BOLLIN et al [14] employed the precipitation strengthening micromechanical base model to predict yield strength of W319 aluminum alloy as a function of aging time and temperature. A modified model was utilized by LIU et al [15] to present quantitative relationships between the yield strength of the alloy and the size, volume fraction of precipitates. There is a lack of comprehensive investigations on the relationship between changes in mechanical properties and microstructure evolution of Al−Mg−Si alloys when cold rolling is combined with precipitation hardening. In this work, the influence of sequence of various degrees of age hardening and different amounts of cold working (CW) on the mechanical properties of AA6061 was studied. This could help to make decision that applying precipitation hardening, whether before shaping the material or as a final treatment of manufacturing, is more convenient.

2 Experimental

AA6061 is one of the most widely used 6xxx aluminum alloys [2]. This material can be heat treated to produce precipitation to various degrees [7]. Mg and Si are the major solutes in this series of aluminum alloys; they increase the strength of the alloy by precipitation hardening. In the present study, AA6061-O sheets with 5 mm in thickness were used. The chemical composition of the materials was determined by spectrometry which is listed in Table 1.

Table 1 Chemical composition of AA 6061 alloy (mass fraction, %)

Mg	Si	Cu	Fe	Mn	Cr	Zn	Ti	Al
0.90	0.41	0.16	0.26	0.07	0.04	0.01	0.01	Bal.

In order to study the influence of various sequences of cold working and age hardening on mechanical properties of AA6061, different series of thermal-mechanical treatments were utilized as illustrated in Fig. 1. In this experimental set up, pre-aging, single and double aging, amount and multiple of reduction in area and order of heat treatment and cold working were the important features of investigation.

Some strips were cut from AA6061-O sheets along rolling direction. All samples were solutionized at 520 °C for 1 h and then quenched immediately in water. Solution treatments of samples of series IV and V were carried out after cold rolling, as shown in Figs. 1(d) and 1(e). Cold working (CW) was conducted by a laboratory rolling mill to the reduction of 20%, 40% and 60% in area. A resistance furnace with atmospheric environment was utilized for heat treatment. Precipitation hardening was performed at 180 °C for 0.5 h (denoted by pre-aging) and 4 h (indicated by final aging). In order to study the influence of microstructural changes during pre-aging on subsequent behavior of material, samples of series II, III and IV were pre-aged at 180 °C for 0.5 h and after cold rolling, finally aged at 180 °C for 4 h. The objective of these treatments was to age the material partially to increase its resistance to thinning without considerable reduction in ductility.

Tensile test specimens were cut from the thermal-mechanically treated strips. The long axis of the test specimen was parallel to the rolling direction (RD). Tensile test specimens were then prepared according to ASTM E-8 sub-size specifications [16]. The gauge length and gauge width of the tensile test specimens were 50 mm and 12.5 mm, respectively. Tensile tests were performed with a crosshead speed of 5 mm/min. Stress—strain curves were then analyzed; next, yield, ultimate tensile strengths and elongation of samples were compared. Meanwhile, micro-hardness of samples was measured using a Vickers hardness indenter under 9.8 N load. The hardness values reported here represent the average of at least three measurements.

3 Results and discussion

The influence of cold working on tensile properties and hardness of series I of samples is shown in Fig. 2. As Figs. 2(a)−(c) illustrated, by increasing the amount of reduction in area, the yield and ultimate strengths and hardness of materials come up. Indeed, dislocation density in the structure of material increases during cold working, which results in rise of yield strength and ultimate tensile strength. It can also be seen that aging at 180 °C for 4 h leads to higher increase in strength and hardness. While the cold rolled strips are subjected to age treatment, further strengthening could occur, which increases the strength and hardness of the material. Meanwhile, heavy strain provides more nucleation sites for precipitation and gives rise in the strength and hardness. First series of samples' elongation is displayed in Fig. 2(d). Increase of amount of reduction in area decreases elongation due to increase in dislocation density, which makes difficulty for flow of material. This figure also indicates that age treatment of cold worked samples improves the ductility of alloy. In fact, heat treatment of material at 180 °C for 4 h could result in dislocation annihilation so strain hardening effect decreases. On the other hand, improvement in elongation as a result of work softening is more than its decline through dislocation pinning by precipitates. When the amount of reduction in area increases, the nucleation sites for precipitation increase and precipitates lock

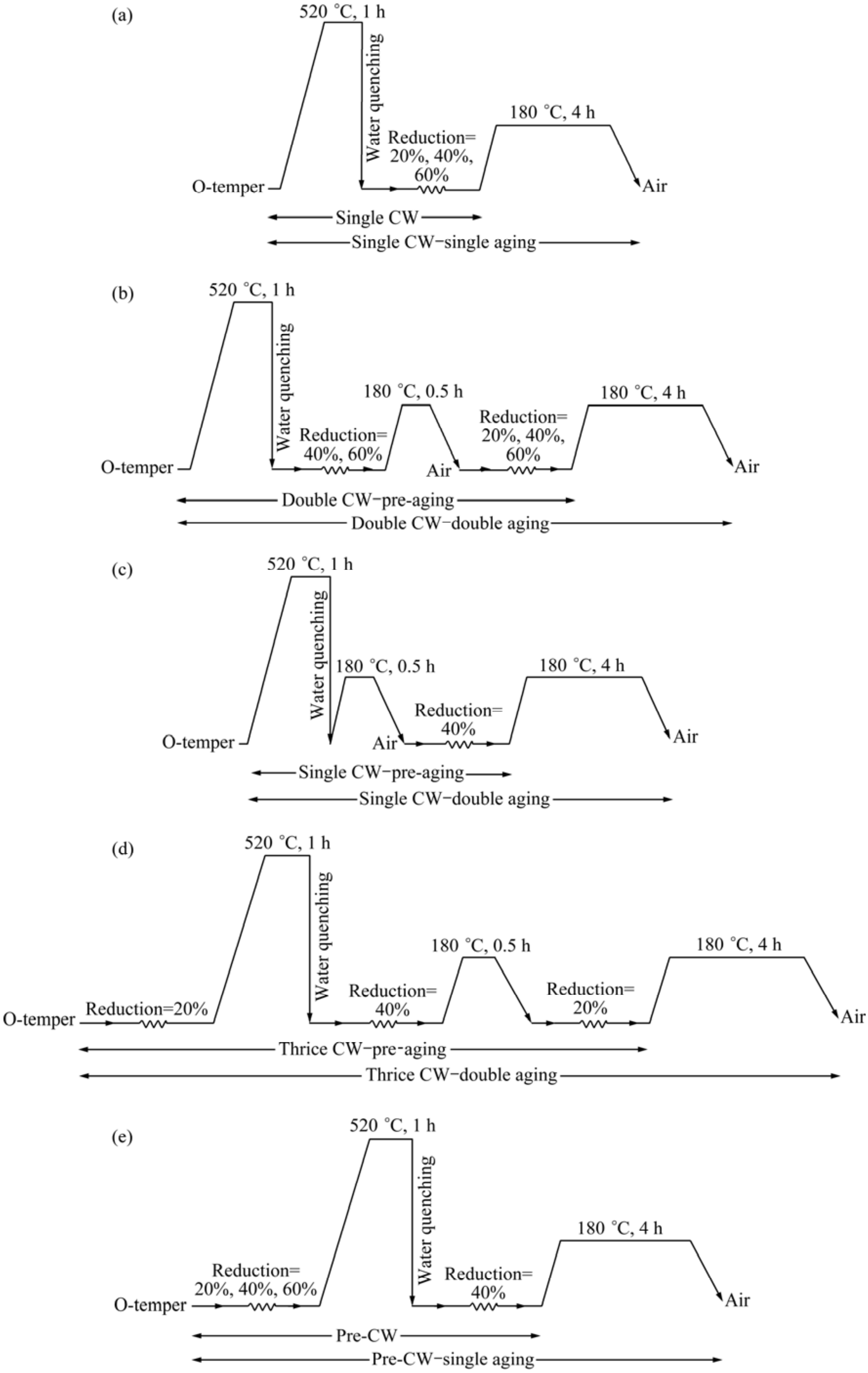

Fig. 1 Different series of thermal-mechanical treatments: (a) I; (b) II; (c) III; (d) IV; (e) V

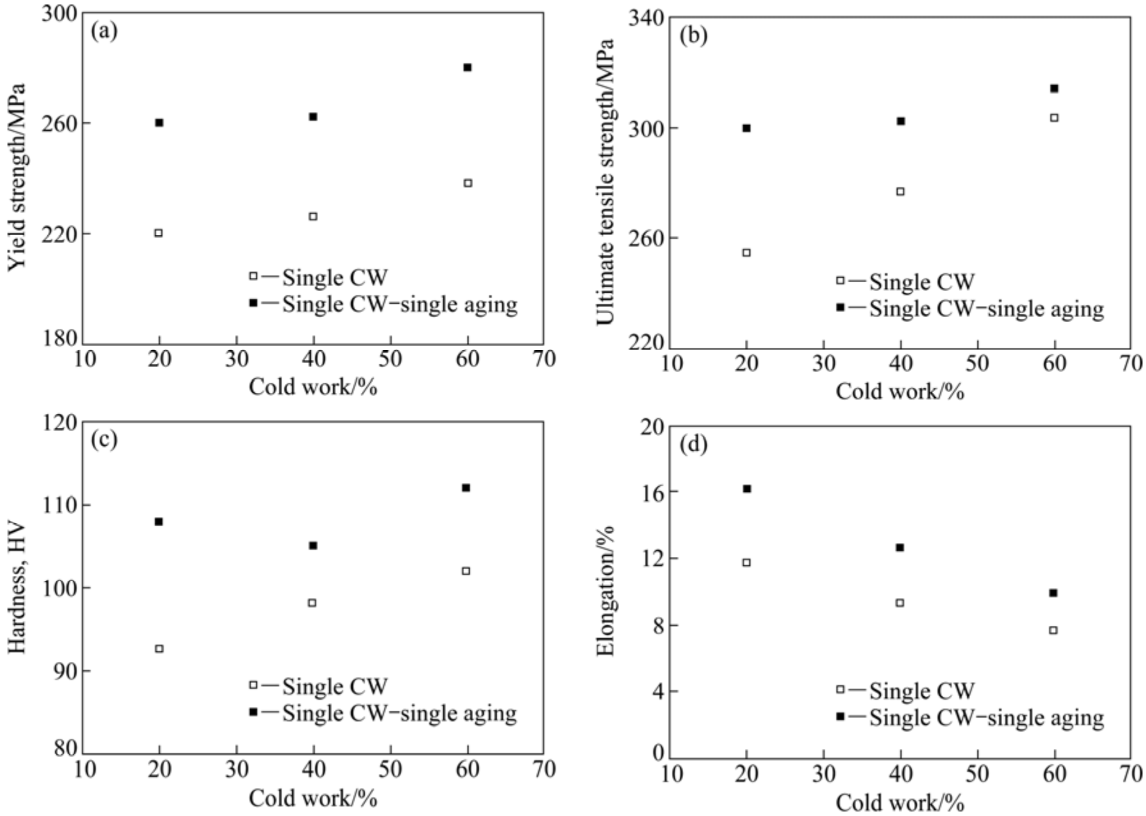

Fig. 2 Mechanical properties of sample of series I after thermal-mechanical treatment (I): (a) Yield strength; (b) Ultimate tensile strength; (c) Hardness; (d) Elongation

dislocations and cause to difficulty of gliding dislocations. Therefore, the less change in elongation of “Single CW” and “Single CW−single aging” samples appears.

Figures 3 and 4 demonstrate the mechanical behavior of series II of thermal-mechanical treated samples. In these processes, the material was initially cold rolled to 40% and 60% reduction in area respectively and pre-aged at 180 °C for 0.5 h. Next, they experienced 20%, 40% and 60% cold working and some of them were finally aged at 180 °C for 4 h. The results in these figures point out that the strength and hardness increase and the elongation decreases with the increase of reduction in area due to the strain hardening of material. However, for the samples subjected to double aging, the changes in mechanical properties are insignificant when the reduction in area increases from 40% to 60%. This is because of the heat treatment of material at 180 °C for 4 h, which softens the microstructure and slows down the strain hardening effect. Meanwhile, comparing “Double CW−pre-aging” with “Double CW−double aging” treated samples shows that precipitation hardening not only does not have positive effect on the material strengthening, but also leads to the decrease of yield and ultimate strengths and hardness in some cases (especially in strips initially cold rolled to 60% reduction in area). In other words, in cases of 20% and 40% reductions in area, the strength and hardness of the aged samples remain almost constant but they decrease by the increase of cold working to 60%. It seems to show that pre-aging has a negative influence on the subsequent material precipitation hardening, which has also been mentioned by other researchers [10,11]. It has stated that the negative response is due to the fact that pre-aging depletes matrix from solute atoms and decreases the nucleation sites for subsequent precipitation process [11]. In fact, while GP zones and β'' precipitates formed during pre-age treatment, there are no sufficient Mg and Si solutes in the matrix. Therefore, the most suitable microstructure from point of super-saturated solid solution is not provided for next precipitation hardening. Furthermore, some precipitates existing within the microstructure of pre-aged samples could grow during the following age treatment and lose their proficiency. Consequently, final aging may not have remarkable impact on the mechanical properties. In addition, the increase in strength due to light precipitation hardening is less than the decrease in strength as a result of restoration process. Therefore, the strength and hardness practically remain constant or decline when the “Double CW−pre-aging” treated samples are subjected to final aging.

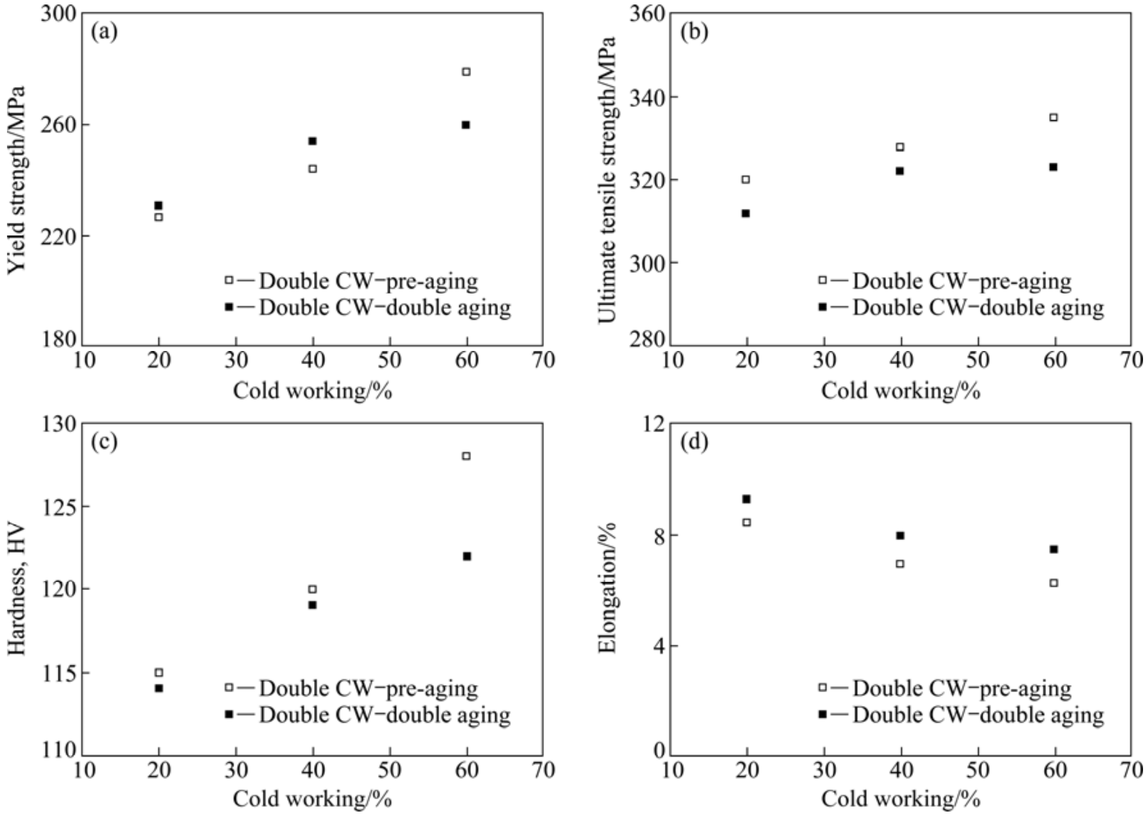

Fig. 3 Mechanical behaviour of "Double CW−pre-aging" and "Double CW−double aging" treated samples (the amount of initial cold working was 40%): (a) Yield strength; (b) Ultimate tensile strength; (c) Hardness; (d) Elongation

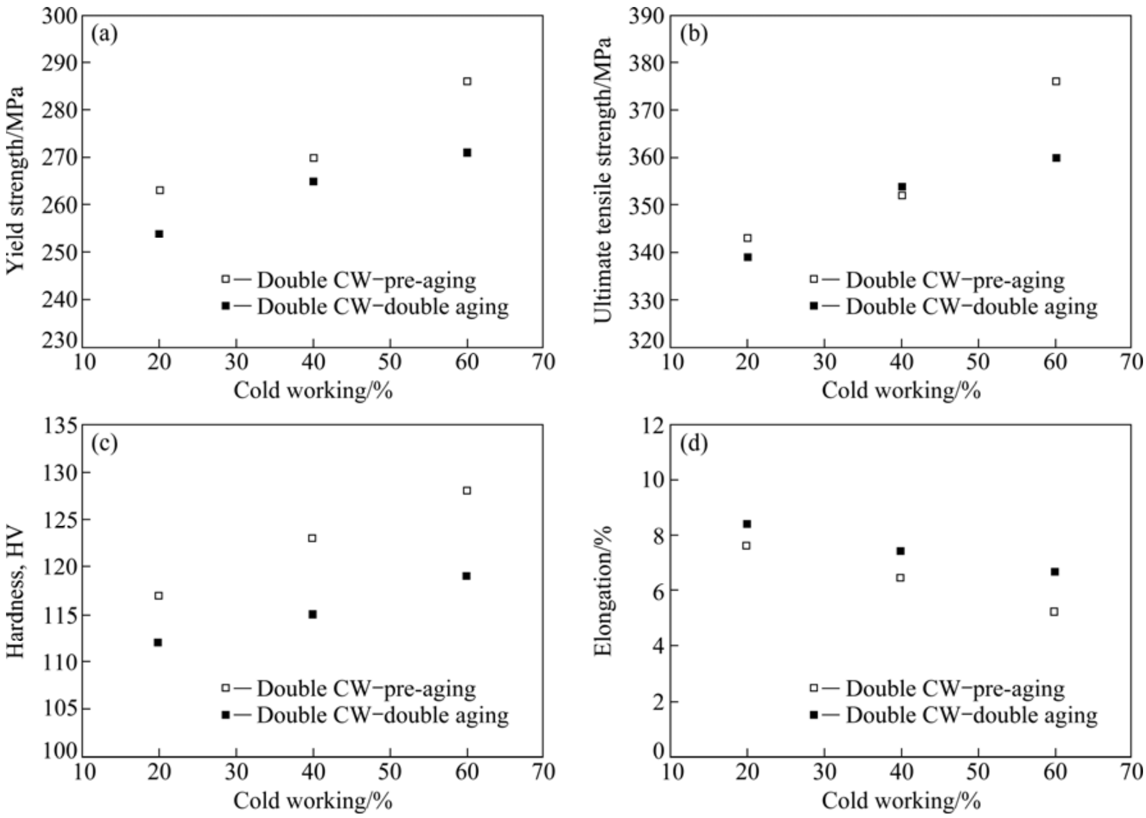

Fig. 4 Mechanical behaviour of "Double CW−pre-aging" and "Double CW−double aging" treated samples (the amount of initial cold working was 60%): (a) Yield strength; (b) Ultimate tensile strength; (c) Hardness; (d) Elongation

Concerning the ductility of material, it is obvious in Figs. 3(d) and Fig. 4(d) that when the reduction in area increases, the elongation decreases. Meanwhile, the precipitation hardening at 180 °C for 4 h gives rise to ductility which is related to the dislocation annihilation occurring over final aging. In fact, the reduction in elongation due to the precipitation hardening is less than the increase of ductility as a result of microstructure softening during age treatment.

Two other thermal-mechanical cycles were investigated in order to examine the positive or negative effect of pre-aging on the mechanical behavior of material. The mechanical properties of samples are respectively listed in Tables 2 and 3. It can be seen that final aging has almost no influence on the material strength and hardness as discussed before for the second series treatment. However, the ductility of materials improves when they are subjected to double aging. Nevertheless, a positive effect of natural pre-aging on the mechanical behavior of the artificial aged Al−Mg−Si alloy was reported by CHANG et al [8]. The results presented in Fig. 3, Fig. 4, Table 1 and Table 2 indicate that conducting final aging on the pre-aged and cold rolled samples only makes elongation better, although the strength remains constant or might decrease. It seems to show that the negative or positive effect of pre-aging mainly depends on the mole ratio of Mg to Si, the amount of cold working and the history of thermal-mechanical treatment conducted on the material.

Figure 5 shows how the initial cold working (before solutionizing) influences the mechanical properties of the thermal-mechanical treated samples (Series V). It can be seen that for both series of “Pre-CW” and “Pre-CW−single aging” treated samples by increasing

Table 2 Mechanical properties of thermal-mechanically treated samples (III)

Thermal-mechanical treatment (III)	Yield strength/MPa	Ultimate tensile strength/MPa	Elongation/%	Hardness, HV
Single CW−pre-aging	200	299	9	111
Single CW−double aging	203	301	12	113

Table 3 Mechanical properties of thermal-mechanically treated samples (IV)

Thermal-mechanical treatment (IV)	Yield strength/MPa	Ultimate tensile strength/MPa	Elongation/%	Hardness, HV
Three times CW−pre-aging	261	323	8	119
Three times CW−double aging	260	327	10	121

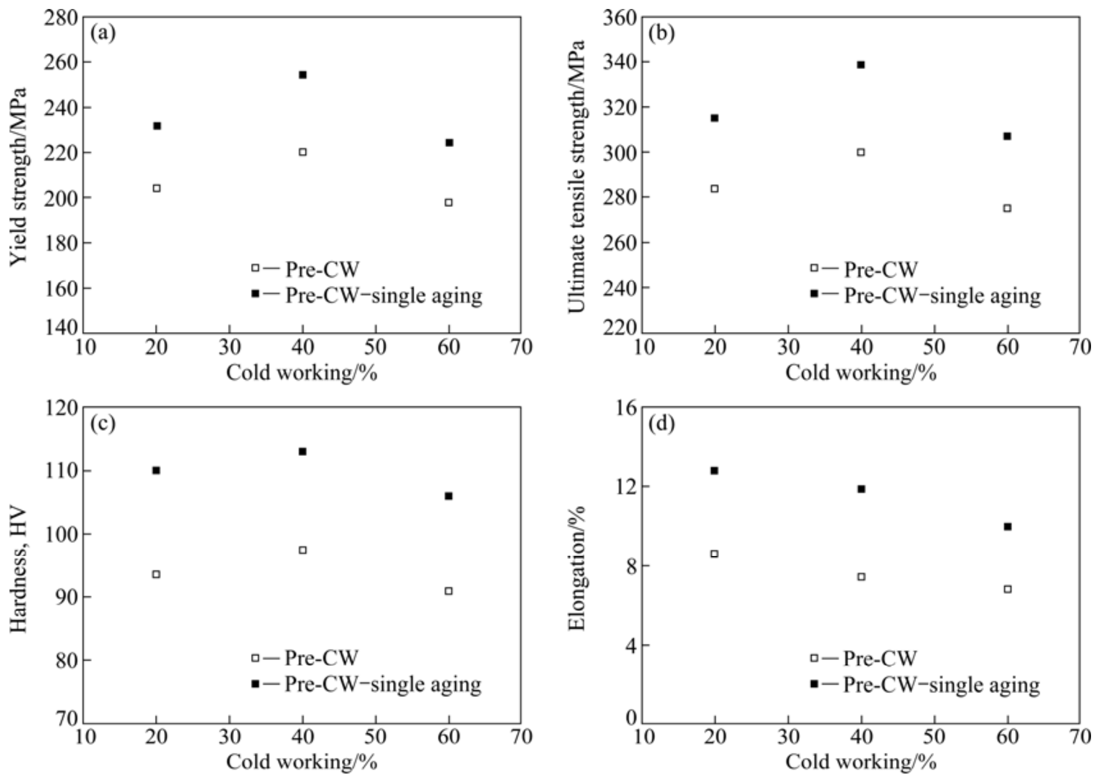

Fig. 5 Mechanical properties of samples after thermal-mechanical treatment (series V): (a) Yield strength; (b) Ultimate tensile strength; (c) Hardness; (d) Elongation

the reduction in area, the yield and ultimate strengths and hardness of the materials first increase and then decrease. However, the elongation decreases while the reduction in area increases. Moreover, the precipitation hardening of cold rolled samples has improved both the strength and ductility.

Solution treatment of cold rolled strips at 520 °C for 1 h could lead to recovery and recrystallization. NIRANJANI et al [17] found that the recrystallization temperature of AA6061 alloy is between 200 °C and 250 °C. They used DSC to identify the recovery and recrystallization temperatures. In fact, the increase of cold working expands the defect density in the microstructure. So, the internal energy and driving force of restoration process rise. Furthermore, the solutionizing temperature is high enough to encourage the grain growth of the recrystallized grains. The more the reduction in area is applied, the faster the kinetics of restoration processes and the grain growth arises. One can assume that the grain growth is more possible for large reduction in area, especially the samples undergo 60% of cold working because the recrystallization is completed quickly in these samples. Therefore, the yield and ultimate strength and the elongation decrease as the amount of cold rolling increases from 40% to 60%. On the other hand, 40% reduction in area before solution treatment provides the most suitable structure from grain size approach. Thus, the subsequent age treatment gives rise to both strength and elongation, as illustrated in Fig. 5.

Employing combination of age hardening and cold rolling is practical from manufacturing process point of view. If the material has to be formed first and then aged, or it is essential to age the material initially and then to shape it. The process mainly depends on the material in its application and mechanical properties. For instance, if the formability of material is important, it can be formed to the proper shape under solutionized condition and then aged. Otherwise, if the strength of the alloy is not high enough, it is important to apply precipitation hardening first in order to increase the resistance of sheet to thinning.

4 Conclusions

1) The influence of thermal-mechanical treatment sequence on the mechanical properties of AA6061 alloy was investigated in different cases.

2) In the cases in which cold working was performed after solution treatment, increasing the reduction in area increases the yield and ultimate strengths and hardness but decreases the elongation. When the samples were finally aged, cold working increase causes the mechanical properties slowly changing due to the competition of softening and hardening mechanisms.

3) Using double aging in different sequences of thermal-mechanical treatments reflects negative effect of pre-aging on subsequent precipitation hardening of material. In this condition, the strength and hardness slightly decrease or remain constant and the ductility nearly improves.

4) The results of present study comply with the literature and show that negative or positive effect of pre-aging mainly depends on the mole ratio of Mg to Si, the amount of cold working and the history of thermal-mechanical treatment conducted on the material.

Acknowledgments

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References

[1] MURTHA S J. New 6xxx aluminum alloy for automotive body sheet applications [J]. SAE International Journal of Materials Manufacturing, 1995, 104: 657−666.

[2] SMITH W F. Structure and properties of engineering alloys [M]. New York: McGraw-Hill, 1993.

[3] RISANTI D D, YIN M, RIVERA DIAZ DEL CASTILLO P E J, ZWAAG S. A systematic study of the effect of interrupted ageing conditions on the strength and toughness development of AA6061 [J]. Materials Science and Engineering A, 2009, 523: 99−111.

[4] OZTURK F, SISMAN A, TOROS S, KILIC S, PICU R C. Influence of aging treatment on mechanical properties of 6061 aluminum alloy [J]. Materials and Design, 2010, 31: 972−975.

[5] DEMIR H, GUNDUZ S. The effects of aging on machinability of 6061 aluminum alloy [J]. Materials and Design, 2009, 30: 1480−1483.

[6] KIM H H, CHO S H, KANG C G. Evaluation of microstructure and mechanical properties by using nano and micro-indentation and nano scratch during aging treatment of rheo-forged Al 6061 alloy [J]. Materials Science and Engineering A, 2008, 485: 272−281.

[7] BUHA J, LUMLEY R N, CROSKY A G. Microstructural development and mechanical properties of interrupted aged Al−Mg−Si−Cu alloy [J]. Metalurgical and Materials Transactions A, 2006, 37: 3119−3130.

[8] CHANG C S T, WIELER I, WANDERKA N, BANHART J. Positive effect of natural pre-ageing on precipitation hardening in Al−0.44 at% Mg−0.38 at% Si alloy [J]. Ultramicroscopy, 2009, 109: 585−592.

[9] LIU Hong, ZHAO Gang, LIU Chun-ming, ZUO Liang. Effects of Different tempers on precipitation hardening of 6000 series aluminum alloys [J] Transactions of Nonferrous Metals Society of China, 2007, 17(1): 122−127.

[10] RAVI C, WOLVERTON C. First-principles study of crystal structure and stability of Al−Mg−Si−(Cu) precipitates [J]. Acta Materialia, 2004, 52: 4213−4227.

[11] YAMADA K, SATO T, KAMIO A. Effects of quenching conditions on two-step aging behavior of Al−Mg−Si alloys [J]. Materials Science Forum, 2000, 331−337: 669−674.

[12] MURAYAMA M, HONO K. Pre-precipitate clusters and precipitation processes in Al−Mg−Si alloys [J]. Acta Materialia, 1999,

47: 1537−1548.

[13] SONG M. Modeling the hardness and yield strength evolutions of aluminum alloy with rod/needle-shaped precipitates [J]. Materials Science and Engineering A, 2007, 443: 172−177.

[14] WEAKLEY-BOLLIN S C, DONLON W, WOLVERTON C, JONES J W, ALLISON J E. Modeling the age-hardening behavior of Al−Si−Cu alloys [J]. Metallurgical and Materials Transactions A, 2004, 35: 2407−2418.

[15] LIU G, ZHANG G J, DING X D, SUN J, CHEN K H. Modeling the strengthening response to aging processing of heat-treatable aluminum alloys containing plate/disc or rod/needle-shaped precipitates [J]. Materials Science and Engineering A, 2003, 344: 113−124.

[16] ASTM Standards, Vol. 03.01. Philadelphia: ASTM, 1984.

[17] NIRANJANI V L, HARI KUMAR K C, SUBRAMANYA SARMA V. Development of high strength Al−Mg−Si AA6061 alloy through cold rolling and ageing [J]. Materials Science and Engineering A, 2009, 515: 169−174.

冷加工和时效处理顺序对 6061 铝合金力学性能的影响

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摘　要：研究不同的析出硬化和冷加工组合对6061铝合金拉伸性能的影响。结果表明，在不同的热处理过程中，在180 °C单时效4 h能提高合金的强度和伸长率。然而，双时效处理不能改善其力学性能。另外，预时效对随后的析出硬化有负面影响。合金力学性能的变化归因于析出硬化、应变硬化和加工软化的竞争而引起的显微组织演变。

关键词：6061 铝合金；时效硬化；硬化；力学性能

(Edited by YANG Hua)