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Design of the multi-stage quenching process for 7050 aluminum alloy

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ABSTRACT

In order to attain good hardenability in the single-stage quenching process of Al–Zn–Mg–Cu alloys, rapid cooling rate is often desirable. But this would inevitably increase the residual stress. Therefore, the aim of this study is to achieve coupling control of the cooling rate and the residual stress by using the multi-stage quenching process. First, a series of single-stage quenching tests were conducted based on the end quenching equipment. Then in the double-stage quenching tests, a higher cooling rate was obtained comparing to the single-stage quenching. Based on this discovery, three kinds of multi-stage quenching processes were designed based on the experimental results of the single-stage quenching tests. The mechanism of the multi-stage quenching has been analyzed by comparing the cooling curves, the microstructure, the hardening depth, and the maximum residual stress. Furthermore the optimal multi-stage quenching process for 7050 aluminum alloy plate was obtained.

1. Introduction

As light constructional materials, Al–Zn–Mg–Cu aluminum alloys have the great real and potential applications in aircraft and automotive industry due to their high specific strength and specific stiffness [1, 2]. In order to achieve the required properties, solution heat treatment, quenching and aging are generally used in the preparation process. The critical problem in the preparation process of large scale products, such as thick plates and heavy forgings, is the inhomogeneity of properties from surface to center [3–5]. The key factor therein is the quench sensitivity, which means the properties of the aged alloy are influenced by the quenching rate. For its practical importance, many investigations [5–9] have been done on the quench sensitivity of Al–Zn–Mg–Cu alloys.

As the development of the large size plate of ultra-high-strength aluminum alloy, many advanced spray quenching processes have sprung up, such as roller-type spray quenching process [10–12]. And this provides a basis for the diversified development of the quenching technology. So far, the researches about the quenching processes were mainly focus on single-stage quenching. Grum et al. [13] investigated the influence of quenching process parameters on residual stresses. Newkirk and MacKenzie [14] reported the characteristics of the microstructure and properties of 7050 aluminum alloy and 7075 aluminum alloy in the Jominy end quench tests. Based on this test method, Dolan et al. [15] determined the time–temperature–property *C* curve of 7175 aluminum alloy. Besides, the influence of quenching process on the subsequent heat treatment or thermal deformation were also investigated, such as the flow behavior of 7050 aluminum alloy under hot compression by Liu et al. [16], the aging behavior of the Al–Zn–Mg–Cu alloy by Tang et al. [17]. However, less attention has been paid to the multi-stage quenching process.

In the single-stage quenching process, attaining good hardenability need to raise the cooling rate as fast as possible. But this will inevitably increase the interior residual stress, which could give rise to lower corrosion resistance and fracture toughness after aging. Consequently, the aim of this study is to achieve coupling control the cooling rate and the residual stress by using the multi-stage quenching process, and obtaining the applicable multi-stage quenching process for 7050 aluminum alloy plate.

2. Experimental details

2.1. Single-stage quenching tests

The 7050 aluminum alloy, of composition shown in Table 1, was used in the experiments. Quenching samples of 40 mm in diameter and 150 mm in height were machined in rolling direction from hot rolled 7050 plates. After solution treated at 470 °C for 30 min, the samples were quickly transferred to the end quenching rig (less than 5 s), as shown in Fig. 1. Spraying pressures used in the experiments are 10 kPa, 50 kPa, 100 kPa, 200 kPa, and 300 kPa. The duration of each test was 300 s and the tests were repeated for different flux densities, e.g. $48\,L\,m^{-2}\,s^{-1}$, $70\,L\,m^{-2}\,s^{-1}$, $90\,L\,m^{-2}\,s^{-1}$,

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Table 1
Chemical composition of 7050 aluminum alloy (wt.%).

Zn	Mg	Cu	Zr	Fe	Si	Cr	Mn	Ti	Al
6.23	2.35	2.26	0.11	0.12	0.05	0.03	0.05	0.05	Bal.

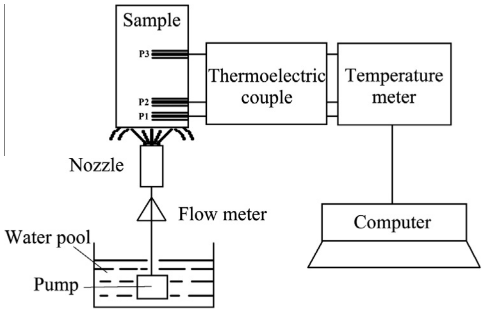

Fig. 1. Schematic diagram of the end quench test by water spraying.

108 L m^{-2} s^{-1}, and 130 L m^{-2} s^{-1}. Three small radial holes (1.5 mm) were drilled at 5, 10 and 60 mm from the quenched end of the specimen for type K thermocouples, so the temperature during the quenching process can be recorded by the computer. The nozzle was placed 20 mm from the quenched end, the water temperature was 25 °C, and the data acquisition rate was 50 Hz.

The surface residual stress magnitudes in the quenched samples were measured using the hole drilling method, as detailed in ASTM: E837-08e2. As illustrated in Fig. 2(a), when a small hole (both diameter and depth are 2 mm) is drilled into the test surface, the relaxed strains can be measured by the pre-installed electrical strain gages in the form of a rosette around the site of the hole. The layer-removal method was used to determine through-thickness residual stress distributions in the quenched samples. As shown in Fig. 2(b), when a 2 mm thick layer was electro-discharge machined from the surface, the residual stresses releases a force and moment acting on the remaining piece, the strain changes during these layer-removal operations can be recorded by the strain gages on the remaining piece. Then the stresses in the layer removed and the change in stresses of the remaining piece can be calculated from force and moment equilibrium, the linear strain change assumption, the strain rosette readings, and the stress–strain properties of the material. The detailed principles and calculation procedures of the two measuring methods have been introduced in several references [18–21]. The thicknesses of the quenched samples, which were used for measuring the residual stress, are 25 mm, 50 mm, 75 mm, 100 mm, and 150 mm.

Table 2
Spraying parameters of the double-stage quenching tests.

Test number	Spraying parameters
1	$q_s = 60$ L m^{-2} s^{-1}, $P = 467$ kPa
2	$q_s = 120$ L m^{-2} s^{-1}, $P = 370$ kPa
3	Step 1: $q_s = 60$ L m^{-2} s^{-1}, $P = 467$ kPa; Step 2: $q_s = 120$ L m^{-2} s^{-1}, $P = 370$ kPa

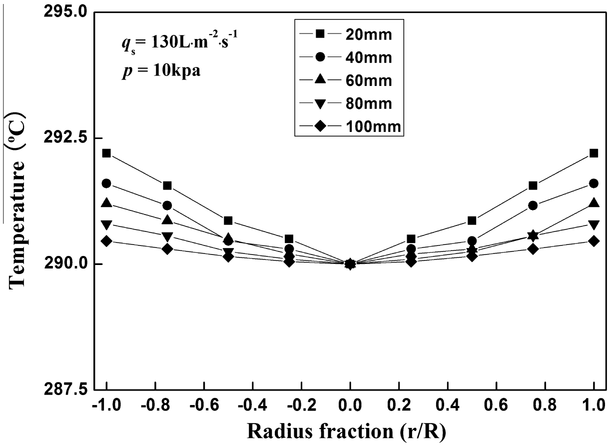

Fig. 3. Radial temperature traverses at different distances from the quenched surface.

2.2. Double-stage quenching tests

In accordance with the procedures of single-stage quenching tests, the double-stage quenching tests were conducted with different spraying parameters, as shown in Table 2. During the quenching process, when the temperature of the point P1 (see Fig. 1) was found reaching 200 °C, the second quenching stage started immediately. After quenching, the samples were aged at 120 °C for 24 h (T6). The Vickers hardness of the aged samples was tested on a HV-5 machine with a load of 3 kg, and at least 10 measurements were made for each sample to obtain an average value.

3. Results

As shown in Fig. 3, the radial temperature traverses were taken at several distances from the quenched surface. It can be seen that the range of temperatures appear very narrow. In other similar

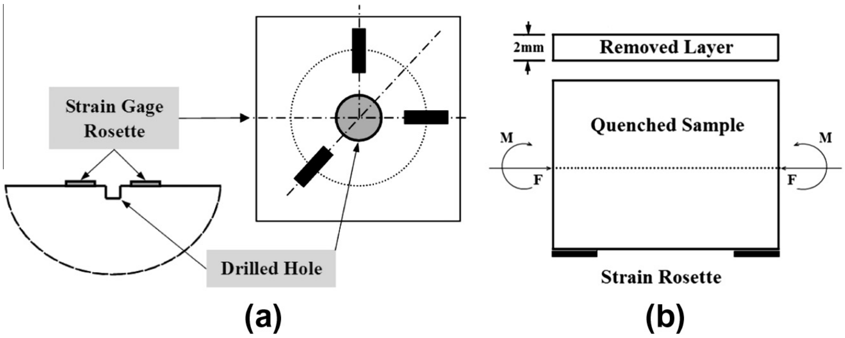

Fig. 2. Schematic illustrations of the residual stress measurement methods: (a) hole-drilling method; (b) layer-removal method.