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Evaluation of residual stress relief of aluminum alloy 7050 by using crack compliance method①

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Abstract: High strength aluminum alloys of 7xxx series have unacceptable levels of quenching residual stresses from solution heat treatment. The residual stress not only results in machining distortion and dimensional instability, but also increases the possibility of stress corrosion cracks. Therefore, it is necessary to reduce the residual stress to an acceptable level. The crack compliance method was adopted to study the influences of various stress relief methods on residual stress patterns in 7050 aluminum alloy. The results show that 90% residual stress can be eliminated by the cold stretching(Tx51) method. And a lower level of residual stress can be achieved by the uphill quenching(Tx53) method or the cold compression(Tx52). However, there is a very steep residual stress gradient normal to exterior surfaces.

Key words: aluminum alloy; residual stress; stress relief; evaluation; crack compliance method

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1 INTRODUCTION

7050 alloy is one of high strength aluminum alloys used mainly as plates and forgings in the aerospace industry. Its high strength is achieved through quenching and ageing. During the rapid quenching operation, high residual stresses develop due to severe thermal gradient. These internal stresses can lead to distortion during subsequent machining operations, and increase the possibility of stress corrosion cracks(SCC). Residual stress may be reduced with the decrease of the cooling rate by applying boiling water or organic quenchants. However, the final mechanical properties of the material are generally lowered since some alloying elements will be precipitated out of the aluminum matrix at a slower cooling rate. In general, the quenching stress should be reduced by mechanical or thermal stress relief methods[1]. Mechanical stress relief methods include stretching deformation(denoted as Tx51), compressive deformation (denoted as Tx52) or their combination(denoted as Tx54), whereas the thermal stress relief method is also known as uphill quenching method(denoted as Tx53)[2-5]. But the stress relief method(Tx51) is only applied to the parts of a uniform cross section in the rolling direction(e.g. sheet products). The stress relief methods of Tx52, Tx54 and Tx53 are normally useful for aluminum alloy forgings with complex configurations. However, the residual stress left after stress relief is still sufficient to cause distortion in aircraft components during subsequent machining operations[5]. In addition, due to low magnitude of residual stress, it is difficult to evaluate by the common measurement techniques, such as layer removal and hole drilling method. For this purpose, a new approach referred to as the crack compliance method, which was originally suggested by Cheng et al[6, 7], was introduced to measure the through-thickness residual stress distribution of high strength aluminum alloy plates after various stress relief treatments. In the crack compliance method, strains are measured as a slot is incrementally cut through the measured part by an electric discharge machining method. Therefore, it is a more sensitive and better spatial resolution than the layer removal or hole drilling method, and is of unique advantages in measuring the through-thickness residual stress profile of aluminum alloy parts.

2 SPECIMENS

The experimental material, 7050 T74 aluminum alloy plate with a thickness of 76 mm(procured from Alcoa INC) was chosen for the study. Several specimens(150 mm × 300 mm) were cut out from the central region of 760 mm wide plates. Table 1 lists the

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nominal chemical composition of 7050 aluminum alloy.

Table 1 Nominal chemical composition limits of 7050 aluminum alloy(mass fraction, %)

Si	Fe	Cu	Mn	Mg
0.12	0.15	2.6-2.0	0.10	2.6-1.9
Cr	**Zn**	**Zr**	**Ti**	**Al**
0.04	6.7-5.7	0.15-0.08	0.06	Bal.

Residual stresses of these specimens were measured under different temper conditions by the crack compliance method. They are referred to as T74, T7451, T7452 and T7453 according to the ASM handbooks as follows[3]:

After solution heat treatment, T74 is quenched in water of 25 ℃ or in organic quenchant of 22% UCN-A and then over-aged.

After solution heat treatment, T7451 is immediately being relieved stress by a 2.5% permanent stretching deformation in the rolling direction at room temperature and then over-aged.

After solution heat treatment, T7452 is immediately being relieved stress by placing specimens in a die and exerting a 2.5% permanent compression deformation in the ST direction at room temperature, and then over-aged.

After solution heat treatment, T7453 is immediately being relieved stress by peak quenching prior to aging. In the peak quenching process, specimens were cycled 4 times by submerging in liquid nitrogen until a uniform temperature of − 196 ℃ of the specimens was achieved, then it was quickly taken out from the liquid nitrogen and was very rapidly peak quenched in a blast of high-velocity steam or in boiling water.

3 EXPERIMENTAL

3.1 Experimental method

The crack compliance method involves incrementally introducing a slot into a part containing residual stress. Strain gages on appropriate surfaces at each increment of slot depth are shown in Fig. 1. These measured strains are used to solve the original residual stresses. The notable advantage of the crack compliance method is its excellent spatial resolution and the method has successfully profiled residual stress variation with depth in surface regions as thin as 0.1 mm and through parts as thick as 166 mm[7].

Since the width and the length of 7050 aluminum alloy plates are much larger than the thickness of rolling 7050 ones, residual quenching stress variation can be expressed as a function of depth z.

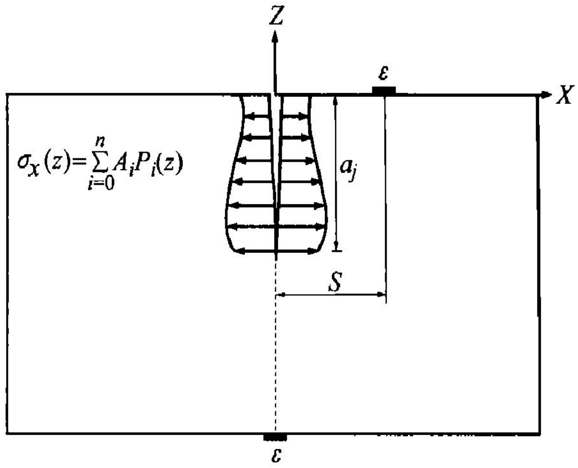

Fig. 1 Coordinate system and strain gage

Assuming that the unknown stress variation as a function of depth z, it can be expressed as a series expansion[6, 7]:

$$\sigma_{x,y}(z) = \sum_{i=1}^{n} A_i P_i(z) \qquad (1)$$

where P_i is some functional series, such as power polynomials, Legendre polynomials, etc. A_i represents unknown coefficients to be solved, and z is generally normalized by the thickness t of plate. For this application, Legendre polynomials expanded over the thickness of the plate were chosen as P_i. Because of including the 0^{st} and 1^{st} polynomial, the resulting stress distribution is guaranteed to satisfy the force and moment equilibrium.

The strains will be measured at the cut depths. a_j is calculated for each term in the series. These are called as the compliance functions C_i, which can be obtained from procedures based on linear elastic fracture mechanics or calculated by numerical computation(e. g. finite element method)[6, 7]. After the $C_i(a_j, s)$ solutions have been obtained, the strains given by the series expansion can now be written as

$$\varepsilon_{x,y}(a_j, s) = \sum_{i=1}^{n} A_i C_i(a_j, s) = [C]\{A\} \qquad (2)$$

Finally, a least-square fit will be used to minimize the error between the strains given by Eqn. 2 and the measured strains and the A_i from Eqn. 1 can be written in a matrix form as

$$\{\boldsymbol{A}\} = ([\boldsymbol{C}]^T\{\boldsymbol{C}\}^{-1}[\boldsymbol{C}]^T\{\varepsilon_{measured}\} \qquad (3)$$

The least-squares fit makes this inversion procedure become very tolerant of noise and errors in the strain measurements.

3.2 Experimental procedure

The first test was performed on 76 mm in thickness 7050-T74(not stress relieved) specimens. For this specimen, the X-direction in Fig. 1 corresponded to the rolling direction of the plate. The cuts were made using a model A500w-E wire electric discharge machine(WEDM) which was made in Japan. A

0.3 mm diameter brass wire was used for cutting a slot and made the slot about 0.45 mm wide. The slot was cut in 1.0 mm increments to a depth of 10 mm and then in 1.9 mm increments for the remainder of the test. In order to minimize the influences of machining forces and heat induced by EDM machining, the WEDM machine was set to "skim cut" setting and the specimen was submerged in 20 ℃ de-ionized water.

On the surface of the specimens, a strain gage was placed very close to the cut on the surface where the cut began (top), and another was centered on the cut plane on the opposite surface (bottom), as shown in Fig. 1. The gages used were BE120-3BC thermally compensated strain gage with an active gage length of 2.8 mm. A model YZ-22 strain analyzer was used to read the strains for the strain gages.

The compliance functions were calculated using a numerical solution for a finite-width rectangular slot in a semi-infinite medium[6, 7]. The calculations were done using the commercial FE code ABAQUS 6.2 version. Only half of the specimens were meshed because of symmetry about the cut plane. A 2-D plane strain mesh was used with quadratic shape function elements (CPE8) sized at about 1 mm. The elastic modulus of 7050 T74 aluminum alloy was taken as 69 GPa and Poisson's ratio as 0.33. Incremental cutting was simulated by incrementally removing symmetry displacement boundary conditions on the cut plane. The strains for the strain gages in Fig. 1 were then calculated using nodal displacements.

Finally, the series expansion coefficients A_i was determined by least squares fit (Eqn. (3)) using the measured strains for the relevant gages and the FE-calculated compliance functions[8]. The order of fit was chosen to minimize the uncertainty in the calculated stresses. An eight term series (Legendre polynomial order 2 to 9) was sufficient for fitting measured strains[9]. The results of calculated residual stresses generated by the fits are shown in Figs. 2-4.

4 RESULTS AND DISCUSSION

After being quenched in 25 ℃ cold water and over-aged, the 7050 T74 aluminum alloy specimens show a typical quenching residual stress distribution of M-shaped stress depth profiling. As shown in Fig. 2, surface compression stresses are balanced by tensile stresses at the core. The maximum stress magnitude (220 MPa) is about 40% greater in the rolling direction than that in transverse direction. While the aluminum alloy specimens are quenched in 22% UCN-A polymer quenchant and over-aged[10], the maximum stress magnitude (147 MPa) is approximately 67% of

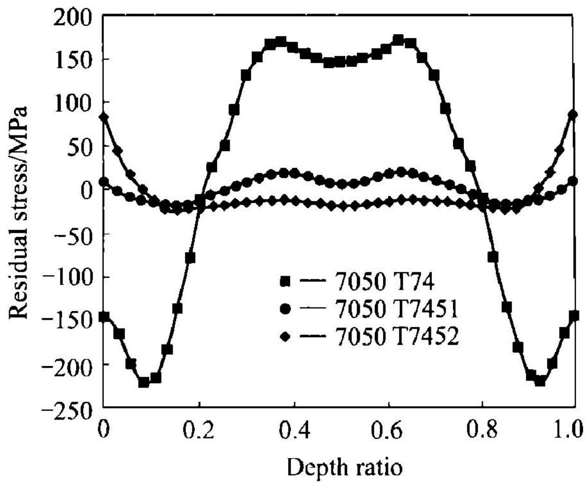

Fig. 2 Comparison of RS relieved by Tx51 and Tx52 methods in rolling direction

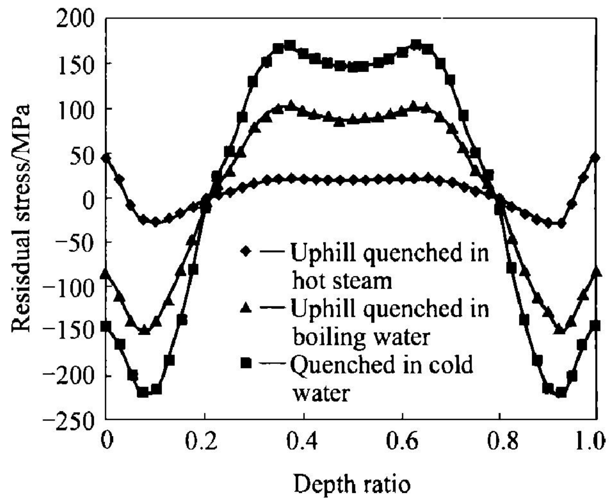

Fig. 3 Residual stresses in 7050 T74 before and after peak quenching

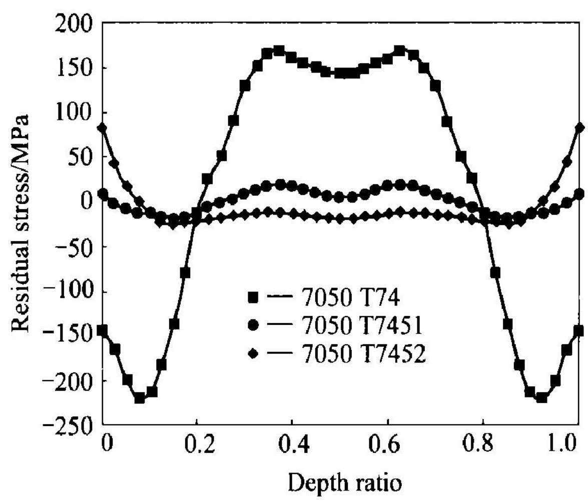

Fig. 4 Comparison of RS relieved by Tx51 and Tx52 methods in rolling direction

that as quenched in 25 ℃ cold water, and the through-thickness residual stress distributions maintain essentially the same stress profiling, as shown in

Fig. 2.

After aluminum alloy specimens are stress-relieved by means of 4 cycles of peak quenching treatment followed by submerging them in liquid nitrogen and extremely rapid heating in agitated boiling water, the residual stresses of aluminum alloy specimens are reduced roughly 40%. However, as much as 83% reduction can be achieved using high-pressure steam in place of boiling water and the maximum residual stress is reduced to less than 45 MPa for 7050 T7453 aluminum alloy specimens, as shown in Fig. 3. But high steep stress-depth gradients exist near surface layer. Therefore, it is suggested that the peak quenching process should be done prior to finish machining or semi-finish machining process.

The mechanical stretching method (Tx51) results in an almost complete removal of residual quenching stresses in aluminum alloy plates, as shown in Fig. 4. The permanent stretching deformation of 2.5% is enough to reduce residual stresses in 7050 T7451 to less than 20 MPa. Respectively, the residual stress distribution in 7050 T7452 aluminum alloy after stress relief of cold compression, may be desirable for machined parts where high surface stresses will be removed and the remaining stresses at the core will be compressive at low magnitude.

5 CONCLUSIONS

1) While aluminum alloy specimens are quenched in 25 ℃ cold water and over-aged, 7075 T74 aluminum alloy plate shows the M-shaped stress-depth profiling with the peak magnitude of 220 MPa near surface. While being quenched in 22% UCN-A polymer quenchant and over-aged, the maximum stress magnitude reduces to about 147 MPa, 67% as of that quenched in 25 ℃ cold water.

2) Cold stretching method (Tx51) is thought as an ideal technique for simple-shaped parts, which can reach a high level of about 90% reduction and almost relieve completely the residual quenching stresses in 7050 aluminum alloy plates.

3) Both the peak quench (Tx53) and the cold compression method (Tx52) are very useful techniques to relieve complex-shaped parts. They can relieve the residual quenching stresses in 7050 aluminum alloy plates to an acceptable level, but a very steep stress gradient exists on outer layers.

4) After stress being relieved by cold compression method (Tx52), the stress distribution in 7050 T7452 aluminum alloy may be desirable for machined parts, where high tensile surface stresses will be removed and the remaining stresses at the core are compressive at low magnitude.

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