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A novel cryogenic treatment for reduction of residual stresses in 2024 aluminum alloy

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A R T I C L E I N F O

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A B S T R A C T

Residual stresses induced during quenching of aluminum alloys cause distortion and have a negative effect on their properties. The purpose of this study is to reduce the residual stresses and improve mechanical properties by using a novel cryogenic treatment. Water quenched samples were cooled down by immersion in liquid nitrogen at −196 °C, following by rapid heating in hot oil at 180 °C and finally they were artificially aged. Residual stresses was measured by the hole drilling strain gauge method. The mechanical properties and microstructure of a heat treated samples were investigated by means of hardness measurements, tensile tests and transmission electron microscopy. The results showed that this treatment can relieve up to 71% of the residual stresses compared to 29% related to the traditional cryogenic treatment that used boiling water as the reheating medium. In addition, there is a considerable increase of about 75 MPa in the ultimate tensile strength in comparison to the T6 heat-treated alloy. TEM observations revealed that the S′ precipitates were fine and uniformly distributed in the microstructure due to deformation during reheating in hot oil.

1. Introduction

The essential step in creating the high strengths in precipitation hardened aluminum alloys is the rapid cooling from the solution heat treatment temperature [1]. When cooling is fast enough, it will lead to higher strength. However, another undesirable effect of rapid cooling is the generation of residual stresses [2].

However, residual stresses have a negative effects on parts properties due to distortion and dimensional variation and it may cause premature failure [3]. Therefore, it is necessary to decrease the residual stresses generated by rapid quenching to improve the dimensional accuracy of the components.

Extensive studies have been carried out with the aim of reduction of residual stresses induced by quenching in aluminum alloys. Some researchers have changed the quench conditions such as quench medium and the temperature, which the required strength to be achieved [4–6]. In some other studies, the effect of size and geometry have been researched on the stress distribution [7]. A methods can be used after quenching to reduce residual stresses for instance the application of cold working [8], low frequency magnetic fields [9], electro-pulsing [10] and cryogenic treatment [11], or a combination of the above.

Cryogenic treatment is the most widely used method to reduce the residual stresses of aluminum alloys and can be utilized to parts with a complex shape. This treatment is also known as uphill quenching or thermo-mechanical method. During conventional cryogenic treatment, water quenched parts are cooled down by immersion in liquid nitrogen at −196 °C, followed by rapid heating in boiling water or high velocity steam. Researchers are reported that the residual stresses due to water quenching can be relieved by up to 80% by using high velocity steam in cryogenic treatment [12–14]. However, this process is associated with some problems. One of the major disadvantages of conventional cryogenic treatment is that it is a relatively expensive process that is often considered too difficult. Moreover, it requires the use of a special steam nozzle and all surfaces should not receive such a similar thermal input [15].

The aim of this research is to redesign the conventional cryogenic treatment to reduce the problems associated with the current methods and to make it more applicable and cheaper to use. Also the changes shall be able to improve the mechanical properties.

2. Experimental procedures

In this work, samples with dimensions of 55×25×25 mm^3 in size were cut from a 2024-T3 industrial extruded profile with the chemical compositions given in Table 1. The samples were solution treated by

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Table 1
Chemical compositions of 2024 aluminum alloy (wt%).

Element	Cu	Mg	Mn	Si	Fe	Cr	Zn	Ti	Al
Nominal	3.8–4.9	1.2–1.8	0.3–0.9	< 0.5	< 0.5	< 0.1	< 0.25	< 0.15	Bal.
In this study	4.37	1.29	0.6	0.3	0.4	0.052	0.075	0.009	Bal.

Table 2
Sample solution heat treatment, quenched media and their corresponding condition.

sample name	Solution heat treatment	Quenched Media	Immersion in liquid nitrogen	Reheating Medium	Aging
QWNA(T4)	2 h 495 °C	water 20 °C	–	–	Natural Aging 30 day
QWAA(T6)			–	–	12 h 190 °C
QWCA1			1 h	Oil 180 °C	
QWCA24			24 h	Oil 180 °C	
QWBW24			24 h	Boiling Water	

Q: Quench, W: Water, N: Natural, C: Cryogenic, B: Boiling for example QWCA24 means quenched in water at 20 °C, immersion in liquid nitrogen for 24 h and followed by artificial aged at 190 °C for 12 h

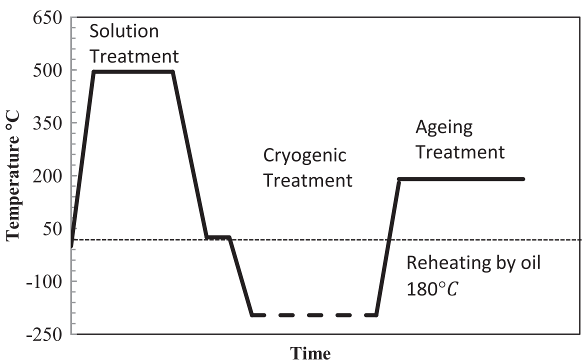

Fig. 1. Heat treatment cycle for new cryogenic treatment by hot oil.

heating to 495 ± 5 °C, holding for 2 h and then quenched in water at 20 °C. Subsequently, the samples were prepared at different cryogenic and reheating treatments and finally were aged at room temperature for 30 days or at 190 ± 6 °C for 12 h. The detailed description along with samples labels are given in Table 2 and the temperature profiles for solid solution treatment, cryogenic treatment and artificial aging are shown Fig. 1.

2.1. Residual stresses determination

Residual stresses were measured using the hole-drilling strain-gauge method according to ASTM E837-01. The RS200 milling guide was used to generate a hole in the samples. FRS-3–23 Type A strain-gauge rosette (Fig. 2a,b) was attached to the samples as stated by the procedure provided by TML Measurements Group Ltd. [16]. The hole was drilled to a depth of 2 mm from the surface. All measurements were recorded at the same location on the samples center. Multiple (repeatability) hole drilling measurements allowed an estimation of one standard deviation of random uncertainties as ± 25 MPa.

2.2. Mechanical properties measurement

Flat tensile specimens were cut from the samples using the electron discharge machining (EDM) method as described in the standard technique ASTM E8 with a gauge length of 9 mm and 2.5 mm in width. Uniaxial tensile tests were carried out with a 500 kN servo-hydraulic utilizing a laser extensometer at room temperature. Uncertainties in the 0.2% yield stress and tensile strength were ± 4% and ± 2% respectively. Three samples were tested for each condition and the average was reported.

The measurement of the Rockwell B hardness was carried out in accordance with ASTM E18-13. For each sample, at least 5 points were measured to obtain an average value with a typical uncertainty of ± 1%.

2.3. Microstructure characterizations

A field-emission transmission electron microscope (JEM-2100F TEM) was used to characterize the microstructure of the samples. The TEM specimens were prepared by mechanical grinding and punching into discs of 3 mm, followed by twin-jet polishing using a solution of 25% nitric acid +75% methanol at a temperature maintained between −40 and −30 °C at 20 V.

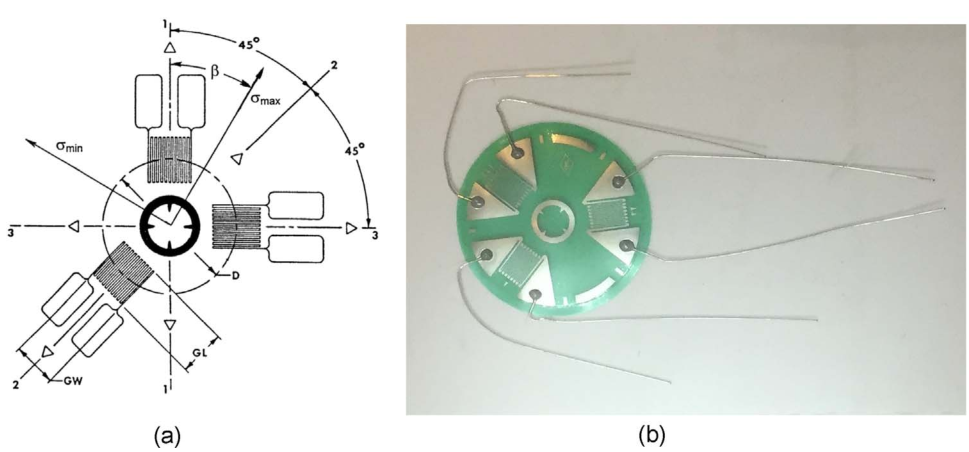

Fig. 2. Strain gauge rosetta type A (a) Schematic (b) FRS-3–23(TML Production).