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On the Distortion and Warpage of 7249 Aluminum Alloy After Quenching and Machining

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The objective of this study is to determine the effect of solution treatment temperature, quenching media, and various machining sequences on the warpage behavior of aluminum 7249 alloy aged to T6 and T7′ tempers. Large extrusions of 7249 aluminum alloy with fins were cut into 108 "T" sections. The samples were solution-treated, aged, and machined. Three solution temperatures (445, 474, and 505 °C), two quenching media (water and 20% polyalkylene glycol), two aging treatments (T6 and T7′), and three machine sequences were used. The flatness of the samples was measured on the surfaces orthogonal to the *z*-axis. Three points were on top of both shoulders (six total), six were at the bottom of the sample, and six were on the top of the fin, in the cases where the fin was not milled off. They were then averaged together by surface to represent the overall warpage of each sample.

Keywords 7249 aluminum alloy, quenching media, T6 temper, warpage

1. Introduction

Warpage is a type of distortion where the surfaces of a part do not follow the intended shape of the design. Warpage is a major problem in the manufacturing process of aerospace and automotive aluminum alloy components because it can lead to arduous, costly, and time-consuming straightening processes. Among the factors that lead to warpage the most common is heat-treatment and subsequent machining. To reduce the thermal gradients, which create residual stresses, polymers are added to water quenchants retarding the heat transfer from the component surfaces (Ref 1). Other sources of distortion include heating rates, position during quenching, part positioning and loading techniques during heating in the furnace, types of quenching media, agitation of the quenching media, temperature of the quenching media, and the severity of the quench (Ref 2).

Quenching involves the rapid cooling of a part from the solution-treating temperature and is done to retain hardening elements in solid solution. The quenching media used is a key factor in the cooling of the part. It was found by Bates (Ref 3) that using a polyalkylene glycol quenching solution reduced the amount of warpage. It was also shown by Es-Said et al. (Ref 1) and Collins and Maduell (Ref 4) that a polyalkylene glycol quenching solution minimizes distortion.

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Samples with non-uniform section thicknesses that heat and cool nonuniformly are another significant cause of distortion (Ref 5). In molded parts, nonuniform section thickness will heat and cool nonuniformly. The thinnest sections of the final part will cool more rapidly than the thick sections. As the thick sections cool, they shrink in the areas connected to the already cooled thin sections. This causes stresses to form near the boundary of the thin to thick sections. Since the already cooled thin sections will not yield, the thick section must (Ref 6).

In ASTM standard A1030/A1030M-05 (Ref 7) various ways of measuring the warpage of a steel sheet are described. The most common method is to measure the cycle of the warpage wave. This involves measuring the distance from the lowest valley to the height of the original surface and the length of the wave, as shown in Fig. 1. In this study, the warpage of a thick "T" section, not a sheet, is studied.

The effect of the aging temper of a component and the effect of machining sequence on warpage were not studied before. This study explores warpage effects from different solution temperature heat treatments, water versus 20% polyalkylene glycol quenching media and various machining sequences for aluminum 7249 aged to T6 and T7′ tempers.

2. Experimental Procedure

The material examined in this study was wide extrusion plates with fins of aluminum alloy 7249 in the T-76 temper. It is a derivative from aluminum alloy 7149 and was developed as a replacement material for Al 7075-T6 forgings that are predisposed to stress corrosion cracking (SCC) (Ref 8). The chemistry of its alloying elements is shown in Table 1 (Ref 9).

One hundred and eight "T" sections were cut out of the extruded plates of 7249 alloy with fins. They were cut to a length of 25.4 cm (10 inches) and each side of the shoulders was milled to a width of 4.7 cm (1.85 inches). A hole is drilled moving across the fin and a tie wire moves through it to make a loop to enable quenching, Fig. 2, 3.

Each sample initially had 18 points marked on it, six on the fin, three on top of both shoulders, and six at the bottom of the sample, Fig. 4. A piece of sheet metal was used as a template to ensure that the initial 18 holes were in a consistent location after each step in the process when a warpage measurement was taken. The flatness of these points was measured using a Brown and Sharp coordinate measuring machine. This system measures points based upon its position in the *x*, *y*, and *z* axis. Once a probe has been touched to all points of interest, six per surface for this study, a calculation of the total point deviation, in mm, is measured and recorded as mm.dev. A measurement was taken and recorded before solution heat treatment. This value was so small that it was determined to be negligible. Next, samples were placed in one of three furnaces maintained at 445 °C (833°F), 475 °C (887°F), and 505 °C (941°F) for 1 h. Immediately after each heat treatment, samples were quenched at a rate of 2.54 cm/s (1 in/s) along the length in either water or 20% polyalkylene glycol. This exaggerated slow rate similar to the procedure of other studies (Ref 1, 10) was performed to amplify the warpage behavior of the thick extrusions.

Two aging methods were explored, a T6 temper and a T7′ temper. The T6 temper involved natural aging of the solution-treated samples for 24 h followed by artificial aging at 121 °C (249°F) for 24 h. The T7′ was an exaggeration of the T7 temper. It involved artificially aging at 250 °C (482°F) for 6 h followed by 350 °C (662°F) for 8 h. The T7′ temper was

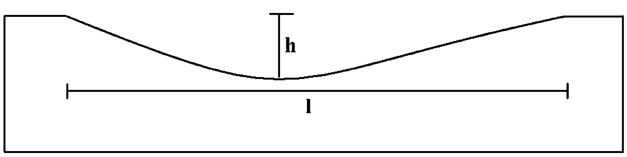

Fig. 1 ASTM A1030/A1030M-05 schematic for the standard for measuring flatness, "l" is the length of the wave from peak to peak, and "h" is the height of the measured warpage from lowest point in the valley to highest point of the wave

Table 1 Chemical make-up of Aluminum 7249 (Ref 9)

Element	%
Zn	7.5-8.2
Mg	2.0-2.4
Cu	1.3-1.9
Cr	0.12-0.18

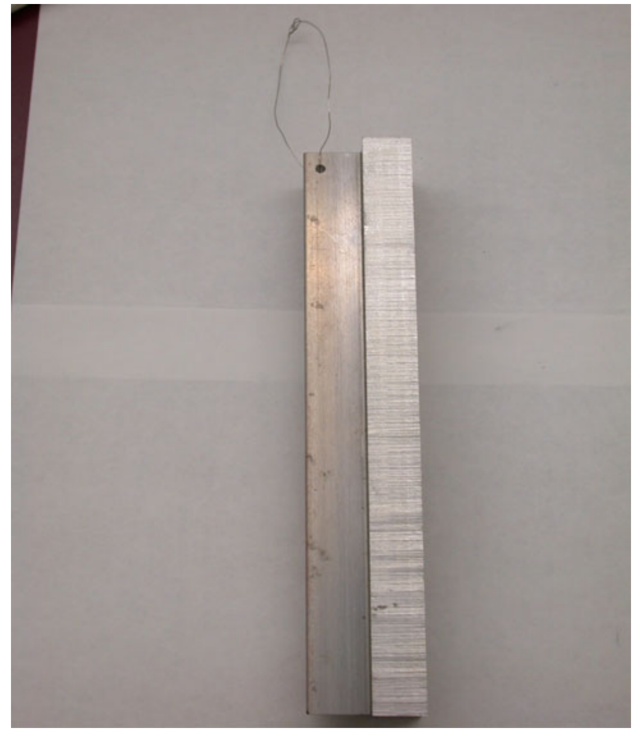

Fig. 3 Initial T section with hole and wire for quenching

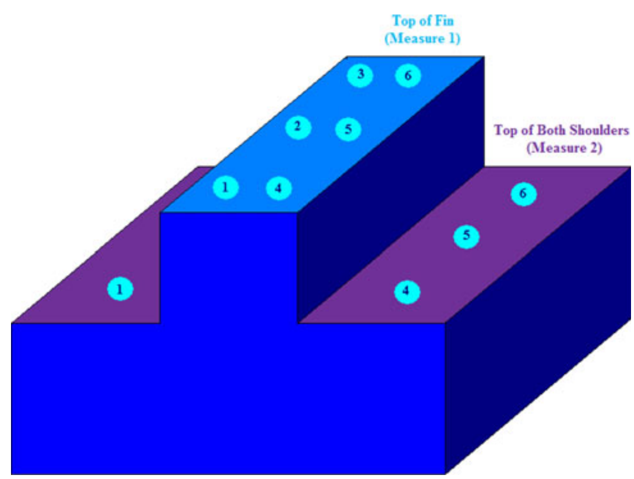

Fig. 4 Location of 18 different points measured on each "T" section. Six additional measurements were taken on the bottom side of the sample (measure 3)

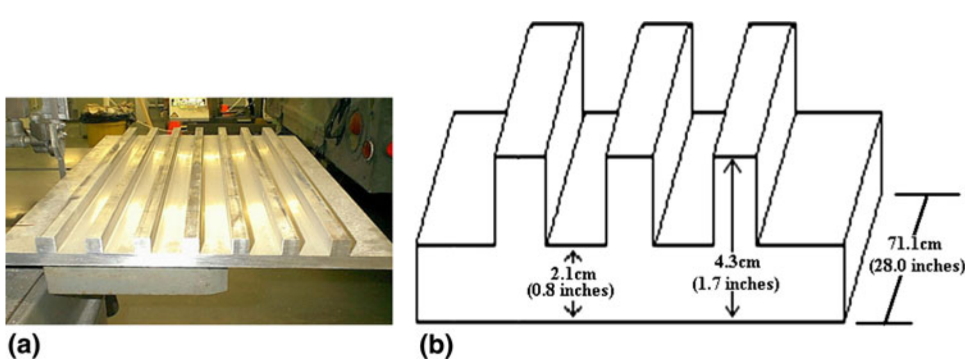

Fig. 2 (a) Extruded plates of 7249 alloy with fins, and (b) Initial dimensions of extruded plates

performed to induce an excessively softened condition of the samples in contrast to the T6 temper. After the aging treatments, the flatness of the marked points was re-measured.

Next each sample was machined in three different sequences, called cuts, Fig. 5. The effects of the three different cuts were measured at different stages of the machining process. In cut 1, the fin was milled off, and then milling proceeded from the top to the bottom until a thickness of 4.95 mm (0.195 in) was reached. The amount of warpage was then measured. Next the samples were milled to a final thickness of 2.54 mm (0.1 in) again from top to bottom. Then the warpage was re-measured. In cut 1, because the fin is milled completely off, there were only two surfaces to measure, resulting in 12 points. In cut 2, the fin was not milled off, leaving the initial 18 points. Milling proceeded from the bottom to the top to an initial thickness of 4.95 mm (0.195 in) where the amount of warpage was measured. Then it was milled to a final thickness of 2.54 mm (0.1 in) and the warpage was re-measured. In cut 3, the fin was milled off, and then milling proceeded from the bottom to the top to an initial thickness of 4.95 mm (0.195 in). The amount of warpage was then measured. Then the samples were milled to a final thickness of 2.54 mm (0.1 in) and the warpage was re-measured. Just like in cut 1, because the fin is milled completely off, there were only two surfaces to measure. This process and the numbered surfaces are shown in Fig. 6. The difference between cuts 1 and 3 is that in cut 3 milling was from the bottom to the top of the sample and in cut 1 milling was from the top to the bottom of the sample.

In summary, six points per surface, i.e., the fin, both shoulders, and the bottom, (12 total for samples in cuts 1 and 3, 18 total for samples in cut 2 because the fin was not milled off) were measured for the as-received samples, after they were aged, after they were initially cut and after they were milled to their final thicknesses. The flatness measurements of the as-received samples were negligible. The measurements taken after aging, after the first cuts and after all cutting/milling was completed were averaged for each surface. Cuts 1 and 3 only have two measurements because after the rib was milled off, the "T" section turned into a rectangular bar and there was no third surface to measure. Thus, there are a total of two measurements for sample cuts 1 and 3 and three measurements for sample cut 2 as illustrated in Fig. 4, 5.

There were 36 different conditions (three solution treatment temperatures, two quenching media, two aging tempers, and three sample cuts), and three samples were tested for each

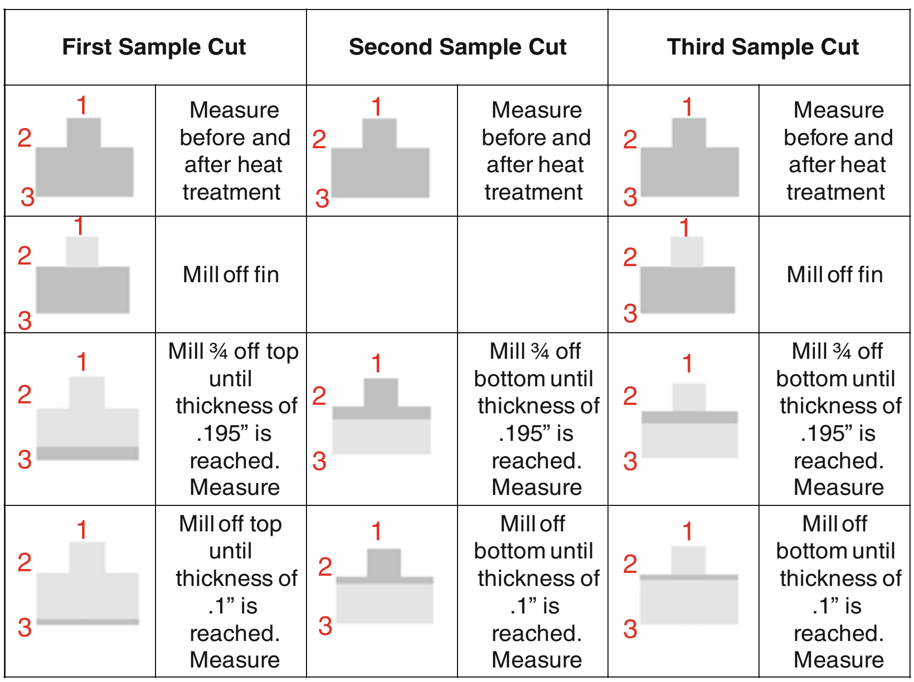

Fig. 5 Sample cuts and surface measurement numbers

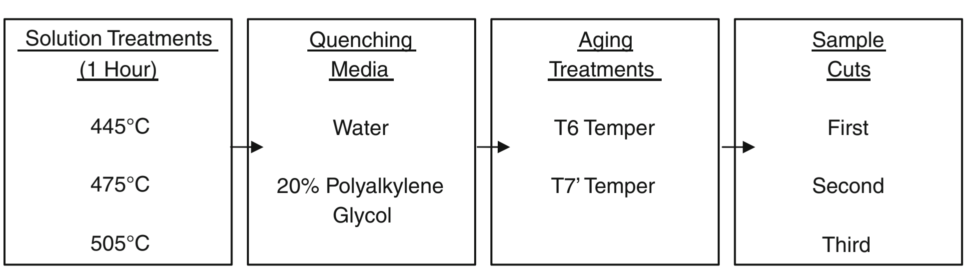

Fig. 6 Schematic of sample preparation procedure: three solution treatments × two quenching media × two aging treatments × three cuts = 36 conditions × 3 samples for each condition = 108 samples

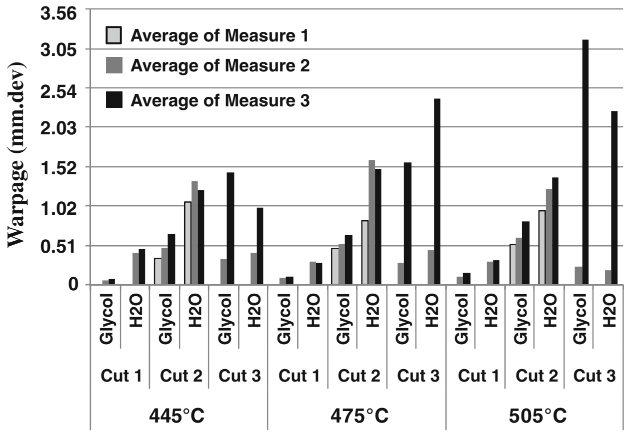

Fig. 7 T6 phase results

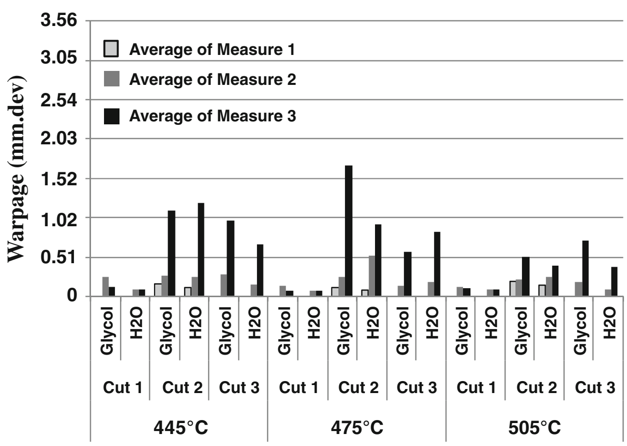

Fig. 8 T7′ phase results

condition. A schematic of the sample preparation procedure is shown in Fig. 6. There were a total of 108 samples tested.

Finally, it should be noted that the warpage profiles shown in Figs. 7, 8, 9, 10, and 11 are the measurement of the amount of warpage on three surfaces of the sample, not the warpage of the whole sample. This means that three separate warpage profiles (cut 2) or two separate warpage profiles (cuts 1 and 3) are shown, not the whole warpage of one sample.

3. Results

3.1 T6 Temper

The results for the T6 temper are shown in Fig. 7. In the plot, average measure 1 is the average of the measurements taken for surface 1, average measure 2 is the average of the measurements taken for surface 2, and average measure 3 is the average of the measurements taken for surface 3, respectively. Average measure 1 is only present in cut 2 because cut 2 is the only cut to leave the fin.

3.1.1 Solution Temperature and Quenching Medium. It was found in cuts 1 and 2 that the solution temperature had little to no effect on the final warpage and that the samples quenched in water showed more warpage. In cut 3, however, warpage is more pronounced at higher solution temperatures.

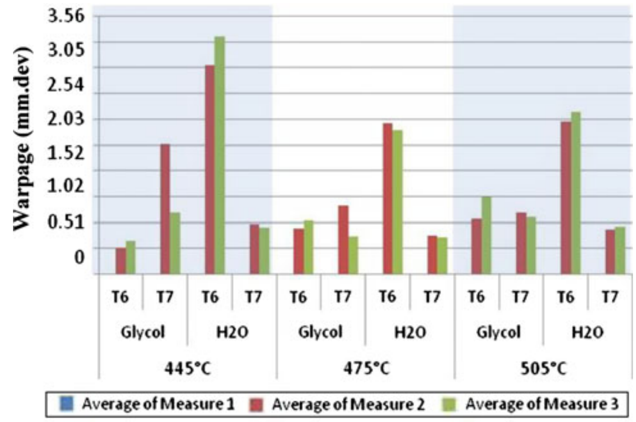

Fig. 9 T6 phase vs. T7′ phase for cut 1

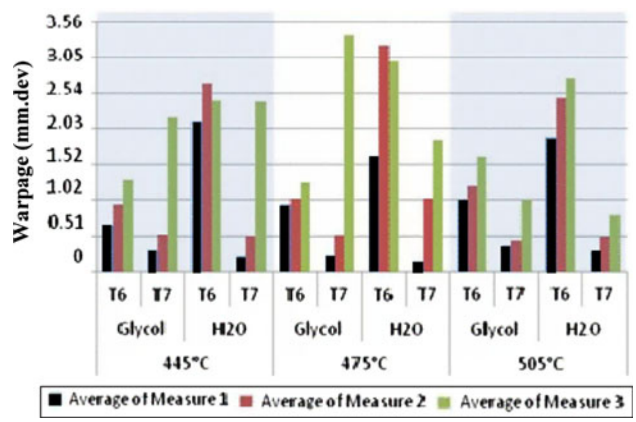

Fig. 10 T6 phase vs. T7′ phase for cut 2

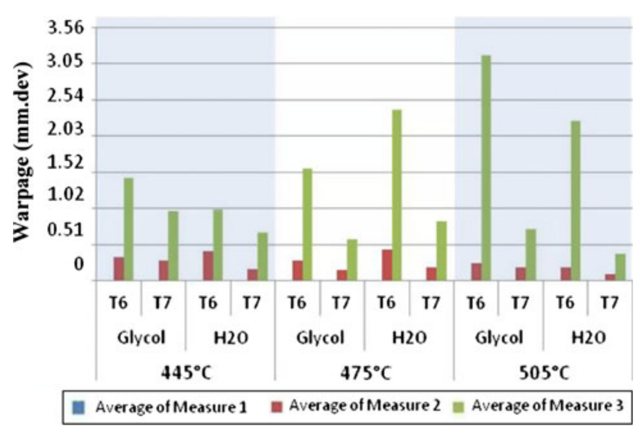

Fig. 11 T6 phase vs. T7′ phase for cut 3

Glycol was found to produce more warpage in some instances, but overall the warpage produced was less than that produced by water quenching.

3.1.2 Machining Process. Overall, it was found that the machining done in cut 1 produced the least amount of warpage and cut 3 produced the most amount of warpage. This is because the milling process in cut 1 removes the residual stresses concentrated at the joint of the fin to the base of the sample, whereas in cut 3 the milling process removes the parts of the sample that have the least amount of residual stresses present.

For cut 2 in the T6 temper, the second and third measurements were slightly higher in warpage than the measured one, especially in water, because measurement 1 experienced no milling procedure. The solution temperature had little effect on warpage and water quenching produced more warpage.

It was noted that overall, the T6 temper experienced the most distortion due to machining as compared to solution treatment or quenching.

3.2 T7′ Temper

The results for the T7′ temper are shown in Fig. 8. The average measures represent the same surfaces as described in Fig. 7.

3.2.1 Solution Temperature and Quenching Medium. It was found that the solution temperature had little to no effect on the warpage of the samples from all cuts. Cut 2 at 475 °C (887°F) in a glycol quench had the highest amount of warpage. The percent difference from the highest amount of warpage, 1.63 mm (0.064 in), to the lowest amount of warpage, 0.51 mm (0.02 in), from the same process but different solution temperature, 505 °C (941°F), in a glycol quench was 66%. However, the numerical difference was only 1.02 mm (0.04 in). This indicates that in this method of measurement only clear and large difference should be considered.

No conclusion can be made from the quenching media in the T7′ temper

3.2.2 Machining Process. It was found that cut 1 produced the least amount of warpage. It was also found that measure 3 for cuts 2 and 3 were consistently higher than the previous measurements.

For all cuts in T7′ temper, the solution temperature had little to no effect on warpage. In cut 1, there was little to no variation between measurements for all cases. Measurement 3 for cuts 2 and 3 was noticeably higher than the previous measurements.

3.3 T6 Versus T7′ Temper

Figure 9, 10, and 11 show the graphical results for the T6 versus T7′ temper analysis for all the three cuts. Cut 1 showed that the T7′ temper, quenched in glycol, experienced more warpage than the T6 temper in the same cases. Probably, this is due to the residual stresses being reduced to the point that the softness effects of the material became more significant. It was found that for cut 2, quenched in water, the T7′ temper had less warpage than the T6 temper. Finally, cut 3 showed the T6 temper produced more warpage than the T7′ temper did for all cases.

Samples in the T6 temper experienced more warpage, overall, than the samples in the T7′ temper. This is due to the exaggerated overaging of the T7′ samples compared to the T6 temper samples. The T7′ temper samples had less stored residual stresses. However, some of the T7′ temper samples experienced more warpage in certain circumstances. It was also noted that the T6 temper samples machined much easier and cleaner than the T7′ samples did.

4. Summary

The thick parts studied together with the difficulty of measuring warpage and distortion with reasonable accuracy leads to variations in the data. However, it can be concluded in general that quenching in water and using peak aged (T6 temper) components leads to more warpage.

For the machining sequence cut 1 had the least warpage and cut 3 has the most. Although the fin was cut on both, the fact that the intersection of the shoulder and the fin was removed (the area of highest residual stresses), cut 1 exhibited the least warpage. Comparing cuts 2 and 3 indicates that with the presence of the fin, the intersection has more balanced residual stresses (cut 2) as compared to not having the fin (cut 3). Accordingly, cut 3 has higher warpage values.

The higher warpage values of the T7′ (in some cases) were only measured after quenching in glycol. This indicates that when the thermal gradients are minimized the softer sample (T7′) yields and the lower strength becomes a factor to be considered.

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