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# Overcoming Residual Stresses and Machining Distortion in the Production of Aluminum Alloy Satellite Boxes

Mandy S. Younger and Kenneth H. Eckelmeyer

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# Overcoming Residual Stresses and Machining Distortion in the Production of Aluminum Alloy Satellite Boxes

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**Abstract**

Distortion frequently occurs during machining of age hardening aluminum alloys due to residual stresses introduced during the quenching step in the heat treatment process. This report quantifies, compares, and discusses the effectiveness of several methods for minimizing residual stresses and machining distortion in aluminum alloys 7075 and 6061.

## ACKNOWLEDGMENTS

Many colleagues participated in portions of this study. The authors appreciate the efforts of Gary Gallegos and Don Green, who conducted the heat treatment and quenching experiments; Jack Stephens, Roger Castillo, and Joe Nekoranec, who machined the test samples and measured subsequent distortions; and Tom Crenshaw and John Laing, who conducted the mechanical tests. We also appreciate the comments and helpful reviews of Jim VanDenAvyle, Don Susan, and Curtis Gibson.

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## EXECUTIVE SUMMARY

Distortion frequently occurs during machining of age-hardening aluminum alloys due to residual stresses that were introduced during the quenching step in the heat treatment process. Options for reducing these residual stresses have been investigated in two extensively used aluminum alloys: 7075 and 6061. This report quantifies, compares, and discusses the effectiveness of several methods: 1) thermal stress relieving during traditional aging and non-traditional overaging, 2) mechanical stress relieving in tension and compression, and 3) quenching in warm water to minimize initial stress. The results are integrated into recommendations for designing, processing, and machining satellite boxes with various strength requirements.

Residual stress magnitudes in conventionally quenched aluminum alloys increase with increasing section thickness until they are eventually limited by as-quenched yield strength. The substantially higher as-quenched yield strength of 7075 makes it inherently more prone to residual stresses and machining distortion than 6061 in relatively thick sections (>0.6 inch). Peak residual stresses are ~22 ksi in as-quenched 7075 plates thicker than 1.3 inches, and ~9 ksi in as-quenched 6061 plates thicker than 0.6 inch.

Traditional age hardening is relatively ineffective in reducing quench-induced residual stresses. Greater stress relief can be obtained by non-traditional overaging, but at the expense of substantial decreases in strength. Mechanical stress leveling in tension removes 80 to 95% of residual stresses with no strength penalty, but is difficult to apply to geometrically complex parts. Mechanical stress relieving in compression is more applicable to complex shapes, but is less effective in reducing residual stresses. Quenching in pre-heated water reduces residual stresses, particularly at temperatures above 150°F. Hot water quenching can be applied regardless of geometric complexity, but moderate reductions in strength can occur in relatively thick sections of highly quench-rate-sensitive alloys, such as 7075.

Machining distortion occurs when material is removed asymmetrically with respect to the balanced pattern of residual stresses. Options for minimizing machining distortion are discussed, including machining strategies to reduce unbalancing the residual stress patterns characteristic of materials with various processing histories.

The residual stresses introduced by cold straightening are also described. Cold straightening is not recommended because it can result in very high residual stresses, which make the material exceptionally prone to distortion during finish machining as well as potentially susceptible to stress corrosion cracking.

# 1. INTRODUCTION

Quench-induced residual stresses are a notorious cause of distortion during machining of age-hardened aluminum alloys. These distortions often make it difficult or impossible to meet tight dimensional tolerances, particularly when large and/or complex parts are being manufactured. In this study, for example, mid-length bending deflections of 0.085 inch occurred when 10-inch-long plates of 1-inch-thick 7075-T6 aluminum alloy were split into two 0.5-inch-thick halves via wire electrical discharge machining. Figure 1 shows an edge-on photograph of a one-inch thick x 10-inch-long plate of 7075-T6 that was electro-discharge wire cut along its center plane. Note the 0.085-inch mid-length distortions that occurred in each half when the plate was cut into two pieces and the dramatic extent of this distortion.

**Figure 1. Distortion in 7075-T6 Plate Electro-Discharge Machined Along Its Centerplane.**

Distortions such as these resulted in very high rejection rates during manufacturing of high strength aluminum alloy frames for satellite mechanical and electrical components. Reducing these rejection rates by overcoming excessive residual stress-induced machining distortion was the impetus for this study.

Residual stresses develop because of non-uniform cooling and the associated contractions that occur during the quench. When relatively thick parts are initially immersed in the quench bath, the surfaces cool first and thus contract more rapidly than the interior. At this time (early in the quench) the hot interior provides little resistance to the contraction of the surfaces – the soft interior plastically deforms to accommodate surface contraction. Later in the quench, however, when the interior cools and wants to contract, its contraction is resisted by the now cold and relatively strong near-surface material. As a result, tensile stresses develop in the interior. The material there wants to contract, but cannot. These tensile interior stresses are balanced by compressive stresses that develop near the surface. These represent the forces that resist contraction of the cooling interior. A symmetric pattern of residual stress develops with maximum compression on each surface and maximum tension along the centerline.

Figure 2 shows patterns of balanced residual stresses through the thickness of a quenched plate with maximum compressive (negative) stresses at each surface and maximum tensile (positive) stresses at the center plane. This illustrates a simple case of a quenched semi-infinite plate. Residual stress patterns can be much more complex in less regular parts. This report will consider only semi-infinite quenched plates, presuming that these reasonably approximate the distorting elements in satellite boxes.

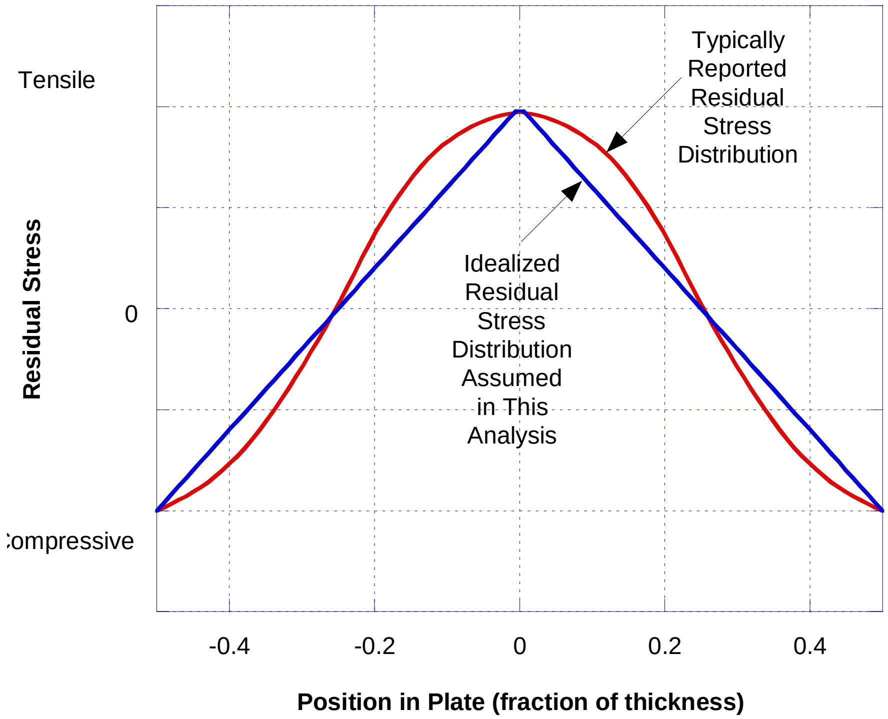


**Figure 2. Balanced Residual Stresses Example.**

The magnitudes of the peak compressive and tensile residual stresses in as-quenched material depend on the severity of the quench,[1] the thickness of the plate,[1] and as will be shown, the yield strength of the material in the as-quenched condition. Typically, residual stresses are quite low in thin sheets and plates, increase with increasing plate thickness, and reach as-quenched yield strength in very thick plates. This occurs because quench uniformity decreases with increasing thickness, i.e., thicker plates exhibit larger surface-to-center temperature differentials during quenching, leading to higher residual stresses.

Bending distortion occurs during subsequent machining when material is removed asymmetrically with respect to the residual stress pattern. Taking the simplest case of a quenched plate with peak compressive stresses on each surface and peak tensile stress on the centerplane, as shown in Figure 2, consider what would happen if the plate was wire electrical discharge machined along its centerplane. The tensile and compressive stresses in each resulting half-plate would no longer be symmetrically balanced – in the absence of shape changes the original surfaces would be in compression, and the opposite surfaces (formerly the centerplane) would be in tension. The resulting stress distribution in each half would be similar to that in an elastically bent beam – tension on one side and compression on the opposite side. When the externally applied bending couples are removed from such a beam it deflects in order to reduce both the tensile and compressive stresses. More precisely, the beam deflects in a way that minimizes its elastic strain energy. The same thing happens in the half plates containing unbalanced residual stresses – each half bends to minimize the elastic strain energy associated with its residual stresses. The result is shown in Figure 1. The compressively stressed regions become the convex sides of the bend (they become longer, thus relieving the compressive elastic stresses), while the regions formerly near the centerplane (in residual tension) become the concave sides (they become shorter, thus relieving the tensile elastic stresses).

This study was conducted to investigate the effectiveness of various approaches to minimizing quench-induced residual stresses and overcoming machining distortion in age-hardening aluminum alloys. Four approaches were considered:

- quenching in warm water (at the end of solution heat treatment) – this reduces the magnitude of residual stresses introduced during the quench, but can prevent full supersaturation from being obtained, thus decreasing the strength achieved by subsequent age hardening,
- mechanical stress leveling (following quenching, before aging) – this reduces residual stress magnitude with no strength penalty, but can be difficult to apply to geometrically complex parts,
- thermal stress relieving (during traditional aging or non-traditional overaging) – relatively small amounts of stress relief occur during traditional age hardening; more stress relief occurs during overaging, but typically at the expense of unacceptable decreases in strength,
- cold straightening (following aging) – this does not decrease residual stress magnitude, but alters residual stress patterns; however, cold straightened parts can re-distort severely during subsequent machining.

## 2. EXPERIMENTAL

Two common age-hardening aluminum alloys were selected for investigation, 7075 and 6061, to represent the opposite extremes in a number of important respects:

- 7075 can be age hardened to very high strength, whereas 6061 is only moderately age hardenable,[2,3]
- 7075 must be very rapidly quenched in order to be fully age hardenable, whereas 6061 can tolerate less severe quenching,[4]
- 7075 is considerably stronger than 6061 in the as-quenched condition.[5] While as-quenched yield strength is not an important engineering design parameter, it can have a profound influence on residual stresses, particularly in relatively thick sections.

The effects of various processes on residual stress magnitude and tendency for distortion during machining were determined by measuring the deflections that occurred when plate samples were sectioned along their centerplanes, as was outlined in the previous section. Samples 10- inches-long x 4- inches wide with thicknesses ranging from 0.25 to 1.0 inch were examined. Following various combinations of quenching, mechanical stress leveling, and aging, these samples were milled from one side to centerplane, thus resulting in test pieces corresponding to half the original samples. The amount of mid-length deflection that occurred when each test piece was unclamped from the milling table was measured using a dial gauge. The accuracy of these distortion measurements was approximately ± 0.002 inch.

Residual stress magnitudes were determined from the amounts of mid-length deflection based on strength of materials relationships for elastically deformed beams in pure bending (roughly equivalent to bending from in-plane residual stresses). For a plate in pure bending, stresses vary linearly through the thickness according to[6]:

$$\sigma = Mc/I = 12Mc/wt^3, \qquad \text{(Eq. 1)}$$

where:
M = bending moment applied at each end of plate,
I = moment of inertia (= $wt^3/12$ for rectangular cross-sections),
c = distance from neutral axis (centerplane),
w = plate width, and
t = plate thickness.

Deflection in pure bending is given by:[6]

$$\delta = Ml^2/8EI = 3Ml^2/2Ewt^3, \qquad \text{(Eq. 2)}$$

where:
$\delta$ = deflection at mid-length,
l = length of plate,
E = elastic modulus (= $10 \times 10^6$ psi for Al alloys).

Combining these equations and solving for peak stress (outer fiber stress, i.e., where c = t/2) as a function of deflection gives:

$$\sigma_{max} = 4Et\delta/l^2. \qquad \text{(Eq. 3)}$$

Equation 3 was used throughout this study to calculate peak residual stress magnitudes from the measured mid-length distortions. Obviously, the values of thickness used in these calculations corresponded to the thicknesses of the samples *after* milling, i.e., half the original plate thicknesses.

The development of Equation 3 assumes that residual stress magnitudes vary linearly with distance from center thickness, as shown in straight-line profile in Figure 2. However, most investigators report that residual stress distributions are not linear, but are typically similar to those shown in the alternative profile in Figure 2. The extent of the error introduced by the assumption of linear stress distribution was assessed by sectioning identically processed 1-inch-thick 7075-T6 plates at quarter-thickness and half-thickness. Any error introduced by the linear stress assumption should be reflected in differences in the amounts of distortion between the quarter-thickness and half-thickness test pieces. The distortions measured were identical within 3%, indicating that very little error was introduced by this assumption.

Several samples were also sectioned via wire electrical discharge machining to ensure that the traditional milling process used in preparing most test pieces did not alter or introduce residual stresses. No differences were observed in the deflections of wire electrical discharge machined versus milled test pieces.

Tensile tests were conducted on samples from 0.25-inch-thick plates of as-quenched 7075 and 6061. These tests were performed within 15 minutes of quenching to ensure that no room-temperature aging occurred.

Tensile tests were also performed on samples taken from near the centers of plates that had been quenched in water at various temperatures before age hardening. These plates ranged in thickness from 0.25 inch to 12 inches. Most 7075 samples had been aged to the T73 condition, whereas 6061 samples had been aged to the T6 condition or a variety of non-standard overaged conditions.

# 3. RESULTS AND DISCUSSION

Throughout this study deflection was the directly measured parameter; peak residual stress magnitude was calculated from deflection based on Equation 3. Hence, it would seem logical to first present and discuss the measured deflections (also referred to as distortions), followed by presentation and discussion of residual stress magnitudes. However, as will become apparent, trends in distortion magnitude sometimes seem confusing until considered in the context of residual stress magnitude. Because of this, residual stress magnitudes will sometimes be discussed first, followed by discussion of distortions.

Similarly, while much of the experimental work in this study focused on methods for *reducing* residual stress, it is important that the reader first understand the *development* of residual stresses in as-quenched material. For the sake of clarity, the results will be presented and discussed in the following order:

1. Residual stresses and machining distortion in fully-quenched material,
2. Stress relieving during conventional age hardening and non-conventional overaging,
3. Quench rate effects:
    a. Effects of section thickness on strength,
    b. Quenching in warm water to reduce residual stresses,
4. Mechanical stress leveling,
5. Cold straightening

## 3.1 Residual Stresses and Machining Distortion in Fully-Quenched Plates

Samples of 7075 and 6061 of varying thickness were tested in the as-quenched condition. These samples were heat treated and quenched in a fixture designed to prevent bending during the quench and to simulate quenching conditions in satellite boxes with roughed-in pockets. Solution heat treatment was done for one hour at the standard temperatures for these alloys (900°F for 7075, 985°F for 6061). The fixtures were then quenched edge-on into unagitated water at room temperature. After removal from the quenching fixture, each residual stress/distortion sample was milled to centerplane. The post-milling distortions were measured as previously described. Peak residual stress magnitudes were calculated from these distortions using Equation 3.

Tensile stress-strain curves for as-quenched 7075 and 6061 are shown in Figures 3 and 4, respectively.

Figure 3 shows a tensile stress-strain curve of as-quenched 7075.

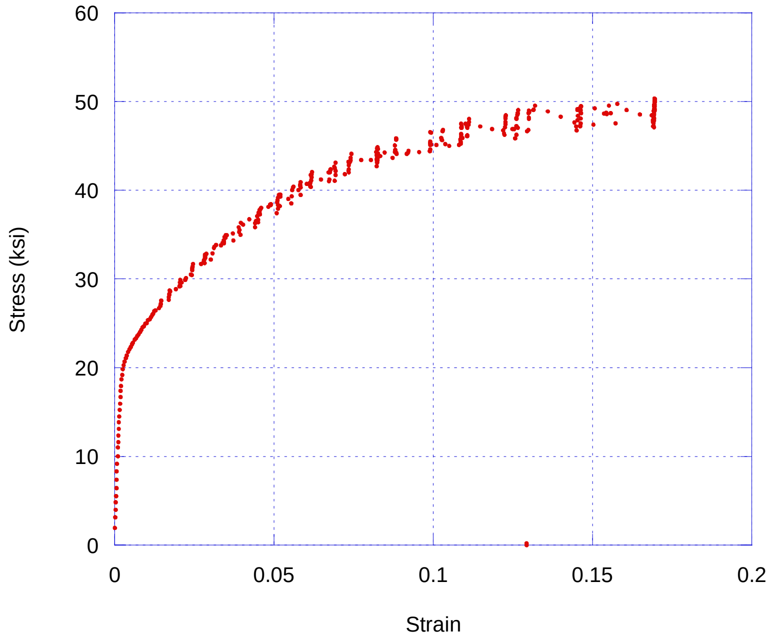


**Figure 3. Tensile Stress-Strain Curve of As-Quenched 7075.**

Figure 4 shows a tensile stress-strain curve of as-quenched 6061.

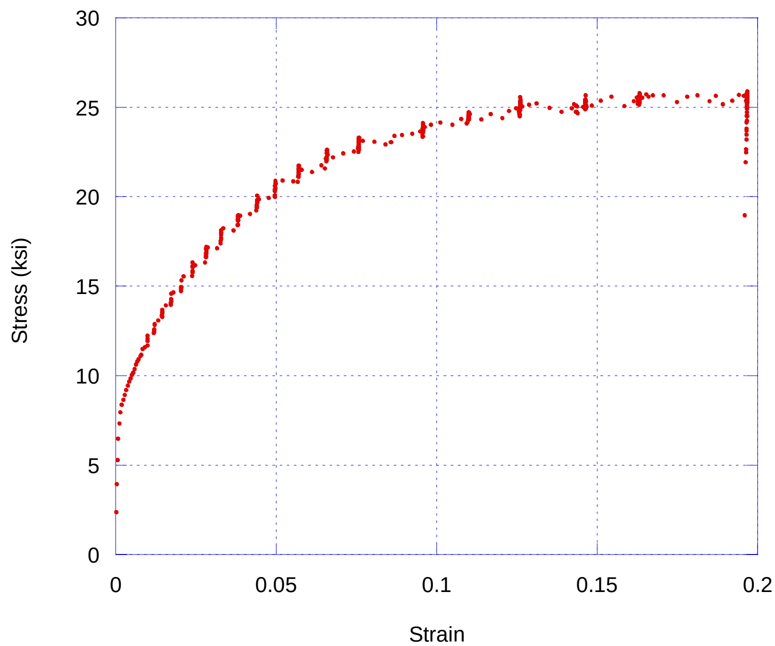


**Figure 4. Tensile Stress-Strain Curve of As-Quenched 6061.**

These tensile samples had been pre-machined before heat treatment and were tested within 15 minutes of quenching. The 0.2% offset yield strength of as-quenched 7075 was 22 ksi. This is in excellent agreement with the previously reported value of 21 ksi.[5] The 0.2% offset yield strength of as-quenched 6061 was 9 ksi. This is in good agreement with the previously reported value of 8 ksi.[5] These as-quenched yield strengths effectively limit the residual stress magnitudes in relatively thick plates, as is crucial to understanding the trends in machining distortion that will be discussed in the following paragraphs. The irregularities in the plastic portions of the stress-strain curves are due to discontinuous plastic deformation, i.e., the formation of Luder lines. Luder lines are commonly observed during straining of solid solution strengthened Al-Mg alloys, as well as age hardening alloys in the as-quenched condition.[7]

Table 1 shows measured mid-length distortions and calculated peak residual stresses in as-quenched samples. The residual stress/distortion results are discussed in the following paragraphs.

**Table 1. Measured Mid-Length Distortions and Calculated Peak Residual Stresses in As-Quenched Samples**

| Alloy | Quenched Thickness (inches) | Peak Residual Stress (ksi) | Deflection at Mid-length* (after milling to centerplane) (inch) |
|---|---|---|---|
| 7075 | 1.0 | 16.4 | 0.082 |
| 7075 | 0.5 | 7.6 | 0.076 |
| 7075 | 0.25 | 3.1 | 0.063 |
| | | | |
| 6061 | 1.0 | 9.0 | 0.045 |
| 6061 | 0.5 | 7.6 | 0.076 |

* All 10-inch-long samples.

### *3.1.1 7075 Aluminum Alloy*

Table 1 shows that the peak residual stress in 1-inch-thick 7075 was 16.4 ksi. This is slightly lower than the ~22 ksi yield strength of as-quenched 7075. Residual stress magnitude decreased dramatically with decreasing plate thickness. This is a reflection of how surface-to-center temperature differentials during the quench decrease with decreasing thickness.[8,9] A plot of peak residual stress versus thickness is shown in Figure 5. It can be seen that residual stress magnitudes in 7075 plates thinner than ~1.3 inches are controlled by temperature gradients during the quench. In plates thicker than ~1.3 inches, peak residual stresses would be limited by the yield strength in the as-quenched condition, i.e., ~22 ksi.

Table 1 also shows that the extent of machining distortion decreases only slightly in thinner plates. Distortion varies much less dramatically than peak stress because the thinner plates have much lower moments of inertia and are, therefore, elastically less stiff. This can be understood in terms of Equations 2 and 3. Equation 2 indicates that elastic stiffness varies inversely with thickness cubed. Rearranging Equation 3 to solve for deflection gives:

$$\delta = \sigma_{max} l^2 / 4Et. \qquad \text{(Eq. 4)}$$

Based on Equation 4 it can be seen that deflection will remain constant if peak residual stress decreases linearly with decreasing thickness. The slightly lower deflections observed in thinner plates (Table 1) is a manifestation of the fact that peak residual stresses decrease slightly more than linearly with decreasing plate thickness. This is consistent with expectations based on thermal analysis,[8,9] as well as with experimental results on cylindrical samples of aluminum alloys.[1]

This has significant implications regarding thickness and machining distortion. While it results in lower residual stresses in relatively thin sections, starting with thinner material does not in and of itself assure dramatic reductions in machining distortion. The primary benefit of quenching thinner starting sections is that it reduces overstock (the amount of material that must be machined off to reach final thickness). When less material must be machined off, the residual stress patterns will be less disturbed. Reducing this level of disturbance is more critical to minimizing machining distortion than is reducing residual stress magnitude, per se. The issue of overstock and machining distortion will be discussed more fully in Section 4.3.

### *3.1.2 6061 Aluminum Alloy*

Table 1 shows that the peak residual stress in 1-inch-thick 6061 was 9.0 ksi, equal to the yield strength of as-quenched 6061. Hence the peak residual stress in 1-inch-thick 6061 is limited by the yield strength of the as-quenched material, rather than by the surface-to-center temperature differential during the quench.

Table 1 also shows that identical residual stresses and distortions were observed in 0.5-inch thick samples of 6061 and 7075. Since both alloys have very similar thermal properties, approximately equal thermal gradients develop during quenching. Their identical distortions indicate that residual stress development was controlled by surface-to-center temperature differential in 0.6-inch-thick samples of both alloys. Based on this, it can be concluded that stress magnitudes in both 6061 and 7075 should be essentially equal in plates thinner than 0.6 inch.

Figure 5 shows the effect of thickness on maximum residual stress in as-quenched 7075 and 6061. Residual stress increases with increasing thickness up to as-quenched yield strength. Beyond that, residual stress is limited by the as-quenched yield strength of the material.

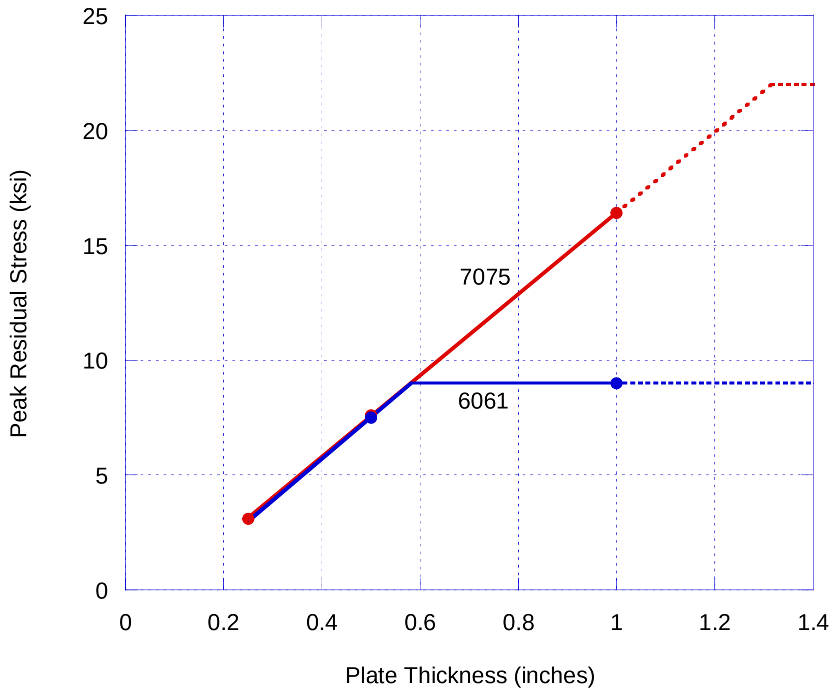


**Figure 5. Residual Stress Increases with Increasing Thickness Up to As-Quenched Yield Strength.**

Based on the measured 9 ksi yield strength of 6061, Figure 5 indicates that residual stresses are limited by as-quenched yield strength in 6061 plates thicker than 0.6 inch.

Significantly more machining distortion occurred in the 0.5-inch-thick 6061 plate than in its 1-inch thick counterpart, as can be seen in Table 1. At first this may seem inconsistent with the distortion trend observed in 7075. However, in 7075 peak residual stress magnitudes decreased dramatically with decreasing thickness because they were controlled by thermal gradients over the entire range of thicknesses investigated. This was not true in 6061: here peak residual stresses were limited by *yield strength* in the 1-inch-thick sample, but by *thermal gradients* in the 0.5 inch-thick sample. Because of this change in the stress-controlling factor, relatively little reduction in residual stress occurred on decreasing thickness from 1 to 0.5 inch. Equation 4 indicates that a small decrease in residual stress combined with a substantial decrease in thickness should produce an increase in distortion – this is exactly what was observed: more machining distortion occurred in the thinner sample of as-quenched 6061.

The overall conclusion is communicated by Figure 5. Residual stresses increase with increasing thickness until the as-quenched yield strength is reached. In thicknesses beyond this, residual stresses are limited by the as-quenched yield strength of the material. This constitutes a substantial advantage for 6061 over 7075 in relatively thick sections, as the as-quenched yield strength of 6061 is only 41% that of 7075. Hence, distortions during machining of parts from relatively thick sections of 6061 will be less than half of those typical of 7075, all other things being equal.

## 3.2 Stress Relieving During Age Hardening and Overaging

Residual stresses can be reduced or eliminated in a wide range of metals and alloys by elevated temperature exposure. Reduction of residual stresses typically begins at temperatures in the vicinity of 0.45 absolute melting temperature (~300°F for aluminum), and complete stress relief is typically obtained in the vicinity of 0.6 absolute melting temperature (~550°F for aluminum). Based on this, partial stress relieving may or may not be expected to occur in 7075 and 6061 during conventional age hardening (at 250 to 350°F). Accelerated stress relieving has been observed in both steels and uranium alloys, however, when fine second phase particles are formed during the stress-relieving process.[10,11] Substantial stress relieving would be expected to occur during overaging at higher temperatures.

### *3.2.1 Stress Relieving During Conventional Age Hardening*

The effects of age-hardening heat treatments were assessed using 1-inch-thick samples and age hardening them following solution heat treatment and quenching in 75°F water. 7075 was aged to two standard conditions: T6 (peak strength) and T73 (a slightly overaged condition that produces 12 to 15% lower strength, but substantially increases fracture toughness and resistance to stress corrosion cracking). 6061 was aged to the standard T6 condition (peak strength).

The post-milling distortions and calculated residual stress magnitudes are shown in Table 2. It can be seen that no stress relief occurred in 7075 aged at 250°F/24 hours (T6 condition), 22% stress relief occurred in 6061 aged at 320°F/18 hours (T6 condition), and 36% stress relief occurred in 7075 aged at 350°F/8 hours (T73 condition).

**Table 2. Effects of Age Hardening on Peak Residual Stresses**

| Alloy | Aged Condition | Peak Residual Stress (ksi) | Deflection at Mid-length* (after milling to centerplane) (inch) | % Stress Relief During Aging |
|---|---|---|---|---|
| 7075 | T6 (24 hours at 250°F/120°C) | 17.0 | 0.085 | 0 |
| 7075 | T73 (6 to 8 hours at 225°F/107°C, followed by 8-10 hours at 350°F/177°C) | 10.5 | 0.0525 | 36% |
| | | | | |
| 6061 | T6 (18 hours at 320°F/160°C) | 7.0 | 0.035 | 22% |

* All 10-inch-long samples.

Stress relieving that occurs during age hardening is difficult to model, as stress relaxation occurs concurrent with dramatic (factor of ~5) increases in strength. Research on other alloys has shown that stress relieving is accelerated and relatively insensitive to stress magnitude during the formation of fine second phases.[10,11] Despite this acceleration, 250°F appears to be below the threshold for significant stress relieving in age-hardening aluminum alloys. Stress relieving during aging appears to begin in the vicinity of 275-300°F. Considering that initial stresses in 6061 are only ~40% of those in 7075, the regular trend in percent stress relief with increasing temperature seems qualitatively consistent with the stress insensitivity reported for other alloys.

From an engineering perspective, the most important observation is that only relatively small percentages of the quench-induced residual stresses were relieved during conventional age hardening. Accordingly, materials in these standard age-hardened conditions are likely to be subject to substantial distortion during machining.

### *3.2.2 Stress Relieving During Overaging*

The effects of overaging on residual stresses and mechanical properties were assessed using 1-inch-thick samples that were overaged following solution heat treatment and quenching in 75°F water. Following overaging these samples were milled to centerline as described in Section 3. Deflections were measured and maximum residual stresses remaining were calculated from these deflections via Equation 3. Tensile samples were also tested to quantify how yield strength and ultimate tensile strength decreased on overaging.

Emphasis was placed on 6061-T6 because decreases in strength during initial overaging are reported to be gradual in this alloy, compared to 7075-T73, which is already on the steep portion of the overaging curve.[4] In addition, programmatic considerations dictated that high priority be given to assessing the feasibility of overcoming machining distortion in 6061-T6 by subsequent "stress relieving heat treatments."

6061 samples were overaged beyond the T6 condition (320°F/18 hours) at temperatures of 350 to 530°F for 18 hours. Less emphasis was placed on 7075 – a single sample was overaged beyond the T73 condition to 375°F/8 hours (a period of 225°F/8 hours preceded this, for consistency with the T73 treatment of 225°F/8 hours followed by 350°F/8 hours). The experimentally determined effects of overaging on residual stress in these alloys are shown in Figures 6 and 7, respectively, along with values predicted by the calculations described below.

Figure 6 shows peak residual stresses after overaging of 1-inch-thick 6061 plates for 18 hours. The 320°F data corresponds to the T6 condition.

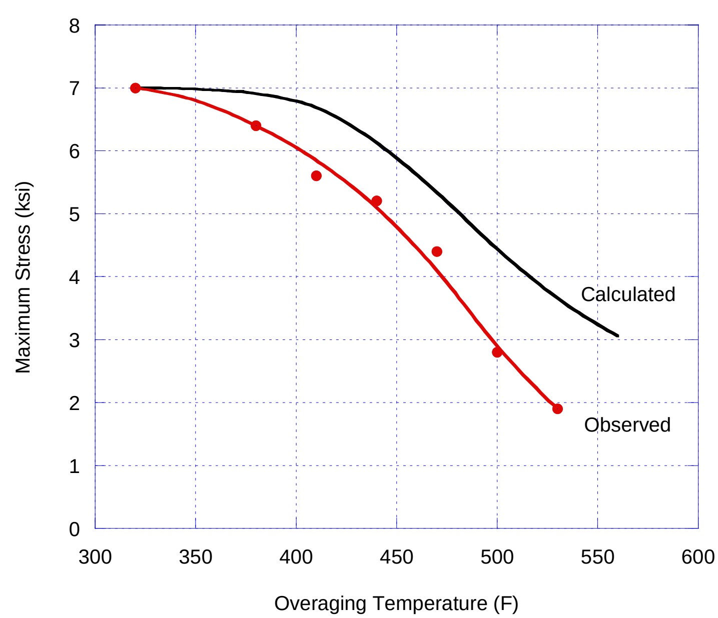


**Figure 6. Peak Residual Stresses After Overaging 18 Hours (6061).**

Figure 7 shows peak residual stresses after overaging of 1-inch-thick 7075 plates for eight hours. The 250°F data corresponds to the T6 condition (this sample was aged for 24 hours), and the 350°F data corresponds to the T73 condition. The 350°F and 375°F samples were pre-aged 225°F/8 hours for consistency with the standard T73 heat treatment.

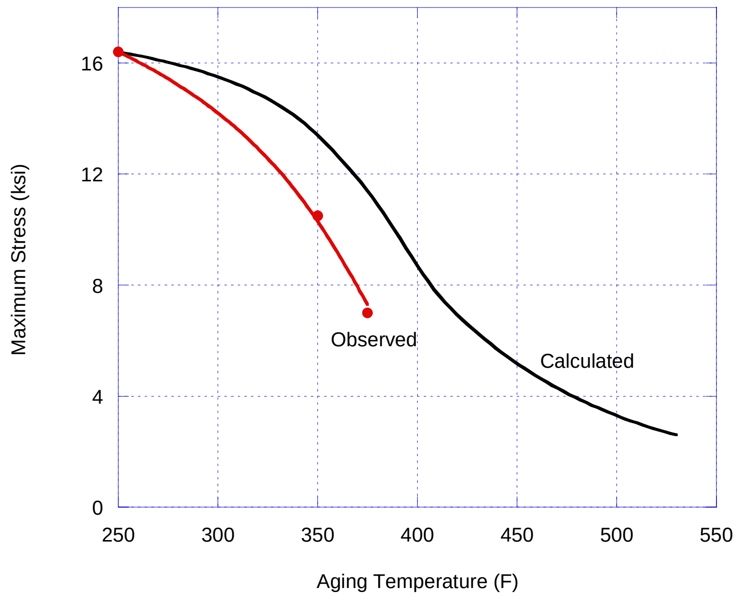


**Figure 7.  Peak Residual Stresses After Overaging 8 Hours (7075).**

Stress-relieving trends during overaging were interpreted based on published creep (elevated temperature time-dependent deformation) data for 6061-T6[12] and 7075-T6.[13] Creep deformation typically follows an equation of the form:

$$\text{Creep Rate} = d\varepsilon/dt = A\ \sigma^n \exp(-Q/RT), \qquad \text{(Eq. 5)}$$

where:
A = constant,
σ = stress,
n = constant characteristic of material and deformation process,
Q = activation energy,
R = gas constant,
T = absolute temperature.

Published creep data for 6061-T6[12] and 7075-T6[13] were evaluated to determine best-fit values of A, n, and Q. The values of Q, 36.8 and 39.1 kcal/mole for 6061 and 7075, respectively, are slightly higher than those for self-diffusion in aluminum, typically reported to be in the range 30-35 kcal/mole.[14] The values of n, 6.25 and 5.50 for 6061 and 7075, respectively, are moderately higher than that of pure aluminum, typically reported as ~4.[15] These best-fit values were substituted into Equation 5, combined with Hooke's law:

$$\sigma = E\varepsilon, \qquad \text{(Eq. 6)}$$

where:
E = elastic modulus,
$\varepsilon$ = strain

and rearranged into differential equations of the form:

$$\int \sigma^{-n}\, d\sigma = AE \exp(-Q/RT) \int dt. \qquad \text{(Eq. 7)}$$

Solution of Equation 7 provided the following equations for the residual stress remaining in 6061 and 7075, respectively, following overaging:

6061: $$\sigma = [\sigma_0^{-5.25} + 2.51\mathrm{x}10^{10} \exp(-36{,}811/1.987T)t]^{-0.19048}, \qquad \text{(Eq. 8)}$$

7075: $$\sigma = [\sigma_0^{-4.50} + 5.58\mathrm{x}10^{12} \exp(-39{,}124/1.987T)t]^{-0.22222}, \qquad \text{(Eq. 9)}$$

where:
$\sigma$ = residual stress remaining after overaging,
$\sigma_0$ = residual stress prior to overaging,
T = overaging temperature (K),
t = overaging time (hours).

The calculated effects of overaging temperature and time on peak residual stresses in 6061 and 7075 are shown in Figures 8 and 9, respectively.

The trends in measured stress follow those calculated for both alloys, but the calculations based on published creep data consistently underpredict actual stress relief by 20 to 50%. This is likely due to the fact that the published creep data reflect the higher strains characteristic of secondary (steady state) creep, while stress relief is controlled mostly by the smaller strains characteristic of more rapid primary creep. Figure 8 shows the calculated effects of overaging temperature and time on peak residual stresses in 1-inch-thick 6061 plate. Starting condition is assumed to be 6061-T6. Experimental results shown in Figure 6 indicate that calculations based on creep data[12] underestimate actual stress relief. Based on this, actual stresses remaining after overaging can be best estimated by applying a 40°F correction, i.e., the 440°F line provides a good estimate of actual peak residual stress following overaging at 400°F.

Figure 9 shows the calculated effects of overaging temperature and time on peak residual stresses in 1-inch-thick 7075 plate. Starting condition is assumed to be 7075-T6. Experimental results shown in Figure 7 indicate that calculations based on creep data[13] underestimate actual stress relief. Based on this, actual stresses remaining after overaging can be best estimated by applying a 40°F correction, i.e., the 440°F line provides a good estimate of actual peak residual stress following overaging at 400°F.

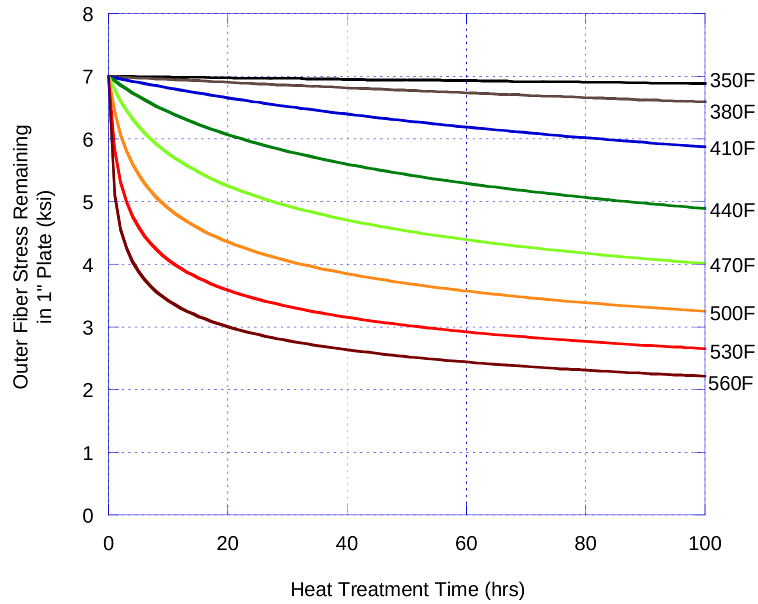


**Figure 8. Calculated Effects of Overaging Temperature and Time on Peak Residual Stresses (6061).**

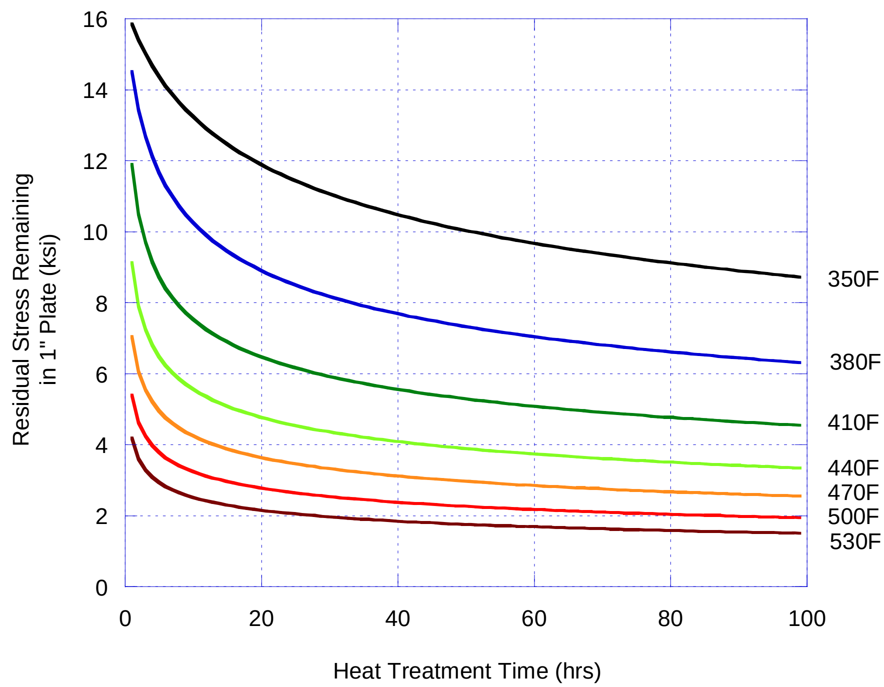


**Figure 9. Calculated Effects of Overaging Temperature and Time on Peak Residual Stresses (7075).**

The measured yield and ultimate tensile strengths of overaged 6061 and 7075 are shown in Figures 10 and 11, respectively.

Figure 10 shows the effect of overaging for 18 hours on yield strength and ultimate tensile strength of 6061. The 320°F data corresponds to the T6 condition.

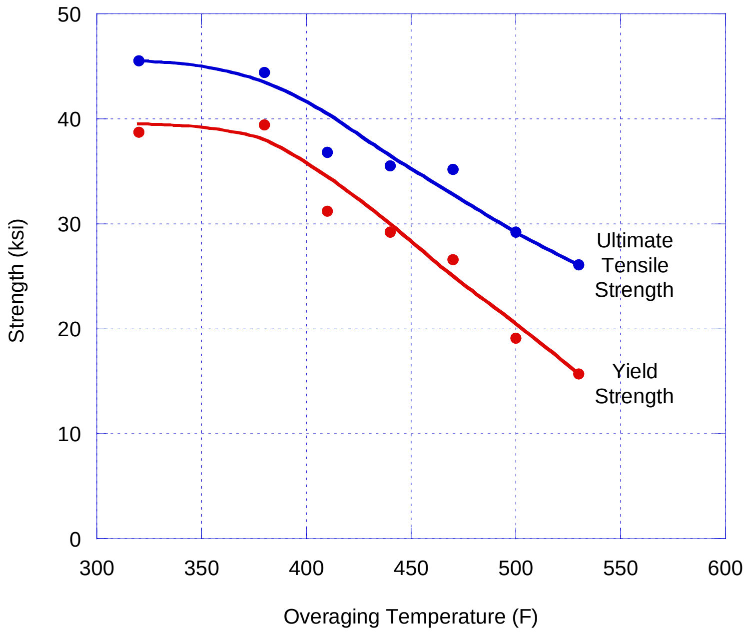


**Figure 10. Effect of Overaging for 18 Hours on Yield Strength and Ultimate Tensile Strength (6061).**

Figure 11 shows the effect of overaging for eight hours on yield strength and ultimate tensile strength of 7075. The 250°F data corresponds to the T6 condition, and the 350°F data corresponds to the T73 condition. The 350°F and 375°F samples were pre-aged 225°F/8 hours for consistency with the standard T73 heat treatment.

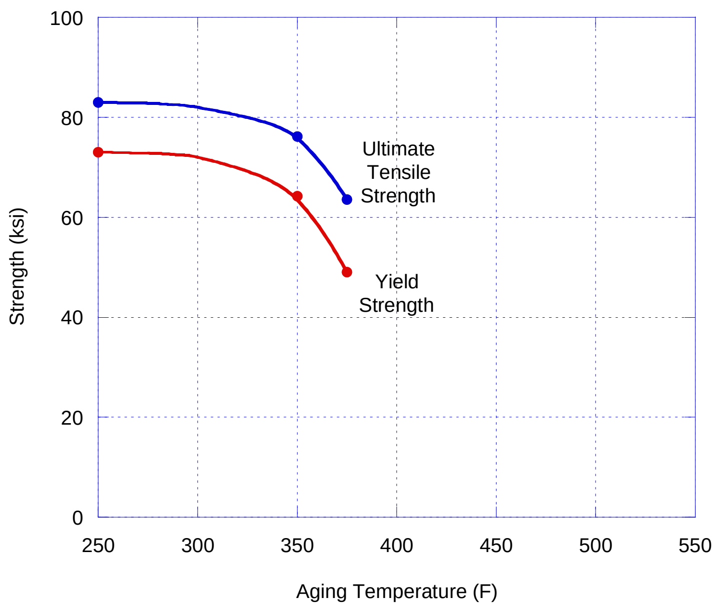


**Figure 11. Effect of Overaging for 18 Hours on Yield Strength and Ultimate Tensile Strength (7075).**

It is apparent that overaging results in substantial decreases in strength for both alloys. From a practical perspective, this makes overaging an unattractive approach for overcoming machining distortion in age-hardening aluminum alloys – the strength penalties typically outweigh the decreases in residual stress and machining distortion. Considerably more favorable combinations of high strength and low residual stresses were obtained by quenching in warm/hot water, as will be discussed in Section 3.3.2.

In particular, these results demonstrate the futility of efforts to "stabilize" parts that have distorted during initial machining by subjecting them to additional "stress-relieving heat treatments." Significant reductions in stress can be accomplished only by overaging at higher temperatures, which result in substantial reductions in strength. In addition, the distortions that occur during early machining decrease the magnitudes of the stresses initially present – the dramatic stress dependence inherent in further stress relieving (evident in Equations 8 and 9) accentuates the increase in temperature required to accomplish additional stress relief.

## 3.3 Quench Rate Effects

### *3.3.1 Effect of Section Thickness on Age-Hardened Strength*

Aluminum alloys must be quenched following solution heat treatment in order to retain the alloying elements in supersaturated solid solution. If cooled too slowly, complete supersaturation will not be retained and the material will not be fully hardened during subsequent aging.

The cooling rates at the centers of plates quenched in room temperature water are documented for standard plate thicknesses up to six inches.[4] The effects of quench rate on strength after subsequent age hardening has also been documented.[4] These data were extrapolated to greater thicknesses and lower cooling rates, then combined to provide predictions of the aged strengths in plates up to 12 inches thick (as have been used for manufacturing recent satellite boxes). The accuracy of these predictions was checked by machining and testing tensile samples from the interior decks and webs of boxes that had been produced from 12-inches-thick plates of 7075-T73 and 6061-T6 in which excessive distortion had occurred.

Figure 12 shows the effect of plate thickness on yield strength and ultimate tensile strength of 7075-T73 and 6061-T6. Lines represent predictions based on extrapolation of published cooling rate versus thickness data, combined with published strength versus cooling rate data.[4] Points indicate strength values measured in this study.

Figure 12 confirms that 7075 is much more quench rate sensitive than 6061, i.e., strength degrades much more dramatically with increasing plate thickness. The experimentally determined values for 12-inches-thick 7075-T73 were in good agreement with the predictions. Thick sections of 6061-T6 were somewhat stronger than predicted.

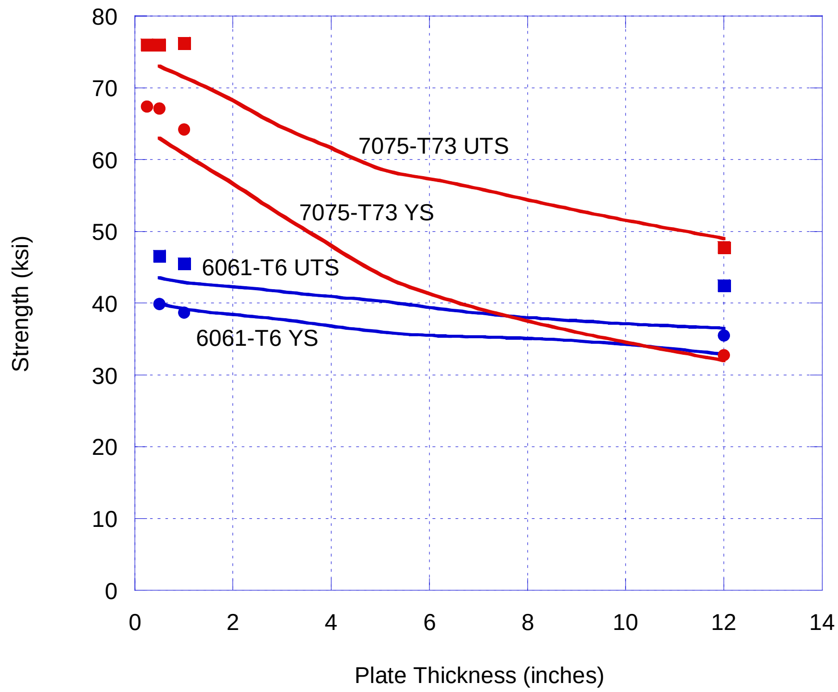


**Figure 12. Effect of Plate Thickness on Yield Strength and Ultimate Tensile Strength (7075-T73 and 6061-T6).**

Figure 12 shows that the yield strength of 6061-T6 is roughly equal to that of 7075-T73 when both are quenched in 12-inches thicknesses. This has important implications for the design and production of satellite boxes. In boxes made from thick plates, the yield strength of 6061-T6 will be roughly equal to that of 7075-T73 (actually slightly higher based on the experimental measurements made here). Ultimate tensile strength is somewhat higher in 7075-T73, but yield strength is a much more important design parameter. Because of this, there is no design advantage to using 7075-T73 over 6061-T6. However, there is a substantial manufacturing *disadvantage*. As was discussed in Sections 3.1 and 3.2, residual stresses in 7075-T73 will be much higher than those in 6061-T6, thus causing greater amounts of distortion in 7075-T73. So using 6061-T6 will minimize distortion without sacrificing yield strength. In cases where the potentially higher strength of 7075-T73 is needed, this material must be quenched in thinner sections. This will be discussed in detail in Section 4.

### *3.3.2 Quenching In Warm Water to Reduce Quench-Induced Residual Stresses*

Since quench-induced residual stresses result from thermal gradients in the material during the quench, reducing these surface-to-center temperature differentials is key to limiting residual stress development. This can potentially be accomplished in two ways: by reducing thickness, or by decreasing the effectiveness of the quench medium, e.g., by quenching in warm or hot water rather than cold water. This section will focus on the effects of quenching samples of varying thickness in pre-heated water.

Samples were solution heat treated as previously described, then quenched into water that had been pre-heated to controlled temperatures ranging from 75°F to 201°F. Following quenching the 7075 samples were aged to the T73 condition and the 6061 samples were aged to the T6 condition. Each sample was then milled from one side to its centerplane, and distortion measurements were made as previously described. Two tensile samples were also machined from each piece and tested to characterize the effects of decreased quench rate on aging response and strength.

Figures 13 through 15 show how machining distortion, residual stresses, and strength varied with quench water temperature in 1-inch-thick samples. As can be seen in Figure 13, relatively little distortion occurred in samples quenched into hot water because hot water cools the sample slowly, thus minimizing thermal gradients and the development of residual stresses. Distortion increased with decreasing quench water temperature, as expected. Essentially equal distortions occurred in 6061 and 7075 samples down to ~150°F. Below ~150°F distortion continued to decrease in 7075, but remained essentially constant in 6061.

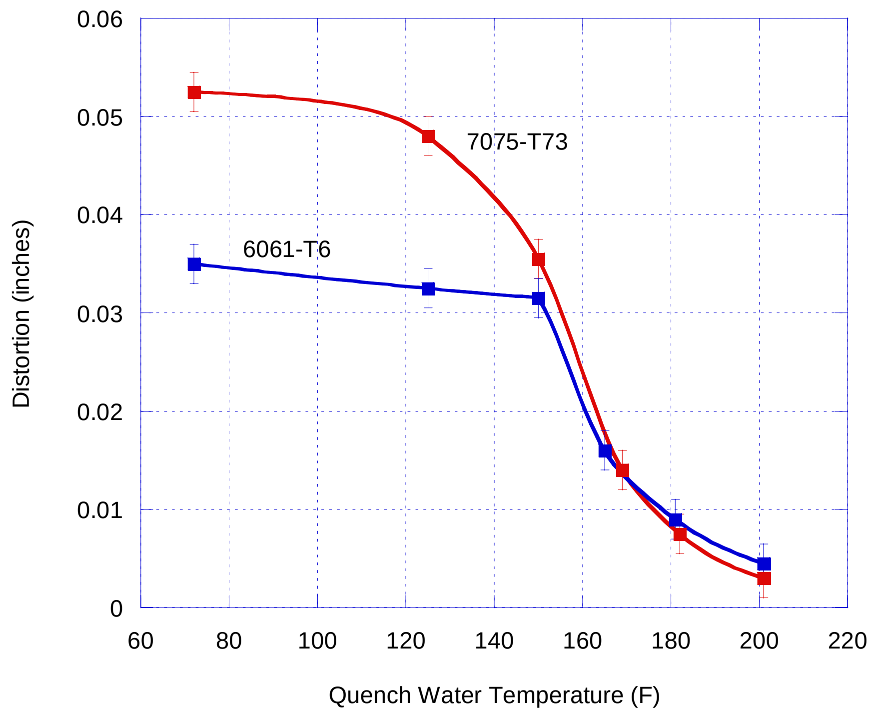


**Figure 13. Effect of Quench Water Temperature on Machining Distortion (7075-T73 and 6061-T6, 1 Inch Thick).**

The distortion behavior shown in Figure 13 can best be understood in terms of the peak residual stresses, shown in Figure 14.

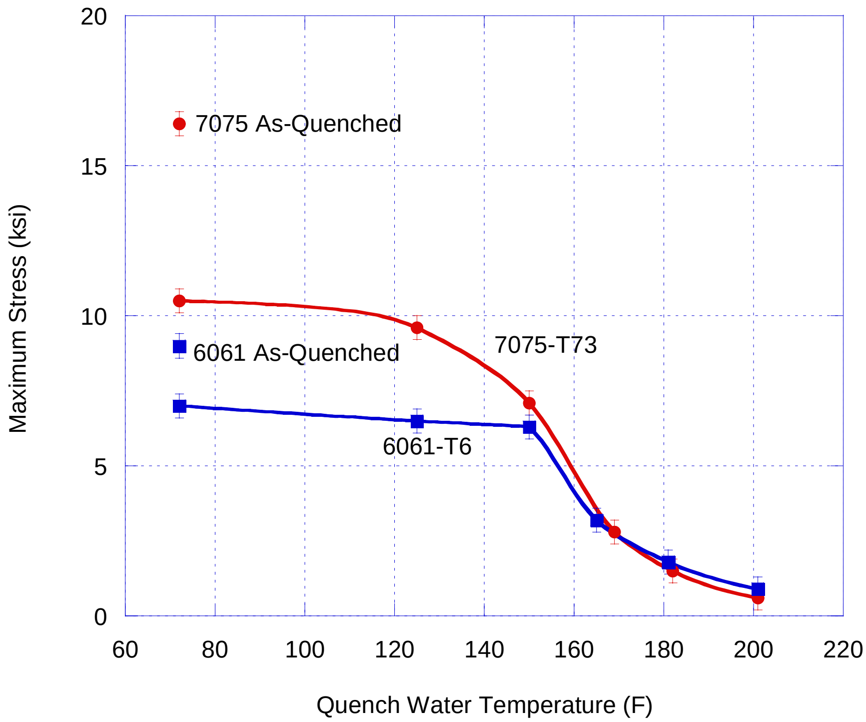


**Figure 14. Effect of Quench Water Temperature on Peak Residual Stress (7075-T73 and 6061-T6, 1 Inch Thick).**

As described in an earlier section, residual stress magnitudes in 1-inch-thick 7075 are controlled strictly by the severity of the thermal gradients in the plate during the quench. Accordingly, as-quenched residual stress magnitudes decreased continuously with increasing quench water temperature, and were then reduced by ~36% during subsequent aging to the T73 condition. The net result was a continuous decrease in 7075-T73 residual stresses with increasing quench water temperature. 6061-T6 behaved almost identically to 7075-T73 at quench water temperatures above ~150°F because thermal gradients in the two alloys were virtually identical (at any given quench temperature). Below ~150°F, however, peak residual stresses in 1-inch-thick 6061 were limited by as-quenched yield strength, rather than thermal gradient, so residual stress magnitude and distortion remained essentially constant.

Figure 15 shows how yield and ultimate tensile strengths degraded with increasing quench water temperature. 7075-T73 strengths began to drop off when quench water temperature exceeded ~140°F, and decreased rapidly above ~165°F. 6061-T6 strengths remained essentially constant up to a quench water temperature of ~180°F, and decreased only slightly above that. 6061 was more tolerant of higher quench water temperatures because it is considerably less quench rate sensitive than 7075, i.e., 7075 must be quenched at much higher cooling rates than 6061 in order to retain full supersaturation and be age hardenable to full strength.[4]

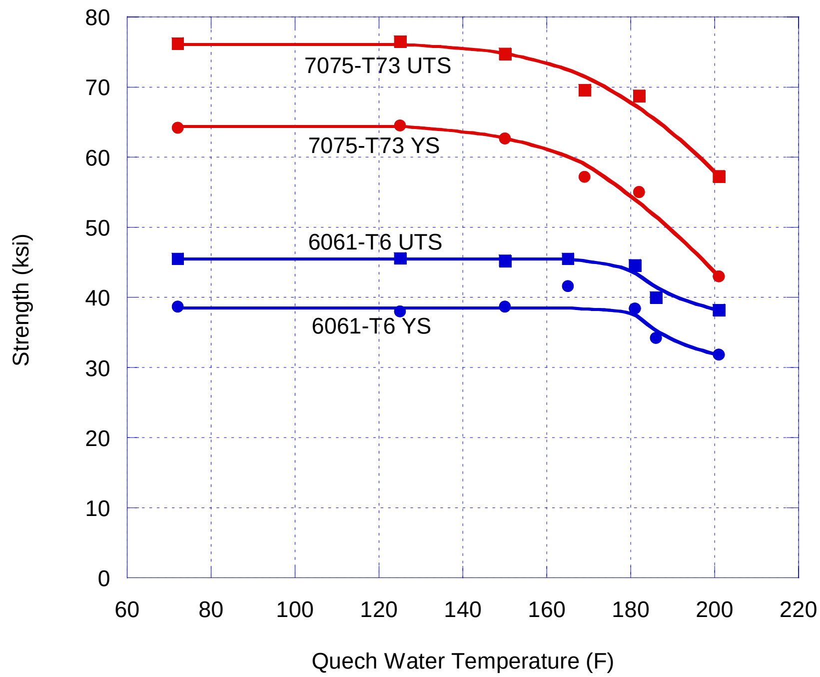


**Figure 15. Effect of Quench Water Temperature on Yield and Ultimate Tensile Strength (7075-T73 and 6061-T6, 1 Inch Thick).**

The effects of thickness variations in 6061 are shown in Figures 16 through 18.

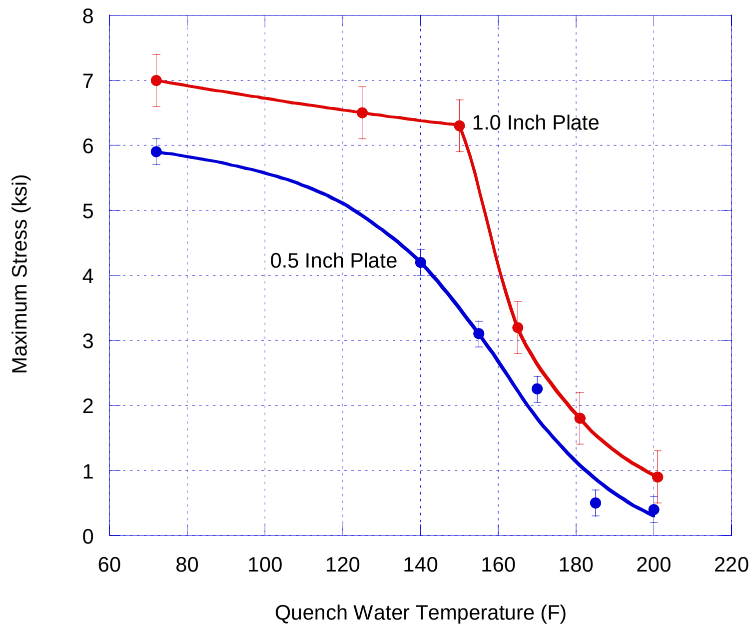


**Figure 16. Effect of Quench Water Temperature and Thickness on Peak Residual Stress (6061-T6).**

Figures 16 and 17 show that residual stresses and machining distortion decreased continuously with increasing quench water temperature in 0.5-inch-thick plates where residual stress development was controlled only by thermal gradients.

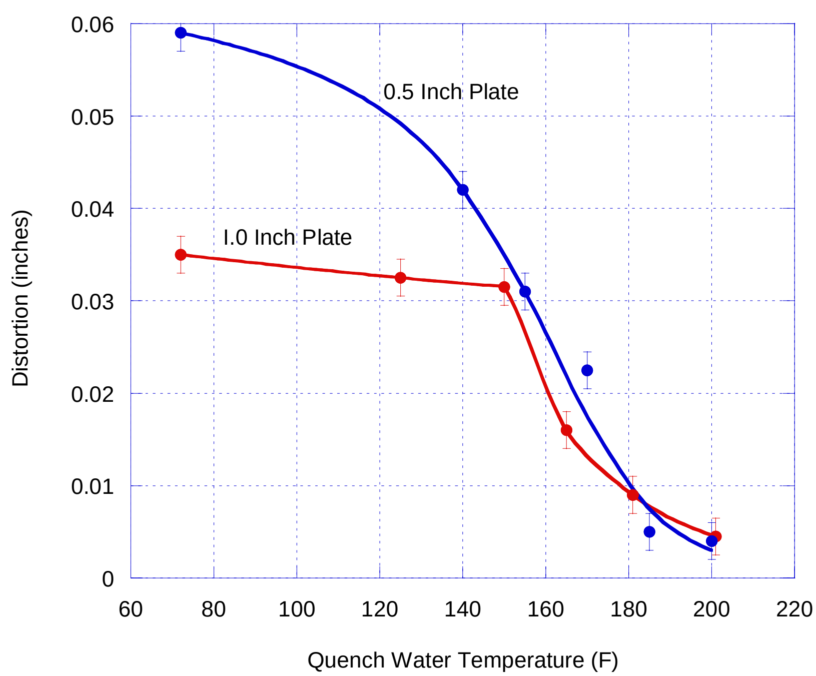


**Figure 17. Effect of Quench Water Temperature and Thickness on Distortion (6061-T6).**

Samples 1-inch-thick behaved similarly down to ~150°F. Below ~150°F, however, residual stresses were limited by as-quenched yield strength, so residual stress and distortion plateaued at lower quench water temperatures. Note in Figure 17 that this transition from as-quenched yield strength limited residual stress to thermal gradient controlled residual stress resulted in considerably greater machining distortion in the thinner plate, as was discussed previously in conjunction with Table 1.

Figure 18 shows that, while the strength of 1-inch-thick 6061-T6 began to drop off above a quench temperature of ~180°F, 0.5-inch-thick material exhibited almost no deterioration at temperatures up to 200°F.

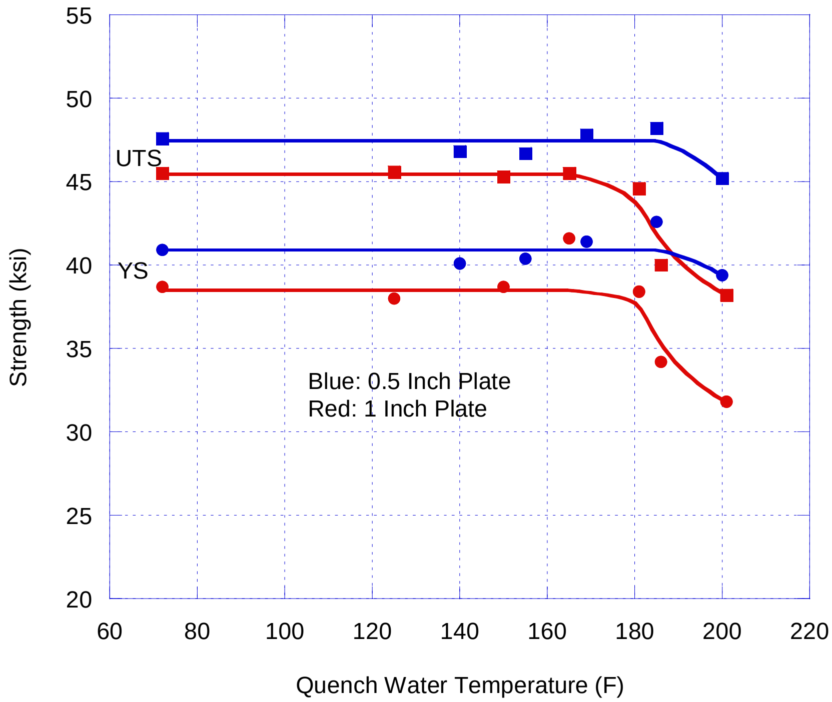


**Figure 18. Effect of Quench Water Temperature and Thickness on Yield and Ultimate Tensile Strength (6061-T6).**

The slight difference in strength between the 0.5-inch and 1-inch materials is believed to be due to slight heat-to-heat variations in chemistry, rather than quenching effects.

The effects of thickness variations in 7075 are shown in Figures 19 through 21. Figure 19 shows that residual stresses decreased continuously with increasing quench water temperature. In addition, stresses decreased substantially with decreasing plate thickness, as would be expected where residual stress development is controlled only by thermal gradients.

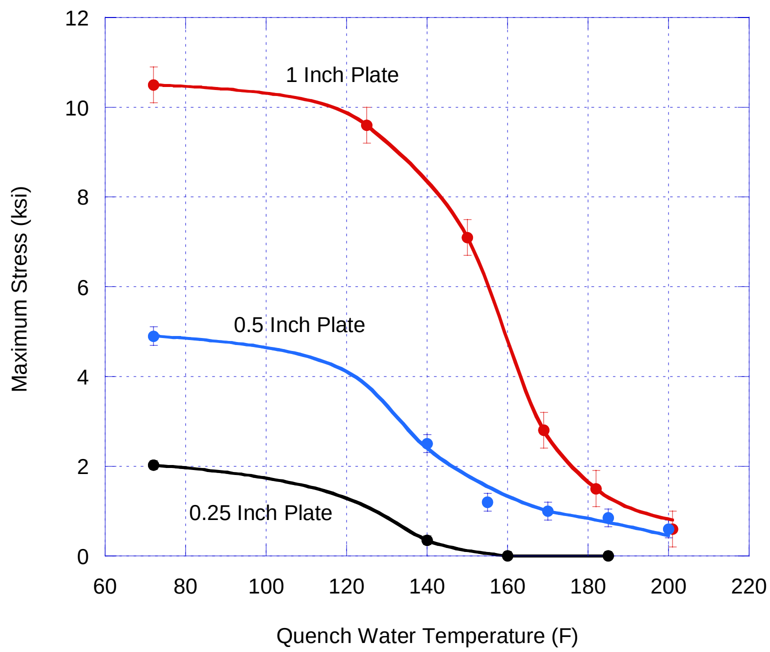


**Figure 19. Effect of Quench Water Temperature and Thickness on Peak Residual Stress (7075-T73).**

Figure 20 confirms that machining distortion decreased with increasing quench temperature and decreasing thickness.

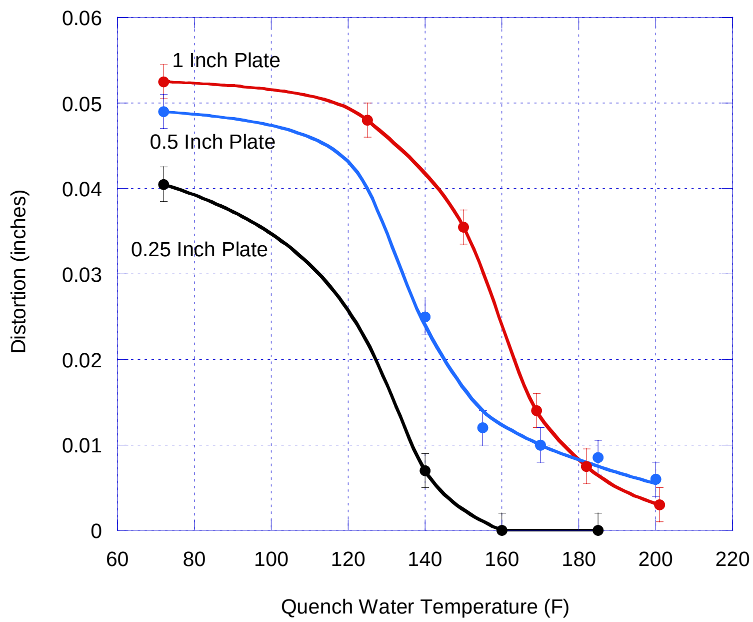


**Figure 20. Effect of Quench Water Temperature and Thickness on Distortion (7075-T73).**

Figure 21 indicates that 0.25-inch-thick plate retained good strength to higher quench temperatures. However, 0.5-inch-thick plate degraded with increasing quench temperature virtually identically to 1-inch plate. This unusual behavior could not be explained by any differences in heat treatment, and is believed to be due to variations in quench rate sensitivity associated with slight heat-to-heat variations in material composition.

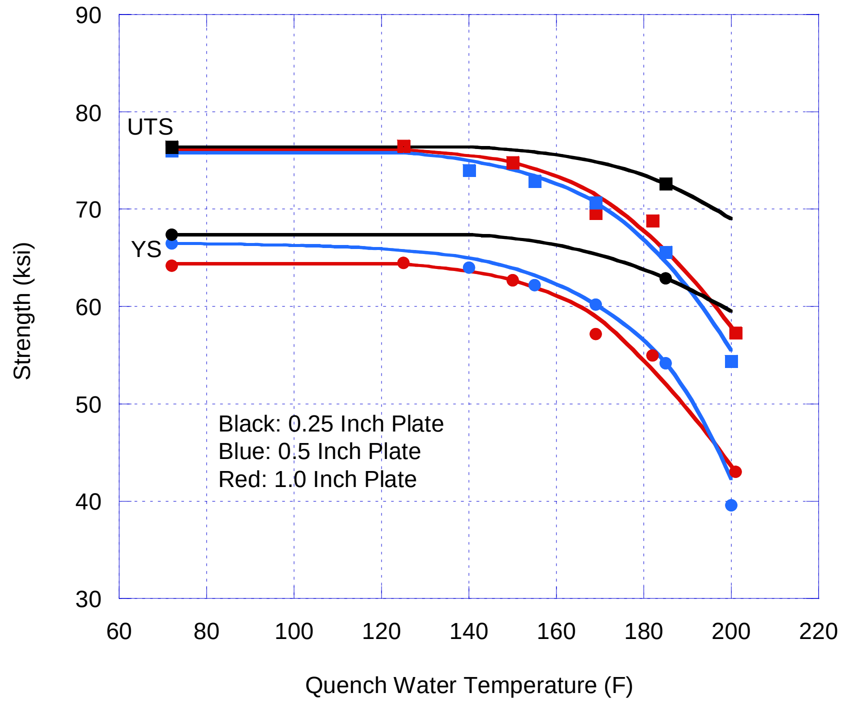


**Figure 21. Effect of Quench Water Temperature and Thickness on Yield and Ultimate Tensile Strength (7075-T73).**

Combining the residual stress, machining distortion, and strength information from Figures 5 and 12 through 21, it is apparent that 6061-T6 has significant advantages over 7075-T73 in distortion-sensitive applications. 6061 has much lower as-quenched yield strength than 7075. This results in lower quench-induced residual stresses and machining distortion, particularly in thicknesses over one inch. In addition, the lower quench rate sensitivity of 6061 makes it more amenable to quenching in thicker sections or in warm water with minimal reductions in strength. It appears that use of 7075-T73 should be limited to applications where strength requirements cannot be met by 6061-T6.

## 3.4 Mechanical Stress Leveling

Mechanical stress leveling is commonly employed to reduce residual stresses that have been introduced by quenching.[16] It consists of plastically deforming the material 1 to 3% after quenching and before aging, as illustrated in Figure 22.

Figure 22 shows the stress-strain curve illustrating how compressive stress leveling reduces residual stresses. Points A and B represent the initial peak residual stresses at the plate surface and center, respectively. During compressive stress leveling these move to positions A’ and B’ (separated by the same difference in strain, but now by a smaller difference in stress, as the compressive yield strength has been exceeded). These unload elastically to positions A” and B” following compressive stress leveling.

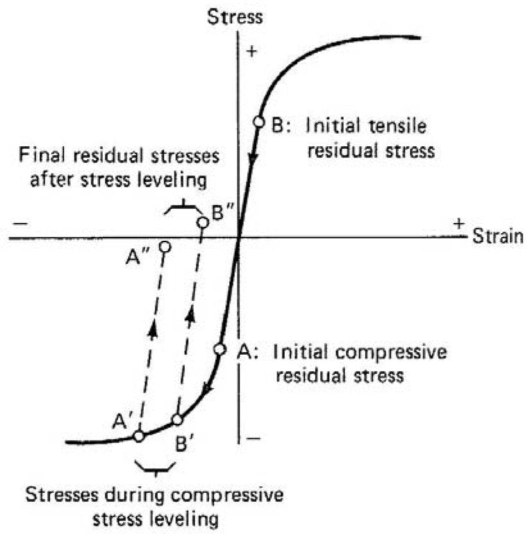


**Figure 22. Stress-Strain Curve.**

Considering this simple uniaxial example, when the regions of residual tension and residual compression are strained by equal amounts and beyond yield, the strain differential that manifested itself as a relatively high residual stress in the elastic region now corresponds to a much smaller stress differential in the plastic region of the stress-strain curve. Unloading occurs elastically, leaving the difference between peak tensile stress and peak compressive stress the same as they were during the plastic straining operation – much lower than they had been originally. Hence, the residual stress magnitude is substantially reduced. Stress leveling in tension is commonly applied to flat products. Tensile “stretching” before aging is common commercial mill practice in the production of 6061 and 7075 sheet and plate – both to reduce residual stresses and to straighten the plate. Less regular geometries, such as forgings, are more typically stress leveled in compression, as illustrated in Figure 22. In the satellite box application, tensile stress leveling could be applied to thick plates before roughing-in of the pockets. Typically, this would be done at the time the plate was manufactured. The temper designation of plates that have been stress leveled in tension before aging are Tx51, e.g., 6061-T651 or 7075-T7351. If the pockets were roughed in prior to solution treatment and quenching, however, compression parallel to the axes of the pockets would be the only option for introducing relatively uniform plastic strain. Boxes that had been compressively stress relieved in this way and then aged would be designated Tx52, e.g., 6061-T652 or 7075-T7352.

The simple uniaxial model presented in Figure 22 suggests that the fraction of residual stresses remaining after mechanical stress leveling should equal the slope of the plastic flow curve divided by the elastic modulus. This indicates that stress leveling should result in a residual stresses pattern similar to that shown in Figure 2, but reduced by 90 to 95% in magnitude from the original quench-induced stress levels. Unfortunately, it is not quite that straightforward in practice. Even in the simplest case of a quenched semi-infinite plate the residual stresses are biaxial, rather than uniaxial; however, mechanical stress leveling imposes deformation in only one dimension. In addition, while deformation is imposed in only one dimension (in-plane longitudinally), plastic strain occurs three-dimensionally, also involving in-plane transverse strain and through-thickness strain. Furthermore, the magnitudes of the x-, y-, and z-components of strain are interrelated and are influenced by position within the plate. For example, through-thickness strain occurs more readily near the surface than in the interior where it is more constrained by surrounding material. Finally, the eventual pattern of three-dimensional elastic stresses that evolve during unloading are interrelated via Poisson's ratio. Because of such complications, the amounts of stress relief accomplished by mechanical stress leveling are difficult to predict with quantitative precision. In some cases, constraint of plastic deformation in the interior even results in a *reversal* of the stress pattern, i.e., after stress leveling the interior residual stresses are *compressive*, while the surface residual stresses are *tensile*, albeit much lower in magnitude than the original quench-induced stresses.[16]

The effectiveness of tensile and compressive stress leveling were investigated in two different experiments. Tensile stress leveling was assessed using commercially processed 1-inch-thick plates of 7075-T651 and 6061-T651 (stress leveled in tension prior to aging), and comparing the results with those from identical samples of 7075-T6 and 6061-T6 (not stress leveled before aging). Strips 10-inches-long x 3-inches-wide were cut from the stress-leveled plates in both the longitudinal and transverse directions. Each strip was measured to document any small amounts of pre-existent bend. They were then milled to centerplane, as previously described, and again measured to determine the amount of distortion that occurred as a result of milling. Peak residual stress magnitudes were calculated using Equation 3. The results are shown in Table 3.

**Table 3. Effects of Stress Leveling in Tension on Peak Longitudinal and Transverse Residual Stresses***

| Material | Orientation | Peak Stress in T651 condition (ksi) | Peak Stress in T6 condition (ksi) | % Stress Relief Accomplished By Stress Leveling |
|---|---|---|---|---|
| 7075 | Longitudinal | 1.4 | 17.0 | 92% |
| 7075 | Transverse | 1.2 | 17.0 | 93% |
| | | | | |
| 6061 | Longitudinal | -1.1 (tensile on surface, compressive in interior) | 7.0 | 84% (and reversed) |
| 6061 | Transverse | 0 | 7.0 | 100% |

* All 1-inch-thick samples.

It can be seen from Table 3 that tensile stress leveling reduced residual stress magnitudes by more than 80% in both the longitudinal and transverse orientations. In one case the sense of the original quench-induced residual stresses was reversed, i.e., after stress leveling the surface stresses were slightly tensile and the interior stresses were slightly compressive.

Compressive stress leveling was investigated by solution heat treating and quenching 10-inches-long x 4-inches-wide x 0.5-inch-thick 7075 and 6061 plates, compressing the as-quenched plates

2 to 3% parallel to the 4-inch dimension, milling them to centerplane, and measuring the resulting distortion perpendicular to the 10-inch direction. Compressive straining was done using a fixture designed to prevent plastic buckling in the relatively thin sample. The resulting transverse residual stresses were calculated using Equation 3. No effort was made to measure longitudinal residual stresses because the short 4-inch dimension would have introduced excessive uncertainty. The results are shown in Table 4.

**Table 4. Effects of Stress Leveling in Compression on Peak Transverse Residual Stresses***

| Material | Orientation | Peak Stress in T651 Condition (ksi) | Peak Stress in T6 Condition (ksi) | % Stress Relief Accomplished By Stress Leveling |
|---|---|---|---|---|
| 7075 | Transverse | -3.6 (tensile on surface, compressive in interior) | 7.6 | 53% (and reversed) |
| | | | | |
| 6061 | Transverse | -2.0 (tensile on surface, compressive in interior) | 7.6 | 74% (and reversed) |

* All 0.5-inch-thick samples.

It can be seen from Table 4 that stress leveling in compression was considerably less effective in reducing transverse residual stress magnitudes, particularly in 7075. In both cases the sense of the original quench-induced residual stresses was reversed, i.e., after stress leveling the surface stresses were moderately tensile and the interior stresses were moderately compressive.

These results confirm that mechanical stress leveling is effective in reducing residual stress magnitudes. Stress leveling in tension appears to be considerably more effective than in compression – perhaps due to increased frictional end effects in compression. Tensile stress leveling is clearly an attractive candidate for reducing residual stresses in thick plates of 6061-T6 – combined with the relatively low yield strength-limited residual stresses in 6061, residual stresses in stress leveled and aged 6061-T651 should never exceed 1 to 2 ksi. Compressive stress leveling is also capable of substantially lowering even transverse residual stresses (perpendicular to the axis of compression). This may make compressive stress leveling a candidate for reducing residual stresses in satellite boxes that were solution heat treated and quenched after the pockets had been roughed in. However, this would require an engineering development effort, and the ~53% reduction in residual stresses would probably not be sufficient to prevent excessive distortion during subsequent machining. Tensile stress leveled thick plates of 7075-T7351 would be unsatisfactory because high quench rate sensitivity seriously degrades the properties of this alloy, as discussed in Section 3.3.1.

## 3.5 The Effects of Cold Bending on Residual Stresses and Machining Distortion

Efforts are sometimes made to mechanically cold-straighten parts that had distorted excessively during rough machining. While cold bending does not reduce residual stresses, it does alter them, thus impacting distortion during any subsequent machining operations. An analysis was conducted to estimate the residual stress patterns and magnitudes that would be introduced by cold bending, as well as the distortions that would occur if finish machining was done on previously cold-straightened plates.

The analytical approach assumed an initially residual stress-free elastic-perfectly plastic (non-strain hardening) plate subjected to pure external bending stresses. The assumption of zero strain hardening should not introduce large errors, since aluminum alloys exhibit relatively little strain hardening, and the plastic strains involved in cold straightening are small – almost always less than 2%. The assumption of an initially residual stress-free plate is also reasonably valid – peak residual stresses can never exceed *as-quenched* yield strength, so residual stresses in age-hardened materials are always less than 25% of age-hardened yield strength before cold straightening (cold bending is almost always done after age hardening). The results of this analysis are summarized in the following paragraphs.

Figure 23 shows residual stress development during cold straightening. Strains during externally applied loading increase linearly with distance from neutral axis.

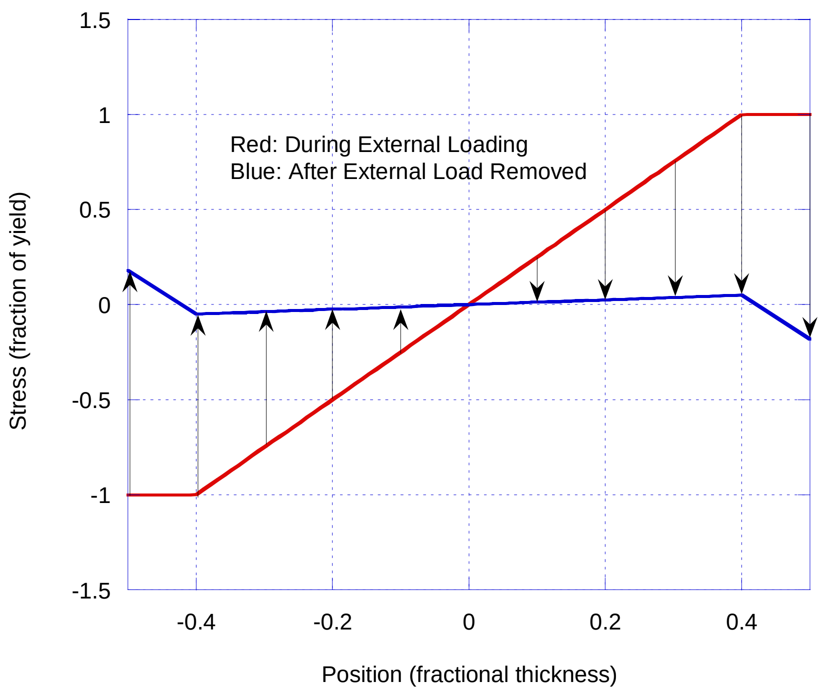


**Figure 23. Residual Stress Development During Cold Straightening.**

Figure 23 shows how non-symmetric residual stress patterns develop during cold straightening. As long as the bending-induced outer-fiber stresses remain below yield strength the stresses and deflections fully reverse on unloading, resulting in no permanent deflection or residual stresses. More severe bending results in yielding of the outer fibers (in the case shown here 10% of thickness adjacent to each surface) and permanent deflection after unloading. Unloading from “externally imposed bending” results in stress reversal in the outer-fiber regions where stresses had exceeded yield strength. Regions that had been plastically deformed in tension go into residual compression, whereas regions on the opposite surface that had been plastically deformed in compression go into residual tension. These opposing surface stresses prevent the stresses in the internal portions (that had not been plastically deformed) from returning to zero, thus resulting in permanent deflection. The equilibrium final deflections and stresses were calculated by minimizing elastic strain energy:

$$\text{elastic strain energy} = \{\text{elastic stress}^2 / [2 \times \text{elastic modulus}]\}, \qquad \text{(Eq.10)}$$

integrated over the entire plate after removal of the externally applied bending load.

Figure 24 shows comparative residual stress profiles in plates in which 10%, 25%, 50%, and 80% of the thickness experienced plastic deformation during prior external loading. Note that yield strength refers to age-hardened yield strength, as cold straightening of the type described here is almost always done after the material has been age hardened.

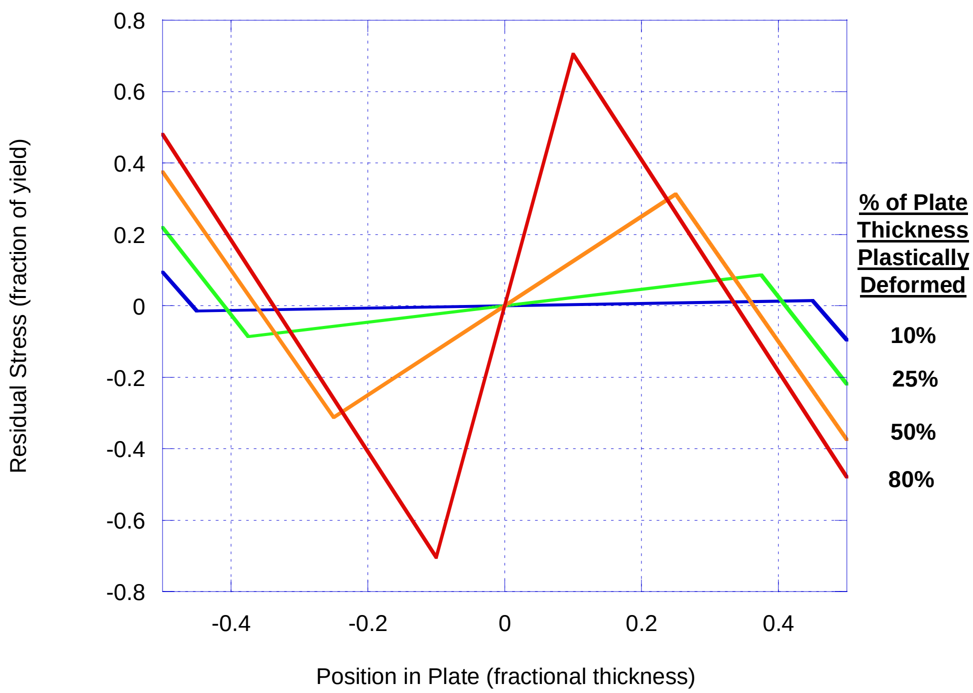


**Figure 24. Comparative Residual Stress Profiles.**

It can be seen that peak residual stresses increase with the extent of prior bending. In all cases the residual stress profiles are asymmetric, i.e., stresses on one side of the centerplane are opposite in sign to those on the opposite side. The magnitudes of the maximum surface stresses and interior stresses both increase with increasing depth of plastic deformation during externally imposed bending, as shown in Figure 25.

Figure 25 shows the maximum surface and internal residual stresses as functions of the fraction of thickness that exceeded yield during prior external loading. The signs of stresses are opposite on opposite sides of centerplane, as shown in Figures 23 and 24.

The deflections that occur during imposed bending, the springback on unloading, and the amount of “permanent set” are presented in terms of dimensionless parameters in Figure 26.

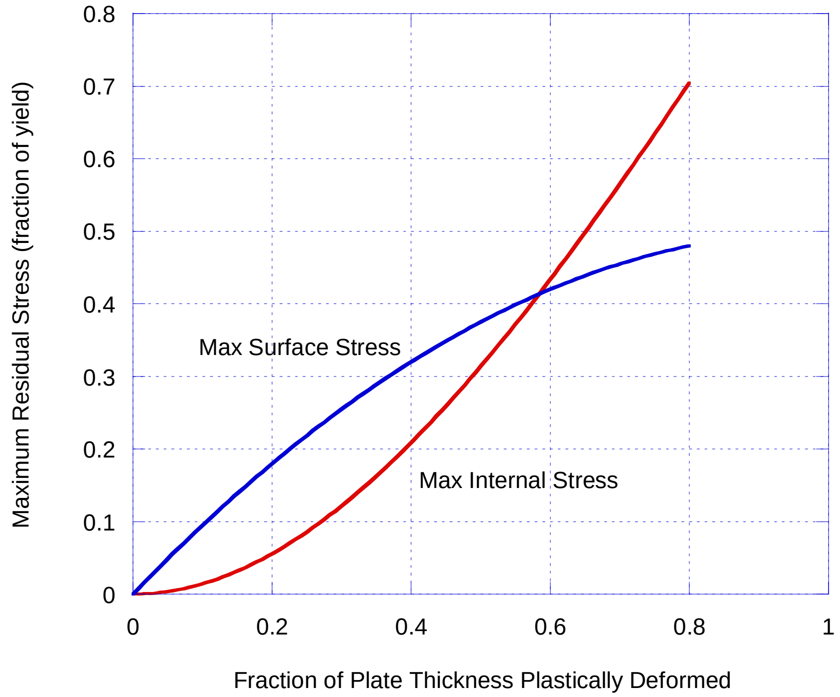


**Figure 25. Maximum Surface and Internal Residual Stresses.**

Figure 26 shows the deflections during and after external loading. The difference between these curves corresponds to the springback that occurs when the externally applied load is removed.

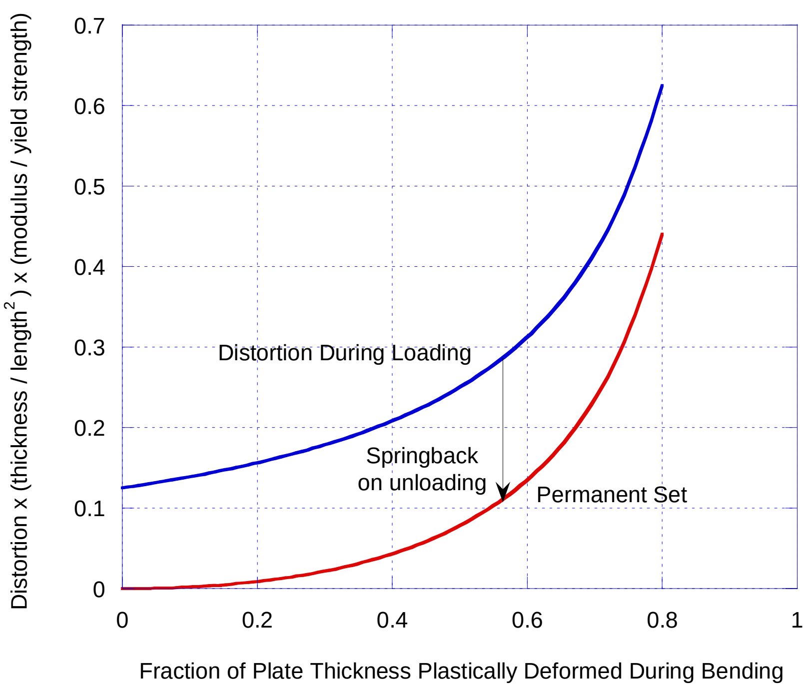


**Figure 26. Deflections During and After External Loading.**

In actual cold straightening, the "permanent set" represents the "straightening distortion" – the bend deliberately introduced to offset the undesirable distortion that had occurred during previous machining.

Since cold straightening is almost always done following age hardening, the yield strengths referred to in Figures 23 through 26 correspond to the *age-hardened yield strength* – typically 3 to 5 times the as-quenched yield strength. As a result, the residual stresses in cold-straightened parts can be considerably higher than residual stresses introduced during quenching. The very high stresses in parts that have been substantially cold straightened can make them susceptible to stress corrosion cracking. This should not be a problem in 7075-T73 or 6061-T6, as these are quite resistant to stress corrosion cracking. However, 7075-T6 is prone to stress corrosion cracking, so it should never be cold straightened.

The high residual stresses and asymmetric stress patterns make cold straightened parts *highly* prone to additional distortion during even light finish machining. Referring to Figures 23 and 24, it can be seen that material cannot be removed in a way that does not unbalance the residual stress pattern, thus causing distortion. Furthermore, stress magnitude is frequently highest at the surfaces, so removal of near-surface material results in maximum upset in residual stresses, causing disproportionately severe distortion. The amounts of distortion occurring during subsequent finish machining were calculated based on the criterion of elastic strain energy minimization.

Figure 27 shows the distortion that "returns" when previously cold straightened plates are finish machined.

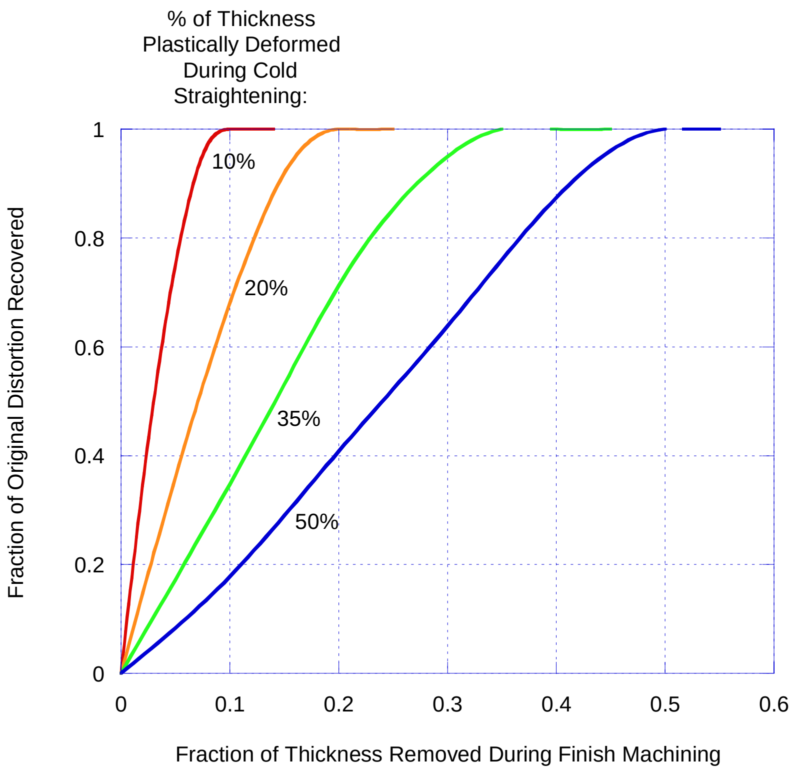


**Figure 27. Returning Distortion When Previously Cold Straightened Plates Are Finish Machined.**

Analysis assumes that finish machining is done from both sides. Note that 100% of the distortion that had been removed by cold straightening returns when 100% of the previously plastically deformed material is machined off.

Examination of Figure 27 shows that 100% of the distortion that had been overcome by cold straightening "returns" when finish machining removed all of the surface layers that had been plastically deformed during cold bending. Furthermore, "distortion return" occurred disproportionately with initial material removal in plates that had been lightly cold straightened.

The return of distortion during finish machining of previously cold-straightened parts can be aptly illustrated by the following example. Suppose a 10-inches-long section of 7075-T73 must be machined to a final thickness of 0.200 inch with a flatness of ±0.005 inch. After the material has been roughed to a thickness of ~0.240 inch it is found to have a mid-length distortion of 0.023 inch – more than four times that allowable. Cold bending is used to straighten the plate, i.e., to remove the 0.023-inch distortion. Referring to Figure 26, the y-value is calculated to be 0.00875 (based on the appropriate values for deflection (0.023 inch), thickness (0.240 inch), length (10 inches), yield strength (63 x $10^3$ psi), and modulus (10 x $10^6$ psi)). Figure 26 shows that this corresponds to 20% of the plate having been plastically deformed during cold bending. Subsequent removal of an additional 0.020 inch from each side during finish machining would correspond to a 16.7% reduction in thickness. Referring now to Figure 27, removal of 16.7% of the thickness from a material in which 20% of the thickness had been plastically deformed will result in a return of ~97% of the original distortion that had previously overcome by cold straightening, i.e., the part will once again exhibit more that four times the allowable distortion.

Combining these results reveals the following regarding cold straightening:

- Relatively small amounts of externally imposed bending result in fully elastic deflections that are fully recovered on unloading. As would be expected, fully elastic deflections result in no permanent straightening, nor any alteration of the original residual stresses in the material.
- Progressively larger amounts of externally imposed bending result in increasing depths of plastic deformation adjacent to the surfaces. Substantially asymmetric residual stress patterns develop on unloading. When plastic deformation is shallow to moderately deep the resulting tensile and compressive residual stresses are highest along the opposing surfaces. Only when greater than ~55% of the thickness has been plastically deformed do peak residual stresses in the interior exceed surface stresses.
- These asymmetric residual stresses give rise to permanent deflections, which can be exploited in cold straightening of distorted parts. The magnitude of the permanent deflection increases with increasing externally imposed bending and resulting depth of plastic deformation.
- Substantial additional distortion occurs upon finish machining of previously cold straightened parts. All of the previously removed distortion returns when finish machining removes all of the material that had been plastically deformed during cold bending, resulting in a frustrating inability to meet dimensional specifications.

Complex parts, such as satellite boxes, are particularly difficult to cold straighten because of the interdependence of the adjacent decks and webs. Efforts to straighten one element almost always cause bending to also occur in other elements, thus making it almost impossible to straighten all elements simultaneously.

Based on the above analysis, it is recommended that cold straightening be avoided.

# 4. ENGINEERING IMPLICATIONS FOR SATELLITE BOX DESIGN AND PRODUCTION

The following paragraphs summarize the findings described in the previous sections and how they relate to the design and manufacturing of satellite boxes.

## 4.1 6061 Versus 7075 Aluminum Alloys

Low as-quenched residual stresses and low quench rate sensitivity (the ability to be solution heat treated and quenched in thick sections) gives 6061 a huge advantage over 7075 in designs where 35 ksi yield strength is sufficient. 7075 should only be considered in cases where yield strength greater than 35 ksi is required.

The mechanical properties of 6061-T6 are relatively insensitive to plate thickness and quench severity (see Figure 12 and Section 3.3.1). Strengths in 12-inches-thick plate are only 10 to 15% lower than in 1-inch-thick material. In addition, residual stresses in 6061 are generally low, as they are limited by its low as-quenched yield strength (see Table 1 and Section 3.1). The relatively low as-quenched residual stresses can be reduced by 80-95% by mechanical stress leveling (see Table 3 and Section 3.4), plus an additional ~22% during subsequent age hardening (see Table 2 and Section 3.2). As a result, 10- to 12- inches-thick plates of 6061-T651 (solution heat treated and quenched in room-temperature water, mechanically stress leveled in tension, and age hardened to peak strength) will exhibit yield strengths of ~35 ksi, but contain peak residual stresses less than 2 ksi.

7075 has the potential of significantly higher strength but is much more quench rate sensitive. Because of this, full strength can only be realized in thicknesses less than ~1 inch (see Figure 12 and Section 3.3.1). In 10- to 12-inches-thick sections its strength after aging to the T73 condition is no higher than that of 6061-T6 in similar thicknesses (see Figure 12 and Section 3.3.1). As a result, the only way to exploit the higher strength of 7075 is to rough in the pockets *before* solution treatment and quenching.

If such a roughed box was solution heat treated and quenched in room-temperature water, very high residual stresses would be introduced into each deck and web (see Table 1 and Section 3.1). Aging to the T73 condition would remove only ~36% of these residual stresses (see Table 2 and Section 3.2.1), so excessive distortion would be expected during subsequent machining. This was experimentally confirmed during the campaign in which boxes could not be made within the required tolerances.[17] However, warm water quenching could be employed in order to substantially reduce residual stresses, at the expense of a modest sacrifice in strength. Solution treating and quenching the roughed box in water heated to 175-180°F and then aging it to the T73 condition would lower the residual stresses by ~80%, while sacrificing only ~15% of strength (see Figures 13 through 15, 19 through 21, and Section 3.3.2). The result would be material with ~55 ksi yield strength and peak residual stresses in the vicinity of 1 to 2.5 ksi, depending on the thickness of the decks and webs in the roughed box during quenching.

Another possibility with 7075 might be to solution treat and quench the roughed box in cold water, then compressively stress level it before aging. Stress leveling should remove ~53% of residual stresses (see Table 4 and Section 3.4), plus an additional ~36% should be removed during subsequent aging (see Table 2 and Section 3.2), providing a total of ~70% stress reduction. The resulting 7075-T7352 material would exhibit the full ~63 ksi yield strength, and peak residual stresses should be 2 to 5 ksi, depending on the thickness of the roughed decks and webs. These residual stresses are higher than desired, and may result in excessive machining distortion. In addition, compressive stress leveling such a complex part might not be straightforward – an engineering development effort would likely be required.

## 4.2 Process Options for Minimizing Residual Stresses: Warm Water Quenching Versus Mechanical Stress Relieving Versus Thermal Stress Relieving

Quenching in warm water reduces the amount of residual stress *introduced* into the material. Mechanical stress leveling and thermal stress relieving lower the magnitudes of the residual stresses *after they are already present*. Mechanical versus thermal stress relieving will be discussed first, followed by discussion of quenching in warm water versus mechanical stress relieving.

Once residual stresses are present (from quenching), mechanical stress leveling is generally more effective than thermal stress relieving in reducing them. Precise levels of mechanical stress relief are difficult to predict, but always exceed 80% in tension and 50% in compression (see Tables 3 and 4 and Section 3.4). Most important, mechanical stress relieving does not involve any decrease in strength. Unfortunately, mechanical stress relieving in tension is limited to very simple geometries, such as plates. Mechanical stress relieving in compression can be done with more complex geometries but cannot be applied to very irregular shapes.

Thermal stress relieving, while applicable to all geometries, always involves reductions in strength. Large strength penalties must be accepted in order to accomplish the 80%+ stress relief available by mechanical stress relieving in tension, or even the 50%+ stress relief available by mechanical stress relieving in compression. The primary limitation of thermal stress relieving is that it cannot realistically be done at temperatures higher than the aging temperature of the alloy unless substantial reductions in strength can be tolerated. Relatively little thermal stress relief occurs during conventional age hardening (see Table 2 and Section 3.2.1). Greater amounts of stress relief occur during overaging, but only at the expense of substantial (usually unacceptable) reductions in strength (see Figures 6 through 7, 10 through 11 and Section 3.2.2).

Alternatively, quenching in warm water is capable of greatly reducing the levels of residual stress introduced into the material and is applicable to parts of all geometries. However, this approach is limited by the quench rate sensitivity of the alloy.

7075 is highly quench rate sensitive, so the strength of 0.5 to 1-inch-thick sections begins to degrade when quench water temperature exceeds ~150°F; however, residual stresses are reduced only ~35% at this temperature. Both residual stresses and strength decrease at higher quench water temperature. 175 to 180°F appears to provide the optimum balance. Here residual stresses are reduced ~80% to 1-2 ksi, while yield strength is reduced only ~15% after aging to the T73 condition (see Figures 13 through 15, 19 through 21, and Section 3.3.2). While the resulting ~55 ksi yield strength is lower than that of "fully quenched" 7075-T73, it is still 15-20 ksi higher than

6061-T6. Quenching of roughed boxes of 7075 in 175 to 180°F water appears to be the best approach in cases where yield strengths higher than ~35 ksi are required.

6061 is not very quench rate sensitive, so in 1-inch thicknesses it can be quenched in 180°F water with no loss of strength (see Figure 18). This reduces residual stresses to less than 2 ksi (see Figures 16 and 17 and Section 3.3.2). However, this is no better than can be achieved in 6061-T6 by mechanical stress leveling (see Tables 3 and 4 and Section 3.4). 6061 can be quenched reasonably effectively in thicknesses up to 10 to 12 inches, then stress leveled in tension, and aged to the T651 condition. This sequence results in yield strength of ~35 ksi and residual stresses less than ~2 ksi. In addition, 6061-T651 plate can be commercially obtained, thus avoiding the complications involved in roughing-in pockets, followed by solution heat treating, warm water quenching (an unconventional process), and aging. Machining satellite boxes from thick plates of mechanically stress leveled 6061-T651 appears to be the preferred method, provided yield strengths greater than 35 ksi are not needed.

## 4.3 Machining Strategies to Minimize Machining Distortion

Machining strategies will vary substantially depending on whether boxes are being machined from thick plates of mechanically stress leveled 6061-T651 or from 7075-T73 pre-forms in which pockets were roughed in before solution treatment, quenching in warm water, and age hardening.

In thick plates of 6061-T651 residual stresses will vary *through the thickness* of the plate, not through the thicknesses of the individual decks and webs being machined. Because of this, longitudinal (end-to-end) bending distortion of the type described in this investigation should be essentially zero. However, some distortion may occur between the front/back and mid-depth of the box (corresponding to the surfaces and centerplane of the original plate). For residual stress magnitudes of 2 ksi, however, these distortions should not exceed ~0.003 inch in a 10-inch- deep box. Most of these distortions should occur when the pockets are first roughed in. Accordingly, the best way to avoid distortion problems is to rough in the pockets first, leaving a modest amount of overstock, then finish machine to final dimensions.

In 7075-T73 boxes in which pockets were roughed in before solution treatment, quenching, and age hardening, however, residual stress gradients will exist *through the thickness of each deck and web*. Because of this, the primary distortion concerns are end-to-end (in decks) and top-to-bottom (in webs). If the roughed-in webs and decks were 0.5 to 1-inch-thick and quenching had been done in cold water, peak residual stresses would be in the vicinity of five to 10 ksi (see Figures 13 through 14, 19 through 20). This could result in end-to-end machining distortions greater than 0.1 inch in a 20-inches-long box! This is consistent with the dramatically excessive machining distortions seen in 7075-T73 boxes that were processed in this way.[17] Quenching in 175 to 180°F water should reduce residual stresses and machining distortion by ~80% (see Figures 13 through 14, 19 through 20, and Section 3.3.2). Additional reductions in distortion can be realized by employing machining approaches that minimize upsets in residual stress patterns.

All of the distortion amounts cited in this report are for the worst case of machining from one side to centerplane. However, lower distortions will occur if machining depth is decreased and/or if machining is done more symmetrically with respect to the centerplanes of the decks and webs that had been roughed in before solution treatment, warm water quenching, and aging.

Machining distortion can be reduced by roughing closer to final dimensions, thereby limiting the amount of overstock during heat treatment and the thickness of material that must be machined off following heat treatment. Two factors combine to produce this benefit. First, lower residual stresses are introduced when thinner plates are quenched. Second, less material must be machined off to get to final thickness. Even for constant stress level and the case of machining from one side, analysis of the distortion required to minimize elastic strain energy indicates that the degree of distortion decreases linearly with decreasing machining depth. For example, if only 20% of the thickness is removed (from one side), the resulting distortion will be 40% of the amount corresponding to machining to centerplane; if 35% of the thickness is removed (from one side), the resulting distortion will be 70% of the amount corresponding to machining to centerplane. While limiting overstock is beneficial, however, it must be recognized that some distortion occurs *during heat treatment and quenching*. If parts are roughed too close to final dimensions, these heat treatment distortions can prevent machining cleanup to the specified dimensions. So a variety of considerations must be balanced in deciding how much overstock to allow during roughing. An even more effective, but unfortunately awkward, way of reducing machining distortion is to incrementally remove material symmetrically from both sides of each deck and web. This helps minimize bending distortion by retaining symmetric residual stresses through the thickness. Unfortunately, incremental machining requires a large number of small machining passes, thus increasing machining time and cost. In the most difficult situations, however, such incremental approaches may enable challenging distortion problems to be overcome.

## 4.4 Cold Straightening

Cold straightening is sometimes attempted to restore parts that distorted during rough machining. As discussed in Section 3.5, however, cold straightening is rarely successful with complex parts, such as satellite boxes. Typically, efforts to straighten some sections result in other sections distorting out of tolerance, making it difficult to get all sections straight simultaneously. In addition, it is important to recognize that cold straightening works by introducing highly asymmetric residual stresses (see Figures 23 and 24 and Section 3.5). Because of this, machining following cold straightening is likely to result in additional distortion (see Figure 27 and Section 3.5). The fact that the highest beneficial residual stresses are near the surfaces of slightly cold straightened parts makes them disproportionately sensitive to even shallow finishing cuts (see Figure 27). As a result, cold straightening should be attempted only as a last resort, and with the understanding that it is not likely to be successful.

## 5. CONCLUSIONS

- Residual stresses are introduced during heat treatment due to thermal gradients that develop during the quench. Residual stress magnitudes increase with increasing plate thickness until they reach the as-quenched yield strength of the material. Peak residual stresses in as-quenched 7075 plates thicker than ~1.3 inches are ~22 ksi (the as-quenched yield strength of 7075). Peak residual stresses in as-quenched 6061 plates thicker than ~0.6 inch are ~9 ksi (the as-quenched yield strength of 6061). As a result, substantially greater distortions occur during machining of 7075 versus 6061 in sections thicker than ~0.6 inch.
- The magnitude of residual stresses introduced during quenching can be substantially reduced by quenching in warm or hot water. This approach is applicable to parts of all geometry, but is limited by section thickness and the quench rate sensitivity of the alloy. In 7075-T73, quenching in 175 to 180°F water reduces residual stresses by ~80% with only a ~15% reduction in strength. Warm or hot water quenching of roughed-out preforms appears to be a promising option for satellite boxes requiring yield strengths between 35 and 55 ksi.
- Following quenching, residual stress magnitudes are best reduced by mechanical stress leveling in tension, given parts of simple geometry (such as plates). Three-dimensional complexities make it difficult to predict the degree of stress reduction precisely, but 80 to 95% reduction can be routinely obtained. The low quench rate sensitivity of 6061 makes it possible to solution heat treat and quench plates this alloy in very thick sections and then mechanically stress relieve them in tension and age them to the T651 condition. Commercially available 6061-T651 plate appears best suited for satellite boxes where ~35 ksi yield strength is sufficient. Mechanical stress leveling in compression could be applied to satellite boxes heat treated as roughed-out preforms, but it is less effective than mechanical stress relieving in tension and is probably not worth the engineering development effort.
- Relatively little stress relieving occurs during conventional age hardening. Greater amounts of stress relieving occur during overaging, but only at the expense of unacceptable decreases in strength. Minimization of residual stresses in complex geometry parts can better be accomplished by quenching in warm or hot water rather than by post-quench stress relieving heat treatment.
- There is no basis for the oft-sited belief that “stress-relieving heat treatments” reduce residual stresses and machining distortion without significant decreases in strength.
- Machining distortion occurs when material is removed in ways that unbalance quench-induced residual stress patterns. Distortion increases with increasing residual stress magnitude, increasing machining depth, and increasing machining asymmetry. Predicting how distortion will vary with changing material, thickness, and processing conditions can only be successfully done by understanding the causative residual stresses.
- Machining distortion can be minimized by employing appropriate machining strategies. Machining satellite boxes from thick plates of 6061-T651 should be relatively straightforward. Machining boxes from 7075-T73 in which pockets were roughed in before solution heat treatment, quenching in warm water, and aging will be more challenging. In the latter case, machining distortion can be minimized by limiting the

thickness of overstock that must be removed following heat treatment and/or by incrementally removing material from opposite sides of each deck or web.

- It is unlikely that out-of-tolerance boxes can be successfully cold straightened. Additional machining after cold straightening is likely to cause the previously removed distortion to return.

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