Aging Behavior of Welded and Unwelded 6061-T651 Aluminum

Prepared for

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By

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1. Background

Hytec, Inc. is currently under contract to Caltech for the design and assembly of several HAM chambers and Beam Splitter Chambers (BSCs). A variety of components will be fabricated and assembled including honeycomb-design optics tables and downtubes, among others. The material selected for the majority of the hardware is the aluminum alloy 6061-T651 based on its excellent weldability and dimensional stability. Hytec has requested information about the aging behavior of the T651 temper for both welded and unwelded conditions. The primary concerns associated with the aging response of this material as a function of time and temperature are: the microstructural stability, *i.e.*, resistance to overaging, microcreep and other sources of internal energy bursts that could produce acoustic noise; and the strength of the tapped holes in the optics tables, especially with regard to their resistance to stripping. The microstructure of the welds and heat affected zones (HAZs) will be different than that of the base material thus producing a disparity in mechanical properties. The relief of residual stresses due to welding and machining must also be addressed.

The purpose of this study was to collect and compile information on the aging behavior of 6061-T651 with respect to microstructural stability and stress relief during machining and welding. The data will be presented and recommendations made for a fabrication sequence that yields the best balance of microstructural stability, internal stress relief, and adequate strength at the tapped holes.

A variety of aging studies have been performed on alloy 6061 to illustrate the effects of time and temperature on mechanical properties. Unfortunately there is not such an abundance of data on the minimum temperatures required for stress relief. The following section will outline the aging behavior of 6061 base material. The aging response of the weld and HAZ will be covered in the next section followed by a section on the implications of internal stress relief. Finally, recommendations on a fabrication sequence will be presented.

2. Aging Behavior of 6061-T651 Aluminum

The aluminum alloy 6061 is an age hardenable alloy with a nominal composition (wt. %): 0.40-.80 Si; 0.7 max Fe; 0.15-0.40 Cu; 0.15 max Mn; 0.8-1.2 Mg; 0.04-0.35 Cr; 0.25 max Zn; 0.15 max Ti; bal. Al. This alloy is strengthened by nucleation and growth of a complex Al-Cu-Mg-Si second phase known as B phase, sometimes referred to as the β. The B phase is very similar to the β phase observed in the Al-Mg-Si ternary system[1]. Strengthening is achieved by the successive nucleation and growth of a series of metastable precipitates that range from the fully coherent Guinier Preston (G.P.) zones to the semi-coherent B" and B' phases.

The T-651 temper is produced by the following thermo-mechanical processing steps:

- Solution heat treat at 970°F-1000°F (520°C-538°C) for 2 - 3 hours
- Stress relieve by stretching up to 3%
- Artificially age at 320°F-360°F (160°C-182°C) for 6-20 hours, the shorter times corresponding to the higher aging temperatures.

The stress relief by stretching is intended to eliminate the residual stresses produced by quenching from the solution heat treatment temperatures. Residual compressive stresses on the skin of the as-quenched plate/tube/sheet are balanced by tensile stresses at the interior. The stretching operation imposes enough plastic deformation, albeit very slight, to evenly redistribute and somewhat relieve the residual stresses.

Tensile data for wrought 6061 in the annealed (0 temper), solution treated + naturally aged (T-4) and solution treated + artificially aged (T-6) conditions are given in Table 1[2].

Table 1: Tensile data for alloy 6061 as a function of heat treatment.

Temper	Ultimate Strength ksi (MPa)	Yield Strength ksi (MPa)	Elongation % in 2 in. (2.5 cm)
6061-0	18 (124)	8 (55)	30
6061-T4, 6061-T451	35 (242)	21 (145)	25
6061-T6, 6061-T651	45 (310)	40 (276)	17

The data for the TX51 tempers are reported with the corresponding unstretched TX tempers. There is no appreciable difference between the aging behavior of the stretched material (T651 temper) and the unstretched material (T6 temper). The small amount of plastic deformation introduced during the stretching procedure acts principally to relieve internal stresses and does not affect the kinetics of aging. Therefore, the aging behavior of 6061-T651 will be treated identically to that of 6061-T6[2-5].

The aging curves shown in Figure 1 (page 3) represent typical artificial precipitation hardening behavior of 6061 sheet.

The curves in Figure 1 show that artificial aging occurs earlier at higher aging temperatures and the peak hardness obtainable increases as aging temperature decreases.

It can be seen by interpolating between the curves for 300°F and 340°F, that an artificial aging treatment of 18 hours at 320°F (160°C) hardens the material to its peak hardness and yield strength. Similarly, an aging treatment of 8 hours at 350°F (177°C) produces peak (or nearly peak) hardness and strength conditions. According to these curves, further aging at the precipitation hardening temperatures will result in a decrease in strength and elongation. In terms of the stripping of the tapped holes in the optical tables, the yield strength is probably a more important indicator than the ultimate tensile strength, although the trends for both are similar as a function of time and temperature.

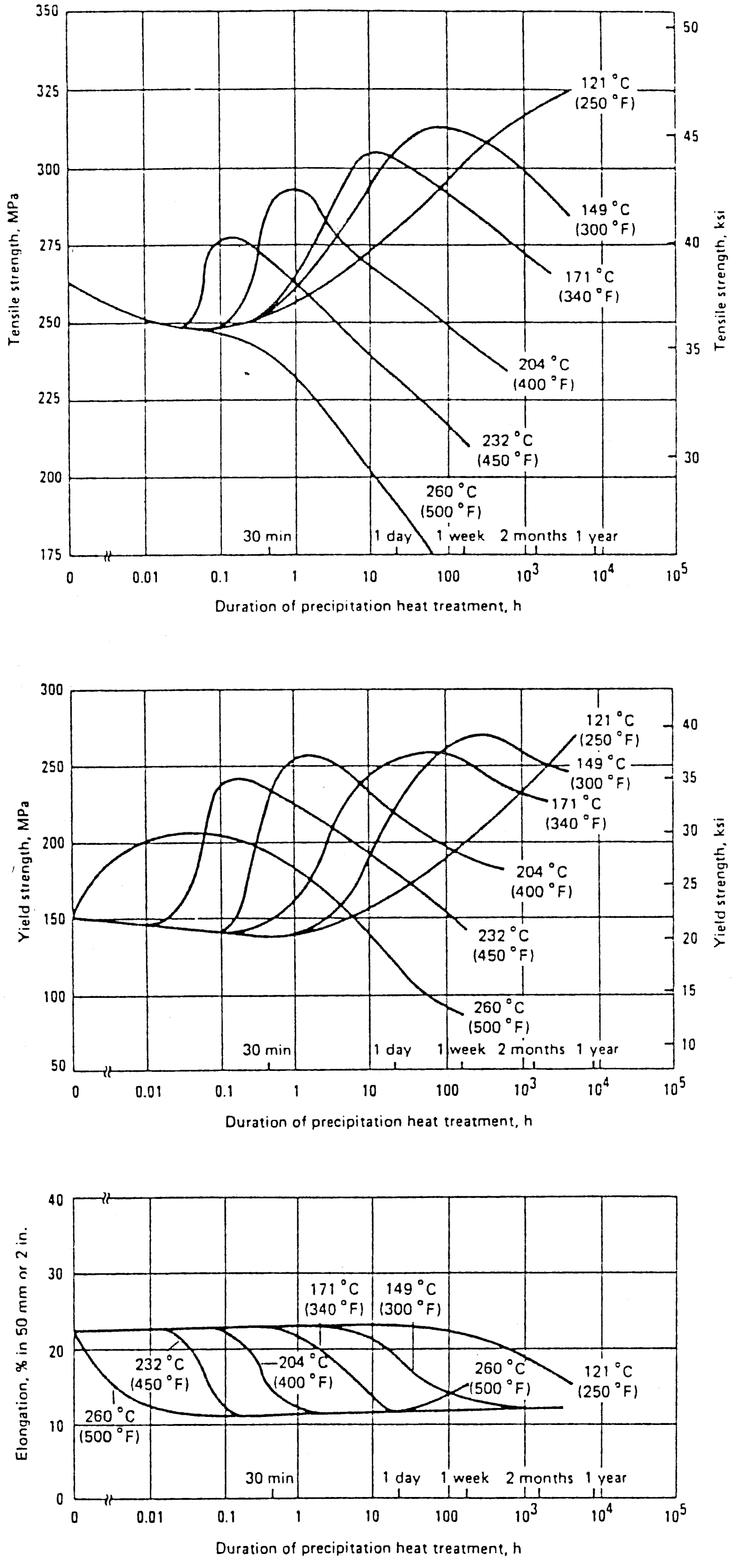

Figure 1: Typical artificial precipitation hardening aging curves for alloy 6061[5].

Another study showing the elevated temperature aging behavior for 6061-T6 plate is shown in Figure 2[6]. The curves show the yield and ultimate strengths of material aged at a variety of temperatures for 100 hours. It can be seen that the strength levels are relatively insensitive to temperature below 350°F (175°C) however they decline rapidly at 400°F (200°C) and above. These data would indicate that the strength levels for the 350°F aging treatment eventually flatten out somewhere between 30 ksi (207 MPa) and 35 ksi (242 MPa). Similarly, the strength levels for the 400°F aging treatment flatten out between 25 ksi (173 MPa) and 30 ksi (242 MPa). Therefore, subsequent aging for <100 hours at these temperatures for the purpose of stress relief should not greatly compromise the strength of this alloy.

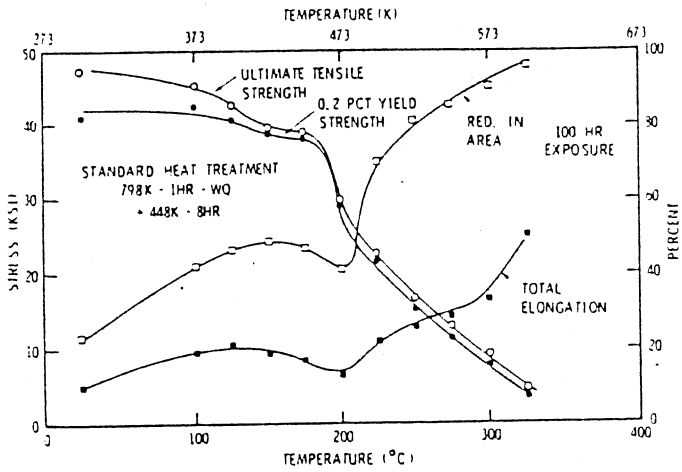

Figure 2: Influence of aging temperature on the tensile behavior of 6061-T6.

Table 2 shows the reheating conditions over a range of temperatures for wrought 6061-T6. The time/temperature combinations indicated in Table 2 represent the maximum allowable time at temperature to maintain 95% of the strength in the T6 or T651 temper.

Table 2: Reheating Conditions for Wrought 6061-T6[7]

Allowable reheating time to maintain less than 5% loss in strength						
300°F (150°C)	325°F (163°C)	350°F (177°C)	375°F (190°C)	400°F (204°C)	425°F (218°C)	450°F (232°C)
100-200 hr	50-100 hr	8-10 hr	1-2 hr	½ hr	15 min.	5 min.

The data in Table 2 reveal that aging behavior is a very strong function of temperature. Although these data do not indicate the degree of loss in strength if aging proceeds beyond these times, Figure 2 shows that aging for 100 hours at 350°F results in ~5% loss in strength while aging for 100 hours at 400°F results in approximately a 25% loss in strength. To achieve any significant levels of stress relief in building the HAMs and BSCs, it will be necessary to heat treat at the highest temperatures possible without a great compromise of strength. The 350°F - 400°F range appears to be the optimum range for this application.

3. Aging Behavior of the Weld and HAZ

The alloy 6061-T651 used in this study is to be gas tungsten arc (GTA) welded, both manually and automatically, using 4043 filler material. The filler is an Al-5.2 wt.% Si alloy that contains an Al-Si eutectic phase. The tensile properties for 6061-T6 welded with 4043 filler in the as-welded condition are given in Table 3[8]. The welding process was reported in reference 8 as "gas-shielded arc-welding" and it is unknown whether it was GTA or gas metal arc (GMA) welding.

Table 3: A comparison of typical tensile properties between 6061-T6 base material and gas-shielded arc-welded butt joints in 6061-T6 welded with 4043 filler material.

Material Condition	Ultimate Strength ksi (MPa)	Yield Strength ksi (MPa)	Elongation % in 2 in. (2.5 cm)
6061-T6/4043 weld	27 (186)	18 (124)	8
6061-T6 base material	45 (310)	40 (276)	17

Table 3 shows that the weld strength in the as-welded condition is quite inferior to that of the base material. The mechanical properties can be restored to those for the T6 temper by postweld heat treating and aging. This however would require a solution anneal at 970°F followed by an aging treatment.

Figure 3 shows strength profiles for three aluminum alloys, including 6061-T6 welded with 4043, in the as-welded condition. Two striking features are evident in the profile for 6061-T6. First, there is a distinct drop in strength across the HAZ compared with the base material; and secondly, the strength of the weld metal is far below that of the base material.

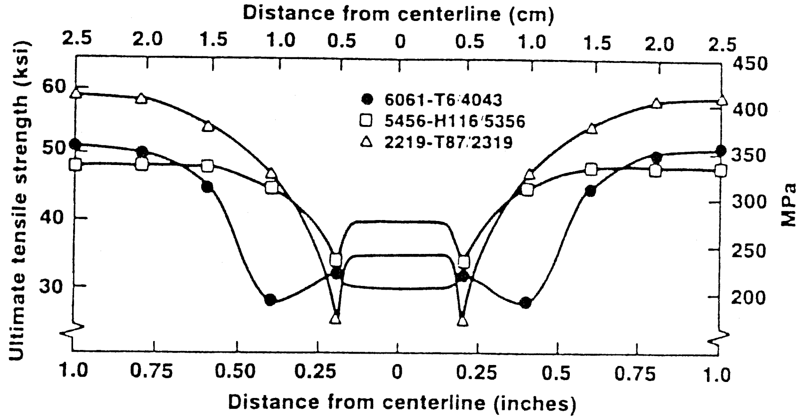

Figure 3: Strength profiles across alternating current GTA welds on 0.125 in. (3.2 mm) thick 6061-T6/4043, 5456-H116/5356, and 2219-T87/2319[8].

The softening in the HAZ is a manifestation of two metallurgical processes,

1. dissolution of the B' and B" phases
2. overaging of the B' and B" phases

The schematic shown in Figure 4 illustrates the location of softening by these two processes within the HAZ.

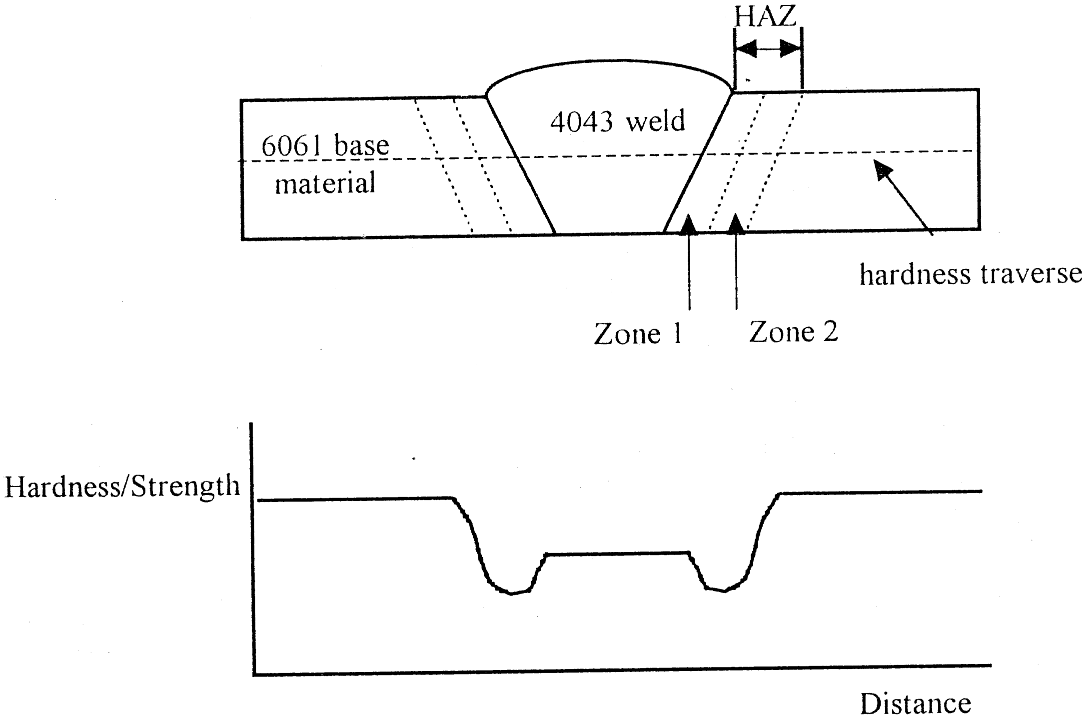

Figure 4: Schematic of the softened Zones 1 and 2 within the HAZ and corresponding hardness/strength behavior in the as-welded condition.

In Zone 1, the local heating from the adjacent molten metal is high enough to redissolve the precipitates formed during aging. The result is a decrease in strength to levels similar to the solution annealed condition. Zone 1 may either partially or totally resolutionize depending upon the time at temperature. Some re-precipitation may also occur if the cooling rate is slow enough. In Zone 2, where peak temperatures are somewhat lower than in Zone 1 during welding, the softening results from overaging of the B" and B' phases as shown by the aging curves in Figure 1.

Postweld aging can increase the strength of both Zones 1 and 2 at the expense of the base material. Strength can be recovered in Zone 1 by re-precipitation of B" and B' phases in the resolutionized material. The regeneration of strength in Zone 2 is less pronounced than in Zone 1 because the material is already overaged. Any increase in strength must be derived from precipitation of B" and B' as a result of minimal solutionizing that may have derived from precipitation of B" and B' as a result of minimal solutionizing that may have occurred in this region. Reversion of the precipitation sequence *i.e.*, B' reverting to B" or B" reverting to G.P. zones has not be substantiated. The advantage of the postweld treatment is generally a large improvement in HAZ strength with a comparatively small sacrifice of base material properties. The net result is a diminished strength differential between the base material and HAZ. Figure 5 shows an example of the improvement in hardness in the T6 and T4 (naturally aged) tempers as a result of postweld aging (PWA) compared with the as-welded (AW) condition[8]. These curves show the advantages of welding material in the T4 versus the T6 temper. The natural aging process results in less hardening of the base material. This allows more time at subsequent reheat temperatures before peak hardening and overaging are attained.

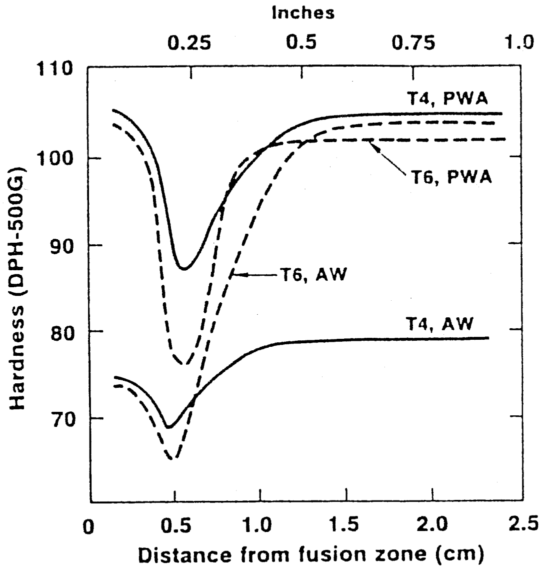

Figure 5: Hardness profiles of the HAZ for 6061-T6 and 6061-T4 in the as-welded (AW) and postweld aged (PWA) conditions.

4. Residual Stress

The T651 temper is expected to relieve the residual stresses due to quenching from the solution heat treatment temperatures of ~970°F. Therefore, welding can be performed on peak-aged, stress-relieved material. Based on the drawings and other information received from Hytec, the residual stresses due to welding are expected to far outweigh those of machining, even in the rough machining stages.

A plot of remaining residual stress versus stress relieving temperature for several aluminum alloys was provided by Hytec and appears in Figure 6.

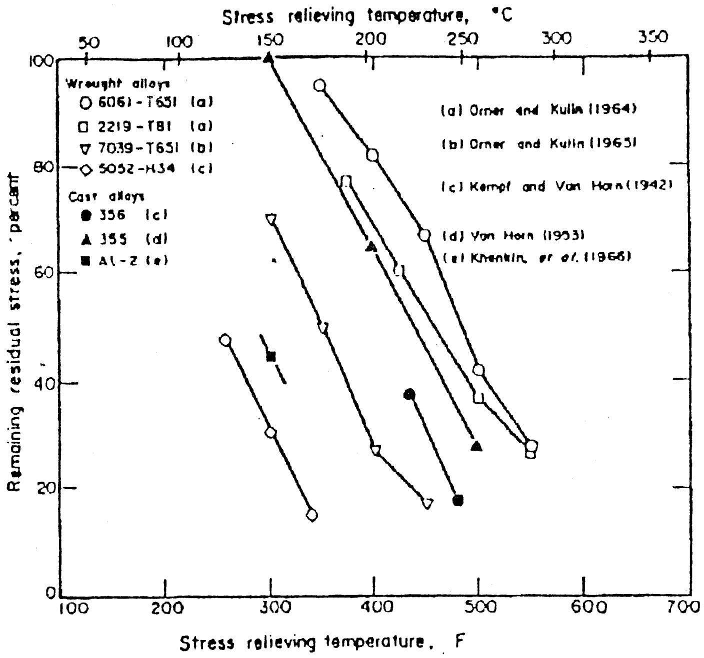

Figure 6: Effect of aluminum alloy composition on the response to stress relief annealing after 10 hr at temperature.

These data indicate that, even after 10 hours at 400°F, residual stress levels remain at ~80%. It is important to recognize that these data are derived from plate material that had been formed into rings[9]. This forming operation would impart an large amount of plastic deformation and residual stress, far exceeding that realized during welding.

The literature search performed in the present study yielded neither qualitative nor quantitative information on stress relieving temperatures for 6061.

5. Recommendations for a manufacturing sequence

The following manufacturing sequence is recommended to Hytec based upon the information presented in Sections 2.0-4.0. The reasoning for each recommended procedure is also given.

1. *Rough machine taking care not to remove too much material.* In the case of thick plate for example, bulk material will be needed for heat-sinking and distortion prevention during welding.

2. *Weld*: If possible, the least critical components should be welded early in the manufacturing process since they will receive the most heat treating cycles. Save the most critical components for the final welding stages.

3. *Stress relieve at 400°F (204°C) for 2 hours.* This relatively high temperature heat treatment will:

    - relieve weld residual stresses
    - overage the base material
    - overage Zone 2 in the HAZ
    - strengthen Zone 1 in the HAZ

    This stress relief cycle is a crucial stage of the manufacturing sequence because it relieves the majority of the residual stress. Failure to relieve the majority of residual stress at this stage could further induce internal stress in subsequent stages.

4. *Machine: either intermediate or finish machine.*

5. *Stabilize at 350°F (177°C) for 4-6 hours, depending upon the amount of material removed during machining.* Longer stress relief times will be required for thick sections that have been machined down to thin sections. Steps 4 and 5 can be repeated as necessary without exceeding 75 hours total time at 350°F. Recognize that each of these will be contributing to the overaging of the base material as well as the welds made in the initial stages of the process.

A qualitative summary of the expected strength behavior resulting from the stress relief temperatures suggested in steps 3 and 5 above is presented in Figure 7. The width of the HAZ has been exaggerated for clarity.

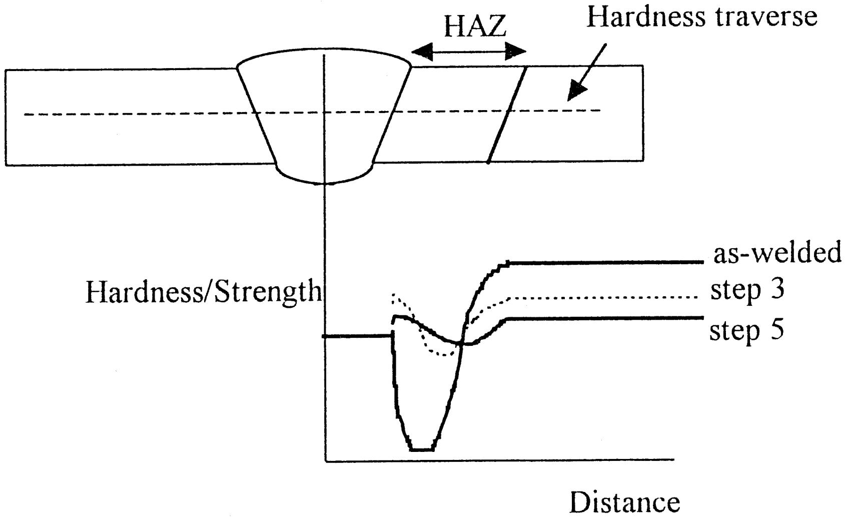

Figure 7: Schematic of expected hardness traverses for 6061-T651 in the as-welded condition and stress relieved according to the recommendations above. Drawing is not to scale.

This schematic is qualitative in nature and is not drawn to scale however there are several noteworthy points. The as-welded condition will produce softening in both Zones 1 and 2 of the HAZ as discussed previously. The 400°F stress relief should recover some strength in both Zones 1 and 2 accompanied by a drop in strength in the base material. Further aging at 350°F will begin to overage the HAZ as well as continue the overaging in the base material.

The aging response of the 4043 weld metal will depend on the level of dilution by the 6061 base material. The weld metal strength increases as the amount of dilution increases. Fillet welds inherently have less dilution than plug welds and therefore a difference in aging behavior may occur. Continued aging of the weld metal in successive heat treating cycles could cause significant softening (instability) over time. The scope of this investigation did not allow time to compile data on the stability of 4043 filler material.

The recommendations made herein are based on a survey of the literature and are therefore *only* recommendations. It is strongly suggested that test panels be subjected to multiple cycles of machining, welding, and heat treating to substantiate the recommendations. Hardness measurements, which are easy and inexpensive to perform, and actual testing of tapped holes with stainless steel screws will provide quantitative information about the viability of the suggested manufacturing sequence.

The most crucial step of the suggested manufacturing sequence is the postweld stress relief. The key issue surrounding this heat treatment is to identify a temperature that adequately stress relieves without unduly compromising the integrity of the base material and HAZ. The appropriate temperature should be identified empirically in this case.

The fact that the material is expected to overage indicates that it should be metallurgically stable. The issue of microstructural stability will depend on complete relief of residual stresses.

It is strongly recommended that a small study be performed on residual stress measurement as a function of time at temperature for both welds and base material. The information rendered would eliminate guesswork and serve as the basis for determining accurate stress relief temperatures throughout the manufacturing sequence. The aging behavior of 4043 fillet and plug welds should also be substantiated empirically in a brief study.

Is this part of the weld coupon test plan? (Is there a written plan?)

6. References

1. Dumolt, "An Investigation of the Microstructural Changes in the Heat Affected Zone of Age Hardenable Aluminum Alloys Using Transmission Electron Microscopy", Ph.D Thesis, Carnegie-Mellon University, 1983.

2. *Standards for Aluminum Mill Products*, 9th Edition, The Aluminum Association, N.Y., N.Y., Nov., 1966.

3. *Alcoa Aluminum Handbook*, Aluminum Company of America, Pittsburgh, PA

4. Private discussions, John Butler, Alcoa Research and Development Laboratory.

5. Metals Handbook 9th Edition, Vol. 4, Heat Treating, ASM International, 1981.

6. Rack, "Elevated Temperature Behavior of Thermomechanically Treated 6061 Aluminum", Scripta Met., vol. 12, No. 9, 1978, pp. 777 - 779.

7. *Source Book on Selection and Fabrication of Aluminum Alloys*, ASM International, Materials Park, OH, 1978.

8. ASM Handbook, Vol. 6, Welding, Brazing, and Soldering, ASM International, 1993

9. Private discussions with Bernie Weinstein, Hytec, Inc.

7. Other References Used

1. *Welding Kaiser Aluminum*, 1st Ed., Kaiser Aluminum & Chemical Sales, Inc., Kaiser Center, Oakland, CA, 1967.

2. *Aluminum, Vol. 1, Properties, Physical Metallurgy, and Phase Diagrams*, ed., K.R. Van Horn, ASM International, Materials Park, OH.

3. *Aluminum: Properties and Physical Metallurgy*, ed., J.E. Hatch, ASM International, Materials Park, OH, 1984.

4. Welding Handbook, Vol. 5, Engineering, Costs, Quality, and Safety, American Welding Society, Miami, FL, 1984.

5. Materials Joining Monograph: Aluminum and Aluminum Alloys, American Welding Society, Miami, FL, 1997.