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An Experimental Investigation of the Heat Affected Zone (HAZ) Properties of AA6060 and AA7046 Following Different Heat Treatment Schedules

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As part of a current project on through process modelling (TPM) of welded aluminium structures, experimental studies have been carried out on butt-welded specimens of aluminium alloy AA6060 and AA7046. Two tempers; T4 and T6 prior to welding were investigated and the subsequent effects of natural ageing (NA) and post weld heat treatment (PWHT) were assessed. Cross-weld tensile tests were carried out with digital image correlation (DIC) to determine the strain field. Variations of the mechanical properties of the material in the vicinity of the weld were also studied by hardness measurements. The experimental results are presented in terms of response curves and hardness measurements. These data will subsequently be used for verification and further development of microstructure based models for predicting the distribution of mechanical properties in the heat affected zone (HAZ) based on coupling to a thermal model. Through further coupling with a non-linear mechanical model, high precision finite element (FE) simulation of welded aluminium structures is sought.

Keywords: *Experimental, HAZ, AA6060, AA7046, heat treatment*

1. Introduction

Welded components made of age-hardening aluminium alloys are to an increasing extent used within the transport and automotive industries due to the alloy high strength, good formability, low density, and good resistance to general corrosion. However, in certain cases, the application of such alloys is restricted by a low heat affected zone (HAZ) strength level due to softening reactions occurring during welding, which tend to reduce the overall load-bearing capacity of the component. In order to utilise the properties of aluminium alloys fully, a better understanding of the strength and ductility of welded joints is needed. The objective of the present paper – which is part of a current project on through process modelling of welded aluminium structures – is to investigate experimentally the HAZ properties on butt-welded specimens of aluminium alloy AA6060 and AA7046 subjected to two initial tempers; T4 and T6 before welding and following different heat treatment schedules. Tensile tests using digital image correlation (DIC) and Vicker Hardness tests were carried out to achieve this objective.

2. Background

2.1 Heat Affected Zone (HAZ) of Al-Mg-Si alloys

During artificial ageing, a high density of fine, needle-shaped β″ particles form uniformly in the matrix. However, since these precipitates are thermodynamically unstable in a welding situation, the smallest ones will start to dissolve in the parts of the HAZ where the peak temperature has been above ~250°C [1]. During Post Weld Heat Treatment (PWHT) significant strength recovery may occur, to an extent depending on both the matrix vacancy concentration and the level of Mg and Si in solid solution. Accordingly, the reprecipitation would be expected to be most extensive in the fully reverted region close to the weld fusion line owing to the combined effect of a high solute content and a high concentration of quenched-in vacancies. Conversely, the renewed β″ formation will be suppressed in parts of the HAZ where the peak temperature is lower because the aluminium matrix in these regions will be depleted with respect to vacancies and solute. This eventually leads to the development of a permanent soft region within the HAZ after PWHT [1].

2.2 Heat Affected Zone (HAZ) of Al-Zn-Mg alloys

GP I zones, GP II zones and η´ are the phases that contribute to the precipitation hardening of the alloys in the underaged and peak-aged conditions, while the equilibrium η ($MgZn_2$) phase forms during overaging [2]. During welding, dissolution of the strengthening precipitates occurs to an extent depending on the peak temperatures and retention times experienced by the different regions of the HAZ in the temperature range from about 200 to 340 °C [3, 4]. Hence, immediately after welding the HAZ yield stress or hardness will be low close to the weld fusion line. Most of the lost strength in this zone can be recovered by natural ageing (NA) due to extensive GP-zone formation after a period of 3-5 months [4]. PWHT causing reprecipitation of the hardening metastable phases is an even more efficient way to recover the strength loss in the HAZ.

3. Experimental work

Tensile specimens were produced from 200 mm wide and 3 mm thick extruded plates that were butt-welded along the extrusion direction to form 400 mm x 400 mm weldments. These were subsequently cut into 40 mm x 400 mm strips oriented perpendicular to the welding direction. The cross-sectional area of the gauge section was reduced relative to that of the remainder of the specimen to secure that deformation and failure were localized in this region. The chemical compositions of the alloys are listed in Table 1. Prior to welding, some of the plates were heat-treated to a temper condition corresponding to T4 while others were given a T6 heat treatment as described in Table 2.

Table 1: Chemical composition (in wt. %)

Alloy	Fe	Si	Cu	Mg	Cr	Mn	Zn	Zr	Ti
AA6060	0.21	0.53	0.001	0.41	0.001	0.02	0.01	0.001	0.01
AA7046	0.19	0.09	0.01	1.22	0.003	0.009	6.59	0.16	-

Table 2: Natural ageing (NA) and Post Weld Heat Treatment (PWHT) programme

AA	Initial T4				Initial T6*			
	NA	PWHT1 =T6	PWHT2 =T7	PWHT3 =KTL**	NA	PWHT1 =T6	PWHT2 =T7	PWHT3 =KTL**
6060	RT > 1 week	7h/175°C	7h/215°C	30min/ 195°C	RT > 1 week	7h/175°C	7h/215°C	30min/ 195°C
7046	RT > 1 week	5h/100+ 6h/150°C	5h/100+ 6h/180°C	30min/ 195°C	RT > 1 week	5h/100+ 6h/150°C	5h/100+ 6h/180°C	30min/ 195°C

*Initial T6 for AA6060:175°C/10h and AA7046:100°C/5h+150°C/6h

** KTL is the German abbreviation for cataphoretic dip painting

The plates were pulsed MIG-welded in one single pass using a stainless steel backing and the filler wire AA5183. The following welding parameters were applied: Current: 145A, Voltage: 15.8V, and welding speed 16mm/s. Natural ageing and PWHT programmes are shown in Table 2.

Vicker Hardness measurements were carried out across the HAZ under the load of 9.8 N and with 1 mm spacing between the indentations using an automatic micro-hardness tester.

The cross-weld tensile tests were carried out at room temperature in a hydraulic Instron test machine with a 250 kN load cell. The specimens were speckle-painted and clamped by hydraulic grips. The experiments were performed under displacement control with a rate of 5mm/min. The test results are presented in terms of nominal stress vs. deformation curves, where the deformation u_{dic} is obtained from the digital image correlation (DIC) measurements over 50 mm gage length that includes the weld.

In the present work, DIC is used for local strain measurements during tensile testing of specimens. As the name suggests, DIC involves comparing digital images to determine the relative displacement of surface features between 'undeformed' and 'deformed' images. Further details of this experimental method can be found in Ref. [5].

4. Results and discussions

4.1 Alloy AA6060

Hardness measurements

Figure 1(a) shows the results from HAZ hardness measurements for initially T6-heat treated samples. For both the naturally aged (NA) as well as the PWHT-KTL weldments, the hardness decreases gradually from the base material T6-strength with decreasing distance from the weld fusion line between 10 mm and 4 mm. This strength reduction is due to dissolution of hardening β″-particles, as explained in Section 2.1. The hardness profile for the PWHT-T6 weldment shows a much smaller drop in hardness compared with the NA and KTL weldments, and this is due to a significant reprecipitation of β″ during the PWHT leading to a complete recovery of the hardness in regions of the HAZ close to the fusion boundary. The hardness profile for the PWHT-T7 weldment differs from the others in Figure 1(a), since the curve is almost horizontal with low base metal hardness, which must be due to severe particle coarsening in the HAZ during the long exposure time at a high temperature.

Figure 1 (b) shows similar result when welding is performed on plates in the initial T4-temper condition. For these welding experiments, the base metal consists of small GP-zones, with low resistance against high temperatures exposure. Hence, these zones start to dissolve at a lower peak temperature than the initially T6-heat treated samples, where the particles are larger and more temperature resistant. It is evident from the curves in Figure 1(b), that the temporary hardness drop during welding due to the dissolution of GP-zones is completely recovered in the whole HAZ during subsequent natural ageing (NA). Full recovery of hardness is also obtained when the welded samples are exposed for different PWHTs, and the curves do not show any soft regions with reduced hardness.

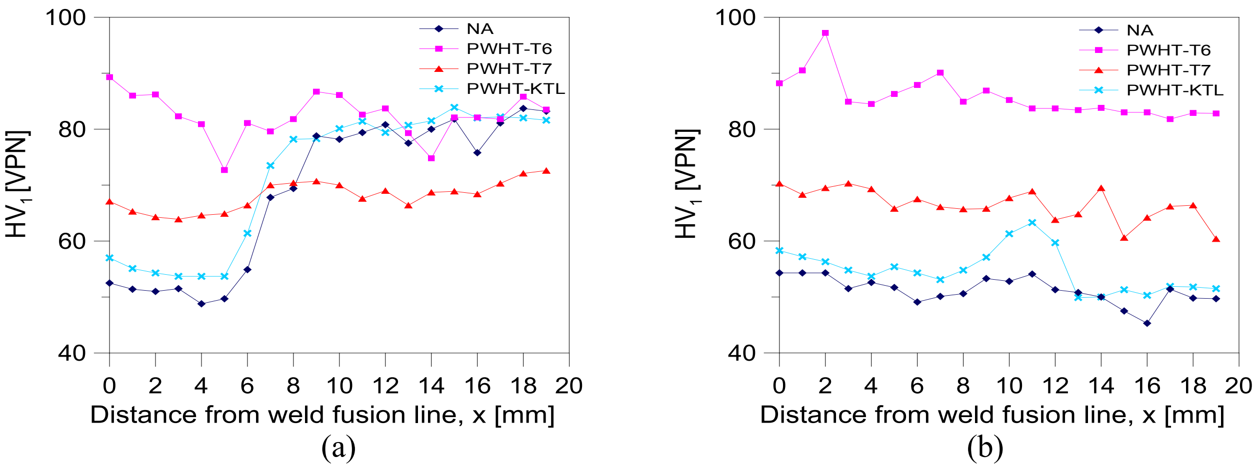
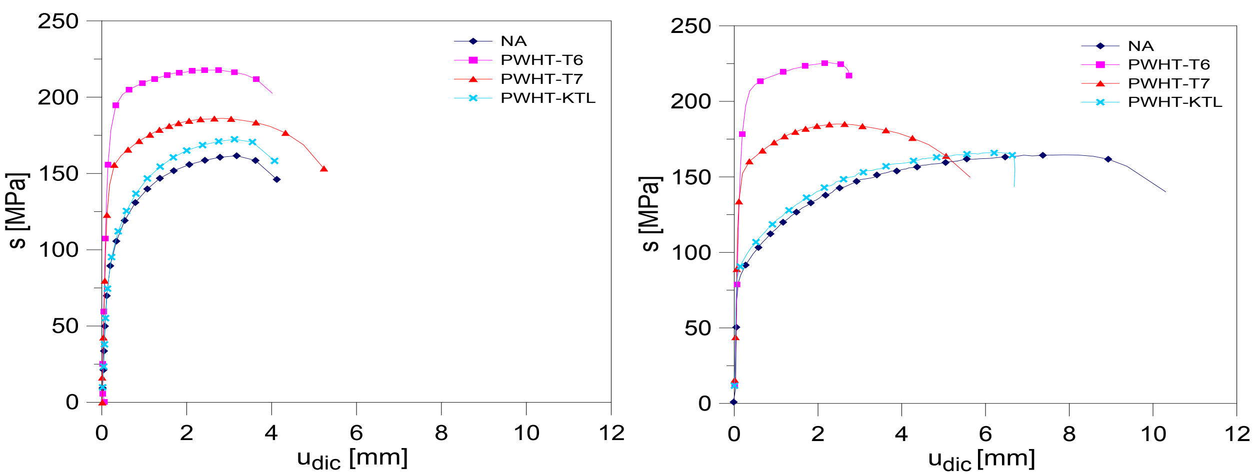


Fig. 1: Measured hardness profiles in the HAZ of butt-welded plates for alloy AA6060,

following natural ageing (NA) and different Post Weld Heat Treatments (PWHT) as defined in the legend. (a) Initial T6 temper condition. (b) Initial T4 temper condition.

Tensile tests

Figure 2 shows results from cross-weld tensile tests of welded samples for alloy AA6060. Each stress-elongation curve is the results of a complex deformation history. The tensile sample may start to yield at a certain position with a low yield stress, but if the work hardening is sufficiently strong, the further plastic deformation may move to some other region on the tensile sample. Figure 2(a) and 2(b) for initial T6 and T4 temper condition, respectively, show similar yield stress for all the different curves, which indicate that the effect of PWHT (or natural ageing following the welding) is much more important for the resulting yield stress than the initial temper condition, which seems to be of less importance with respect to the measured HAZ yield stress. For the measured elongation, the situation is different, since the initial temper condition yields a strong effect on the results. Hence, by comparing Figures 2 (a) and (b), it is evident that the elongation to fracture is more than doubled when the initial temper condition is T4 compared with T6, when the welding is followed by natural ageing (NA).



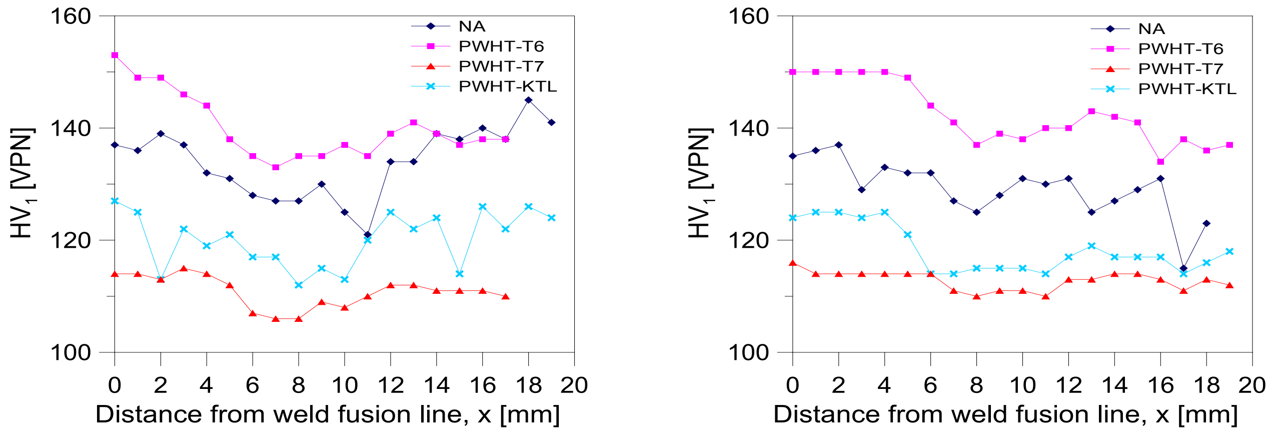
(a) (b)

Fig. 2: Measured nominal stress versus deformation for cross-weld tensile specimens of alloy AA6060, following natural ageing (NA) and different Post Weld Heat Treatments (PWHT) as defined in the legend. (a) Initial T6 temper condition. (b) Initial T4 temper condition.

4.2 Alloy AA7046

Hardness measurements

The measured HAZ hardness profiles for alloy AA7046 shown in Figure 3 are qualitatively different from the ones observed for alloy AA6060. Figure 3(a) shows that there is no pronounced minimum hardness for the initial T6 temper condition for any of the following PWHTs, except for the NA-sample, which seems to yield a minimum hardness at a position 11mm from the fusion line. In contrast to the curves for AA6060, the lowest hardness is found for the PWHT-T7 condition, which is expected to give a coarse particle structure due to severe coarsening. It is also evident from Figure 3(a) and (b) that the strength recovery by natural ageing (NA) is substantial for both initial temper conditions (i.e. T4 and T6).

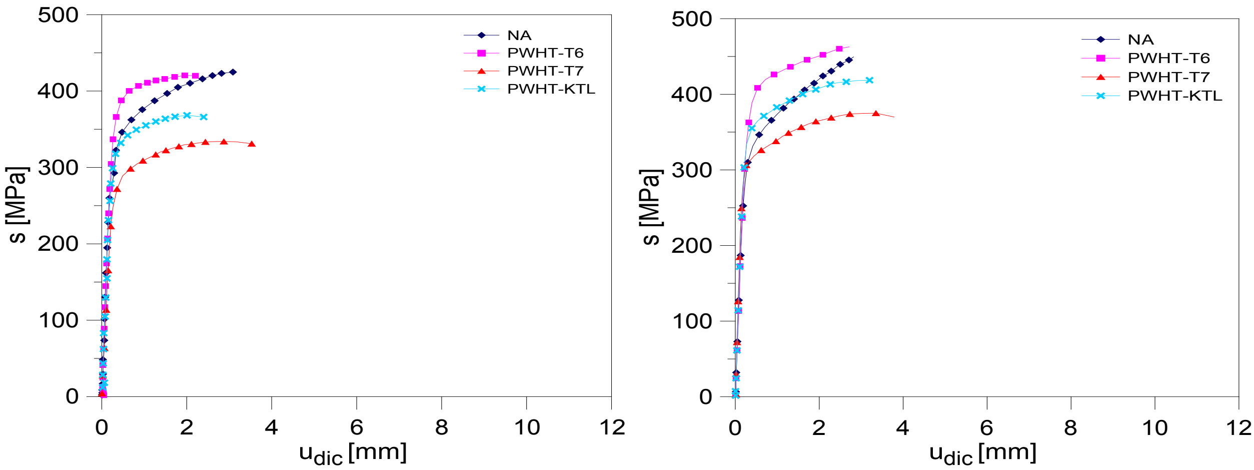


(a) (b)

Fig. 3: Measured hardness profiles in the HAZ of butt-welded plates for alloy AA7046, following natural ageing (NA) and different Post Weld Heat Treatments (PWHT) as defined in the legend. (a) Initial T6 temper condition. (b) Initial T4 temper condition.

Tensile tests

Figure 4 presents results from cross-weld tensile tests of welded samples from alloy AA7046. A comparison between Figure 4(a) and 4(b) reveals that the initial temper does not seem to affect the resulting stress-displacement response significantly, and the curves seem to be determined from the final PWHT or NA.



(a) (b)

Fig. 4: Measured nominal stress versus deformation for cross-weld tensile specimens of alloy AA7046, following natural ageing (NA) and different Post Weld Heat Treatments (PWHT) as defined in the legend. (a) Initial T6 temper condition. (b) Initial T4 temper condition.

Comparing hardness measurements and tensile test results

From the hardness measurements, it is possible to predict an approximate yield stress using simple regression formulas reported in the literature. For Al-Mg-Si and Al-Zn-Mg extruded profiles, the following equations have been shown to give fair estimates of the yield stress [6, 7].

AA6060: $$Rp_{0.2}\ (\text{MPa}) = 3.0.\ HV - 48.1. \quad (1)$$

AA7046: $$Rp_{0.2}\ (\text{MPa}) = 3.7.\ HV - 100.0. \quad (2)$$

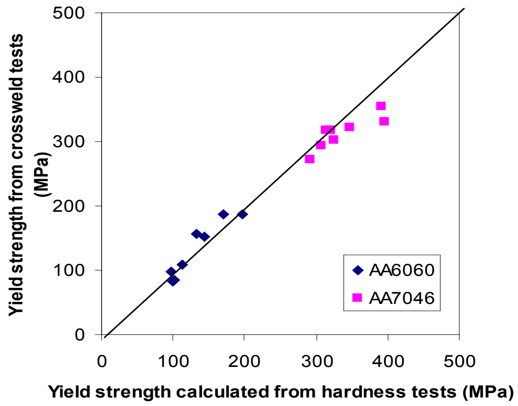


Fig. 5: Correlation between minimum HAZ yield stress converted from hardness measurements, and measured yield stress in tensile testing of the HAZ normal to the welding direction.

The yield stress obtained from cross-weld tensile tests should be expected to give almost the same yield stress as estimated from the measured minimum HAZ hardness, which is confirmed by the good correlation shown in Figure 5. The small discrepancy observed, is probably due to the fact that the yield stress values from cross-weld tensile tests represent mean values over the specimen cross-sectional area, whereas the yield stress values from hardness measurement values are referring to a point within this area. It might be expected that the narrower the specimen tested, the better the correlation [8].

5. Conclusions

Post weld heat treatment (PWHT) or an alternative natural ageing (NA) was shown to give a significant effect on the resulting HAZ hardness distribution as well as cross-weld tensile properties for the alloys AA6060 and AA7046. Conversely, the initial temper condition seems to be of less importance for the same properties. However, the initial temper condition affects the resulting base material hardness as well as the elongation to fracture for the 6xxx alloy.

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