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Mechanical Properties of Friction Stir Welds in Thin Sheet of Aluminium 2024, 6013 and 7475

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Summary

The objective was to characterise the mechanical properties of butt welds produced in three different aerospace aluminium alloys using Friction Stir Welding. The test pieces were fabricated of thin sheet material in the alloys 2024-T3, 6013-T6 and 7475-T76.

The friction stir welding was performed at SAPA Finspång. The mechanical properties evaluated were tensile strength at room temperature, bend performance and fatigue strength. The properties were tested transverse to the weld. Static strength and bending properties were found superior to what is usually achieved with conventional welding methods. The fatigue strength was tested using test specimens in the as welded condition as well as after surface milling of the weld top side. In the milled condition the welded specimens approach the fatigue strength of the parent material while the as welded specimens have a fatigue strength exceeding that of Kt 2,5 specimen.

Failure characteristics were evaluated using fractographical and metallographical techniques.

Introduction

The Friction Stir Welding (FSW) process opens up possibilities for the aerospace industry to use cost or weight saving designs due to reduced frequency of riveting. This is made possible as the FSW process can produce sound welds in high strength aerospace alloys which are not readily weldable with fusion welding processes. The main objective of this report was to acquire data on mechanical properties of FSW welded aerospace alloys.

This report describes the results from static, bend and fatigue testing of thin sheet material welded with FSW. The results are followed up with a metallurgical examination of the weld nugget and the heat affected zone. The study covers three precipitation hardening alloys with special interest to the sponsors Saab AB and BAE Systems; 2024, 6013 and 7475.

Welding data

Strips of thin sheet material were FSW welded at SAPA Finspång. The strips were welded in a fixture using square butt joints orientated in the LT direction of the sheet. The welded blanks had the dimension 140 x 700 mm and were used for fabrication of test specimens. The welding tool used is referred to as "Standard Tool" in reference 1. The pin diameter was $\varnothing$ 4 mm. Table 1 below outlines the welding parameters used.

Table 1. Welding data for the three alloys tested

Alloy and condition at welding	Type of alloy	Material thickness (mm)	Rotational speed (rpm)	Travelling speed (mm/min)
2024 T3	AlCu	2,0	1180	110
6013 T4	AlMgSi	1,6	2000	208
7475 T76	AlZnMg	2,0	950	110

Inspection and weld quality

Welded blanks of each alloy were inspected using visual inspection and radiography. The visual inspection revealed that the degree of burrs formed at the advancing side of the weld (see figure 1) showed a minimum for the 7475 and a maximum for the 6013 alloy. Radiographs indicated a defect type referred to as "tunnel defect" or an "internal void" in some sheets of alloy 7475. The defect typically extended 100 mm from the start of the weld. The cause for this defect is likely insufficient friction heat during welding. All other parts of the weld were without remarks. Welds of 6013 and 2024 were without remarks.

The blanks of 6013 T4 were artificially aged to T6 condition while the blanks of 2024 and 7475 were left as welded. Deburring was performed on all blanks before specimen manufacturing.

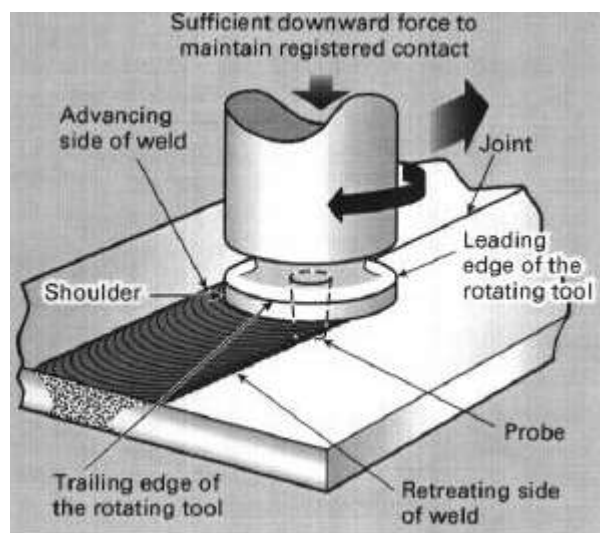


Figure 1. Nomenclature of FSW tool and details of the weld according to reference 2.

Testing and Result

Tensile testing

Tensile specimens were manufactured out of welded blanks and of parent material and tested according to SS-EN 10 002. The parameters recorded were ultimate tensile strength (UTS), proof stress at 0,2 % strain and elongation of a 15 mm length over the weld width (A_{15}). The results outlined in table 2 below are based on four specimens tested for each condition. The four specimens were from different positions along the FSW. However, no significant variation was found in test data from near starting point to near stop point of the defect free FSW. The weld factor (UTS_{FSW}/UTS_{parent}) for alloy 6013 is 0,75 and thus exceeding what can be achieved by TIG welding. The alloys 2024 and 7475 have weld factor 0,9 in as welded condition.

Some specimens of 2024 and 7475 were resolution heat treated and aged. This treatment increased the weld factor for 7475 further but did not affect the weld factor for 2024.

Table 2. Results from tensile testing of FSW welded joints

Material	Post Weld Heat Treatment	0,2 % Proof Stress (MPa)	UTS (MPa)	A_{15} (%)	UTS_{FSW}/UTS_{parent}
2024 T3	None	310	441	16,3	0,90
2024 T3	Solution Heat Treated and Aged	302	445	14,5	0,90
6013 T6	Aged to T6	253	291	8,3	0,75
7475 T76	None	381	465	12,8	0,92
7475 T76	Solution Heat Treated and Aged	476	512	10,0	0,97

The fracture sites for all alloys in the as welded condition were located on the retreating side of the weld. Reheat treatment of 2024 changes the fracture location and appearance. Fracture site moves towards the centre of weld ("nugget"). The fracture surface is coarse grained and somewhat laminated.

Bend testing

Bend test specimens were produced as plain strips with the dimension 100 x 10 mm. The testing was carried out according to EN 910 with the bend angle 120° and the FSW weld centred over the mandrel. The bend specimens were tested using top and root side of the FSW weld in tension. The mandrel dimension was chosen according to the Saab specification for minimum allowable bending radius. The results of double tests for each condition are summarised in table 3. Liquid fluorescent penetrant was used to detect cracks.

Also for bend testing, some specimens of 2024 and 7475 had been solution heat treated and aged. This heat treatment had a detrimental effect on the bending performance.

Table 3. Results from 120° bend testing of FSW welded joints

Material	Post Weld Heat Treatment	Face of weld in tension	Mandrel dimension (mm)	Result
2024 T3	None	Top	16	OK
2024 T3	None	Root	16	OK
2024 T3	Solution Heat Treated and Aged	Top	16	Crack
2024 T3	Solution Heat Treated and Aged	Root	16	Minor cracks
6013 T6	Aged to T6	Top	8	OK
6013 T6	Aged to T6	Root	8	OK
7475 T76	None	Top	16	OK
7475 T76	None	Root	16	OK
7475 T76	Solution Heat Treated and Aged	Top	16	Crack
7475 T76	Solution Heat Treated and Aged	Root	16	Crack

Fatigue testing

Plain un-notched specimens were used in the fatigue testing of the FSW welds, see figure 2.

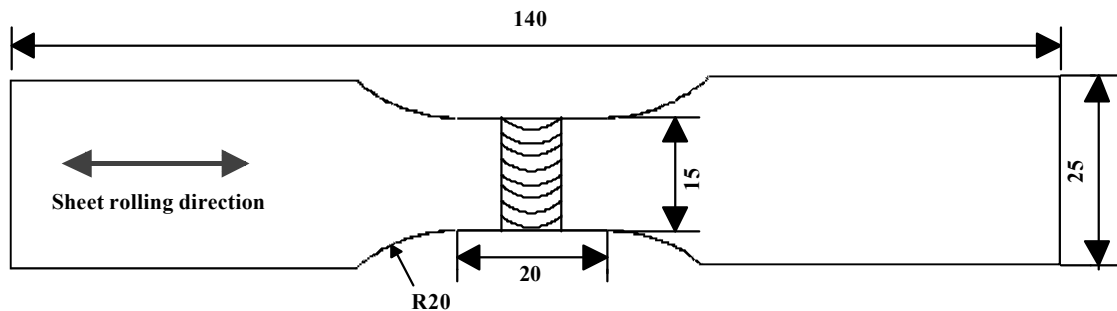


Figure 2. Dimensions of the fatigue test specimen used ($K_t = 1,0$). The figure shows the FSW weld transverse to load direction.

The specimens were tested both in the as welded condition and after flush milling of the weld top side. However the 6013 specimens, initially tested, were flush milled on both the top side and the root side. By the milling operation 0,10 to 0,15 mm material was removed from the weld and the sheet adjacent to the weld. Parent sheet material was fatigue tested for reference. The fatigue specimens used for testing parent material were both an un-notched specimen similar to the weld specimen geometry and a central open hole specimen, 25 mm wide with a 5 mm hole causing a stress concentration $K_t = 2,5$. The loading frequency was 25 Hz. The fatigue testing was carried out with constant amplitude at the stress ratio $R = 0,1$ ($\sigma_{\min}/\sigma_{\max}$).

The fatigue results are shown in figures 3, 4 and 5 as best fit S/N-curves for the FSW series in comparison with curves for the parent material of Kt-values 1,0 and 2,5. Individual test points are for clarity shown for the FSW series only. The curves show maximum stress for stress ratio 0,1.

The results are similar for the three alloys in one aspect. In the as welded condition the S/N-curve for the FSW specimens is above the reference curve for the open hole specimens of the parent material ($K_t = 2,5$). Surface milling of the welds raises the S/N-curves for alloys 6013 and 7475 close to the reference curve for parent material ($K_t = 1,0$). The 2024 alloy shows an enhancement as well by the milling, but does not fully reach the level for the reference material.

Location of the fatigue crack initiation is clearly depending on the surface preparation. In the as welded condition the three alloys had fatigue cracks starting from the top side of the weld. The 6013 still showed fatigue crack originating from the top side for both the top and the root side milled. For the alloys 2024 and 7475 the top side milling caused top side initiation equally frequent as root side initiation.

Looking in detail, the top side crack initiation was primarily located to the retreating side or to the central part of the weld. Alloy 7475 was the exception with crack initiation equally distributed in all parts of the weld.

In absolute values the FSW series for as milled specimens reaches a maximum stress of 250 MPa at 10^6 cycles for alloys 7475 and 2024. The medium strength alloy 6013 reaches 200 MPa at 10^6 . It can be seen that the curve for 6013 levels off at high stress aiming at the ultimate static strength of the weld (291 MPa).

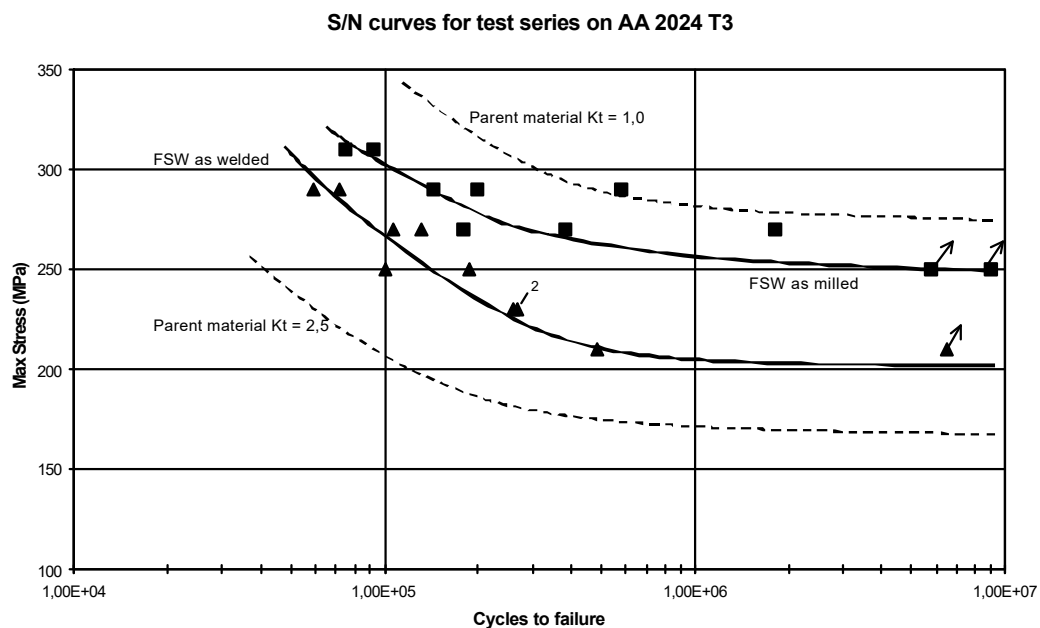


Figure 3. Fatigue results for 2024 T3. Constant amplitude $R = 0,1$.

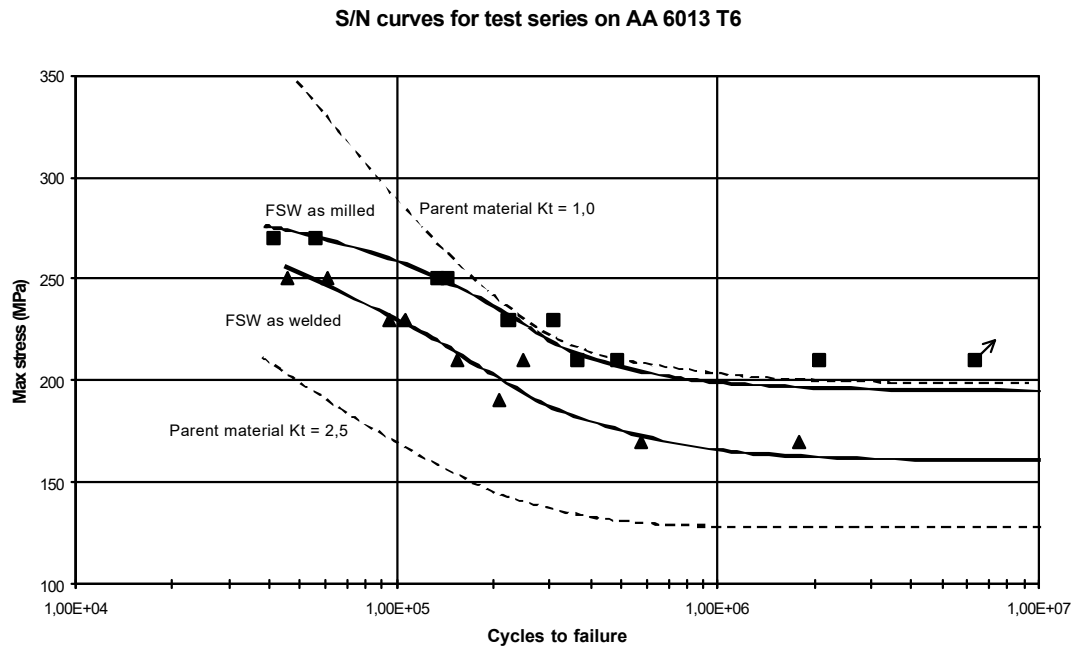


Figure 4. Fatigue results for 6013 T6. Constant amplitude $R = 0,1$.

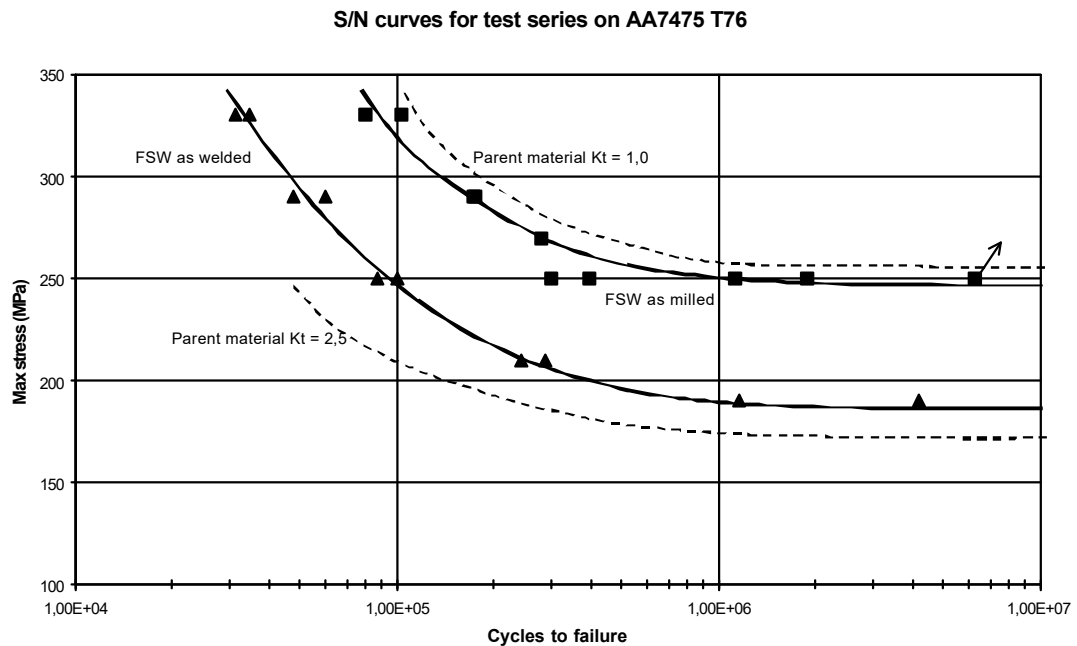


Figure 5. Fatigue results for 7475 T76. Constant amplitude $R = 0,1$.

Metallurgical Examination

Microsections normal to the welding direction were prepared for metallographic studies of the weld nugget and the heat affected zone. All sections were prepared looking in the welding direction resulting in the advancing side of the weld to the left. Additional sections were prepared from bend test specimens that were solution heat treated and aged after welding. All sections were etched using Kellers reagent.

Macrographic and micrographic studies were supplemented by hardness profile measurements over the welds in the as welded condition. The width of the zone affected by a hardness drop (HAZ) was measured to 11 mm for 2024, 13 mm for 6013 (postweld aged) and 13 mm for 7475 in the centre of the sheet thickness. The hardness profiles are shown in figure 6.

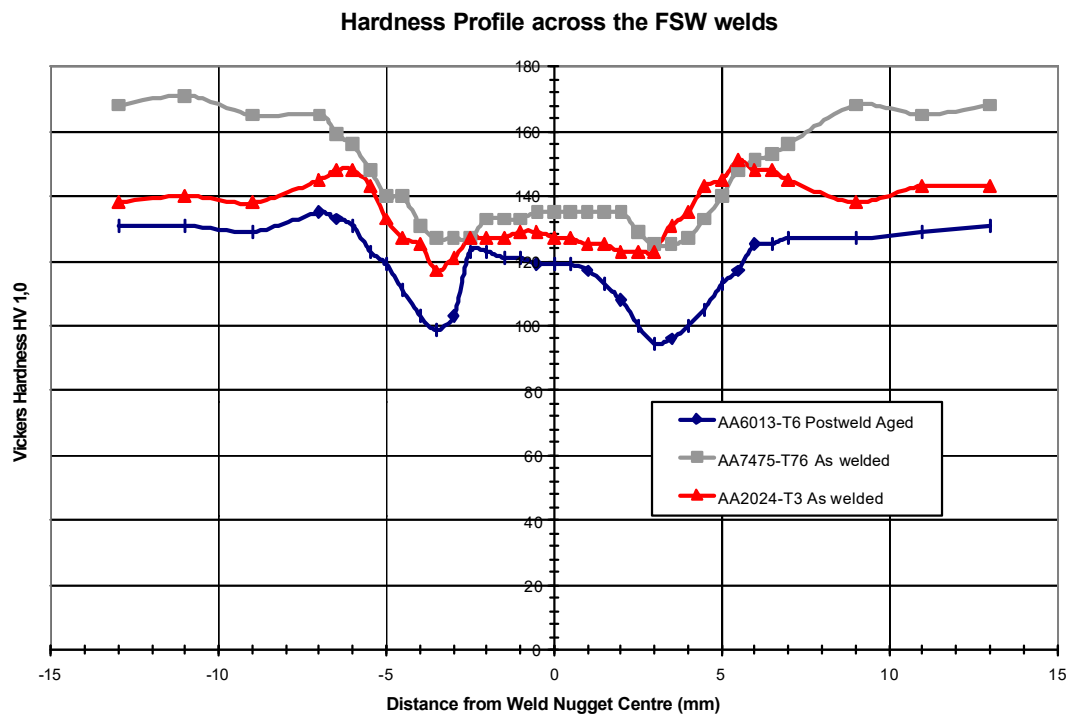


Figure 6. Micro hardness of the three alloys.

Figures 7, 8 and 9 show the macrostructure of the weld nugget and the surrounding heat affected zone in the as welded condition and after plane deburring. The dark-etching v-shaped zone includes a recrystallized zone in the centre of the thermomechanically affected zone according to reference 3. The feature called "onion rings", that is visible in the weld nugget is believed to correspond to variation in grain size. Onion rings are tied to the thread of the tool and are seen as a sign of good weld quality.

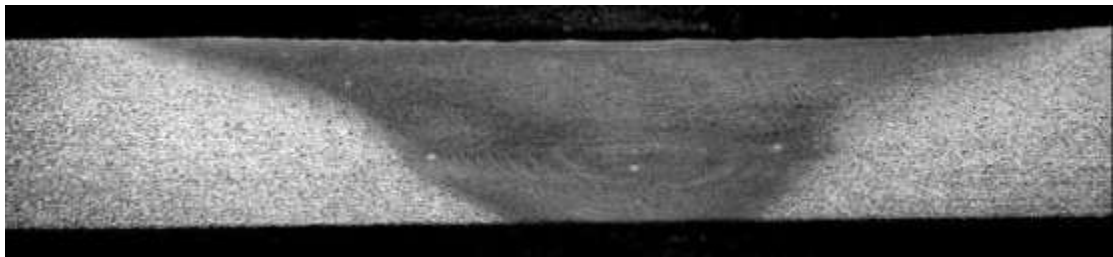


Figure 7. Cross section of 2024 T3 as welded. Faint "onion ring pattern" visible in the recrystallized nugget. Top surface of the weld is smoother than for 6013 and 7475. Magnification 14 X.

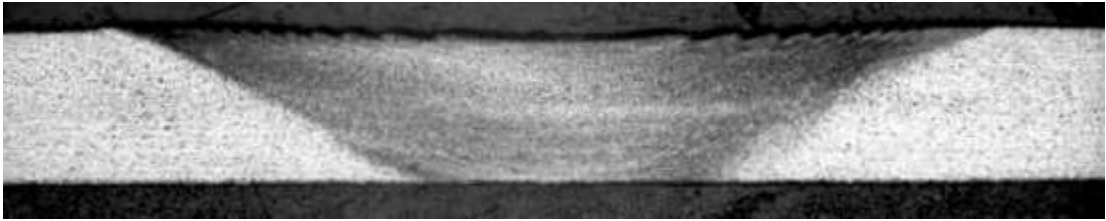


Figure 8. Cross section of 6013 T6 PWA. Irregular surface on top side of weld due to movement of welding tool. Magnification 14 X.

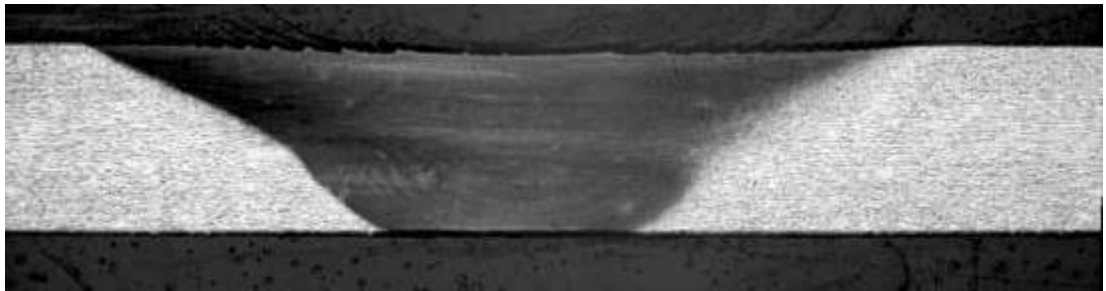


Figure 9. Cross section of 7475 T76 as welded. The dark area consists of recrystallized grains of small size surrounded by a plastically deformed zone. "Onion ring pattern" is visible. Magnification 14 X.

A thin layer of reoriented grains close to the top surface in alloy 7475 outlined by mashed oxide particles was detected at higher magnification, see figure 10. This may have affected the reduced fatigue strength in the as welded condition.

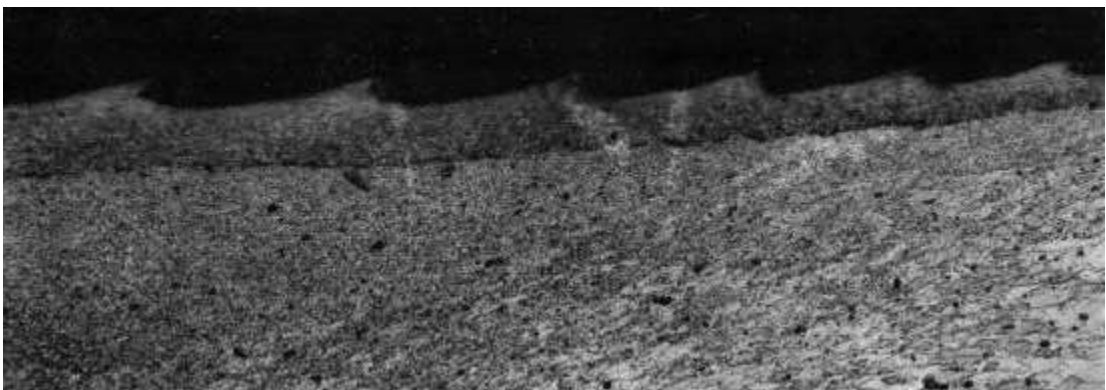


Figure 10. Detail of top surface in figure 9 (7475) showing a 0,04 mm thick zone consisting of reoriented grains outlined by mashed oxide particles.

Magnification 160 X.

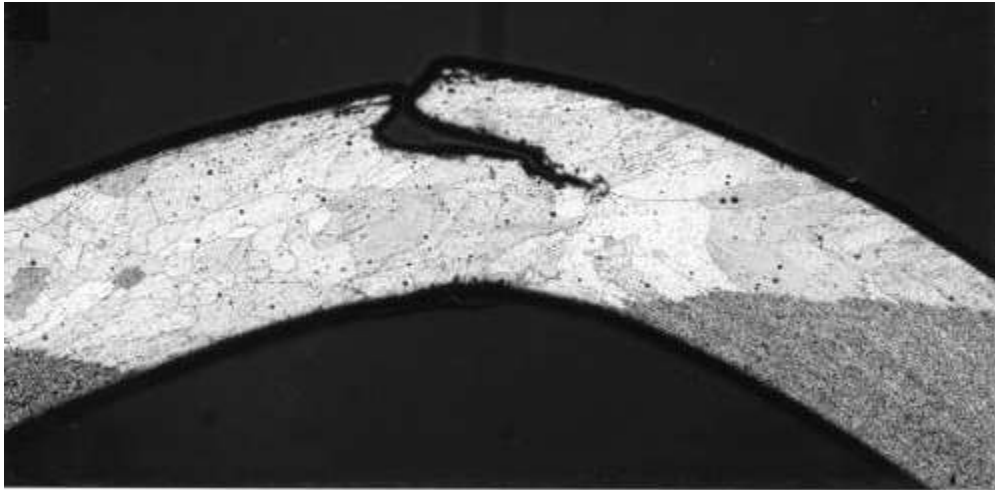


Figure 11. Failure in bend test specimen of 2024 T3 solution heat treated and aged after welding. The dramatic grain growth in the plastically deformed zone results in failed bend test. Magnification 14 X.

Comments

The results shown are encouraging particularly as the welds were produced after only a few test runs on these specific aircraft alloys. We also found that the solution heat treatment should not be performed after FSW, due to grain growth in the thermomechanically affected zone. The static strength is increased by the heat treatment for 7475 in particular but the decrease in bending ductility may have a detrimental impact.

The fatigue strength and the crack propagation data are the critical properties for application in aircraft fuselage structures. By constant amplitude fatigue tests it has been shown that FSW has the potential for replacing mechanical joints to a large extent. The fatigue test result indicates the importance of a post weld machining operation of the weld top side in order to optimise the fatigue strength. Since this is not always feasible, the tool development aiming to a smoother weld surface is essential.

Conclusions

The results from this study can be summarised as follows:

- Tensile tests showed an ultimate tensile strength of 90% and 92% of parent material for 2024 respectively 7475 in the as welded condition. The corresponding value for 6013 is 75% which is similar to the strength of fusion welding.
- The examined alloys fulfilled the criteria for bend testing according to EN 910 in the as welded condition. Resolution heat treatment after welding of the alloys 2024 and 7475 resulted in failure due to weakening caused by grain growth in the plastically deformed zone caused by the FSW process.
- The fatigue tests indicated that milling of the top side of the weld increased the fatigue strength to approach that of parent material.
- For optimal fatigue properties milling of the FSW top surface is essential.

- Defect free FSW welding of 7475 may be achieved using revised welding data to increase heat input. Optionally, not artificially aged material could be used for welding.

References

1. Patent no. US 5813592.
2. Thomas W. M., "Friction stir welding and related friction process characteristics", proceedings from INALCO '98.
3. Threadgill P. L. and Leonard A. J., "Macro and microstructural features of friction stir welds in various materials", TWI CRP report 693/1999.

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