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The effect of post weld heat treatment on the properties of 6061 friction stir welded joints

K. N. KRISHNAN*
CRC for Welded Structures, Department of Mechanical Engineering, The University of Adelaide, Adelaide 5005, Australia
E-mail: knkrishn@mecheng.adelaide.edu.au

Post weld heat treatment (PWHT) of Friction Stir Welds (FSW) was carried out at solutioninsing temperatures of 520, 540, and 560°C followed by ageing at 175°C or 200°C. It was found that the weld (stir) region exhibited very coarse grains after the PWHT. The hardness was found to be uniform across the weldment after the PWHT. The samples failed after PWHT during root bend test. Heat treatments to reduce the grain size did not reduce the brittleness of the welds. The brittleness was attributed to the presence of precipitate free zones adjacent to the grain boundaries and the equiaxed structure of the weldment microstructure and the failure was due to a ductile intergranular fracture mechanism.

1. Introduction

Friction Stir welding (FSW) is finding increased use in difficult-to-weld alloys like the 2XXX and 7XXX aluminium alloys and the moderately fusion weldable 6061 alloys. The HAZ (Heat Affected Zone) of FSWs was to have lower hardness than the rest of the region when the base material is in the peak hardened condition [1]. In order to restore the properties a PWHT in form of ageing has been tried for 6082 alloys [1]. It was found if the base material was under T6 condition, after a post weld ageing, the HAZ had lower hardness while the rest of region regained their hardness. When the material was under T4 condition, there was recovery of hardness across the entire weldment.

Normally the FSWs are used in the as welded condition, but there maybe some advantages in carrying out the welding with base material in a soft condition and the PWHT would restore the properties. The welding tool forces were found to be low if the base material was in soft "O" condition compared to when it is in T6 condition [2]. This means that the FSW system need not be very expensive. The other advantage is after the welding is carried out under O condition, the post weld forming operation can be much more easily performed if the base material were in O condition. PWHT later can restore the properties. More work is required in this area to understand the effects of heat treatment state of material prior to welding.

In this paper the effect of post weld heat treatment on the properties of FSW joints is discussed.

2. Experimental details

2.1. Material and welding

The experiments were conducted on a 6061 alloy whose composition (%wt) is given in Table I.

If one were to convert the Si and Mg compositions to %atom, it can be seen that this alloy is a very nearly balanced alloy and the excess Si is only 0.07%wt. The total Mg_2Si is 1.72%wt. The content of Mn is very low compared to other alloys [3] and is unlikely that it would have contributed enough dispersions to control grain size.

The base material thickness was 5 mm and had an O temper, i.e., annealed condition. The welding and spindle speeds were 288 mm/minute and 1440 rpm respectively.

2.2. Post weld heat treatment

The PWHT consisted of solution heat treatment and precipitation or ageing treatment. Since the grain growth occurs at higher temperatures, three different temperatures of 520, 540 and 560°C were chosen for the solution heat treatment. The solution treatment was carried out for 1 hour at all the above temperatures. The samples were quenched in water at 20°C without any delay. After the quenching of the samples, the specimens were subjected to precipitation hardening treatments. Two precipitation hardening treatments given to the solution heat treated samples were 175°C for 8 hours and 200°C for 1 hour. After metallographic polishing the samples were etched in Tucker's reagent which consists of 15 ml HCl, 5 ml HNO_3, 5 ml HF, and 8 ml water.

2.3. Hardness measurements

This test provides a trend for monitoring the changes taken place throughout the weldment. Hardness is quite sensitive to heat treatment and can be directly related to tensile strength. The relationship between hardness

*Homepage: www.mecheng.adelaide.edu.au/staff/kris/krishna.html

TABLE I Composition of the alloy used in this work

Si	Mg	Mn	Fe	Cu	Cr	Ti	Zn	Al
0.69	1.1	0.11	0.3	0.21	0.15	0.01	0.01	Rest

and tensile strength is a near straight line and the scatter band is about 50 MPa [4]. The tests were conducted on a micro Vickers hardness testing machine using a load of 300 gm. The test was performed in the mid thickness of the specimens. The readings were plotted as a function of distance.

2.4. Bend tests

The root bend test has the ability to concentrate the strain in a localised region, like the weld. This test was used as a qualitative test to detect any cracking in the specimens. The bend radius used was only 5 mm against a recommended radius of 15 mm. It was felt that 15 mm bend radius was highly conservative and while a 5 mm bend radius was found to be very sensitive to ductility changes. Bend test was used as a major qualifying test in this program.

The Scanning electron microscopy (SEM) was used primarily to understand the fracture mechanism in FSW welds. Since it was known that the peak aged alloys exhibited intergranular cracking, the effect of various heat treatments in changing the ductility or toughness of the welds can be followed using the SEM.

3. Results

3.1. Microstructures

The microstructure of the as received base material is shown in Fig. 1. Since the material is in annealed condition, it essentially shows coarse dispersoids possibly Al-Fe intermetallics. The grains could not be resolved

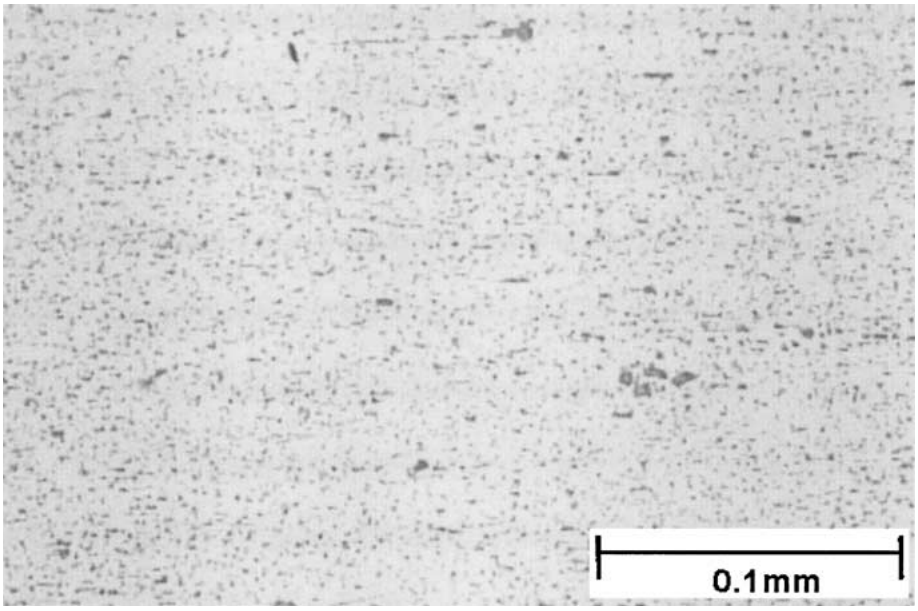

Figure 1 Microstructure of base material in O condition.

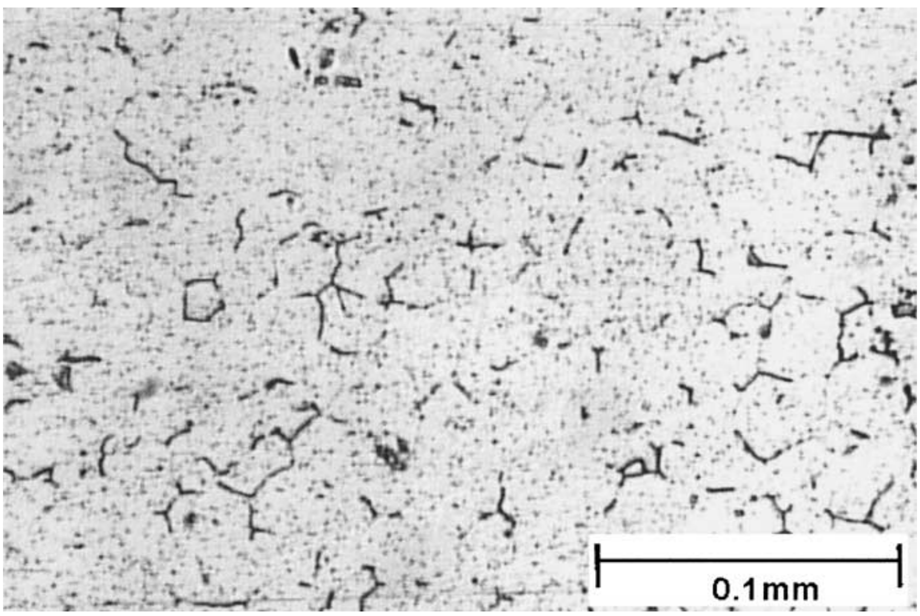

Figure 2 Microstructure of the weld region in as weld samples showing recrystallised grains.

and a banded structure typical of material having undergone a rolling operation is seen.

The microstructure of the weld region in the as welded condition is shown in Fig. 2. The microstructure consists of recrystallised grains with clear grain boundaries. Not all of the grain boundary surrounding the grains could be seen. Other researchers [5–7] have also have found similar recrystallised grains in the weld region of FSWs. In their case they had used material already in peak hardened condition.

3.2. Post weld heat treated samples

The macrostructure of a sample post weld heat treated (PWHT) by solution treating it at 540°C for 1 hour followed by ageing is shown in Fig. 3. It can be seen from this picture that there is extensive grain coarsening in the weld region.

The grains in the base metal have an orientation along the rolling direction; whereas the grains in the weld region are equiaxed. This has an important implication for fracture toughness as explained later.

The microstructure of the weld region in sample in Fig. 3 is shown in Fig. 4. The picture shows thick grain boundary precipitation. The thick grain boundary means that there should be a wide PFZ (precipitate free zone) associated with it. The dispersoids are still seen even after heat treatment. The microstructure of the base metal is shown in Fig. 5. This picture shows that the grains are fully developed but they have a much smaller size in the thickness direction than the grains in weld.

The samples heat treated at 520°C for 1 hour and aged for 175°C is shown in Fig. 6. The significant difference is that the grain size in the weld was smaller than the samples solutionised at higher temperatures.

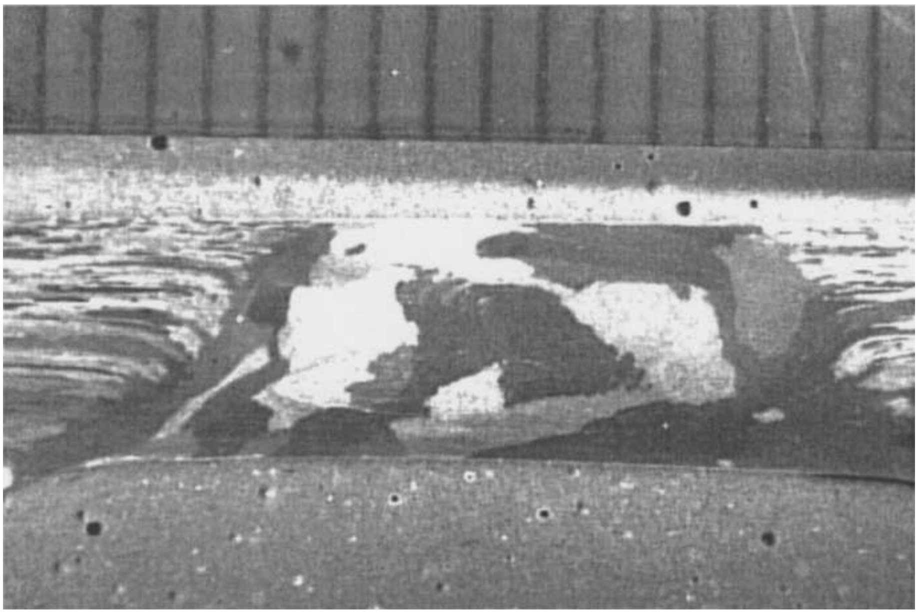

Figure 3 Post weld heat treated sample (540°C, 1 hour + 175°C for 8 hours) showing coarse grains in the weld region.

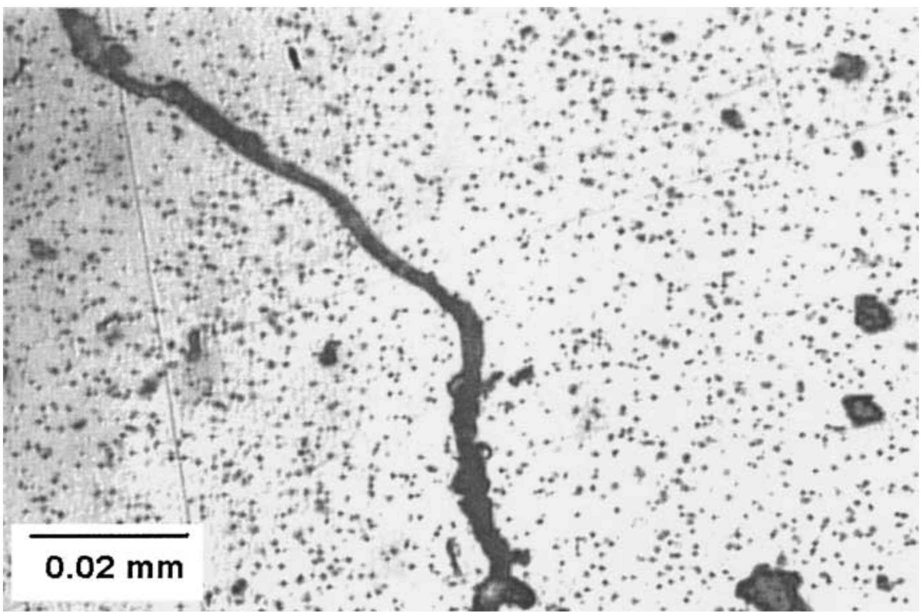

Figure 4 Microstructure of sample (540°C, 1 Hour + 175°C, 8 hours) showing thick grain boundary precipitate and dispersoids.

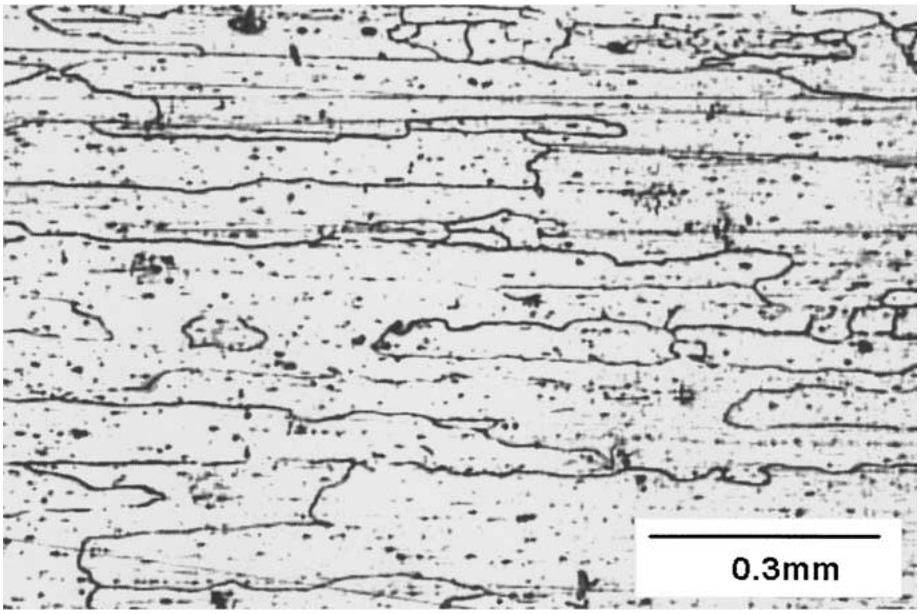

Figure 5 Microstructure of base metal heat treated at 540°C, 1 hour + 175°C for 8 hours, showing thick grain boundary precipitates and dispersoids.

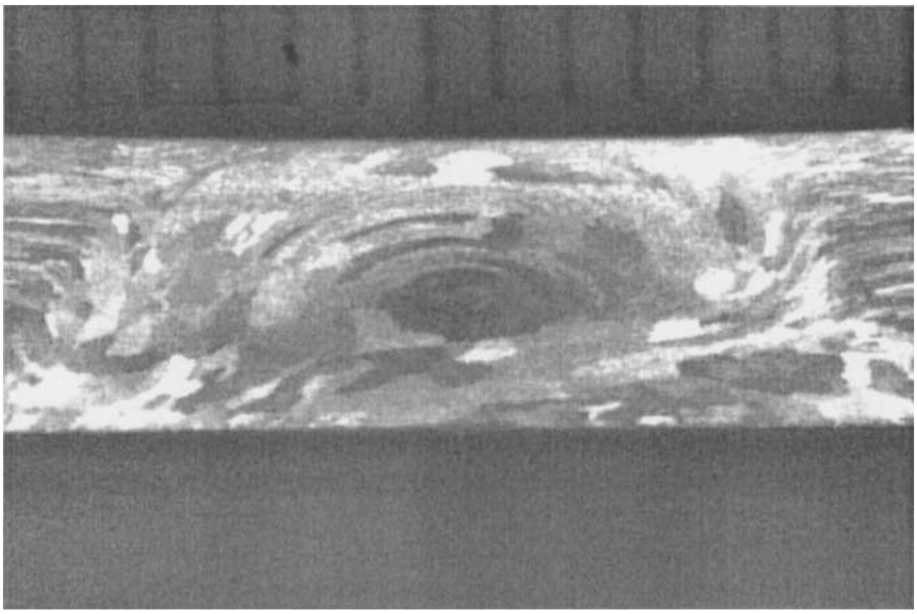

Figure 6 Macrostructure weld heat treated at 520°C for 1 hour + 175°C for 8 hours.

3.3. Hardness values

3.3.1. As weld samples

The hardness of the as welded sample is shown in Fig. 7. It can be seen from this figure that the weld had a higher hardness than the base metal. The hardness values are consistently higher to one side of the weld, which was the advancing side of the weld.

3.3.2. Post weld heat treated samples

The PWHT samples showed hardness values depending on the temperature of solution treatment and ageing.

The hardness values for PWHT samples are shown in Fig. 8. The samples that were solutionised at 520°C showed much lower hardness values than the samples that were solution heat treated at 540 or 560°C. The samples aged at 200°C showed somewhat lower hardness than the samples aged at 175°C. The difference was more prominent in samples solutionised at 520°C.

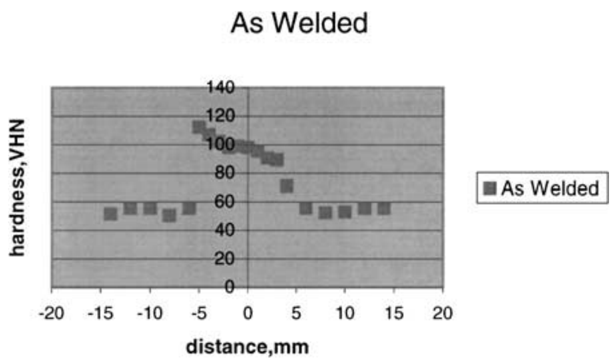

Figure 7 Hardness of as welded FSW sample; note the higher hardness in the weld.

In fact, the hardness in the weld of the samples solutionised at 520 and 540°C and aged at 200°C were lower than the weld region of the as weld samples. The samples solutionised at 560°C did not show much

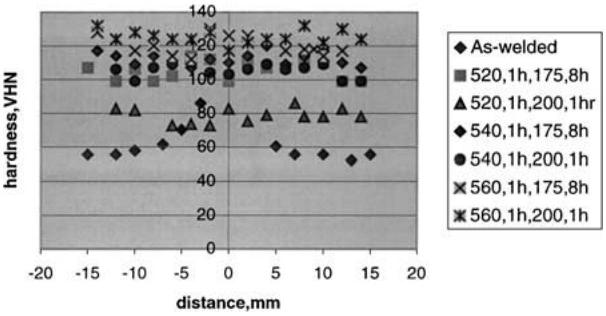

Figure 8 Hardness traverses across post weld heat treated samples.

differences in the hardness values after different ageing treatments. The samples solutionised at 560°C showed the maximum hardness.

3.4. Bend tests
Root bend test was used as an important tool to understand about the ductility and toughness of the friction stir welds. All the as weld samples passed the 180° bend test. All of the samples that were post weld heat treated were found to have bend failures. The samples that were heat treated at 520°C though they had lower hardness also failed in the bend tests. The failures in general were found to be brittle as shown in Fig. 9. Bend test were also conducted on samples that were solution heat treated at 520°C for 0.5 and 0.75 hour and aged. It was found that these samples did not fail in the bend test.

The base metal portion of the samples that had failures in the weld in the bend tests were extracted and were subjected to the same bend test. It was found that the base metal did pass the test. It was unexpected to note that the base metal passed the test while the weld metal did not.

The above tests were conducted using a bend radius of 5 mm. Since this was a severe test a bend test using the recommended standard bend radius of $3t$ (=15 mm), t is thickness, was conducted on a sample which was solution heat treated at 540°C and aged at 200°C for 1 hour. The sample showed many cracks along the rootside of the weld but did not fracture completely as in the tests using 5 mm bend radius. The cracks some quite big and many tiny ones were seen as shown in Fig. 10. It is clear that the material was brittle and the non standard bend test was more sensitive to material properties.

3.5. Fractography
The fractured samples from the bend test were examined under the scanning electron microscope (SEM). Some of the PWHT samples were mounted side-on so that the fracture path can be examined under optical and SEM. The fracture path of the sample PWHT at 540°C for 1 hour and aged at 175°C for 8 hours is shown in Fig. 11. It is clear from this photographs that the crack path is predominantly intergranular.

This fracture surface was examined under SEM and the picture is presented in Fig. 12. This picture reveals that the fracture surface consists of flat regions with a few large dimples. These dimples are in the regions of the grain boundary and are due to the large grain boundary precipitates. The dimples form at the interface between the precipitate and the matrix. On close examination of the flat region at higher magnification, it was found that this region was covered with finer dimples as shown in Fig. 13. The fracture surface also shows coarse slip lines and folds. The fracture surfaces of base metal also showed similar features of intergranular cracking. Similar pictures were found by other investigators for peak hardened Al Mg Si alloys [8–15].

4. Discussion
The significant aspect of this research was that when PWHT is carried out, the properties deteriorate in the

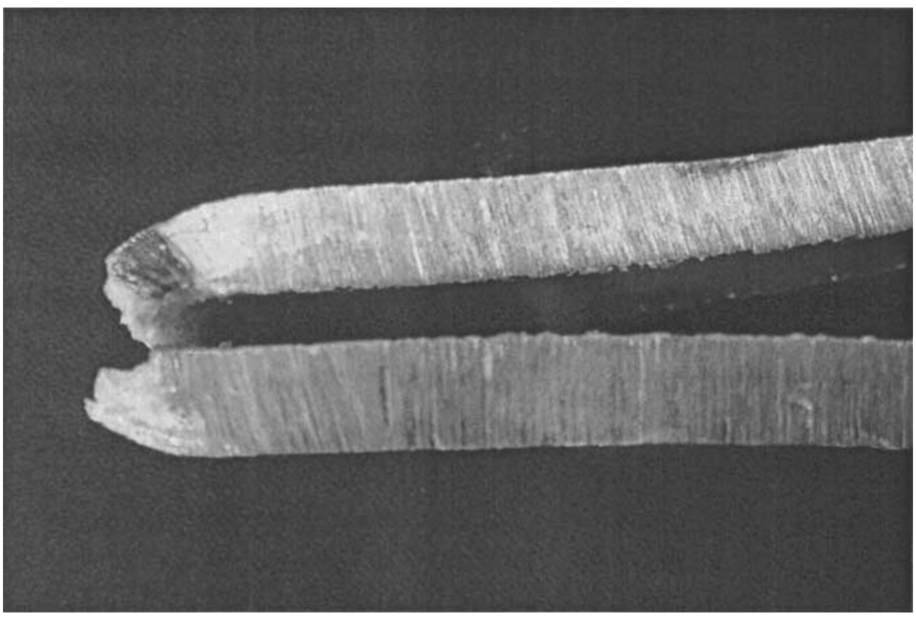

Figure 9 A typical failure of a PWHT sample showing brittle fracture of the weld.

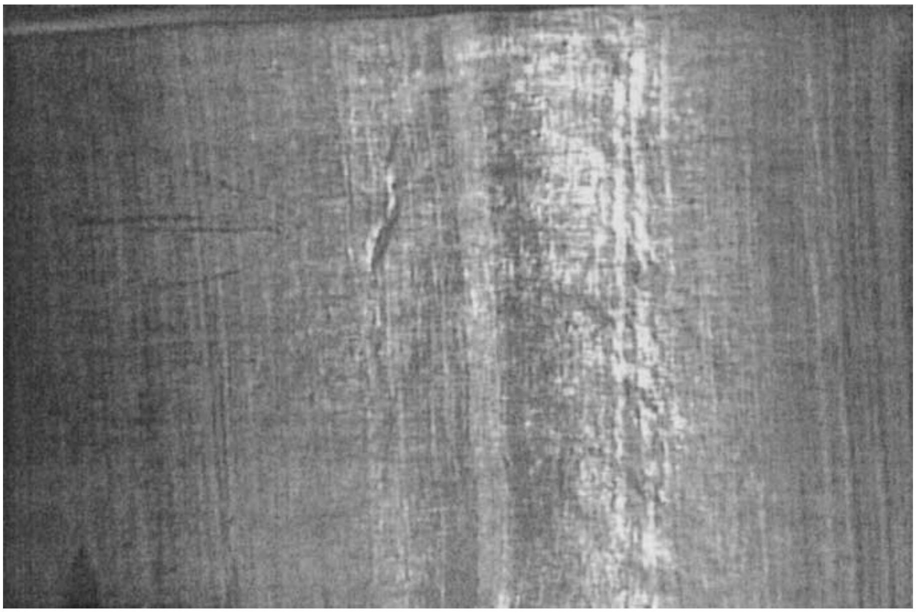

Figure 10 Cracks seen sample (540°C, 1 h + 200, 1 h) put through a standard bend test.

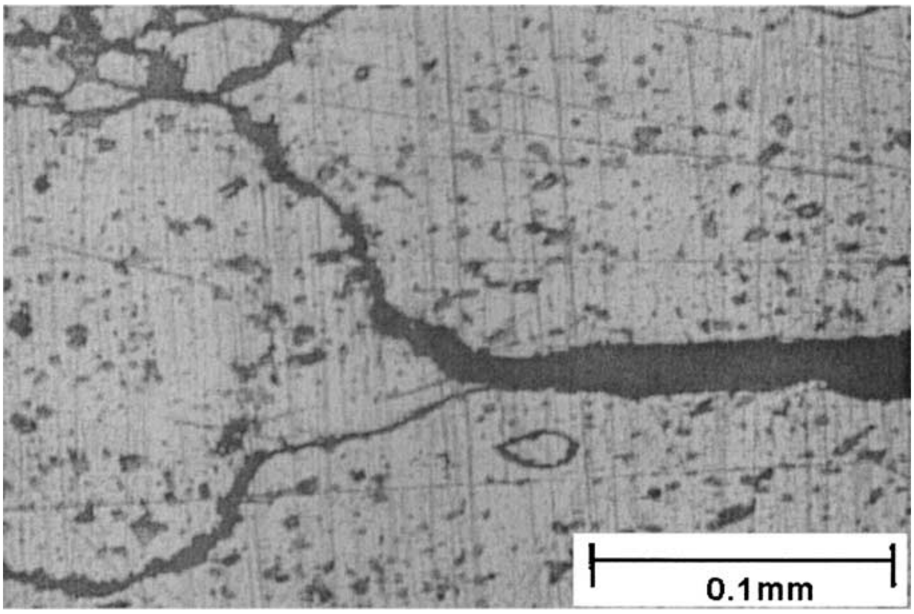

Figure 11 Intergranular cracking in the weld.

weld. The maximum hardness was obtained in the weld when the samples were solution treated at 560°C. This is because the amount of quenched-in vacancies would be higher at higher temperatures thus increasing the number of nucleation sites. As the temperature is increased the PFZ size also increases resulting in brittle failure of the weld. Less time at temperature decreases the hardness and the size of the PFZ. That is the reason the why samples solution treated at 520°C for 30 and 45 minutes did not fail in the bend test whereas the one solution treated for 1 hour showed brittle fracture in bend test and this is in spite of the fact that the grain size was smaller.

The failure of the samples in the bend tests can be explained by the presence of PFZ (precipitate free zones) Many studies have been carried out to explain the presence of PFZ with brittleness [8–16]. The mechanism for such brittleness that has been put forth is that the slip is concentrated in a few slip bands as there is nothing there to disperse it. This coarseness of slip also reduces the fracture toughness [3, 15, 16] and can easily be responsible for crack initiation by raising the stress concentration at the grain boundaries [8]. Since the PFZ is soft, strain concentration will be extreme eventhough the macroscopic strain is very low. This produces voids at the PFZ which then grow and coalesce along the PFZ leaving a fine dimpled structure as shown in Fig. 13. Coarse slip bands are also seen in this picture. If there are coarse grain boundary precipitates, they may produce coarse dimples as seen in Fig. 12. In general, the result is a low energy fracture resulting in brittleness in samples that had a wide enough PFZ. Samples that were solution treated at 520°C for 30 and 45 minutes did not fail in the bend test because the size of the PFZ would be smaller and of course, the hardness of the general structure itself was lower as shown in Fig. 14.

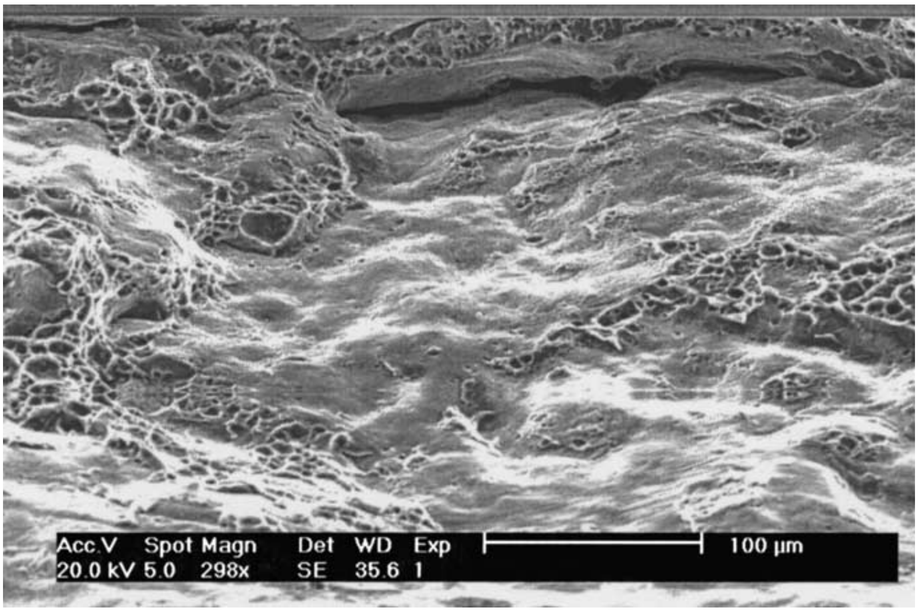

Figure 12 SEM of fracture surface of weld showing flat regions and coarse dimples along grain boundaries.

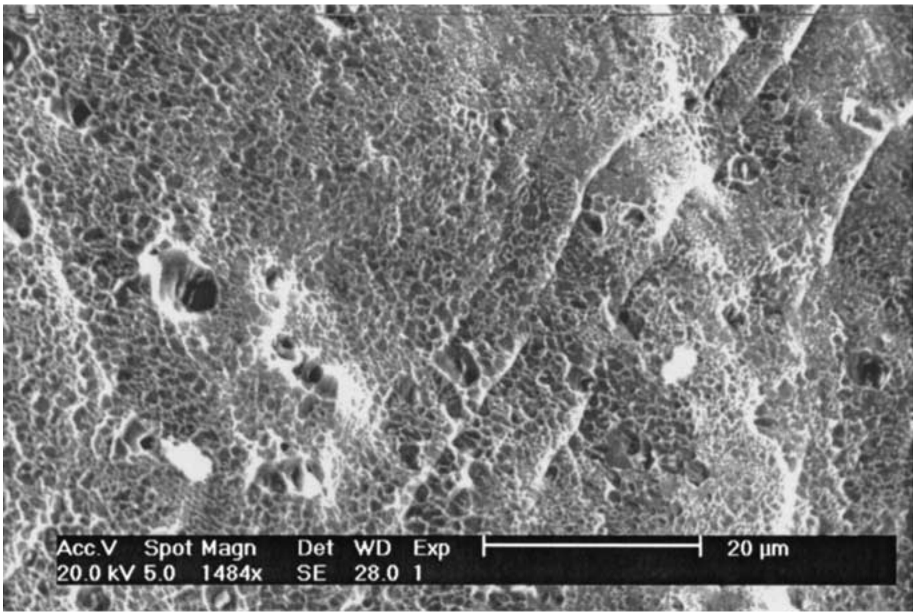

Figure 13 A close examination of flat regions in Fig. 35 exhibiting finer dimples.

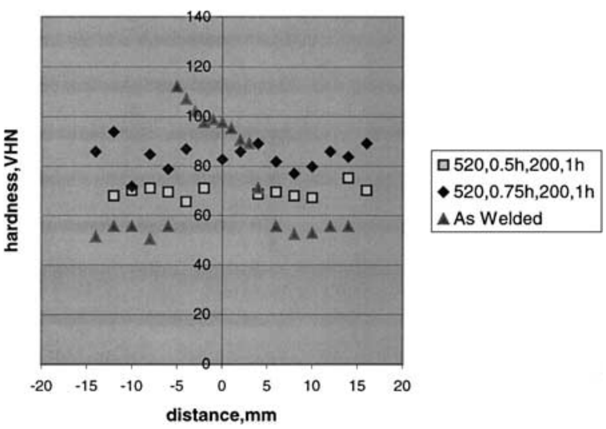

Figure 14 Hardness of underaged samples.

Similarly the as welded samples did not fail because they would not have had time to develop a PFZ. This is in spite of the fact that some of the samples had quite high values of hardness. So it is clear that it appears that one must compromise on the hardness and carry out lower temperature solution treatments in order to avoid brittle fracture in FSWs. More study is necessary to look at other remedial measures.

The directionality of the grains is also a very important factor. The base metal even though had undergone a similar heat treatment as the weld did not fail in bend test. The reason is that the base metal had elongated grains as shown in Fig. 5. The cracks would have to go through a tortuous path in order for them to propagate and the cracks are likely to be deflected at grain boundaries. Equiaxed large grains are likely to have the lowest fracture [17]. There have been attempts at improving the fracture toughness of the Al-Mg-Si alloys and the fracture mechanisms studied [8–16]. It was found that unless dispersions were introduced in the form of Mn or Cr intermetallic compounds the coarseness of the slip always produced intergranular fracture in peak hardened alloys irrespective of grain size. When Al-Mn intermetallics were introduced, the slip became more distributed and the fracture toughness increased [3, 15, 16]. The fracture mechanism also changed from intergranular to transgranular.

5. Conclusions

1. The as weld samples did not fail in bend test.
2. The solution and ageing treatments to produce high hardness resulted in failures in the bend test.
3. The PWHT, in general, produced massive grain sizes and equiaxed grains.
4. The failure of the PWHT weld region in bend test has been attributed to low fracture toughness, equiaxed grains and the presence of precipitate free zones.

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