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Friction stir welding of automotive aluminium alloys

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Abstract

Friction stir welding has several benefits in **welding** difficult to weld aluminium alloys and dissimilar materials. However, the **friction stir welding** process requires careful selection of **welding** parameters, mainly tool rotation speed and travel speed as well as tool geometry, in order to prevent defect formation. The aim of this investigation is to study the effect of **friction stir welding** parameters on the microstructure and mechanical properties of welds in two automotive aluminium alloys. Welds were made in 1 mm thick sheets of Al 5182-H111 and Al 6016-T4 alloys. The **welding** process was carried out in both materials, in two series, using in each series different tool design and **welding** parameters. The **welding** parameters were selected in order to give colder welds in the second series than in the first series. Both **welding** process parameters gave welds with good appearance and free from defects. The central zone of the welds, commonly designated as the nugget, is formed of small equiaxed grains, though

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Author Keywords

Aluminium alloys; **Friction stir welding**; Process parameters

Matched Terms:

Index Keywords: Friction stir welding; **Friction welding**
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FRICTION STIR WELDING OF AUTOMOTIVE ALUMINIUM ALLOYS

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Friction stir welding; Process parameters; Aluminium alloys

Abstract:

Friction stir welding has several benefits in welding difficult to weld aluminium alloys and dissimilar materials. However, the friction stir welding process requires careful selection of welding parameters, mainly tool rotation speed and travel speed as well as tool geometry, in order to prevent defect formation.

The aim of this investigation is to study the effect of friction stir welding parameters on the microstructure and mechanical properties of welds in two automotive aluminium alloys. Welds were made in 1 mm thick sheets of Al 5182-H111 and Al 6016-T4 alloys. The welding process was carried out in both materials, in two series, using in each series different tool design and welding parameters. The welding parameters were selected in order to give colder welds in the second series than in the first series. Both welding process parameters gave welds with good appearance and free from defects. The central zone of the welds, commonly designated as the nugget, is formed of small equiaxed grains, though these grains are difficult to distinguish in some welds. No substantial change was observed in the hardness of the welds of the first series as opposed to the welds of the second series in both materials. The change in the process parameters influenced the weld efficiency too.

1. INTRODUCTION

Friction stir welding (FSW) has several benefits in welding difficult to weld aluminium alloys and dissimilar materials. However, friction stir welding process requires careful selection of welding parameters, mainly tool rotation speed, travel speed and plunge depth as well as the tool geometry, in order to prevent defect formation [1, 2]. A strict control of the process parameters is needed, chiefly in welding of very thin sheets of aluminium alloys.

The effect of FSW parameters on microstructural evolution in the thermo-mechanically affected zone (TMAZ) and heat-affected zone (HAZ) of welds in aluminium alloys has been studied in last years [3, 4]. The hardness profile of welds in precipitation-hardenable alloys is largely governed by the dissolution and growth of strengthening precipitates during the weld thermal cycle. Several factors such as the strain hardening, the grain size or the distribution of small particles in the weld, have been mentioned as having influence in the hardness profile of welds in solid-solution-hardened alloys. Post-weld mechanical properties, such as strength and ductility, are directly related with microstructural evolution in each zone of the welds [5].

The aim of this investigation is to study the effect of friction stir welding parameters on the microstructure and mechanical properties of welds in thin sheets of two automotive aluminium alloys AA 5182-H111 and AA 6016-T4.

2. EXPERIMENTAL PROCEDURE

Welds were produced in 1 mm thick plates of aluminium alloys AA 5182-H111 and AA 6016-T4, mainly used in automotive applications. The nominal chemical composition and mechanical properties of the plates are shown respectively in tables 1 and 2. Welds were performed using a conventional milling machine provided with a clamping device to firmly fix the plates to the table of the machine tool.

Table 1 – Nominal chemical composition of the aluminium alloys, wt-%

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
AA 5182-H111	0.2 max.	0.35 max.	0.15 max.	0.2 – 0.5	4.0 – 5.0	0.1 max.	0.25 max.	0.1 max.
AA 6016-T4	1.0 – 1.5	0.5 max.	0.2 max.	0.2 max.	0.25 – 0.6	0.1 max.	0.2 max.	0.15 max.

Table 2 – Tensile properties of the base materials

Alloy	$R_{p0.2}$ (MPa)	R_m (MPa)	A_{50} (%)
AA 5182-H111	114	275	24
AA 6016-T4	115	226	24

$R_{p0.2}$ - yield stress; R_m – tensile strength; A_{50} – elongation on fracture.

Two series of welds were carried out in booth alloys using different process parameters. In the first series a tool of 10 mm shoulder diameter with a threaded probe of 3 mm in diameter and 0.9 mm in length was used. The tool utilized in the second series had a scrolled shoulder of 14 mm diameter, in order to reduce the tool tilt angle to zero. The probe was similar in both tools. The welding parameters applied in both series are shown in table 3. The welding parameters were selected in order to get warm welds in the first series and colder welds in the second series.

Table 3 – Welding parameters.

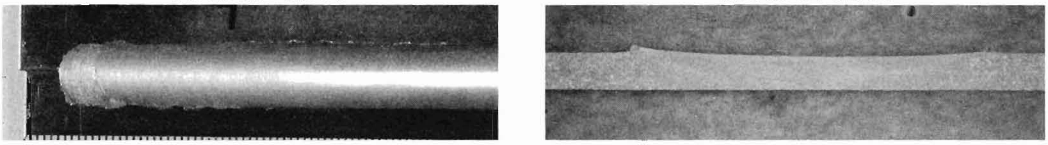
Series	rotation speed ω (rpm)	travel speed v (mm/min)	Tool angle α (°)	Plunge depth (mm)	Rotation to travel speed ratio (ω/ v)
1rst	1800	160	2.5	0.95	11.25
2nd	1120	320	0	0.95	3.5

Macroscopic and X-ray examination of the welds was performed previously to metallographic and mechanical testing. Metallographic examination was done in the cross section of the welds as well in several planes parallel to the plate surface. Metallographic specimens were etched with two different reagents: a modified Poulton's reagent was applied for 20 s to reveal the grain boundaries; Hatch reagent (1 g NaOH, 100 ml H2O) is more efficient in revealing the grain size of both welds. Hardness and tensile tests were conducted on specimens removed transversely the welding direction.

3. RESULTS AND DISCUSSION

Weld appearance – The surface appearance of the of booth weld series is very smooth, without significant barbs, as is illustrated in Fig. 1 for welds of the first series in both alloys. The reduction in plate thickness is an important factor in this case because sheets of 1 mm thick were being welded. The scrolled tool shoulder was used in the second series with the objective of reducing to zero the tool tilt angle in order to minimize the plate thickness reduction.

AA 5182-H111 AA 5182-H111



AA 6016-T4 AA 6016-T4

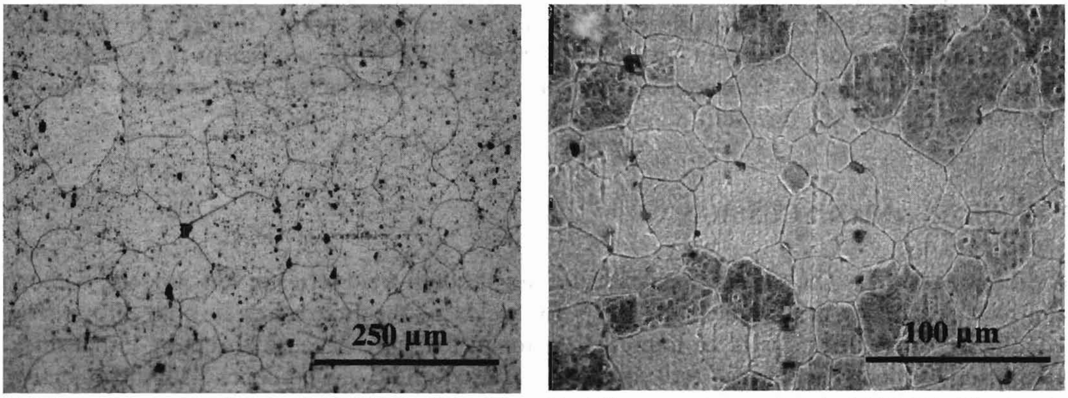
Fig 1 – Appearance of the surface and cross section of welds of the first series in alloys AA 5182-H111 and AA 6016-T4.

A small reduction in plate thickness was observed in both materials and series. The reduction in plate thickness was always less than 0.1 mm and typically 0.01 mm. However the welds of the second series show only a small prominence(less than 0.1 mm high) in the advancing side as opposed to the welds of the first series that depicted prominences up to 0.3 mm high. This result suggests the tool design influences the weld surface profile

Microstructure - The microstructure of the alloys AA 5182-H111 and AA 6016-T4 is composed of approximately equiaxed grains, with an average size of respectively 73 μm and 31 μm, almost without any preferential orientation as shown in Fig.2 a) and b). However a large dispersion in grain size can be observed mainly in alloy AA 6016-T4. The same figure, Fig 2 c) and d), illustrates also the change in the microstructure in the central zone of the welds. This region is usually designated as the nugget and it is composed of small equiaxed grains, difficult to distinguish, with an average grain of 12 μm and 7 μm, respectively for welds of the first series in alloys AA 5182-H111 and AA 6016-T4. This recrystallized fine-grained microstructure results from the intense plastic deformation and large frictional heat generated by the tool.

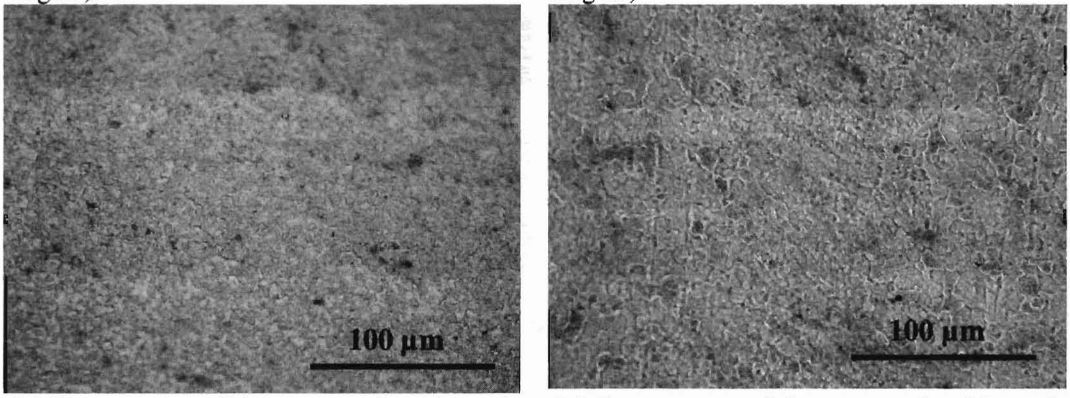
In the welds of the second series a refinement of the grain (5 μm) was observed in the nugget of the welds carried out in AA 5182-H111. This observation is consistent with the results of Sato et al [6] which report a decrease in grain size by decreasing the tool rotation rate at constant tool traverse speed, that is decreasing the heat-input in the process. It was not possible distinguish the grains in the nugget of the welds of the second series in alloy AA 6016-T4.

The microstructure of the thermo-mechanically affected zone outside the nugget is similar in all the welds and it is basically composed of plastically deformed grains following the material flow pattern. The dissolution of precipitates in this zone as well the dissolution and coarsening of precipitates in the heat-affected zone are being investigated by transmission electron microscopy (TEM).



a) Microstructure of AA 5182-H111 (Hatch's reagent)

b) Microstructure of AA 6016-T4 (Poulton's reagent)



c) Microstructure of the nugget of welds made in alloy AA 5182-H111 (Poulton's reagent)

d) Microstructure of the nugget of welds made in alloy AA 6016-T4 (Poulton's reagent)

Fig 2 – Microstructures of welds performed in alloys AA 5182-H111 (second series) and AA 6016-T4 (first series).

Hardness - Fig.3 shows the hardness profiles of welds of both series done in alloy AA 5182-H111. The hardness evolution in the base material is also depicted in the same figure. Hardness measurements were performed in planes parallel to the plate surface. The boundaries of the different zones of the welds are also indicated in Fig. 3. No significant increase in hardness was observed in the TMAZ of welds of the first series in alloy AA 5182-H111. This behaviour is governed by two competitive effects: strain hardening given by the plastic deformation of the grains and material softening favoured by the new recrystallized grains in the nugget, mentioned above, and recovered grains outside the nugget.

A substantial increase in hardness was obtained in the TMAZ of the welds of the second series in this alloy, see Fig 3. In this case the softening effect of the recrystallized grains observed in the nugget was not enough to compensate the hardening effect of plastic deformation. According to Hall-Petch relationship the grain refinement observed in the nugget of these welds can even contribute for the strengthening of this zone.

Fig 4 illustrates the hardness profiles of both series of welds in alloy AA 6016-T4 as well the hardness of the base material. Friction stir welds of the first series showed a softened region in each side of the weld, in the heat-affected zone. This softening is commonly attributed to the dissolution and coarsening of strengthening precipitates during the weld thermal cycle [7]. Softening is more evident in the retreating side suggesting the heat generated in the retreating side is higher than in the advancing side.

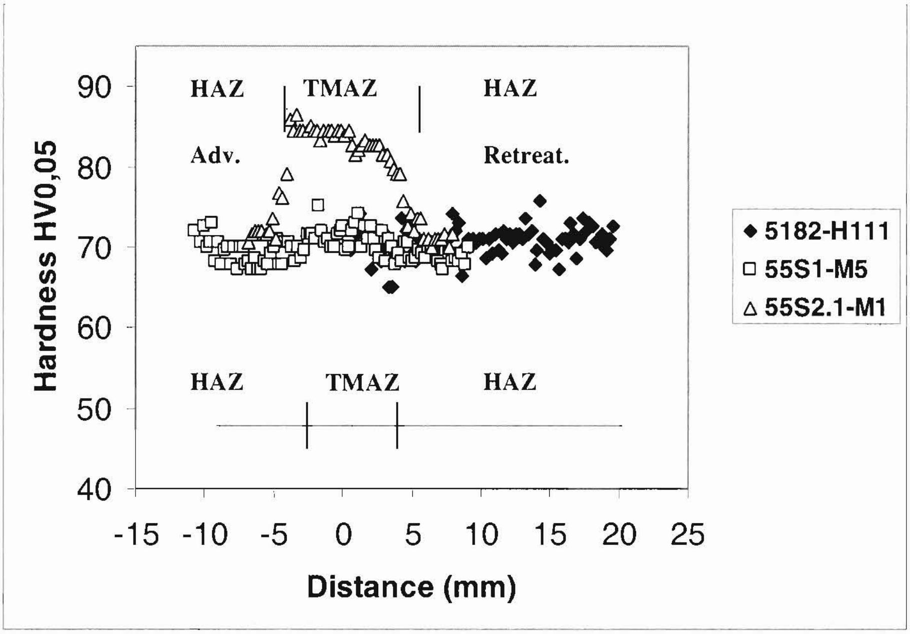


Fig 3 - Hardness profiles of welds in alloy AA 5182-H111. Data labels: 5182-H111 – Parent material; 55S1-M5 – Weld of the first series; 55S2.1-M1 - Weld of the second series.

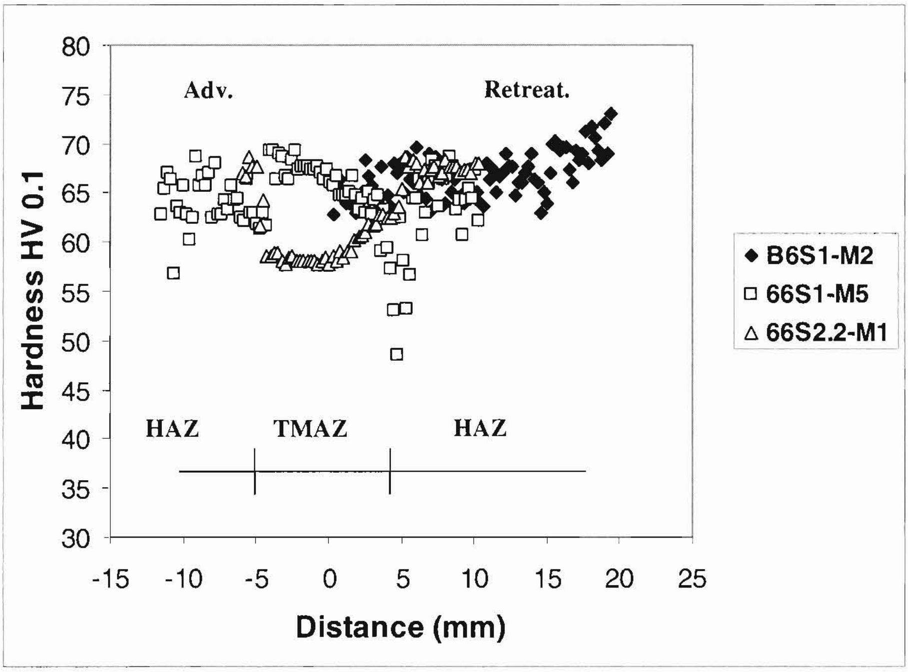


Fig 4 - Hardness profiles of welds in alloy AA 6016-T4. Data labels: B6S1-M2– Parent material; 66S1-M5 – Weld of the first series; 66S2.2-M1 - Weld of the second series.

However in the TMAZ the hardness is identical to that of the base material. This behaviour can be explained by the dissolution of strengthening precipitates followed by reprecipitation due to an aging mechanism. In fact a large proportion of heat was generated in these welds because of the high rotation to travel speed ratio (ω / v) used.

The welds of the second series in the same material showed a decrease in hardness around 10 HV0.1 in the TMAZ. The heat generated in the process in this case seems to be only enough for partial or total dissolution of strengthening precipitates without significant subsequent reprecipitation. Add to this recovering mechanism can participate in softening effect because no refinement of the grain was observed in the nugget.

Tensile properties – The average tensile properties of the welds of both series, conducted transversely to the welding direction, are summarised in table 4. The efficiency of the welds, defined as the proportion of the yield stress ($\eta_{Rp0.2}$) or tensile strength (η_{Rm}) of the welded specimen to the base material is also shown in the table.

Table 4 - Tensile properties of the welds.

Weld ref.	$R_{p0.2}$ (MPa)	R_m (MPa)	A_{50} (%)	$\eta_{Rp0.2}$	η_{Rm}	Fracture localization
55S1	113	268	18	0.99	0.97	HAZ
55S2	117	282	23	1	1	BM
66S1	109	200	15	0.95	0.89	TMAZ/HAZ
66S2	116	185	9	1	0.82	TMAZ

$R_{p0.2}$ - yield stress; R_m – tensile strength; A_{50} – elongation on fracture; $\eta_{Rp0.}2$ – yield efficiency; η_{Rm} – tensile efficiency.

Welds done in alloy AA 5182-H111 gave yield and strength efficiencies close to 1 showing the tensile strength the welds is equal or superior to the tensile strength of the base material. This increase in strength comes from plastic deformation of the material in TMAZ and grain refinement in the nugget and is in good agreement with the changes in hardness mentioned previously. For that reason tensile specimens removed from these welds fractured in the HAZ or BM. A small reduction in ductility was also obtained in welded specimens proving the tensile properties of the weld zone are high enough to promote the transfer of plastic deformation to the base material.

On the contrary, the welds of both series carried out in alloy AA 6016-T4 were in the undermatched condition, as revealed by the strength efficiency values inferior to 1 as depicted in table 4. All these specimens fractured in the TMAZ or in the transition between TMAZ and HAZ. This is in agreement with the results of hardness tests that show the lowest values of hardness in this zone. A significant reduction in ductility was observed in these welds, mainly in second series welds, because TMAZ is the softest region and plastic deformation concentrates in this zone, preventing the transfer of plastic flow to the BM and leading to premature fracture. It should be referred that an improvement of the tensile properties is generally linked to the decrease of heat-input the welding process as opposed to the actual results. This contradiction can be explained by the mechanism of dissolution and reprecipitation of strengthening precipitates, mentioned above.

4. CONCLUSIONS

The effect of friction stir welding parameters on microstructure and mechanical properties of welds in 1 mm thickness sheets of AA5182-H111 and AA 6016-T4 automotive aluminium alloys was investigated. Welds were done in two series, using in each series different tool design and process parameters. The welding parameters were selected in order to give colder welds in the second series than in the first series. The decrease in heat-input refined the microstructure of the nugget and increased the hardness of the thermo-mechanically affected zone of welds in AA5182-H111, without reducing joint efficiency. On the contrary the welds of the second series in AA 6016-T4 showed a reduction in hardness and joint efficiency. The tool with scrolled shoulder allowed reducing the tool tilt angle to zero and the prominence in the advancing side of the welds.

5. ACKNOWLEDGEMENTS

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