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A Study on Friction Stir Processing of AA6061


B.Prashanth
Assistant Professor,
Department of Mechanical Engineering,
MLR Institute of Technology,
Hyderabad.


K.Shravan Kumar
Assistant Professor,
Department of Mechanical Engineering,
MLR Institute of Technology,
Hyderabad.

Abstract:
Over the last few years a lot of research has been going on in the area of Friction Stir Welding and Friction Stir Processing (FSP). FSP has developed as a new processing technique to improve the surface characteristics of materials especially Aluminium. In this research we have tried to improve the surface properties, mainly corrosion resistance of Aluminium alloy AA6061 by using an external filler plate during the FSP. A thin sheet of commercial Aluminium was coated on the AA6061 base plate with the help of FSP technique. Different combinations of process parameters like tool speed and plunge depth along with various external cooling modes and backing plates were tested to optimize the process. FSP was also carried out on weld zones of fusion welded samples. Later the processed samples were subjected to various tests like salt spray corrosion test, grain size measurement etc. The test results show that the coating of commercial Aluminium plate did improve the corrosion resistance considerably.

Keywords— ***AA6061, Corrosion resistance, Friction Stir Processing.***

I. INTRODUCTION

AA6061 is a precipitation hardening aluminium alloy, containing magnesium and silicon as major alloy additions. Magnesium and silicon forms Mg2Si which in turn forms a simple eutectic system with Aluminium. It is the precipitation of Mg2Si after artificial aging (temper T6) that allows these alloys to reach their full strength. They exhibit good mechanical properties and weldability along with excellent corrosion resistance. Their applications include construction of aircraft structures, marine fittings and hardware, hydraulic pistons, couplings, valves, bicycle frames, boat hulls, automotive parts such as wheel spares, cans for packaging food stuffs etc.

Severe localized distortions during FSP leads to breaking up of second phase particles and a uniform distribution of the precipitates like Mg2Si formed by the alloy additions [1]. This uniform distribution reduces the chances of forming anodic regions and thus improves the corrosion resistance [2]. Friction Stir Processing has been found to be most suitable with aluminium and its alloys. Aluminium being a low melting point metal solid state process like FSP has a genuine advantage. The low hardness and strength of aluminium also makes it easier to make the non-consumable processing tool.

The loads and temperatures generated during the processing of aluminium require the tool to be made with alloys like EN31 which are easily available, machinable and affordable.

Aluminium is considered to be among those metals which are difficult to be welded by normal fusion welding processes. Low melting point and high thermal conductivity are the two major factors contributing to this phenomenon. GTAW and to some extent GMAW are the most preferred fusion welding techniques for aluminium and its alloys. The most common and simplest of fusion welding processes, SMAW, is not usually used because of the difficulty of use and resulting inferior weld with defects like blowholes, porosity and undercut. FSP has been found to be very successful in removing surface defects like porosity and in improving the overall grain structure [3]. So as to study the effectiveness of FSP in improving the properties of fusion welded aluminium, the process was carried out with SMAW welded joints. As these joints would have the most inferior welds, it would provide the worst case scenario.

II. EXPERIMENTAL SETUP

The material used in the present study is AA6061 rolled aluminium plate with 2mm thickness. Commercial aluminum plates of thickness 1.5mm were coated on to the 6061 plates at different parameters. A modified milling machine was used to perform the Friction Stir Processing.

EN31 tool was used for the process. A concave shaped tool with a shoulder diameter of 20 mm was selected. The pin of the non-consumable tool was a threaded circular pin with a diameter of 4mm and length of 1mm [4].

A. Process parameters

The AA6061 aluminum alloy plate and the 1xxx commercial aluminium plate were cut into the required dimensions. The plates were shear cut to avoid any mis-alignment.

Plate Dimensions:

AA6061 - 100mm x 50mm x 2mm
Commercial Aluminium – 100mm x 50mm x 1.5mm

The tool RPM and traverse speed were kept constant throughout the processes. Here the emphasis is laid on the plunge depth, cooling rate and backing plates.

Tool RPM – 1120 rpm; Tool traverse speed – 80 mm/min

The commercial aluminium plate was kept on the 6061 plate and held in position with the help of a clamp. The entire setup was kept in the vice of the converted milling machine.

Various combinations of the parameters – plunge depth, external cooling and backing plate - were employed.

TABLE I
PROCESS PARAMETERS EMPLOYED

Plunge Depths	0.5 mm	0.75 mm	1 mm
External cooling modes and backing plates	Steel/Air	Steel/Air	Steel/Air
	Steel/Water	Steel/Water	Steel/Water
	Copper/Air	Copper/Air	Copper/Air
	Copper/Water	Copper/Water	Copper/Water

Plunge depth was measured as the depth to which the shoulder is forced in to the plates. The vertical feed of the milling machine was properly manipulated for this purpose. As such 12 processed samples were obtained.

B. FSP on Fusion welded sample

To make the SMAW joint, special type of low heat input electrodes with the brand name LH 409 alloy electrodes (ADOR Fontech) were used. It has UTS of 10 – 15 Kgf/mm2. The joint surface was properly cleaned from scales, grease and dirt before welding. A current of 150 Amps as specified by the manufacturer was used and DC power supply was employed. The fusion welded joints were subjected to further friction stir processing. Of the three fusion welded joints one was retained in the as welded condition, another was subjected to FSP without any filler plate and the third was processed with the use of a commercial aluminium filler plate.

III. TESTS AND ANALYSIS

A. Macrostructure Study

Macrostructural study was carried out by using optical microscope for getting different regions of friction stir processed specimen. The processed sample was cut and the cross section of processed zone was taken as test specimen. The samples were cold mounted, mirror polished and properly etched. The etchant used was modified Keller‗s reagent. Modified Keller's – HCl, HNO3, Ethanol in equal proportions and 1 drop of HF acid.

All the samples were viewed at 1X magnification and images were taken.

Macro images can help us to study the depth and area of the coating. It also gives an idea about the penetration of the commercial aluminium layer into 6061 base plate.

‗Image J‗ software was used to analyse and measure the depth and area of the coated aluminium layer.

B. Microstructure and Grain size

Grain size evolution is one of the major advantages with FSP [5]. Cold mounted samples were prepared, polished and then etched with modified Keller‗s reagent. Cold mounting was employed to avoid any microstructural changes taking place during hot mounting. Images of different regions like stir zone, base metal, TMAZ were captured with help of an image analyzer. Grain size was determined with the help of software ‗MOTIC IMAGES‗.

C. Corrosion test

Aluminium has good corrosion resistance, especially in the atmosphere, due to the natural oxide layer. Corrosion of metals is an electrochemical reaction which involves oxidation of the anode into a positive ion, which is released from the solid metal.

As we had coated commercial aluminium over 6061, the corrosion properties were supposed to have changed. Tests were carried out on the basis of ASTM standards [6].Weight of the samples were measured before and after corrosion test. The weight loss measurements were used as a measure of corrosion rate. The surfaces of the corroded samples were studied to evaluate the extent of corrosion.

Salt spray test was employed as it would reveal the general corrosion behaviour. The test was carried out in accordance with ASTM B117 standards. This test works primarily by the creation of a salt fog inside a glass chamber. The test solution consisted primarily of 95% by weight water and 5% by weight NaCl. This solution was sprayed into the chamber and atomized with help of compressed air to form the salt fog. The chamber temperature was maintained at 350C. The specimens were arranged in the salt spray chamber by hanging them from strings. The test was carried out for a total period of 24 hours. The presence of salt mist corrodes the samples. After the test, the specimens were cleaned thoroughly in nitric acid bath, then in running water and acetone to wash away the salt and corrosion residue. Weight was then measured to 4 decimal accuracy. Percentage change in the weight of samples was calculated and comparison was done. The present study is focused on the corrosion behavior of the processed surface, and hence this surface alone was exposed to the corrosive medium. All other surfaces were protected by paint to avoid any corrosion.

IV. RESULTS AND DISCUSSION

Processing was done with different processing parameters listed above. Various tests were also carried out and values tabulated. The results are discussed in the following section. Broadly the processing parameters used can be classified as,

Plunge depths – 0.5 mm, 0.75 mm, 1 mm external cooling – Air or Water

Backing plates – Steel or Copper

It was assumed, based upon the theory and the available literature that variations in the above processing parameter can bring about changes in the microstructure and other properties of the material. Plunge depth could directly affect the coating

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thickness and the width of the coated layer. It could also influence the metallurgy as the frictional heat developed and subsequent mixing of the 2 metal layers varies with the varying depths of tool plunges. As with the cooling modes and backing plates used, they were directly affecting the effective cooling produced or the net heat taken away [7] [8]. Simple heat transfer analysis was carried out to evaluate the net cooling effect produced in each case.

A. Heat Transfer Analysis

The four possible conditions of cooling were, Air – Steel, Air – Copper, Water – Steel, Water – Copper

The total heat generated was considered to be the same during all the plunge depths.

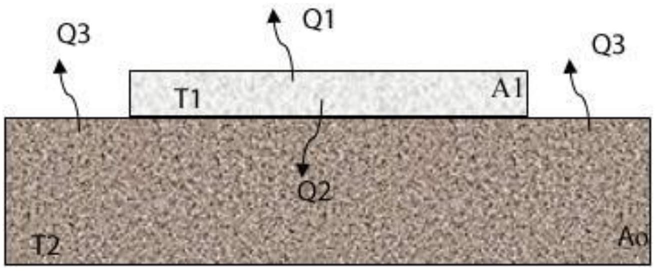


Fig 1: Experiment Setup

We consider mainly three modes of heat transfer.Q1 is the convective heat loss from the processed plate to the surrounding fluid, i.e., the coolant air or water. Q2 is the conduction heat transfer from the processed plate to the backing plate. Q3 is the heat transfer from the backing plate to the coolant through convection.

As per the laws governing heat transfer,

$Q1 = h \times A1 \times (T1 – Ta)$ $Q2 = (T1– T2)/(t/kA1)$

$Q3 = h \times (Ao – A1) \times (T1 – Ta)$

T1 is the temperature on the processed aluminium plate and was assumed to be 400oC based on the findings of R.S. Mishra.

Backing plate temperature, T2 for steel and copper were found out as 150oC and 250oC respectively. Ambient temperature Ta is taken as 30oC.

A1 = 50 * 100 = 5000mm2 Ao = 100 * 120 = 12000 mm2

Backing plate thickness t = 15 mm; for steel = 6 mm; for copper

Conductivity, k = 60.5 W/mK; for steel= 386 W/mK; for copper

Heat transfer coefficient, h = 20 W/m2K; for air at 30oC =50W/m2K; for water at 27oC

Total heat loss, Q = Q1 + Q2 + Q3

Therefore the total heat losses in different conditions are,

Air – Steel = 5129 watts Air – Copper = 48339 watts

Water – Steel = 5262 watts

Water – Copper = 48472 watts

These results show that the maximum cooling takes place when copper is used as the backing plate. There is a large difference in the heat carried away in the case of steel and copper backing plates. It also revealed that the cooling fluids, air and water don‘t vary much in their cooling effect. These values were then used for analysis and comparison of all further test results like microstructure, coating thickness etc.

B. Microstructure and Grain size

Tables Grain size comparison was primarily done by taking two criterions – plunge depth and cooling effect. The measured grain sizes are shown in table 2.

Base metal – 43.9 μm

TABLE II
GRAIN SIZE IN STIR ZONE

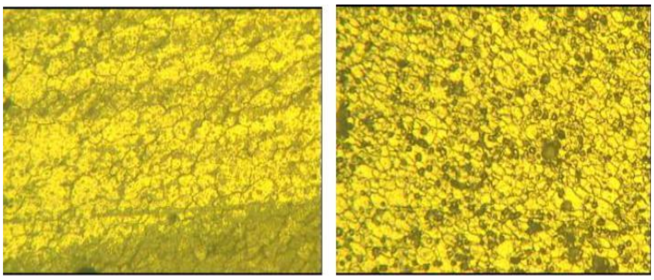
Plunge depth	Description	Grain size(μm)
0.5 mm	Steel/Air	11.52
0.75 mm	Steel/Air	16.10
	Copper/Air	13.87
	Steel/Water	14.84
1 mm	Steel/Air	17.56

For comparing the grain sizes at different plunge depths; air – steel samples were studied. It showed that the grain size increased as the plunge depth increased. We know that as the plunge depth is increasing, there will be more and more plastic deformation and more friction heating.

Grain size is primarily affected by these two variables – degree of deformation and peak temperature.

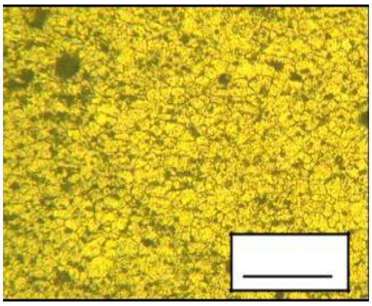
The increase in degree of deformation results in a reduction in the recrystallized grain size according to general principles of recrystallisation. On the other hand increase in peak temperatures during FSP leads to generation of course recrystallized grains and also results in remarkable grain growth. The variation of recrystallized grain size depends on which factor is dominant. Previous studies have indicated that peak temperature is the dominant factor in determining the recrystallised grain size[9].

25 µm 50 µm



0.50 mm plunge 0.75 mm plunge

50 µm



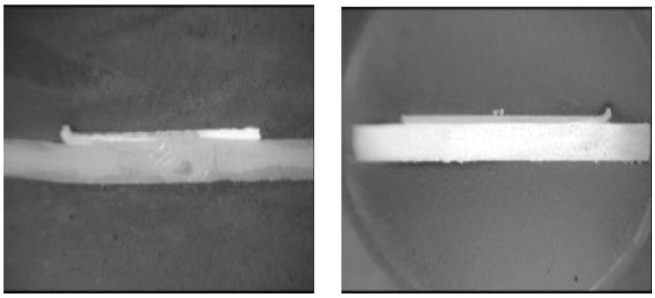
1 mm plunge

Fig 2: Microstructures of samples processed at 0.5 mm, 0.75 mm, 1 mm plunge depths

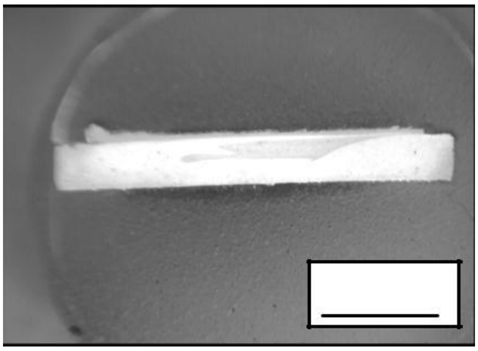
To compare the cooling effectiveness in controlling the grain size, samples processed with 0.75mm plunge depth were arbitrarily selected. As per the heat transfer analysis, maximum cooling takes place when copper is used as the backing plate. The obtained grain sizes are decreasing in the order of increasing cooling effect.

C. Macrostructure

Macro images helps in identifying different layers of metals and the depth of adhesion of the filler plate. The mounted and etched samples were photographed with macro image analyser. Macro images for samples with different plunge depths are shown below.



0.50 mm 0.75 mm



1 mm

Fig 3: Macro images for 0.5 mm, 0.75 mm, 1 mm plunge depths

The macro images show that the coating thickness is decreasing with the increasing plunge depth but on the other hand the width of the layer is increasing. The average coating thickness over the entire surface was measured with the help of ‗Image J‘ software and was tabulated. Coating thickness showed considerable variation from sample to sample. The average thickness of commercial aluminium layer varied from approximately 0.25mm to 1.1 mm. In certain samples the coating was non uniform. In the samples processed with 1mm plunge depth, the one with water-copper showed layer thickness ranging from 0.31 to 1.34 mm. The thickness was more on the retreading side than on the advancing side. This can be attributed to the normal metal flow pattern observed during FSP.

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During FSP metals flows from advancing side to the retreading side under the effect of pin and shoulder. The values of layer thicknesses are shown in table 3.

TABLE III
COATING THICKNESS OF COMMERCIAL AL LAYER

Plunge depth	cooling mode	Coating thickness(mm)
0.5 mm	air-steel	0.5030
	air-copper	0.5100
	water-steel	0.7500
	water-copper	0.6725
0.75 mm	air-steel	0.4350
	air-copper	0.6950
	water-steel	0.6225
	water-copper	0.4340
1 mm	air-steel	0.2900
	air-copper	0.2425
	water-steel	0.6840
	water-copper	0.7200

D. Corrosion – Salt spray fog test (ASTM B117)

The mass loss gives a hint of the corrosion rate of the material as the corrosion process involves metal oxidizing into ions. In the aluminium and water system, the metal is the anode and the water is the electrolyte. The weight loss observed in different samples after the salt spray test was different. There are many different types of corrosion but the most common type in the aluminium - water system, at room temperature, is pitting corrosion.

The rate of corrosion of aluminium in water depends on several parameters like pH value of water, temperature, ions and impurities in the water etc. It also depends on the alloy composition, heat treatment and surface condition. Chlorides in salt water are among the most corrosive elements. They initiate lots of pits in aluminium. In the propagation stage aluminium oxidises into aluminium ions at the bottom of the pit [10].
The results of salt spray test are shown below.

TABLE IV
COATING THICKNESS OF COMMERCIAL AL LAYER

Plunge depth	cooling mode	Weights (g)		Weight loss (g)	% Change (*0.01)
		Before test	After test		
0.5 mm	air-steel	0.9632	0.9626	0.0006	6.23
	air-copper	0.9461	0.9455	0.0006	6.34
	water-steel	0.9901	0.9894	0.0007	7.07
	water-copper	0.9982	0.9974	0.0008	8.01
0.75 mm	air-steel	0.8937	0.8934	0.0003	3.36
	air-copper	0.9060	0.905	0.0004	4.41
	water-steel	0.9672	0.9666	0.0006	6.20
	water-copper	0.8535	0.8530	0.0005	5.86
1 mm	air-steel	0.7196	0.7189	0.0007	9.73
	air-copper	0.7493	0.7482	0.0011	14.68
	water-steel	0.9988	0.9981	0.0007	7.01
	water-copper	0.8884	0.8881	0.0003	3.38
Fusion welded samples	Gas welded	2.1038	2.1026	0.0012	5.70
	FSP	1.6934	1.6928	0.0006	3.54
	FSP with layer	1.8360	1.8354	0.0006	3.27
Base Metals	AA6061	2.4284	2.4277	0.0007	2.88
	1xxx	0.4088	0.4087	0.0001	2.45

Comparisons of the corrosion test result are carried out between the samples having different plunge depths and also between those fusion welded samples. It has to be borne in mind that the FSP samples had a surface which was not so flat. This is because surface grinding was avoided to preserve the coating layer. Therefore those surfaces had the tool travel marks. The presence of such non smooth surfaces can increase the corrosion.

The percentage change in weight is the response we are most concerned with. There does not seem to be any relation between the cooling mode and the corrosion resistance as is shown by the non linear variation of weight loss with different cooling mode process in all three plunge depths. Consistently low weight loss was observed when 0.75 mm plunge depth was used. It should be remembered at this point that from the macro images it was clear that the most uniform thickness of coating was obtained when 0.75 mm plunge depth was employed.

It is easy to assume that corrosion resistance should have been dependent on one factor primarily – coating thickness and the uniformity of this coating. The coatings formed by 0.75 mm plunge depths are shown below.

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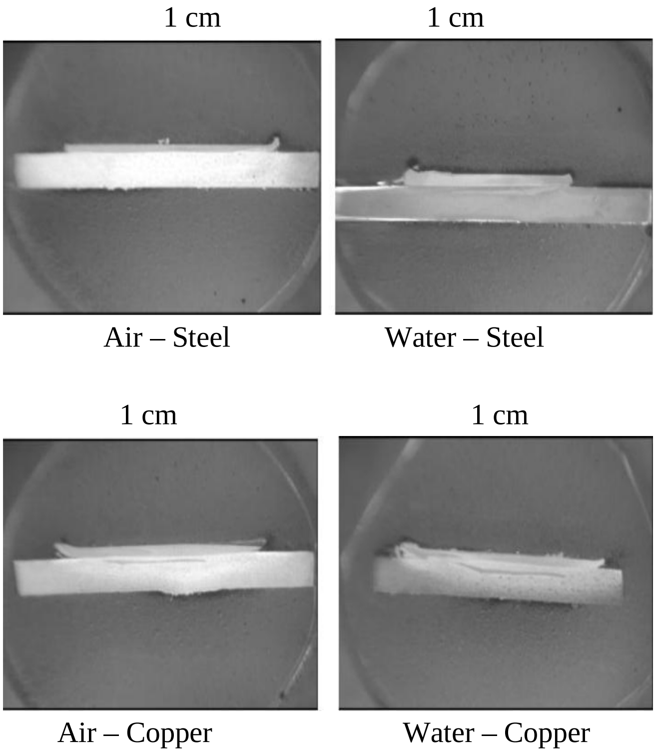

Fig 4: Coatings formed at 0.75 mm plunge depths

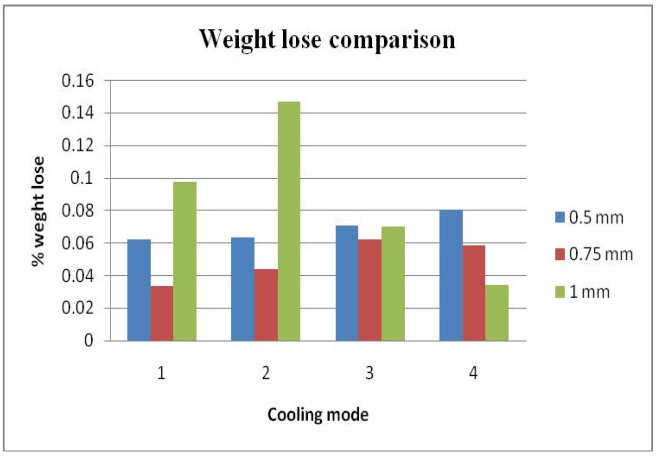

Fig 5: Weight lose comparison chart

In the case of fusion welded samples there is a considerable improvement in corrosion resistance in case of FSP samples. This improvement is very much on the expected lines as FSP homogenizes the weld microstructure and repairs the weld defects. But the use of coating does not show much appreciation in corrosion resistance.

V. CONCLUSION

Friction Stir Processing of 6061 aluminium alloy was performed and effects of various process parameters were evaluated.

A new surfacing technique was carried out by using commercial aluminium as filler plate above the 6061 plate. Corrosion resistance of AA6061 showed considerable improvement when a commercial Al layer was coated by FSP technique. Plunge force variation of the tool leads to variations in the thickness of the commercial aluminium layer formed on the surface of base metal. Backing plate could affect the cooling effect to a larger extent than the cooling fluids, as is evident from the case of copper backing plate. Grain size showed significant reduction when an external cooling was provided during processing. Corrosion resistance and other properties of fusion welded aluminium were found to improve by processing of the weld zone.

Further investigation can be carried out to study the use of liquids like Nitrogen to obtain fine grain structure. Also specific corrosion tests may be employed to find out the effectiveness of the coating layer. Analysis with SEM can reveal the surfaces to a higher degree and would give a more detailed picture of the process.

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Author Details

Prashanth Bhatti, completed his Masters degree with Advanced Manufacturing systems specialization from JNTUH University. Currently working as assistant professor in MLR Institute of Technology, Hyderabad. He has published a journal in International conference and interested to continue his academics further in Material processing and manufacturing areas.

K.Shravan Kumar completed his Masters degree with Design for manufacturing specialization. Currently working as assistant professor in MLR Institute of Technology in Hyderabad. He is interested to continue his researches in Material processing and manufacturing areas.