Proceedings of the International Conference on Applied Mechanical Engineering Research (IC-AMER2019)
NIT Warangal, India – May 02-05, 2019
Paper No. XXX (The number assigned when the papaer is accepted)

Influence of multi-pass and underwater cooling on microstructure and mechanical properties of friction stir processing of AA6061

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Abstract:

Friction stir processing is a new method invented for preparation of surface composites and modifies the microstructure in most of the aluminum alloys. AA6061 is widely used in aerospace applications and industries. In the present work, the influence of multi-pass and under water cooling FSP on grain size and mechanical properties of AA6061 alloy were studied. Process parameters were optimized from the trial experiments. The macrostructural analysis was carried out and it was observed that fine grains were produced in third-pass as compared to the other two passes. So, three-pass FSP was conducted in ambient conditions i.e at room temperature and in the water environment. The tensile test was carried out to find the ultimate tensile strength of FSP 3-pass sample. Micro-hardness values are found using a Vicker's hardness test. Underwater friction stir processing resulted in better mechanical properties compare to air cooling.

***Keywords*:** Friction stir processing; Multi-pass; Underwater cooling; AA6061.

1. Introduction

Friction stir processing (FSP) is one of the best methods for producing grain refinement in aluminium alloys. The advantages of grain refined metals include superior mechanical properties, improved superplasticity and better corrosion resistance etc. The working principle of FSP is quite the same as friction stir welding (FSW). In FSP, instead of joining the plates, the rotating non-consumable tool is penetrated into the single plate and traversed along the line of processing region. The stirring action of the tool causes severe plastic deformation which results in dynamic recrystallization in the processing region. The FSP sample consists of three zones namely stirred zone (SZ), thermos-mechanically affected zone (TMAZ) and heat affected zone (HAZ). Each zone has different properties and microstructures [1-3].

AA6061 is low strength-precipitation hardened aluminium alloy has magnesium and silicon as a major alloying addition. It is easily machinable and weldable due to its low strength. Various methods are available for achieving grain refinement in friction stir processing of aluminium alloy. The methods include optimization of process parameters, multi-pass experiments, post-process rapid cooling and underwater experiments etc. [4-6].

Liu et al [7]. conducted the friction stir welding in air underwater with varying tool rotational speeds 400 rpm and 800 rpm to produce the ultrafine grained structure in AA6061. He found that water cooling produces more grain refinement at tool rotational speed 400 rpm. Feng et al. [8] conducted the submerged FSP on AA2219 to evaluate the microstructure. He achieved ultrafine grain structure and observed that the grain size was decreased marginally in stirred zone due to under water cooling. Chen et al. [9] performed the three-pass FSP on AA5083 to produce more grain refinement. The results indicated that the rational speed is responsible for grain size, the grain size is increased with an increase in rotational speed.

2. Experimental Setup

The experiments were performed on 3-Tonne capacity FSW Machine. Underwater setup was designed and fabricated as per the table dimensions of FSW machine. The base is made of aluminium alloy sheet of thickness 2 mm and sides are made with the transparent fibre sheet and both of them attached with silicone gel.

A 4mm thick AA6061-T6 alloy is used as a base metal for present study. **Table 1.** gives the composition of AA6061 alloy. With the existing literature, hot-worked tool steels are the most preferred material because of their easy availability, machinability, thermal fatigue resistance and wear resistance especially for processing of aluminium and copper. So, AISI H13 was selected as a friction stir welding tool material. For present investigation a taper threaded pin profile with conical shoulder tool was used as tool is shown **in Fig 1.**

Trial experiments were conducted to set the process parameters for the regular experiments. The process parameters considered for the experiments are tool rotational speed (ω), traverse speed (ν), and axial load (f). The plates are cut across the joint perpendicular to the direction of weld for the microstructural analysis. The specimen is well polished using four grades of emery papers 1/0, 2/0, 3/0, 4/0 and then polished using disc polishing machine to get a scratch free surface. Keller's reagent was used as an etchant and the samples were etched for 150s to reveals the grain boundaries. The microstructures of various parameters and various zones of samples were also captured using an optical microscope. The Vicker's hardness tester was used for measure the hardness with a load of 100 gf and dwell time 10s. Tensile samples are cut according to the standard ASTM E8 shown in **Fig 2.** The samples are cut in the transverse direction to the processed region using wire-cut Electric Discharge Machining (EDM) and tested by 30 kN capacity CNC Universal testing machine.

Table 1. Composition of AA6061-T6 alloy.

Component	Al	Mg	Si	Cr	Cu	Fe	Mn	Ti	Zn	others
Composition (Wt%)	Remaining	1.1	0.6	0.18	0.2	0.6	0.1	0.1	0.18	0.15

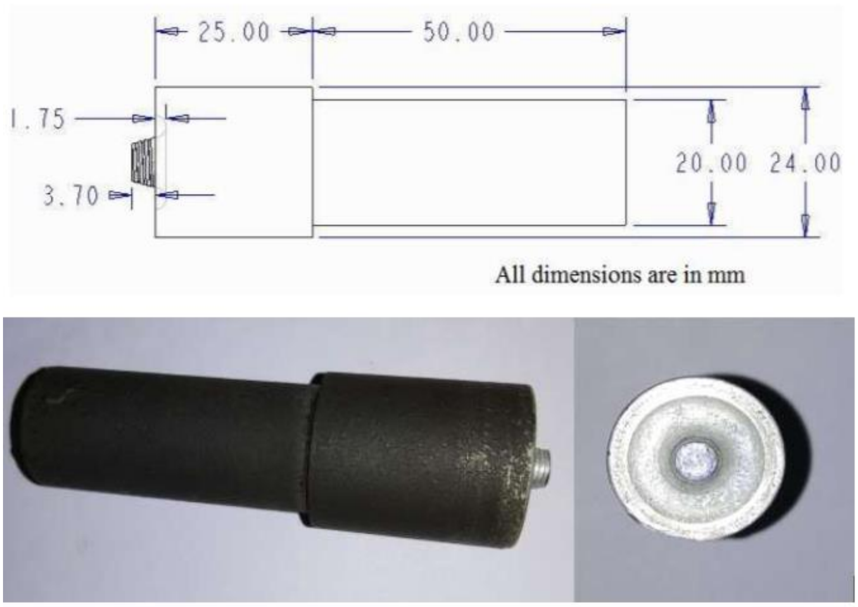

Fig. 1. Tool material with geometry.

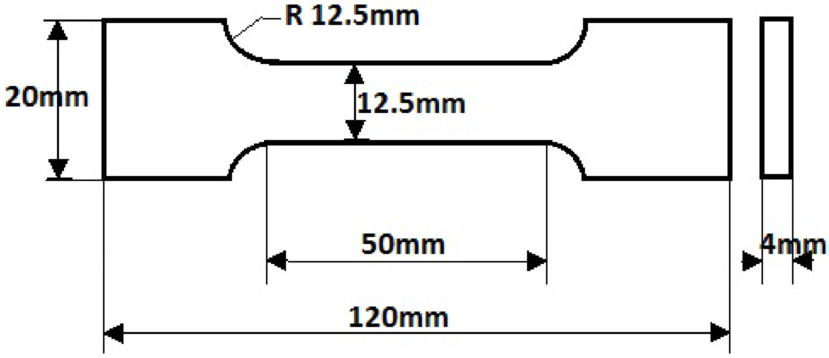

Fig. 2. Dimensions of tensile specimen.

3. Results and Discussion

3.1 Selection of process parameters and number of passes

The initial set of trial experiments were conducted at an axial force which is kept constant at 10 kN. Various combinations of FSP were tried to select the optimum process parameters. From the trial experiments, the tool rotation speed of 1100 rpm and traverse speed of 15mm/min is selected as an optimum condition. With these process parameters, the effect of a number of passes using different techniques was studied. **Fig. 3 (a-c)** Shows the macrostructures of AA 6061 at different passes. Form the macrostructure, it was observed that there are no defects in the structures. The area of the stir zone is increased to increase the number of passes from one to three. This is attributed to more heat input in the second and third pass to plasticize the material. Comparing the first and second pass, the material in the stir zone got properly mixed in the third pass. The stirring action of the pin at the same location causes the fragments of the coarse particle to fine particles. This overlap of various passes continues to homogenize the microstructure and its properties. Microhardness of the base material is 107 HV. Microhardness values in **Table 2.** indicate a softening of the processed material at the friction stir processed zone compared to base material due to the in-built nature of the process. According to Hall-Petch relation, hardness gets increased as the grain size gets reduced. With an increase in the number of passes, an increase in the microhardness values is observed in the processed materials. Hence the third pass is used for further processing.

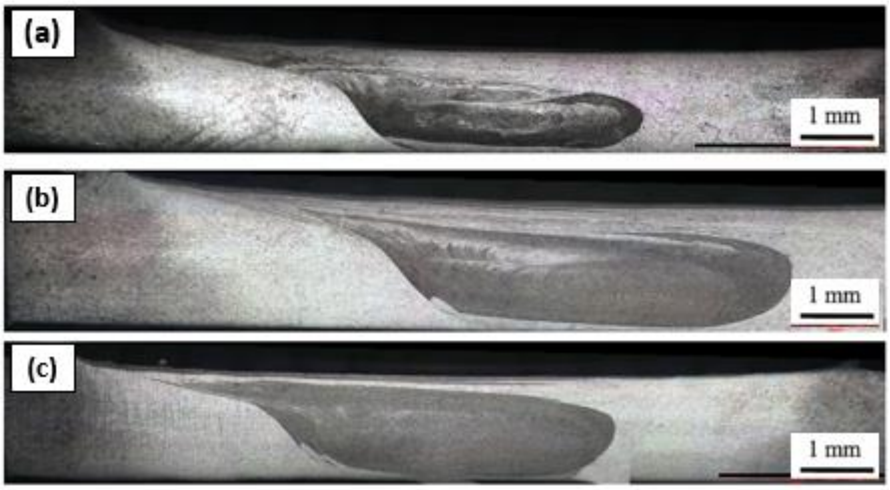

Fig. 3. Macrostructures of AA6061 (a) First pass (b) Second pass (c) Third pass.

Table 2. Area, grain size and hardness of stir zone for a number of passes.

	1st pass	**2nd pass**	**3rd pass**
Area of stir zone (mm^2)	1.412727	5.100996	5.152842
Grain size (µm)	5.03	3.705	3.56
Hardness (HV)	57.5	65.0	71.6

3.2 Microstructure and mechanical properties

With the use of optimum process parameters, the 3-pass FSP was conducted in air and underwater. The micrographs of air-cooled stir zone (ACSZ), air-cooled heat affected zone (ACHAZ), underwater stir zone (UWSZ) and underwater heat affected zone (UWHAZ) are shown in **Fig.4 (a-d**). The microstructure of stir zone in air-cooled friction stir processed sample (ACFSP) and underwater friction stir processed (UWFSP) reveals the fine equiaxed grains with the presence of uniform distributed precipitates. This is due to dynamic recrystallization and severe plastic deformation. Due to the absence of mechanical stirring, un-recrystallized grains were observed in heat affected zones of natural cooled and underwater samples. During FSP the HAZ experience only temperature changes during FSP. So, this is also a reason for grain coarsening in HAZ. **Table 3.** represents grain size and mechanical properties of FSP samples processed in air and underwater. Compare to ACSZ, more grain refinement was observed UWSZ. Due to the more cooling effect, the grains are further fragmented into fine grains in under water cooling.

The hardness was measured along the stir zone with the diamond indenter. The distance between two successive indentations is 0.5 mm. As we seen in the FSP of Aluminium alloys, the hardness trend follows 'w' shape shown in **Fig 5.** Among three zones of FSP samples, the highest hardness was recorded in stir zone as a result of dynamic recrystallization. Due to the lack of dynamic recrystallization, the hardness was decreased in TMAZ. There was a further reduction of hardness in HAZ. This is attributed to the grain coarsening in HAZ. After HAZ, the material has similar properties of the base metal. The sample processed in underwater resulted in better mechanical properties compare to sample processed in air. The average hardness in stir zone and Ultimate tensile strength (UTS) of ACFSP and UWFSP samples are shown in **Table 3.** In UWFSP, the average hardness and UTS were 10.21% and 20.86% more than the ACFSP. These results are attributed to the grain fragmentation by rapid cooling effect and uniform precipitate distribution in UWFSP.

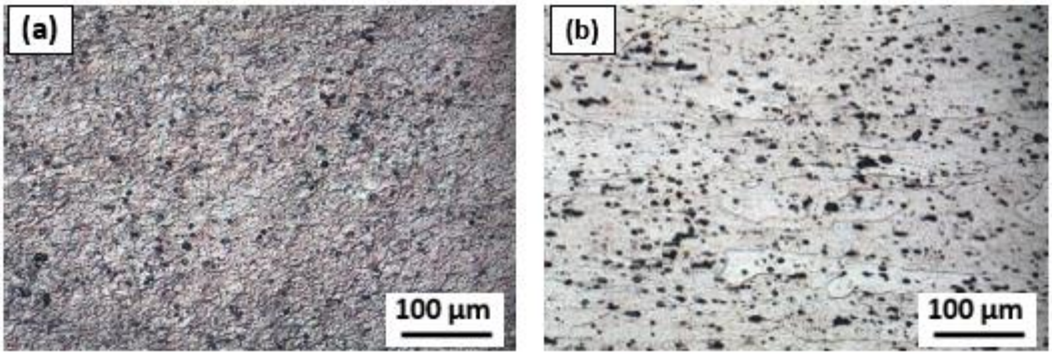

Fig. 4. Microstructures of a) Air cooled stir zone, b) Air cooled heat affected zone, c) Underwater stir zone d) Underwater heat affected zone.

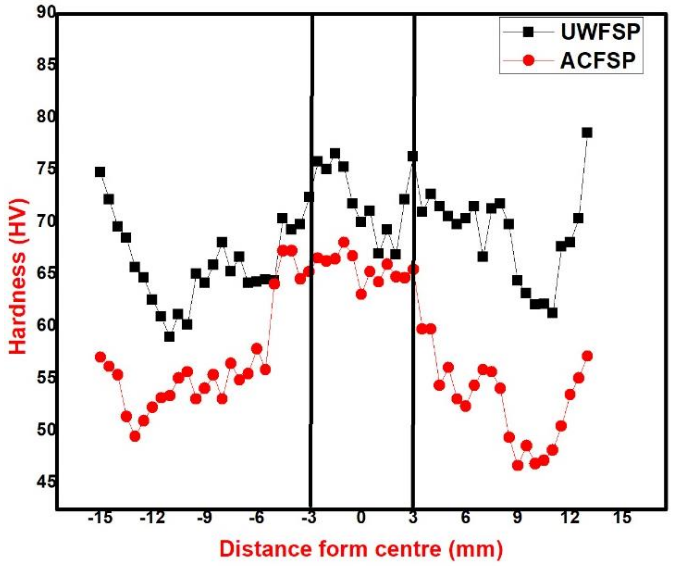

Fig. 5. Hardness profile ACFSP and UWFSP at different zones.

Table 3. Grain size and mechanical properties of FSP samples.

Condition	Grain size in stir zone (µm)	Average hardness in stir zone (HV)	Ultimate tensile strength (UTS)
ACFSP	3.56	65.6	154.3
UWFSP	2.45	72.3	186.5

Conclusions

In this study, the effect of multi-pass and underwater cooling on microstructure and mechanical properties were studied and the following conclusions were made.

1. Of various combinations of trail experiments tool, the rotational speed of 1100 rpm & 15 mm/min was selected as process parameters for conducting multi-pass experiments. From multi-pass experiments, 3-pass FSP was opted for conducting further experiments.
2. Off three different zones in ASFSP and UWFSP highest hardness was obtained in stir zone due to more grain refinement caused by intense plastic deformation and recrystallization.
3. Compare to the ASFSP, mechanical properties were enhanced in UWFSP due to the cooling effect.

Acknowledgements

The authors would like to thank the Aeronautical Research Board and Development (ARDB), New Delhi, India for providing the financial assistance and National Institute of Technology, Warangal, India for providing the lab facilities to carry out the project smoothly.

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