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Influence of Tool-Pin Profile on Properties of Friction Stir Processed AA 2014 Under Natural and Flood Cooling

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Abstract - Aluminium alloys, possessing good strength to weight ratio, are extensively employed in various fields of technology. Friction stir processing (FSP) is an allied process of friction stir welding (FSW) that is used to transform the material properties. FSP performed on surface can transform the surface properties of certain material and can also transform the mechanical properties, if carried out in bulk of material. Investigations have been carried out by number of researchers to see the influence of FSP parameters and the simultaneous cooling on different properties of different materials. In the present research work, the work was carried out to see the influence of tool-pin profile on the properties of aluminium alloy AA2014, under natural and flood cooling conditions. AA2014 is commonly used in aerospace industry and in defence equipment. AA2014 was friction stir processed with three types of tool-pin profiles and freezing the other process parameters of FSP, on the basis of literature. The processed specimens were characterized with X-ray radiography and microstructure analysis. Micro-hardness and the tensile strength of the processed specimens were also tested. Among the processed specimens, the highest hardness was obtained with square tool-pin profile under flood cooling conditions. The refinement in microstructure has been observed to be the reason of the same.

Keywords: Friction stir processing, microstructure, micro-hardness, tool-pin profile, flood cooling.

1. INTRODUCTION

Aluminium and aluminium alloys have a wide range of applications, due to its many outstanding attributes including good corrosion and oxidation resistance, high electrical and thermal conductivities, low density, high reflectivity, high ductility and reasonably high strength, and relatively low cost (Pushpanathan et al., 2012; Kapoor et al., 2013;Vagh and Pandya, 2012). Aluminium and its alloys are used commonly in aerospace and transportation industries because of their low density and high strength to weight ratio. Aluminium alloys are generally classif ed as non-weldable because of the poor solidif cation microstructure and porosity in the fusion zone. These factors make the joining of these alloys by conventional welding processes unattractive. Some aluminium alloys can be resistance welded, but the surface preparation is expensive, with surface oxide being a major problem. Friction stir welding (FSW) was invented at The Welding Institute (TWI) of UK in 1991 as a solid-state joining technique and it was initially applied to aluminium alloys. The basic concept of FSW is remarkably simple. Recently friction stir processing (FSP) has come up as a solid state technique for microstructure modif cation, based on the basic principles of FSW (Misra and Ma, 2005; Pushpanathan et al., 2012; Elangovan and Balasubramanian, 2008). In FSW, a non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of plates, to be joined and then traversed along the line of joint, while shoulder touches the plates. Due to stirring action of the tool-pin, the friction heats both the materials at the joint. The two materials in visco-plastic state on solidification give a good welded joint. Thus, a welding joint is produced in solid state by localized heat from the friction between the tool and work piece and plastic deformation of the material. In FSP, the same process is used for modification of the material properties by the process of friction stirring in the single material only. Then the tool is plunged into the material at pre-determined rotational speed and traversed across it, as shown in Fig. 1. The heat is generated by the friction between the tool-pin and work piece. The localized heating softens the material around the pin. The combination of tool rotation and translation cause the movement of material from front to the back of the pin, which results in the processing of the material (Misra and Ma, 2005).

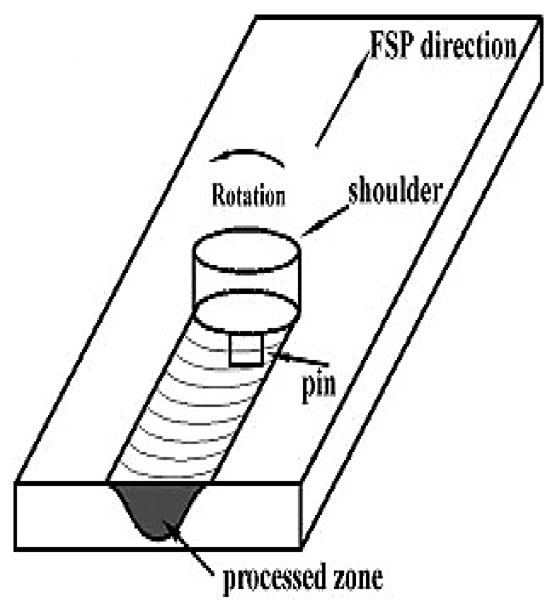


Fig. 1: Schematic representation of FSP principle (Yadav and Bauri, 2012).

Friction stir processing is done on a single sheet of material to change the mechanical properties by changing the microstructure in which different tool-pin profiles can be used (Pushpanathanet et al., 2012; Elangovan and Balasubramanian, 2008). The FSP is done in two ways, one is in-volume FSP that means processing of full thickness of substrate material and the second is surface FSP that means processing of surface of material up to a small depth. The overlap ratio is very important factor for the evaluation and alteration of microstructure and mechanical properties respectively (Kurt et al., 2011). Effect of different tool-pin profiles also plays a major role in modifying the surface properties in FSP (Elangovan and Balasubramanian, 2008). The microstructure and mechanical properties of processed zone can also be accurately controlled by optimizing the tool design, FSP parameters and active heating and cooling (Pushpanathan et al., 2012). The present work is focussed to study the influence of tool-pin profile on the properties of friction stir processed (in-volume FSP) aluminium alloy 2014 in both flood and natural cooling conditions. Friction Stir Processing was performed on vertical milling centre with three different tool-pin profiles (square, hexagonal and round). Friction stir processing was done under natural and flood cooling conditions with each tool-pin profile, by keeping other parameters constant. The processed specimens have been characterized with micro-hardness testing and microstructure testing. The tensile properties have also been evaluated. A significant improvement in micro-hardness has been observed under flood cooling condition with square tool-pin profile. The microstructure images of the processed specimens depict the grain refinement, which seems to be the cause of significant improvement in micro-hardness. The tensile strength is also observed to be more in case of specimens processed with square tool, under flood cooling condition, as compared with the processing done with other tools or cooling conditions.

2. EXPERIMENTAL PROCEDURE

The substrate material chosen in the present study, aluminium alloy2014, was procured from the local market of Ludhiana in plate shape having thickness 6mm, with dimensions of 600mm × 50mm. The chemical composition of substrate material is determined with the help of the Spectrometer available at the R and D Centre for Bicycle and Sewing Machine parts, Ludhiana. The specimens required for FSP were prepared by wire EDM so as to avoid any temperature rise to cause microstructural changes. The required numbers of samples of 6mm thickness, having dimensions 100 mm × 50mm were cut by wire EDM from the procured substrate material in plate shape. Auto CAD software was used for designing the tools for FSP. In the design, the selected tool dimensions are presented in Table 1.

TABLE 1 TOOL DIMENSIONS

Tool Parameter	Dimension (mm)
Shoulder diameter	18
Tool-pin diameter for round tool / diameter of circle circumscribed about square or hexagonal tool-pin profiles	6
Tool-pin length	5.7

CNC machine was used to manufacture the tools at the R and D Centre for Bicycle and Sewing Machine parts, Ludhiana. The drawings of tools manufactured are presented in Fig. 2.A hexagonal (⬡), square (□), and round (○) tools respectively were employed for FSP.

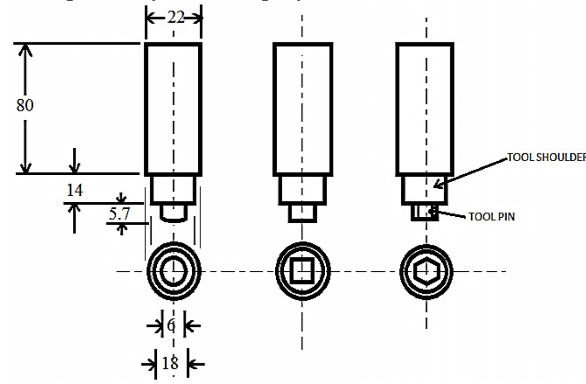


Fig. 2 Drawing of different FSP tools.

Before starting machining on any machine, a fixture is necessary to hold the job firmly on the work table for the proper machining of the work piece. So fixture plays an important role in the FSP for secure and proper mounting of specimen into the fixture cavity. The fixture was modeled in Auto CAD software for friction stir processing of samples having dimensions 100mm × 50mm× 6mm. The designed fixture was manufactured at R and D Centre for Bicycle and Sewing Machine parts, Ludhiana using CNC milling machine. Friction stir processing was done on a verticle milling machineby using specially designed fixture, which was empolyed for preparing the friction stir processed specimen at the research and development centre, Ludhiana. In pesent study, the verticle milling machine was used with three different types of tool-pin profiles viz. square, hexagonal and round. Friction Stir Processing was done under flood and natural cooling conditions having feed 45mm/min and speed 1400 r.p.m.

The polishing was carried out with alumina powder suspension to obtain mirror like surface finish on polishing machine. To contrast the different phases of microstructure, etching of polished specimens was done with the Keller's etching reagent. The polished specimens were subsequently etched with this Keller's etching reagent. Each specimen was examined under inverted optical metallurgical microscope (RMM-77) for obtaining the microstructures of processed specimens. The microstructure images and graphs of micro-hardness of all types of specimens are presented in result and discussion. Micro-hardness tester (Mitutoyo) was used to measure the hardness of specimens.. It was done at a load of 0.5 kg for 10 seconds. Tensile test was also performed under dry and flood cooling. Friction stir processed tensile specimens of standard size and shape were produced from the processed material to be tested for tensile testing as per ASTM E8M-04 standard. The tensile test specimens were prepared using wire EDM machine. Tensile test was performed on a HEICO universal testing machine at Baba Farid College of Engg. and Technology, Bathinda (Punjab).

3.RESULTS AND DISCUSSION

3.1 Macro analysis of friction stir processed specimens

Macro analysis of all friction stir processed specimens has been studied. The macrographs of specimens after FSP have been presented in Fig. 3 and 4.

Fig. 3 Macrographs of specimens processed with FSP under natural cooling condition with different tool-pin profiles (a) square tool, (b) hexagonal tool, (c) round tool.

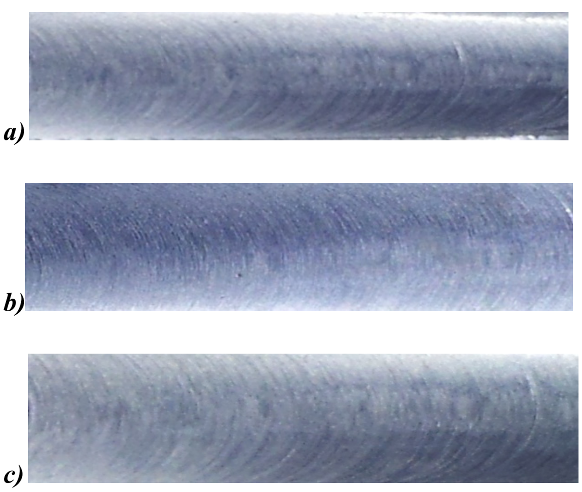


Fig. 4 Macrographs of specimens processed with FSP under flood cooling condition with different tool-pin profiles (a) square tool, (b) hexagonal tool, (c) round tool.

Looking at the surface obtained after FSP, it is clear from the macrographs that top surface of processed specimens is clean and no obvious defects could be identified as shown in Fig.3 and 4. Therefore, FSP produced clean surface without any voids/holes on its surface.

3.2 Micro-hardness analysis

Micro-hardness of top surface of the specimens of material AA2014 processed with FSP was measured. In this section, the effect of tool-pin profile and cooling on micro-hardness was analysed and discussed in following two subsections, respectively.

3.2.1 Effect of Tool-pin Profile on Micro-hardness

The surface micro-hardness values of processed material in both dry and flood cooling by using different tool-pin profiles such as Square, Hexagonal and Round are summarized respectively for natural cooling and for flood cooling conditions. In both the cases of FSP, the highest value of Micro-hardness has been obtained for square tool-pin profile. The Micro-hardness of specimens processed with round tool-pin profile is observed to be minimum, out of the three used tool-pin profiles. The hardness exhibited a significant improvement after FSP in all cases shown in Fig. 5 and 6 than that of base metal.

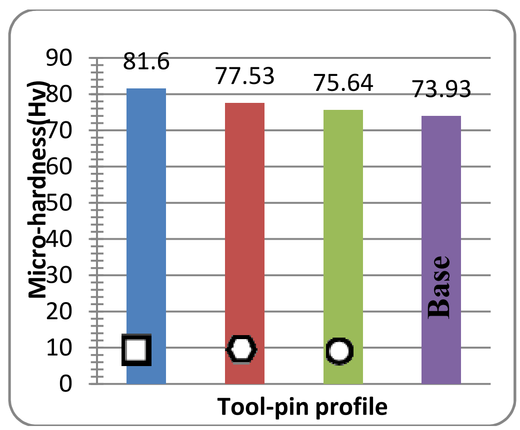


Fig. 5 Effect of tool-pin profiles on the micro-hardness in FSP underdry condition.

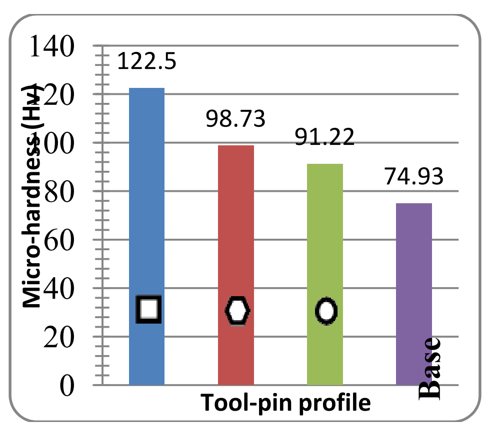


Fig. 6 Effect of tool-pin profile on the Micro-hardness in FSP under flood cooling.

The increase in hardness is attributed to grain refinement and dislocation interaction. Nakata et al. (2006) also observed that hardness increases in friction stir processed aluminium die casting alloy due to grain refinement. The bar-graphs in Fig.5 and 6 clearly indicate that the improvement in the micro-hardness is more in case square tool-in profile in both the conditions of FSP under natural and flood cooling condition. As observed for different aluminium alloys through a lot of research done earlier (Elangovan and Balasubramanian, 2008), tool-pin profile plays an important role in enhancement of micro-hardness. The primary function of tool-pin is to stir the plasticized metal and move the same behind it to have good surface properties enhancement. In this work also, it has been observed that square tool-pin profile gave best results in terms of Micro-hardness improvement through FSP than that of other tool-pin profiles because of higher number of pulsating action experienced in the stirring zone due to vertical flat surface. Elangovan and Balasubramanian (2008) also observed that the square tool-pin profile produced 80 pulses/s, when tool rotated at a speed of 1200 r.p.m. There is no such pulsating action in case of other (Hexagonal and round) pin profiles.

3.2.2 Effect of cooling on the micro-hardness

The graphical representation of variation of micro-hardness with cooling for individual tool-pin profiles (Square, Hexagonal and Round) are shown in given Fig. 7, 8 and 9 respectively. It has been observed that the cooling has improved the micro-hardness substantially for all tool-pin profiles. This may be due to the cooling action of flooded coolant. The cooling action during FSP process increased hardness of material considerably; this is related to a decrease in grain size.

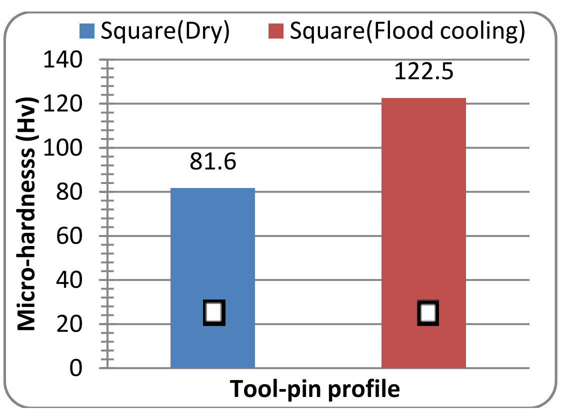


Fig. 7 Effect of cooling on the micro-hardness in FSP with square tool.

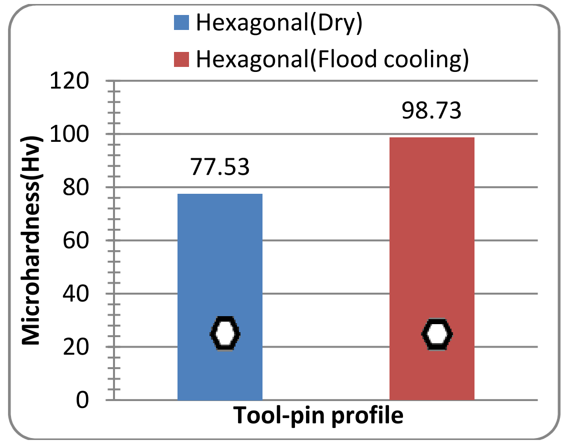


Fig. 8 Effect of cooling on the Micro-hardness in FSP with Hexagonal Tool.

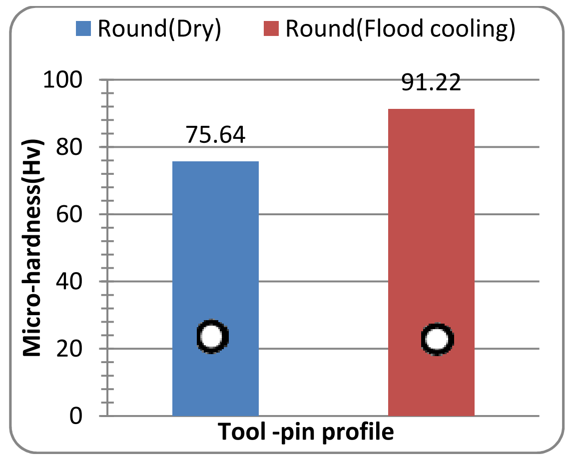


Fig. 9 Effect of cooling on the micro-hardness in FSP with round tool.

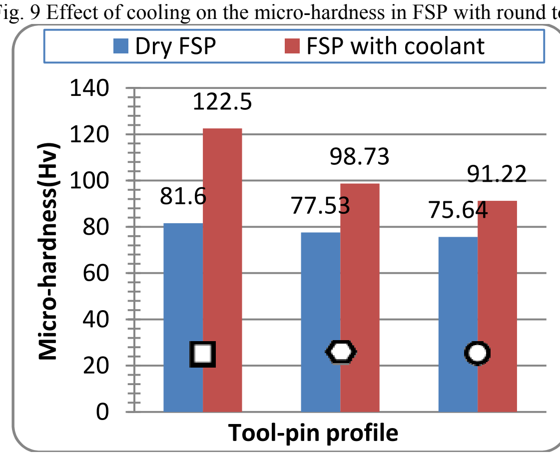


Fig. 10 Relative effect of cooling on the micro-hardness in FSP under dry/flood cooling for different tool-pin profiles.

An increased hardness is improved the mechanical properties of the material. Figure 10 clearly demonstrate that in FSP under flood cooling, the improvement in the micro-hardness in case of square tool is more as compared to hexagonal and round tool.

3.3 Microstructure Analysis

Microstructure images of specimens of AA0214 after FSP, form surface for all tool-pin profiles, under dry and flood cooling conditions were captured. In this section, the effect on the microstructure of different tool-pin profiles and cooling has been analysed and discussed in following two subsections respectively.

3.3.1 Effect of Tool-pin Profile in FSP on the Microstructure

In microstructure analysis, specimens under dry and flood cooling are analysed at magnification (20X) using the optical microscope to reveal quality of microstructure details. Fig. 12 and 13 presents the typical optical microstructure of processed surfaces carried out employing square, hexagonal and round pin profile with dry/flood cooling respectively. The parent material is composed of large grains of non-uniform size, with non-uniform distribution of coarse second phase particles as shown in Fig.11. The surfaces of specimens under all tool-pin profiles such as square, hexagonal and round after processing appear brighter than the parent metal. The Ramanjaneyulu et al. (2013) observed same result and also discussed that during friction stir processing, rotational and translation speed of tool have significant effects on the grain size evolution in the processed surface. The main purpose of several plastic deformation processes is to produce the material with homogeneous, fine grain size and distribute precipitates to improve the mechanical properties.FSP is effective in the grain refinement, precipitate breakup simultaneously and this can be attributed to accelerated diffusion kinetics. The observations made from the microstructure are presented in Table 2 and 3.

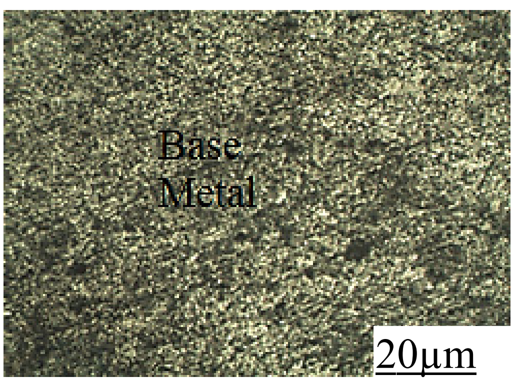


Fig. 11 Microstructure of base material

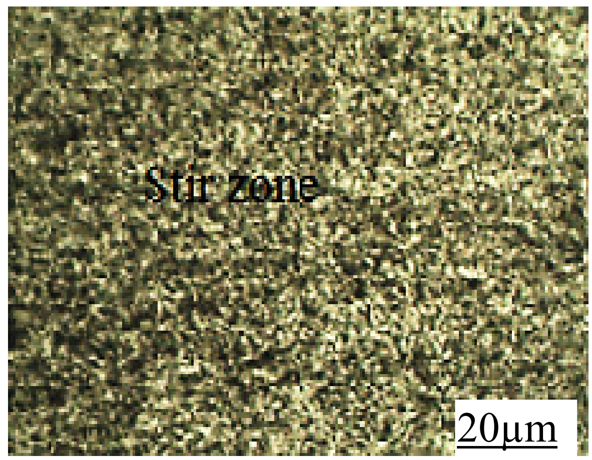
TABLE 2 MICROSTRUCTURE OBSERVATION UNDER DRY CONDITION

Tool-pin profile	Observation
Square □	Fine recrystallized grain structure
Hexagonal ⬡	Dense recrystallized grain structure
Round ○	Homogeneous grain structure

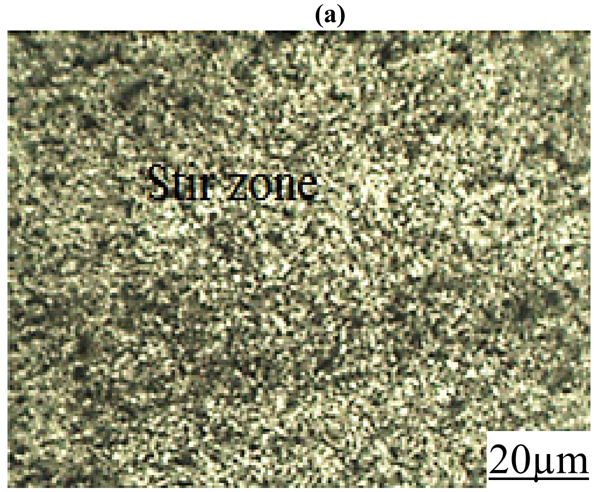
TABLE 3 MICROSTRUCTURE OBSERVATION UNDER FLOOD COOLING CONDITION

Tool-pin profile	Observation
Square □	Fine and more uniform, equiaxed recrystallized grain structure
Hexagonal ⬡	Medium grain structure
Round ○	More homogeneous grain structure

The effects of tool-pin profile on the microstructure of friction stir processed specimens under dry and flood cooling conditions are shown in Fig. 12 and 13 respectively.



(a)



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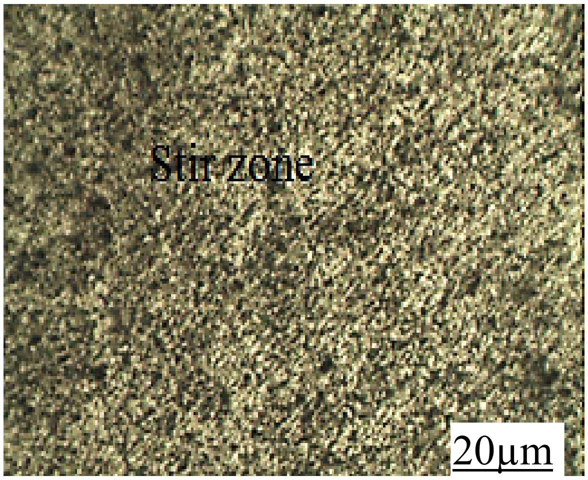
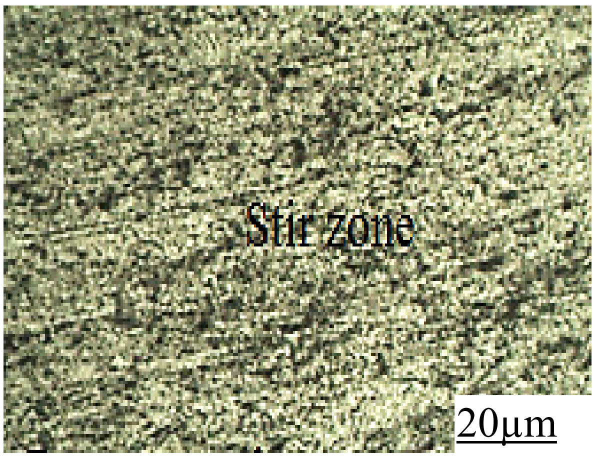
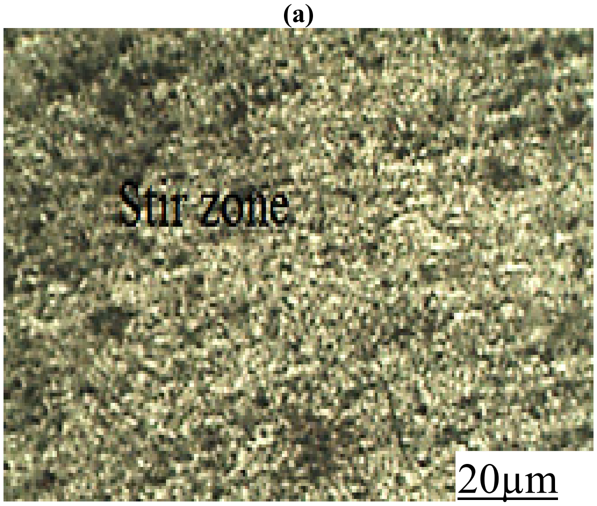


(c)

Fig. 12 Microstructure images of AA2014 processed under dry condition with different tool-pin profiles (a) square (b) hexagonal and (c) round.



(a)



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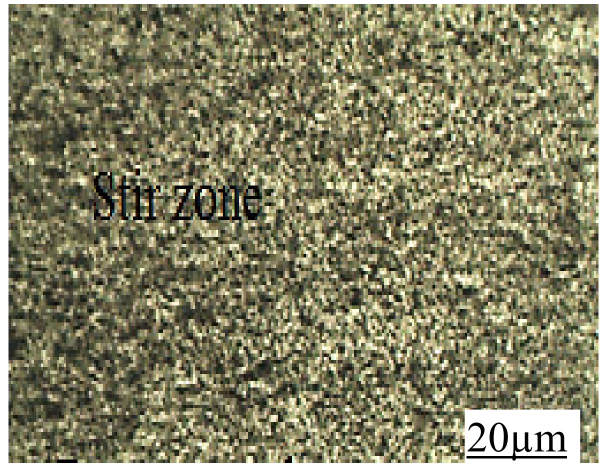


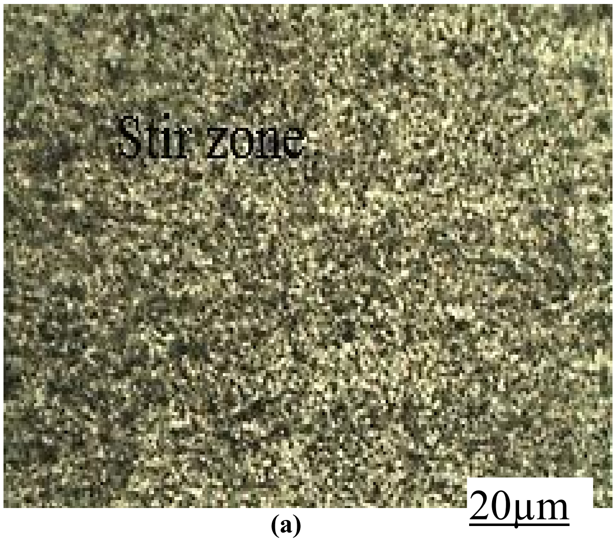
(c)

Fig.13 Microstructure images of AA2014 processed with FSP under flood cooling condition with different tool-pin profiles (a) square (b) hexagonal and (c) round.

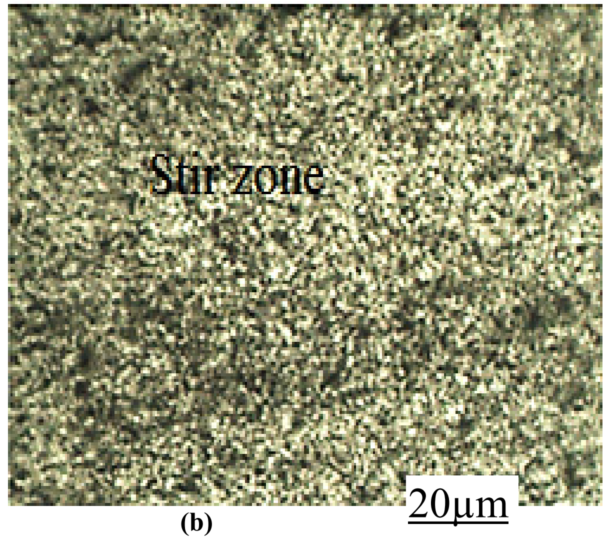
From the analysis of microstructure images, it can be inferred that the microstructure can be controlled by changing the tool-pin profile and formation of defects free friction stir processed surface is also a function of tool-pin profile. From the above investigation, the processed region of specimens, show a fine recrystallized grain structure due to heavy plastic deformation, which is due to dynamic recrystallization due to thermo mechanical processing by the square tools. It can also be seen that sample processed by square tool-pin profile has finer equiaxed grain structure relative to sample processed by the other pin profiles as shown in Fig. 12(a) and Fig. 13(a). These results are in conformance with Elangovan and Balasubramanian (2008) in the case of aluminium alloy. The grain refinement is attributed to the higher number of pulsating action experienced in the stirring zone of square pin profile as compared to that in other tool-pin profiles.

3.3.2 Effect of Cooling on the Microstructure

The FSP process under the cooling conditions changed the coarse and inhomogeneous microstructure of specimen to a fine and uniform microstructure. The cooling process decreases grain size and increased its uniform distribution. Reduction of the process temperature with cooling system and lowering the total time of cooling process results more uniform and similar grain size microstructure. The similar result was observed by Darras and Kishta (2006) in submerged friction stir processing of AZ31.Nia et al., (2013) also observed that cooling process decreased grain size and increased its uniform distribution. So that FSP under flood cooling have a fine and equiaxed grain structure than that of FSP dry conditions as shown in Fig. 14, 15 and 16 respectively.

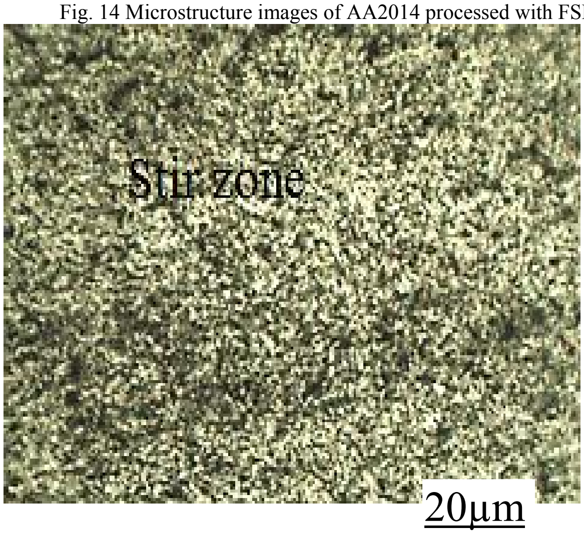


(a)

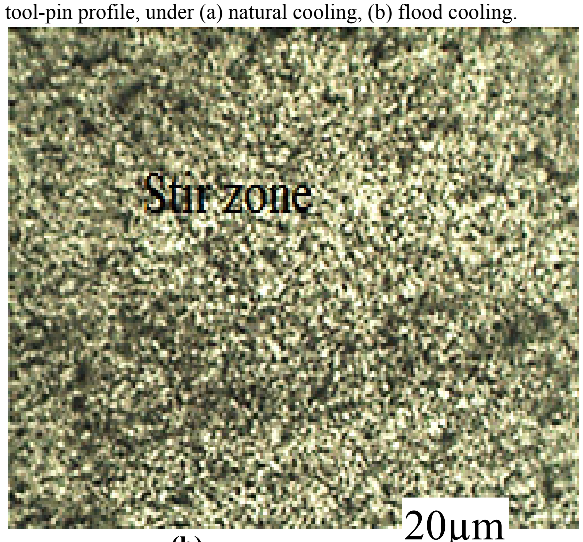


(b)

Fig. 14 Microstructure images of AA2014 processed with FSP with square tool-pin profile, under (a) natural cooling, (b) flood cooling.

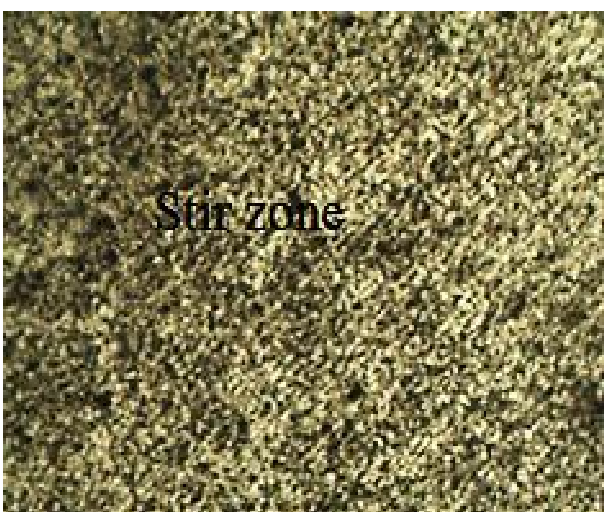


(a)



(b)

Fig. 15 Microstructure images of AA2014 processed with FSP with hexagonal tool-pin profile, under (a) natural cooling, (b) flood cooling



(a)

(b)

Fig. 16 Microstructure images of AA2014 processed with FSP with round tool-pin profile, under (a) natural cooling, (b) flood cooling.

3.4 Tensile strength Analysis

Tensile properties of specimens of material AA2014 processed with FSP were described.FSP is generally done to improve the surface properties of certain material. If tool-pin length is increased such that it becomes equal or slightly lesser than the thickness of the material being processed. In the present work, the length of tool-pin is kept slightly shorter than the thickness of workpiece. It was done to stir the bulk of material and check its effect on the bulk properties in addition to effect on surface properties. In this section, the effect of tool-pin profile and cooling on tensile properties has been analysed and discussed in following two subsections, respectively.

3.4.1 Effect of Tool-pin Profile on the Tensile Strength

The Longitudinal tensile properties such as ultimate tensile strength, percentage elongation of the FSP specimen have been evaluated and their results are shown in fig.17 and 18. It can be noted that tensile strength value for FSP with cylindrical tool is the lowest among six. On the other hand for
FSP with square tool, the same is the Highest. In case of hexagonal tool, mean tensile strength values are intermediate between the square and cylindrical tool in both cases. The highest tensile strength for square tool can be obtained by increases the volume of material deformation.

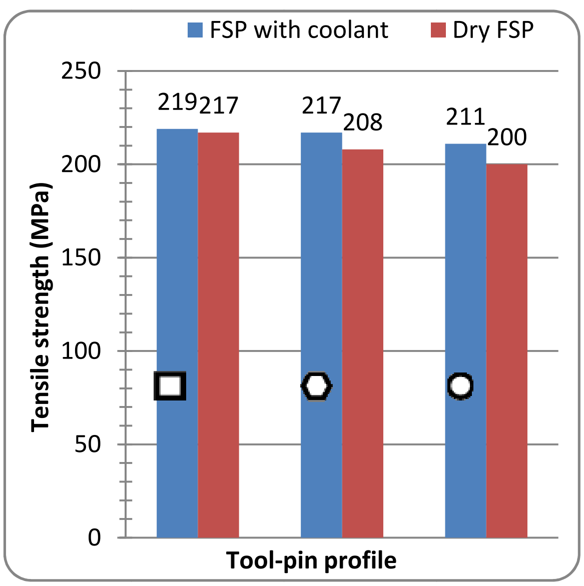


Fig. 17 Effect of tool-pin profile on the tensile strength in FSP under dry and flood cooling condition.

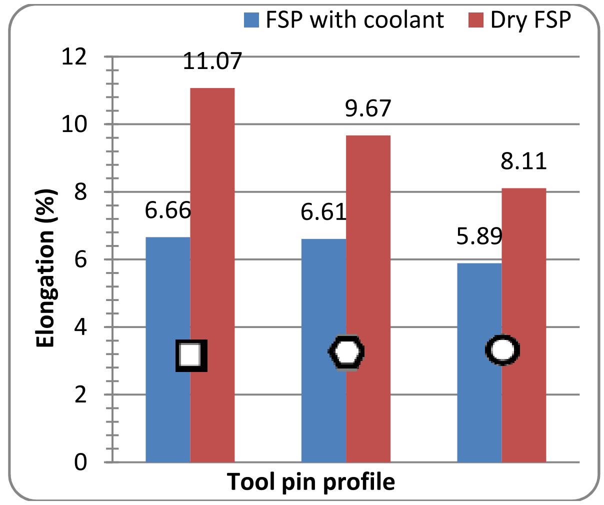
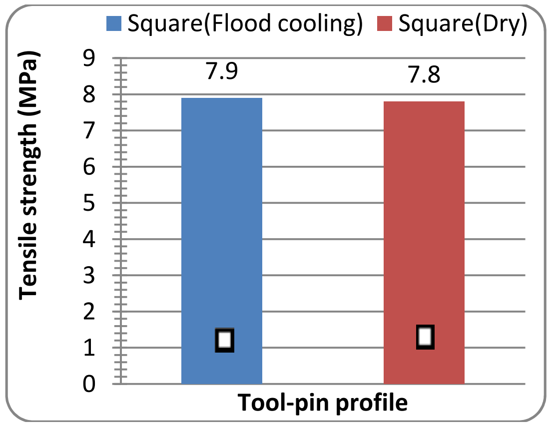


Fig.18 Effect of tool-pin profiles on the elongation in FSP under dry and flood cooling.

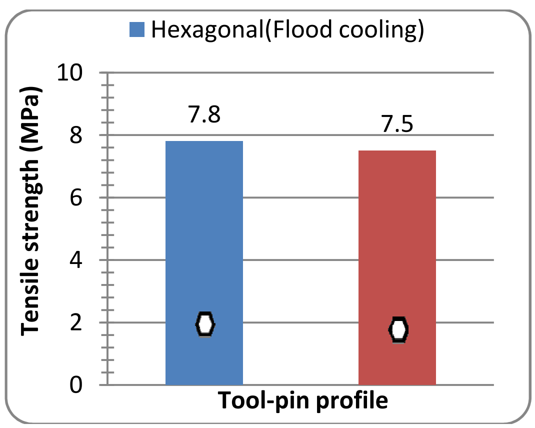
Because of changing the surface area of a square tool to round, there is a significant difference in the heat input through friction and material deformation. The tensile test analysis has been carried out in the friction stir processed region of all the specimens. Friction Stir Processing by the square tool-pin profile caused high degree of plastic deformation, due to its higher eccentricity and its pulsation effect provides high tensile strength, when compared with the specimens processed with other tool profiles. It is observed from the Fig. 17 and 18 that out of six specimens, the specimens processed with square tool-pin profile exhibited superior tensile properties as compared to specimens processed with other tool-pin profile, irrespective of FSP cooling condition (dry/flood cooling condition). It has also been observed that tool-pin profiles (square, hexagonal, round) under FSP have very little effect on tensile strength. Xu et al., 2013 also expressed the same that the FSP parameters have a great effect on the strength and ductility, whereas tool-pin profile has little effect on tensile properties. According to Vijay and Murugan (2010), the tensile strength of specimens processed using hexagonal, tapered hexagonal, octagonal and tapered octagonal tool-pin profile tools, do not change significantly.

3.4.2. Effect of Cooling on the Tensile Strength

It can be noted that tensile strength values for specimens processed under dry conditions in all tool-pin profiles is the lowest than that obtained in flood cooling. On the other hand, elongation for FSP under dry conditions in all tool-pin profiles is the highest than that in flood cooling. Percentage elongation nearly found to be double as compared with that obtained in flooded cooling condition, for all tool-pin profiles. It is always noteworthy that the mechanical properties in the longitudinal direction registered a gradual increase from cylindrical to square tool-pin profile. This observation may be attributed to the difference in the mechanism of heat generation in various tool-pin profiles, where additional deformation heat complements the frictional heat generation. It can also be seen that ultimate tensile strength values are ranging from 200 to 217 MPa in case of natural and from 211 to 219 MPa in case of flood cooling. It can be concluded that there is drastic reduction in ductility of the material due to FSP, as maximum percentage elongation is noted 11.07 % against nominal value of 13 %, in case of square tool-pin profile. Wen et al. (2012) observed that multi-pass FSP exhibits higher ultimate tensile strength and elongation than a single pass specimen due to grain refinement. Furthermore this is mainly attributed to the significant breakup and dissolution of coarse phase and remarkable microstructural refinement and homogenization. The dissolution of coarse phase can significantly reduce the formation and growth rate of cracks and dramatically improve the ductility of FSP specimens. The graphically representation of results of effect of cooling on the tensile strength and elongation on friction stir processed specimens under dry/flood cooling are shown in Fig. 19 and 20.



(a)



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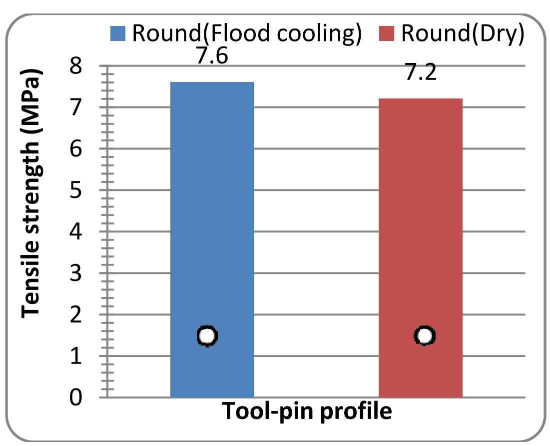
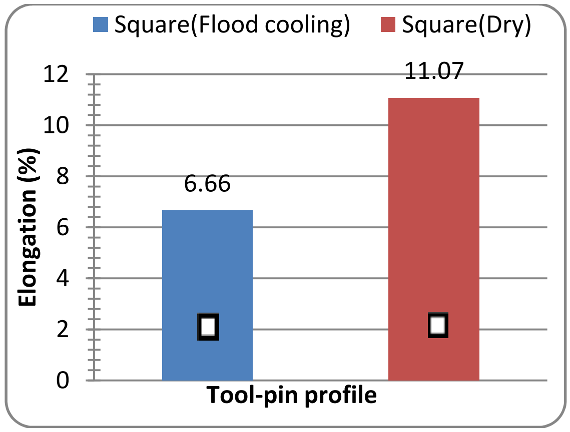
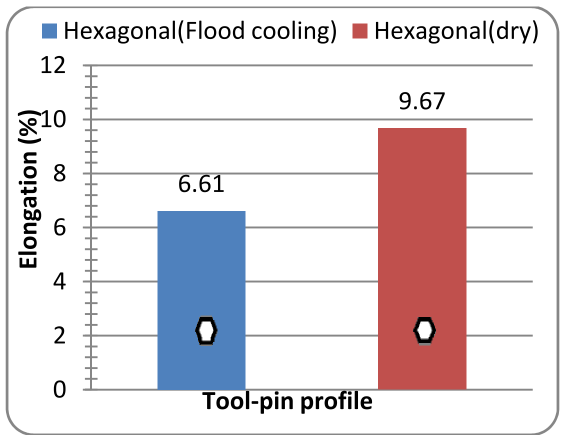


(c)

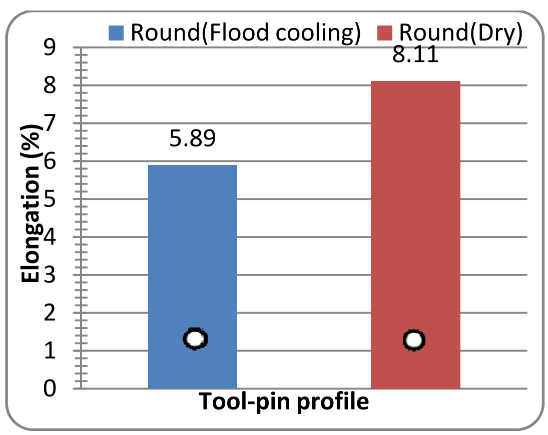
Fig. 19 Effect of cooling on the tensile strength with (a) square, (b) hexagonal and (c) round tool-pin profile respectively.



(a)



(b)



(c)Fig. 20 Effect of cooling on the elongation with (a) square, (b) hexagonal and (c) round tool-pin profiles respectively.

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