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Direct Effects of Process Parameters on the Mechanical Properties of the Friction Stir Welding of Aluminium Alloys A319 and AA6063

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Abstract-
Aluminium is a soft, lightweight metal recognized in dull silvery white appearance. It is the second most plentiful element on the earth. Aluminium has become an important metal in the 19th century owing to its light weight and corrosive resistant properties. Dissimilar Al alloy welds are important in structural, automotive and aerospace applications and need attention as it substitutes the conventional welding techniques with low cost and high efficiency one like friction stir welding (Priya et al 2010). This paper focuses on the friction stir welding of wrought aluminium alloys 6063 and cast aluminium alloy A319 that are extremely highly used in the structural and automotive industries. This paper presents a study of the effect of FSW process parameters on the desired responses using the design of experimental approach. It analyse the relationships of various FSW process parameters selected for study and their effect on weld characteristics like ultimate tensile strength, yield strength, percentage elongation and hardness on the development of mathematical models. Response Surface Methodology (RSM) is used to develop regression equations relating to response characteristics and process parameters. Results of the models are presented in graphical form for better understanding. Validation of the mathematical modeling of FSW tool probe geometry effects on the aluminum alloy weld is presented using analysis of variance (ANOVA) regression models.

Keywords- *A319 and AA6063 alloys, FSW, welding procedure, FSW process quality, mechanical properties*

Introduction-

Aluminium is the second most malleable element (after gold) and it is the sixth most ductile element. It is three times lighter than steel and yet it offers high strength in its alloy form. It is lower in density (2.7 gm/cm3), low in melting temperature (Tm-660°C) and face cubic crystal (fcc) structure which makes aluminium components to be produced and fabricated more easily and with less cost. Pure aluminium is soft and has low tensile strength of 40-50 MPa in annealed condition. It is strengthened by making it undergoing several processes like alloying, cold working and heat treatment. Aluminium is alloyed with numerous other elements to improve its formability, thermal conductivity, high strength and corrosion resistance.

The number series ranges from 1xxx - 9xxx series for wrought aluminium alloys and 1xx.x - 9xxx for cast aluminum alloys. These series are classified according to the major alloying elements that are added to the aluminium. Wrought and cast aluminium alloys are subdivided under heat treatable and non heat treatable aluminium alloys.1xxx, 3xxx, 4xxx, 5xxx series of wrought aluminium alloys and 1xx, 2xx are grouped under non heat treatable aluminium alloys. 2xxx, 6xxx, 7xxx of wrought aluminium alloys and 3xx, 4xx of cast aluminium alloys are grouped under heat treatable aluminium alloys (Polmear 1995). Heat treatable aluminium alloys are thermally treated or mechanically treated to achieve improvement in the desired properties such as strength and hardness etc. 6xxx series constitute under group of wrought aluminium alloys with silicon (Si) and magnesium (Mg) as the major alloying element. These Al-Si-Mg alloys are heat treatable and have moderately high strength coupled with excellent corrosion resistance. They naturally have high weldability. These alloys constitute major portion of architectural and structural applications owing to its excellent formability when high strength to weight ratio is critical. 6xxx series constitute more than 80 percent of aluminum alloy extruded throughout the worldwide in the manufacturing industry (Marchive 1983).

Aluminium alloy 6063 is one of the most widely used aluminium alloy because of its formability, medium strength and high corrosive resistant. AA6063 contains magnesium and silicon in appropriate composition to form magnesium silicide which makes them heat treatable (Aramide Fatai Olufemi 2012). AA6063 is used in architectural extrusions (interior and exterior), window frames and irrigation pipes. Aluminium alloy 319 is heat treatable cast aluminium alloy with the composition of Si, Mg and Cu as major alloying elements. They also possess a complex eutectic system due to the presence of Mn and Fe as impurities (Backerud et al 1990). They exhibit good castability, weldability, pressure tightness, moderate strength and are stable in their casting forms. These sand castings are widely used in internal combustion and diesel engine crank cases, gasoline tanks, oil pans, water cooled cylinder heads, rear axle housings and other engine parts.

Literature Review-

Many studies have been undertaken to friction stir weld dissimilar aluminum alloys, copper alloys and magnesium alloys to other metals. Many of these studies on material flow visualization and no optimum FSW parameters and tool geometry are identified in these systems (Murr 2010, Khaled 2005, Nandan et al 2008, Karlsson 2010). Even for many of the combinations of wrought and cast aluminium alloys optimum process parameters are not identified. The weld strength is observed to reduce if a very hard aluminum alloy is stirred with a very soft aluminum alloy. It was reported that the locations of two dissimilar alloys exerted a significant effect on material flow pattern and the resultant weld quality. For example, FSW of AA5083 to AA6082 (Larsson 2000) and AA6061 to Cu (Teimournezhad2010) show that the low-strength material should be placed on the advancing side to produce better welds.

Lederich (Lederich et al 2001) obtained high tensile strength when high-strength AA 2024 is placed on the advancing side of the weld for the combination 2024Al alloy /D357 steel.

Koilraj et al (2012) optimized FSW process with respect to tensile strength of the dissimilar welds AA2219 and AA5083 using five different tool profiles. The process parameters chosen were rotational speed, Transverse speed and D/d ratio where D= shoulder diameter and d= tool pin diameter respectively. The optimum values obtained were 700 rpm, 15 mm/min and 3 respectively for the cylindrical threaded pin tool profile.

Singh et al (2011) talks about the effect of post weld heat treatment (T6) on the microstructure and mechanical properties of friction stir welded 7039 aluminium alloy joints. FSW parameters are optimized by making welds at constant rotary speed of 635 rpm and welding speed of 8 and 12 mm/min. It is observed that the thermomechanically affected zone (TMAZ) exhibit coarse grains than that of stir zone. The results reveal that PHWT lowers the yield strength and ultimate tensile strength but improves the percentage elongation of the joints.

Priya et al (2009) investigates the effect of post weld heat treatment on the microstructure and mechanical properties of dissimilar friction stir weldments of AA6061 and 2219 in peak aged T6 temper. It is found that hardness is the reason for the increase in weld zone alone and there is no effective improvement in HAZ hardness in direct post weld ageing, whereas post welds solution treatment at 520°C followed by ageing at 165°C result in significant improvement in hardness across the whole weldment. The direct post weld ageing did not influence the grain structure of the weld nugget. The post welds solution heat treatment followed by ageing results in coarsening of the grains in the weld nugget.

Material and preparations of specimens-

AA6063 belongs to a group of heat treatable 6xxx series which contains Al-Si-Mg as major composition. AA6063 is procured as roller plates of 6mm thickness. The required welding sizes of 100mm x 50 mm x 6mm were taken from the sheet.

Table 3.1 Composition of A319 and AA6063-T6

Base Metals	Si	Cu	Mg	Mn	Ti	Zn	Fe	Al
A319	6.2	3.4	0.1	0.5	0.3	0.1	0.7	Bal
AA6063	0.3	0.1	0.5	0.1	0.1	0.1	0.3	Bal

Table 3.2 Mechanical properties of A319 and AA6063-T6 aluminium alloys

Base Metals	UTS (Mpa)	YS (MPa)	Elongation %	Hardness (Hv)
A319	186	124	12	85
AA6063	245	214	2.5	80

Welding Procedure

The following are the stepwise welding procedure adopted to perform the friction stir welding:

- **a)** On the basis of the trial experiments conducted, the friction stir welding of the dissimilar aluminium alloys A319 and AA6063 is conducted by varying the process parameters like tool rotational speed, welding speed and axial load.
- **b)** The second step is to form the design matrix based on the range of the process parameters and experimentations performed as per the design matrix.
- **c)** Single pass friction stir butt welding is followed to fabricate the joints for all the welding conditions.
- **d)** The friction stir weldment comprises of two plates joined together that has the dimensions (100 x 50x 6) mm. The plates are cleaned before welding by grinding with grinding paper of 500 grit in order to remove any stains and the aluminium oxide layer that is formed on top of the aluminum sheets.
- **e)** The plates to be joined are securely clamped in the specially designed fixture so that the plates stay in place and do not move in the process of welding. The plates are ensured to be placed parallel to the FSW table.
- **f)** The rotational motion of the spindle starts and the tool is then kept in direct contact with the surface of the plates and the pin is penetrated to the predetermined depth into the surface of the plates to be welded.
- **g)** The tool takes time to rotate in contact with the surfaces to soften the material due to the frictional heat that is produced and afterwards the tool is given forward motion which forms the weld. The tool is withdrawn after the weld is completed. The process leaves a hole at the end of the joint.
- **h)** The post weld ageing treatment is carried on some samples to test the effects of post weld ageing treatment on the mechanical and metallurgical properties.
- **i)** Visual inspection is performed on all welded sample in order to verify the presence of possible macroscopic external defects such as surface irregularities, excessive flash and lack of penetration or surface open tunnel and voids.

Post weld of Mechanical Properties-

Post weld of Mechanical Properties as like heat treatment consists of solution hardening and ageing of the FS welded samples in the heat treatment furnace. The furnace used for the current experiment is the Muffle furnace.

Procedure for Post Weld Heat Treatment

The mechanical and microstructural properties of friction stir welded aluminium alloy A319 and AA6063 joints are experimented for the effect of post weld heat treatment. A schematic diagram of PWHT is given in Figure 1.

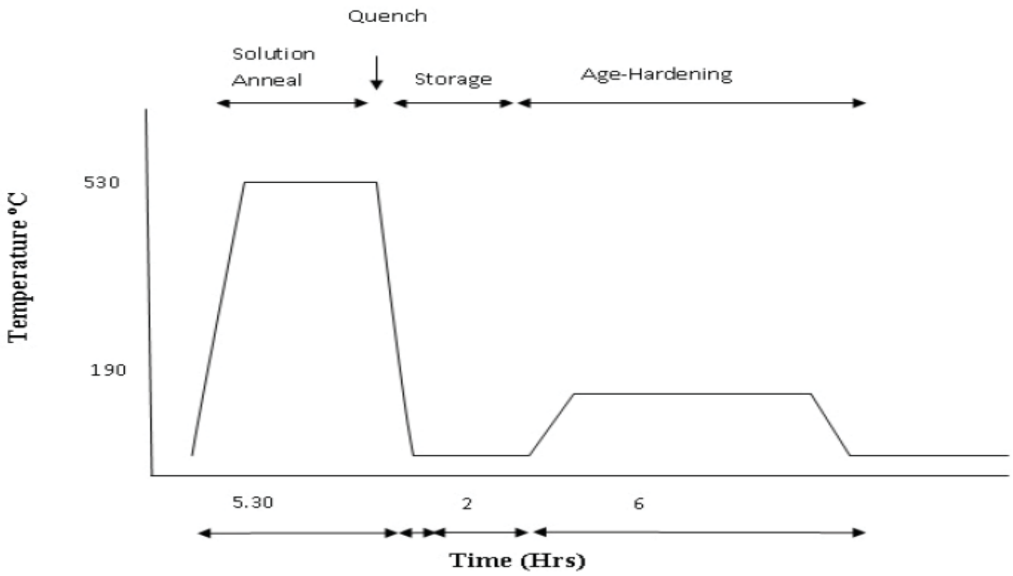


Figure1. Schematic representation of PWHT of FSW joints

Post Weld Heat Treatment involves the following procedure

a) Solution Hardening- Solution Hardening or solution heat treatment (SHT) is a thermal processing step that is used to strengthen the heat treatable alloys like aluminium. SHT is conducted at an elevated temperature at 540º C in which the solubility of the alloying elements in the aluminium solid solutions are maximum.

b) Quenching- This process involves sudden cooling of the SHT samples by quenching it in water bath at room temperature. Quenching is carried out in order to avoid slow cooling as slow cooling may be detrimental to the mechanical properties or to the corrosion resistance of the alloys due to the precipitation of phases. In order to avoid the precipitation of phases, solid solutions formed during solution heat-treatment are quenched rapidly without interruption to produce a supersaturated solution at room temperature.

c) Post weld artificial ageing (AA) treatment- In post weld artificial ageing (PWA) treatment joints are placed into the muffle furnace and heated to the soaking temperature of 190°C for a period of 6 hours. Joints are cooled down in the furnace to room temperature at the end of the soaking period. Artificial aging imparts high strength and hardness to aluminium alloys without sacrificing other mechanical properties. It also improves resistance of these alloys to corrosion.

Process Parameters Affecting the FSW Process Quality

The FSW experimentation is based on many process parameters. Some parameters are fixed. The different process parameters were listed as below:

a) Material
b) Alloy composition
c) Thickness
d) Tool rotation speed
e) Welding speed (or) Feed rate
f) Tool design (Shoulder and pin)
g) Axial force
h) Tool pin shape
i) Angle of tool with respect to workpiece (or) tool tilt angle

Table 4.1 Working range of FS welding parameters of A319 and AA6063

Process Parameters	Unit	Symbol	Levels				
			-1.682	**-1**	**0**	**1**	**1.682**
Tool rotational speed	rpm	N	800	901	1050	1198	1300
Welding Speed	Mm/min	S	20	24	30	36	40
Axial Load,	kN	F	3	4	5.5	7	8

Experimental Study of Direct Effects of FS Welding Process Parameters

(a) Direct Effects of Friction Stir Welding Process Parameters on UTS

The direct effect of the process parameters for UTS is given in Figure 3 (a) (b) & (c). The direct effects are considered by keeping one of the process parameter as variable and other two parameters as the center value. Ultimate tensile test results show the increasing trend with the increase in the tool rotational speed. It reaches the maximum value at 1198 rpm as shown in Figure 3(a). At the tool rotational speed of 800 rpm, UTS obtained is 132 MPa. UTS value of 151 MPa and 163 MPa are obtained for 901 rpm and 1050 rpm respectively. The maximum UTS value of 174.5 MPa is obtained at 1198 rpm. Further increase in the tool rotational speed, from 1198rpm to 1300 rpm, led to higher heat input resulting in slow cooling rate. Slow cooling rate provides ample time for the grains to grow in the stir zone and HAZ .This was supported by the SEM fractographs showing coarser dimples Figure2 (a) (b) & (c). It may be the reason of low tensile strength of the joint welded at higher tool rotational speed.

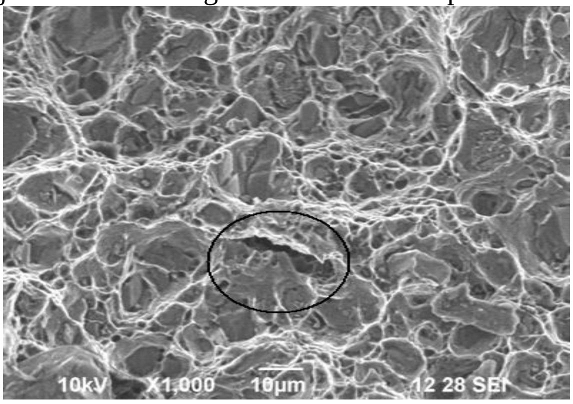


Figure (a)

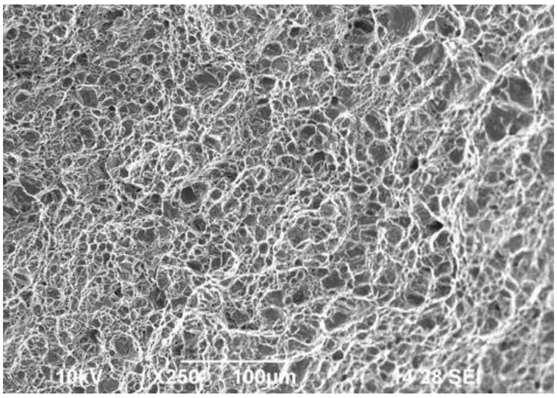


Figure (b)

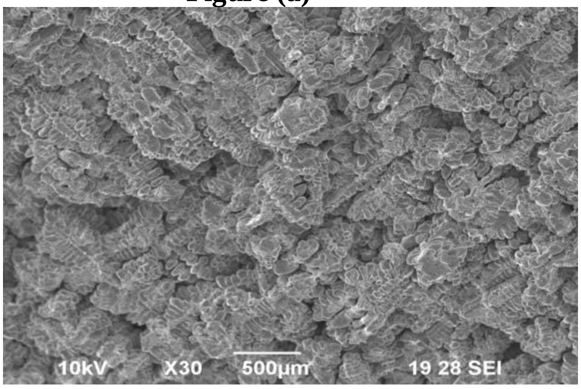
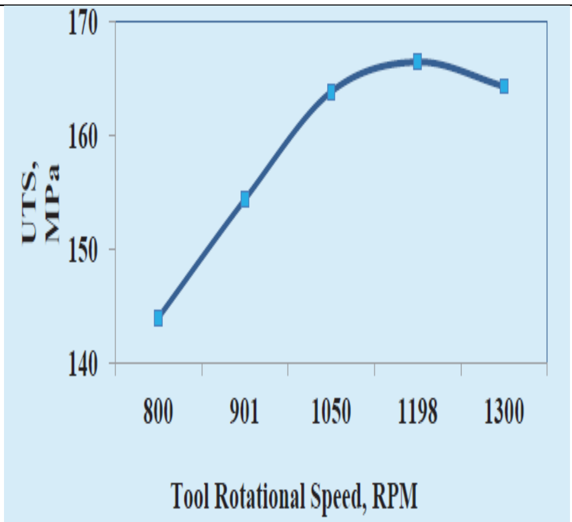


Figure (c)

Figure 2 SEM micrographs showing fracture surface of AA6063 and A319 alloy (a) Brittle failure (b) Ductile failure with dimples (c) Fracture surface under high magnification



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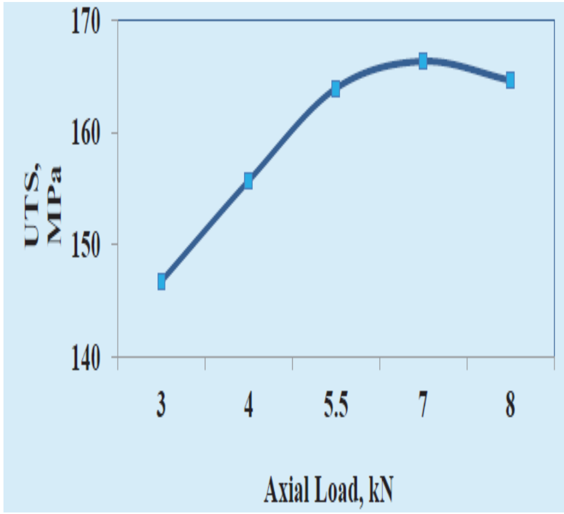

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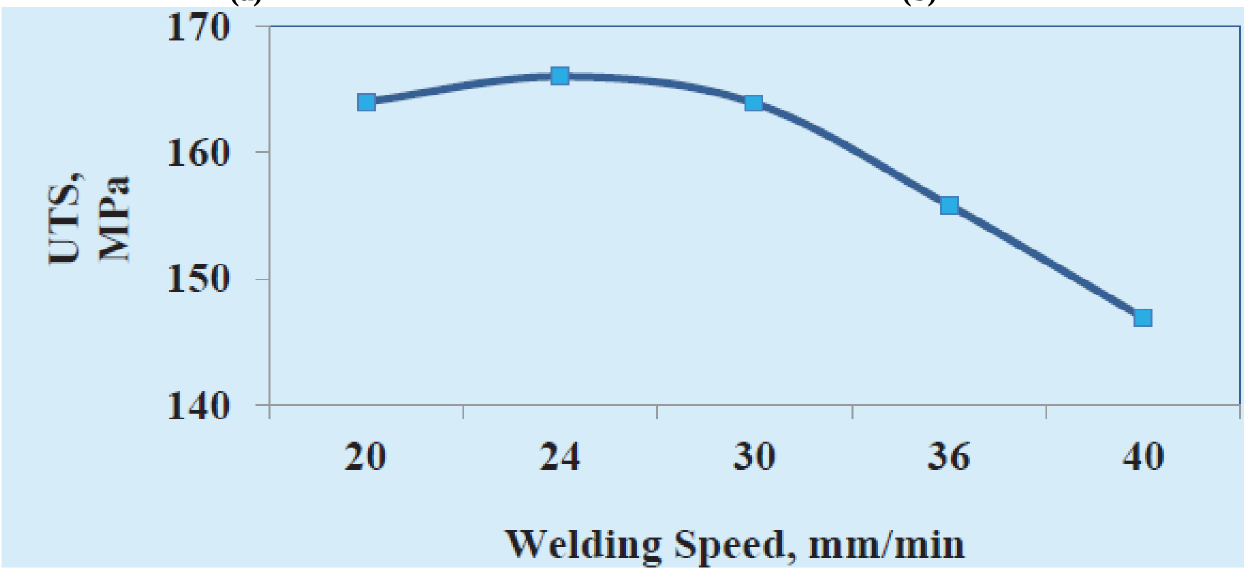


(c)

Figure 3 Direct Effects of FSW Process Parameters on UTS (a) N (b) F & (c) S

Ultimate tensile test results show the increasing trend with the increase in the axial force. It reaches the maximum value at 1198 rpm as shown in Figure 3 (b). At the axial force of 3kN, UTS obtained is 146 MPa. UTS value of 151 MPa and 163 MPa are obtained for 4kN and 5.5kN respectively. The maximum UTS value of 167 MPa is obtained at 7kN. The further increase in axial force beyond 7 kN, resulted in the significant decrease in the tensile strength of the joint was observed. Insufficient and excessive axial force is one of the reasons of lower tensile strength of the joints at the lower axial force, insufficient heat was generated due to escape of the heat from the upper surface of the base plate.

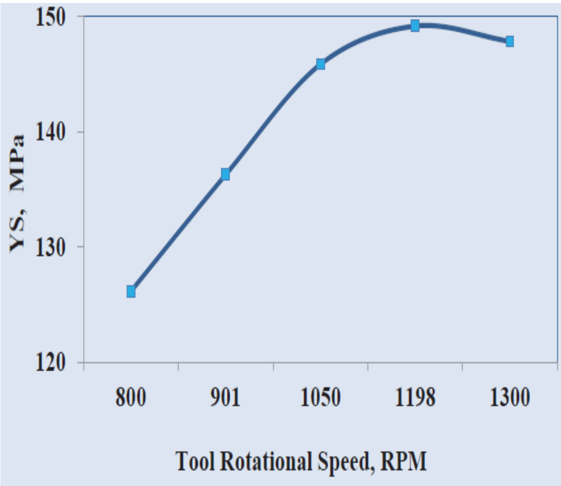
Additionally heat generation was more due to increase in the axial force and the loss of heat diminished due to the confinement of the material inside the weld cavity. Therefore sufficient heat was available in the stir zone for weld formation which resulted in higher tensile strength of the joints as observed at 5.5 kN and 7 kN axial force. Due to sufficient axial force, the shoulder contact increases with base plate and the material escaped interacts more with the shoulder and as deflected back to the weld cavity. But at the higher axial force 8 kN, some material was lost as a flash due to excessive rubbing of tool shoulder and base plate resulting in decreased cross sectional area. The excessive rubbing results in high friction heat generation, but some heat may be lost along with the removal of the material from the surface of base plate. Therefore the availability of heat for weld formation decreased marginally. It is considered to be the reason for decrease in tensile strength at higher axial force more than 7 kN. When the welding speed was lower, heat input in the weld zone was high. Due to high heat input coarse grains were developed in the stir zone [Cavalierb et al., 2006]. These may be the reasons for lower tensile strength of the joint at lower welding speed of

20mm/min. With the enhancement of welding speed, interaction between tool and work piece was improved. Due to improved interaction of tool and work-piece frictional heat generation per unit length of the weld gets reduced [Ghosh et al., 2010].

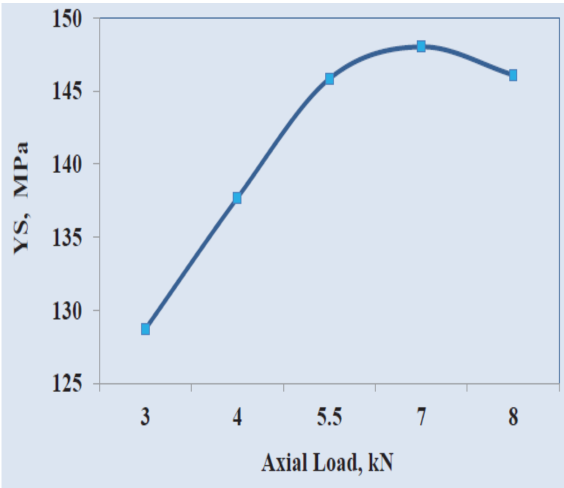
Therefore increase in tensile strength of the joints was observed at 25 mm/min and 30 mm/min welding speeds. With further increase in the welding speed the material received less frictional heat which was insufficient for plastic flow of the metal in the stir zone resulting in the formation of coarse grains. Under such conditions, the plasticized material is cooler and less easily forged by the tool shoulder resulting in lack of bonding which may be the reason of lower tensile strength of the joint at 35 mm/min welding speed.

(b) Direct Effects of Friction Stir Welding Process Parameters on YS

From the Figure 4, it is inferred that tool rotational speed, welding speed and axial force have significant influence on YS. The maximum YS is found at 142 MPa for 1198 rpm and lowest YS is at 108 MPa at 800 rpm as shown in Figure 4 (a). The YS value increases with increase in tool rotational speed up to 1200 rpm and it exhibits a decreasing trend at 1300 rpm. Similar trend also occurs for axial load as seen in Figure 4 (b). At lower rotational speed, frictional heat generated is lower which results in poor plastic flow of materials being FS welded, and therefore, lower YS is observed. The higher rotational speed results in metallurgical transformation such as solubilisation, reprecipitation and coarsening of precipitates at the weld zone and lowering of dislocation density (Threadgill 1999). Therefore, at higher rotational speed lower yield strength is observed. The same trend is observed as UTS in case of tool axial force as shown in Figure 4. (b). When the welding speed was lower, heat input in the weld zone was high. Due to high heat input coarse grains were developed in the stir zone [Cavalierb et al., 2006]. These may be the reasons for lower YS of the joint at lower welding speed of 20mm/min. With the enhancement of welding speed, interaction between tool and work piece was improved. Due to improved interaction of tool and work-piece frictional heat generation per unit length of the weld gets reduced [Ghosh et al., 2010]. Therefore increase in YS of the joints was observed at 25 mm/min welding speeds. With further increase in the welding speed the material received less frictional heat which was insufficient for plastic flow of the metal in the stir zone resulting in the formation of coarse grains. Under such conditions, the plasticized material is cooler and less easily forged by the tool shoulder resulting in lack of bonding which may be the reason of lower YS of the joint at 35 mm/min welding speed as shown in Figure 4 (c).



(a)



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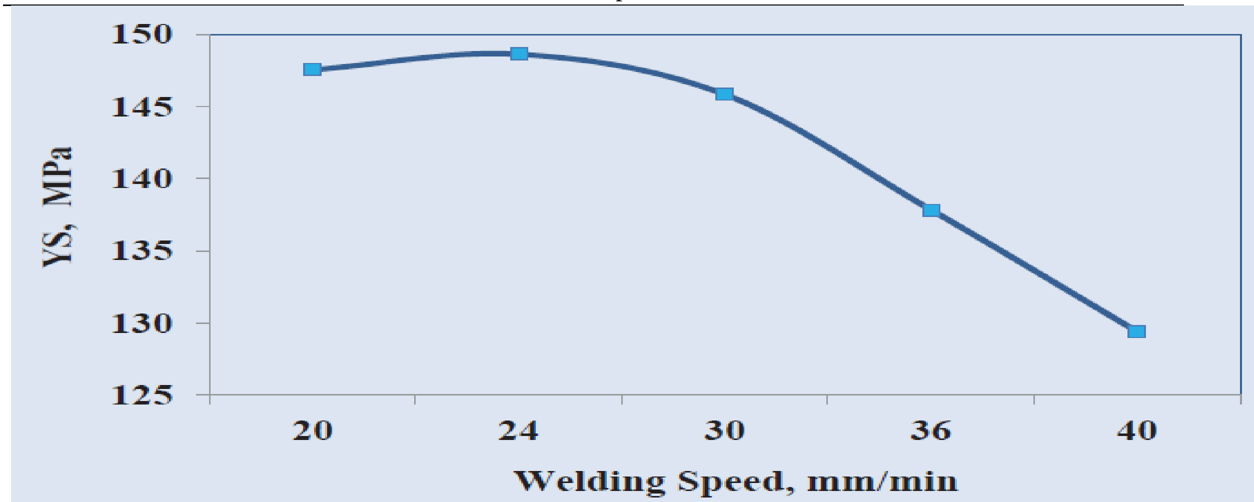
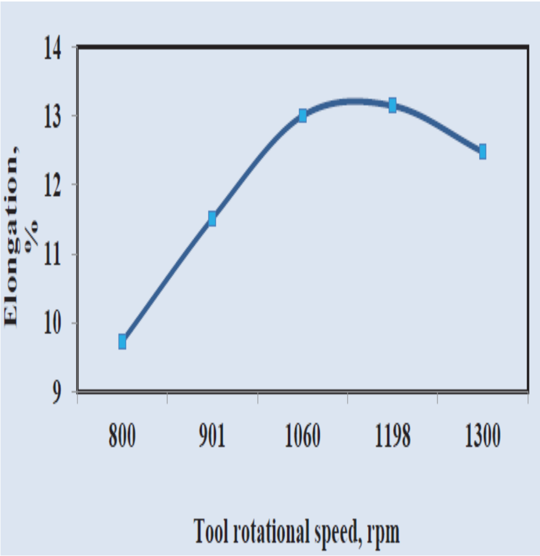


(c)

Figure 4 Direct effects of friction stir welding process parameters on Yield Strength (a) Tool rotational speed (b) Axial load (c) Welding speed

(c) Direct Effects of Welding Parameters on %E



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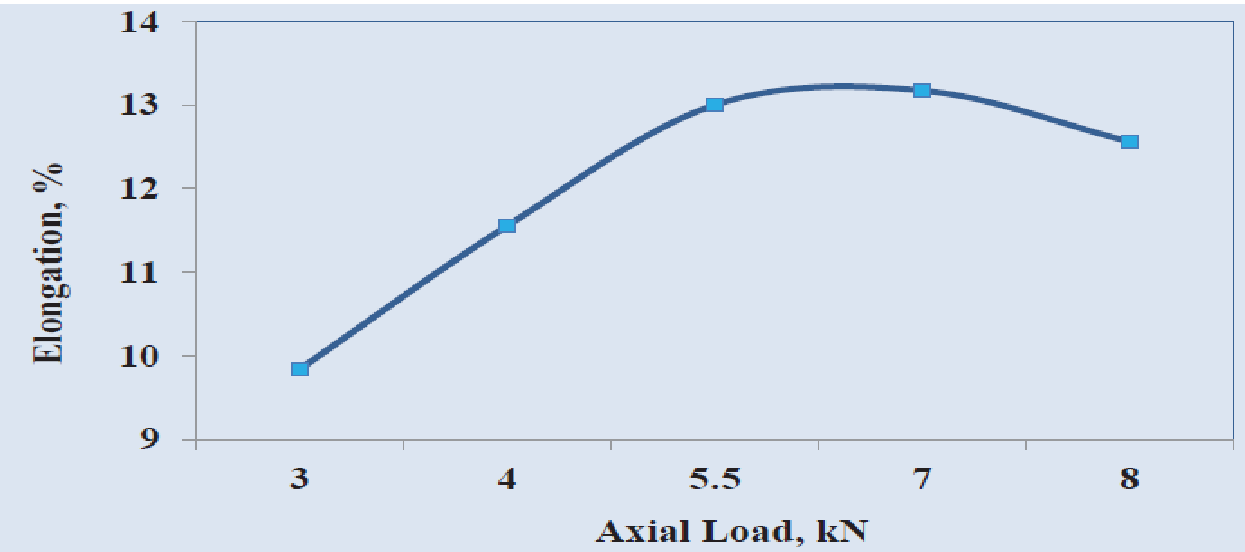


(c)

Figure 5 Direct effects of friction stir welding process parameters on %E (a) Tool rotational speed (b) Axial Load (c) Welding speed

The effect of process parameters on %E is given in Figure 5 (a, b and c). The maximum %E of 13 is obtained for the tool rotational speed 1198 rpm and the minimum value of 5 is obtained at 800 rpm. The %E increases with increase in tool rotational speed and axial force and decreasing after 1198 rpm. Similarly, increase in welding speed results in decrease in the %E. The increasing trend in elongation with increase in tool rotational speed may be due fine grains in the stir zone with the increased plastic flow of material in the WN and TMAZ. But with further increase in tool rotational speed from 1198 rpm to 1300 rpm the elongation of the weld decreased from 13.5% to 12%. This may be due to coarse grains in the stir zone. The increase in the tool axial force leads to the increase in the frictional heat generated and increase in the plunge depth of the tool into the work pieces. Therefore, the increase in the tool axial force beyond 7 kN results in the decrease in the % elongation of dissimilar FS welded joints of Al alloys.

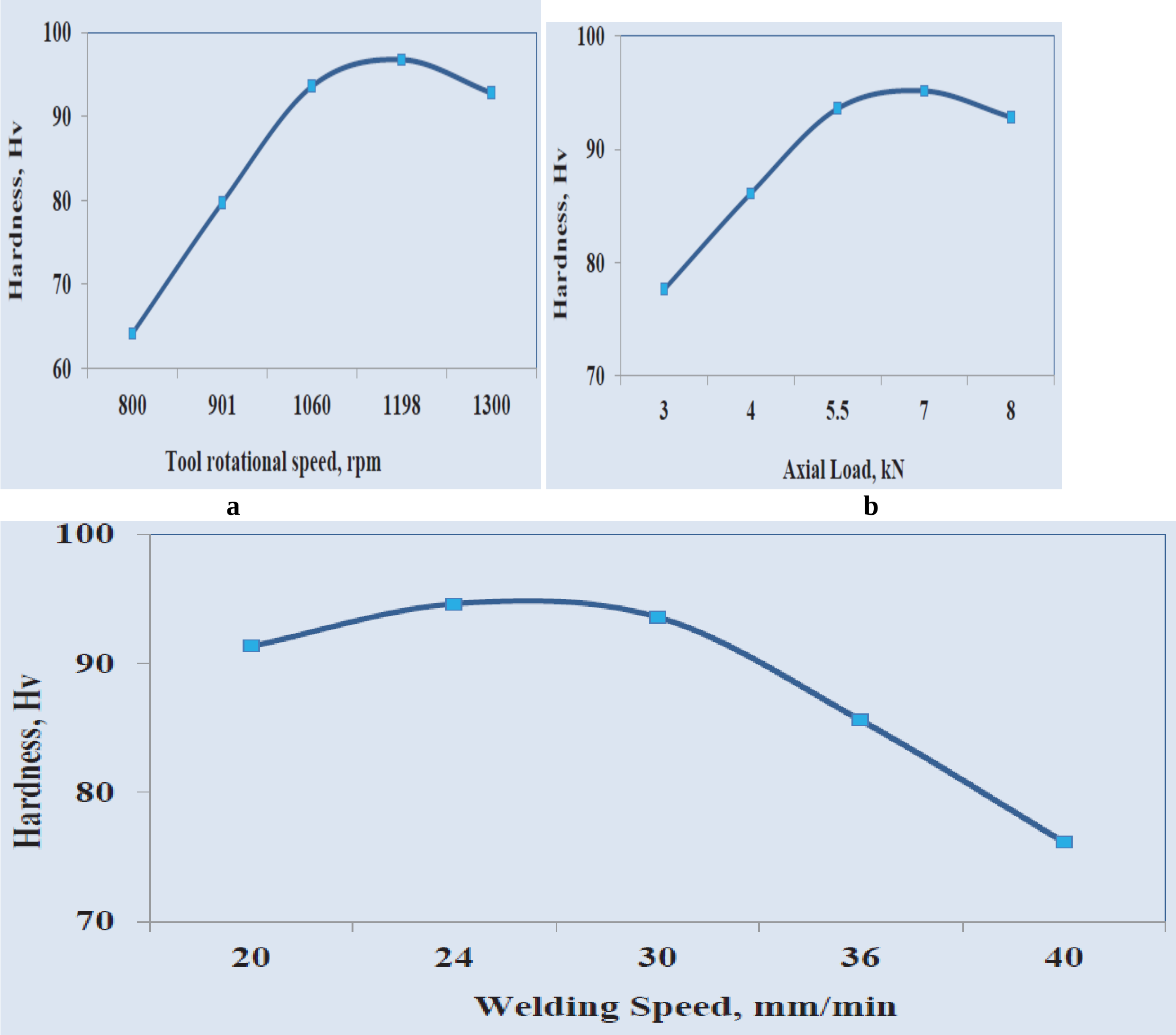
(d) Direct Effects of Welding Parameters on Hardness

As seen in Figure 6 shows that the hardness of the weld joint increases at lower welding speeds. The micro hardness of the joint is lower for the welding speed of 40 mm/min and higher at 24 mm/min for square tool pin profile. The decrease in welding speed tends to increase the heat input per unit weld length. The increase in heat input leads to more grain growth. Generally the hardness of the FS zone area has a direct relation with temperature that it has reached in that area (Woo et al 2009). The hardness decreases with the increase in temperature because higher temperature leads to coarser grain growth. High heat input increases the solute concentration in the weld nugget zone. Moreover increase in welding speed reduces the tool-work interactions and reduces the heat input.

But with the increase in welding speed to 35 mm/min, the interaction between tool and work-piece is reduced resulting in reduction in the heat input. Lee et al (2003) correlated the variations of hardness with that of grain growth. Stir zone always have lower hardness value than the base metal at different tool rotational speed. The effect of tool rotational speed on micro hardness is presented in Figure 6 (a). As the tool rotational speed increased from 800 rpm to 1198 rpm the micro hardness of the stir zone increased from 65 Hv to 95 Hv. Increasing the tool rotational speed led to fine grain structure due to the sufficient heat input. The micro hardness of the weld joints was correlated to the average grain size in the same point. The behaviour of micro hardness with grain size shows that the strong influence on mechanical behaviour of the different specimens was due to the micro structural evolution obtained by employing the different welding parameters. But beyond the tool rotational speed of 1198 rpm, the heat input in the stir zone was high, leading to slow cooling rate resulting in coarse grain structure and decrease in hardness. As shown in the Figure 6 (b), the hardness of the weld joints increases with increase in welding speed at 20 mm/min but after 24 mm/min the hardness of the joint starts decreasing. At the lower welding speed of 20 mm/min, the average micro hardness of the weld joint was 90 Hv because the decrease in welding speed would increase the heat input per unit weld length.

But with increase in welding speed to 24 mm/min, the interaction between tool and work-piece was reduced resulting reduction in the heat input. Due to decrease in heat input, grain size decreased and the average micro hardness of the joint was improved (94 Hv). But with further increase in welding speed beyond 24 mm/min the average micro hardness of the joints reached 73 Hv. Lee et al 2003 reported that the variation of hardness may be correlated to the grain growth. Generally the hardness of the FS zone area has a direct relation with temperature reached in that area [Woo et al., 2009]. As the temperature increases the hardness decreases because higher temperature leads to more grain growth. High heat input increases the solute concentration in the weld nugget owing to reversion.

It is observed from the Figure 6 (c), that as the axial force increased from 3 kN to 7 kN the micro hardness of weld joint improved, reaching maximum before falling again at higher axial force (8 kN). The mean hardness increased from 77 Hv to 94 Hv with increase in axial force from 3 kN to 7 kN. With increase the axial force, both the hydrostatic pressure beneath the shoulder and the temperature in the weld nugget increase resulting in fine grain structure in the weld joints and improving the micro hardness of the weld joint. The nugget hardness recovery was due to recrystallization of a very fine grain structure. But the higher axial force (8 kN) resulted in higher heat input, due this grain growth and severe clustering of precipitates in the SZ, which resultantly produced lower hardness (90 Hv) in the SZ.



(c)

Figure 6 Direct effects of friction stir welding process parameters on Hv (a) Tool rotational speed (b) Axial Load (c) Welding speed

It shows that the sufficient axial force is required to form good weld. This is because the temperature during friction stir welding defining the amount of plasticized metal and the temperature is greatly dependent on the axial force.

Conclusion-

The effect of post weld heat treatment on the microstructure and mechanical properties of the dissimilar FS joints are analyzed by choosing a range of process parameters with variable rotational speeds while keeping other process parameters at optimum level. One half of the FS welded specimen is used for the post weld heat treatment. The heat treatment comprises of solution hardening of FS welded samples at 540°C for a soaking period of 5 hours and 30 minutes followed by rapid quenching in water and annealing at 90°C for 6 hrs. The scopes for the future research work are the effects of preheating in the mechanical and microstructural properties of the dissimilar joints can be studied; the FSW process can be simulated using dynamic simulation software and other finite element software that predicts the temperature distribution at the different zones and FSW process can be optimized for different tool profiles of different materials and their effect on mechanical microstructural properties can be analyzed.

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