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Optimization of process parameters for Friction Stir Welding of Cast Aluminium Alloy (A413)

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ABSTRACT

Cast aluminium alloy used in automotive and aerospace applications are increasing due to their light weight and castability. It is necessary to weld aluminium castings to themselves and various applications. These alloys are not easily weldable by conventional fusion welding techniques because the quality of the welded joint is deteriorated due to the presence of porosity, hot cracking and distortion. Friction Stir Welding (FSW) process is an emerging solid state joining process in which the material that is welded, does not melt. FSW creates the weld joint without bulk melting. In addition, the thermo mechanical deformation induces dynamic recovery refine structure of the stir region. Therefore, welds made by FSW to have much improved mechanical properties than corresponding fusion welds. Hence, the present investigation is carried out to make a systematic study to understand the effect of FSW process parameters on mechanical and metallurgical properties of cast aluminium-silicon alloy. This paper focus on effect of tool rotation speed, welding speed and axial force for optimum tensile strength, hardness and microstructure of friction stir welded joints of A413 alloy.

Keywords: Cast Aluminium Alloy, Friction Stir Welding, Porosity, Weld Joint, Mechanical Properties

I. INTRODUCTION

Welding is one of the most important joining processes in any manufacturing industry. Friction stir welding (FSW) technique has high joining speed welding process that improved metallurgical properties and reduced need for human skill with comparison with conventional fusion welding method. Friction stir processing zone is affected by material flow behaviour under the action of rotating tool.

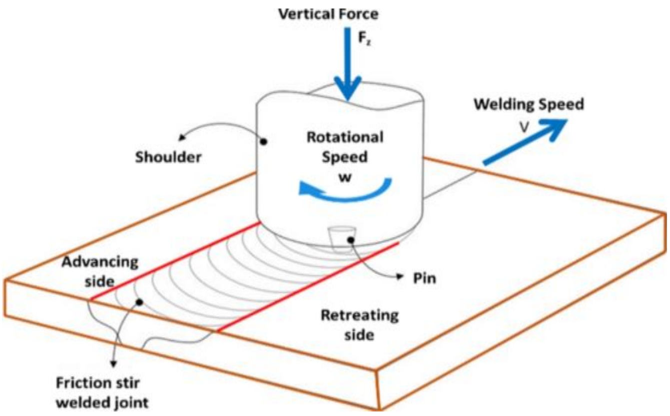


Fig.1: Friction Stir Welding

The usage of cast aluminium alloy in automotive and aerospace applications is ever increasing due to their light weight and castability. It is already known that the joint between cast aluminium alloys has lot of potentials for expanding the usage of economic casting in aircraft and automotive applications. These alloys are not easily weldable by conventional fusion welding techniques because the quality of the welded joint is deteriorated due to the presence of porosity, hot cracking and distortion. Friction Stir Welding (FSW) process is an emerging solid state joining process in which the material that is being welded does not melt and recast. FSW creates the weld joint without bulk melting. In addition, the extensive thermo mechanical deformation induces dynamic recrystallization and recovery that refine the microstructure of the stir region. Therefore, welds made by FSW are shown to have much improved mechanical properties such as the tensile strength and the fatigue life than the corresponding fusion welds. Friction welding processes are mainly used to join circular shafts and pipes. Hence it has got wide application in the area of joining carbon-steel vehicle axles and sub axles. It is also used to fabricate suspension rods, steering columns, gear box forks and engine valves. Thus it finds wide applications in automotive industries.

II. LITERATURE REVIEW

Literature review on FSW has been carried out for experimental. Some papers have focussed on the measurement of process parameters like tool rotation, tool torque and temperature distribution along longitudinal and transverse direction of friction stir welding specimen while welding both similar and dissimilar materials by various researchers. **Won Bae Lee et al** investigated the FSW joints of AA6061 aluminium alloy and they observed that the hardness of the stir zone increased with the tool rotation speed. **Hwang et al.** have experimental study on temperature distributions within the workpiece during FSW of aluminium alloys. **Jayaraman. M et al.** have to improve strength of welded joints in fusion welding of cast Al alloys, friction stir welding technique may employed to eliminate porosity, hot cracking etc. **Jau-Wen Lin et al.** have done experiments on FSW process to compare the mechanical and micro structure properties of pure copper welded using FSW and TIGW. **Ericsson. M et al.** have done experiments to evaluate the influences of welding speed on the fatigue of friction stir welded joints and compare the same with the joints from MIG and TIG welding. For the experiment two materials have been considered. They have found that welding speed had no major influence on mechanical and fatigue properties of the friction stir welded joints except some areas. **Marzoli et al.** have done FSW of AA6061/Al_2O_3 alloy. The joints produced have been subjected to mechanical and micro structure characteristic studies. It is seen that tool's stirring effect has significant effect on the reinforcement particle distribution and shape. **Heurtier et al.** has done the numerical study for the mechanical and thermal modelling of FSW using AA2024-351 alloy. The model has predicted the strain rates, temperature distribution and hardness at various zones. **Ceschini et al.** have conducted experiments to find the effect of FSW on microstructure, tensile and fatigue properties of the AA7005/Al_2O_3. Friction stir welded joints have exhibited high tensile values. **Hwang et al.** have conducted experimental study on temperature distributions within the workpiece during FSW of aluminium alloys. Welding processes have been achieved by appropriately controlling the maximum temperature during the welding process. They have also evaluated hardness and tensile strength of welded joints. **Zhang et al.** have conducted numerical studies on controlling process parameters in FSW. A thermo-mechanical model has been developed by them to predict the material deformation and temperature histories in FSW. It is found that welding temperature has been increased with the increase in tool rotation. It is also noticed that the input power has been increased with the increase in welding speed. **Hwang et al.** have conducted experiments to weld copper metals (C11000) using FSW. The study mainly aimed to explore the thermal history of work piece during FSW. The temperature data combined with preheat temperature records them for obtaining effective friction stir welded joints. Hardness test has been conducted on the weld to evaluate the hardness distribution in thermal-mechanical affected zones, heat affected zones and the base metal. **Yu-E-Ma et al.** have done experiments to study the effect of welding process parameters on mechanical and fatigue properties of friction stir welded 2198-T8 Aluminium Lithium Alloy joints. **Durso. G et al.** have done experiment to study the fatigue crack growth in the welding nugget of FSW joints of 6060 aluminium alloy. Tensile tests, metallographic analyses and Vickers tests have also been carried out to evaluate the mechanical properties of the joints as a function of process parameters. **Singh. V et al.** have to optimize and make it aluminium –magnesium alloys welded joints using friction stir welding and to obtain the desired mechanical properties, certain welding process parameters. **P. Pradeep et al.** In this paper, we study a review of friction stir welding process and the effect of process parameters of this welding technique on mechanical as well as microstructural behaviour of aluminium alloys. **Vishvesh J. Badheka et al.** In this study, we use friction stir welding of dissimilar aluminium alloys. **Kumaran S. S. et al.** in this paper a knowledge of the process of friction stir welding of Inconel alloys that highlighting characteristics of Inconel alloys and this paper will show the results of different works concerning the behavior of tensile properties, hardness and microstructure of FSW joints of the alloy.

From the literature review, it is understood that friction stir welding process is an efficient process to join cast aluminium alloys. Though the reported literature on FSW of wrought aluminium alloys is enormous, the published information on FSW of cast aluminium alloys could be counted with fingers. Hence, the present investigation was carried out to understand the effect of FSW process parameters on tensile strength of welded cast aluminium alloy.

III. METHODOLOGY

In this work, Al-Si alloy A413 was used. Castings were made by sand casting method and machined to rectangular plates of size 175mm × 75mm × 6mm. Single pass welding procedure was used to fabricate butt joints. Joints were fabricated using different levels of tool rotation speed, welding speed and axial force. Specimens were prepared from the welded joints. Tensile test, hardness measurement analyses on specimens were carried out. The experimental plan of the present investigation is illustrated in the form a flow chart as shown in Fig.2.

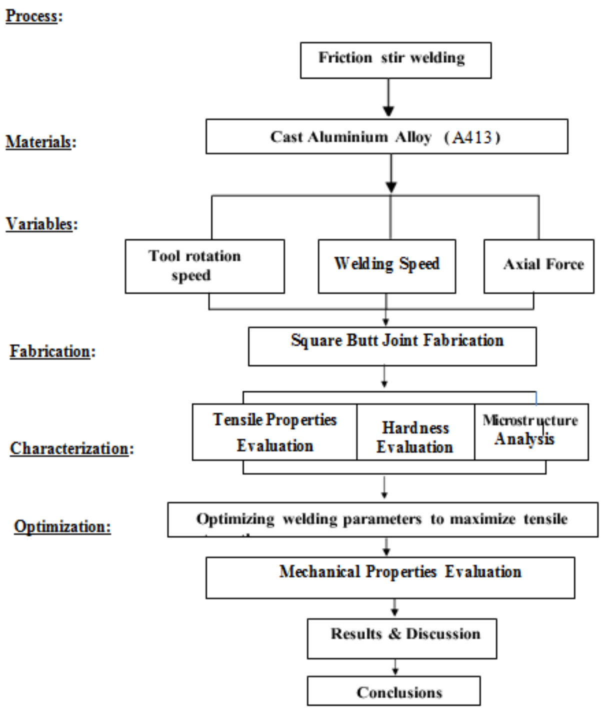


Fig.2: Experimental Plan

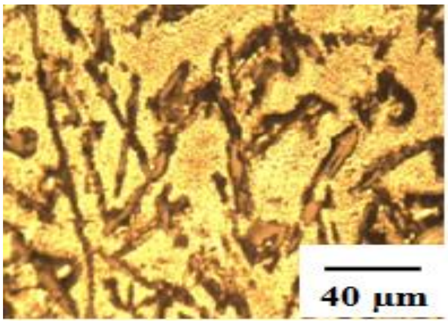
Material: The material used for obtaining friction stir welded joints is Cast Aluminium alloy (A413). It is heat treatable alloy with excellent cryogenic properties and is nick named as wonder alloy. It is basically Al-Si-Mg turnery alloy with minor additions of Cu, Mn and Zn. The chemical composition of Cast Aluminium alloy (A413) is given in Table 1. The mechanical characteristics of the same are given in Table 2.

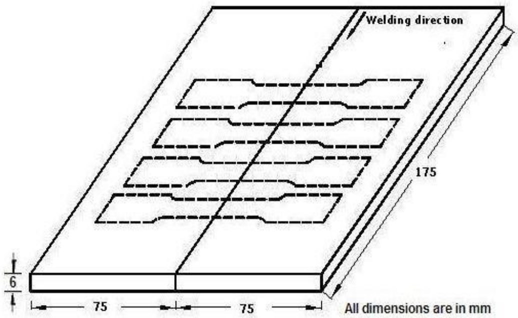
Table 1: Chemical compositions (wt %) of base metal

Base metal	Si	Mg	Fe	Mn	Cu	Zn	Ni	Al
A413 alloy	11.6	0.05	0.32	0.04	0.03	0.01	--	Bal

Table 2: Mechanical properties of base metal

Base metal	Ultimate Tensile Strength (MPa)	Vickers Hardness (Hv) (0.05 kg)
A413 alloy	143	64





(a) Optical micrograph of base metal (A413 alloy) **(b)** Scheme of welding of tensile specimens

Fig.3: (a) & (b)

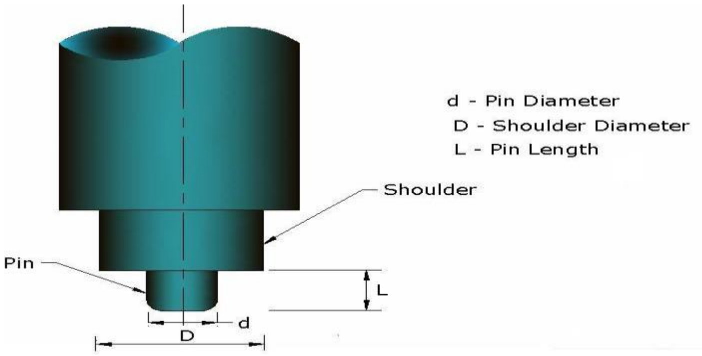


Fig.4: FSW tool nomenclature

Table 3: Details of FSW tool dimensions

Pin Length, L (mm)	5.7
Tool shoulder diameter, D (mm)	18
Pin diameter, d (mm)	6
D/d Ratio of tool	3.0

Tool inclined angle (deg)	0
Tool pin geometry	Thread
Pitch (mm) and included angle (deg) of threaded pin	1 and 60
Hardness of the tool	70
Chemical composition of the tool (wt%)	C-0.75, Si-0.25, Mn-0.32 (High carbon steel)

Experimental Setup : FSW setup from a vertical milling machine attached with a suitable friction stir welding tool. A friction stir welding tool is always subjected to static and dynamic loading due to tool axial forces, its stirring effect at the joining faces of workpiece, frictional effect due to the initial piercing into the work pieces, frictional force due to its own rotation and traversing along the joining line of workpiece and the high thermal loading occurred at the time of FSW process. The main purpose of a fixture is to hold the workpiece during machining operation.

Fig.5: Experimental Setup of Friction Stir Welding

Fabrication of Joints: Aluminium-silicon based alloy of A413 was made by sand casting method and machined to rectangular plates of size 175mm × 75mm × 6mm. The degassing of molten metal was carried out prior to casting. The initial joint configuration was obtained by securing the plates in position using mechanical clamps. Single pass welding procedure was used to fabricate the square butt joints. Non-consumable tool made of high carbon steel with threaded pin was used to fabricate the joints. Total, fifteen joints were fabricated using 5 levels each of tool rotation speed, welding speed and axial force. The photographic view of the fabricated joints of cast aluminium alloy (A413) is shown in fig.6.

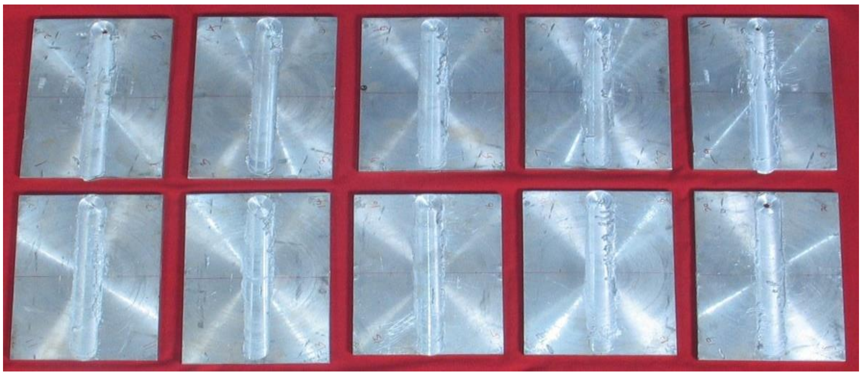
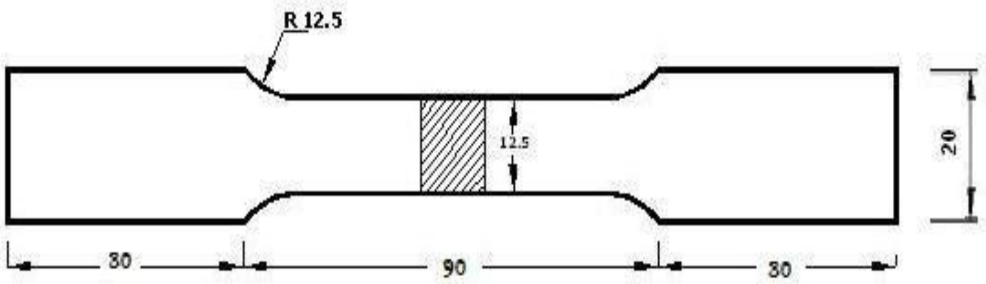


Fig.6: Photographic view of some of the fabricated joints of cast aluminium alloy (A413)

Specimen Preparation for Testing:

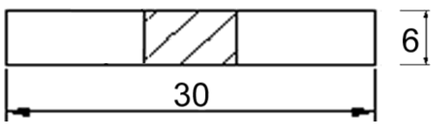
Tensile specimen: The welded joints were sliced in the transverse direction using power hacksaw and then machined to the required dimensions to prepare tensile specimens as shown in fig.7 (a). American Society for Testing and Materials (ASTM-E8M-04) guidelines were followed for preparing the tensile test specimens.

Hardness and Microstructure specimen: The specimens were sectioned to the rectangular size of 30mm × 30mm × 6mm as shown in fig.7 (b) from traverse direction of the weld region of the joint and polished using different grades of emery papers. Final polishing was done using the diamond compound (1μm particle size) in the disc polishing machine. Specimens were etched with Keller's solution to reveal the macro and microstructures.



All dimensions are in mm

(a) Dimensions of tensile test specimen



(b) Dimensions of hardness andmicrostructure specimen

Fig.7: (a) & (b)

Results and Discussion:

Effect of Tool Rotation Speed: Tool rotation speed appears to be the most significant process variable since it also tends to influence the translational velocity. Higher tool rotation speed resulted in a higher temperature and slower cooling rate in the FSP zone after welding. Five joints was fabricated from A413 cast aluminium alloy by varying the tool rotation speed and keeping welding speed and axial force constant.

Table 4: FSW process parameters used to fabricate the joints

Alloy		Tool rotation speed (rpm)	Welding speed (mm/min)	Axial force (kN)	Heat input* (kJ/mm)
A413	Joint 1	700	72	4	0.1758
	Joint 2	900	72	4	0.2261
	Joint 3	1100	72	4	0.2767
	Joint 4	1300	72	4	0.3266
	Joint 5	1600	60	5	0.6029

Welding speed = 72 mm/min Axial force = 4 kN

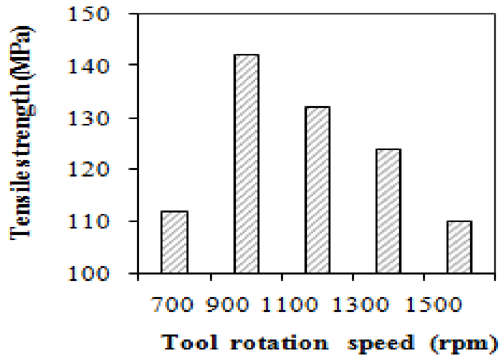


Fig.8: Effect of tool rotation speed on tensile strength of A413 cast aluminium alloy

Welding speed = 72 mm/min Axial force = 4 kN

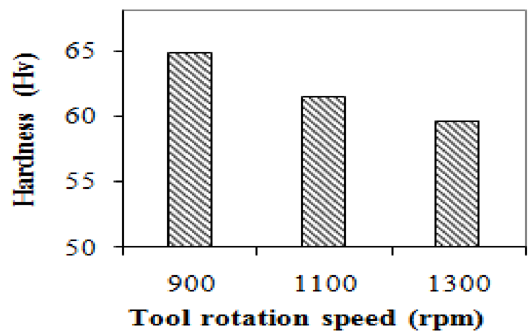
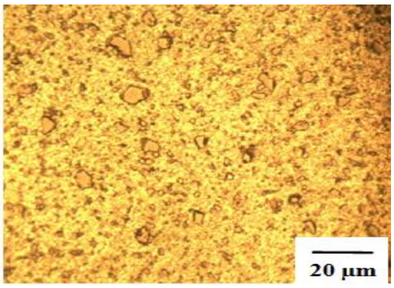


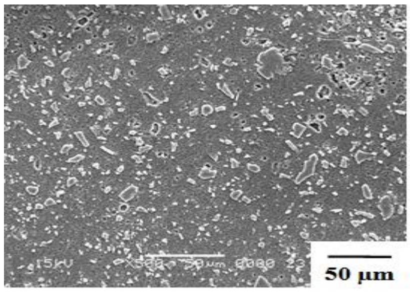
Fig.9: Effect of tool rotation speed on hardness of weld zone

Optical Micrograph

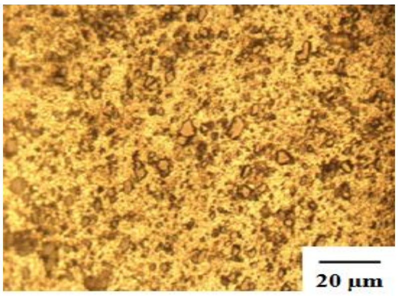


(a) 900 rpm

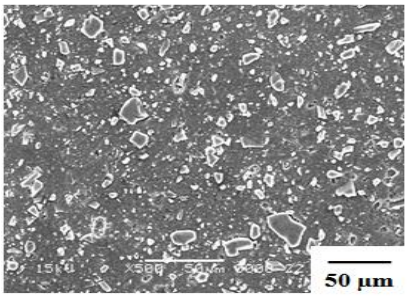
SEM Micrograph



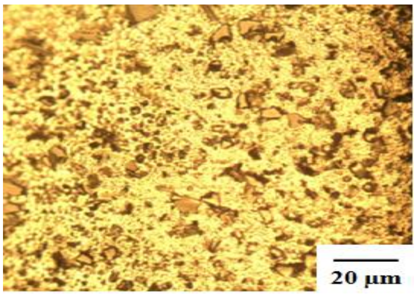
(d) 900 rpm



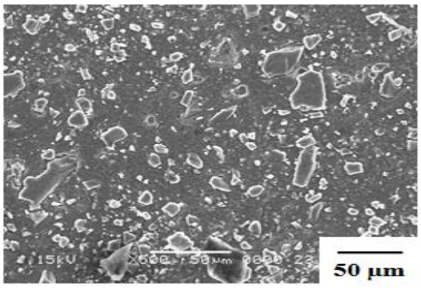
(b) 1100 rpm



(e) 1100 rpm



(c) 1300 rpm



(f) 1300 rpm

Fig.10: Effect of tool rotation speed on weld region microstructure of A413 alloy

So, we can say that the effect of tool rotation speed on tensile strength, hardness and microstructure of friction stir welded A413 cast Al-Si alloys was analysed in detail. In this investigation, a tool rotation speed of 900 rpm for A413 found to be optimum to get maximum tensile strength of FSW joints. Defect free weld region with very fine, uniformly distributed particles are the reasons for higher hardness and superior tensile strength of these joints.

Effect of welding speed: The welding speed has a strong impact on productivity in streamlined production of friction stir welding of aluminium alloy. Thus, the tensile strength of as welded aluminium alloy has a proportional relationship with welding speed. Higher welding speeds are associated with low heat inputs, which result in faster cooling rates of the welded joint. Five joints were fabricated from A413 cast aluminium alloy by varying the welding speed and keeping tool rotation speed and axial force constant.

Table 5: FSW process parameters used to fabricate the joints

Alloy		Tool rotation speed (rpm)	Welding speed (mm/min)	Axial force (kN)	Heat input (kJ/mm)
A413	Joint 1	900	12	4	1.3565
	Joint 2	900	24	4	0.6782
	Joint 3	900	48	4	0.3391
	Joint 4	900	72	4	0.2261
	Joint 5	900	96	4	0.1696

Tool rotation speed = 900 rpm   Axial force = 4 kN

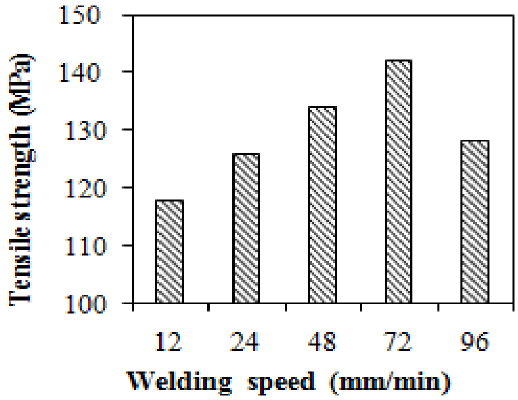


Fig.11: Effect of welding speed on tensile strength of cast aluminium alloys

Tool rotation speed = 900 rpm   Axial force = 4 kN

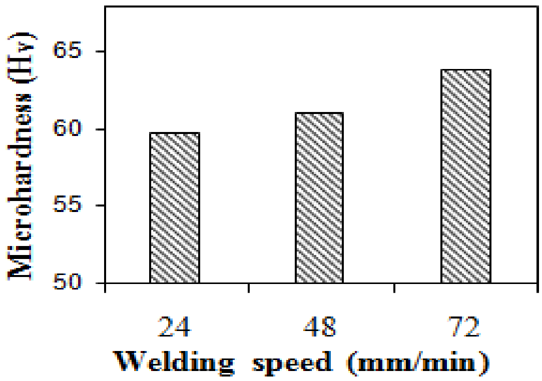
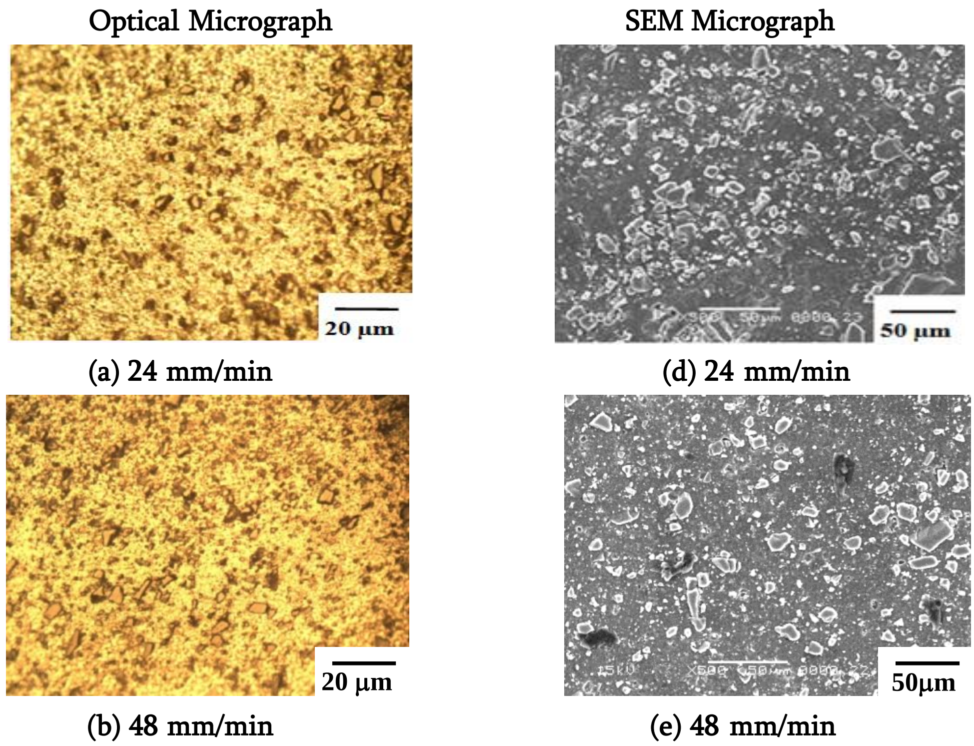
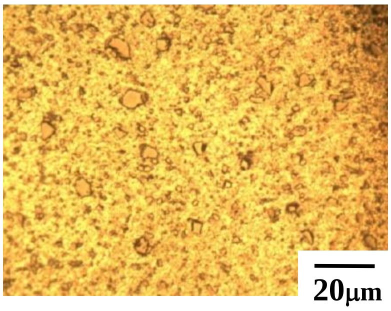
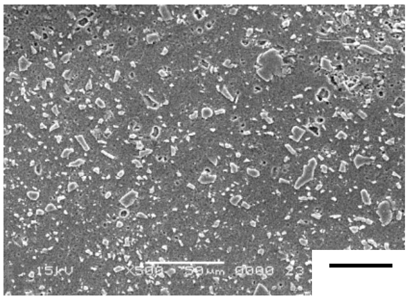


Fig.12: Effect of welding speed on hardness of weld zone







(c) 72 mm/min (f) 72 mm/min

Fig.13: Effect of welding speed on weld region microstructure of A413 alloy

So, we can say that the effect of welding speed on tensile strength, hardness and microstructure of friction stir welded A413 cast Al-Si alloys was analysed. It is found that the joint fabricated at a welding speed of 72 mm/min exhibited higher tensile strength in A413 alloy.

Effect of Axial Force: The load characteristics associated with a linear weld have focused upon the forces exerted by the tool, especially the shoulder force that is directly responsible for the plunge depth of the tool pin into the workpiece. Five joints were fabricated from A413 cast aluminium alloy by varying the axial force keeping tool rotation speed and welding speed constant.

Table 6: FSW process parameters used to fabricate the joints

Alloy		Tool rotation speed (rpm)	Welding speed (mm/min)	Axial force (kN)	Heat input (kJ/mm)
A413	Joint 1	900	72	2	0.1130
	Joint 2	900	72	3	0.1696
	Joint 3	900	72	4	0.2261
	Joint 4	900	72	5	0.2826
	Joint 5	900	72	6	0.3391

Tool rotation speed = 900 rpm Welding speed = 72 mm/min

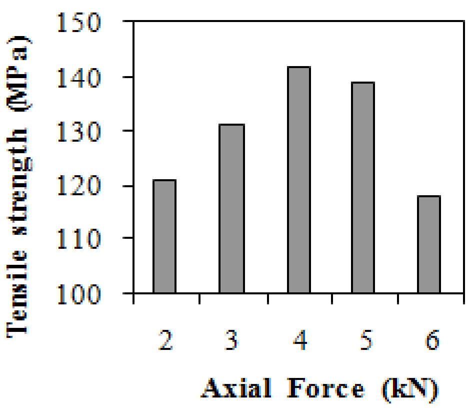


Fig.14: Effect of axial force on tensile strength of cast aluminium alloy

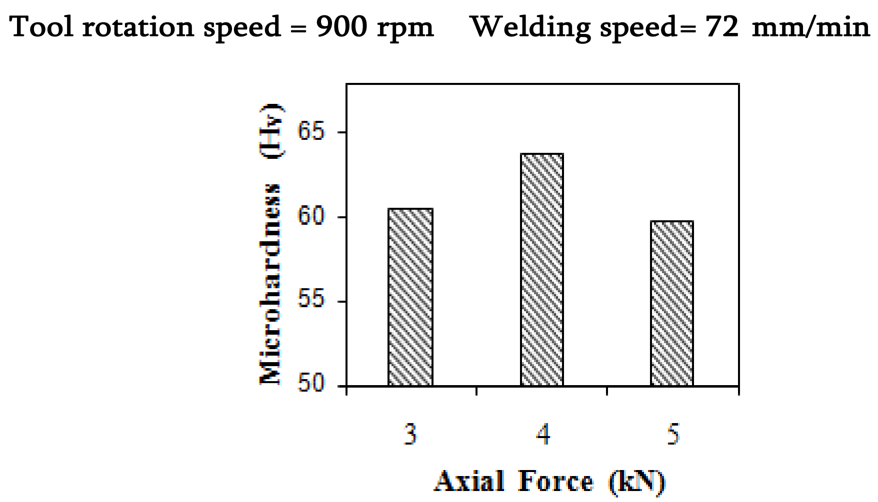
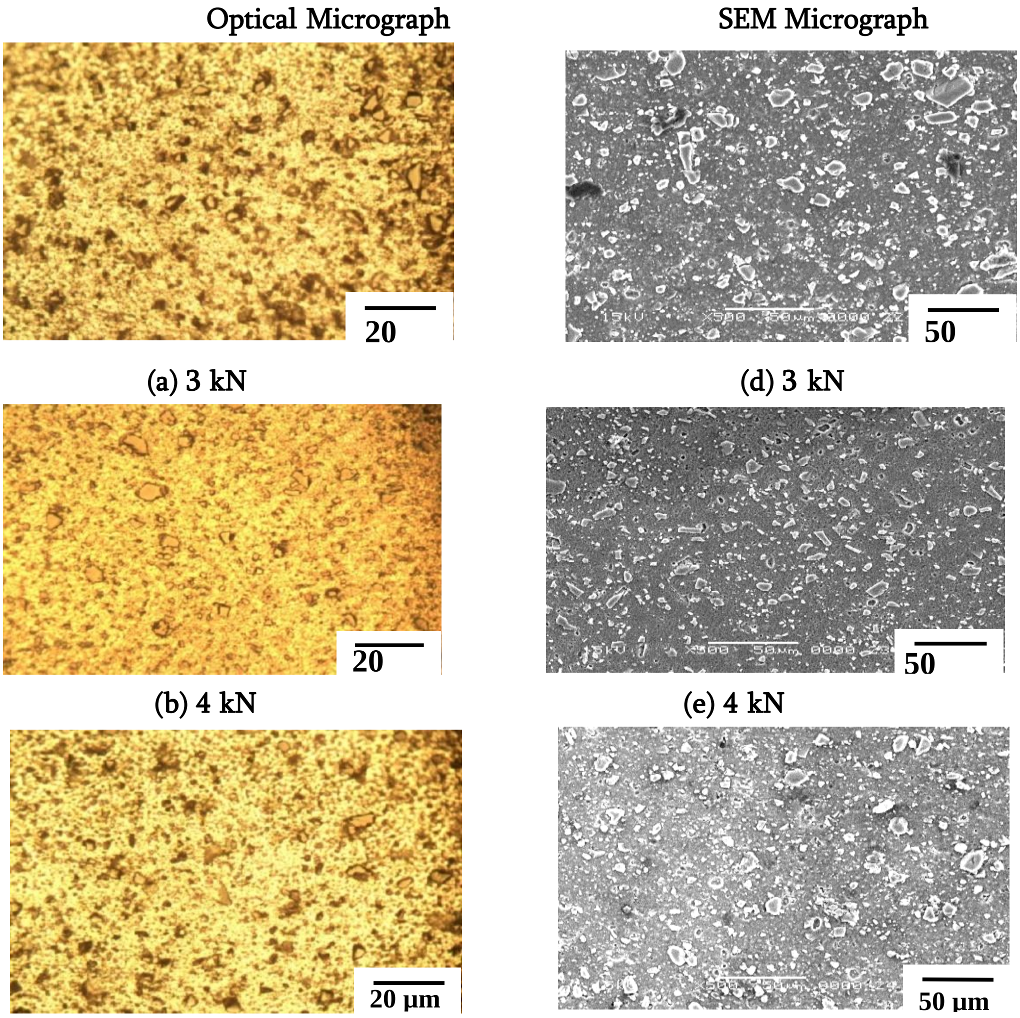


Fig.15: Effect of axial force on hardness of weld zone



(a) 3 kN (d) 3 kN

(b) 4 kN (e) 4 kN

(c) 5 kN (f) 5 kN

Fig.16: Effect of axial force on weld region microstructure of A413 alloy

So, we can say that the effect of axial force on tensile strength, hardness and microstructure of friction stir welded A413 cast aluminium alloys was analysed. It is found that the joint fabricated using an axial force of 4 kN exhibited higher tensile strength in A413 alloy.

Optimization of FSW Process Parameters: Tool rotation speed (N), welding speed (S) and axial force (F) are the independently controllable important process parameters of FSW process. These are the primary process parameters contributing to the heat input and subsequently influencing the mechanical and metallurgical properties of friction stir welded aluminium alloy joints. To obtain the desired strength, it is essential to have a complete control over the process parameters to maximize the tensile strength on which the quality of a weldment is based. Therefore, it is very important to select and control the welding process parameters for obtaining maximum strength.

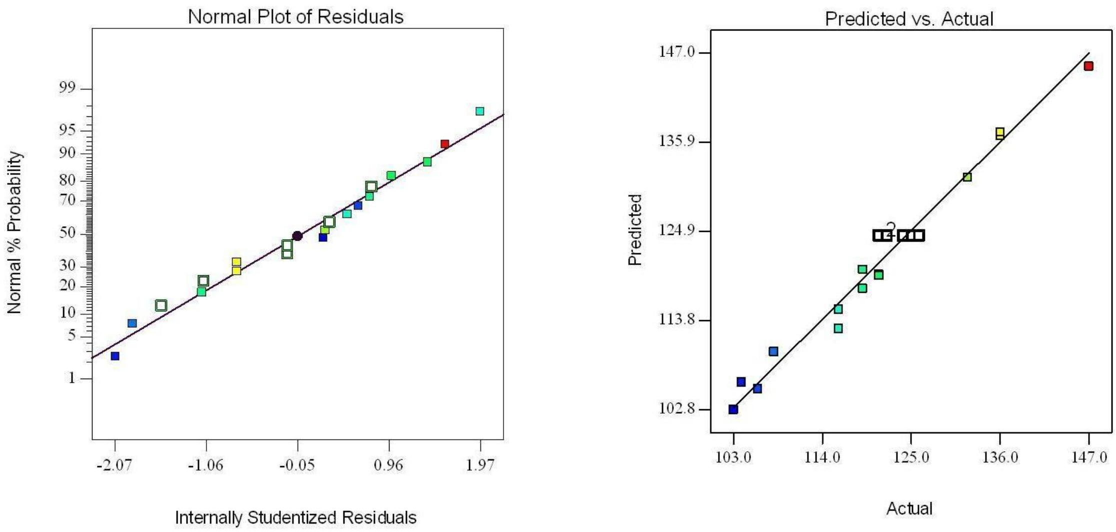


Fig. (a): Normal probability plots of A413 alloy **Fig. (b):** Correlation graphs of A413 alloy

Fig.17: (a) & (b)

Table 7: Optimized process parameters for A413 alloy

S.No	Parameters	Unit	Optimized Values	Tensile Strength (MPa)
1	Tool rotation speed (N)	Rpm	900	148.79
2	Welding Speed (S)	mm/sec	70	
3	Axial force (F)	kN	4	

IV. CONCLUSION

The conclusions derived from this experimental investigation are presented below.

- In this investigation an attempt was made to weld cast aluminium alloy A413 using indigenously designed and developed friction stir welding machine and the effort was very successful.
- The FSW joints fabricated using a tool rotation speed of 900 rpm in A413 alloy showed higher tensile strength compared to other joints.

- The FSW joints fabricated at a welding speed of 72 mm/min in A413 alloy yielded higher tensile strength than other joints.
- The joint fabricated using an axial force of 4 kN in A413 alloy exhibited higher tensile strength compared to other joints.
- The formation of defect free weld region along with the fine and uniform distribution of strengthening particles under the above conditions may be responsible for attaining higher hardness and tensile strength in the respective joints.
- FSW process parameters were optimized using response surface methodology to attain maximum tensile strength. There is a good agreement between experimental values and predicted values.

V. Future Scope

The study could be extended for the cast aluminium alloy by considering other process parameters, which include tool material, tool pin profile and shoulder design. The effect of post weld heat treatment on mechanical and metallurgical properties of cast aluminium alloy could also be explored.

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