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Friction stir welding of aluminum alloy and the effect of parameters on weld quality- A Review

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Abstract

Friction stir welding (FSW) is a relatively new solid state joining process that uses a non-consumable tool to join two different materials without melting the work piece material. The heat is generated by friction between the rotating tool and work piece material, this joining process is energy efficient, environmental friendly and versatile. FSW was developed for microstructural modification of metallic material This Review paper present the overview of the effect of FSW mechanism responsible for the formation of weld, microstructure refinement, wear of FSW tool and other mechanical properties.
Keywords: Surface modification,Tool rotation speed (TRS), Welding speed (WS), Ultimate tensile strength (UTS)

1. Introduction

Friction stir welding is a type of solid state welding technique in which the metal is joined without melting. Friction stir welding process was invented in 1991 by a welding institute named TWI (The Welding Institute). It is a novel welding technique in which a rotation tool is used to produce heat required to join two metal pieces by friction between the workpiece and the tool. Tool used in friction stir welding consisting of some special features having a pin, shoulder and a shank. Rotating tool pin gets inserted in the paring line of the two pieces which are needed to join by friction stir welding. The friction between the tool pin and the work piece material produces the heat that soften the material and rotation of pin mix the soften material and joined them. The shoulder of the tool works as a cap for the material which is extruded out by the pin during welding and produce additional heat.

2. Literature Review

The literature consisting of the various works which is done by a various researchers for joining aluminium alloys by friction stir welding. Now a day's aluminium alloys are most widely used in the field of automobile, aerospace industries and marine industries because of their light weight and high strength. So welding of aluminium alloys by friction stir welding is a topic of interest for the researchers. This literature describes the effect of the various parameters on the weld quality and strength of joint of different aluminum alloys by friction stir welding.

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S. N	Year	Author	Title of paper	Work-Piece	Tool & type of joint	Input parameters	Output parameters	Finding
1	2003	Prado, R.A., Murr, L.E., Soto, K.F.& McClure, J.C.	Self-optimization in tool wear for friction-stir welding of Al 6061_/20% Al2O3 MMC	Al 6061 and 20% Al2O3	butt joint	welding speed , tool shape	Tool wear and the rate of wear	Result shows that tool wear decreases on increasing welding speed
2	2005	Fratini,L., Buffa,G.	CDRX modelling in friction stir welding of aluminium alloys	AA 6082-T6	butt joint		strain, strain rate, temperature distribution	A linear regression based an inverse identification approach was used in order to develop the proper material characterization.
3	2012	Jonckheere,C., Meester,B.D., Cassiers,C., Delhaye.,M., & Simar,A	Fracture and mechanical properties of friction stir spot welds in 6063-T6 aluminum alloy	AA 6063-T6		tool pin diameter, plunge rate	fracture, weld lap shear strength	A hooking effect at the tip of the natural notch existing in spot welds, as well as joint line remnants distributed along the thermomechanical affected zone and through the weld, was observed on non-broken samples
4	2012	Liu, H. J., Li,J.Q., Duan,W.J.	Friction stir welding characteristics of 2219-T6 aluminum alloy assisted by external non-rotational shoulder	AA 2219-T6		Non-rotational shoulder dia., welding speed	micro structure, hardness and tensile strength	Microstructures and Vickers hardness distributions showed that this new welding process is beneficial to improving the asymmetry and inhomogeneity, especially in the weld nugget zone. The maximum tensile strength was up to 69 % of the base material.
5	2007	Scialpi,A., De Filippis,L.A.C. , Cavaliere,P.(	Influence of shoulder geometry on microstructure and mechanical properties of friction stir welded 6082 aluminium alloy	AA6082		Shoulder geometries	transverse Tensile strength, microstructure	The investigation results showed that, for thin sheets, the best joint has been welded by a shoulder with fillet and cavity.
6	2011	Padmanaban,G ., & Balasubramani an,V.	An experimental investigation on friction stir welding of AZ31B magnesium alloy	AZ31B magnesium alloy	Square butt joint, highcarbon steel with threaded pin profile	tool rotational speed, welding speed, and axial force	Tensile properties microstructure and fatigue properties	Joints fabricated using a tool rotational speed of 1,600 rpm, a welding speed of 0.67 mm/s, and an axial force of 3 kN yielded superior tensile properties compared to other joints. Fatigue properties less than base metal.
7	2007	Zhang, H.W., Zhang, Z., & Chen, J.T.	3D modeling of material flow in friction stir welding under different process parameters.	AA 6061 - T6		tool rotation speed , welding speed and axial force	Material flow	It seems that there is a quasi-linear relation between the change of the axial load on the shoulder and the variation of the equivalent plastic strain. The material flow can be accelerated with the increase of the translational velocity and the angular velocity of the pin.

8	2006	Zhang, H., Lin,S.B., Wu,L., Feng	Defects formation procedure and mathematic model for defect free friction stir welding of magnesium alloy	AZ31 Magnesium alloy		welding speed and welding rate	to get the best conditions for defect-free weld	The pore firstly occurred near the welding line at relatively low welding speed, but move into advancing side and up part of the weld when continues to increase the welding speed. Faster the welding speed is, larger the pore is.
9	2008	Raghu Babu,G., Murti,K.G.K., Janardhana,G. R	An Experimental Study On The Effect Of Welding Parameters On Mechanical And Microstructural Properties Of Aa 6082-T6 Friction Stir Welded Butt Joints.	AA6082-T6	butt joint & HSS tool	tool rotational speed, welding speed, and axial force	tensile strength, hardness and microstructure	The tensile strength of the joint is lower than that of the parent metal. And it is directly proportional to the travel / welding speed.
10	2005	Heurtier,H., Jones, M.J., Desrayaud, C., Driver, J.H., Montheillet,F. & Allehaux,D.	Mechanical and thermal modelling of Friction Stir Welding	AA2024-T351	butt joint		strains, strain rates, and estimations of the temperatures and micro-hardness	The semi-analytical model can be used to obtain the strains, strain rates, and estimations of the temperatures and micro-hardness in the various weld zones
11	2011	Aval,H.J., Serajzadeh,S., & Kokabi, A.H.	Theoretical and experimental investigation into friction stir welding of AA 5086.	5086 aluminum alloy		Tool rotation speed , welding speed	Temperature distribution, yield & tensile effect.	Work-hardened and annealed conditions, can significantly affect the final microstructures and mechanical properties of welded alloy.
12	2016	Zhang Z., Xiao B.L. & Ma. Z.Y.	Enhancing mechanical properties of friction stir welded 2219Al-T6 joints at high welding speed through water cooling and post-welding artificial ageing	AA2219-T6		welding speeds, water-coolingand air-cooling conditions & post-welding artificial ageing	hardness of LHZs and tensile strength	A combination of high welding speed and post-welding artificial ageing is proven to be the optimal path to improving the mechanical properties of FSW2219Al-T6 joints, with a maximum joint efficiency of 91% obtained.
13	2015	Hsieha M.J., Chioua B.Y.C., Leea R.T.,	Friction stir spot welding of low-carbon steel using anassembly-embedded rod tool	low carbonsteel (SS400)	lap joint	Tool rotation speed, downward force	Thickness of upper/lower plate pair on the maximum interface temperature, failure load, bonded area and shear strength using the plain and AER tools.	The failure load fora 4 mm thick upper plate using the AER tool is still greater than that for a thinner plate using the plain tool. The strong bonding mechanism using the AER tool could be explained by diffusion reaction at a high interface temperature with a deep TMAZ.
14	2016	Guillo.M & Dubourg.L	Impact & improvement of tool deviation in friction stir welding: Weld quality & real-time compensation on an industrial robot	AA5754-H22	FSW tool made of H13 tool steel	Rotational speed, traveling speed, tilt angle		This paper shows that a robot with an embedded real time algorithm for the compensation of the lateral tool deviation can reproduce the same FSW quality as a gantry-type CNC system.

15		Baillie.P., S.Campbell.W. ,Galloway.A.,C ater.S.,Pherson. N.,	A Comparison of Double Sided Friction Stir Welding in Air and Underwater for 6mm S275 Steel Plate	S275 structural steel	DH36 steel,	travel speed, angular and longitudinal distortion	Tensile Strength , Micro-Hardness , Charpy Impact Toughness	It was also shown that underwater FSW has benefits compared to SAW and FSW in air. This was apparent in the distortion results where it was shown that FSW underwater significantly reduces angular and longitudinal distortion in the work piece.
16	2016	Nam N.D., Dai .L.T., Mathesh.M, Bian.M.Z.,Thu. V.T.H.	Role of friction stir welding - Traveling speed in enhancing the corrosion resistance of aluminum alloy	6061 aluminum alloy	SKD11 with a columnar shape and a narrower probe	welding speed	Potential dynamic and EIS studies	The study suggests that high quality and better characteristics of thin film on the surface results in high corrosion resistant alloy. This may be due to the homogeneous distribution of the impurities in the alloy by the FSW, on which homogeneous passive film was formed to enhance the corrosion resistance.
17	2009	Babu.S., Elangovan.K., Balasubramani an.V., and Balasubramani an.M.,	Optimizing Friction Stir Welding Parameters to Maximize Tensile Strengthof AA2219 Aluminum Alloy Joints	AA2219 aluminum alloy	Non-consumable tools made of high carbon steel	Tool pin profiles, tool rotational speed welding (traverse)	Tensile strength	A mathematical model has been developed here to predictthe tensile strength of friction stir welded AA2219 aluminium alloy joints with a 95 % confidence level.
18	2015	RAMBABU.G, BALAJI NAIK.D,et al	Optimization of friction stir welding parameters for improved corrosion resistance of AA2219 aluminum alloy joints	aluminium alloyAA221 9-T87	Non-consumable tools made of high carbon steel	tool profile (P), rotational speed (N), welding speed (S) and axial force (F)	Corrosion current,	A mathematical model was developed to predict the corrosion resistances of friction stir welded AA2219 aluminium alloy joints with 95% of confidence level. The model was developed by incorporating the welding parameters and tool profiles using statistical tools, such as design of experiments and regression analysis.
19	2015	Dongxiao.L.Ya ng.X.,Zhang.X. ,	Investigation of stationary shoulder friction stir welding of aluminum alloy 7075-T651	7075-T651 aluminum alloy	Butt joint	Tool rotational speed (rpm), Welding speed (mm/min)	Microstructural characteristics, welding process, Hardness and tensile strength	The low crack initiation energy in the heat affected zone (HAZ) can be attributed to both the presence of precipitates and the redistribution of constituent particles. The presence of precipitates in the HAZ was the major reason for the decreased tensile strength of SSFSW joint.
20	1999	Mishra. R.S ,Mahoney.M. W., McFadden S.X..,	High strain rate super plasticity in a friction Stir processed 7075 al alloy	6.35 mm thick 7075-T651 Al Alloy	Single pass FSP zone of 0.3 m length	traverse speed was 15 cm/min.	Strain rate, Tensile strength, optical microstructure.	The present results demonstrate the feasibility of friction stir processing to produce a microstructure amenable to high strain rate super plasticity in a commercial Al-alloy

21	2008	Elangovan.K., Babu.S., et al	Developing an Empirical Relationship to Predict TensileStrength of Friction Stir Welded AA2219 Aluminum Alloy	The rolled plates of 6 mm thickness, AA2219, size (300 mm× 150 mm)	Non-consumable tools, made of high-carbon steel were used	tool pin profiles Straight Cylindrical, Taper Cylindrical Threaded Square Triangular,	Yield strength,Ultimate tensilestrength, Elongation %, Vickers hardness (0.5 kg)	A mathematical relationship has been developed to predictthe tensile strength FSWed AA2219 joints by incorporating welding parameters and tool profiles using statistical tools such as designof experiments, ANOVA, and regression analysis.The joints fabricated using square pin profiled tool with a rotational speed of 1600 RPM, welding speed of0.75 mm/s, and axial force of 12 KN exhibited superiortensile properties compared to other joints.
22	2017	Husain Mehdi et al	Mechanical properties and microstructure studies in Friction Stir Welding (FSW) joints of dissimilar alloy- A Review	AA5083 and AA7022 Aluminium, CY16, WC Tool, alloys in single and multiple passes Thickness - 10mm	FSW tool made of H13 tool steel	2100 rpm and travel speed of 2.33 mm/s 650 rpm and a traverse speed of 203 mm/min Tool rotation rate of 300,700, 900 and 1100 rpm.	UTS XRD Microstructure Micro-Hardness	Grain structures had equiaxed and fine grains due to the recrystallization in the SZ while Nano-sized alumina particles distributed differently because of different stirring action. An average grain size as low as 1.46 μm was obtained for a particular process parameters setting.
23	2017	Husain Mehdi et al	Mechanical properties and microstructure studies in Friction Stir Welding (FSW) joints of dissimilar alloy- A Review	CY16, W-La, WC-411 tool	FSW tool made of H13 tool steel	350 rpm and 15 mm/min 2236 rpm to 1500 rpm	Mechanical Properties Wear Property Microstructure Macrostructure	Welding parameter such as tool rotation, transverse speed and axial force have a significant effect on the amount of heat generated and strength of FSW joints. Microstructure evaluation of FSW joints clearly shows the formation of new fine grains and refinement of reinforcement particles in the weld zone with different amount of heat input by controlling the welding parameter
24	2017	Husain Mehdi et al	Influences of Process Parameter and Microstructural Studies in Friction Stir Weldingof Different Alloys: A Review	CY16, W-La, WC-411 tool	FSW tool made of H13 tool steel	2236 rpm and travel speed of 2.33 mm/s 700 rpm and a traverse speed of 203 mm/min Tool rotation rate of 300,700, 900 and 1100 rpm.	Mechanical Properties Microstructure Macrostructure Wear Properties	The mechanical properties of welded joint by friction stir welding are largely dependent on the combined effect of both the composition of alloying element and processing parameter.

25	2013	Selvaraj.M.,Koteswara Rao.S, et al	Mechanism of Weld Formation during Friction Stir Welding of Aluminum Alloy	The rolled 6 mm thick plate 6061 of aluminium alloy were made into size of 150 x 75 x 6mm	1) Shoulder radius- 9 mm,2) Pin mean radius - 3 mm,3) Pin length - 5.5 mm,4) Pin taper angle - 10o,5) Normal load - 15.5 kN	Rotational speeds - 300 - 2000 rpm2) Welding velocities - 300, 600, 900, 1400 and 1800 mm/min.	Temperatures at different locations were measured using five K-type thermocouples embedded in the advancing side located at a distance of 4 mm, 7 mm, 10 mm, 15 mm and 25 mm from the center line of the weld, Effect Of WS And TRS On Weld Formation,	The process parameters for sound weld during FSW of aluminium alloy have been identified. The interface temperature range for defect free weld during FSW of AA6061 aluminium alloy is 400 – 525^{0}C. In the insufficient material flow zone, the defect size isfound to be inversely proportional to rotational speed whereas in the case of excessive material flow zone the defect size is directly proportional to rotational speed. As weldingvelocity increases, rotational speed is to be increased proportionally to form a sound weld. The relation between weld parameters, temperature, matrix movement and weld formation has been established
26	2011	Dehghani.K.,Mazinani.M.,	Forming Nanocrystalline Surface Layers in Copper Using Friction Stir Processing	The pure copper (99.9wt%) sheet of 3mm thick	An H-13 steel tool having the shoulder diameter of 16mm was used.As the sheet used for FSP was thin, no pin was used	The applied rotational and traverse speeds were 1600rpm and 50mm/min, respectively. These conditions resulted in the temperature of 600 ± 2 C during the FSP of copper.	Microstructural Evolutions Nanograin Formation during the FSP of CopperMicrohardness Profile through the Thickness	Nanograin layer about 90 m thick was formed on the surface of copper by FSP. The formation of equiaxed nanograins and ultrafine grains (with size of 50–200nm) during the FSP of copper can be attributed to the occurrence of both dynamic recrystallization and dynamic recovery. The significant grain refining by FSP resulted in almost three times increase in the hardness of nanograin layer. The changes in the hardness, from the top surface toward the center of workpiece, can be attributed to the temperature and strain gradient along the cross-section of the FSPed specimen. The surface nano-structuring can be of significant importance in terms of surface-dependent properties such as fatigue, wear, coating, and even corrosion
27	2010	Suresha.C., Rajaprakash.B. ,et al	A Study of the Effect of Tool Pin Profiles on Tensile Strength of Welded Joints Produced Using Friction Stir Welding Process	Rolled plates of AA7075-T6 aluminium alloy of 5mm thickness were used	Square butt joints. No consumable tools made of hot die steel 1) Square tool 2) conical tool	Tool rotational speed (900,1120,1400RPM), Welding speed (40,50,63mm/min) Plunge depth (4.93,4.96,4.99 mm)	Tensile strength, joint efficiency, and S/N ratio of conical tool and square tool	The welded joints produced by the conical tool show better joint efficiency when compared to the square tool. The percentage of contribution of these FSW process parameters were determined by ANOVA, and it was found that the tool rotational speed has a major contribution compared to weld traverse speed and plunge depth in the case of both conical and square tools. It has been also observed that in both the tool profiles, the tool rotational speed exhibits more influence on

								tensile strength than weld traversing speed (welding speed) and plunge depth, and that the tool having conical profile results in better joint efficiency than the tool having square profile
28	2012	Lukin.V .,Ioda.E.,et al	Friction stir welding of V-1469 high strength aluminium–lithium alloy	4-mm-thick blanks taken from the central zone of a35-mm plate of V-1469 alloy	The tool was made of R18 steel.butt joint	Welded joint: 130 mm/min; theangle of inclination of the tool a- 28; the speed ofrotation of the tool -1000 rpm.	FSW - single passFSW - quenching , artificial ageing FSW - two passes FSW - repair welding by manual argon-shielded arc welding	The experimental results show that the main type ofdefects are lack of fusion defects, associated withinsufficient mixing of the metal, especially in the rootpart of the welded joint, and cavities formed as aresult of overheating the welded metal. The results of investigations of the effect of the technology for repairing defects, formed in friction stir welding of V-1469 aluminum alloy (secondary pass, manual argon-shielded arc welding), and of the effect of heat treatment on the mechanical properties and nature of failure of the welded joints are presented.
29	2015	Amini.S.,Amiri .M.,	Pin axis effects on forces in friction stir welding process	friction stir welding on aluminum 5083with dimensions of 120 mm×60 mm×4 mm.	Four tools from AISIH13 have been used. Shoulder dia. - 18 mm, Pin dia. - 5.5 mm, angle - 9°, Pin height - 3.85 mm	Rotational speed - (560,900,1120, 1400rpm), Translational speed- (63,100 mm/min), Tool tilt angle - (1.5°)	Measured parameters include vertical force (in the direction of tool axis) and welding force (along the direction of welding)	The effects of tool shape on the above-mentioned parameters along with the changes of rotational speed have been considered in this research and results are as follows: The effect of the tool with offset pin on the decrease of vertical force and welding force (between 50 and 70 %) is more than the effect of the tool with concentric pin with the axis of tool shoulder on these forces. Tools with half pin and arched pin have more exerted forces than tool with offset pin and they have less exerted forces than tool with concentric pin.
30	2010	Surekha.K.,Els -Botes.a., et al	Development of high strength, high conductivity copper by friction stir processing	Pure Cu (600 * 200* 3 mm in size)	Non-consumable non-threaded tool made up of HSS. Shoulder dia 12 mm , Pin diameter - 5 mm^3) Length- 2.8 mm	Tool rotation speed - 300 rpm, Transverse speed- 50 ,100,150,200,2 50 mm /min	Microstructural characterization, Tensile test, hardness	The mechanical properties viz, the yield strength, ultimate tensile strength and the elongation increased in the processed samples compared to the base metal. The electrical resistivity of the processed samples was same as that of the base metal. The hardness of the processed sample was higher than the base metal (85 HV) at all parameters and the hardnessincreased from 102 to 114 HV with the decrease in grain size.

31	2012	Magdy. M. E.Ehab A. E.,	The influence of multi-pass friction stir processing on the microstructural and mechanical properties of Aluminum Alloy 6082	AA- 6082-T651 plates , 6mm thick	Tool material Mo–W tool steel Tool shoulder - 15mm diameter, and a concentric square pin with an edge length of 6mm, and 5mm long.	Tool rotational speed - 850 rpm, Transverse speed- 90,140,224 mm /min	Microstructural characteristics, Second phase particles, Mechanical characteristics, Influence of tool rotational speed on the mechanical and microstructural characteristics of the SZ	Hardness and tensile test results is that increasing the number of passes caused softening and reduction of the ultimate tensile strength, whereas, increasing the traverse speed increased the strength and hardness. FSP caused dynamic recrystallization of the stir zone leading to equiaxed grains with high angle grain boundaries which increased with increasing the number of passes. The accumulated heat accompanying multiple passes resulted in increase in the grain size, dissolution of precipitates and fragmentation of second phase particles. The parameter combination which resulted in highest ultimate tensile strength was further compared with additional two rotation speeds.
32	2014	Leon.J.,Jayakumar.V.,	Investigation of mechanical properties of aluminium 6061 alloy friction stir welding	The rolled plates of AA6061 aluminium alloys (300mm X 150mm)	Square butt joint A non-consumable, rotating tool made up of high carbon steel was used. Probe diameter is 6 mm, shoulder diameter is 18 mm and pin length is 5.5 mm.	The rotational speed was chosen as: 720, 910, 1120 and 1400 rpm while the traverse speeds were 16, 20, and 31.5 mm/min.	Macro and Microscopic Visual Examination Hardness, Tensile Properties	The weld root surface of all the weldments showed visually a well joined defect free sound flat surface. The increase in stir–probe rotation speed more than 1200 rpm enhanced the weld soundness which may be a result of softening process associated with dynamic recovery and recrystallization process at the weld. The formation of fine equiaxed grains and uniformly distributed, very fine strengthening precipitates in the weld region are the reasons for the superior tensile properties of FSW joints. From this investigation it was found that the joint made from the FSW yielded superior tensile properties and impact strength due to the higher hardness and fine microstructure.
33	2014	Sanderson.S., Mahoney.M.,Fleck.D.,	Friction Stir Welding of Line-Pipe Steels	The pipeline steels used herein included both X52 and X65 carbon steel	Q70 is pcbn ceramic based (70 wt/% cBN) with a metal WRe (30 wt/%) binder. Sacrificial Anvil.	Weld parameters selected for the pipe welds included a tool rotation rate of 275 rpm at 1.7 mm/sec (4ipm) with variable normal load.	Metallography Bend Tests	Friction stir weld studies completed on 32 cm (12.75 inch) diameter X52 and X65 pipeline steels using both 6 mm (0.25 inch) and 12 mm (0.5 inch) wall thickness, have demonstrated the ability to achieve consistent full penetration welds when using sacrificial anvil. Metallography illustrates the remnants of a lazy-S remnant of the prior faying surfaces but this "flaw" did not open or fail during a root bend test.

34	2016	Emamian.,s et al	Influences of tool pin profile on the friction stir welding of aa6061	AA6061-T6	Tool steel H13	Tool rotational speed (SS) - 800,1200,1600 rpm, Welding speed (WS) 40,70,100 mm/min, pin profiles: cylindrical, conical (C), & square (S)	Tensile Strength, Thermal Cycle	Increasing the welding speed will effect on tensile properties. Threaded shape is effectiveness on mechanical properties. Differences between peak temperatures of samples welded by different pin profiles are very little and not significant. However, square pin profile produced higher temp.
35	2014	Krishna.G.G., et al	Effect of Tool Tilt Angle on Aluminum 2014 Friction Stir Welds	aluminium AA2014-T4 alloy of 5mm thick	die steel (AISI – H13)	Tool shoulder diameter (15mm), Pin dia (4.5mm), Spindle speed 800 rpm, Traverse speed 100 mm/min, Tilt angle 0.5º, 1º, 1.5º, 2º, 2.5º and 3º	Macro and Microstructure, Force and Torque analysis, Temperature Analysis	High tool tilt angle of around 3º is recommended for welding AA 2014 aluminium alloy for the given value of feed 100 mm/min and speed 1000 rpm to get defect free welds. Defects are formed on the surface and inside the weld due to lack of filling at lower tilt angles.
36	2010	Arora.A.,et al	Toward optimum friction stir welding tool shoulder diameter	AA6061 alloy	die steel (AISI – H13)	Shoulder diameter (mm) 15, 18, 21, Pin diameter (mm) - 6, Pin length (mm) - 5.5, Pin profile Cylindrical, no thread, Tool Rotational velocity (rpm) - 900-1500	Mechanical properties Yield strength (MPa), Ultimate tensile strength (MPa)	The optimum tool shoulder diameter computed from this principle using a numerical heat transfer and material flow model resulted in best weld metal strength in independent tests and peak temperatures that are well within the commonly encountered range.
37	2015	Baillie.P.	Friction Stir Welding of 6mm thick carbon steel underwater and in air	S275 hot rolled structural steel	Hybrid WRe-pcBN, Q70 (70 vol % cBN)	Travel speed- 100 (mm/min), Speed of rotation 200 (revs/min). FSW Travel speed- 100 (mm/min) Speed of rotation 240 (revs/min)	Distortion, Macrostructure, Microstructure Mechanical Properties Tensile Strength , Fatigue ,	Between the processes the longitudinal tensile results are the same, the micro hardness does not vary. It was also shown that underwater FSW has benefits compared to SAW and FSW in air. Charpy impact toughness was however shown to decrease for the underwater weld. Within the available data it is difficult to fully explain the toughness difference as the relative grain sizes do not vary significantly. The potential difference may lie in fine scale differences in the microstructures.

38	2013	Panneerselvam .K., et al	Study on friction stir welding of nylon 6 plates	Nylon 6 Thickness - 10mm	tool made - mild steel	Tool shoulder dia (24mm), Pin dia (6mm), Tool pin length (9.5mm), Tool rotating speed (rpm) 750 to 4000, Welding Feeds 10- 100 mm/min.	Mechanical Properties:- Tensile Strength Elongation/%	By using secondary heat sources with 0.5 or 0.6mm gap provision in between shoulder and top of the workpiece is the optimal gap to weld the nylon 6 material without any visible defects. When fixed welding speed in between 600 and 1200 rpm and feed rate also in between 10 and 40mm/min, got good weld region compared with the other feed and speed rate.
39	2014	De.A., et al	Friction stir welding of mild steel: tool durability and steel microstructure	C–Mn 1018 steel	HSLA 65 steel	Tool rotational speed 300, 450, 600, 750, 900 rev/min, Welding speed - 0.42 , 1.05, 2.10 mm/s, Tool shoulder diameter (mm) 15, 18, 21, 24 Pin diameter (mm) 7.9, 9.0 Tool pin length (mm) - 9.5	Microstructure Tool durability index	For the FSW of mild steel, an increase in either the tool shoulder diameter or the tool rotational speed increases workpiece temperature and hence, enhances tool durability. A faster welding speed reduces peak temperature, increases stresses on the tool and thus, reduces tool durability. In contrast, thicker tool pins increase tool durability because of enhanced structural stiffness.
40	2013	Sato.Y.S., et al	Evaluation of microstructure and properties in friction stir welded superaustenitic stainless steel	NSSC 270 superaustenitic stainless steel Thickness - 6 mm	Polycrystalline cubic boron nitride tool (PCBN),convex scrolled shoulder step spiral (CS4)	Rotational speed400 and 800 rev min, Traverse speed - 1.0 and 0.5 mm /s	Microstructure Mechanical properties :- Corrosion properties	Findings of the present study suggest that low heat input friction stir welding is an effective method to produce a weld with relatively good properties in superaustenitic stainless steels. The high rotational speed drastically reduced mechanical and corrosion properties of the weld due to the high density of intermetallic phases, while the reduction of the properties was not significant at low rotational speed.
41	2017	Ramesh.R., et al	Microstructure and mechanical characterization of friction stir welded high strength low alloy steels	High strength lowalloy HSLA plates Thickness - 3 mm	Tungsten-rhenium alloySquare butt	Tool shoulder diameter 18 mm. Tool pin length 2.7 mm. Pin profile was tapered cylindrical with a dia 8 mm) Traverse speed 57, 67, 77,87mm/min	Macrostructure of welded joints, Microstructure of welded joints, Mechanical properties	The joint strength was 540 MPa at 57 mm/min and 407 MPa at 97 mm/min. The higher strength below 78 mm/min traverse speed was due to hard weld nugget. The lower joint strength with further increase in traverse speed was due to poor consolidation and macroscopic defects. The tendency to form macroscopic defects increased with increase in traverse speed. Root flaw and groove defect were observed at a traverse speed of 97 mm/min.

42	2013	Gan.W., et al	Tool materials selection for friction stir welding of L80 steel	High strength pipe steel L80	Commercial pure tungsten	Tool Travel speed 1.7 mm/s. Tool Rotational speed 170 rev/min, Pin length 1.5 mm	Thermal couple, Thermal analysis, Mechanical analysis	The results indicate that the physical wear amounts to a material loss of 7% of the original volume. Mushrooming of the tool was successfully predicted. The calculations also indicated that the pin tool material should have a yield strength larger than 400 MPa at 1000uC to avoid mushrooming.
43	2013	Bahrami.M., et al	On the role of pin geometry in microstructure and mechanical properties of AA7075/SiC nano-composite fabricated by friction stir welding technique	7075-O Aluminum Alloy Thickness - 6 mm	H13 Tool steel	Tool rotational speed 1250 rpm, Tool traverse speed 40 mm/min, Pin profile Threaded tapered (TT) diameter - 6 & 4 mm, Triangular (T) dia 6 mm, Square 6 mm.	Macrostructural studies, Macrostructural studies, Material flow in the stir zone. Tensile properties (i) UTS (MPa), % elongation, Grain size (lm) SiC cluster size (nm), Average micro hardness value (Hv), Fractography, Hardness	The most uniform particle distribution was found in the case of using threaded tapered pin tool. Reinforcements had severely accumulated in the SZ of specimen friction stir welded (FSWed) with four-flute cylindrical pin tool. Moreover, threaded tapered and four-flute cylindrical specimens showed the highest and the lowest micro hardness, respectively. Highest ultimate tensile strength (UTS) was recorded for the specimen FSWed with triangular pin tool.
44	2013	Bahrami.M., et al	A novel approach to develop aluminum matrix nano-composite employing friction stir welding technique	7075-O Aluminum plate Thickness - 6 mm	H13 hot working steel	Tool shoulder diameter - 16 mm, Threaded taper pin profile height - 5.7 mm, Tool Rotational speed - 800, 1000,and 1250 rpm, Traverse speed -30.5, 40, and 50 mm/min.	Microstructural observation, Mechanical properties (Tensile properties, Fractography, Hardness)	7075 Aluminum matrix Nano-composite reinforced with SiC particles was developed in the stir zone. At high rotational speed (1250 rpm) powder dispersion improved due to effective stirring action of the pin. UTS of specimen FSWed with powder at 1250 rpm and 40 mm/min was 31% superior to that of the specimen FSWed without powder. The addition of SiC particles led to 76.1% enhancement of elongation.

3. Conclusions & Recommendations

1. The surface composite layer of Nano reinforcement particles by friction stir processing on magnesium alloys improves tensile behavior, hardness, corrosion resistance, percentage and wear resistance behavior of the workpiece material.
2. The friction stir processing with multiple passes could effectively cure the onion premature splitting by accumulating a higher degree of strain and the initial grains gets fully recrystallize and to improve the microstructure.
3. Increasing the tool rotational speed results greater heat input and increases grain size of the metal alloy and simultaneously more shattering effect of rotation, results a better distribution of nano particles.
4. Water cooling durin friction stir welding on magnesium MZ91 enhances the hardness and reduces the final grain size, while the amount of oxide particles in the processed area increases.

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