International Journal of Research in Engineering and Innovation (IJREI)
journal home page: http://www.ijrei.com
ISSN (Online): 2456-6934

Effect of process parameters using friction stir processing /welding of steel- a review

R.S. Mishra, Tanusha
Department of Mechanical, Production & Industrial and Automobiles Engineering
Delhi Technological University Delhi
E Mail: rsmishra@dce.ac.in, tanushadtu.96@gmail.com

Abstract

Microstructural changes and flow of material have be comprehensively studied by many researchers. A lot of studies have been conducted by changing the process parameters such as axial load, feed, speed of the tool, tool geometry, tool tilt angle etc. to find the optimum process parameters. Friction stir welding can be applied on various materials such as aluminum, manganese, copper. Till date majority of the research and development was done on aluminum alloys. This is so because Al alloys are easy to deform at relatively low temperatures (approximately below 550 Celsius). Also, they are easier to weld as compared to other materials. But these days a lot of studies are being conducted on carrying out friction stir processing on steel. This process improves mechanical properties like tensile strength, ductility, micro-hardness etc.

Keywords: Micro-structure, Tensile strength, Micro-hardness, FSP, Steel

1. Introduction

Friction stir processing (FSP) is a process of modifying the microstructure of a metal by intense and localized heating leading to plastic deformation. The tool used consists of non-consumable tool having a pin and shoulder of a predefined diameter. The tool is made to revolve in a stirring motion and transverse motion is then provided to the tool. FSP can be performed in multiple passes. Multi-pass FSP has a certain number of overlap generally half the diameter of the pin between successive passes which is required for large contact areas. It leads to localized heating of the work piece till plastic deformation due to friction between the tool and the work piece. This leads to refinement of grain structure. The size of the particles decreased significantly thereby enhancing mechanical properties such as tensile strength and ductility. However it does not change the physical state of the material while changing the physical properties.

This is a two steps process, i.e., first localized heating and then material flow. Whereas heat treatment is a multistep process including heating to recrystallization temperature and then quenching. This helps in increasing ductility and improves corrosion and wear resistance properties. FSP is majorly used for various cast aluminum and magnesium and copper alloys however it is been now employed to modify steel also.

It offers advantage over heat treatment and other modes of strengthening as it does not produce any by-products which may be toxic. It is the most environment friendly and sustainable form of processes. This is an upcoming and promising process for the aerospace, aviation and automobile industry as it helps enhance mechanical properties of the alloys as well as pure metals of aluminum, copper, manganese and even steel.

The varied research work done by scientists and authors regarding the effect of FSP parameters including tool geometry, rotational speed, axial load, tool tilt angle etc. has been taken into consideration for this review study.

2. Literature Review

The following is a review of the published data on the effects of process parameters such as rotational speed, tool tilt angle, feed, load, tool geometry etc. on steel by friction stir processing (FSP).The table below gives the details considered by various authors and their conclusion.

Corresponding author: R.S.Mishra
Email Address: rsmishra@dce.ac.in

S.No.	Author	Material Used	Tool Used	Parameters	Conclusion
1.	Z. Feng, M. L. Santella, and S. A. David	Two uncoated AHSS steels were used. One of 600MPa strength (DP600) and other 1310 MPa strength (M190).	Single tool of polycrystalline cubic boron nitride. Tool pin height 2mm and shoulder diameter 10mm.	For all experiments tool rotation speed was kept constant at 1500 rpm. Tensile test and shear test conducted with specimens 38.1-mm width and 127-mm length and cross section 50.8-mm width and 152.4-mm length.	It produced approximately a hundred welds without noticeable wear. The TMAZ section showed similar microstructure and micro-hardness as in the base metal for both steels under study. The M190 steel showed significant softening. Tensile strength reduced significantly for both the steels. While the joint strength for both the steels increased.
2.	H. K. D. H. Bhadeshia and T. DebRoy	Multiple tools of different studies	Multiple tools of different studies	Different studies	Joining is a problem for steel which cannot be tackled using conventional techniques. Thus adaptation of this process for steel in industry is a bit difficult especially in under water joining in case of underwater pipelines. Tool wear during the process also processes problems for its strength and hardness.
3.	Y.S. Sato , T.W. Nelson , C.J. Sterling , R.J. Steel , C.-O. Pettersson	SAF 2507 super duplex stainless steel of thickness 4 mm , 300 mm length, 100 mm width.	PCBN friction stir welding tool with shoulder diameter 25 mm and pin height 3.8 mm.	Atmosphere of argon was introduced through a gas chamber at the tool flow rate of 2.8 × 105 mm3/s. Tilt angle was kept at 3.5 degrees. Rotational speed was kept at 450 rpm and feed at 1mm/sec. Micro-structure and Vickers hardness test were conducted at 9.8N load.	Increased the weld ability of the material. The ferrite and austenite phases were refined through dynamic recrystallization. Increased hardness and strength in stir zone was observed. The ultimate tensile strength was roughly the same as that of the base metal.
4.	H.S. Grewal, H.S. Arora, H. Singh, A. Agrawal	Hydroturbine steel, 13Cr4Ni was used for the analysis. Sample size 80 mm × 40 mm × 5 mm was chosen. All samples were grinded to ensure flatness.	Tool chosen was tungsten carbide with pin diameter 4mm and pin height 0.5 mm. Electron polishing machine was chosen.	The specimens after processing were methanol quenched at kept at -20 degree Celsius. Rotation speed was kept at 2500 rpm, feed at 20mm/sec. Tool pressure was 0.3mm.	Microstructure was redefined consisting of ultrafine and sub-micron grains and large carbide particles were disintegrated. About 2.6% improvement in micro-hardness. Greater resistance to cavitations erosion. Fatigue was observed in the base metal at the time of processing. Increased ductility when compared to the base metal.
5.	Yutaka S. Sato, Tracy W. Nelson , Colin J. Sterling	304L austenitic stainless, hot rolled, with thickness 6.4mm.	PCBN tool with shoulder diameter 25mm, pin height 3.2 mm. Pin tapered from 9mm (shoulder) to 7mm (pin).	Surface polished by 80 grit emery cloth. Atmosphere of argon was introduced through a gas chamber at the tool flow rate of 2.8 × 105 mm3/s. Tilt angle was kept at 3.5 degrees. Rotational speed was kept at 450 rpm and feed at 2mm/sec.	Initially undergoes dynamic crystallization, at the time of intense deformation and heating, the undergoes static recrystallization in those regions of high dislocation densities. Increased hardness and strength in stir zone was observed. The ultimate tensile strength was roughly the same as that of the base metal.

6.	Hidetoshi Fujii, Rintaro Ueji, Yutaka Takada, Hiromoto Kitahara, Nobuhiro Tsuji, Kazuhiro Nakata and Kiyoshi Nogi	Ultra-low-carbon IF steel of thickness 1.6mm , length 300mm,width 30mm for the experiment.	Accumulative roll-bonding (ARB) process was applied to get ultra-refined grain structure. Tool made up of tungsten carbide with shoulder diameter 12 mm, pin diameter 4mm, pin height 1.4mm.	Multiple pass was used 5 times.Samples were annealed at 600 degree Celsius.Samples were butt welded using fsw machine. Tool tilt angle was kept at 3 degree, rotation speed 400 rpm. Argon shielding gas was used during welding.	It decreased the mean size of the grains from 24.2 to 0.7 µm. The hardness of the stir zone increased with the decrease in the grain size. The steel with grain size of approximately 1.8 µm gives highest hardness.
7.	Nhon Q. Vo, David C. Dunand, David N. Seidman	Al 4.1, Mg 0.47 Sc 0.022 Zr 0.041 Ti 0.15 Fe 0.043 Si by %wt.	Pin height 2.2 mm,pin diameter 3.75mm at the tip and 6mm at the shoulder. Shoulder diameter 12mm.	Varied rotational speed i.e. 325 rpm and 400 rpm. Transverse speed 3.4 mm/sec. Tool tilt angle 2.5 degree. Load applied at 300gm/10sec. SEM machine used to record results.	Increased strength up to 1350±35MPa (maximum) because of strengthening of grain boundary.
8.	Y. Morisadac, H. Fujii, T. Mizuno, G. Abe, T. Nagaoka, M. Fukusumi	Tool steel	Tool made up of tungsten carbide. Conical shape with column diameter 12mm and probe diameter 4mm and probe height 0.5mm.	Multi pass heating conducted. Rotational speed was kept at 400rpm. Overlap between the passes was 0.3mm. Tool tilt angle 3^o. Crystal structure after FSP was identified by XRD. Micro-hardness measured by Vickers micro-hardness tester with a load of 300g.	There were no coarse carbide particles in the FSP zone. Increase in micro-hardness from 260 to 473HV. Particle size reduced to less than 1µm.
9.	H Schmidt, J Hattel and J Wert	Two aluminium plates with 3mm thickness,60mm width,150mm length.	2043 T3 heat treatable alloy with shoulder cone angle of 10^o. Pin diameter 6mm and pin height 2.5mm.	Rotational speed 400 rpm.Feed was kept at 120mm/min. Tool tilt angle 1^0	Heat generation equation is proposed.
10.	A.P. Reynolds, Wei Tang, T. Gnaupel-Herold, H. Prask	304L stainless steel Composition: 0.03C, 2 Mn, 0.75 Si,8-12 Ni,18-20 Cr,0.1 N,0.03 S,0.045 P, balance Fe. Plate dimensions 305mm X102mm X 3.2mm.	Tungsten alloy tool of shoulder diameter 19mm.	Rotational speed of 300 rpm and 500 rpm. For tensile strength width, thickness and gauge length were 4mm, 3mm and 50mm.	Residual stress pattern were similar to fusion welding. With 500 rpm grain size was 13µm and with 300 rpm grain size was 7.6µm. Thus with reduction of rotational speed the grain size reduces.

11.	P. Xue, B.L. Xiao, W.G. Wang, Q. Zhang, D. Wang, Q.Z. Wang, Z.Y. Ma	Plain low carbon steel of composition: 0.17 C,1.3 Mn, 0.35 Si, 0.017 P, 0.018 S, balance Fe.	Tool steel with end shoulder titanium carbide. Shoulder diameter 14mm.	Rotational speed 400 rpm and feed 50mm/min. Scanning electron microscope for micro-structural analysis. Vickers hardness performed on 200g load for 10 sec.	Ultra-fine grain structure was formed. Increased strength and ductility.
12.	J.D. Escobar, E. Vela´squez , T.F.A. Santos , A.J. Ramirez, D. Lo´pez	UNS 32205 DSS having composition: 0.023 C, 1.8 Mn, 0.3 Si, 22.5 Cr, 5.4 Ni,2.8 Mo, 0.03 P, 0.01 S, 0.16 N Plate dimensions: 350x150x6 mm.	Friction stir welding machine with PCBN-40%W-Re tool with pin height 6mm.	Untitled, rotational speed 200 rpm and feed 100 mm/min.	Enhanced wear rate and incubation time and this was due to modification of mechanical properties like refinement of grain and reduction of grain size. It was observed that it reduced porosity level in the specimen.
13.	G. Buffa , L. Fratini, S. Pasta, R. Shivpuri	AA7075-T6 aluminium alloy with dimensions 90x60mm.	H13 tool steel	Rotational speed 715rpm. Tool plunge 2.95mm and feed 50mm/min. Tool tilt angle 2^o.	Residual stresses are mainly because of thermal flux due to friction between work piece and tool in the shoulder work piece interface. There is no residual stress due to stirring action of tool pin.Result in modification of metallurgical properties.
14.	Hoon-Hwe Cho et al	API X100 grade linepipe steel of composition: 0.05-0.07 C,0.25Si, <2 Mn,<0.01 P, <0.001 S,<0.05 Nb, <0.05 V, <0.3Mo, and thickness 10mm.	PCBN tool with shoulder diameter 16mm and pin diameter 4mm.	Tool rotation speed 450 rpm and feed 127mm/min.	Fine grain microstructure was obtained. Significant difference between base metal and fsw weld.
15.	Yoshihiko Hangai et al	Aluminium foam sandwich with aluminium foam core and two metallic face sheets.	Friction stir welding machine with SKH51 high-speed tool steel tool of shoulder diameter 17mm, pin diameter 6 mm and pin height 5mm.	Rotational speed 2200 rpm and feed 100mm/min. Tool tilt angle 3^o. Plunge depth was set at 0.2mm.	Metallurgical bonding between aluminum and steel sheets can be achieved by friction stir welding with a reliable interface bonding.
16.	W H Jiang, R Kovacevic	6061-T6 Al alloy and AISI 1018 mild steel were welded. Composition of 6061-T6 alloy : 0.25 Cu , 1 Mg, 0.6 Mn, 0.6 Si, balance Al. Composition of AISI 1018 mild steel: 0.18 C, 0.75 Mn, P<0.04, S<0.04, balance Fe.	H13 tool steel with shoulder diameter 25mm and pin diameter 5.5mm.	Butt welded with single pass. Rotational speed 914rpm,feed 140mm/min.	Weld so obtained after performing FSW is free of cracks and porosity. Weld has high tensile strength. Hardness is much greater than that of the base alloy.

17.	Husain Mehdi ,R.S. Mishra	Ti-6Al-4V, F357, Al-4Mg-1Zr	H13 tool steel, CY16	The rotation speed of pin was 350 rpm, 1500 rpm and travel speed was 15mm/min	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, there for, the mechanical performance of friction stir welding joint should be evaluated accordingly.
18	Husain Mehdi ,R.S. Mishra	Al-7075, A356, 6061, Al-4Mg-1Zr	H13 tool steel	Tool rotaion speed was 400,600, 800, 1200 and 1600 rpm whereas tool transverse speed was 100 and 400 mm/min were used.	FSW is a potential welding process to achieve defect free joint. 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.
19.	Yoshiaki Morisada et al	Cold worked tool steel, SKD11, having chemical composition: 1.48C, 0.29Si, 0.35 Mn, 0.25P, 0.01 S, 0.09Cu, 11.74Cr, 0.85Mo, balance Fe.	Tungsten carbide-cobalt hard metal tool was used without a pin. Shoulder diameter 12mm.	Tool rotation speed 400 rpm, feed 400mm/min. Tool tilt angle 3^o. Micro-structure was analysed through XRD and micro-hardness was tested with Vickers micro hardness tester.	Diffusion zone is formed without any nitrate particles formation.

3. Conclusions

After study of various studies of investigators, it was concluded that FSP is an advantageous and most ecofriendly green technology. Due to grain boundary strengthening the tensile strength and ductility increases when compared to the base metal. It can be used to convert heterogeneous metal to homogeneous metal. It reduces porosity significantly.

Multi pass processing produces enhanced mechanical properties compared to single pass. It is simple and easy to control and produces no toxic by-products as against conventional methods and thus is sustainable green technology. It is a simple two-step process compared to multi step process of heat treatment.

Also, it does not change the physical state of the work piece but changes the micro-structure. It minimizes surface defects thereby increasing fatigue strength and reducing crack growth rate.

References

[1] Z. Feng, M. L. Santella, and S. A. David,(2005), Friction Stir Spot Welding of Advanced High-Strength Steels –A Feasibility Study. SAE International.

[2] H. K. D. H. Bhadeshia*1 and T. DebRoy2 2009 Critical assessment: friction stir welding of steels Science and Technology of Welding and Joining, 14(3), 195-202.

[3] Y.S. Sato, T.W. Nelson, C.J. Sterling , R.J. Steel , C.-O. Pettersson (2005), Microstructure and mechanical properties of friction stir welded SAF 2507 super duplex stainless steel Materials Science and Engineering A 397 376–384.

[4] H S Grawal, HS Arora, H Singh, A Agrawal (2013), Surface modification of hydroturbine steel using friction stir processing Applied Surface Science, - Elsevier, press, U K

[5] Yutaka S. Sato,, Tracy W. Nelson b, Colin J. Sterling (2005) Recrystallization in type 304L stainless steel during friction stirring Acta Materialia, Elsevier, Vol-53, page-637–645.

[6] Hidetoshi Fujii1, Rintaro Ueji, Yutaka Takada1, Hiromoto Kitahara, Nobuhiro Tsuji, Kazuhiro Nakata1 and Kiyoshi Nogi1 (2006) Friction Stir Welding of Ultrafine Grained Interstitial Free Steels, Materials Transactions, (The Japan Institute of Metals)Vol. 47, No. 1 pp. 239 to 242

[7] Nhon Q. Vo, David C. Dunand, David N. Seidman92012) Atom probe tomographic study of rfriction stir processed Al-Mg-Sc alloy

[8] Y. Morisadac, H. Fujii , T. Mizunob, G. Abeb, T. Nagaokac, M. Fukusumic (2009) Nanostructured tool steel fabricated by combination of laser melting and friction stir processing Materials Science and Engineering Vol- 505 page157–162

[9] H Schmidt, J Hattel and J Wert (2004) Analytical model for heat generation in friction stir processing Journal of Modelling Simulation . Mater. Sci. Eng. Vol-12, page- 143-157

[10] A.P. Reynolds, Wei Tang, T. Gnaupel-Herold, H. Prask (2003) Structure, properties, and residual stress of 304L stainless steel friction stir welds Scripta Materialia, Elsevier, Vol- 48 , page 1289–1294

[11] P.Xue,B.L.Xiao,W.G.Wang,Q.Zhang,D.Wang,Q.Z.Wang,Z .Y.Ma (2013Achieving ultrafine dual-phase structure with superior mechanical property in friction stir processed plain low carbon steel , Materials Science & Engineering A Elsevier) ,Vol-575,page 30-34.

[12] T.F.A.Santos, A.J.Ramirez, D.Lopez (2013), Improvement of cavitation erosion resistance of a duplex stainless steel through friction stir processing (FSP), A Wear, Elsevier, Vol-297, page-998-1005

[13] G. Buffa, L. Fratini1 , S. Pasta, R. Shivpuri (2008)) On the Thermo-mechanical Loads and the Resultant Residual Stresses in Friction Stir Processing Operations, CIRP, Annals, Manufacturing Technology , Dec-2008

[14] Hoon-Hwe Cho , Suk Hoon Kang, Sung-Hwan Kim , Kyu Hwan Oha, Heung Ju Kim ,Woong-Seong Chang c, Heung Nam Han (2012) Microstructural evolution in friction stir welding of high-strength linepipe steel, Material and Design,Elsevier, Vol-34, Page-258-267.

[15] Yoshihiko Hangai1, Nobuyuki Ishii,, Shinji Koyama1, Takao Utsunomiya,Osamu Kuwazuru and Nobuhiro Yoshikawa4 (2012) Fabrication and Tensile Tests of Aluminum Foam Sandwich with Dense Steel Face Sheets by Friction Stir Processing Route, Materials Transactions, (The Japan Institute of Metals), Vol. 53, No. 4 pp. 584 to 587,

[16] W H Jiang and R Kovacevic (2004), Feasibility study of friction stir welding of 6061-T6 aluminium alloy with AISI 1018 steel, Proceedings of the Institution of Mechanical Engineers Part B Journal of Engineering Manufacture,2004.

[17] Husain Mehdi, R,S,Mishra, Mechanical Properties and Microstructure Studies in Friction Stir Welding (FSW) Joints of Dissimilar Alloy – A Review, Journal of Achievements in Matrials and Manufacturing Engineering, 77 (1), 2016, 31-40.

[18] Husain Mehdi, Influences of Process Parameter and Microstructural Studies in Friction Stir Welding of Different Alloys: A Review, International Journal of Advanced Production and Industrial Engineering, special issue, 2017, 55-62.

[19] Yoshika Morisada, Hidetoshi Fujii, Tadashi Mizuno Genryu Abe (2009), Surface Modification of nitride layer on cold-work tool steel by laser melting and friction stir processing & Coatings Technology, Elsevier, Vol-204, page-386–390.