 ISSN : 2249-5762 (Online) | ISSN : 2249-5770 (Print)

Numerical Analysis and Performance of Friction Stir Welding: A Review

Adil Wazeer
School of Mechanical Engineering, Galgotias University, Greater Noida, India

Abstract

Friction Stir Welding (FSW) is a solid state joining process which is mainly characterized by the use of a non – consumable tool of electrode for the joining of two metal pieces together. In this type of welding the tool or the material used for welding metal pieces does not melt and is non consumable unlike other welding processes. During the operation of this process a large amount of heat is generated between the rotating tool and the workpiece. In order for the correct determination and analysis of the experiments performed from FSW process, it is sometimes difficult to evaluate the right outcome due to the complex geometry of the workpieces involved. Therefore numerical analysis improves this procedure and also results in accurate results as compared from other processes. This article reports the comprehensive review on the developments and advancements in the friction stir welding process, the structure and properties of the friction stir welding.

Keywords

Friction Stir Welding, Numerical Analysis, Non-Consumable Tool, Mechanical Properties, Weld Nugget.

I. Introduction

Welding of materials plays a considerable role inthe overall performance of the system which is under study. Friction stir welding is one of the most prominently used joining processes mainly implied in the aircraft industry for the joining processes. This process also results in the light weight structures in the manufacturing processes. Friction Stir Welding (FSW) is a solid-state joining technique which was invented at The Welding Institute (TWI), UK, in 1991 [1]. Considerable effort has been expended to develop various joining processes and assess their suitability for use in lightweight structures [2-6].

This welding processes is mainly applied for the joining of metal that are hard to join with any other joining processes. FSW is also ideal for joining of the alloys of aluminum, magnesium, titanium, etc. The heat generation due to the friction caused between the rotating tool and the workpiece causes the metal to soften and melt near the FSW region and to come in contact and join together. The high strain and heat energies experienced by the base metal during stirring causes dynamic recrystallization, which is the formation of new grains in the weld zone [1]. FSW is a highly complex process comprising several highly coupled (and non-linear) physical phenomena. These phenomena include large plastic deformation, material flow, mechanical stirring, surface interaction between the tool and the workpiece, dynamic structural evolution and heat generation resulting from friction and plastic deformation [7]. Friction welding process creates extremely high quality, high strength joints with low distortion. Friction Stir Welding produces a weld with high weld strength and toughness, plus a fine grain structure that resists fatigue stress. Due to the low heat and small heat-affected zone, there is minimal distortion of the joined parts, reducing the costs associated with preparing the part for subsequent use. The FSW method can be used to weld dissimilar alloys even combinations not compatible with conventional welding methods.

FSW is a green process i.e. friction stir welding is environmentally friendly, with a process that features low energy input and requires no consumables, flux, filler material, or shielding gases to run, like conventional welding methods. Friction Stir Welding also does not emit smoke, fumes, or gases that need to be exhausted on the back end. FSW is also capable of fabricating either butt or lap joints in a wide range of material thickness and lengths. FSW being a solid state process eliminates many of the defects associated with fusion welding techniques like shrinkage, solidification cracking and porosity. This welding process has been a subject for the experimental study. Nandan et al. [8] give a very comprehensive review on the process, structure and properties of FSW. Threadgill et al. [9] provided an exhaustive overview of the FSW of aluminum alloys and Çam [10] reviewed extensively FSW of other alloys.

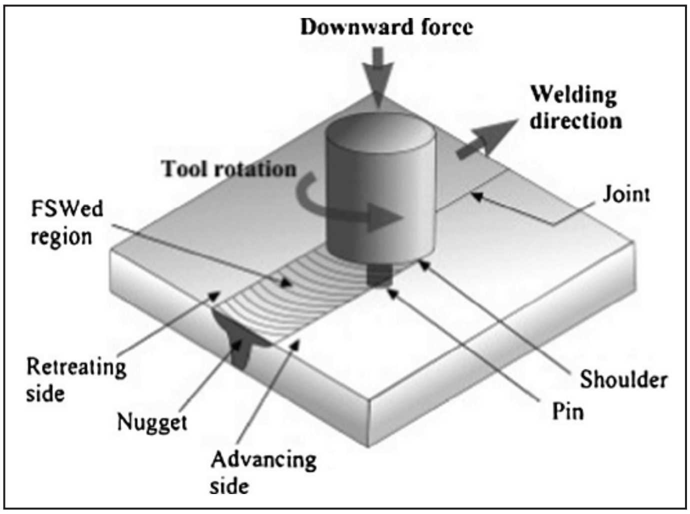

Fig. 1: Schematic Diagram of FSW Process [11].

II. Friction Stir Welding Process

The FSW is a solid state welding process that does not requires any filler metal for the joining of two metal surfaces together. It only works on the heat that is generated during the friction between the revolving non-consumable tool and the workpiece. The parameters of the process can be varied and thereby altering the FSW process. Numerical analysis and simulation enables us to determine the results of the process with proximity by varying the parameters and observing the changes that are altering the outcomes of the process. Due to the complexity of the FSW process, it is very difficult to gain insight into the joint during the actual forming process [7]. Numerical simulation helps overcome this problem by providing an effective way of analyzing the formation of FSW joints [12]. Simulating the FSW process is a complex problem which involves physical couplings between mechanics and heat transfer, very large deformations and strain rates in the stirring zone around the pin [7]. The most prominent benefit of the friction stir welding is that it has few elemental processes to control as compared to the other traditional joining processes. However in conventional welding processes factors like feed speed, arc gap, wire feeding, filler metal, etc. has to be kept under keen observation and control. The most significant advantage of FSW process that it does not require filler metal like other conventional joining processes without which joining of two metals is not possible. Reynolds et al. [13] proposed a single expression for the involved physics in FSW. The achievements of the prediction of what will happen at the tool and workpiece interface can be achieved through many ways. The concept of combining the latest FE and Discrete Element (DE) multiscale numerical technologies for modeling the tool/workpiece interface during high shear processing was described [14-15]. In friction stir processes there are only three parameters to be controlled namely rotation speed, travel speed and pressure all of which can be easily controlled. In FSW process there is no need of joint preparation before the welding process only degreasing is done. High quality welds are obtained which in turn enhances the properties of the metal like high tensile strength, good fatigue properties and corrosion resistance. The numerical model is continuum solid mechanics-based, fully thermo-mechanically coupled and has successfully simulated the FSW process including plunging, dwelling and welding stages. Several field variables are quantified by the model including temperature, stress and strain [7].

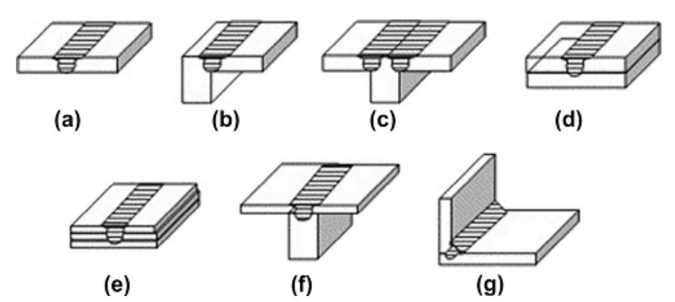

Fig. 2: Joint Configurations for FSW: (a) square butt, (b) edge butt, (c) T butt joint, (d) lap joint, (e) multiple lap joint, (f) T lap joint and (g) fillet joint [16].

Friction stir welding has low operational cost, no consumables and low energy costs. In this no post treatment is required and has low distortion and shrinkage.

III. Tool Design

The authenticity and performance of the FSW depends on the type and quality of tool that is being used during the machining process. The main features of a FSW tool is pin and shoulder. The pin of the tool rotates and causes the material near the contact area of the pin to soften, melt and join and the shoulder applies pressure for the creation of heat and to maintain contact between the tool and workpiece. Tool geometry greatly influences the mechanical properties, energy input and other important factors. The effect of changing the tool geometry parameters on thermo-mechanical behavior in FSW of AA5086 aluminum alloy was investigated numerically and experimentally by Jamshidi Aval et al. [17-18]. In FSW tool design the most important geometric parameter is shoulder diameter which is mainly designed by trial and error methods. A criterion for the design of a tool shoulder diameter based on the principle of maximum utilization of supplied torque for traction was proposed and tested [19]. The effects of variation in tool geometry parameters, such as the tool shoulder surface angle etc., on the FSW process on AA2024 aluminum alloy were also investigated numerically [20].

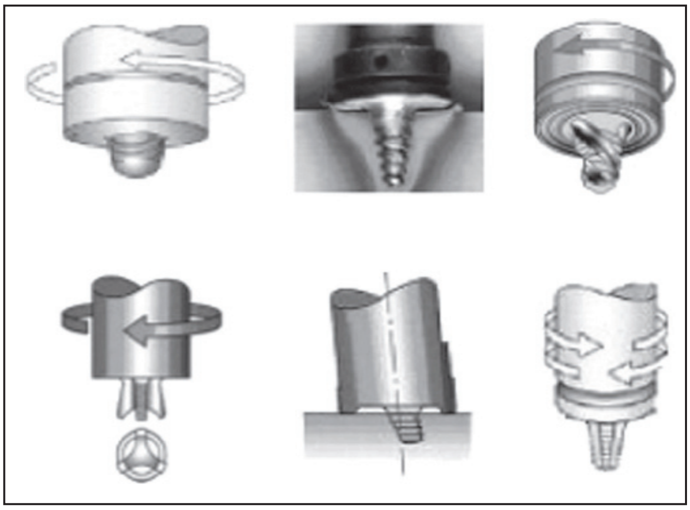
Fig. 3: A Selection of Tools Designed at TWI [21].

IV. A. Parameters of Welding

The welding parameters in the FSW process that can controlled are transverse speed and the rotational speed, and most importantly the angle of contact between the tool and the workpiece. The reason of FSW being the most suitable welding process is because it has very less parameters to control unlike other conventional methods. The higher speed of the rotation of the tool result in more friction which in turn results in high heat generation which causes the mixing of the material more vigorous and leads to a more strong and durable weld between the two metal surfaces. A constant heat is generated during the rotation and the softening and melting of the metal. A thermo-mechanical fully coupled 3D FE analysis was carried out in a study of the effect of tool geometry and advancing speed on the FSW of AA7075 aluminum alloy [22]. The working temperature of the FSW process is varied and the changes that are encountered are recorded and compared with the optimum values and also with the initial and the final results obtained with the optimum combinations of the input parameters. The configurations and the sizes of the tool greatly influences the working of the tool and the resultant weld of the workpiece. A new idea was proposed for the FSW of the thin plate of AI alloy by using a rotational tool without a pin [23-24]. The comparisons of numerical and experimental results showed that the equivalent plastic strain can approximately correlate with the microstructural evolution. It was found from both the numerical model and the experiments that the quality of the FSW can be improved when the angular velocity of the pin is increased or the welding speed is decreased. With the increase of the angular velocity of the pin, the equivalent plastic strain is increased. The equivalent plastic strain is decreased with the increase of the translational velocity of the pin [7]. If the rotation speed is increased and the transverse speed is decreased then the stirring effect of the tool will increase which further improves and enhances the quality of weld. On increasing the angular speed of the tool there is a decrease in the tool forces in three directions and on increasing the transverse speed the tool forces are increased. When the traverse speed becomes higher, the rotating speed must also be increased to avoid any possible welding defects such as voids. Simultaneously increasing the rotation and translating speeds of the welding tool can lead to an increase in the residual stress [7].

B. Wear of Tool

Due to the rigorous working action of the tool and the generation of heat due to friction between the revolving tool and the workpiece wearing of tool occurs which results in the decrement in the quality and performance of the tool. This wearing of tool finally results in the poor and distorted weld and also the contamination of the weld area because of the mixing of the tool particles in the melted metal and results in weaker weld. The wearing of tool also starts hindering the welding of hard metal for which friction stir welding is recommended. A 3D ABAQUS FE analysis model was developed to study the thermo-mechanical processes involved during the plunge stage [25-26]. The traverse force and torque during FSW were computed using a 3D heat transfer and viscoplastic material flow model, considering the temperature and strain rate-dependent flow stress of the work-piece material [27]. An experimental study of tool life in the FSW of titanium alloys sheets provided useful Insights [28]. A transient 3D FE heat transfer model of workpieces was developed to predict the influence of preheating on the temperature distribution and heat flux within the workpieces [29]. FSW is considered for the welding of the hard materials like steel and titanium but before time of premature wearing of tool leads to the disruption of the application of friction stir welding.

V. Grain Size and Microstructure of FSW Joints

In particular the Continuous Dynamic Recrystallization (CDRX) phenomena result in a highly refined grain structure in the weld nugget and strongly affect the final joint resistance [7]. For various analytical methods were goaled for the determination of microstructure of grain size of FSW of the alloys of aluminum studies were presented by Fratini et al.'s [30-35]. The experiments showed that during tube forming fine equally-axed grain were produced in both the weld nugget and also in the base material. Ultra-thin wall tubes were produced using a hybrid process combining FSW and spinning [36]. A numerical model based on the Kampmann and Wagner method was developed to predict the evolution of precipitate distribution during the FSW of the aerospace aluminum alloy, AA7449 [37-38]. The microstructure of 6082 T6 alloy FSSW joints was extensively examined and a new modeling procedure that enables correct evaluation of the mechanical behavior of the joints was also developed [39]. The mechanical properties of thick (>25 mm) aluminum alloy AA2139-T8 FSW plates were studied numerically and experimentally [40]. The results from the numerical analysis enables the interpretation of the grain size obtained after the weld has been done. Texture patterns on transverse, longitudinal and horizontal cross-sections in the FSW were studied experimentally and numerically [41]. The final grain size and yield strength were predicted by generating transition rules, relating them to temperature, strain-rate and strain evolved during FSW [7]. FSW lap joints of Ti–6Al–4V were produced and the effect of the main process parameters was studied through macro and micro investigations highlighting mechanical resistance, microhardness profiles, grain size and phase distributions [42].

VI. Properties

A. Residual Stress

Numerical analysis of process and mechanical tests of the FSW can add very useful information in defining how the process parameters influence the joint behavior [43-44]. Residual stresses are generated in significant amount which result in the degradation of the performance and the structural integrity of the component. The maximum residual stresses are located in the HAZ and the minimum compressive residual stresses are located on the advancing side just beyond the weld zone [16]. It is therefore important to predict and determine the residual stresses in order for the proper functioning and the life of the joint between the welded pieces. A 3D FE model can be used to study the thermal history and evolution of stress in the FSW process and subsequently, to compute mechanical forces in the longitudinal, lateral and vertical directions [45-47]. A 2D model of FSW was used to study the distributions of the longitudinal residual stress and the material flow under different process parameters [48]. Residual stresses disrupt the overall functioning of the component by varying the internal stresses and mechanical properties of the component. Utilizing experimentally validated FE modeling methods, it was demonstrated that FSW induced residual stresses have a significant influence, and that collapse behavior is less sensitive to advanced process effects and process effect magnitudes than initial buckling behavior in the panel. FSW processes used to build large stiffened structures are responsible for introducing geometrical imperfections, changing the material properties and adding residual stresses. These factors can affect the panel's structural behavior when subjected to compressive load [7]. The longitudinal residual stresses that arise from FSW processes were measured by means of the contour method [49].

B. Hardness

Hardness of the FSW joint is one of the chief characteristics which defines the strength of the joint and also its durability. If the hardness of the component is altered then the complete component is unreliable due to the changes in the strength and the mechanical factors of the component. The hardness in the nugget zone is higher than that in HAZ and TMAZ, and an area of maximum hardness is located around the center of weld, whereas outside of this region, hardness reduces slightly in TMAZ and HAZ, and then rises sharply, moving towards base metal [50].The proper and complete evaluation of the tensile and the compressive stresses is done to estimate the shear bearing capacity of the component. A fully coupled thermo-mechanical FE model was used to predict the FSW behaviors of AA5083 and AA2139 aluminum alloys [51]. Hardness is the mechanical property of the component that has to be effectively analyzed so that there should be no defects remaining in the machining component.

C. Fatigue Behavior

The most common cause of failure of FSW joints is fatigue failure. The fatigue life of a FSW joint results from a combination of crack initiation and propagation stages which are followed by the fast failure stage. Identifying and interpreting the locus of failure, crack initiation and propagation behavior are significant aspects in evaluating the mechanical characteristics of the FSW joints [7]. Fig. 4 represents the specimen geometry and finite element mesh for small scale yielding problem solving for single edge notch.

The fatigue tests are to be done for the determination of fatigue in the component which would lead the distortion of the component. The propagation of a fatigue crack through a FSW joint of 2024-T351 Al alloy was investigated numerically [53]. The Thermo-Elastic Stress Analysis (TSA) can be used to study the propagation characteristics of fatigue-cracks in FSW aluminum sheets. The TSA measurement system allowed crack evolution to be observed in real-time during fatigue cycles and allowed the stress fields to be derived from the measured variation in temperature [7]. Fatigue tests were performed under tension with a load ratio of 0.1 and all the tests were conducted to failure point [54]. Due to design constraints, FSW components may include notches in the weld (friction stirred material), and there is a lack of information on the fatigue behavior of the weld in those conditions [7]. The use of residual K (Kres) approaches for the prediction of fatigue crack growth rates in residual stress fields was studied [55].

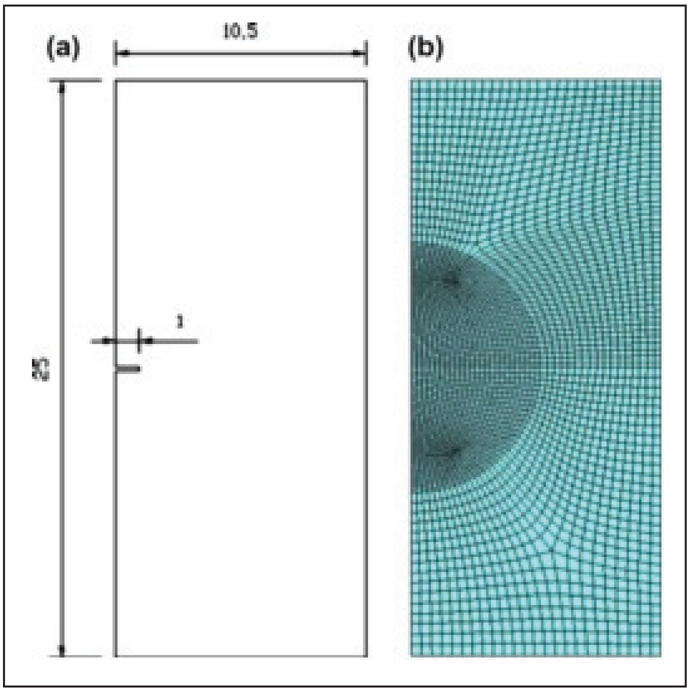

Fig. 4: Specimen Geometry and Finite Element Mesh for Small Scale Yielding Problem Solving for Single Edge Notch, all Units are in mm [52].

D. Dynamic Behavior of JSW Joints

Investigations at the micro-mechanical level were reported for aluminum alloy 6111 spot FSW joints welded with different processing times [56-57]. Deformation and fracturing in impulsively loaded FSW sandwich panels were studied [58]. Apart from microstructural studies and micro-hardness tests, a new approach to characterizing the distribution of the weld zone modulus using modal vibration tests on micron scale cantilever array specimens with a micro-scanning laser vibrometer and the corresponding FE simulations was developed [7]. A combination of experimental and modeling methods was used to investigate the mechanical response of edge-clamped sandwich panels subjected to the impact of explosively driven wet sand [59]. A Computational Fluid Dynamic (CFD) model was presented to simulate the material flow and heat transfer in the FSW of 6061-T6 aluminum alloy (AA6061) [60]. Micro-hardness and miniature tensile coupon testing revealed that FSW reduced the strength and ductility in the welds and in a narrow heat-affected zone on either side of the weld, by about 30% [7].

VII. Conclusion

Although friction stir welding has been the undisputed choice for the joining of hard materials like steel and titanium but the stage of this joining process is still early. The developments in the field of joining the hard metals is still in under study and the improvisation in the welding through friction stir welding has been continuously studied in order to inculcate new methods for in and some alteration in this field. Numerical analysis has played a vital role in the study of FSW joining process. The references presented in this study present the different methods and with different materials for the study of the FSW process. It also represent the application of numerical analysis in the study of the friction stir welding process. The main of this review paper is to present the performance and the developments in the area of the concerned study.

References

[1] Thomas WM, Nicholas ED, Needham JC, Murch MG, Temple-Smith P, Dawes CJ.,"Friction stir butt welding", International Patent Application No. PCT/GB92/02203; 1991.
[2] He X, Gu F, Ball A.,"Recent development in finite element analysis of self-piercing riveted joints", Int J Adv Manuf Technol 2012;58:643–9.
[3] He X.,"Finite element analysis of laser welding: A state of art review", Mater Manuf Process 2012;27:1354–65.
[4] He X.,"A review of finite element analysis of adhesively bonded joints", Int J Adhe Adhe 2011;31:248–64.
[5] He X.,"Recent development in finite element analysis of clinched joints", Int J Adv Manuf Technol 2010;48:607–12.
[6] He X, Pearson I, Young K.,"Self-pierce riveting for sheet materials: State of the art", J Mater Process Technol 2008;199:27–36.
[7] Xiaocong He, Fengshou Gu, Andrew Ball,"A review of numerical analysis of friction stir welding", Progress in Materials Science 65 (2014) 1–66.
[8] Nandan R, DebRoy T, Bhadeshia HKDH,"Recent advances in friction-stir welding – process, weldment structure and properties", Prog Mater Sci 2008;53:980–1023.
[9] Threadgilll PL, Leonard AJ, Shercliff HR, Withers PJ.,"Friction stir welding of aluminum alloys", Int Mater Rev 2009;54:49–93.
[10] Çam G.,"Friction stir welded structural materials: beyond Al-alloys", Int Mater Rev 2011;56:1–48.
[11] Gemme F, Verreman Y, Dubourg L, Jahazi M.,"Numerical analysis of the dwell phase in friction stir welding and comparison with experimental data", Mater Sci Eng A 2010;527:4152–60.
[12] He X.,"Numerical studies on friction stir welding of lightweight materials", Adv Mater Res 2013;743:118–22.
[13] Reynolds AP, Tang W, Khandkar Z, Khan JA, Lindner K.,"Relationships between weld parameters, hardness distribution and temperature history in alloy 7050 friction stir welds", Sci Technol Weld Join 2005;10:190–9.
[14] Krzyzanowski M, Davies PS, Rainforth WM, Wynne BP.,"Combined discrete/finite element multiscale approach for modelling of the tool/workpiece interface during high shear processing: Hot rolling and friction stir welding applications", Mater Sci Forum 2010;638–642:2622–7.
[15] Krzyzanowski M, Rainforth MW.,"Advances on modelling of the tool/workpiece interface during high shear processing", Mater Sci Forum 2010;654–656:1634–7.
[16] Mishra RS, Ma ZY.,"Friction stir welding and processing", Mater Sci Eng R: Rep 2005;50:1–78.
[17] Jamshidi Aval H, Serajzadeh S, Kokabi AH.,"The influence of tool geometry on the thermo-mechanical and microstructural behaviour in friction stir welding of AA5086", Proc Inst Mech Eng Part C 2011;225:1–16.
[18] Jamshidi Aval H, Serajzadeh S, Kokabi AH. Evolution of microstructures and mechanical properties in similar and dissimilar friction stir welding of AA5086 and AA6061", Mater Sci Eng A 2011;528:8071–83.

[19] Arora A, De A, Debroy T.,"Toward optimum friction stir welding tool shoulder diameter", Scr Mater 2011;64:9–12.
[20] Li H, MacKenzie D, Hamilton R.,"Parametric finite-element studies on the effect of tool shape in friction stir welding", Proc Inst Mech Eng Part B 2010;224:1161–73.
[21] The Welding Institute TWI. [Online] Available: www.twi.co.uk.
[22] Buffa G, Hua J, Shivpuri R, Fratini L.,"Design of the friction stir welding tool using the continuum based FEM model", Mater Sci Eng A 2006;419:381–8.
[23] Zhang LG, Ji SD, Luan GH, Dong CL, Fu L.,"Friction stir welding of al alloy thin plate by rotational tool without pin", J Mater Sci Technol 2011;27:647–52.
[24] Ji SD, Zhang LG, Jin YY, Luan GH.,"Numerical simulation of rotational tool shoulder shape's effect on transfer behavior of welding plastic metal in friction stir welding", Mater Sci Forum 2012;704–705:1167–74.
[25] Mandal S, Rice JM, Elmustafa AA.,"A numerical study of the plunge stage in friction stir welding using abaqus", In: Proc frict stir weld process IV – TMS 2007 annual meet exhibit; 2007. p. 127–33.
[26] Mandal S, Rice JM, Elmustafa AA.,"Experimental and numerical investigation of the plunge stage in friction stir welding", J Mater Process Technol 2008;203:411–9.
[27] Arora A, Mehta M, De A, Debroy T.,"Load bearing capacity of tool pin during friction stir welding", Int J Adv Manuf Technol 2012;61:911–20.
[28] Buffa G, Fratini L, Micari F, Settineri L.,"On the choice of tool material in friction stir welding of titanium alloys", Trans North Am Manuf Res Inst SME 2012;40:785–94.
[29] Able N, Pfefferkorn F.,"Laser-assisted friction stir lap welding of aluminum", In: Proc ASME summer heat transfer conf, vol. 4; 2005. p. 425–9.
[30] Fratini L, Buffa G.,"CDRX modelling in friction stir welding of aluminium alloys", Int J Machine Tool Manuf 2005;45:1188–94.
[31] Buffa G, Fratini L, Shivpuri R.,"CDRX modelling in friction stir welding of AA7075-T6 aluminum alloy: Analytical approaches", J Mater Process Technol 2007;191:356–9.
[32] Fratini L, Buffa G.,"Metallurgical phenomena modeling in friction stir welding of aluminum alloys: Analytical versus neural network based approaches", J Eng Mater Technol, Trans ASME 2008;130:0310011–16.
[33] Fratini L, Buffa G.,"Continuous dynamic recrystallization phenomena modeling in friction stir welding of aluminum alloys: a neural-network-based approach", Proc Inst Mech Eng Part B 2007;221:857–64.
[34] Buffa G, Fratini L, Micari F.,"A neural network based approach for the design of FSW processes", Key Eng Mater 2009;410– 411:413–20.
[35] Fratini L, Buffa G, Palmeri D.,"Using a neural network for predicting the average grain size in friction stir welding processes", Comput Struct 2009;87:1166–74.
[36] Yuan SJ, Hu ZL, Wang XS.,"Evaluation of formability and material characteristics of aluminum alloy friction stir welded tube produced by a novel process", Mater Sci Eng A 2012;543:210–6.
[37] Kamp N, Sullivan A, Tomasi R, Robson JD.,"Modelling of heterogeneous precipitate distribution evolution during friction stir welding process", Acta Mater 2006;54:2003–14.
[38] Kamp N, Sullivan A, Tomasi R, Robson JD. Modelling heterogeneous precipitation in 7xxx aluminium alloys during complex processing", Mater Sci Forum 2006;519–521:1435–40.
[39] Fanelli P, Montanari R, Rovatti L, Ucciardello N, Vivio F, Vullo V.,"Microstructural characterization and modelling of Friction Stir Spot Welded joints in 6082 aluminium alloy", Metall Italiana 2011;103:43–9 [in Spanish].
[40] McWilliams BA, Yu JH, Yen CF.,"Numerical simulation and experimental characterization of friction stir welding on thick aluminum alloy AA2139-T8 plates", Mater Sci Eng A 2013;585:243–52.
[41] Xu SW, Deng XM.,"A study of texture patterns in friction stir welds", Acta Mater 2008;56:1326–41.
[42] Buffa G, Fratini L, Schneider M, Merklein M.,"Micro and macro mechanical characterization of friction stir welded Ti–6Al–4V lap joints through experiments and numerical simulation", J Mater Process Technol 2013;213:2312–22.
[43] Biro AL, Chenelle BF, Lados DA.,"Processing, microstructure and residual stress effects on strength and fatigue crack growth properties in friction stir welding: A review. Metall Mater Trans B 2012;43:1622–37.
[44] He X.m"Computational investigation of mechanical behaviour of FSW joints", Appl Mech Mater 2013;389:260–6.
[45] Chen CM, Kovacevic R.,"Finite element modeling of friction stir welding – thermal and thermomechanical analysis", Int J Mach Tools Manuf 2003;43:1319–26.
[46] Chen C, Kovacevic R.,"Thermomechanical modelling and force analysis of friction stir welding by the finite element method", Proc Inst Mech Eng Part C 2004;218:509–20.
[47] Chen CM, Kovacevic R.,"Parametric finite element analysis of stress evolution during friction stir welding", Proc Inst Mech Eng Part B 2006;220:1359–71.
[48] Zhang HW, Zhang Z, Chen JT.,"Effect of process parameters on material flow and residual stress in friction stir welding", Chin J Mech Eng 2006;42:103–8 [in Chinese].
[49] Paulo RMF, Carlone P, Valente RAF, Teixeira-Dias F, Palazzo GS,"Integrated design and numerical simulation of stiffened panels including friction stir welding effects", Key Eng Mater 2013;554–557:2237–42.
[50] Pashazadeh H, Masoumi A, Teimournezhad J.,"Numerical modelling for the hardness evaluation of friction stir welded copper metals", Mater Des 2013;49:913–21.
[51] Grujicic M, Arakere G, Yen CF, Cheeseman BA., "Computational investigation of hardness evolution during friction-stir welding of AA5083 and AA2139 aluminum alloys", J Mater Eng Perform 2011;20:1097–108.
[52] Cavaliere P, De Santis A, Panella F, Squillace A, "Thermoelasticity and CCD analysis of crack propagation in AA6082 friction stir welded joints", Int J Fatigue 2009;31:385–92.
[53] Golestaneh AF, Ali A.,"Application of numerical method to investigation of fatigue crack behavior through friction stir welding", J Failure Anal Prevent 2009;9:147–58.
[54] Cavaliere P, De Santis A, Panella F, Squillace A. Thermoelasticity and CCD analysis of crack propagation in AA6082 friction stir welded joints. Int J Fatigue 2009;31:385–92.
[55] Ma YE, Staron P, Fischer T, Irving PE.,"Size effects on residual stress and fatigue crack growth in friction stir welded 2195- T8 aluminium – Part II: modelling. Int J Fatigue 2011;33:1426–34.

[56] Thoppul SD, Gibson RF.,"Mechanical characterization of spot friction stir welded joints in aluminum alloys by combined experimental/numerical approaches", Part I: micromechanical studies. Mater Charact 2009;60:1342–51.
[57] Thoppul SD, Gibson RF.,"Mechanical characterization of spot friction stir welded joints in aluminum alloys by combined experimental/numerical approaches. Part II: Macromechanical studies. Mater Charact 2009;60:1352–60.
[58] Wadley HNG, Borvik T, Olovsson L, Wetzel JJ, Dharmasena KP, Hopperstad OS, et al.,"Deformation and fracture of impulsively loaded sandwich panels", J Mech Phys Solids 2013;61:674–99.
[59] Rimoli JJ, Talamini B, Wetzel JJ, Dharmasena KP, Radovitzky R, Wadley HNG.,"Wet-sand impulse loading of metallic plates and corrugated core sandwich panels", Int J Impact Eng 2011;38:837–48.
[60] Atharifar H, Lin DC, Kovacevic R.,"Numerical and experimental investigations on the loads carried by the tool duringfriction stir welding", J Mater Eng Perform 2009;18:339–50.

Adil Wazeer is a B. Tech scholar and currently pursuing his B. Tech degree in Mechanical Engineering at Galgotias University, Greater Noida, India. His research interests includes the areas of mechanical engineering specially focusing on renewable energy specifically gasification process and its types and the manufacturing sciences. At present he is engaged in downdraft gasification system using different types of raw material.