Review on Friction Stir Welding of Dissimilar Alloy

Rajkumar.T[1], Kalidass.M[2], Cheran.S[3], Harissh.S[4],Mohamed Hanifa.M[5], Arunkumar.G[6]
Department of Mechanical Engineering
[1,2,3,4,5,6] K Ramakrishnan College of Technology, Samayapuram – Trichy – 621 112

Abstract- *In this paper, we are going to study about the welding process in aluminum alloy AA2024 & AA2099.The joining of aluminum alloys was welded by (FSW). The process parameters were obtained by using statistical approach. In this process of welding the temperature difference is created by the response surface method, this difference will helps to make a efficient welding of dissimilar materials The rotational speed and transverse speed of tool over the micro structural and tensile properties should be investigated*

Keywords- friction stir welding, Aluminum alloy, Process parameter.

I. INTRODUCTION

The joining of dissimilar alloy is difficult when compared to the joining process of similar aluminum alloy, Due to the changes in mechanical properties. Chemical composition of the base material.[1].The alloy material is fixed in the pattern of FSW machine. The rotating tool is moves in forward direction towards the workpiece. The optimum rotational speed for processing aluminum alloy is 590-900 rpm, Transverse speed around 15-40mm/min and ratio 3:1[1]. The grain size is directly proportional to the rotational speed.[2]. The tool is work on the work piece and depth is given by the stopper and the atom are collapsed in the middle range of the work piece[3]. Its make a joining process and it is continuous and complete the joining process. Threaded, squared, triangle and hexagon shaped tool pin profile are efficient in material transfer from the top joint to bottom joint by the action of stir. The temperature difference is make a joining of the two aluminum alloys of AA2024 and AA2099 the friction of the work piece and the tool creates the temperature difference in the joining process. The response surface methodology is used for joining the two aluminum alloys. The fig 1.1 shows the methodology of the welding process.

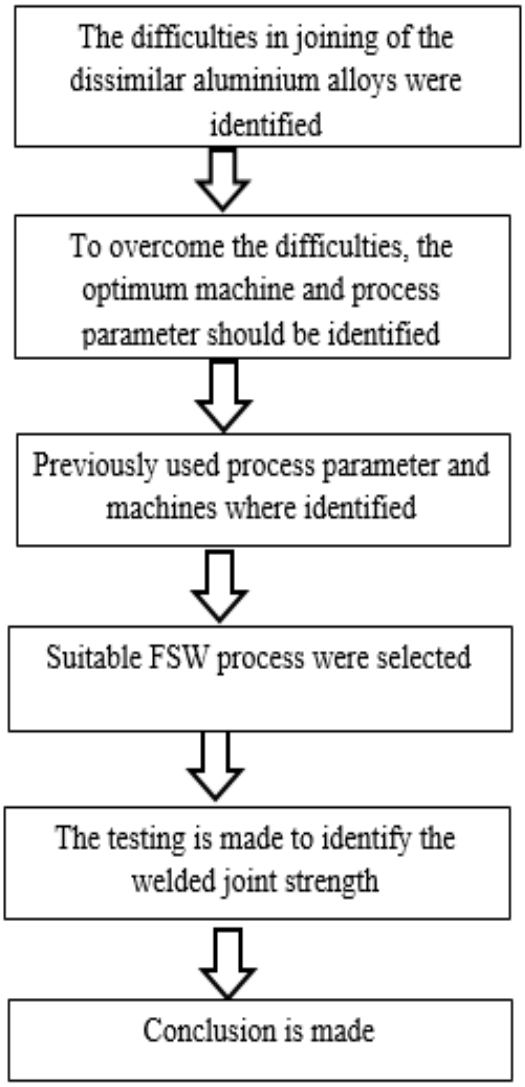

Fig1.1 Methodology

II. SOLID STATE JOINING TECHNIQUES

2.1 DIFFUSION BONDING

It is a joining of two metallic surface by the diffusion of atoms under pressure and temperature over time.

2.2 PULSE PLASMA ASSISTED DIFFUSION BONDING

It is a joining of two metallic surfaces by hard pressing and pulsed direct electric current through pins that apply pressure to the sample.

2.3 ROTARY FRICTION WELDING

It is the solid state joint that the axial loaded rotational energy is used to form a joint.

2.4 FRICTION STIR WELDING

It is the solid state join that uses friction to plasticize and a stir bit to join the parts together.

III. EXPERIMENTAL PROCEDURE

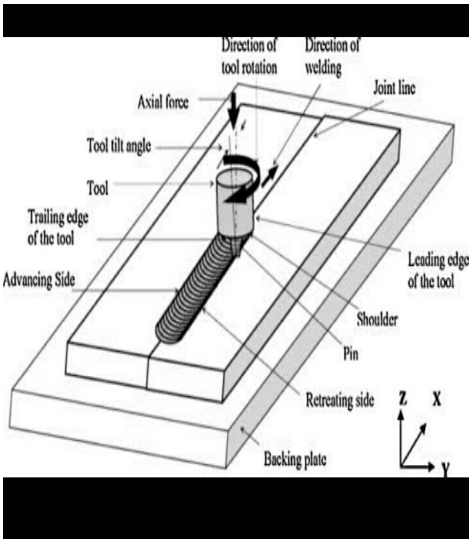

Fig1.2 General arrangements

The fig1.2 shown the general arrangement Of friction stir welding process

The geometric size of the work piece sample is 3mm thick plate. The bar of aluminum alloy is cutter into 100*50mm rectangular plate. The materials used in this study are AA2024 and AA2099.The chemical composition of the materials is listed below. AA2024 contains the following si-0.10, Mn-0.61, Cu-4.53, Fe-0.20, Zn-0.16, Mg-1.28, Cr-0.010, Ti-0.012, Al-93.01.

AA2099 contains the following si-0.026, Mn-0.29, cu-2.30, Fe-0.027, Zn-0.71, Mg-0.28, cr-0.0003, Ti-0.028, Al-95.39. The welding tool material used in this study was HS186.The different tool profiles were studied for joining process, they are cylinder pin, squared pin and hexagonal pin. Among the 3 tool pin profile the cylinder is very optimum and hence it selected. The metallurgical characteristics of aluminum alloys are calculate by the energy dispersive spectroscope (EOS) method.

IV. FSW TOOL COMPOSITION AND TOOL GEOMENTRY

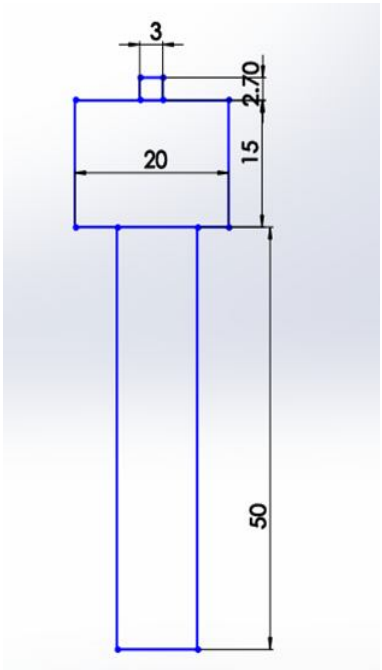

Fig1.3 Tool geomentery

The Fig1.3 shows the tool geomentry.

The tool used in friction stir welding have the chemical composite.

- FSW of aluminium is an established technique.
- FSW of steels now made possible due to the development of a tool made from Polycrystalline Cubic Boron Nitride (PCBN).
- Tool design constantly being improved to extend tool life
- The material of tool used is high speed steel.

Vivekanandan.P et.al [6] Showed that the mechanical properties of the material which is welded by using fusion welding is defected because of the heat affected zone exists in the welded components the mechanical properties are severely affected by intense heating.

V. MATERIAL TO BE USED

The material used for the friction stir welding is having a dissimilar properties, both mechanically and chemically.The material used are AA2024 and AA2099 .

5.1 COMPOSITIONS OF AA2024

The materials used for this investigation are aluminum alloy AA2024.The standard chemical composition and base material was discussed in introduction. The above mentioned aluminum alloy (AA2024) are used in the emerging fields of marine, space and aerospace industries. Pipelines, frames and storage tank are manufactured by this method.

S.NO	COMPONENTS	PERCENTAGE (%)
1.	copper	2.4-3
2.	lithium	1.6-2
3.	zinc	0.4-1
4.	magnesium	0.1-0.5
5.	silicon	0.05

5.2 COMPOSITIONS OF AA2099

S.No	COMPONENTS	PERCENTAGE (%)
1.	Aluminum	90
2.	Copper	4.3-4.5
3.	Magnesium	1.3-1.5
4.	manganese	0.2-0.3
5.	Zinc, Bismuth, etc	0.5

The materials used for this investigation are aluminum alloy AA2099.The standard chemical composition and base material was discussed in introduction.The above mentioned aluminum alloy (AA2099) are used in aircraft frames and marine industries.

VI. BASIC PROPERTIES OF ALUMINUM ALLOY

Aluminum alloy has density of 2.78g/cm3, electrical conductivity of 30% IACS,young's modulus of 73GPA, melting point of 500 degree.c,ultimate tensile strength of 140-210mpa and maximum yield strength below 97mpa.

Sivakumar.M et al [5] showed that the other welding process like arc, Laser and fusion welding, the heat source is supplied externally. But in FSW the heat is generated by the joining process itself by means of friction created in tool and work piece. The analysis done on the effect of rotational speed and traverse speed.

Gopala Krishna.G et al [7] has studied the friction stir is developed for the material which is having a less melting. The aluminum alloy has a low melting point. The FSW process is also used for steel and composite materials. The FSW is the solid state welding process; the material is not melted during the joining process.

Sadeesh.P et al [1] attempted to consider as the quality welding process due to the correct amount of heat input provided by the friction between the tool and work piece.

The macrostructure test is made to identify the effective stir of both the base material in the stir is tested on both sides of the base materials by microstructure test.

VII. BENEFITS OF FSW

1) No hot cracks and no gas pores on work samples.
2) No shielding gases while performing welding process
3) Possibilities of joining dissimilar alloys materials
4) Limited weld seam preparation.
5) Constant weld quality achieved together with high productivity.
6) No UV radiation while performing welding Process.
7) No welding fume is generated.

VIII.CONCLUSION

The mechanical and welding properties are selected in welding process to optimize the FSW process parameters. The welded quality influenced by the tool pin profile. Since fusion welding of dissimilar aluminum is hard, hence (FSW) is the simplest method to join dissimilar materials. FSW plays a revolutionary role in aircraft frames, wings and marine industries.

REFERENCES

[1] Sadeesh P,venkatesh kannan M."studies on friction stir welding of AA2024and AA2061 dissimilar metals", vol 75. Page no:145-149
[2] Y. Feng, A. Vairis2017, "Impact of cold spraying on microstructure and mechanical properties of optimized friction stir welded AA2024 T3 joint", vol. A702. page no:73-80
[3] Santoshk.sahu,Debasishmishra,2017,"Friction stir welding of polypropylene sheet" ,Vol 201. Page no:226-235
[4] RameshG,srimuthunathI,2018,"Characterization of microstructure and hardness of friction stir welded brass plate",vol 5. page no:2721-2725

[5] Sivakumar, vignesh bose, Raguraman D,"Review paper of friction stir welding of various aluminium alloy",IOSR journal of mechanical engineering,2014.Page no :46-52

[6] Vivekananda.P, Arunachalam V , prakash T,"Experimental analysis of friction stir weldingofaluminiumcomposites",international journal of metallurgical engineering",2012

[7] Gopala Krishnan G, P Ram Reddy, Manzoor Hussian M,"Mechanical Behaviour of friction stir welding joint of aluminium alloy of AA6351 withAA6351 and AA6351 with AA5083,"Vol 10.Page no:4-8

[8] Y.M. Yue, Z.W. Li, S.D. Ji, Y.X. Huang, Z.L. Zhou, E□ect of reverse-threaded pin on mechanical properties of friction stir lap welded alclad 2024 aluminum alloy, J. Mater. Sci. Technol. 32 (2016) 671–675.

[9] .M. Bahrami, M.F. Nikoo, M.K.B. Givi, Microstructural and mechanical behaviors of nano-SiC-reinforced AA7075-O FSW joints prepared through two passes, Mater. Sci. Eng. A 626 (2015) 220–228.

[10] P.L. Niu, W.Y. Li, Z.H. Zhang, X.W. Yang, Global and local constitutive behaviors of friction stir welded AA2024 joints, J. Mater. Sci. Technol. (2017).

[11] Y. Deng, B. Peng, G.F. Xu, Q.L. Pan, R. Ye, Y.J. Wang, L.Y. Lu, Z.M. Yin, Stress corrosion cracking of a high-strength friction-stir-welded joint of an Al–Zn–Mg–Zr alloy containing 0.25 wt% Sc, Corros. Sci. 100 (2015) 57–72.

[12] E. Bousquet, A. Poulon-Quintin, M. Puiggali, O. Devos, M. Touzet, Relationship between microstructure, microhardness and corrosion sensitivity of an AA 2024-T3 friction stir welded joint, Corros. Sci. 53 (2011) 3026–3034.

[13] A.T. Kermanidis, A. Tzamtzis, An experimental approach for estimating the e□ect of heat a□ected zone (HAZ) microstructural gradient on fatigue crack growth rate in aluminum alloy FSW, Mater. Sci. Eng. A 691 (2017) 110–120.

[14] .R. Ni, D.L. Chen, B.L. Xiao, D. Wang, Z.Y. Ma, Residual stresses and high cycle fatigue properties of friction stir welded SiCp/AA2009 composites, Int. J. Fatigue 55 (2013) 64–73.

[15] G. Biallas, E□ect of welding residual stresses on fatigue crack growth thresholds, Int. J. Fatigue 50 (2013) 10–17.

[16] P.S. Prevey, J.T. Cammett, The influence of surface enhancement by low plasticity burnishing on the corrosion fatigue performance of AA7075-T6, Int. J. Fatigue 26 (2004) 975–982.

[17] C. Genevois, A. Deschamps, A. Denquin, B. Doisneau-Cottignies, Quantitative in- vestigation of precipitation and mechanical behaviour for AA2024 friction stir welds, Acta Mater. 53 (2005) 2447–2458.

[18] G. İpekoğlu, G. Çam, E□ects of initial temper condition and postweld heat treatment on the properties of dissimilar friction-stir-welded joints between AA7075 and AA6061 aluminum alloys, Metall. Mater. Trans. A 45 (2014) 3074–3087.

[19] G. Liu, S.C. Wang, X.F. Lou, J. Lu, K. Lu, Low carbon steel with nanostructured surface layer induced by high-energy shot peening, Scr. Mater. 44 (2001)1791–1795.

[20] C.S. Paglia, K.V. Jata, R.G. Buchheit, The influence of artificial aging on the mi- crostructure, mechanical properties, corrosion, and environmental cracking sus-ceptibility of a 7075 friction-stir-weld, Mater. Corros. 58 (2007) 737–750.

[21] Arunkumar. G | Dr. P. Navaneetha Krishnan | Dr. T. Senthil Kumar, "Experimental Enhancement of Heat Transfer Analysis on Heat Pipe using SiO2 and TiO2 Nano Fluid," Int. J. Trend Sci. Res. Dev., vol. 2, no. 4, 2018

[22] K. Chinnarasu, M. Ranjithkumar, P. Lakshmanan, and K. B. Hariharan, "Analysis of Varying Geometri Structures of Fins using Radiators," vol. 11, no. 2015, pp. 115–119, 2018.

[23] A. G. A. S. Dinesh and S. A. K. Rajaguru V. Vijayan, "Analysis and optimization of performance parameters in computerized I.C. engine using diesel blended with linseed oil and leishmaan's solution," Mech. Mech. Eng., vol. 21, no. 2, 2017.

[24] S. Dinesh, G. A. A, S. Karuppusamy, S. K. B, and V. Vijayan, "Experimental Investigation and Optimization of Machining Parameters in CNC Turning Operation of Duplex Stainless Steel," Asian J. Res. Soc. Sci. Humanit., vol. 6, no. 10, pp. 179–195, 2016.

[25] G. Navaneethakrishnan, V. Selvam, and S. J. Jaisingh, "Development and Mechanical Studies of Glass / Banana Fiber Hybrid Reinforced Silica Nano Particles with Epoxy Bio-Nanocomposites," J. Chem. Pharm. Sci., no. 7, pp. 197–199, 2015.

[26] C. S. G. Navaneethakrishnan1, V. Selvam1*, "Effect of CaCO 3 and Al 2 O 3 Fillers on Mechanical Properties of Glass / Epoxy Composites," Int. J. Mod. Trends Sci. Technol., vol. 3, no. 6, pp. 207–214, 2017.

[27] A. Journal, "A sian R esearch C onsortium Optimization of Face Milling Parameters for Material Removal Rate and Surface Roughness on Inconel 718 using Response Surface Methodology and Genetic Algorithm," vol. 6, no. 9, pp. 1198–1201, 2016.

[28] C. M. V. and S. D. K. Pradeep Mohan Kumar, V. Vijayan, B. Suresh Kumar, "Computational Analysis and Optimization of Spiral Plate Heat Exchanger," J. Appl. Fluid Mech., vol. 11, pp. 121–128, 2018.

[29] 4S. Dinesh K. RadhaKrishnan, 2A. Godwin Antony, 3K. Rajaguru, "Experimental Investigation on Machining of

Aluminium Metal Matrix using Electrical Discharge Machining," Adv. Nat. Appl. Sci., vol. 73, no. 6, pp. 1061–1069, 2013.

[30] S. D. K. RadhaKrishnan, A. Godwin Antony, K. Rajaguru, "Experimental Investigation on Machining of Aluminium Metal Matrix using Electrical Discharge Machining," Adv. Nat. Appl. Sci., vol. 11, no. 7, pp. 809–816, 2017.

[31] I. J. I. premkumar1* and G. N. K. K.Lingadurai1, "Investigation of Production and Evaluation of Mono Alkyl Esters in Compression ignition Engines," Int. J. ChemTech Res., vol. 10, no. 2, pp. 1071–1078, 2017.

[32] S. Kannan, N. Baskar, M. Varatharajulu, and B. Suresh Kumar, "Modeling and optimization of face milling parameters on brass component using response surface methodology and genetic algorithm," Int. J. Appl. Eng. Res., vol. 10, no. 76, pp. 219–224, 2015.

[33] T. D. B. Kannan, G. R. kannan, B. S. Kumar, and N. Baskar, "Application of Artificial Neural Network Modeling for Machining Parameters Optimization in Drilling Operation," Procedia Mater. Sci., vol. 5, pp. 2242–2249, 2014.

[34] V. M. Kannan. S., Suresh Kumar. B, Baskar. N, "Selection of Machining Parameters of Face Milling operation for Aluminium with HSS cutter using Response Surface Metho ....," J. Adv. Chem., vol. 12, no. November, pp. 4938–4949, 2016.

[35] S. Karuppusamy et al., "Experimental Investigation of Al2O3-Polyethylene Glycol and TiO2-Polyethylene Glycol Nanofluids Flow through a Minichannel Heat Sink," Asian J. Res. Soc. Sci. Humanit., vol. 6, no. 7, pp. 129–134, 2017.

[36] S. Karuppusamy, G. Karthikeyan, S. Dinesh, and T. Rajkumar, "Design and Analysis of Automotive Wheel Rim by using ANSYS and MSC Fatigue Software," Asian J. Res. Soc. Sci. Humanit., vol. 6, no. 10, pp. 196–212, 2016.

[37] B. S. Kumar, V. Vijayan, and N. Baskar, "Optimization of Drilling Process Parameters for Material Removal Rate and Surface Roughness on Titanium Alloy using Response Surface Methodology and Fire Fly Algorithm," A sian R esearch C onsortium, vol. 6, no. 5, pp. 1251–1253, 2016.

[38] B. S. Kumar and N. Baskar, "Integration of fuzzy logic with response surface methodology for thrust force and surface roughness modeling of drilling on titanium alloy," Int. J. Adv. Manuf. Technol., vol. 65, no. 9–12, pp. 1501–1514, 2013.

[39] B. S. Kumar and N. Bskar, "Experimental investigation of machining parameters in drilling operation using conventional and CNC machines on titanium alloy," Int. J. Eng. Technol., vol. 6, no. 2, pp. 872–880, 2014.

[40] B. S. Kumar, V. Vijayan, and N. Baskar, "Comparison of coated and uncoated carbide drill bits for drilling titanium grade 2 material,"Mechanika, vol. 22, no. 6, pp. 571–575, 2016.

[41] J. K. Kumar, C. S. Raj, P. Sathishkumar, P. Gopal, and A. G. Antony, "Investigation of Performance and Emission Characteristics of Diesel Blends with Pine Oil," J. Appl. Fluid Mech., vol. 11, no. 2015, pp. 63–67, 2018.

[42] R. N. Kumar and D. S. Kumar, "Experimental Investigation of Al2O3-Polyethylene Glycol and TiO2-Polyethylene Glycol Nanofluids Flow through a Minichannel Heat Sink," A sian R esearch C onsortium, vol. 6, no. 9, pp. 1404–1418, 2016.

[43] T. B. Kumar, N. Balaji, and J. Esakiappan, "Intensifying the Mechanical Properties of Is-4454 / 1981," A sian R esearch C onsortium, vol. 6, no. 12, pp. 681–683, 2016.

[44] P. Lakshmanan, P. Kaliyappan, M. Ranjithkumar, K. Aravinth, and D. Vakkachan, "An Experimental Investigation to Study the Performance and Emission Characteristics of Chicken Fat Oil Fuelled DI Diesel Engine," J. Appl. Fluid Mech., vol. 10, pp. 85–91, 2017.

[45] T. Moorthy, S. T. Selvamani, S. Divagar, M. Vigneshwar, and K. Sabareesh, "Performance and emission evaluation of VCR diesel engine using mahua oil methyl ester," Int. J. Appl. Eng. Res., vol. 10, no. 83 Special Issue, pp. 55–60, 2015.

[46] H. Nishikawa and S. Ozawa, "Radial basis function network for multitask pattern recognition," Neural Process. Lett., vol. 33, no. 3, pp. 283–299, 2011.

[47] N. H. Padmaraj, L. G. Keni, K. N. Chetan, and M. Shetty, "Mechanical Characterization of Areca husk-Coir fiber reinforced hybrid Composites," Mater. Today Proc., vol. 5, no. 1, pp. 1292–1297, 2018.

[48] P. Parameswaran, A. Godwin Antony, S. Dinesh, and K. Radhakrishnan, "Experimental study on mechanical and corrosion characteristics of nab alloy with the addition of chromium," Mater. Today Proc., vol. 5, no. 2, pp. 8089–8094, 2018.

[49] P. Parameswaran, A. M. Rameshbabu, G. Navaneetha Krishnan, R. Yogeshwaran, and R. Ramkumar, "Study of the corrosion properties in a hot forged Cu-Al-Ni alloy with added Cr," J. Mech. Behav. Mater., vol. 27, no. 3–4, pp. 1–6, 2018.

[50] A. Parthiban, R. Ravikumar, B. S. Kumar, and N. Baskar, "Process performance with regards to surface roughness of the CO2 Laser Cutting of AA6061'T6 Aluminium Alloy," Lasers Eng., vol. 32, no. 5–6, pp. 327–341, 2015.

[51] R. Rajesh, V. Vijayan, and T. Karthikeyan, "Topology Optimization and Flexible Building Block Design and Analysis of Compliant Mechanism for Vibration Isolation," Int. J. Sci. Eng. Res., vol. 4, no. 8, p. 46, 2013.

[52] A. M. Rameshbabu, P. Parameswaran, V. Vijayan, and R. Panneer, "Diffraction, microstructure and thermal stability analysis in a double phase nanocrystalline Al20Mg20Ni20Cr20Ti20high entropy alloy," J. Mech. Behav. Mater., vol. 26, no. 3–4, pp. 127–132, 2017.

[53] P. P. S. DINESH, A. GODWIN ANTONY, K. RAJAGURU, "Comprehensive analysis of wire electric discharge machining process in machining high chromium high carbon steel," Int. J. Mech. Prod. Eng. Res. Dev., vol. 8, no. 1, 2018.

[54] V. V. S. Dinesh, A. Godwin Antony, K. Rajaguru, "Experimental investigation and optimization of material removal rate and surface roughness in centerless grinding of magnesium alloy using grey relational analysis," Mech. Mech. Eng., vol. 21, no. 1, 2017.

[55] A. G. A. S. Dinesh, K. Rajaguru, V. Vijayan, "Investigation and prediction of material removal rate and surface roughness in CNC turning of EN24 alloy steel," Mech. Mech. Eng., vol. 20, no. 4, 2016.

[56] V. V. S.Dinesh, Prabhakaran.M, A.Godwin Antony, K.Rajaguru, "INVESTIGATION AND OPTIMIZATION OF MACHINING PARAMETERS IN PROCESSING AISI 4340 ALLOY STEEL WITH ELECTRIC DISCHARGE MACHINING," Int. J. Pure Appl. Math., vol. 117, no. 16, pp. 385–391, 2017.

[57] C. Sakthivel, P. Gopal, C. Rameshkumar, and B. S. Kumar, "Co-Combustion Analysis of Lignite Coal and Groundnut Shell using TGA," vol. 11, pp. 75–78, 2018.

[58] B. Saranathancollege, "Selection of Machining Parameters of Face Milling operation for Aluminium with HSS cutter using Response Surface Metho ....," vol. 12, no. November, pp. 0–11, 2016.

[59] A. Sudhahar and K. Sridevi, "Experimental Investigation on Replacement of Fine Aggregate with Dolomite Silica Waste in Cement Concrete Roads," A sian R esearch C onsortium, vol. 6, no. 10, pp. 640–641, 2016.

[60] B. Suresh Kumar, V. Vijayan, and N. Baskar, "Burr dimension analysis on various materials for convenantionally and CNC drilled holes," Mech. Mech. Eng., vol. 20, no. 3, pp. 347–354, 2016.

[61] M. S. and S. D. T. Avudaiappan, V. Vijayan, S. Sundara Pandiyan, "Potential Flow Simulation through Lagrangian Interpolation Meshless Method Coding," J. Appl. Fluid Mech., vol. 11, no. Special issue, pp. 129–134, 2018.

[62] R. Venkatesh and V. Vijayan, "Performance evaluation of multipurpose solar heating system," Mech. Mech. Eng., vol. 20, no. 4, pp. 359–370, 2016.

[63] V. Vijayan and T. Karthikeyan, "Passive vibration isolation by compliant mechanism using topology optimization with building blocks," Res. J. Appl. Sci. Eng. Technol., vol. 8, no. 13, pp. 1522–1530, 2014

[64] V. Vijayan and T. Karthikeyan, "Material Selection of Compliant Mechanism for Vibration Isolation," Mech. Mech. Eng., vol. 18, no. 2, pp. 121–134, 2014.

[65] B.S. Kulkarni, S.B. Pankade, S.R. Andhale, C.L. Gogte, "Effect of backing plate material diffusivity on microstructure, mechanical properties of friction stir welded joints: a review" vol no. 20(2018) page no. 59

[66] Yeh, J. et al. Nanostructured high entropy alloys with multiple component elements: novel alloy design concepts and outcomes. Adv. Eng. Mater. 6, 299–303 (2004).

[67] Cantor, B., Muticomponent and high entropy alloys, entropy 16, 4249–4268 (2014).

[68] Li, Z. et al. Metastable high-entropy dual-phase alloys overcome the strength-ductility trade-off. Nature 534, 227–30 (2016).

[69] Li, Z. et al. A TRIP-assisted dual-phase high-entropy alloy: grain size and phase fraction effects on deformation behavior. Acta Mater. 131, 323–335 (2017).

[70] Deng, Y. et al. Design of a twinning-induced plasticity high entropy alloy. Acta. Mater. 94, 124–133 (2015).

[71] Li, Z. & Raabe, D. Strong and Ductile Non-equiatomic High-Entropy Alloys: Design, Processing, Microstructure, and Mechanical Properties. JOM 69, 2099–2106 (2017).

[72] Heczel, A. et al. Defect structure and hardness in nanocrystalline CoCrFeMnNi High-Entropy Alloy processed by High-Pressure Torsion. J. Alloys Compd. 711, 143–54 (2017).

[73] Hammond, V. H. et al. Equal channel angular extrusion of a low density high entropy alloy produced by high energy cryogenic mechanical alloying. JOM 66, 2021–2029 (2014).

[74] Kumar, N. et al. Friction stir processing of a high entropy alloy Al0.1CoCrFeNi. JOM 67, 1007–1013 (2015).

[75] Palanivel, S. et al. A framework for shear driven dissolution of thermally stable particles during friction stir welding and processing. Mater. Sci. Eng. A 678, 308–314 (2016).

[76] Valiev, R. & Langdon, T. G. Principles of equal channel angular pressing as a processing tool for grain refinement. Prog. Mater. Sci 51, 881–981 (2006).

[77] Zhilyaev, A. P. & Langdon, T. G. Using high pressure torsion for metal processing: fundamentals and applications. Prog. Mater. Sci 53, 893–979 (2008).

[78] Calcagnotto et al. Orientation gradients and geometrically necessary dislocations in ultrafine grained dual-phase steels studied by 2D and 3D EBSD. Mater. Sci. Eng. A 527, 2738–2746 (2010).

[79] Martin, S., Ullrich, C. & Rafaja, D. Deformation of austenitic CrMnNi TRIP/TWIP Steels: nature and role of the ε martensite. Mater. Today Proc. 2, 643–646 (2015).

[80] Trichter, F. A study γ → ε phase transformation in Fe-Mn alloys induced by high pressure and plastic deformation. Scripta Metall 12, 431–434 (1978).
[81]
[82] Guimares, J. R. C. & Rios, P. R. Martensite start temperature and the austenite grain-size. J. Mater. Sci. 45, 1074–1077 (2010).
[83] Takaki, S., Nakatsu, H. & Tokunaga, Y. Effects of austenite grain size on ε martensitic transformation in Fe-15mass%Mn alloy. Materials Transactions 34, 489–495 (1993).
[84] Mishra, R. S. & Ma, Z. Y. Friction stir welding and processing. Mater. Sci. Eng. R 50, 1–78 (2005).
[85] Cao, X. & Jahazi, M. Effect of welding speed on the quality of friction stir welded butt joints of a magnesium alloy. Mater. Des. 30, 2033–2042 (2009).
[86] Suhuddin, U. F. H. R., Mironov, S., Sato, Y. S., Kokawa, H. & Lee, C. W. Grain structure evolution during friction-stir welding of AZ31 magnesium alloy. Acta Mater. 57, 5406–5418 (2009).
[87] Feng, A. H. & Ma, Z. Y. Microstructural evolution of cast Mg-Al-Zn during friction stir processing and subsequent aging. Acta Mater. 57, 4248–4260 (2009).