INFLUENCE OF PROCESS PARAMETERS ON THE MECHANICAL PROPERTIES OF FRICTION STIR WELDED AA 2014-T6 ALLOY USING TAGUCHI ORTHOGONAL ARRAY

A. S. Vagh[1], S. N. Pandya[2]

[1]Mechanical Engineering Department, Shree Swami Atmanand Saraswati Institute of Technology, Surat, Gujarat, India.
asvagh@gmail.com
[2]Mechanical Engineering Department, Sardar Vallabhbhai National Institute of Technology, Surat, Gujarat, India.
s.pandya@med.svnit.ac.in

ABSTRACT

The AA 2014-T6 is widely used in the air craft structure and truck body. The alloy cannot be welded by gas welding techniques due to poor weldability. Welding of this Al alloy by Arc & Resistance welding require special techniques & hence costly. The most suitable method for welding AA 2014-T6 is Friction Stir Welding Process. The effect of Friction Stir Welding process parameters on the mechanical properties of the AA 2014-T6 alloy joints produced by friction stir welding have been discussed in this study. Effects of tool design, tool rotation speed & tool travels speed on mechanical properties have been analysed using Taguchi orthogonal array design of experiments technique. There are three different tool rotation speeds (1000, 1400 & 2000 rpm) and three different tool traverse speeds (14, 20, 28 mm/min). For each combination of tool rotation speeds and tool traverse speeds three different types of tool pin profiles (threaded cylindrical pin, Stepped pin and Threaded cone pin) have been used. The study indicates that Tool design is the main process parameter that has the highest statistical influence on mechanical properties. However, other parameters such as Tool rotation speed & Tool travel speed has also significant effect on mechanical properties.

KEYWORDS: *Friction Stir Welding, Tool Design, Mechanical Properties, Taguchi Orthogonal Array, Analysis of Variance (ANOVA).*

I. INTRODUCTION

AA 2014 is most widely used in heavy-duty forgings, plate, extrusions for aircraft fittings, wheels, major structural components, space booster tankage, truck frame and suspension components. These applications demands, high strength and hardness as well as good elevated temperatures properties [1]. Friction Stir Welding (FSW) is an emerging solid state joining process in which the material is welded without melting of faying surfaces [2]. Friction stir welding (FSW) was invented at the welding institute (TWI), UK in 1991. Friction Stir welding is a continuous, hot shear, autogenous process involving non-consumable rotating tool of harder material than the work material [3].
Defect free welds with good mechanical properties can be made in a variety of Aluminium alloys, including alloys which are not weldable by fusion welding process. Here, phase transformations which occur during cooling of the weld are of solid state nature. Due to the absence of melting of the metal, the Friction Stir Welding (FSW) process is observed to offer several advantages over fusion welding [4]. Earlier Threadgill [5] identified four different micro structural zones observed in a FSW weld such as: (i)Base Metal(BM) (ii)Heat Affected Zone(HAZ) (iii) Thermo mechanically Affected Zone (TMAZ) & (iv) Nugget Zone (NZ).

Hakan Aydın et. al.[6] have found as welded joint yield strength & tensile strength of Friction Stir Welded 2024-T4 Alluminum alloy 279 MPa & 389 MPa respectively against 351 MPa & 492 MPa that of unwelded metal. However, yield and tensile strength of the 2024-T6 (190 oC – 10 h) joint are found 24% and 11% greater, respectively, than those of the as-welded joint. K. Elangovan & V. Balasubramanian [7] made experiments to know influence of tool pin profile and welding speed on the formation of friction stir processing (FSP) zone in AA2219. The study revealed that out of Straight cylindrical, taper cylindrical, threaded cylindrical, square, triangular tool pin profile; square tool pin profile gives the highest tensile strength and yield strength value in FSP zone at 0.76 mm/s welding speed. Biallas et al. [8] have illustrated transverse tensile strength of the welded joint as a function of sheet thickness and FSW process parameters. For 4 mm thick 2024-T3 Al sheet, the tensile strength ranges have been obtained in between 408 to 432 MPa against the parent-metal strength of 497 MPa. Hashimoto et al. [9] evaluated tensile properties of friction stir welded 2024-T6 Al alloy and illustrated a post-friction stir weld tensile strength of 440 MPa. N. Rajamanickam & S. Balusamey [10] observed the variation of tensile properties of AA 2014 at various tool traverse speeds and tool rotational speeds. From the experimental results, it was found that the ultimate tensile strength increases with increase in weld speed in the test range. It was also observed that decreasing the parameter of tool rotation speed increases the tensile strength. Strangwood et. al. [11] investigated the mechanical properties of friction stir welded 0.25 inch thick 2014-T6 plate. Welding was performed at 3.14-4.62 in/min. No other weld parameters or tooling information were disclosed, and the authors did not indicate the welding direction was or publish a joint profile. Alloy microstructures were investigated, using TEM. G. Madhusudhan Reddy & Suresh D. Meshram [12] observed the influence of tool rotation speed and tool pin profile on defect formation/elimination in AA 2014-T6 weld. Two different types of pin profiles- threaded & threadless have been used during FSW. Micro structural characterization of Weldments produced with process parameters has been discussed.

It should be noted that although these studies have made attempts to assess effects of FSW process parameters on microstructure & mechanical properties of 2xxx group wrought Al alloys, there is not any systematic study which directly compares effect of tool pin profile on mechanical properties of 2014-T6 Al alloy welds using Taguchi DOE technique. Taguchi techniques have been widely applied for optimization in material processing [13-20]. Recently it has emerged as a proven technique.

Hence in this investigation effect of tool design, tool rotation speed and tool travel speed on tensile strength and hardness of the friction stir welded AA 2014-T6 joint have been analysed with Taguchi's robust design concept (L9 orthogonal array).Initially an overview of experimental procedure has been discussed in brief. In subsequent section result and discussion has been included. At the last concluding remarks has been put. The study indicates that Tool design is the main process parameter that has the highest statistical influence on mechanical properties. However, other parameters such as Tool rotation speed & Tool travel speed has also significant effect on mechanical properties.

II. EXPERIMENTAL WORK

Friction Stir Welding was carried out on AA 2014-T6 plates having dimensions 180 mm (l) × 90 mm (w) × 5mm (h) in butt joint configuration. The chemical composition and mechanical properties of base metal are tabulated in Table 1 and 2 respectively. For the present work EN-8(BS) hot worked tool steel has been chosen as tool material. EN-8 is a medium carbon steel with good tensile strength & wear resistance. Ultimate Tensile Strength (UTS) of EN-8 tool steel is 650 N/mm2 [20]. The Chemical composition of the tool material EN-8 (BS) is given in Table 3.

The Design of three newly developed tools which were used in the present work is illustrated in Figure1. It should be noted that, in each design shape and size is same and having shoulder under surface is diamond knurled concave surface. The shoulder diameter is 25 mm. The shoulder area in contact with work piece surface is same in all three cases. However, the main important design parameter which differentiates among these tools is the shape of the pin.

Three different shapes of the pin which were used include (a) threaded cylindrical pin (Tool design I), (b) stepped pin (Tool design II) and (c) threaded cone pin (Tool design III). It should be noted that length of the pin is same in each case while surface area of the pin in contact with abutting base metal plates are different & depends upon pin shape. For welding purpose BATLIBOI make BVF-5 Vertical Milling machine was used. Trial runs were conducted prior to conducting actual experiments. A pilot hole of 8 mm diameter was purposefully machined at the abutting surface. During the welding Tool tilt angle was kept constant at 20. FSW welding was carried out with different tool design, tool rotational speed and tool travel speed using taguchi orthogonal array Design of experiments technique. Other process parameters like downward force & heat sink etc. were kept constant. Weldments prepared by Friction Stir Welding processes were visually inspected for their soundness.

Table 1. Chemical composition of AA2014-T6 [1]

Elements	Cu	Si	Mg	Fe	Zn	Ti	Ti + Zn	Mn	Cr	Al
Amount (wt. %)	3.9 - 5.0	0.5 - 0.7	0.3 – 0.8	0.7 max	0.25 max	0.15 max	0.2 max	0.40 - 1.2	0.1 max	Balance

Table 2. Mechanical properties of AA2014-T6 [1]

Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)	Hardness (HB)	Shear Strength (MPa)	Fatigue Strength (MPa)
483	414	13	135	240	125

Table 3. Chemical composition of EN-8 [1]

Elements	C	Si	Mn	P	S
Amount (wt. %)	0.36 – 0.44	-	0.60 – 1.00	0.050	0.050

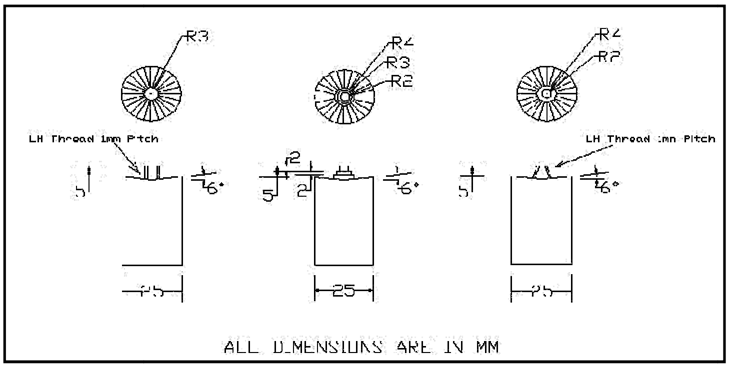

Figure 1. Design and drawing of FSW tools

For the present study Taguchi orthogonal array design of experiment with three factors at three levels was used. Following three variables have been chosen as independent variables: Tool design, Tool rotation speed and Tool travel speed. All the factors and their levels are tabulated in Table 4.

Table 4. DOE-Experimental levels and factors

Factors	Tool Design	Tool Rotation Speed (RPM)	Tool travel speed (mm/min)
Notations	**B**	**C**	**D**
Levels			
1	I	1000	14
2	II	1400	20
3	III	2000	28

For obtaining tensile test specimen Friction stir welded plates were sliced (Figure2) in traverse direction using a power hacksaw. Tensile test specimens were prepared as per ASTM E8M-04 using CNC Milling machine (Figure3&4) [21]. Two tensile specimens were prepared for each combination of process parameters. Then average values of these two tests have been reported. Tensile tests have been carried out on 400 kN, electro-mechanical controlled Universal Testing Machine. The specimen is loaded at the rate of 1.5 kN/min as per ASTM specifications [13].

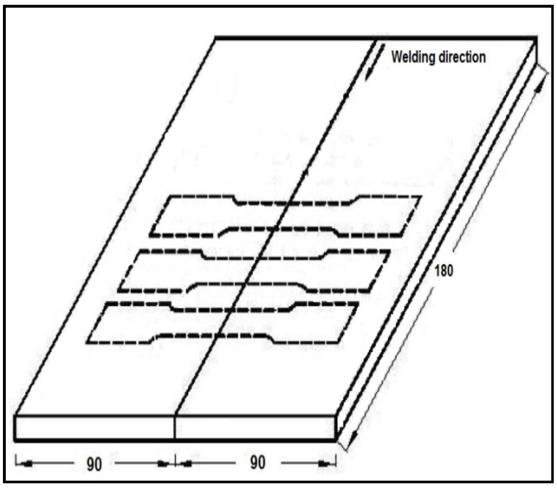

Figure2. Schematic for sampling of tensile test specimens

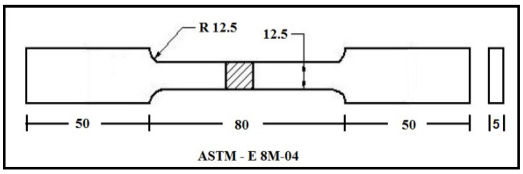

Figure 3. Tensile specimen drawing

Figure 4. Photograph of Machined tensile specimen

III. Results and Discussion

Design of experiments methodology used is standard taguchi L9 orthogonal array. Results of Transverse Tensile tests, nugget hardness and % elongation are tabulated in Table 5. It can be seen that Ultimate Tensile Strength (UTS) values are ranging from 78 MPa to 260 MPa. Against nominal UTS of base metal 483 MPa, with maximum joint efficiency 54 %. It can be concluded that there is drastic reduction in ductility of the material due to welding, as maximum percentage elongation is noted 4.76 % against nominal value of 13 %. Almost all tensile test specimens have been fractured from nugget zone indicating that weld nugget is the weakest area.

Table 5. Tensile Strength, Nugget Hardness & % Elongation result data

Test sp. No.	Tool Design	Tool Rotation Speed (RPM)	Tool Travel Speed (mm/min)	Tensile Strength (MPa)	% Elongation	Nugget Hardness (BHN)
1	I	1000	14	105.95	1.48	166.51
2	I	1400	20	113.80	0.50	135.07
3	I	2000	28	78.48	0.50	186.29
4	II	1000	20	243.29	4.76	72.83
5	II	1400	28	232.30	1.48	85.65
6	II	2000	14	226.02	2.44	93.23
7	III	1000	28	260.55	3.38	101.77
8	III	1400	14	189.14	1.96	101.77
9	III	2000	20	97.32	0.50	122.45

It can be noted that Mean Tensile Strength value for Tool design I (with cylindrical probe) is the lowest (99.41MPa) among three. On the other hand for Tool design II (with stepped probe) the same is the Highest (233.87MPa). In case of Tool design III, mean Tensile strength values are intermediate between Tool design I & II. The highest Tensile Strength for Tool design II can be obtained to stepped probe which increases the volume of material deformation. Because of changing surface area of the tool (Design-I > Design-III > Design-II) there is a significant difference in the heat input through friction and material deformation.

The main effect plot for Tensile Strength (Figure 5) with respect to tool rotation speed is very interesting to note. There is an inverse proportionality between the Tensile Strength and Tool rotation speed. Increasing the Tool rotation speed resulted into reduced the Tensile Strength. There is very minor variation is obtained in Tensile Strength with increasing tool travel speed from 14 mm/min to 28 mm/min.

Main effect plots for percentage elongation (Figure 5) indicates that with increment in tool rotation speed there is drastic decrement in percentage elongation. However slight decrement can be seen for increased tool traverse speed. It also indicates decreasing ductility. However obtained percentage elongation is very less in comparison to percentage elongation of base metal. The highest percentage elongation is observed with tool rotation speed of 1000 rpm and Tool design-II i.e. stepped probe.

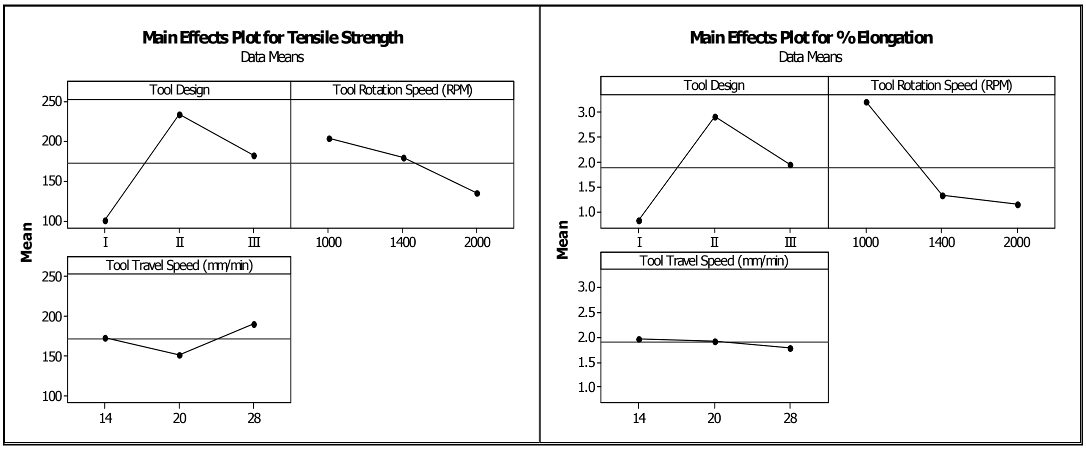

Figure5. Main effect plots for tensile strength and % elongation

A main effect plot for nugget hardness is shown in Figure 6. Notable variation in BHN hardness can be seen with change in tool design. Mean BHN value for Tool design I (with cylindrical probe) is the highest (162.62 BHN) among three. On the other hand for Tool design II (with stepped probe) the same is the lowest (89.90 BHN). This can be explained on the basis of higher surface area of tool in contact with deeper areas of weld nugget in case of Tool design I in comparison to Tool design II resulting into higher heat input & cooling rate. On the other side, with Tool design II there is shallow temperature gradient from crown to root due to steps on the probe. In case of Tool design III, mean BHN values are intermediate between Tool Design I & II.

The main effect plot for BHN with respect to tool rotation speed is very interesting to note. There is not significant variation in BHN with change in tool rotation speed from level 1 (113.70 BHN, 1000 rpm) to level 2 (107.50 BHN, 1400 rpm). However, at level 3 (2000 rpm) there is drastic increment of more than 10% (133.99 BHN). The difference in nugget hardness between the fast and slow welds can be attributed to higher peak temperature in the fast weld, resulting in solution heat treatment of the fast weld nugget and over-aging of the slow weld nugget; additionally, the fast weld nugget will have experienced a higher cooling rate than the slow weld nugget.

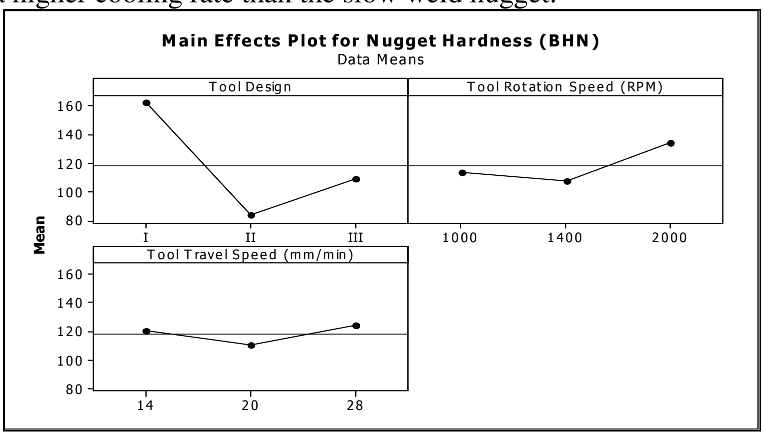

Figure 6. Main effect plot for Nugget hardness

ANOVA results are tabulated in table 6 to 8. It is observed that the Tool design (P = 74.01%) and Tool rotation speed (P = 19.84%) and Tool travel speed (P = 6.15%) have statistical significant effect on the tensile strength obtained. Similarly it can be noted that the Tool design (P = 44.82%) and Tool rotation speed (P = 54.83%) have statistically significant effects on the percentage of elongation obtained. The Tool travel speed does not present percent of statistical significance of contribution on both tensile strength and percentage elongation. There is very minor variation in BHN with change in tool travel speed from 14 mm/min to 28 mm/min. From Table 6 (b) it can be concluded that tool design is the most affecting (86.74 %) parameter to hardness of welded joints. The next to it is tool rotation speed having 10.28 % contribution & Tool travel speed having only 2.97 % contribution.

Table 6. ANOVA for Tensile Strength of weldment

Factor	SS	DF	MS	F	%P
A	27612.93	2	13806.47	12.04	74.01
B	7401.20	2	3700.60	3.23	19.84
C	2294.06	2	1147.03	1.00	6.15
Total	37308.20	6	18654.10		100.00

Table 7. ANOVA for Tensile Nugget Hardness of weldment

Factor	SS	DF	MS	F	%P
A	9721.69	2	4860.84	29.16	86.74
B	1152.23	2	576.11	3.46	10.28
C	333.38	2	166.69	1.00	2.97
Total	11207.23	6	5603.65		100.00

Table 8. ANOVA for % Elongation

Factor	SS	DF	MS	F	%P
A	6.42	2	3.21	129.94	44.82
B	7.86	2	3.93	158.96	54.83
C	0.05	2	0.02	1.00	0.34
Total	14.33	6	7.16		100.00

It can be seen from plotted hardness variation (BHN) across transverse direction of welded joint in Figure 7 that Hardness values have been distributed in typical 'W' shape curve in the transverse direction for all 9 runs. In this way, Hardness results are in accordance to an Al alloy welded by Friction Stir Welding process. Range of the BHN value is from 72 BHN to 186 BHN in the transverse direction for Nugget Zone, HAZ, TMAZ & Base metal, while nominal hardness value for the base metal is 101 BHN. In each case, there is hardness peak at the weld centreline. According to prevalent techniques of determining Nugget Zone described in the literature it can be concluded that nugget zone in each case is nearly up to 10 mm on both side from weld centreline as there is observed a local minima. Similarly, Heat Affected Zone (HAZ) & Thermo Mechanically Affected Zone (TMAZ) is from 10 mm to 25 mm on both side while rest is the parent metal. In general, BHN values at a distance of 10 mm on advancing side (-10 mm on plots) are lower than those on retreating sides for all runs.

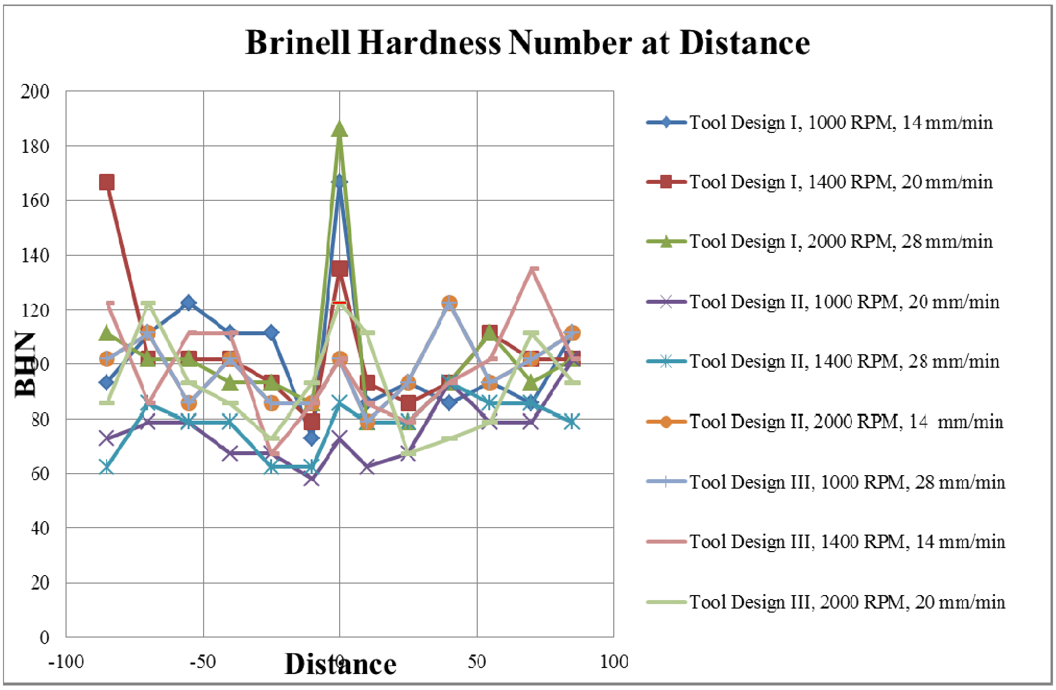

Figure 7. Brinell hardness number at different location in transverse direction

IV. CONCLUSIONS

Friction stir welding has been carried out successfully on 2014-T6 aluminium alloy. Taguchi orthogonal DOE technique is used to analyse effect of major process parameters-Tool rotation speed, Tool Traverse Speed and Tool Pin Profile on mechanical properties of weldments.
The joint efficiency of the AA 2014-T6 aluminium alloy joints are obtained up to 55%. The percentage elongations of all the joints are far lower than those of the base materials. The highest strength is obtained at Tool Design-II, 1400 rpm Tool rotation speed & 20 mm/min Tool travel speed. Highest elongation is obtained at Tool Design-II, 1000 rpm Tool rotation speed & 20 mm/min Tool travel speed.
From the ANOVA, it can be concluded that the Tool Design is the main input parameter that has the highest statistical influence on Tensile strength (74.01%) and nugget hardness (86.74%).
It is also found that, there is very minor variation in the mechanical properties by changing the Tool travel speed.

ACKNOWLEDGEMENTS

The authors wish to express their sincere thanks to Sardar Vallabhbhai National Institute of Technology, Surat, Gujarat, India for the technical & financial support to carried out this investigation.

REFERENCES

[1] ASM Handbook – Vol. 02 (1992) Properties and Selection Nonferrous Alloy and Special – Purpose materials (3470s).
[2] Thomas, W.M., (1991) Friction stir welding, International Patent Application No. CT/GB92/02203 and GB Patent Application No. 9125978.8, December 1991, U.S Patent No. 5,460,317.
[3] Dawes, C.J., (1995) An introduction to friction stir welding and its development. Weld. Met. Fabr., 12.
[4] Cao, G., Kou, S. (2005) Friction stir welding of 2219 aluminium: behaviour of (AlCu) particles. Weld. J., 1s–8.
[5] C.J. Dawes and W.M. Thomas (1996), Weld. J., Vol. 75, p 41.
[6] Hakan Aydın, Ali Bayram & Ismail Durgun(2010)The effect of post-weld heat treatment on the mechanical properties of 2024-T4 friction stir-welded joints, Materials and Design 31 2568–2577

[7] K. Elangovan, V. Balasubramanian(2008); Influences of tool pin profile and welding speed on the formation of friction stir processing zone in AA2219aluminium alloy, journal of materials processing technology 200, 163–175.
[8] G. Bussu and P.E. Irving (2003), The Role of Residual Stress and Heat Affected Zone Properties on Fatigue Crack Propagation in Friction Stir Welded 2024-T351 Aluminum Joints, Int. J. Fatigue, Vol. 25, p 77–88.
[9] T. Hashimoto, N. Nishikawa, S. Tazaki, and M. Enomoto, Mechanical Properties of Joints for Aluminum Alloys with Friction Stir Welding Process, Joints in Aluminum, INALCO, 1998: Seventh International Conference, Vol. 2, Abington Publishing, 1999.
[10] N. Rajamanickam& S. Balusamey, Effects of process parameter on mechanical properties of friction stir welds using design of experiments, Indian Journal of Engineering and material sciences, Vol. 15, August 2008, pp. 293-299.
[11] M. Strangwood, J.E.Berry, D.P.Cleugh, A.J.Leonard and P.L.Threadgil: First International Symposium on Friction Stir Welding (Session 11), Thousand Oaks, California, USA, 14-16 June 1999.
[12] G. Madhusudhan and Suresh D. Meshram: StudyEffect of Tool Rotation Speed and Tool pin Profile on AA 2014 Aluminium Alloy Friction Stir welds, Proceedings of the IIW International conference on Global Trends in Joining, Cutting and Surfacing Technology, Chennai Trade Centre, Chennai, India, 21-22 July 2011.
[13] Ersan A, Necip C C&Burak B R, Design optimization of cutting parameters when turning hardened AISI 4140 steel (63 HRC) with Al203 + TiCN mixed ceramic tool, Mater Design, 28 (2007) 1618-1622.
[14] Lin T R , Experimental design and performance analysis of TiN coated carbide tool in face milling stainless steel, J Mate Proc Tech, 127 (2002) 1-7.
[15] Davim J P, Design optimization of cutting parameters for turning metal matrix composites based on the orthogonal arrays, J Mater Proc Tech, 132 (2003) 340.
[16] Ghani J A, Choudhury, I A & Hassan H H, Application of Taguchi method in the optimization of end milling operations, J Mater Proc Tech, 145 (2004) 84-92
[17] Palanikumar K, Application of Taguchi and response surface methodologies for surface roughness in machining glass fiber reinforced plastic by PCD tooling, Int J AdvManuf Tech (in press).
[18] Paulo D J, Study of drilling metal-matrix composites based on the Taguchi techniques, J Mater Proc Tech, 132 (2003) 250-254.
[19] ASM Handbook – Vol. 01 – Properties and Selection Irons, Steels, and High Performance alloy (1618s), 1992.
[20] Douglas C. Montgomery, Design and Analysis of Experiments, 5th Edition, Wiley India Publication, 2007, 490-491.
[21] Standard Test Methods for Tension Testing of Metallic Materials [Metric], ASTM E 8M – 04.

Authors

Ankur S. Vagh. Presently working as an Assistant Professor at S.S.A.S.I.T, Surat, Gujarat, India. I have completed my M.Tech. (Mechanical with specialization in Industrial Process Equipment Design) from S.V.N.I.T., Surat, Gujarat, India and B.E. from C.K.P.C.E.T., Surat, Gujarat, India.