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EFFECT OF FRICTION STIR PROCESSING PROCESS PARAMETERS ON QUALITY CHARACTERISTICS OF AL 6063/B4C COMPOSITE

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Abstract— **Al6063 has good surface finishing, high corrosion and resistance, is readily suited to processing has low hardness. Friction stir processing (FSP) is a novel technique used for enhancing the mechanical and metallurgical properties of the material and also to make the structural defects in the material. It eliminates the micro structural defects and porosity in the material. In this study, manufacturing of composite Al6063 and boron carbide (B4C) particles with 20-60 µm particle size were added as reinforcement. In this study, different types of tools are used (cylindrical, tapered and square).The tool shoulder is vary from 16 mm. The friction stir processing tool is made of high speed steel with a pin length 3 mm. The 16 mm shoulder diameter produces sufficient amount of heat to properly plasticize and flow of material during the FSPed process thus producing finer grain size within the nuggest zone and processes high micro-hardness of the material. The maximum micro-hardness achieved is 34.12 Hv. The micro-hardness values of the composite fabricated with square pin tool profile were higher as compare to other selected tool pin profile. The maximum tensile strength achieved is 88 MPa.**

In this study, at first, the optimum frictional stir processing parameters namely rotational speed, pin profile and tilt angle for production of the sound welds with adding the B4C micro particles have been investigated. B4C has unique combinational properties such as high melting point, thermal stability, extreme abrasion resistance, high hardness and low density, due to which it is a good choice as reinforcement in engineering materials. The incorporation of micro-particles can greatly improve the mechanical properties; hence can be used as reinforcement for fabrication of composites. The FSP was performed on untreated Al6063 plates with HSS tools of different probe shape. The effect of rotational speeds, different probe shapes of tool and tilt angle on microstructures and hardness were evaluated for fabricated composites. Experiment is planned according to Taguchi's L9 OA. ANOVA is used to find out optimum processing parameters to attain uniform distribution of reinforcement particles in the composite.

Index Terms— **Friction stir processing, AL 6063/B4C COMPOSITE.**

I. INTRODUCTION

High strength to weight ratio is the most attractive demand in current engineering materials especially in the automobile and aerospace industries. Therefore, the replacement of conventional materials by the lighter materials namely aluminium alloy is highly desirable. However, aluminium alloys are not sufficiently strong, therefore, reinforcements in of materials having high strength are necessary [1]. The fabrication of surface metal matrix composites by conventional techniques based on liquid phase processing at high temperatures, such as laser melt treatment and plasma spraying, may lead to the deterioration of composite properties. It is very complicated to eliminate the interfacial reaction between reinforcement and metal matrix and formation of some detrimental phases [2]. Recently, much attention has been paid to friction stir processing (FSP) as a microstructural modification and fabrication of metal matrix composites technique based on the basic principles of FSW. In FSP instead of welding two different pieces, tool will be inserted into a single part. Tool shoulder plays a key role in generation of surface friction and rise of work-piece temperature [3]. In FSP, a rotating cylindrical tool with a shoulder and probe (pin) is first plunged in to a metallic plate and then traversed along the surface of the work-piece. The rubbing action of tool shoulder with the plate's surface generates frictional heat and softens material under the shoulder which also undergoes severe plastic deformation at high strain rate by rotating pin (called stirring). During FSP, material is subjected to a combination of material is subjected to a combination of metal working processes namely friction, extrusion and forging which caused intense plastic deformation, material mixing, and thermal exposure, resulting in significant microstructural refinement, densification, and homogeneity of reinforcement, leads to significant improvement in mechanical properties of processed zone [4-3].

In current scenario, the ability of aluminium (Al) based materials to exhibit excellent mechanical properties such as hardness and tensile strength has been an emerging field of research activities targeted primarily for the further development. However, the mechanical properties of the aluminium alloys are not so significant to enhance their applications. The mechanical properties of aluminium alloys have been improved by fabrication of aluminium matrix composite using various advanced techniques. In particular, composite fabrication by Friction stir processing (FSP) has recently motivated a great deal of research work on this subject [5]. FSP is a solid state material processing technique based on the principles of friction stir welding development by The Welding Institute (TWI) in 1991 [5]. In FSP, a rotating cylindrical tool with a shoulder and probe (pin) is first plunged in to a metallic plate and then traversed along the surface of the work-piece. The rubbing action of tool shoulder with the plate's surface generates frictional heat and softens material under the shoulder which also undergoes severe plastic deformation at high strain rate by rotating pin (called stirring) [6]. This deformation leads to the formation of very fine equiaxed recrystallized grains within the friction stir-processed zone (FZ). The grain sizes were approximately10–100 times smaller than those in the original work-piece materials. The maximum temperature which the FZ reached during processing decreased with the tool rotation speed, so that the grain size within the FZ decreased. [7].

A. Friction stir processing

Friction stir processing is a method of changing the properties of a metal through intense localized plastic deformation. This deformation is produced by forcibly non-consumable tool into the workpiece, and revolving the tool in a stirring motion as it is pushed laterally through the workpiece. The precursor of this technique, friction stir welding, is used to join multiple pieces of metal without creating the heat affected zone typical of fusion welding. When ideally implemented, this process mixes the material without changing the phase (by melting or otherwise) and creates a microstructure with fine, equiaxed grains. This homogeneous grain structure, separated by high-angle boundaries, allows some aluminium alloys to take on super-plastic properties. Friction stir processing also enhances the tensile strength of the metal. In tests with actively cooled magnesium-alloy workpieces, the micro-hardness was almost tripled in the area of the friction stir processed seam.

B. .Applications

The friction stir processing (FSP) is used when metals properties want to be improved using other metals for support and improvement of the first. This is promising process for the automotive and aerospace industries where new material will need to be developed to improve resistance to wear, creep, and fatigue. Examples of materials successfully processed using the friction stir technique include AA2519, AA5083 and AA7075 aluminium alloys, AZ61 magnesium alloy, nickel-aluminium bronze and 304L stainless steel [8].

C. Research Objective

The primary aim of this research work is to fabricate surface of aluminium alloys AA6063 through B4C particles as reinforcement under various parameters and to study mechanical properties.

- Fabrication of experimental setup of B4C particles.
- Selection of process parameters and their ranges.
- To investigate the fabrication through microstructure.
- To investigate the fabrication through scanning electron microscopy.

- To investigate the fabrication through tensile fractography.
- To investigate the fabrication through residual stresses.
- To investigate the mechanical properties of fabrication like tensile strength and hardness..
- To optimize the process parameters with respect to responses using Taguchi Technique.

D. Scope for research work

Aluminium alloys are extremely useful for many industrial applications, especially automotive and aerospace, because they are relatively light weight and have an excellent strength-to-weight ratio. Because of their low density, the use of aluminium alloys in automotive applications is growing. The fabrication of aluminium alloy components is however still limited. Unfortunately, the conventional fusion welding of aluminium alloys often produces porosity and hot cracks in the fabrication joint. Friction stir processing is based on the basic principle of friction stir welding. The microstructural changes affect the corrosion behaviour of the fabrications. Pitting corrosion is dominant in an aluminium alloy fabrication, and is exceeding destructive, since a perforation resulting from a single pit can be disastrous.

II. Literature Review

In the present scenario, FSP is known as advanced solid state fabrication technique for the synthesis of metal matrix composite having excellent mechanical properties by using metallic alloys such as aluminium and magnesium alloys. This section presents the already fabricated composites, process parameters, modelling and their respective mechanical properties.

Pol et al. (2018) fabricated AA7005/TiB2-B4C surface composite with different weight fractions of TiB2 and B4C particles by FSP for enhancing ballistic resistance. Micro-hardness abrasion and depth tests were conducted to evaluate the ballistic properties of surface compounds. The surface hardness of the compound was found to be 70 HV higher than the base alloy [9].

Abraham et al. (2018) investigated the microstructural characterization of vanadium particles reinforced AA6063 aluminium matrix composites via FSP with improved tensile strength and ductility. The homogeneous and consistent dispersion of vanadium particles enhanced AA6063 AMC effectively using FSP. The interface between the vanadium particles and the aluminium matrix did not show any proliferation or interaction during treatment due to the low temperature of the treatment. A very accurate and equal granular structure was found in the compound due to the dynamic crystallization. A change in the form of vanadium particles was observed due to the high stress rate in the process [10].

Sinha et al. (2019) investigated the ternary immiscible nanostructured Cu-Al-Nb alloys, produced by mechanically compressed particles in FSP. Subsequently, aging treatment at different times was carried out at 563K. Under peak aging conditions (6 hours aging), this material exhibits a hardness of 4.3 ± 0.1 GPa, which is important in Cu based ternary miscible alloys. The excellent strength of this material is due uniform distribution of nano scale Al and Nb-rich precipitates or clusters [11].

Khorrami et al. (2019) investigated the texture variation and mechanical properties of aluminium with SiC nanoparticles as reinforcement under FSP. The incorporation of SiC nanoparticles led to an increase in the yield strength and young's modulus values of the stir zone without a considerable reduction in the elongation. A microstructure-mechanical properties relationship was established considering the strengthening mechanisms to estimate the yield strength of the stir zone [12].

III. MATERIAL AND FABRICATION OF AA 6063/B4C COMPOSITE AND MECHANICAL TESTING

A. Materials

Commercially available rolled sheets of AA 6063 aluminium alloy with chemical composition and mechanical properties given in Table 1 and Table 2 was used in this study. The sheets were cut into rectangular sheets with dimensions of 90×45×5 mm3. The commercially available boron carbide (B4C) powders of average size 20-60 µm were used as reinforcement Particle. High speed steel (HSS) tool was used for FSP. Three different types of HSS tools having different shapes ofpin profiles namely cylindrical, tapered and square were used for the experimentation. Tool has a shoulder diameter and pin length, 16 mm and 3 mm, respectively as shown in Fig 1 and 2.

Table 1: Chemical Compositions of AA6063alloy

Chemical Elements	Mn	Fe	Mg	Si	Zn	Ti	Cr	Cu	Others	Al
Percent Composition	0.0-0.10	0.0-0.35	0.45-0.90	0.20-0.60	0.0-0.10	0.0-0.10	0.0-0.10	0.0-010	0.0-0.15	Balance

Table 2: Mechanical Properties of AA6063alloy

Young's Modulus	Tensile Strength	Elongation	Poisson's Ratio
68.3 GPa	145-186 MPa	18-33 %	0.3

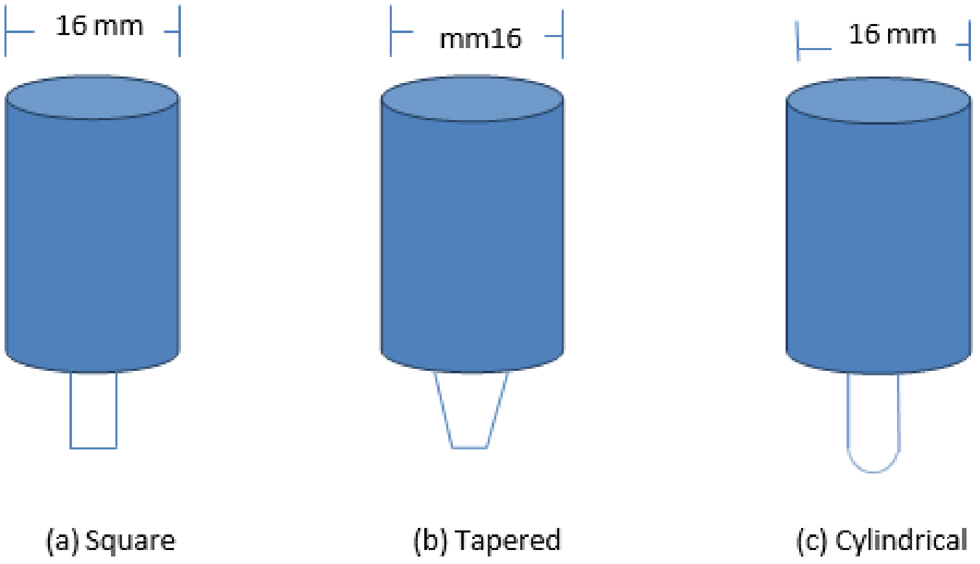

Figure 1: Differents types of tool (in standard form).

Figure 2: Photographs of tools with different probes

Figure 3 shows the fabrication of the AA 6063 plates

Figure 3: Friction stir processing work-piece

B. Process parameters of FSP

FSP is a composite fabrication process consisting of complex interactions between a large numbers of variables such as machine tools, work-piece materials and operating parameters. However, to facilitate experimental data collection, only three dominant factors were considered in the planning of experimentation. The Ishikawa diagram (cause and effect diagram) is constructed as to identify the FSP process parameters that may influence the quality of fabricated composite with addition of B4 Cparticles. In the present investigation, three level process parameters, i.e. rotational speed, tilt angle and pin profile are considered for deciding the quality of composite. The levels of these parameters were selected by performing the pilot test on a machine. A pilot experimentation using one-factor-at-a-time approach was conducted to identify feasible ranges of process parameters. On the basis of pilot experimentation, the ranges and subsequently the levels of the machining parameters were chosen (in Table) .Trial experiments are carried out using 5 mm thick rolled plates of Al6063 aluminium alloy to fix the working range of FSP process parameter. The parameters, selected for experimentation, were as shown in Table 3, along with their limits, units and notations.

Table 3: Process parameters and their levels

Process Parameters	**Level**		
	1	**2**	**3**
Rotational Speed (RPM)	970	1500	2030
Tilt Angle (Degree)	1º	2º	3º
Pin Profile	Cylindrical	Tapered	Square

C. Fabrication of AA 6063/ B4C composite and mechanical testing

Initially, Al alloy plates are cleaned with acetone to remove dirt and organic impurities. The plates were machined at the middle along the length using WEDM to form a groove for filling B4C particles. The length, width and depth of the grooves were 90 mm, 2 mm and 2.5 mm, respectively. The FSP procedures were operated on numerically controlled milling machine with a friction stir welding (FSW) tools of HSS having different pin profiles (cylindrical, tapered and square). Before FSP, B4C particles were filled into the groove and rammed by a plastic plate.. The principle of the FSP can be understood by the Fig 1 in which the rotating tools with different pin profiles are placed on the groove filled with reinforcement powder for frictional stir processing results the fabrication of composites.

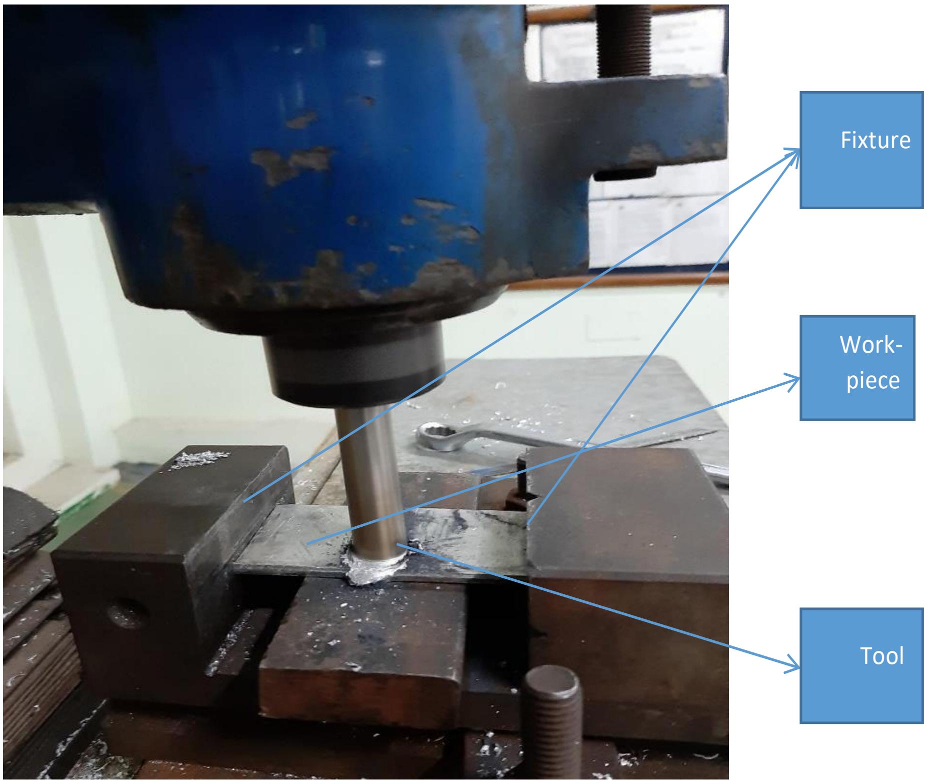

Figure 4: Experimental set-up of friction stir processing

Two passes in opposite direction were carried out to achieve uniform distribution of reinforcing particles in the surface composite layer. Samples were cut from the cross-section of the fabricated surface composites for macro-structural examination. The polished cut section was etched using the Keller's reagent. Optical microscope and scanning electron microscope (SEM) was used for macro and micro structural examination. Micro-hardness of all the samples was measured at three different locations (at 1 mm cut-off value) on the sample applying 100 g load for 10 s dwell time using a HMV-G series Micro Vickers Hardness Tester. However, the differences in the readings of hardness are much higher that may be possible due the presence of reinforcement particle at that particular location. So, the instrument will be able to distinguish between the values clearly, and hence measurements made by this instrument could be considered as accurate enough for the present study. The microstructures of the composites has been evaluated by using optical microscope.

IV. METHODOLOGY

A. Optimization technique

Taguchi method

Taguchi method is used to optimise the performance characteristics of the FSP. Taguchi method is a methodical application of design and investigation of experiments for the purpose of designing and improving the product quality. The view point of Taguchi method is to attain a vigorous engineering design through optimizing design parameters against sensitivity to parameter variations. In Taguchi method, a special design of OAs is used to study the entire process parameter space with a small number of experiments only. A loss function is defined to calculate the deviation between the experimental value and the desired value. Taguchi's loss function is used to measure the performance characteristics deviating from the desired value. The value of the loss function is further transformed into a signal-to-noise (S/N) ratio. Here, the experimental results (or data) are transformed into a signal-to-noise (S/N) ratio. There are several S/N ratios available depending on the types of characteristic; lower is better (LB),Nominal is best (NB) and higher is better (HB). The characteristic whose higher value represents better response such as 'micro-hardness, is called 'HB'. Therefore, 'HB' for micro-hardness is selected for obtaining optimum maximum hardness of composite.

V. RESULTS AND DISCUSSION

A. *Effect of rotational speed on micro-hardness*

Figure 5 shows that the micro-hardness increases with increase the rotational speed up to 2030 r/min after that, micro-hardness decreases. At 2030 r/min rotational speed, plastic deformation of materials is appropriate due to sufficient heat input resulting in defect free fabrication. At a lower rotational speed of 1500 r/min, excessive heat generated around the contact surface between work-piece and tool. Due to excessive heat, the grain become coarse and oxidization of metal occurs in welded zone resulting in the lower tensile strength.

B. *Effect of tilt angle on micro-hardness*

Figure 5 represents that micro-hardness increase with increase the tilt angle. It is due to surface contact between work-pieces and tool shoulder. At lower tilt angle, large surface contact between work-piece and tool causes excess that heat generated. At higher tilt angle, the flow of plasticized material is sufficient due to good forging action.

C. *Effect of tool pin profile on micro-hardness*

Figure 7 shows the different values of micro-hardness for different types of tool pin profile. It is observed that the square type tool pin profile gives the maximum value of micro-hardness. The cylindrical type of tool pin profile produces good material stir quality during fabrication. Tapered and square type tool pin profile produce insufficient mixing because tool pin is incapable of deforming appropriate material during rotation.

D. *Analysis of variance for S/N ratio*

The first step in data analysis of the present study is to summarize the test results for each experiment performed by the use of Taguchi's 9OA. The S/N ratios are then computed in each of the 9 trial conditions, and the values, the average of each parameter at different levels, for main effect (raw data) and S/N ratio, respectively. Both main effect as well as S/N ratio analysis suggests that the factors at levels RPM3, TA1 and PP3 are the best levels that give the maximum value of micro- hardness.

In order to study parameter significance, ANOVA was performed as shown in Table 6. However, F-values have been estimated on 95 % confidence, F.05, 2, 2= 19 that is greater than the estimated F-values for each parameter in Table 6, which verifies the significance of all three parameters rotational speed of tool, tilt angle and pin profile in the FSP.

From Table 6, it could be seen that the rotational speed of tool, tilt angle and pin profile significantly affects the variability in micro-hardness of 51.05%, 32.28%, and 16.30%, respectively.

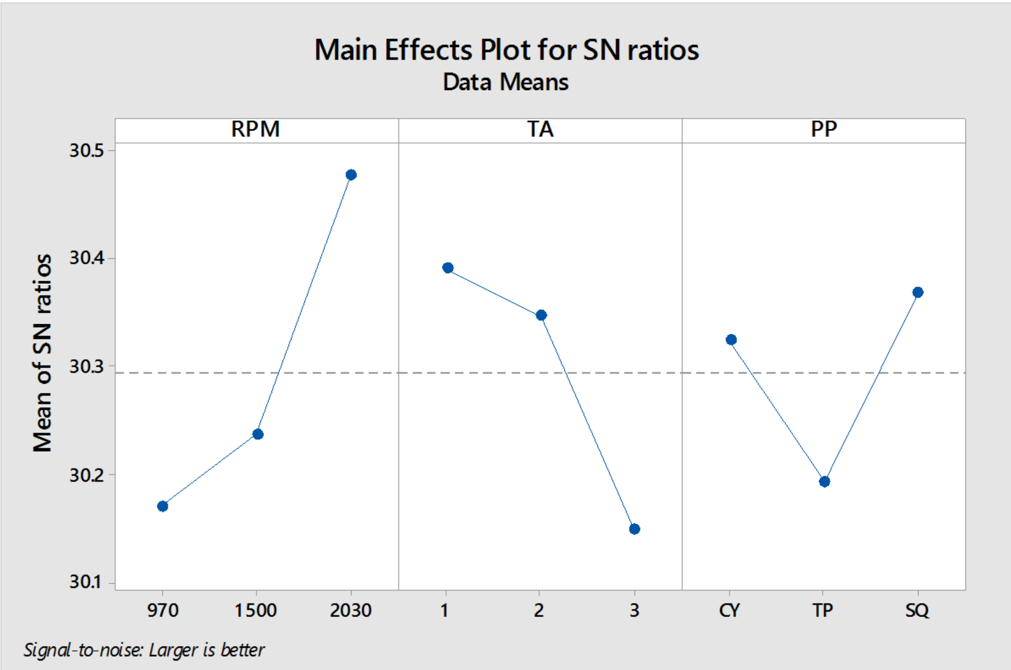

Figure 5: Effects of process parameters on hardness (S/N ratio).

Table 4: Average of Main effect (raw data)

Level	**RPM**	**TA**	**PP**
1	32.25	32.08	32.83
2	32.50	32.92	32.33
3	32.42	32.17	33.00
Delta	1.17	0.92	0.67
Rank	1	2	3

Table 5: Average of S/N ratio

Level	**RPM**	**Tool Angle**	**Pin Profile**
1	30.17	30.39	30.32
2	30.24	30.35	30.19
3	30.48	30.15	30.37
Delta	0.31	0.24	0.17
Rank	1	2	3

Tables 6 present the ANOVA result for mean and S/N ratio. The rotational speed, tilt angle and types of pin profile are significant parameters for micro-hardness.

Table 6: ANOVA for micro-hardness (S/N ratio data)

Source	DOF	Sum of squares	Variance	F-ratio	Percentage contribution (% P)
RPM	2	2.26389	1.13194	183.00	51.09
TA	2	1.43056	0.71528	103.00	32.28
PP	2	0.72222	0.36111	52.00	16.30
ERROR	2	0.01389	0.00694		0.33
TOTAL	8	4.43056			

E. Estimation of optimum performance characteristic

Table 7: main effect on micro hardness (raw data)

Process parameters	Levels	Rotational speed (A)	Tilt angle	Pin profile
Average value (micro-hardness)	L1	32.25	33	32.83
	L2	32.5	32.91	32.33
	L3	33.41	32.16	33
Main effects	L2-L1	0.25	-0.083	-0.5
	L3-L2	0.91	0.75	0.66
Differences	{(L3-L2)-(L2-L1)}	0.41	0.83	1.67

L1 ,L2and L3 represent levels 1, 2 and 3respectively L2-L1 is the average main effect when the corresponding parameter changes from level 1 to 2. L3-L2 is the average main effect when the corresponding parameter changes from level 2 to 3.

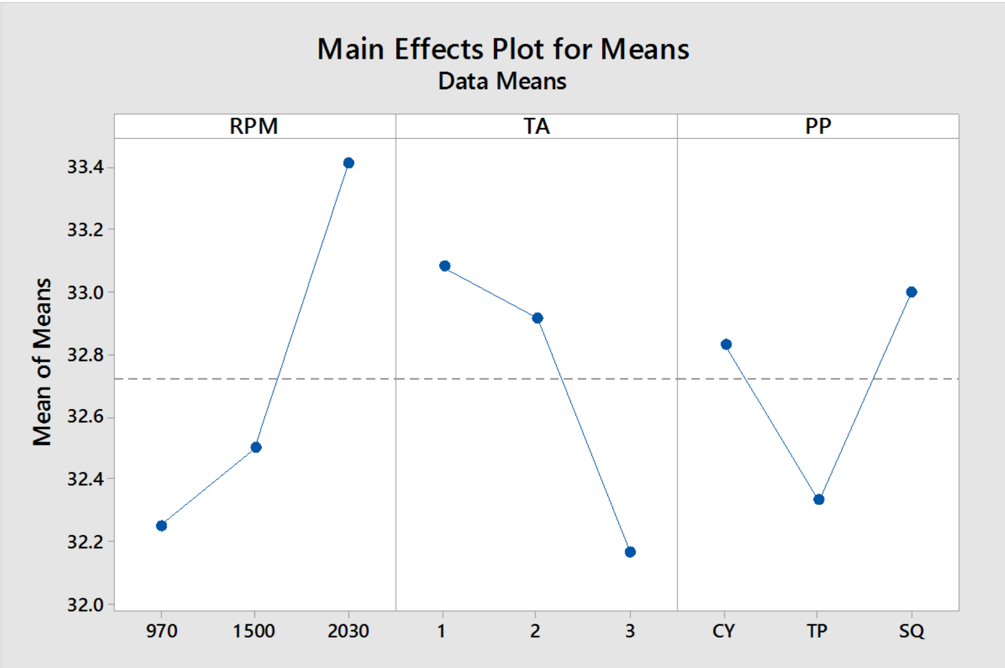

Figure 6: Effects of process parameters on hardness (main effect).

F. Confirmation Test(for micro-hardness)

Conducting a confirmation experiment is a crucial, final and necessary part of the Taguchi method. Its aim, after selecting the optimal parameters, is to predict and verify the improvement of the performance characteristics with the selected optimal processing parameters, i.e. to verify the optimum condition suggested by the L9 OA experiment estimating how close the respective predictions are with the real ones. Experiments were performed three times with combination of different parameters at their optimum level are shown in Table 5.

Table 8: Result of confirmation experiment (for micro-hardness)

Optimal level combination	Test 1	Test 2	Test 3	Average
RPM3, TA1, PP3	33.98	34.49	33.89	34.12

G. Effect of parameters on tensile strength

Figure 7 show the effect of process parameters on Tensile strength for raw data and S/N ratio respectively.

H. Effect of rotational speed on tensile strength

It is fact that the rotational speed is directly proportional to heat generation in FSP up to certain extent. The frictional heat produced the facilitates recrystallization of plasticized material that causes grain refinement in stir zone. At low rotational speed, tunnel defects occurred in middle side due to insufficient heat generated in joint region. Figure 7 represents that tensile strength increase with increase the rotational speed.

I. Effect of tilt angle on tensile strength

The tool tilts significantly affect the appearance of the fabrication joints. Figure 7 represents that tensile strength increase with increase the tilt angle. When the tool tilt angle increases, the tensile strength is decreases. At lower tilt angle, the contact between tool shoulder and workpiece surface are more that causes large heat affected zone.

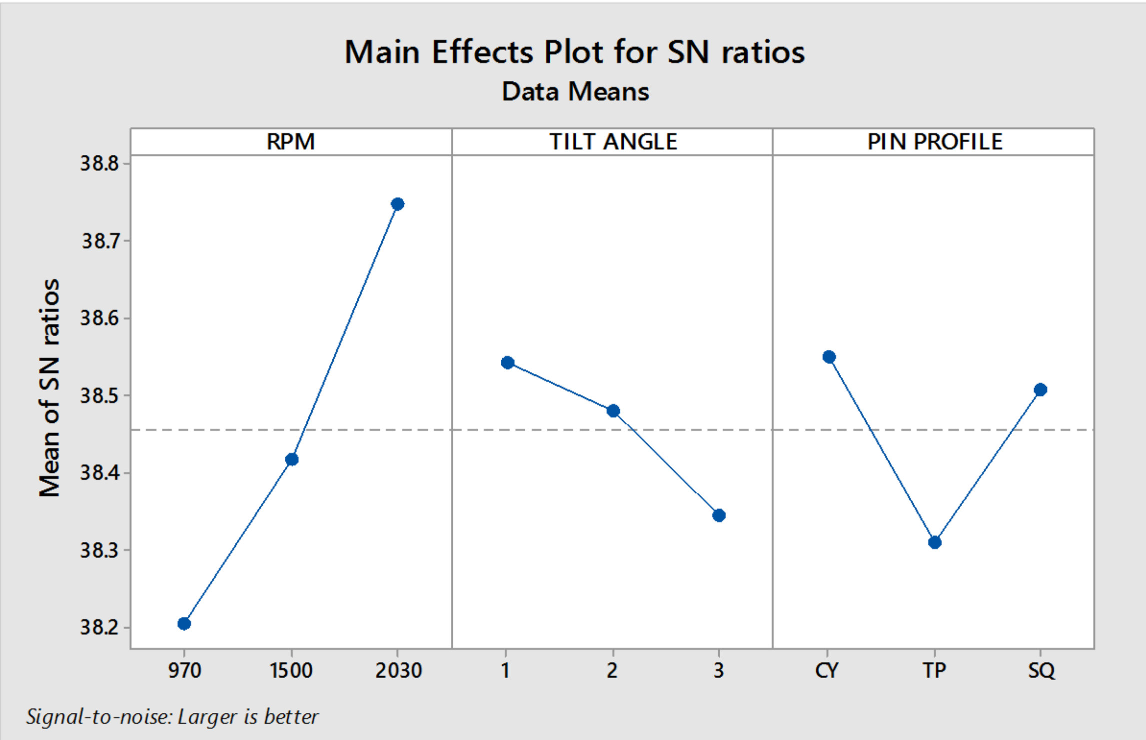

Figure 7: Effects of process parameters on tensile strength (S/N ratio)

J. Effect of tool pin profile on tensile strength

The types of tool pin profile appreciably affect the tensile strength. Tool pin profile is responsible for appropriate heat generation and stirring of plasticized. The cylindrical type of tool pin profile produces good material stir quality during fabrication.

VI. CONCLUSION AND FUTURE SCOPE

In the present work, AA 6063/B4C composite was fabricated using friction stir processing and the effect of B4Cparticles on microstructure, residual stresses and micro hardness was analysed. The obtained results can be summarized as follows:

1) Tool holding square pin profile performed better compared to cylindrical and tapered pin profile because square pin profile tool acts as a steerer having two linearly opposite blades which were responsible to produce sufficient amount of frictional heat in SZ.
2) Rotational speed of the tool was the most critical parameter in comparison to tool tilt angle and pin profile of the tool to produce sound quality composites.
3) There is no micro fracture or depression visible on the top surface of the samples of FSPed composites.
4) The vigorous rotation of tool holding square pin profile was primarily cause of broken up and fragmentation of B4C particles due to the high plastic strain during FSP.
5) The composites with refined and uniform distribution of B4C particles can be obtained by optimal setting of rotational speed, tilt angle of tool and the type of pin of the tool.
6) B4C particles significantly improved the micro-hardness of the composite. Micro- hardness value was improved up to 30% comparing with as-received 6063 aluminium alloy.
7) A considerable amount of compressive residual stresses are formed at the surface region of the stir zone and thermo-mechanical affected zone mainly because of mechanical compression of the tool shoulder, improves the mechanical properties of the composites.
8) Further research on FSP could be conducted for other remaining mechanical properties of composites such as tensile strength, fatigue, wear and creep response with novel tool design for enhancing the grain refinement and uniform distribution of reinforcement particles into the matrix materials.
9) Increase the tensile strength at level (rotational speed 2030 r/min, tilt angle 2 and cylindrical is the pin profile). The maximum tensile strength achieved is 88 MPa.

Scope for future

Research needs to be done in the area of FSP as it has proved to be viable method that could be used to improve mechanical and metallurgical properties of various aluminium alloys, Aluminium alloys are normally grouped according to their applications in industry and the introduction of FSP tends to improve an otherwise good alloy by introducing super plastic properties and grain refinement of the parent material.

REFERENCES

[1] P. Cavaliere*, Mechanical properties of Friction Stir Processed 2618/Al2O3/20p metal matrix composite, Composites: Part A, Volume 36, 2005, Pages 1657-1665.

[2] S.A. Alidokht, A. Abdollah-zadeh*, S. Soleymani, H. Assadi, Microstructure and tribological performance of an aluminium alloy-based hybrid composite produced by friction stir processing, Materials and Design, Volume 32, 2011, Pages 2727- 2733.

[3] A. Dolatkhah*, P. Golbabaei, M.K. BesharatiGivi, F. Molaiekiya, Investigating effects of process parameters on microstructural and mechanical properties of Al5052/SiC metal matrix composite fabricated via friction stir processing, Materials and Design, Volume 37, 2012, Pages 458-464.

[4] Adem Kurta, IlyasUygurb*, ErenCete*, Surface modification of aluminium by friction stir processing, Journal of Materials Processing Technology, Volume 211, 2011, Pages 313-317.

[5] S. Sahraeinejad, H. Izadi, M. Haghshenas, A.P. Gerlich, Fabrication of metal matrix composites by friction stir processing with different particles and processing parametes, Materials Science And Engineering: A, Volume 626, 25 February 2015, pages 505-513.

[6] Namrata Gangil, Arshad Noor Siddiquee, Sachin Maheshwari, Aluminium based in-situ composite fabrication through friction stir processing: A review, Journal of Alloys and Compounds, Volume 715, 25 August 2017, Pages 91-104.

[7] Y.J. Kwon, I. Shigematsu, N. Saito, Mechanical properties of fine-grained aluminium alloy produced by friction stir process, Scriptamaterialia, Volume 49, Issue 8, October 2003, Pages 785-789.

[8] https://en.m.wikipedia.org

[9] Nitin kumar pol, GauravVerma, R.P. Pandey, T. Shanmugasundaram, Fabrication of AA7005/TiB2-B4C surface composite by friction stir processing: Evaluation of ballistic behaviour, Defence Technology, Volume 15, Issue 3, June 2019, Pages 363-368.

[10] Sahayam Joyson Abraham, Isaac Dinaharan, Jebaraj David Raja Selvam, Esther TitilayoAkinlabi, Microstructural characterization of vanadium particles reinforced AA6063 aluminium matrix composites via friction stir processing with improved tensile strength and appreciable ductility, Composites communications, Volume 12, 2019, Pages 54-58.

[11] Subhasis Sinha, Mageshwari Komarasamy, Saket Thapliyal, Bharat Gwalani,… Rajiv S. Mishra, Immiscible nanostructured copper-aluminium-niobium alloy with excellent precipitation strengthening upon friction stir processing and aging, Scripta Materialia, Volume 164, 15 April 2019, Pages 42-47.

[12] M. Sarkari Khorrami, N. Saito, Y. Miyashita, M. Kondo, Texture variations and mechanical properties of aluminium during severe plastic deformation and friction stir processing with SiC nanoparticle, Materials Science & Engineering A, Volume 744, 2019, Pages 349-364.