

Experimental investigation on roundness error in friction drilling and mechanical properties of Al/SiCp-MMC composites

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Abstract – Silicon carbide particulate reinforced aluminum (Al/SiCp) Metal Matrix Composites (MMC) is finding increased applications in Industries due to its unique advantages. Holes are to be drilled in many applications for joining and assembly purposes. Friction drilling is a newer non-traditional hole-making chip less process used to make holes in a single step. The manuscript first discusses the mechanical properties such as tensile strength and micro hardness of Al/SiCp-MMC composites, then it discusses the roundness (hole diameter accuracy) errors on dry friction drilled holes. The parameters considered for the experiments are: the composition of work piece, work piece thickness, spindle speed, and feed rate. The results indicated that the increase in the composition of wt% of SiCp particles increases the tensile strength, hardness. The drilling test results indicated that moderate wt% of SiCp gives better results. Higher spindle speeds and higher feed rates increase the roundness error. The highly influential parameter which affects the roundness error is feed rate. Increase in plate thickness also increases the roundness error in drilling of MMC composites.

Key words: Metal matrix composites (MMCs) / mechanical properties / drilling / friction drilling / roundness error

1 Introduction

Metal matrix composites (MMC) have been subject of scientific investigation and applied research for about two decades but only in the past few years these advanced materials became realistic candidates in engineering components, such as electronic heat sinks, automotive drive shafts, ground vehicle brake rotors, jet fighter aircraft fins or explosion engine components. Their greatest potential is the large variety in combining matrix and reinforcement and enables tailor-made material properties to meet the highest requirements [1]. MMCs have a proven track record as successful “high-tech” materials in a range of applications, bringing significant benefits (in terms of energy savings, or component lifetime) and having documented engineering viability [2]. For many researchers the term “metal-matrix composites” is often equated with the term “light metal matrix composites” (LMMCs). Substantial progress in the development of light metal matrix composites has been achieved in recent decades, so that they could be introduced into the

most important applications. In traffic engineering, especially in the automotive industry, MMCs have been used commercially in fiber reinforced pistons and aluminum crank cases with strengthened cylinder surfaces as well as particle-strengthened brake disks [3].

Effective machining of Al/SiCp-MMC is a challenge to the manufacturing industries which mainly restrict the wide spread application of this advance metal matrix composite in practice [4]. Drilling is one of the most commonly used machining processes in various industries and due to the increasing competitiveness in the market, cycle times of the drilling processes must be decreased along with maintaining close geometric tolerance requirements [5]. Researchers are finding some difficulty in drilling of composite materials by ordinary drilling and few applied new tool type and tool material to machine Al/SiCp composites. Manna and Bhattacharayya [4] reported that during turning of Al/SiCp-MMC with uncoated tungsten carbide (WC) (HW-K10) fixed rhombic tools, due to friction, high temperature and pressure the particles of the Al/SiCp-MMC adhere to the cutting tool materials forming a built up edge (BUE). Xing Xin Xu et al. [6] applied a method of ultrasonic vibration drilling for hole-making

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Nomenclature

α	Included angle of the cone-shaped center region, radians
h_c	Height of the cone-shaped center region, mm
β	Included angle of the cone-shaped conical region, radians
h_n	Height of the cone-shaped conical region, mm
h_l	Length of cylindrical region, mm
d	Diameter of cylindrical region, mm
h_{la}	Length of shoulder region, mm
d_a	Diameter of shoulder region, mm
h_{lb}	Length of shank region, mm
d_b	Diameter of Shank region, mm
S	Spindle speed, rpm
F	Feed rate, mm.min ⁻¹
W	Weight percentage of SiCp, %
P	Plate thickness, mm
Ra	Roundness error, μm
T	Torque of spindle, Nm

of particle reinforced metal aluminum-matrix composites (PRMMCs) to improve drilling locating precision, hole surface quality and they reduced 30% drilling torque.

Basavarajappa et al. [7] studied the influence of cutting parameters (cutting speed, feed rate and their interaction) on burr formation in drilling of Al/SiCp and Al/SiCp-Gr composites with carbide and coated carbide drills. Gaitonde et al. [8] conducted machining experiment with aluminum alloy reinforced with 20% of SiC particulates (A 356/20/SiCp-T6) by using a polycrystalline diamond (PCD) tool and did mathematical model using response surface methodology (RSM). Palanikumar et al. [9] notified that various studies on machining of Al/SiC composites proved that Poly Crystalline Diamond (PCD) cutting tools are ideal cutting tool materials and PCD tools showed very good wear resistance and produced better surface finish. Hung et al. [10] proposed a systematic and economical procedure to study machinability and noted that matrix hardness affect the MMC machinability. CBN and PCD tools are one and two orders of magnitude better than WC tools in terms of wear resistance and CBN and PCD tools should be used for finishing operations since they minimize the surface damage.

Quigley et al. [11] studied the factors affecting the machinability of an Al/SiC metal-matrix composite and investigated the influence of cutting tool coatings on flank wear and surface finish and found that triple-coated carbide, having a top layer of TiN, performed best in terms of flank wear but gave the poorest surface finish. Iulianoa et al. [12] conducted high-speed turning experiments on metal matrix composites and concluded that in the chip formation process, the reinforcing particles pile up along shear planes which divide the deformed chip into layers. They reported that this phenomenon was more evident as the cutting speed or feed increased, because the increased temperature enabled the alumina particles to move more freely. Caroline et al. [13] machined aluminum/SiC composite using diamond inserts and observed that the initial flank wear on both the PCD and the CVD diamond tools

was generated by abrasion due to the very hard SiC particles present in the work piece material. As machining progressed, thin films of the work piece material were found to be adhering to the worn areas. Further tool wear in these areas is believed to be caused by a combination of the abrasive wear and the adhesive wear mechanisms.

Davim and Baptista [14] used harder than SiCp, polycrystalline diamond (PCD) drills to make holes in aluminum with 7.0 per cent silicon and 0.4 per cent magnesium, reinforced with 20 per cent by volume silicon carbide (SiCp) particles. The performance of the sintered carbide friction drill was compared with the tungsten carbide (WC) twist drill in drilling AISI-304 material by Han-Ming Chow et al. [15]. They concluded that WC twist drill damaged seriously after three drilling runs but the friction drill showed little wear only after 60 runs of the drill and also good quality hole surface could be obtained. In this context, a novel drilling process using a friction tool is experimented here for its effectiveness in drilling Al/SiCp MMC plates of varied thickness. Friction drilling is a non-traditional hole-making method that utilizes the heat generated from friction between a rotating conical tool and the work piece to soften and penetrate the work-material and generate a hole in the work piece [16]. In this research, a new dry chip less drilling process is developed for making holes and the quality of produced holes in terms of roundness is analyzed. The literature available on friction drilling of Al/SiCp MMC plates and on roundness error of drilled holes is very limited. In the recent past to the knowledge of the authors, neither systematic work nor modeling of process parameter is carried out in friction drilling of Al/SiCp composites. Hence in this study a comprehensive analysis has been carried out for friction drilling of Al/SiCp MMCs with low range of SiCp composition excluding bushing formation and including hole quality in terms of roundness error.

This friction drilling process will pave way for reducing the tool wear and reducing time in manufacturing and the objective is the successful application of friction drill in making holes with very less tool wear. The present study first deals with the micro hardness and tensile strength properties of 5, 10, 15, 20 and 25 wt% of SiCp reinforced BS 1490 grade LM6 aluminum casting alloy and then an analysis have been carried out for the influence of machining parameters such as spindle speed, feed rate along with the influence of weight % of SiC particles and plate thickness on hole quality in terms of roundness error. This practical research analysis and test results on the drillability of Al/SiCp-MMC will provide effective guidelines to the present day manufacturing engineers. The research work finding will also provide useful economic machining solution by utilizing friction drill for making hole in Al/SiCp-MMC, which is otherwise usually drilled by costly PCD or CBN tools.

2 Experimental procedure

Friction drilling is usually applied to ductile sheet metal of 2 mm thick to form a clean and chip less hole

Table 1. Important factors and their levels.

S. No.	Parameter	Notation	Unit	Levels				
				(-2)	(-1)	0	(+1)	(+2)
1.	Spindle speed	$S(X_1)$	rpm	2000	2500	3000	3500	4000
2.	Tool feed rate	$F(X_2)$	mm.min ⁻¹	40	50	60	70	80
3.	Weight % of SiCp	$W(X_3)$	%	5	10	15	20	25
4.	Plate thickness	$P(X_4)$	mm	2	2.5	3	3.5	4

Table 2. The composition of aluminum matrix used.

Element:	Si	Fe	Cu	Mn	Mg	Zn	Ni	Pb	Sn	Ti	Al
Percentage:	10–13	0.6	0.1	0.5	0.1	0.1	0.1	0.1	0.005	0.2	remaining

with bushings. The purpose of the bushing is to increase thickness for threading and available clamp load [16]. Friction drilling is preferred over twist drilling as this is a chip less and single step process whereby the cycle time is drastically reduced and the nuisance of chip entanglement and chip disposal is totally avoided. In this novel process the friction drill is not cutting the material grains but plasticizes and pushes the grains. The wear of conventional twist drills is mainly due to cutting the abrasive SiC particles and hence in this study instead of cutting the SiCp particles, the friction drill will push them which will reduce tool wear in drilling Al/SiCp composites [17].

Based on the literature and trial work done on these cutting parameters for friction drilling aluminum alloy by author [18], the independently controllable predominant drilling parameters that have greater influences on the roundness variations of the friction drilled Al/SiCp MMC plates have been identified. They are:

- (i) spindle speed (S),
- (ii) feed rate (F),
- (iii) wt% of SiCp (W) and
- (iv) plate thickness (P).

The factors used, notations, units and their levels are presented in Table 1.

2.1 Production and testing of metal matrix composites

Al/SiCp MMC plates containing five levels of composition of SiC particles (5, 10, 15, 20 and 25 wt%) of mean particle size 37 μm were prepared using a melt stirring-gravity casting route. The matrix material was BS 1490 grade LM6 aluminum casting alloy. The chemical composition of the matrix is given in Table 2. Prior to the particulate addition, 0.5 wt% of Mg was also added to improve the wetting capability of reinforcements [19].

2.2 Friction drilling and mechanical property evaluation experiments

Friction drilling is one of the important operations in manufacturing engineering getting importance due to

its simplest operation. Figure 1 illustrates stages in friction drilling of Al/SiCp MMC work piece. First, the tool comes into initial contact with the work piece as shown in Figure 1a. Next, at the main thrust stage, the tool penetrates the work piece and a high axial force is encountered as shown in Figure 1b. The friction associated with the friction drilling between the contact surfaces produce heat which softens the work material and the protrusions of the displaced work piece material starts appearing as shown in Figure 1c. The tool is advanced further, and the protrusions of the displaced work piece material starts appearing above as well as below the work piece as shown in Figure 1d. Provision of space for the movement of protruding metal is necessary. Figure 1e shows the material separation stage, where the tool penetrates through the work piece and makes a hole. Finally, the tool retracts with minimal friction and leaves a hole with protrusions on the work piece, Figure 1f [16]. The mechanical properties of the fabricated MMCs were examined by using Micro Vickers Hardness Tester for hardness, and UTM equipment for tensile strength measurements.

The drilling tests were performed at CNC machining center with the following specifications:

Capacity-X-axis	: 700 mm
Capacity-Y-axis	: 300 mm
Capacity-Z-axis	: 150 mm
Table size	: 1270 \times 254 mm
Spindle speed range	: 60–5000 rpm
Maximum feed	: 3000 mm

KISTLER 3 component Dynamometer, 5 kN -9257B is used for measuring the cutting forces and torque. The work piece was kept on Hylam sheet to insulate the heat generated by friction drilling and clamped firmly as there was a tendency to rotate the work piece because of the high torque involved. A highest torque value of 2.66 Nm is recorded as shown in Table 3. All the trials are carried out according to the order presented in the Table 3 using fresh tool for every set. The experimental setup used in this work is presented in Figure 2. The holes are drilled by using friction drill and the ratio of t/d (thickness of plate to drill diameter) is varied between 0.377 and 0.754. The friction drill used for the present study is presented in Figures 3a and b. The tool used for the present investigation is TiN coated high speed steel with the coating

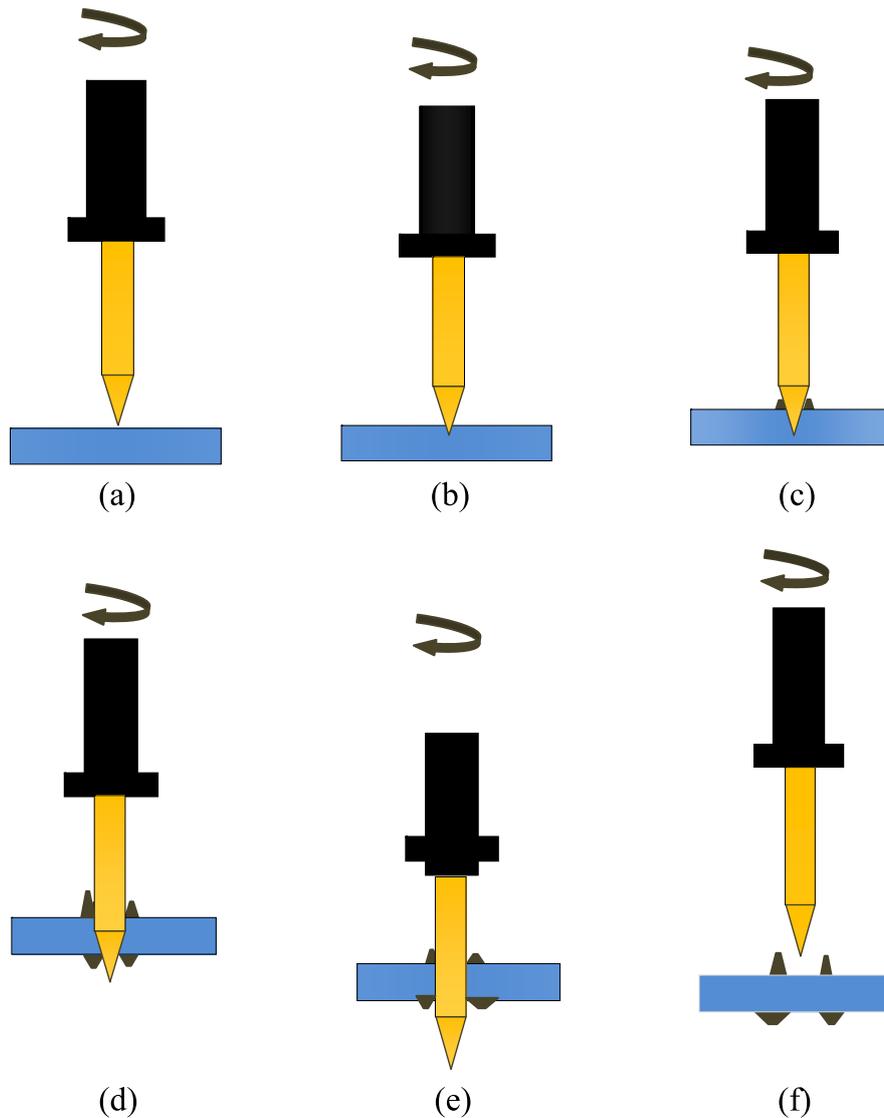


Fig. 1. Stages in friction drilling process.

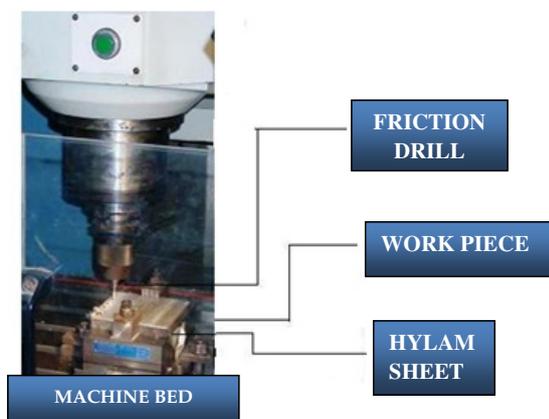


Fig. 2. Experimental set up used for the present investigation.

thickness of $4 \mu\text{m}$ and the coating film hardness is 2800 HV. The tool geometry and key dimensions of the

friction drill are provided in Table 4. The drilling cycle time was set for 50 s and maximum temperature of 314°C is observed at the entry point of the tool by using Raytek non-contact infrared (IR) thermometer during the experimentation. After the experimentation very negligible wear was noticed on the friction drill.

Pictures of friction drilled holes on Al/SiCp MMC plates are shown in Figure 4. This picture is taken after friction drilling of the work piece. The picture shows the protrusion and burrs formed on the work piece. After the drilling operation, the protrusion and burrs of the drilled holes are removed and smoothed by using flat file. The smoothed hole is presented in Figure 5. The plates were used in as cast condition for the experiments. The composite plate materials were faced and cut to a plate of 100×100 with varying thicknesses of 2, 2.5, 3, 3.5 and 4 mm. The roundness errors [20] were measured using Carl-Zeiss Rondcom 54 and the typical roundness profiles observed is shown in Figure 6. Rondcoms use the TIMS

Table 3. Layout of central composite rotatable design with results.

S.No	Spindle speed, (<i>S</i>) rpm	Feed rate, (<i>F</i>) mm.min ⁻¹	wt.% of SiCp, (<i>W</i>)	Thickness of plate, (<i>P</i>) mm	Torque, <i>T</i> , Nm	Roundness error, <i>R</i> _a , μm
1	2500	50	10	2.5	0.47	110
2	3500	50	10	2.5	0.53	125
3	2500	70	10	2.5	0.9	186
4	3500	70	10	2.5	0.85	244
5	2500	50	20	2.5	-0.88	142
6	3500	50	20	2.5	-1.08	141
7	2500	70	20	2.5	-0.79	100
8	3500	70	20	2.5	-1.34	121
9	2500	50	10	3.5	1.41	107
10	3500	50	10	3.5	0.79	122
11	2500	70	10	3.5	2.66	232
12	3500	70	10	3.5	1.15	266
13	2500	50	20	3.5	0.53	188
14	3500	50	20	3.5	-0.19	196
15	2500	70	20	3.5	1.32	190
16	3500	70	20	3.5	0.18	227
17	2000	60	15	3	1.48	103
18	4000	60	15	3	0.1	143
19	3000	40	15	3	0.21	151
20	3000	80	15	3	0.31	244
21	3000	60	5	3	1.11	222
22	3000	60	25	3	0.35	194
23	3000	60	15	2	0.36	112
24	3000	60	15	4	0.44	189
25	3000	60	15	3	1.9	176
26	3000	60	15	3	0.91	192
27	3000	60	15	3	0.58	198
28	3000	60	15	3	0.6	168
29	3000	60	15	3	0.85	192
30	3000	60	15	3	0.72	175
31	3000	60	15	3	0.11	182

Table 4. Friction drilling tool geometry and Key dimensions

α , degrees	β , degrees	Centre region, height, <i>h</i> _c , mm	Conical region, height, <i>h</i> _n , mm	Cylindrical region, <i>h</i> ₁ , length/dia, <i>d</i> , mm	Shoulder region, <i>h</i> _{1a} , length/dia, <i>d</i> _a , mm	Shank region, <i>h</i> _{1b} , length/dia, <i>d</i> _b , mm
90	36	1	10	15/5.3	7/12	30/10

software strategy which includes trace input for contours, *R* axis follow for roundness and 3-point alignment.

3 Results and discussions

3.1 Microstructure and determination of mechanical properties

Figure 7 shows the micro structure of Al/SiCp work piece, with weight percentages of 5%, 15%, and 25%. Analyzing microstructure of composite specimens obtained by melt stirring-gravity casting route reveals that the distribution of SiC particles is uniform up to 15% weight percentage. Clustering of SiC particles are seen after 15% weight percentage and the size of the clustering is growing bigger at 25% weight percentage, may be due to the clustering behavior of the particles when their number

is large enough [21]. The energy dispersive x-ray spectroscopy (EDX) analysis is carried out for the work piece material in the inner surface of the friction drilled hole and a typical profile and data is presented in Figure 8. EDX element profile indicates the presence of more silicon in the work piece which might have come from silicon in the matrix aluminum alloy. Comparing EDX profiles of both work piece and chip shows the Si percentage of chips are higher than the work piece indicating the migration of SiC particles during the friction drilling process.

Specimens for tensile testing are prepared as per ASTM Standards and hardness and tensile strength of materials which were produced by melt stirring-gravity casting route by adding 5, 10, 15, 20 and 25 wt% of SiCp to BS 1490 Grade LM6 Aluminum casting alloy are shown in Figures 9 and 10. In composites, hardness increases proportionally by increasing reinforcement amount. Change of hardness values for various wt% of SiCp is demonstrated in Figure 9. Interestingly there is a marginal

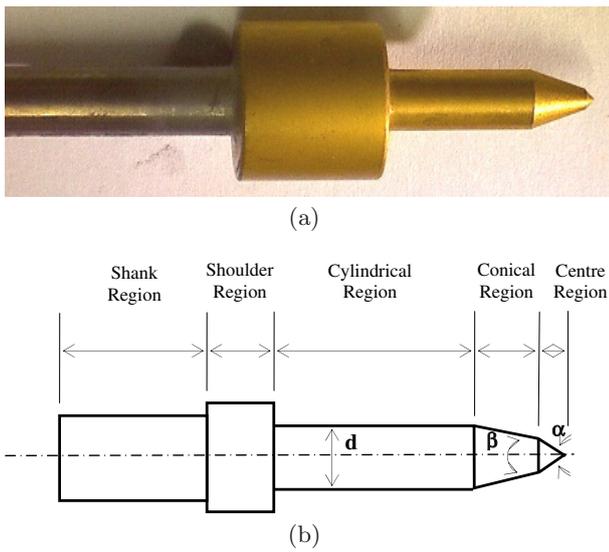


Fig. 3. Tool used for friction drilling. (a) Picture of the friction drill. (b) Line diagram of the tool used.



Fig. 4. Pictures of friction drilled holes with protrusions and burr.



Fig. 5. Smoothened holes after hand filing.

decrease in the hardness value at 10% may be due to the less presence of hard SiCp particles at the inspection site as they play a significant role in increasing the hardness values [19, 22, 23]. Changes in the values of tensile strength of Al/SiCp-MMC depending on wt% of SiCp are demonstrated in Figure 10. However, tensile strength of 10 and 15 wt% of SiCp reinforced composite material decreased because of broken particles and inadequate inter-face bond between particulates and matrix [19]. The tensile strength value increases gradually from 15, 20 and up to 25 wt% of SiCp due to the maximum influence of

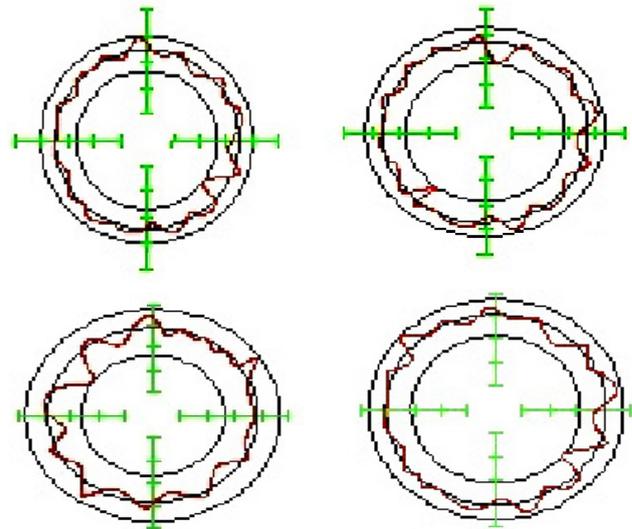


Fig. 6. Typical roundness profile.

matrix and minimum influence of SiCp particles which are clustering together. Though the material is having 25 wt% of SiCp, it behaves like 5 Wt% of SiCp and this trend is continuing further. Ozben et al. [19] reported that reinforcements' particle size, distribution within matrix and its angular structure cause the composite to demonstrate a low strength characteristic. Min Song and Dai-hong Xiao [24] found out that the fracture toughness and tensile ductility of the composite are lower than the comparative alloys and decrease as the volume fraction of the SiC particles increases.

3.2 Discussion on variation of roundness error while friction drilling

Metal matrix composites are finding increased application in different fields. Friction drilling, one of the newer manufacturing process used in industries is studied for metal matrix composites. In this study, effects of SiCp reinforcement to Al/SiCp material at different ratios on hole quality in friction drilling of MMC material have been investigated in terms of selected spindle speed, feed rate and plate thickness. Many researchers used PCD drills [9, 10, 13] to overcome the rapid tool wear because of the abrasive feature of SiCp, the reinforcement material. In this study coated HSS friction drill is successfully used to drill holes with negligible wear.

3.3 Influence of spindle speed on roundness error for various values of wt% of SiCp and specific three values of feed rate

Influence of spindle speed on roundness error for various values of wt% of SiCp and feed rate is presented in Figure 11. The trend of the graphs shows that the influence of wt% is not having much variation at spindle

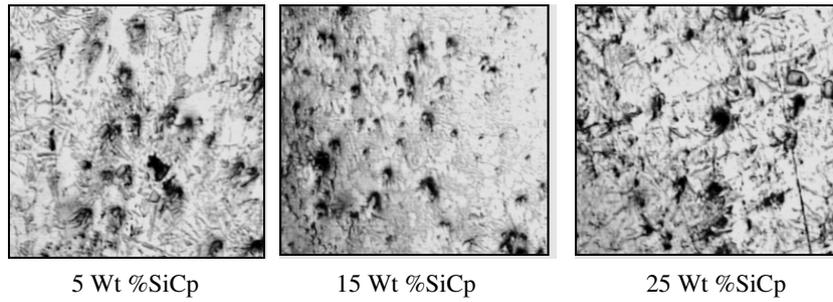
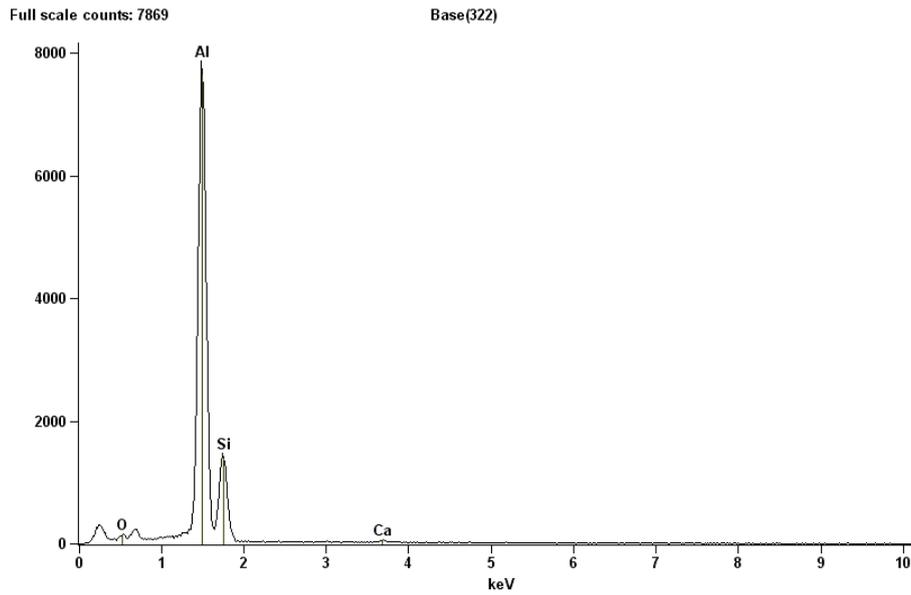


Fig. 7. Typical microstructure of Al/SiCp MMC.



Element	Net Counts	Net Counts Error	Weight %	Atom %	Formula	Compound %
O	181	+/- 156	1.05	1.78	O	1.05
Al	85679	+/- 1284	72.33	72.71	Al	72.33
Si	16497	+/- 771	25.92	25.03	Si	25.92
Ca	334	+/- 126	0.70	0.48	Ca	0.70
Ca	0	+/- 207	---	---	---	---
Total			100.00	100.00		100.00

Fig. 8. Typical EDX profile observed in the chip of friction drilled composite.

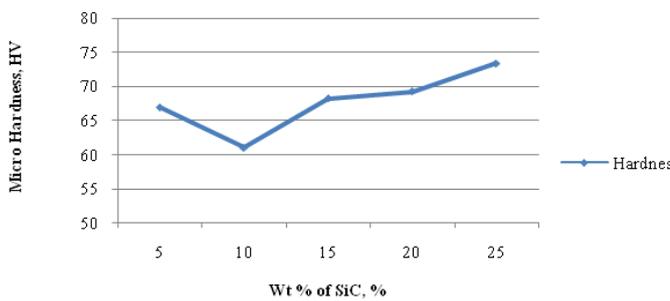


Fig. 9. Vickers hardness values of MMC.

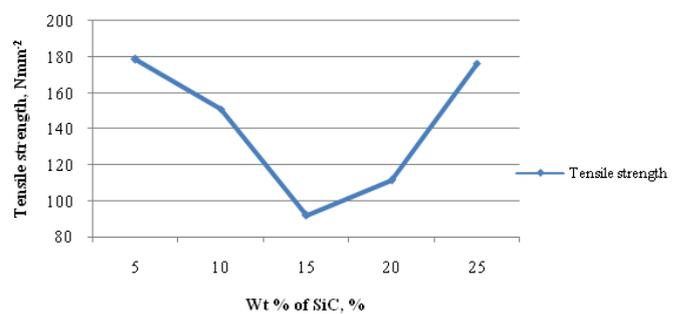


Fig. 10. Tensile strength values of MMC.

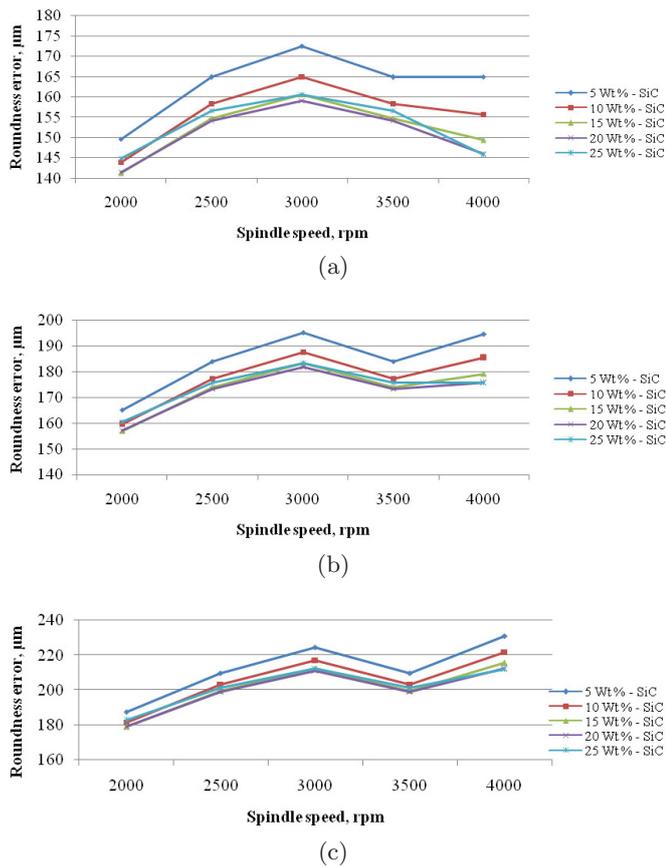


Fig. 11. Influence of spindle speed on roundness error. Feed rate = 40 mm.min⁻¹. (b) Feed rate = 60 mm.min⁻¹. (c) Feed rate = 80 mm.min⁻¹.

speed of 2000 rpm but at 4000 rpm there is some variation. General trend is as the wt% increases the roundness error values are decreasing and the values are not varying much for 15, 20 and 25 wt% of SiC particles. When values of spindle speed, wt% of SiCp and plate thickness are kept constant the roundness error increases with increasing feed values. Highest roundness error value of 231 µm is recorded when spindle speed is 4000 rpm, feed rate is 80 mm.min⁻¹, and composition of SiCp is 5 wt% and 3 mm plate thickness. Interestingly 5 wt% of SiCp composition is giving higher roundness error value showing the less influence of SiCp presence in the matrix. At 5% level, due to their less proportion of composition their significance is not exhibited.

3.4 Influence of feed rate on roundness error for various values of wt% of SiCp and specific three values of spindle speed

Influence of feed rate on roundness error for various values of wt% of SiCp and spindle speed is presented in Figure 12. In all the graphs roundness error values are gradually increasing with the increase of feed rate but after feed rate of 60 mm.min⁻¹ there is a decrease in roundness error value and again it increases after the feed rate

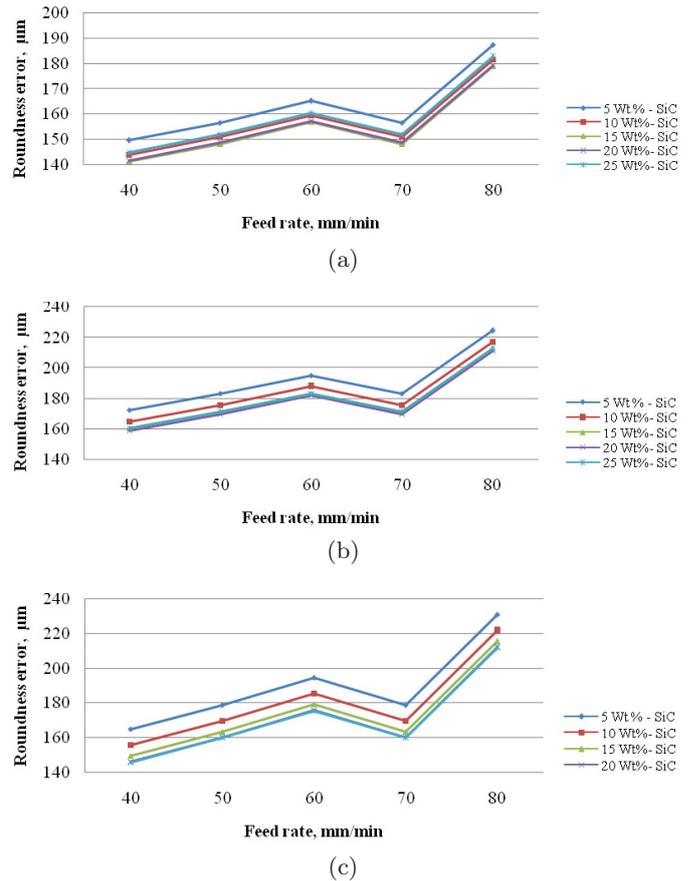


Fig. 12. Influence of feed rate on roundness error. (a) Spindle speed = 2000 rpm. (b) Spindle Speed = 3000 rpm. (c) Spindle speed = 4000 rpm.

of 70 mm.min⁻¹. The reason for decreasing roundness error values may be owing to the correct balancing of forces and easy penetration of the tool due to sufficient heat generated which reduces vibration of the tool. When values of feed rate, wt% of SiCp and plate thickness are kept constant the roundness error increases up to 3000 rpm and then reduces further as the tool stabilization takes place at higher values of spindle speed.

3.5 Influence of spindle speed on roundness error for various values of plate thicknesses and specific three values of feed rate

Influence of spindle speed on roundness error for various values of feed rate and plate thicknesses is presented in Figure 13. General trend of the graphs shows that increasing plate thickness increases the roundness error value and the higher values are at the higher speed and feed values. A minimum roundness error value of 91 µm is obtained when spindle speed is 2000 rpm, feed rate is 40 mm.min⁻¹, and composition of SiCp is 15 wt% and 2 mm plate thickness. While keeping all the drilling parameters same and increasing the spindle speed only from 2000 rpm to 4000 rpm, roundness error value too

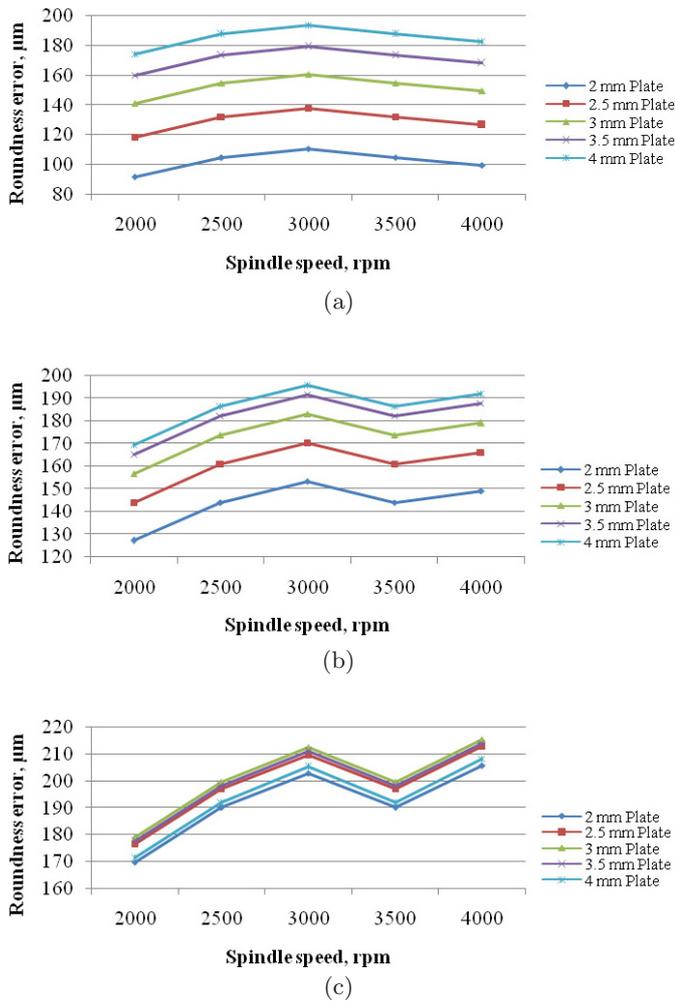


Fig. 13. Influence of spindle speed on roundness error. Feed rate = $40 \text{ mm}\cdot\text{min}^{-1}$. (b) Feed rate = $60 \text{ mm}\cdot\text{min}^{-1}$. (c) Feed rate = $80 \text{ mm}\cdot\text{min}^{-1}$.

is increased to $99 \mu\text{m}$ exhibiting the influence of spindle speed. High roundness error value of $215 \mu\text{m}$ is recorded when spindle speed is 4000 rpm , feed value is $80 \text{ mm}\cdot\text{min}^{-1}$, composition of SiCp is $15 \text{ wt}\%$ and 3 mm plate thickness. The trend at lower feed rate is that roundness error increases gradually with increase of spindle speed up to 3000 rpm and then reduces due to the correct balancing of forces which reduces tool vibration.

The trend at higher feed rate is that roundness error increases gradually with increase of spindle speed up to 3000 rpm and reduces up to 3500 rpm and then increases. This may be due to the act of balancing of forces which reduces tool vibration, takes place after 3000 rpm and goes only up to 3500 rpm . After 3500 rpm the higher feed value increases the tool vibration owing to imbalance of forces which produces higher roundness errors. When values of spindle speed, wt% of SiCp and plate thickness are kept constant the roundness error increases with increase of feed value.

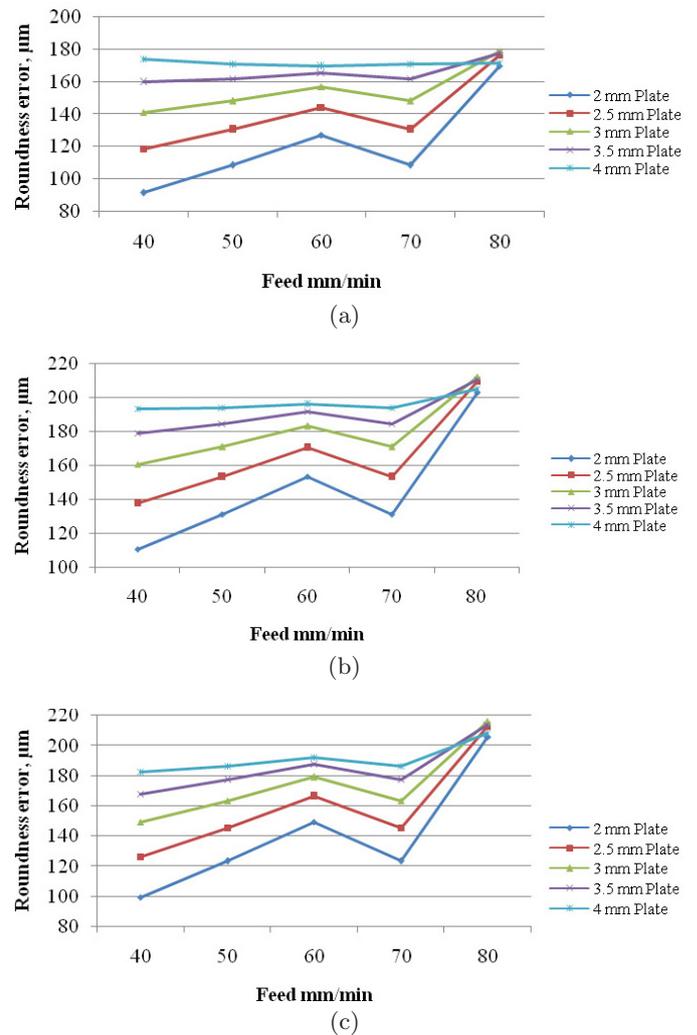
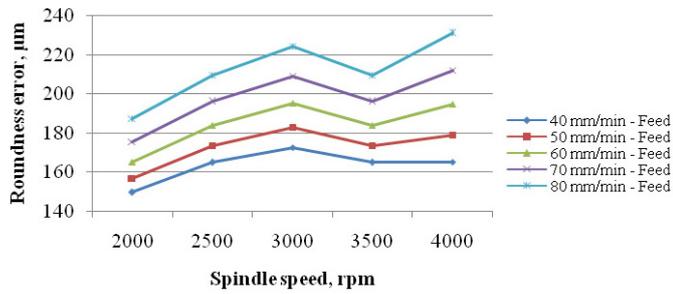


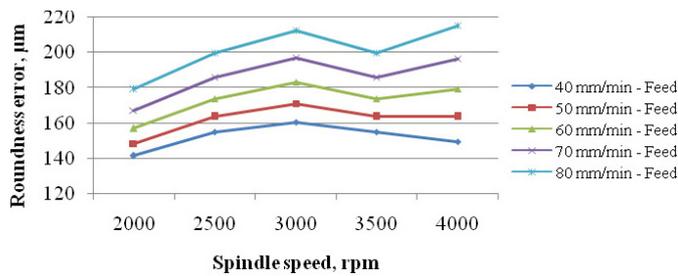
Fig. 14. Influence of feed on roundness error. Spindle speed = 2000 rpm . (b) Spindle speed = 3000 rpm . (c) Spindle speed = 4000 rpm .

3.6 Influence of feed on roundness error for various values of thicknesses of plate and specific three values of spindle speed

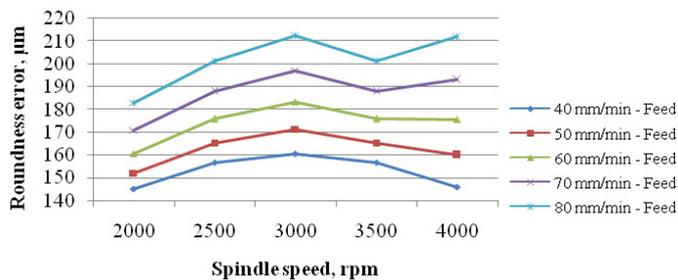
Influence of feed rate on roundness error for various values of plate thicknesses and spindle speed is presented in Figure 14. General trend is as the plate thickness increases the roundness error values are increasing showing the influence of plate thickness. In all the graphs except graph pertaining to 4 mm plate the roundness error values are gradually increasing with the increase of feed rates but after feed rate of $60 \text{ mm}\cdot\text{min}^{-1}$ there is a decrease in roundness error value and again it increases after the feed rate of $70 \text{ mm}\cdot\text{min}^{-1}$. The roundness error variation for 4 mm plate is very marginal at lower speed and feed rates but it is also varying much at higher level. When values of feed rate, wt% of SiCp and plate thickness are kept constant the roundness error increases up to 3000 rpm and then reduces as the tool stabilization takes place at higher



(a)



(b)



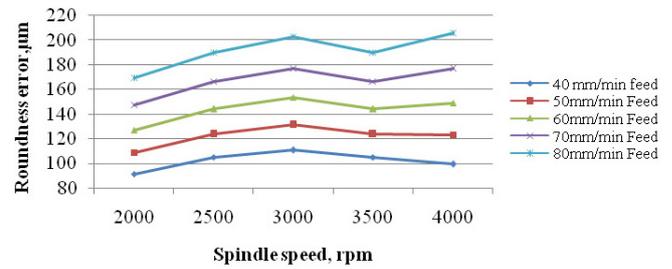
(c)

Fig. 15. Influence of spindle speed on roundness error. (a) Wt% of SiCp = 5%. (b) Wt% of SiCp = 15%. (c) Wt% of SiCp = 25%.

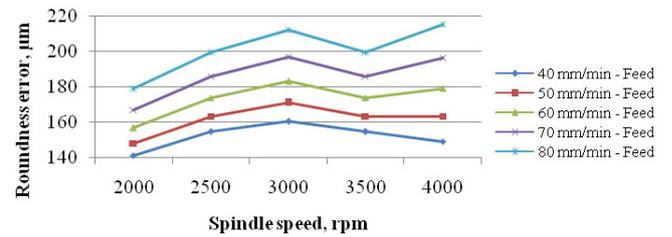
speed. General trend of the graphs shows that increasing plate thickness increases the roundness error value and the higher roundness error values are at the higher spindle speed and feed rate values.

3.7 Influence of spindle speed on roundness error for various values of feed rate and specific three values of wt% of SiCp

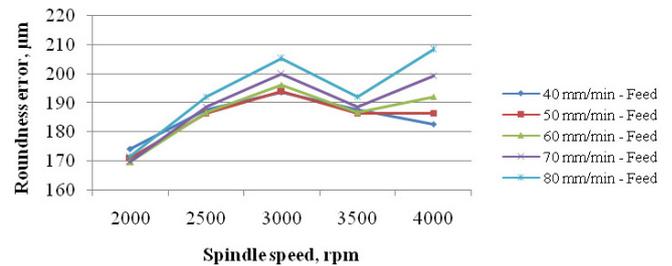
Influence of spindle speed on roundness error for various values of wt% of SiCp and feed rates is presented in Figure 15. General trend is as the wt% of SiCp increases the roundness error values are decreasing and as the feed rates are increasing the error values are increasing. The roundness error increases gradually with increase of spindle speed up to 3000 rpm and then decreases. When spindle speed is 2000 rpm, feed rate is 40 mm.rev⁻¹ and plate thickness is 3 mm, roundness error values are marginally changing from 141 μm to 145 μm according to wt% SiCp variation.



(a)



(b)



(c)

Fig. 16. Influence of spindle speed on roundness error. (a) Plate thickness = 2 mm. (b) Plate thickness = 3 mm. (c) Plate thickness = 4 mm.

3.8 Influence of spindle speed on roundness error for various values of feed rate and specific three values of plate thicknesses

Influence of spindle speed on roundness error for various values of plate thicknesses and feed values is presented in Figure 16. General trend is as the plate thickness increases the roundness error values are increasing and as the feed values are increasing the error values are increasing. The roundness error variation is not much for 4 mm plate. General trend in both Figures 15 and 16 is that roundness error increases gradually with increase of spindle speed up to 3000 rpm and decreases for lower feed rates but after spindle speed value of 3500 rpm it increases for higher values of feed rate.

3.9 Observation on the SEM images of cut section of the friction drilled hole and the inner surface

The SEM images of cut section of the friction drilled hole and the inner surface are presented in Figures 17 and 18. The image exhibits the presence of SiCp dispersed at various locations of the matrix. Also seen are

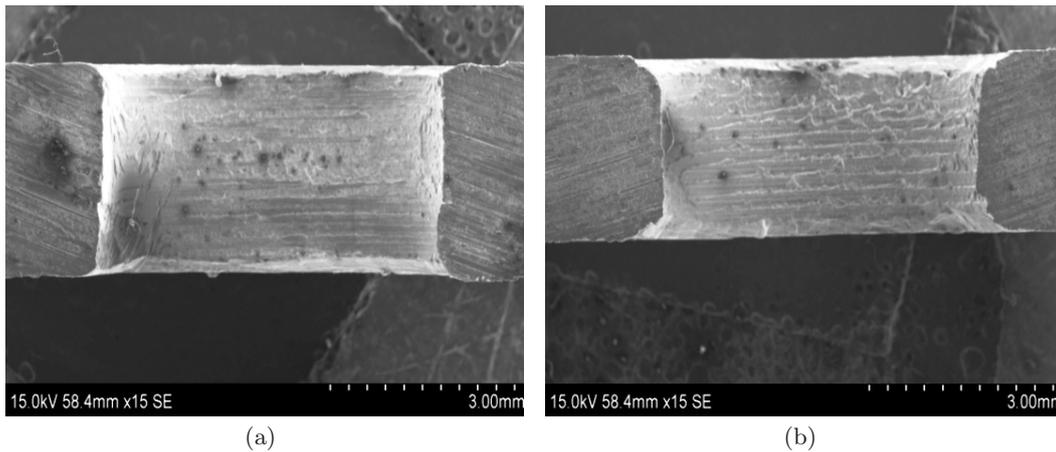


Fig. 17. SEM images of the cut section of the friction drilled hole. (a) Drilling parameters: spindle speed = 3000 rpm feed rate = 60 mm.min⁻¹. Wt% of SiCp = 15. Plate thickness = 3 mm. (b) Drilling parameters: spindle speed = 4000 rpm feed rate = 80 mm.min⁻¹. Wt% of SiCp = 5. Plate thickness = 3 mm.

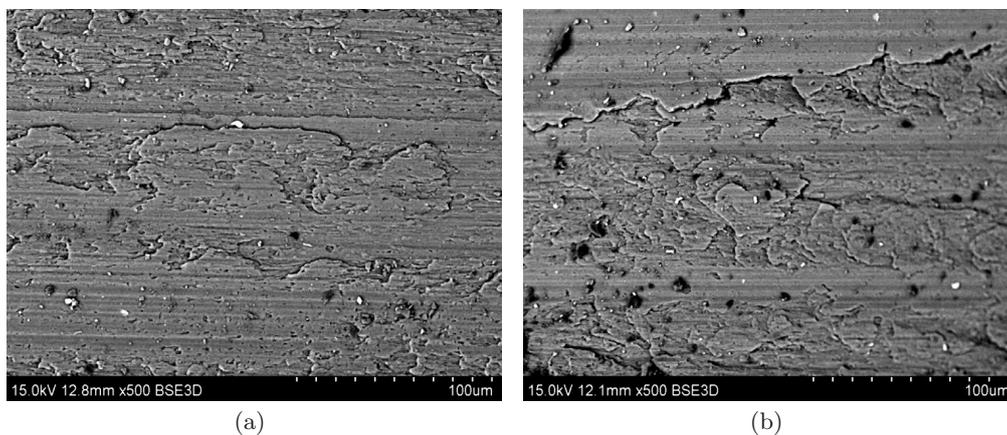


Fig. 18. SEM Images of inner surface of the friction drilled hole. (a) Drilling parameters: spindle speed = 3000 rpm, feed rate = 60 mm.min⁻¹; wt% of SiCp = 15; plate thickness = 3 mm. (b) Drilling parameters: spindle speed = 4000 rpm; feed rate = 80 mm.min⁻¹; wt% of SiCp = 5; plate thickness = 3 mm.

the scripts like Al-Si eutectic particle present in the base alloy and fissures like chips plastically deformed one over the other. Yanming Quan and Bangyan Ye [25] observed when machining Al/SiCp composites (an A356 matrix and 15%SiCp weight fraction) the machined surface changed into recast structure. One reason for the appearance of fissures and fragmented SiC particles could be the matrix used (LM6) is not a wrought variety. Huber et al. [26] reported that SiC particles are found embedded into the Al-Si-eutectic between the dendritic arms of α -Al-phase. In accordance with their observation the SiC particles as well as the eutectic Si seem uniformly distributed in Al/SiCp Composite.

3.10 Observation on the SEM image of the fractured composite

The SEM image of the fractured composite is presented in Figure 19. The image shows the fractured



Fig. 19. SEM Image of fractured composite.

surfaces with crust and troughs. Chipping of the particles lead to trough and embedded particles lead to crest. The SEM images of chips removed from the friction drilled hole are presented in Figure 20. SEM Image shows that chips are evenly distributed with SiC particles and the

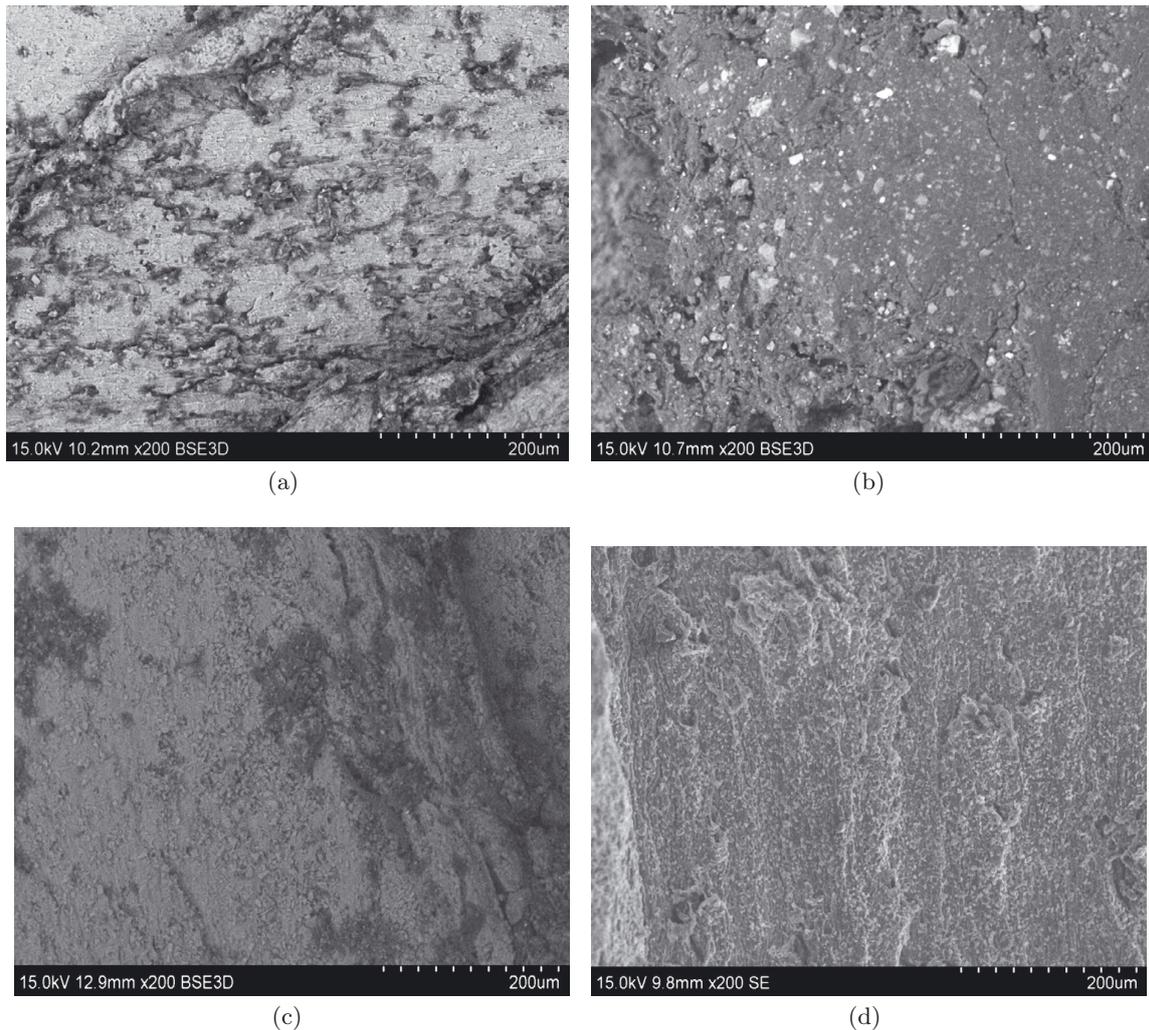


Fig. 20. SEM Images of chips removed from the friction drilled hole. (a) Drilling parameters: spindle speed = 2500 rpm; feed rate = 60 mm.min⁻¹; wt% of SiCp = 25; plate thickness = 2 mm. (b) Drilling parameters: spindle speed = 2000 rpm; feed rate = 70 mm.min⁻¹; wt% of SiCp = 20; plate thickness = 2.5 mm. (c) Drilling parameters: spindle speed = 3000 rpm; feed rate = 50 mm.min⁻¹; wt% of SiCp = 15; plate thickness = 3.5 mm. (d) Drilling parameters: spindle speed = 4000 rpm; feed rate = 40 mm.min⁻¹; wt% of SiCp = 10; plate thickness = 4 mm.

presence of net work of Al-Si eutectic with dispersion of SiC particles and clustering of SiC particles. Clustered SiC particles accumulated at one place lead to fragmentation. This phenomenon is correlated by the higher percentage of Si present in the EDX analysis of chip. Also present in the images are the fragments of Al-SiCp eutectic which are seen as dull white. Coagulation of metal, a characteristic of friction drilling process is exhibited in these images which may be due to excessive force applied while the friction tool is pushing it's way through the composite.

4 Conclusion

- Increasing the composition of wt% of SiCp particles, tensile strength and hardness values of Al/SiCp-MMC material increased from 15 wt% onwards.
- Interestingly 5% wt composition of SiCp is giving higher roundness error value showing the less influence of SiCp presence in the matrix.
- Increasing the composition of wt% of SiCp particles the roundness error values are decreasing and the values are not varying much for 15 and 20 wt% showing the influence of SiCp particles.
- Increasing the composition of wt% of SiCp particles is not having much influence at 2000 rpm but at 4000 rpm there is some influence.
- Increasing plate thickness increases the roundness error.
- Influence of feed is stronger than that of speed is exhibited in comparing the higher values of roundness error.
- Friction drilling process was very rapid taking maximum of 12 s and negligible amount of tool wear.

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