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Influence of cryogenic treatment duration of drills on drilling performance and hole quality of metal matrix composite materials

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Abstract In this study, investigation of aluminum-silicon carbide (Al/SiC) with and without cryogenic treated drills has been performed. The influence of drill treatment condition coupled with processing parameters on machinability of Al/SiC was observed in terms of thrust forces, drill vibration and hole surface integrity. It was observed that the cryogenic treatment is suitable to enhance the machinability of Al/SiC as it does not alter the drill morphology and reduce various drilling related issues. Cryogenic treatment increased drill hardness and reduced thrust force and drill vibration. Vibration acceleration decreases from 110 m/sec^2 to 98 m/sec^2 and 92 m/sec^2 at maximum feed rate, with 24 hrs and 48 hrs cryogenic treatment, respectively. The reduction in drilling vibrations was the influential parameters that reduced drill diameter, delamination and surface roughness of the workpiece. Surface roughness was improved from Ra 1.96 µm to 1.7 µm at maximum feed rate with 24 hrs and 48 hrs cryogenic treatment, respectively.

1. Introduction

Metal matrix composites (MMCs) are a new class of materials that has received substantial attention during the past decade due to their exceptional properties such as low density, high hardness, wear resistance, specific strength and thermal conductivity [1, 2]. MMC consists of hard ceramic reinforcement in tough metallic matrix which results in improved performance in comparison with the conventional materials [3, 4]. These outstanding properties of MMC lead to the higher use in the lightweight application sectors, such as marine, automobile, aviation, defense, sports and medical industries [5]. However, machining of MMC specially Aluminum reinforced with silicon carbide (Al/SiC) is most challenging factor due to uncontrollable spreading, low plasticity and non-uniformity of SiC in the workpiece [6, 7]. Drilling is most frequently used process among prominent conventional machining operations of MMC due to the requirements of large number of rivets and nut/bolts required in the final assembly especially for aviation sector [8, 9]. In the aerospace industry, almost 40-60 % material removal process is completed by drilling [10, 11].

Owing to their exceptionally wide range of applications, several researches have been reported on the machining and machinability of Al/SiC MMCs. Davim et al. [12] investigated the machinability of A356/20 % SiC-T6 based MMCs during the drilling operation to establish the relationships of cutting velocity, feed rate and cutting time with tool wear, the specific cutting pressure and the hole surface roughness using PCD drill. Tosun et al. [13, 14] observed the influence of various drill bits during the machining of Al/SiC MMC and reported that the TiN coated high speed steel drill bits result in better performance in drilling of MMC. They also suggested that apart from the drill bits, drilling parameters have substantial influence on the machinability behavior. Rajmohan et al. [15] established relationships between process parameters and thrust force, surface roughness and burr height in the drilling of Al/SiC/Mica hybrid composites. It was observed that the feed rate, speed and percentage contribution of SiC reinforcement are the prominent factors that control the overall machinability behavior. Muthukrishnan et al. [16] used statistical and machine learning based techniques to investigate optimal processing parameters suitable for the machining of Al/SiC MMC. Similarly, Gaitonde et al. [17] also investigated optimal processing parameters for reduced machining force, cutting power and specific cutting in machining of MMCs by response surface methodology. Rajmohan et al. [18] researched surface roughness in the drilling of Al/SiC MMC with coated and uncoated carbide and PCD drills. Ahamed et al. [19] studied tool wear, surface roughness and surface integrity in the drilling of Al-5 %SiCp-5 %B4Cp hybrid composites using HSS drills with a low speed and low feed rate combination. Basavarajappa et al. [20] examined the effects of cutting parameters on cutting forces, surface roughness and chip formation in drilling of Al2219/ 15SiCp and Al2219/15SiCp-3Gr composites with coated carbide drills. They stated that while reducing the cutting forces and burr height, Gr addition increased surface roughness. Rajmohan et al. [21] studied cutting forces in the drilling of Al356/SiC-Mica hybrid MMCs with coated carbide drills. They analyzed the effects of cutting speed, feed rate and percentage amount of SiC reinforcement on cutting forces using RSM.

From a detailed literature review, it was observed that although several researchers have worked on the machining of different MMCs including Al/SiC, however the work is mainly in preliminary stages. The main focus of these investigations were on establishing correlations between various processing parameters and also optimizing them. Different cutting tool materials were also investigated however, despite, the severe abrasive nature of MMCs due attention is still not paid to the influence of cutting tools on sustainable machinability of MMCs. Cryogenic treatment is an established procedure to enhance the strength and wear resistance of cutting tool materials. However, no such work on drill bits in machining of Al/SiC MMCs is reported in literature until now. Cryogenic treatment can significantly enhance tool life and thus needs to be investigated for improving the overall process output. Therefore, in this paper an attempt has been made to provide the basics for establishing relationships between different cryogenic treatment durations. Influence of cryogenic treated cutting tools on a number of machinability outputs such as cutting force, surface roughness, hole profile etc. were investigated with respect to deep cryogenic treatment duration and machining parameters as well.

2. Materials and methods

2.1 Selection of workpiece material

In this study, aluminum silicon carbide (Al/SiC) metal matrix composite (MMC) was used to conduct the drilling experiments. Small plates of MMC were cut from alloy sheet with HF320Ma wire cut electrical discharge machining (WEDM). The dimension of each individual workpiece plate was 90 mm×30 mm× 9 mm and three plates were used during this study. The MMC plate and schematic diagram with drilled holes are shown in Fig. 1. The physical properties and chemical compositions of used Al/SiC plate are shown in Tables 1 and 2, respectively.

Table 1. Physical properties of Al/SiC MMC.

Flexure strength (MPa)	410
Modulus of elasticity (GPa)	220
Density (g/cm^3)	2.94
Hardness (HV; MPa)	120

Table 2. Chemical composition of Al/SiC MMC.

Element	% weight
Si	20
Mn	0.11
Zn	0.10
Pb	0.02
Sn	0.01
Ni	0.86
Ti	0.10
Mg	0.81
Cu	1.0
Al	Equilibrium

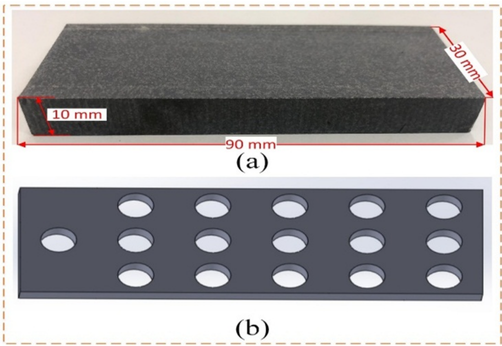


Fig. 1. (a) Al/SiC material used in the experiment; (b) schematic diagram of workpiece used in the experiment.

2.2 Selection of drill

To carry out various drilling experiments, the commercially available K-10 grade twist drills (B105A07000) from Kennametal were considered as shown in Fig. 2. Twelve uncoated drills with constant geometry of 7 mm diameter, three flute of helix angle 30° and 130°-point angle, were used in this study. The drill geometric parameters are also stated in Table 3. These twelve drills were divided into main three categories, Untreated drill (UTD), 24 hours cryogenically treated drill (24-hrs CTD) and 48 hours cryogenically treated drill (48-hrs CTD). Four new drills for each category were prepared and each drill was used for same spindle speed and different feed rate. So,

Table 3. Drill summary.

Drill reference	410B105A07000
Grade	K10
Diameter	7 mm
Coating	Uncoated
Point angle	130°
Cutting edge length	43 mm

Fig. 2. Kennametal K10 drill bit used in this study.

overall four drills (same category) were used for 4 different spindle speeds at different feed rates.

2.3 Cryogenic treatment

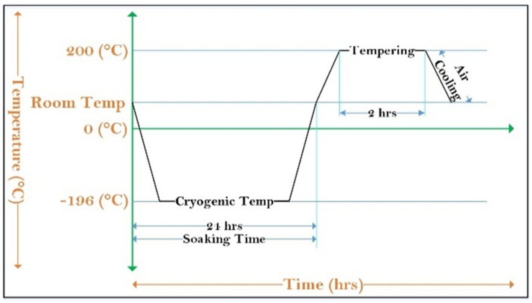
Cryogenic treatment process helps in increasing the tool hardness and drill life through microstructural variations [22]. Cryogenic treatment consists of soaking the drill at significantly low temperature (-180 °C to -196 °C) for a specific period in the tank containing liquid nitrogen. Afterwards the drill is brought back to the room temperature gradually and slowly. Subsequently, the drill goes through tempering heat treatment process to relieve the residual stresses and improve the microstructure of the cutting tool [23, 24]. In current experimental study, deep cryogenic treatment was carried out for 24 hours and 48 hours for two different drill sets and subsequently names as 24-hrs CTD and 48-hrs CTD. Then tempering heat treatment was performed for a time period of 2 hours at 200 °C and subsequently brought back to the room temperature by natural convection. The schematics of the cryogenic treatment with temperature and soaking time for 24-hrs CTD and 48-hrs CTD are shown in Fig. 3.

2.4 Drilling procedure

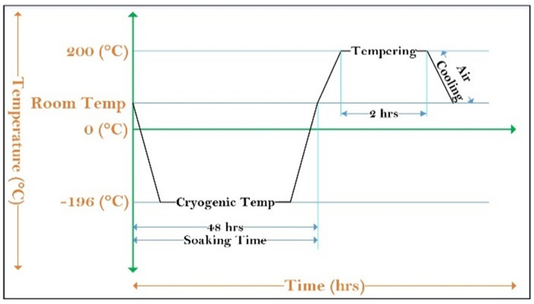
All the experiments were conducted on vertical machining center Daewoo ACE V500 under dry drilling conditions. All experiments were performed twice under similar drilling conditions and processing parameters to reduce or minimize any possible error. Four different levels were generated by varying spindle speeds from 1500 rpm to 6000 rpm and feed rates from 0.05 mm/rev to 0.2 mm/rev to perform the drilling experiments. The drilling parameters and their adopted levels are also reported in Table 4. It can be seen from Table 4 that four different levels of spindle speeds are 1500, 3000, 4500 and 6000 rpm whereas four different feed rates are 0.05, 0.1, 0.15 and 0.2 mm/rev. Overall, 16 different spindle speeds and feed rates combination were made and 16 holes were drilled with each drill category (UTD, 24-hrs CTD and 48-hrs CTD) in first phase of experiments and we performed twice (16 holes in second phase of experiments) under same drilling conditions and used average values to reduce possible errors. Totally 32 holes were drilled with each drill category. All the above experiments were conducted for all types of drills (UTD, 24-hrs CTD and 48-hrs CTD). Schematic of data acquisition system and experimental setup for drilling is shown in Fig. 4.

Table 4. Drilling parameters used in the drilling of MMC.

Parameters	Units	Levels			
		Level 1	Level 2	Level 3	Level 4
Spindle speed	rpm	1500	3000	4500	6000
Feed rate	mm/rev	0.05	0.1	0.15	0.2



(a)

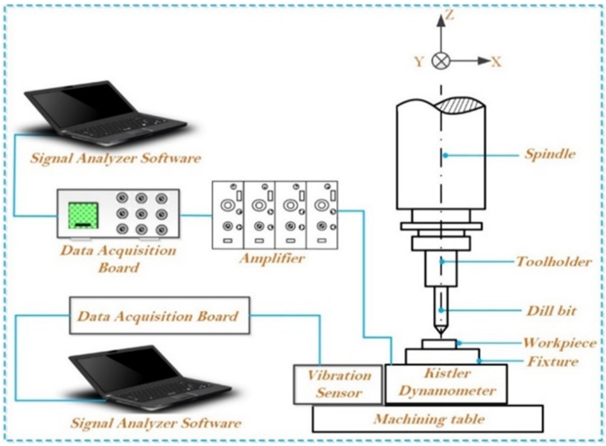


(b)

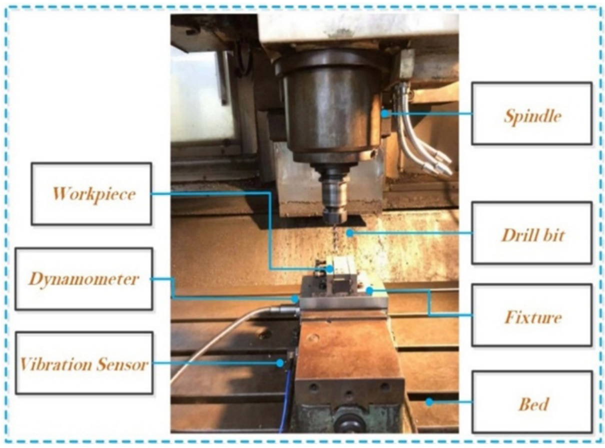
Fig. 3. Schematic of cryogenic treatment of tungsten carbide drills at (a) 24-hrs; (b) 48-hrs.

2.5 Measurement equipment and techniques

Micro hardness test was performed to measure the hardness of untreated and cryogenic treated drills by Digital Type Vickers Hardness Tester HVS-50, which is capable of applying load in the range of 9.8 N to 490 N (1 kgf to 50 kgf). Micro hardness was measured with 30 kgf load (HV30) and a dwell time of 10 seconds. Ten measurements were made for each drill (untreated, 24-hrs cryogenic treated and 48-hrs cryogenic treated with heat treatment) and the average value is considered as



(a)



(b)

Fig. 4. (a) Schematic of data acquisition system and experimental setup; (b) experimental setup for drilling of MMC.

final hardness value. X-ray diffraction (XRD) analysis was performed to determine the microstructural and composition changes in the drills after cryogenic treatment. Versatile digital Dino-Lite Microscope was used to take images of drilled holes and to find the drilled holes diameter by Dino-Capture 2.0 software. These images were used to find out delamination factor.

Thrust force (Fz) was measured using Kistler dynamometer (Kistler 9257B) and experimental signals of thrust force were converted into force data using amplifier and Dyno wave software. Vibration acceleration (ax) was measured during the drilling operation using vibration sensor (PCB 356A15) whereas, DAQ express (NI) software was used to acquire vibration acceleration from vibration sensor. Surface roughness measuring device (TR-200) was used to determine the surface roughness of drilled holes from inner side in terms of arithmetic mean surface roughness Ra. Surface roughness was measured for each hole at 3 different positions and the average value was used. Scanning electron microscopy (SEM) (Supra-55, Zeiss, Germany) was used to access the drilled hole quality and delamination by taking images from the locations of entry point of hole, middle of hole and exit side of each drilled hole. Moreover, energy-dispersive spectrometer (EDS) (PV9900, Philips, Netherlands) sensor attached with the SEM was used to investigate the chemical composition of workpiece material in the drilled holes.

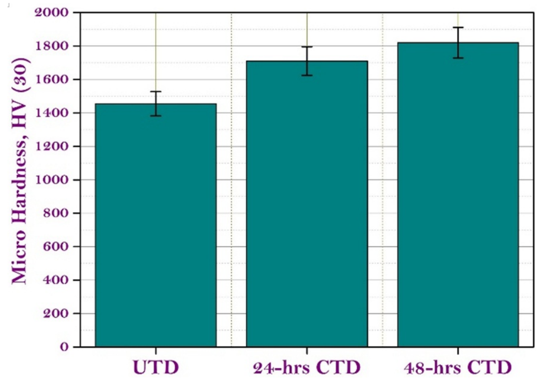


Fig. 5. Micro hardness of untreated and cryogenically treated drills.

3. Results and discussions

3.1 Micro-hardness and XRD analysis of drills

Micro-hardness for untreated drills and cryogenically treated drills were measured ten times and average value was considered as a final value of hardness before the drilling which can be seen in Fig. 5. It can be observed from the Fig. 5 that micro-hardness of 48-hrs CTD is much higher than that of 24-hrs CTD and UTD. This increase in hardness for 48-hrs CTD can be attributed to the uniform distribution of fine η phases' in composite matrix. It was also reported by previous investigations that the carbide formations at cryogenic treatment also contributes to the hardness increase [25]. This higher value of micro-hardness improves the wear resistance of 48-hrs CTD against higher drilling temperatures. Same observation was also reported by the Gill et al. [26].

In order to investigate any possible composition and elemental variation, XRD patterns of drill bits were also observed and are reported in Fig. 6. Fig. 6(a) shows the XRD pattern of samples for analyzing the crystal structure before and after treatment. It can be observed that the XRD peaks of UTD sample match well with the WC, as shown by data from the PDF # 51-0939. The major peaks of planes like; (001), (100), (101) etc. for 24, 48 hours treated samples also match well with the WC. Therefore, from the XRD data, it can be stated that the WC composition even after the treatments are retained and no prominent shift was observed.

Fig. 6(b) is showing the enlarged XRD peaks from 47.5° to 49° which highlight the shift towards bigger angle due to treatment. The peak shift towards a larger angle suggests the contraction of crystal structure. With this contraction there might be a reduction in the crystal volume. Moreover, it was also observed that by increasing treatment time, it causes the contraction in the crystal structure, which might help us in increasing hardness of the material.

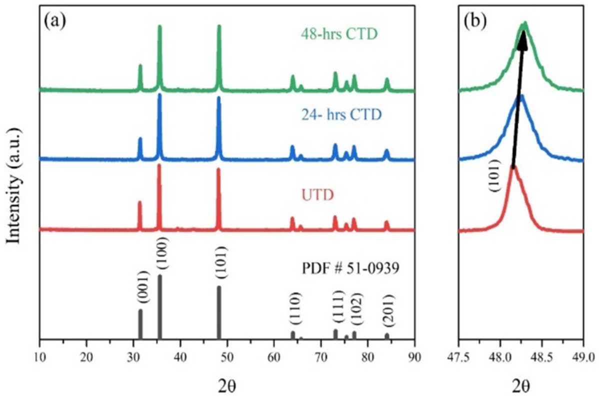


Fig. 6. XRD pattern of untreated and cryogenically treated drills.

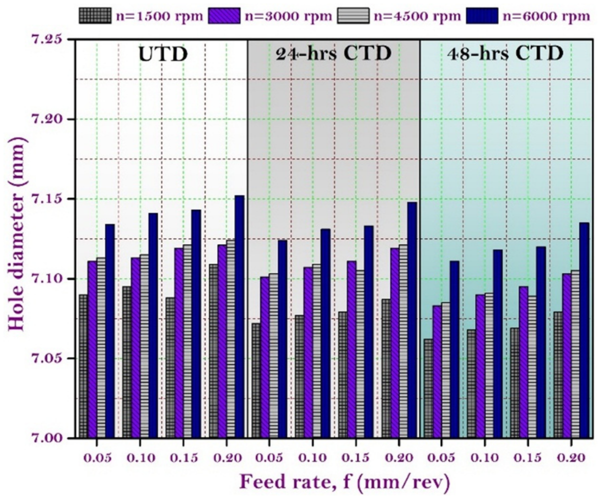


Fig. 7. Entry side hole diameter under various drilling conditions.

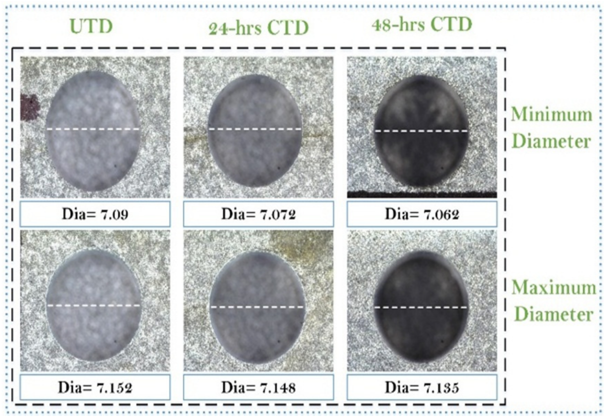


Fig. 8. Microscopic images of minimum and maximum diameter of entry hole.

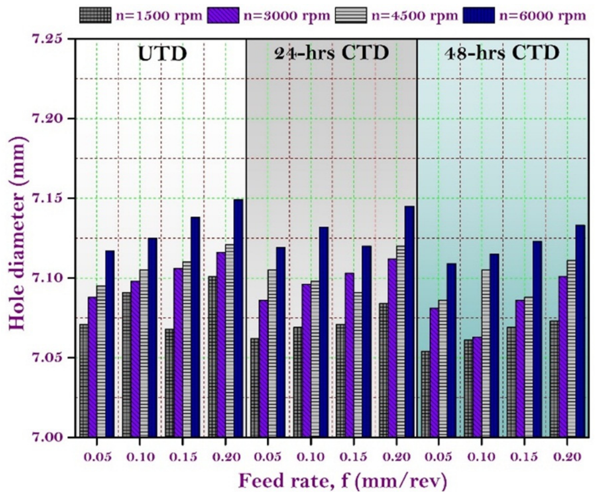


Fig. 9. Exit side hole diameter under various drilling conditions.

3.2 Hole diameter

The influence of the cryogenic treatment and processing parameters on the hole diameter was also investigated. The hole diameter acts as a symbolic measure to the accuracy of drilling operation performed under the specific drilling conditions. Hole diameter at entry, microscopic images of entry holes at minimum and maximum diameters, Hole diameter at exit and microscopic images of exit holes at minimum and maximum diameters are given in Figs. 7-10, respectively. Maximum entry hole diameter was observed to be 7.152 mm which is 0.152 mm larger than the drill diameter. A nominal increase of 0.152 mm from the drill diameter is acceptable and also relates to the fact that adopted range of processing parameters namely drilling speed and feed rate are well within acceptable range for drilling of Al/SiC MMCs. Furthermore, it was also observed that irrespective to the drill treatment conditions, almost for all the investigated conditions, entry hole diameter was increased by increasing both the feed rate and drilling speed. Microscopic images of entry side of drilled holes at maximum and minimum diameter for UTD, 24-hrs CTD, 48-hrs CTD are shown in Fig. 8. An increase in hole diameter with increasing feed rate is obvious, as large feed rate increases uncut chip thickness and hence, increases the load applied on the drill. Large drilling loads increases the drill vibrations and hence, increases hole diameter. Furthermore, large feed rates are also more prone to large chunk removals during drilling which may also be a cause for large drill diameter. High drilling speeds on the other hand although does not increase uncut chip thickness but, high speed results in more deflection of drill and hence increases the hole diameter to some extent.

It is also interesting to note that the increase in hole diameter from the size of drill decreases with the application of cryogenic treatment. As stated in previous section, the drill hardness was considerably enhanced by the application of cryogenic treatment. This enhanced hardness consequently reduces the ductility and hence, the drill is less prone to deflection. This enhanced stiffness/hardness is the main reason for low hole dimensions. The increased hardness with increasing cryogenic treatment time is also obvious in the results as shown in Figs. 7 and 9. Another interesting outcome of the current investigation

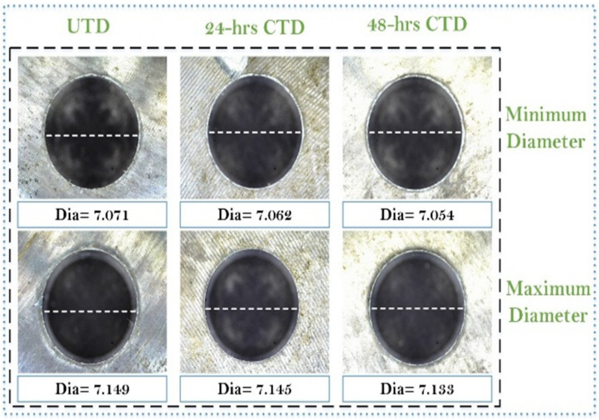
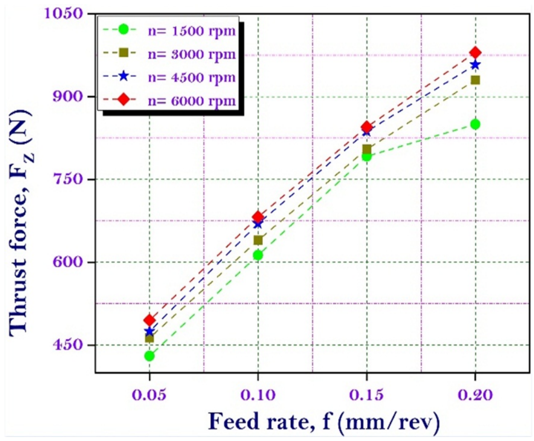


Fig. 10. Microscopic images of minimum and maximum diameter of exit hole.

is the variation between entry and exit hole diameters. As it can be seen from the comparison of Figs. 7 and 9, it was observed that the hole diameter of the entry hole is relatively larger than the exit hole diameter. This decrease, although minor, is mainly due to the fact that around the exit region, drill is enclosed from surroundings which provide some sort of support to drill and also restrict its wobbling and chatter. Therefore, the exit hole has relatively low magnitude of increase in comparison with drill diameter than the entry hole diameter. Microscopic images of exit side of drilled holes for UTD, 24-hrs CTD, 48-hrs CTD are shown in Fig. 10. Minimum diameter is observed at minimum spindle speed and feed rate i.e. 1500 rpm and 0.05 mm/rev while maximum diameter is found at maximum feed rate and maximum spindle speed i.e. 0.2 mm/rev. and 6000 rpm.

3.3 Thrust force

The variations in thrust force measured as a function of feed rate during the drilling of Al/SiC for UTD, 24-hrs CTD and 48-hrs CTD for four different spindle speeds of 1500 rpm, 3000 rpm, 4500 rpm and 6000 rpm, respectively, are shown in Fig. 11. The thrust force recorded during drilling of Al/SiC for 24-hrs CTD was found to be greater than those recorded for UTD and 48-hrs CTD. The variation in thrust force can be explained by the unique cutting pressures produced by the drill and the workpiece materials [27]. It can be seen in Fig. 11(a) that when there is an increase in feed rate from 0.05 mm/rev to 0.20 m/rev, thrust force also increases for all spindle speeds of 1500 rpm, 3000 rpm, 4500 rpm and 6000 rpm, respectively. For 1500 rpm spindle speed of UTD, the increase in thrust force for feed rate of 0.05-0.20 mm/rev is 97 %. Similarly, for spindle speeds of 3000 rpm, 4000 rpm and 6000 rpm, the increase in thrust force is 97 %, 96 % and 88 %, respectively. It means that for UTD, maximum rise in thrust force is observed for 1500 rpm and 3000 rpm and also, when we increase the spindle speed, there will be less rise in thrust force as observed in case of 4500 rpm and 6000 rpm.



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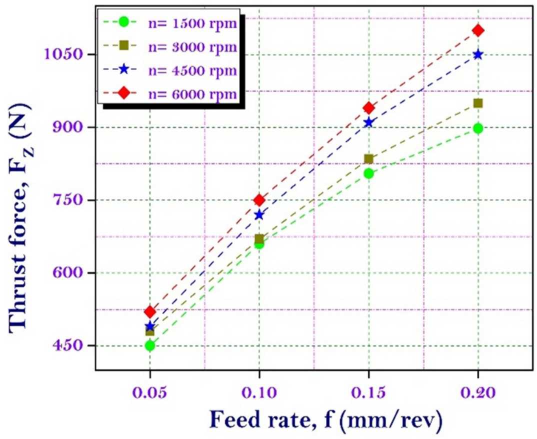

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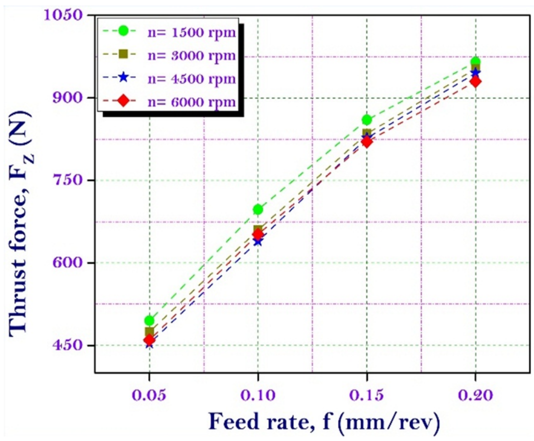


(c)

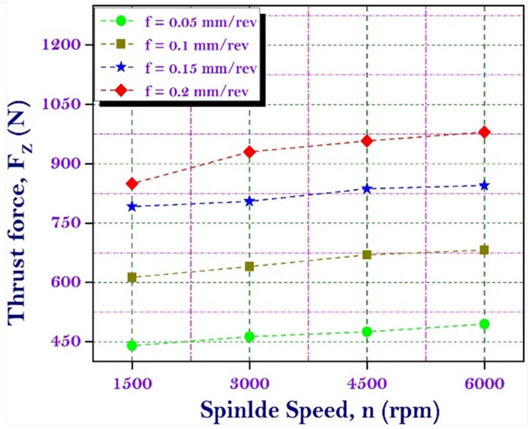
Fig. 11. Impact on thrust force by varying feed rate using different drills: (a) UTD; (b) 24-hrs CTD; (c) 48-hrs CTD.

Similarly, Fig. 11(b) shows that for 1500 rpm spindle speed of 24-hrs CTD, the increase in thrust force for feed rate of 0.05-0.20 mm/rev is 100 %. Moreover, for spindle speeds of 3000 rpm, 4000 rpm and 6000 rpm, the increase in thrust force is 100 %, 114 % and 109 %, respectively. It means that for 24-hrs CTD, maximum rise in thrust force is observed for

4500 rpm and 6000 rpm and also, when we decrease the spindle speed, there will be less rise in thrust force as observed in case of 3000 rpm and 1500 rpm. But still, this increase in thrust force for 24-hrs CTD is higher than that of UTD. Fig. 11(c) shows that for 1500 rpm spindle speed of 48-hrs CTD, the increase in thrust force for feed rate of 0.05-0.20 mm/rev is 94 %. Similarly, for spindle speeds of 3000 rpm, 4000 rpm and 6000 rpm, the increase in thrust force is 104 %, 111 % and 102 %, respectively. It means that for 48-hrs CTD, maximum rise in thrust force is observed for 4500 rpm and 3000 rpm and when spindle speed is 6000 rpm and 1500 rpm, there will be less rise in thrust force compared to that in case of 4500 rom and 300 rpm. This increase in thrust force for 48-hrs CTD is lower than that of 24-hrs CTD and UTD. Overall, maximum thrust force can be observed in case of 24-hrs CTD for spindle speed of 6000 rpm.

The variation in thrust force measured while drilling Al/SiC as the function of spindle speed for UTD, 24-hrs CTD and 48-hrs CTD for four different feed rate of 0.05 mm/rev, 0.10 mm/rev, 0.15 mm/rev and 0.2 mm/rev, respectively, is shown in Fig. 12. It can be seen in Fig. 12(a) that when there is an increase in spindle speed from 1500 rpm to 6000 rpm, thrust force also increases at all feed rate of 0.05 mm/rev, 0.10 mm/rev, 0.15 mm/rev and 0.2 mm/rev, respectively. For UTD, the increase in thrust force for feed rate of 0.05 mm/rev is 12.5 % with increasing spindle speed. Similarly, for feed rate of 0.10 mm/rev, 0.15 mm/rev and 0.2 mm/rev, the increase in thrust force is 11.25 %, 6.7 % and 15.29 %, respectively. It means that for UTD, maximum rise in thrust force is observed for feed rate of 0.20 mm/rev and when there is decrease in feed rate, there will be less rise in thrust force as observed in case of 0.05 mm/rev, 0.10 mm/rev and 0.15 mm/rev. Similarly, Fig. 12(b) shows that for 24-hrs CTD, the increase in thrust force for feed rate of 0.05 mm/rev is 15.5 % with increasing spindle speed. Similarly, for feed rate of 0.10 mm/rev, 0.15 mm/rev and 0.2 mm/rev, the increase in thrust force is 13.6 %, 16.8 % and 22.5 %, respectively.

It means that for 24-hrs CTD, maximum rise in thrust force is observed for feed rate of 0.20 mm/rev and when there is decrease in feed rate, there will be less rise in thrust force as observed in case of 0.05 mm/rev, 0.10 mm/rev and 0.15 mm/rev. But still, this increase in thrust force for 24-hrs CTD is higher than that of UTD. Fig. 12(c) shows that for 48-hrs CTD there is decrease in thrust force with increase in spindle speed from 1500 rpm to 6000 rpm, respectively. The decrease in thrust force for feed rate of 0.05 mm/rev is 7.6 % with increasing spindle speed. Similarly, for feed rate of 0.10 mm/rev, 0.15 mm/rev and 0.2 mm/rev, the decrease in thrust force is 6.9 %, 4.8 % and 3.8 %, respectively. It means that for 24-hrs CTD, maximum decrease in thrust force is observed for feed rate of 0.05 mm/rev and when there is increase in feed rate, there will be less fall in thrust force as observed in case of 0.05 mm/rev, 0.10 mm/rev and 0.15 mm/rev. Overall, maximum thrust force can be observed in case of 24-hrs CTD for feed rate of 0.20 mm/rev.



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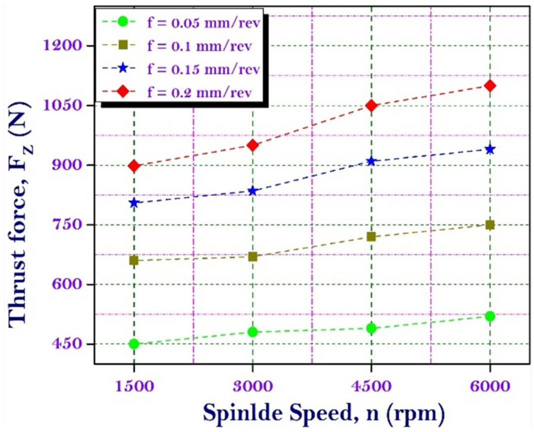

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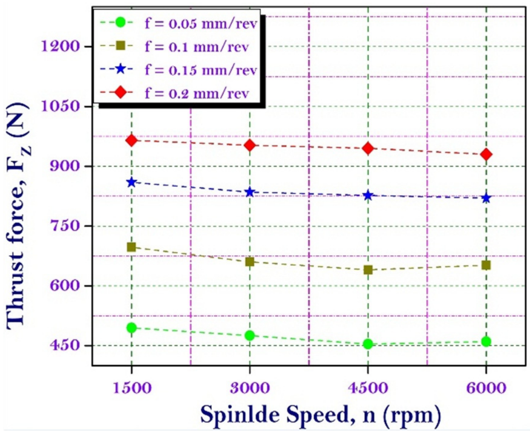
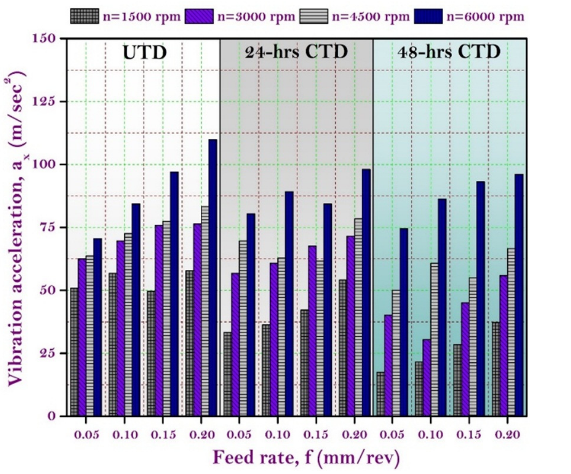


(c)

Fig. 12. Impact on thrust force by varying spindle speed using different drills r: (a) UTD; (b) 24-hrs CTD; (c) 48-hrs CTD.

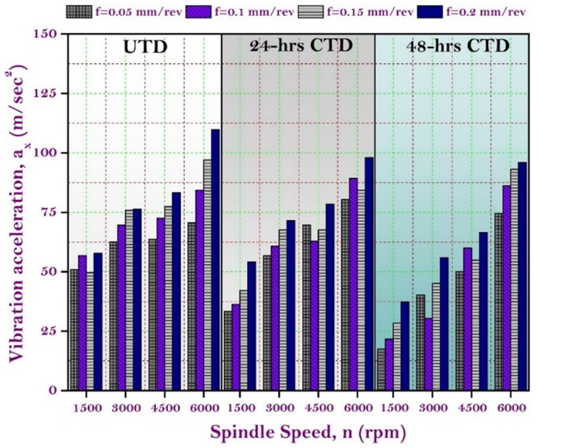
3.4 Vibration acceleration

The variation in vibration acceleration measured while drilling Al/SiC as the function of feed rate for UTD, 24-hrs CTD and 48-hrs CTD for four different spindle speeds of 1500 rpm, 3000 rpm, 4500 rpm and 6000 rpm, respectively, is shown in Fig. 13. The vibration acceleration recorded during drilling of



(a) (b) (c)

Fig. 13. Impact of vibration acceleration (a_x) by varying Feed rate using different drills: (a) UTD; (b) 24-hrs CTD; (c) 48-hrs CTD.



(a) (b) (c)

Fig. 14. Impact of vibration acceleration (a_x) by varying spindle speed using different drills: (a) UTD; (b) 24-hrs CTD; (c) 48-hrs CTD.

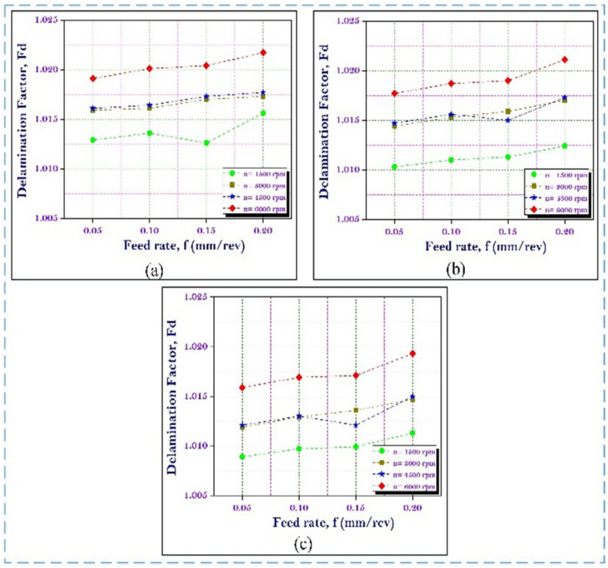


Fig. 15. Impact of feed rate and spindle speed on delamination factor using different drills: (a) UTD; (b) 24-hrs; CTD; (c) 48-hrs CTD.

Al/SiC for UTD was found to be greater than those recorded for 24-hrs CTD and 48-hrs CTD. It can be observed in Fig. 13 that the vibration acceleration tends to increase with increasing feed rate due to chip load per teeth [28]. Maximum vibration acceleration with increasing feed rate is observed in case of UTD and minimum vibration acceleration in case of 24-hrs CTD. It means that in order to reduce the vibration acceleration, drill must be treated cryogenically for 48-hrs, the same trend is also observed by the author in his research [28].

The variation in vibration acceleration measured while drilling Al/SiC as the function of spindle speed for UTD, 24-hrs CTD and 48-hrs CTD for four different feed rate of 0.05 mm/rev, 0.10 mm/rev, 0.15 mm/rev and 0.2 mm/rev, respectively, is shown in Fig. 14. It can be observed in Fig. 14 that the vibration acceleration tends to increase with increasing spindle speed. At maximum spindle speed for maximum feed rate, maximum vibration acceleration is observed. At lower spindle speed, the vibration acceleration is observed minimum in all the three cases. Overall, the vibration acceleration is observed lower in CTD as compared to that in UTD. If we analyze the vibration acceleration in CTD, 48-hrs CTD will have less vibration acceleration than 24-hrs CTD.

3.5 Delamination

Delamination is a prominent issue associated with the drilling of composite materials. Delamination factor is defined as the ratio of maximum drilled diameter with the original diameter of the drill. Delamination factor is represented by Fd, shown below

$$\mathrm{Fd} \equiv \frac{D\max}{Do} \tag{1}$$

where D_{max} is the maximum diameter of drilled hole and D_o is the original diameter of the drill. Delamination factors for all the investigated drilling parameters and drill conditions are presented in Fig. 15. From Fig. 15, it can be observed that like hole diameter, the delamination factor increases with increasing spindle speed and feed rate whereas, it decreases with cryogenic treatment and also by increasing the duration of cryogenic treatment. The increased drill load at high feed rates and the drill chatter increase at high drilling speeds are the main reasons for enhanced delamination at the respective parameters. The cryogenic treated drills result in lower delamination factors thus creating a cleaner machined surface and high dimensional accuracy. The reduced drill vibration/chatter due to high hardness after cryogenic treatments are the main factors effecting the behaviors of treated drills. It is also important to note that for the investigated cases, the delamination factor is less than 2.5 %. This also endorses the fact that selected process parameters are suitable for high performance

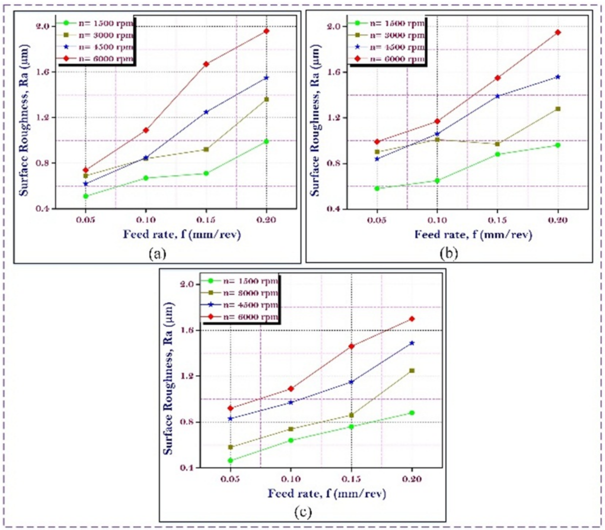


Fig. 16. Impact of surface roughness (μm) by varying feed rate using different drills: (a) UTD; (b) 24-hrs CTD; (c) 48-hrs CTD.

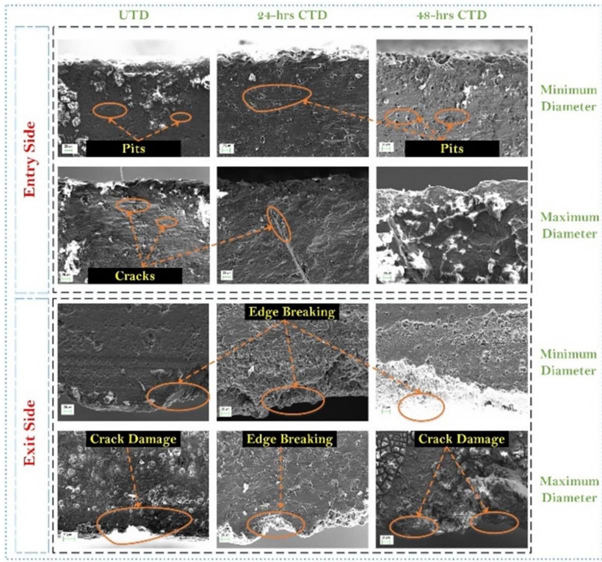


Fig. 17. SEM analysis of entry and exit side for UTD, 24-hrs CTD and 48-hrs CTD at minimum diameter and maximum diameter of drilled holes.

and high accuracy drilling of Al/SiC MMC.

3.6 Surface roughness

Surface roughness depends greatly on spindle speed and feed rate. Fig. 16 shows the variation in surface roughness as a function of feed rate and different fixed spindle speed for UTD, 24-hrs CTD and 48-hrs CTD. It can be observed that increasing feed rate leads to increased surface at each spindle speed, irrespective of the drill used. In case of UTD, it can be observed in Fig. 16(a) that at spindle speed of 1500 rpm, 3000 rpm and 4500 rpm, the surface roughness is lower which means that surface quality is better than at 6000 rpm. And if we increase the spindle speed to 6000 rpm, greater surface roughness with increasing feed rate is observed. But this surface roughness is reduced in case of 24-hrs and 48-hrs CTD. Minimum surface roughness (0.463 μm) is found in case of 48-hrs CTD at 1500 rpm spindle speed and feed rate of 0.05 mm/rev and maximum surface roughness (1.96 μm) is found in case of UTD at 6000 rpm and 0.20 mm/rev, respectively. It means that by treating the drills cryogenically, surface roughness can be reduced.

SEM analysis was conducted to view the hole surface in depth. SEM was done by cutting the drilled hole from center equally and SEM performed from entry and exit side. Fig. 17 shows the SEM images of entry and exit side for UTD, 24-hrs CTD and 48-hrs CTD at minimum diameter and maximum diameter of drilled holes. It can be seen from Fig. 17 that surface of entry side is much better than the surface of exit side. It might be due to the pulling out effect of drill wear and drill edge which causes severe poor surface at exit side. Crack damage and edge breaking are obvious at exit holes and some pits are found at entry hole for minimum diameter as well as maximum diameter images. Comparatively, surface texture at minimum diameter (1500 rpm spindle speed and 0.5 mm/rev feed rate) is much better than the surface at maximum diameter (spindle speed 6000 rpm and feed rate 0.2 mm/rev). The poor surface roughness at high spindle speed is due to maximum temperature at high spindle speed which soften the workpiece and in result rough surface found. Damage at entry side is not much severe as it is at exit side. If we compare the images with respect to UTD and other cryogenic treated drills, it can be seen that the surface texture of cryogenic treated drills are much better than simple untreated drill.

4. Conclusions

MMC's are a new class of materials that have the light weight nature of composite materials and have high strength like metallic materials. Al/SiC is one such MMCs that has prominent applications in several high-performance areas. Therefore, they often require the secondary operations like drilling. Drilling of Al/SiC MMCs is often considered as a complex operation due to the abrasive nature of the material. Therefore, in this paper an ecofriendly drill treatment process i.e., cryogenic treatment and its influence on the machinability of Al/SiC MMCs over a wide range of process parameters has been investigated and presented. Prominent conclusions that can be drawn from this work are as following:

- Cryogenic treatments increase the hardness of drills and the magnitude of increase in hardness values increases with increasing cryogenic treatment time. Furthermore, it was also observed that cryogenic treatment does not have the tendency to alter the phase and elemental combination of drill material.
- Hole diameter increases with increasing both the feed rate and drilling speed. However, this increase can be minimized by the help of cryogenic treatment of drills.
- A complex relationship between the drilling force and proc-

ess parameters as well as the cryogenic treatment was observed. As drilling force generation is a complex phenomenon and depends on a number of process parameters, any variation in one or more of these parameters may result in variation of drilling forces and therefore needs to be considered during the drilling phase. Overall behavior also suggests that the cryogenic treatment has the tendency to decrease the drilling forces generated.
- Drill vibration was also observed to be directly proportional with feed rate and drilling speed and inversely proportional with the cryogenic treatment and its duration. A reduced drill vibration at 48-hour cryogenic treated drill may provide a way for much stable drilling operation.
- The reduction of drill vibration for cryogenic treated drills also has considerable effects on the machined surface integrity and reduces both the delamination factor as well as the surface roughness.

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Nomenclature

Al/SiC : Aluminum silicon carbide
MMC : Metal matrix composite
WEDM : Wire cut electrical discharge machine
UTD : Untreated drill
24-hrs CTD : 24 hours cryogenically treated drill
48-hrs CTD : 48 hours cryogenically treated drill
hrs : Hours
°C : Degree celsius
n : Spindle speed
rpm : Revolution per minute
f : Feed rate
mm/rev : Millimeter per revolution
Kgf : Kilogram force
N : Newton
XRD : X-ray diffraction
F_d : Delamination factor
D_{max} : Maximum diameter
D_o : Original diameter
Dia : Diameter
F_z : Thrust force
a_x : Vibration acceleration
Ra : Surface roughness
SEM : Scanning electron microscopy

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