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Experimental Studies on Turning of Discontinuously Reinforced Aluminium Composites under Dry, Oil Water Emulsion and Steam Lubricated Conditions Using TAGUCHI's Technique

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ABSTRACT

This paper reports on the experimental investigations carried out under dry, oil water emulsion and steam lubricated conditions in turning of DRACs. The measured results were then collected and analyzed with the help of the commercial software package MINITAB15. The experiments were planned on orthogonal arrays, made with prefixed cutting parameters and different lubricated conditions. An analysis of variance (ANOVA) was carried out to check the validity of the proposed parameters and also their percentage contributions. The results of the tests show that with proper selection of the range of cutting parameters, it is possible to obtain better performance under steam lubricated condition.

Key Words: *DRACs, Cutting force, Cutting temperature, Design of experiments, ANOVA, Hystrix cristata.*

1. INTRODUCTION

Discontinuously reinforced Aluminium composites (DRACs) is one of the important composites among the metal matrix composites, which have SiC particles in an aluminium matrix; this is harder than tungsten carbide (WC), which pose many problems in machining. When DRACs are being chosen for high volume and machine-intensive components, it is crucial that the machinability of the materials be understood. The machinability of DRACs has been investigated actively worldwide since the 1980s, and most researchers have found that polycrystalline diamond (PCD) or cubic boron nitride tools can be used to machine DRACs effectively. Driven by the high cost of these tools, it is still desirable to optimize the cutting conditions, such as the effect of cutting fluid, since there has been no comprehensive study undertaken in this area.

A Discontinuously Reinforced Aluminium Composites (DRACs) can be described as a material which is made up of a continuous metallic phase (the matrix) into which a second phase (or phases) has been artificially introduced. Early DRACs had their application confined to military and aerospace applications, their extensive usage was hindered due to their high production costs, limited production methods, and restricted product forms [1].

Machining of Discontinuously reinforced Aluminium composites (DRACs) presents a significant challenge to the industry since a number of reinforcement materials are significantly harder than the commonly used high speed steel (HSS) tools and carbide tools [2]. The reinforcement phase causes rapid abrasive tool wear; thus the widespread usage of DRACs is considerably impeded by their poor machinability and high machining costs. Based on the available literature on DRACs it is clear that the morphology, distribution and volume fraction of the reinforcement phase, as well as the matrix properties are all factors that affect the overall cutting process [2-3], but as yet relatively few published reports are related to the optimization of the cutting process.

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The positive effect of the use of cutting fluids in metal cutting was first reported in 1894 by F.Taylor, who noticed that by applying large amounts of water in the cutting area, the cutting speed could be increased up to 33% without reducing tool life. Since then, cutting fluids have been developed resulting in an extensive range of products covering most workpiece materials and operations.

As research shows, the application of gases as cutting fluids has been used since 1930s. [4,5] reported the experimental results of carbon dioxide gas application in machining. It was noticed that application of carbon dioxide gas as coolants and lubricants reduced the cutting force and obtained a higher tool life. [6–10] also deeply studied application of oxygen gas as cutting fluids in cutting process . [10] observed these results were promising that the application of oxygen gas was an effective agent to reduce contact length of tool–chip . However, In the 1990s, [11-13] used water vapor as coolants and lubricants in turning and milling operation. The results showed water vapor lubrication in comparison with liquid one ensures more uniform cooling and the application of vaporous lubrication allows increasing the carbide cutting tools lifetime about 2–2.5 times in turning and 2–4 times in milling carbon and stainless steels. In 2007 [14] used pressurized steam jet approach in turning of discontinuously reinforced aluminium composites. The result showed the steam pressure as the dominant parameter for surface roughness followed by feed. [15] also carried out experimental investigations under dry, oil water emulsion and steam lubricated conditions using orthogonal array in turning of DRACs, he concluded that the tool wear and surface roughness were found to be lesser for steam cutting, where as these two parameters showed much variation during oil water emulsion and dry cutting. [16] used a pressurized steam jet approach to tool wear minimization in cutting of metal matrix composites by full factorial design of experiments, he concluded that the effect of the pressured steam jet plays a significant role on the tool wear followed by tool inserts and depth of cut. Further, fluid jet assisted machining as a highly effective method for cutting of conventional materials has been well explored [17–30], in which fluids, such as air, water or steam, mainly act as transportation carriers carrying the heat away from the cutting region, and the efficiency of such a cooling method largely depends on the jet pressure. Therefore, it is necessary to understand the relationship among the various controllable parameters and to identify the important parameters that influence the quality of turning. Moreover, it is necessary to optimize [31-33] the cutting parameters to obtain an extended tool life and better productivity, which are influenced by cutting force and cutting temperature. Design of experiment [DOE] is a statistical-based approach to analyze the influence of known process variables over unknown process variables. The current article investigates the influence of cutting parameters and lubricating conditions on cutting force and cutting temperature in turning of DRACs with Cubic boron nitride inserts (CBN) KB-90 grade.

2. METHODOLOGY

2.1 Material

Al–SiC MMC workpiece specimens popularly known as DRACs having aluminum alloy 6061 as the matrix and containing 15 vol. % of silicon carbide particles of mean diameter 25μm in the form of cylindrical bars of length 120mm and diameter 40mm manufactured in Vikram Sarbhai Space Centre (VSSC) Trivandrum by stir casting process with pouring temperature 700-710°C, stirring rate 195 rpm, extrusion at 457°C, extrusion ratio 30:1, direct extrusion speed 6.1m/min to produce Ø40mm cylindrical bars. The specimen were solution treated for 2h at a temperature of 540oC in a muffle furnace, temperatures were accurate to within ±2oC and quench delays in all cases were within 20s. after solutionising, the samples were water quenched to room temperature, and subsequently aged for six different times to obtain samples with different Brinell hardness number (BHN), out of which one samples were selected, one with 94 BHN obtained at peakage condition i.e 2h at 220oC respectively. Sample selected were kept in a refrigerator right after the heat treatments. Figure 1 shows the microstructure of DRACs.

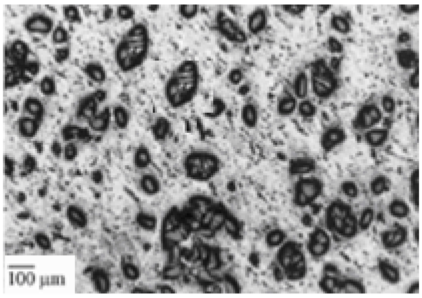

Figure 1. A microstructure of an DRACs (6061 Al/ 15% SiC 25p).

2.2 Machining Test

The chemical composition of the specimen is given in Table 1. Turning, as a machining process was selected. The experimental study was carried out in PSG A141 lathe (2.2 KW) with different cutting speeds, feeds and a constant depth of cut. The selected cutting tool was cubic boron nitride insert KB-90 (ISO code), for machining of DRACs. The ISO code of cutting tool inserts and tool holder are shown in Table 2. The level of variables used in the experiment is given in Table 3. The schematic representation of cutting force measurement is shown in Figure 2 and was measured by using IEICOS Digital tool dynamometer respectively. The measurement of cutting temperature was carried out by thermocouple embedded in tool as shown in Figure 3. For the thermocouple, a groove was cut in the tool by using electrical discharge machining (EDM). The groove was made in the rake face 1.70 mm from the cutting edge and the thermocouple wire was placed in the groove near the cutting edge Figure 4 shows the photograph of tool embedded with thermocouple. This was chosen due to the combination of getting good results in a shorter interval than other method, and because of its ease in implementation after it has been calibrated, and also due to its low cost [34, 35].

Table 1. Nominal chemical composition of base metal (6061 Al alloy).

Element	Cu	Mg	Si	Cr	Al
Weight. percentage	0.25	1.0	0.6	0.25	Balance

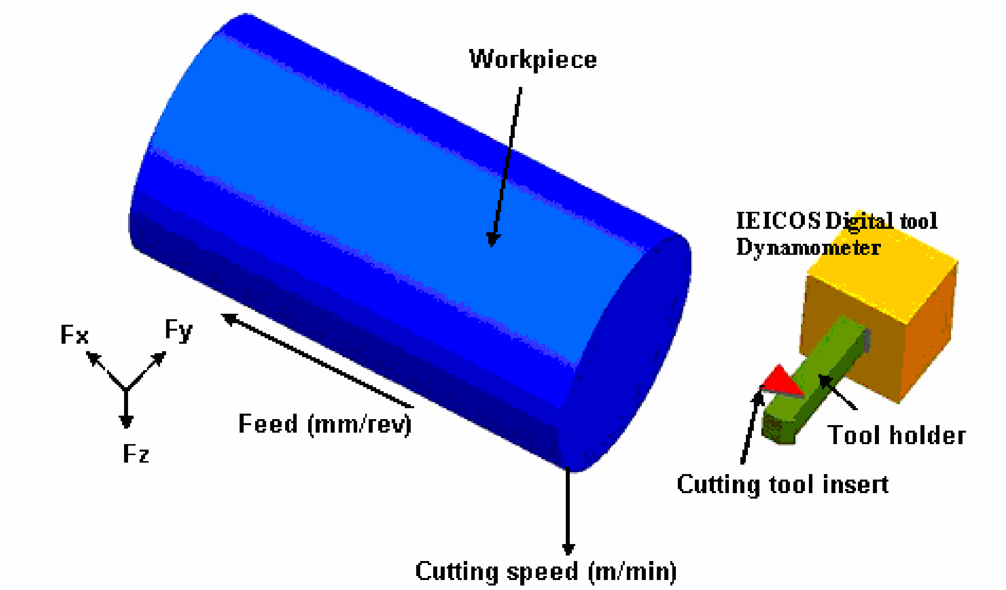

Figure 2. The schematic representation of cutting force (Fz) measurement.

Table 2. Details of cutting tool and tooling system used for experimentation.

Tool holder Specification	STGCR 2020 K-16 CTGPR 1212 F 11
Tool geometry Specification	Approach angle:91^0 Tool nose radius:0.4 mm Rake angle: 0^0 Clearance angle: 7^0
Tool insert CBN (KB-90) Specification	TPGN160304-LS TPGN 110304-LS

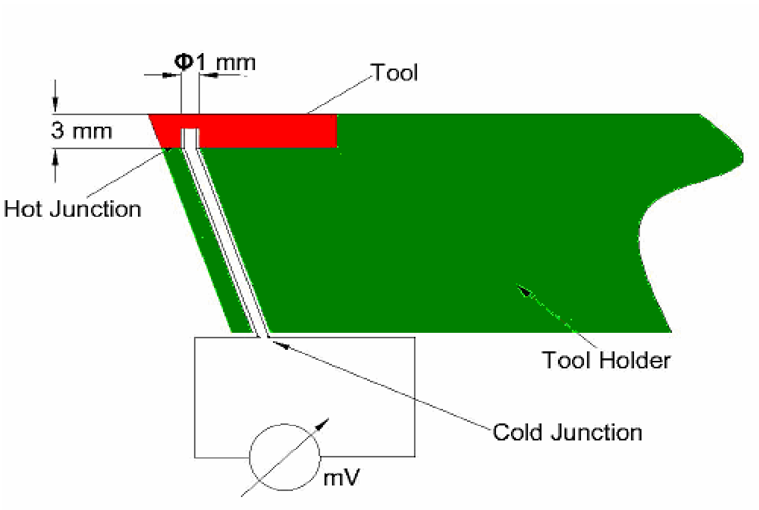

Figure 3. Thermocouple embedded in the tool.

Figure 4. Thermocouple position in the tool.

Table 3.Levels and factors.

Levels	(A) Lubricated condition	(B) Cutting speed (m/min)	(C) Feed (mm/rev)
1	Dry	45	0.11
2	Oil water emulsions	73	0.18
3	Steam	101	0.25

2.3. Steam Generator and Steam Feeding System

The steam generator and steam feeding system are developed in which jet flow parameters (pressure, flow rate) and cooling distance (the distance between nozzle and cutting zone) are controllable. Figure 5 shows the steam generator and steam feeding system.

Figure 5. Steam generator and steam feeding system.

3. TAGUCHI'S METHOD

Taguchi techniques have been used widely in engineering design [36, 37]. The main trust of the Taguchi techniques is the use of parameter design, which is an engineering method for product or process design that focuses on determining the parameter (factor) settings producing the best levels of a quality characteristic (performance measure) with minimum variation. Taguchi designs provide a powerful and efficient method for designing processes that operate consistently and optimally over a variety of conditions. To determine the best design requires the use of a strategically designed experiment which exposes the process to various levels of design parameters.

Experimental design methods were developed in the early years of 20th century and have been extensively studied by statisticians since then, but they were not easy to use by practitioners [37]. Taguchi's approach to design of experiments is easy to adopt and apply for users with limited knowledge of statistics, hence it has gained a wide popularity in the engineering and scientific community. There have been plenty of recent applications of Taguchi techniques to materials processing for process optimization. Some of the previous works are listed in [38–43]. In particular, it is recommended for analyzing metal cutting problems for finding the optimal combination of parameters [43].

3.1. Design of Experiments

The orthogonal array for two factors at three levels was used for the elaboration of the plan of experiments the array L_{27} was selected, which has 27 rows corresponding to the number of tests (26 degrees of freedom) with 13 columns at three levels. The factors and the interactions are assigned to the columns.

The first column was assigned to the lubrication condition (A), the second column to cutting speed (B), the fifth column to the feed (C) and remaining were assigned to interactions. The outputs to be studied were the cutting temperature and the cutting force. Further, an analysis of variance (ANOVA) was carried out separately for each response.

4. RESULTS AND DISCUSSION

4.1. Cutting Force in Turning of DRACs

Figure 6 shows the comparison of cutting force (Fz) in steam application with dry and oil water emulsion. It is observed that the cutting force decreases with increase in cutting speed [44] further cutting force was lower in steam application, compared to dry and oil water emulsion. In steam application, the cutting fluid is supplied at high pressure and high velocity, which penetrates in to the tool chip interface causing reduction in frictional contribution to the cutting force, these minute capillaries exist at the tool chip interface and as the chip moves up it contacts mainly at the top of the asperities, these points of contact zones creating capillaries between the chip and the tool. These capillaries draw in steam, which chemically react to produce a thin solid film of low shear strength, which keeps the chip and the tool apart, it causes reduction in friction. During steam as cutting fluid, the cutting fluid is fragmented into tiny globules and the size of which is inversely proportional to the pressure of injection. The velocity varies as a function of the square root of the injection pressure. This high velocity facilitates better penetration of the steam to the underside of the chip facilitating its passage to the tool chip interface resulting in the reduction of friction. Such a condition is not possible in oil water emulsion, where no such fragmentation is taking place and the kinetic energy of the fluid jet is in no way comparable to that during steam injection.

From the Figure 6 it can be observed that, cutting force decreases with an increase in cutting speed. Under smaller cutting speed, the tool cutting edge will impact on the reinforcement particles, the impacted particles will then either be dislodged from the matrix, without harming the tool, or be embedded into the matrix, ploughing on the tool flank, resulting in a higher order cutting force. As the cutting speed increases, the tool would cut better without ploughing, resulting in a drop in cutting force.

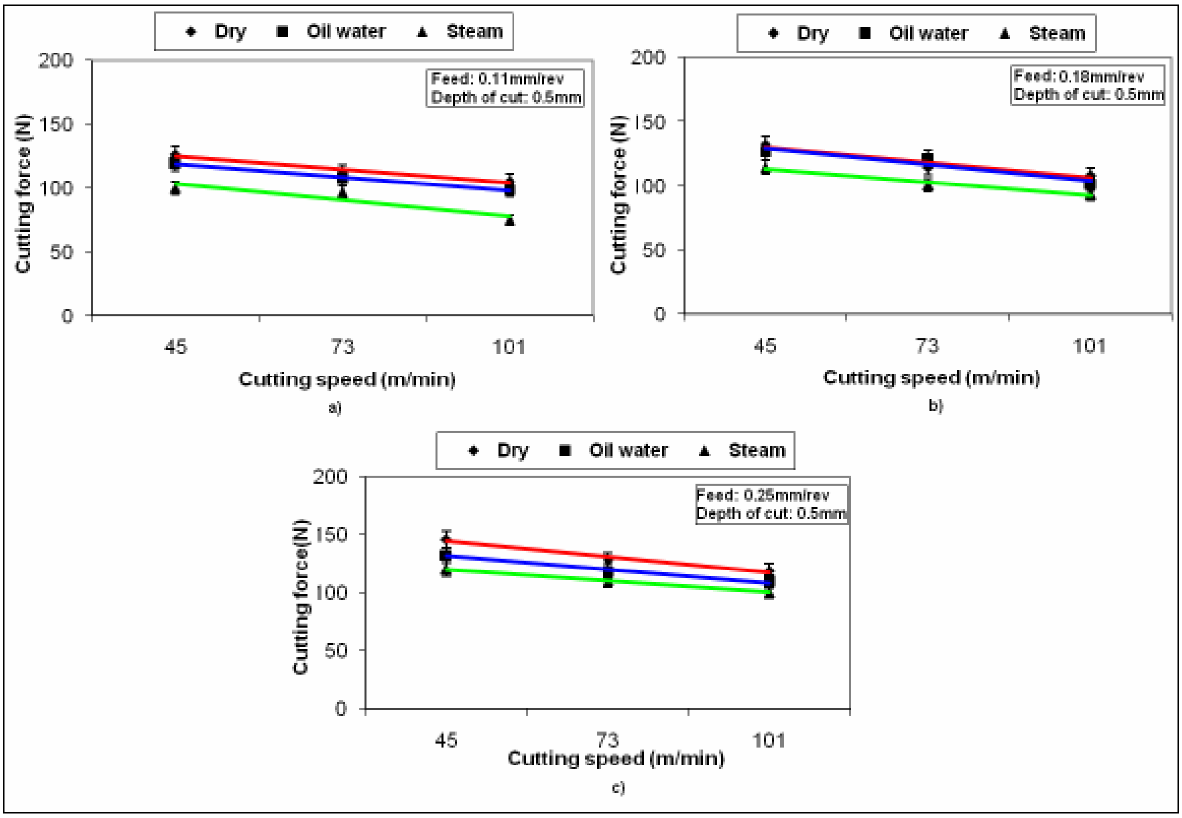

Figure 6. Variation of cutting force with cutting speed for different lubrication conditions (a) feed (0.11mm/rev) (b) feed (0.18mm/rev) (c) feed (0.25 mm/rev).

4.2. Cutting Temperature in Turning of DRACs

The temperature θ_c of machining DRACs is dependent on the cutting speed V and the type of material pair involved in machining and can be expressed as

$$\theta_c \propto V^b \quad (1)$$

The comparison of cutting temperature in steam lubrication with oil water emulsion and dry cutting with varying speed and feed keeping depth of cut constant are shown in Figure 7. The cutting temperature observed in steam application is comparatively less to that of oil water emulsion and dry cutting.

Cutting temperature plays a major role in deciding the tool wear as well as wear mechanisms such as abrasion, adhesion, diffusion, chemical action, etc. During the application of oil water emulsion the heat is extracted only by convective heat transfer, but during steam lubrication, cooling occurs by convective as well as evaporative heat transfer. During steam lubrication fluid droplets due to their high velocity can puncture the blanket of vapor formed and reach the hot tool interfaces facilitating evaporative heat transfer, which is more efficient than the convective heat transfer. Steam application thus provides better lubrication and effective heat transfer leading to low cutting temperature than that is possible during oil water emulsion and dry cutting. The influence on cutting temperature in all three cases shows an increasing trend Figure 7.

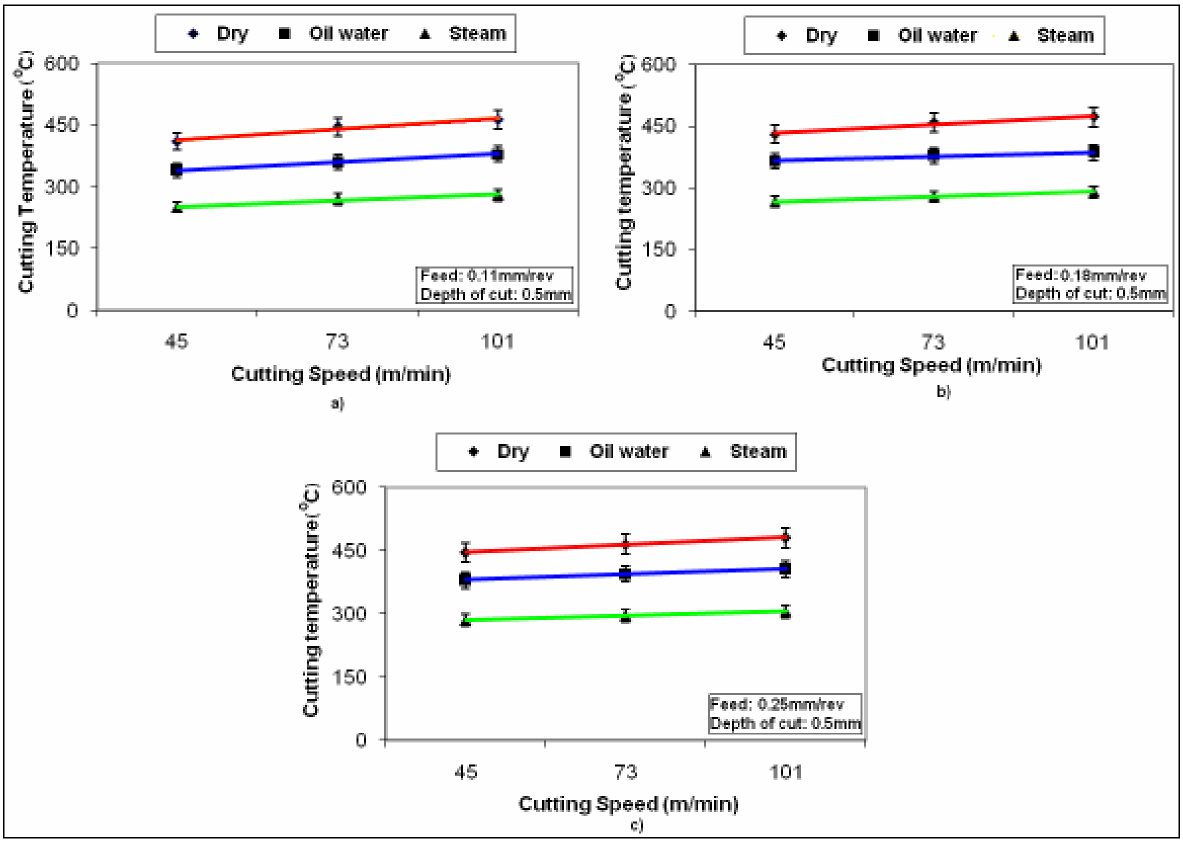

Figure 7. Variation of cutting temperature with cutting speed for different lubrication conditions (a) feed (0.11mm/rev) (b) feed (0.18mm/rev) (c) feed (0.25 mm/rev).

4.3. Analysis of Variance (ANOVA) and Factor Effects for Cutting Force and Cutting Temperature

In Taguchi’s DOE method, the term “signal” represents the desirable value and "noise" represents the undesirable value. The objective of using S/N ratio is to obtain a measure of performance to develop products and processes insensitive to noise factors. The S/N ratio indicates the degree of the predictable performance of a product or process in the presence of noise factors. Process parameter settings with the highest S/N ratio always yield the optimum quality with minimum variance. The S/N ratio for each parameter level is calculated by averaging the S/N ratios obtained when the parameter is maintained at that level. Table 4 and Table 5 shows the S/N ratios obtained for different parameter levels.

Table 4. Response table for signal to noise ratios smaller is better cutting force (N).

Level	Lubrication condition	Cutting speed (m/min)	Feed(mm/rev)
1	-41.64	-41.84	-40.31
2	-41.18	-40.98	-40.99
3	-40.05	-40.05	-41.57
Delta	1.59	1.79	1.26
Rank	2	1	3

Table 5. Response table for signal to noise ratios smaller is better (cutting temperature).

Level	Lubrication condition	Cutting speed (m/min)	Feed(mm/rev)
1	-53.09	-50.76	-50.82
2	-51.50	-51.23	-51.16
3	-48.92	-51.53	-51.53
Delta	4.17	0.77	0.71
Rank	1	2	3

The calculated S/N ratio for three factors on the cutting force and cutting temperature during machining of DRACs for each level is shown in Figures 8-9. As shown in Table 4 and Figure 8 steam is a dominant parameter on the cutting force followed by cutting speed and feed. Hence from mean S/N graph for Cutting force from quality characteristic considered in the investigation “smaller the better” we can conclude that selection of steam lubrication,101m/min cutting speed and 0.11 depth of cut would be ideal for machining of DRACs. Similarly for cutting temperature, from mean S/N graph we can conclude that selection of steam lubrication, 45m/min cutting speed and 0.11mm/rev feed would be ideal for machining of DRACs.

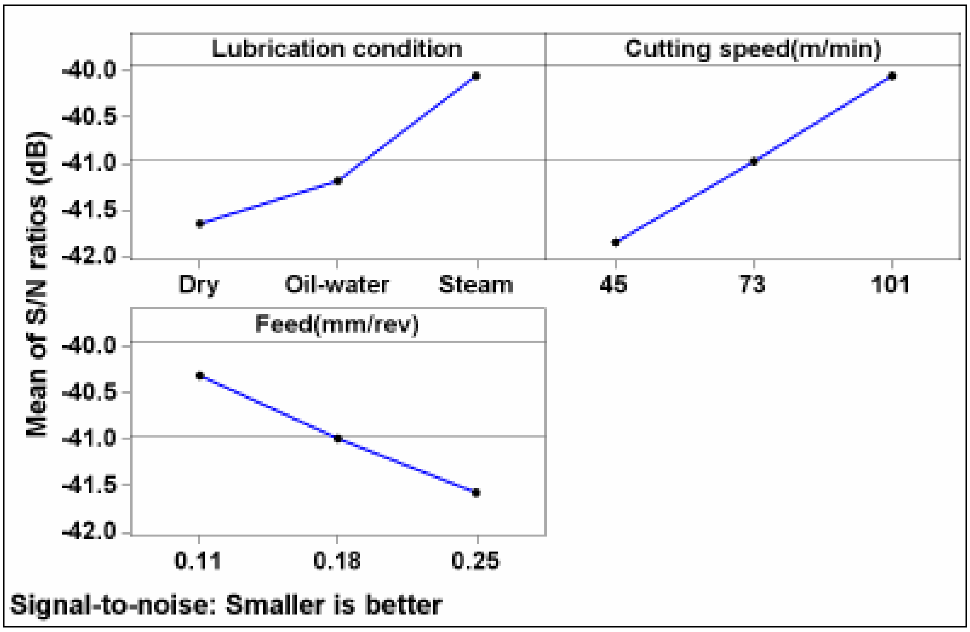

Figure 8. Mean S/N graph for cutting force (N).

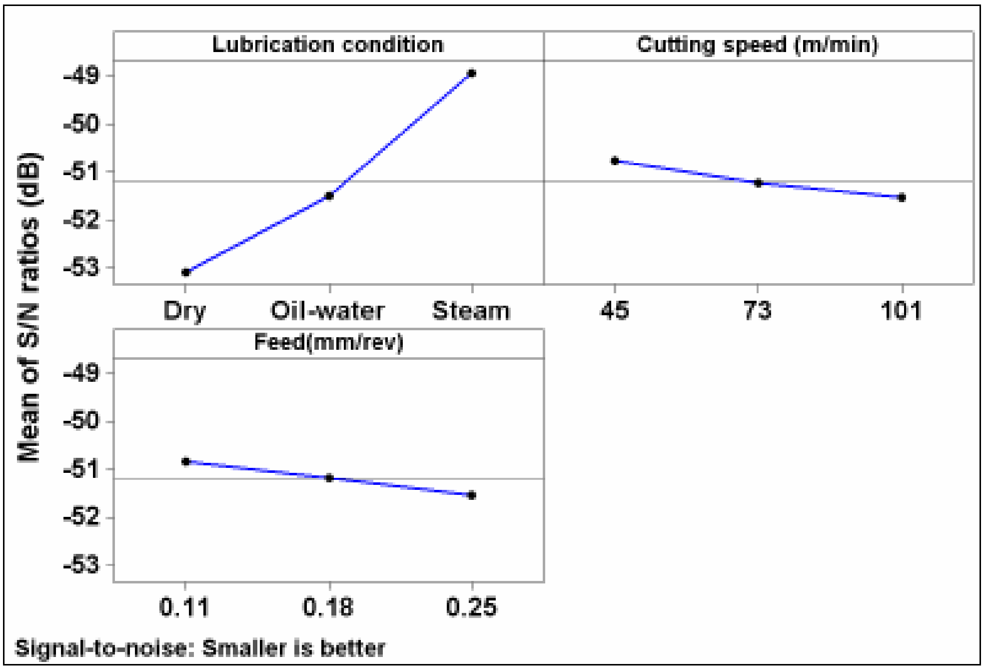

Figure 9. Mean S/N graph for cutting temperature.

On the examination of the percentage of contribution (P%) of the different factors Tables 6-7, for cutting force and cutting temperature, it can be seen that lubrication condition has the highest contribution of about 35.11% for cutting force and 94% for cutting temperature, Followed by cutting speed and feed. Further Interactions (AxB),(AxC),(BXC) do not present a statistical significance, nor a percentage of physical significance of contribution to the cutting force. But interactions (AxC), (BXC) present a statistical significance, and a percentage of physical significance of contribution to the cutting temperature.

Table 6. Analysis of variance for the cutting force (N).

Source	DOF	Seq SS	Adj SS	Adj MS	F	P	Percent P (%)
(A)Lubrication condition	2	12.0988	12.0988	6.04938	55.85	0.000	35.11
(B)Cutting speed (m/min)	2	14.4414	14.4414	7.22071	66.66	0.000	41.91
(C)Feed (mm/rev)	2	7.1611	7.1611	3.58055	33.06	0.000	20.78
AXB	4	0.3877	0.3877	0.09694	0.89	0.510	0.56
AXC	4	0.9580	0.9580	0.23950	2.21	0.158	1.39
BXC	4	0.1650	0.1650	0.04126	0.38	0.817	0.24
Residual Error	8	0.8665	0.8665	0.10832			
Total	26	36.0786					100

Table 7.Analysis of variance for S/N ratios for cutting temperature.

Source	DOF	Seq SS	Adj SS	Adj MS	F	P	Percent P (%)
(A)Lubrication condition	2	79.7457	79.7457	39.8729	10429.58	0.000	94
(B)Cutting speed (m/min)	2	2.6746	2.6746	1.3373	349.79	0.000	3.15
(C)Feed (mm/rev)	2	2.2479	2.2479	1.1240	293.99	0.000	2.65
AXB	4	0.0293	0.0293	0.0073	1.92	0.201	0.017
AXC	4	0.1547	0.1547	0.0387	10.11	0.003	0.091
BXC	4	0.1376	0.1376	0.0344	9.00	0.005	0.081
Residual Error	8	0.0306	0.0306	0.0038			
Total	26	85.0204					100

4.4. Confirmatory Experiments

To predict and verify the improvement in the cutting force and cutting temperature for machining of DRACs by the turning process with respect to the chosen initial parameter setting, verification tests are used. Figure 10 shows the comparison of cutting force and cutting temperature values obtained by experiments with Taguchi's design of experiments for obtaining optimal cutting condition for machining of DRACs using steam lubrication. From the graphs shown below, it is clear that the least value of cutting force 75.132 N is obtained at a cutting speed of 101m/min and a feed of 0.11mm/rev under steam lubrication. Similarly, lowest cutting temperature 250°C was obtained for a cutting speed of 45m/min and feed 0.11mm/rev under steam lubrication. The minimum values of the cutting force and cutting temperature matched with the values as shown in the mean S/N graph Figures 8-9.

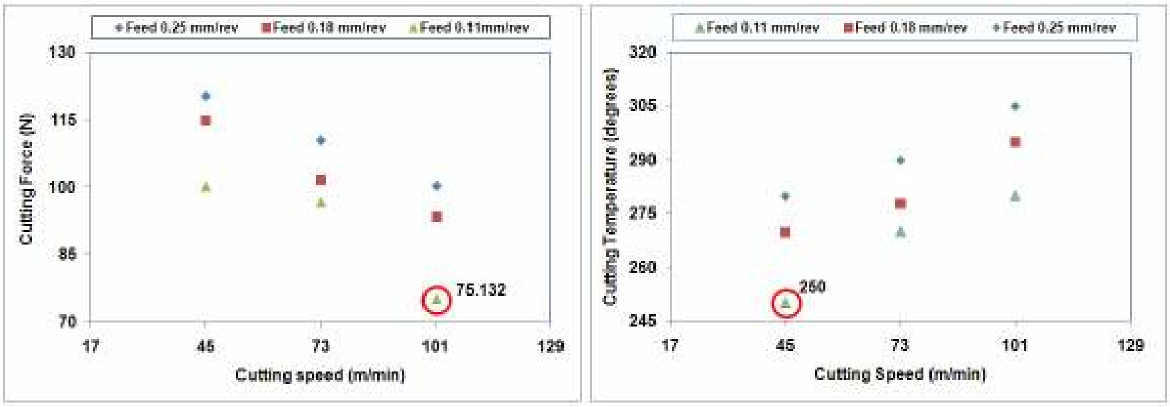

Figure 10. Shows the comparison of cutting force and cutting temperature values obtained by experiments.

5. CONCLUSIONS

The cutting force and cutting temperature were studied in turning of DRACs with cubic boron nitride tool under dry, oil water emulsion and steam lubricated conditions using experimental and Taguchi's orthogonal array. From the study, it can be concluded that the steam lubrication can replace the dry and oil water emulsion if the parameters are chosen carefully. However, the process is new and much further research is needed. Based on the emperical study, the following conclusions can be drawn:

1. The cutting force and cutting temperature were found to be lower during steam cutting compared to oil water emulsion and dry cutting.
2. The cutting force decreases with increase of cutting speed and with increase in feed. The cutting temperature increases with cutting speed and feed.
3. The effect of lubrication condition is found to be having highest physical as well as statistical influence on the cutting force and cutting temperature (94% and 35.11% respectively)
4. The cutting speed is found to be the influential cutting parameter that affects cutting force and cutting temperature of about 41.91% and 3.15% respectively.

5. Optimum machining condition from mean S/N graph and from experimental results for cutting force is selection of steam lubrication, 101m/min cutting speed and 0.11mm/rev feed. Similarly for cutting temperature, selection of steam lubrication, 45m/min cutting speed and 0.11mm/rev feed would be ideal for machining of DRACs.

6. The results of the study show that with a proper selection of machining parameters, it is possible to obtain a performance better in steam lubrication condition in turning of DRACs.

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