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STUDY ON SURFACE ROUGHNESS MINIMIZATION IN TURNING OF DRACs USING SURFACE ROUGHNESS METHODOLOGY AND TAGUCHI UNDER PRESSURED STEAM JET APPROACH

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ABSTRACT

This paper discusses the use of Taguchi and response surface methodologies for minimizing the surface roughness in turning of discontinuously reinforced aluminum composites (DRACs) having aluminum alloy 6061 as the matrix and containing 15 vol. % of silicon carbide particles of mean diameter 25µm under pressured steam jet approach. The measured results were then collected and analyzed with the help of the commercial software package MINITAB15. The experiments have been conducted using Taguchi's experimental design technique. The matrix of test conditions included cutting speeds of 45, 73 and 101 m/min, feed rates of 0.11, 0.18 and 0.25 mm/rev and steam pressure 4, 7, 10 bar while the depth of cut has been kept constant at 0.5 mm. The effect of cutting parameters on surface roughness is evaluated and the optimum cutting condition for minimizing the surface roughness is determined. A second-order model has been established between the cutting parameters and surface roughness using response surface methodology. The experimental results reveal that the most significant machining parameter for surface roughness is steam pressure followed by feed. The predicted values and measured values are fairly close, which indicates that the developed model can be effectively used to predict the surface roughness in the machining of DRACs.

Keywords: surface, roughness, DRACs, taguchi, aluminum, response surface methodology.

1.0. INTRODUCTION

Considerable research in the field of material science has been directed towards the development of new lightweight, high performance engineering materials like composites. The applications of composite materials are among the most important developments in materials engineering in recent years, DRACs being one amongst them. These DRACs have become necessary in various engineering applications, such as aerospace, marine, automobile and turbine-compressor engineering applications because of their light weight, high strength, stiffness, and high temperature resistance [Ibrahim *et al.*, (1991); Sinclair *et al*., (1997); Gone *et al*., (2000)].

In the 1990s, [Podgorkv (1992) and Godelvski *et al*., (1998)] proposed a new and pollution-free green cutting technique with water vapor as coolant and lubricant during cutting process. Further fluid jet assisted machining as a highly effective method for cutting of conventional materials has been well explored [Li and Seah (2001); Li (1996); Kaminski and Alvelid (2000); Hung *et al.,* (1997); Weinert (1993); Wang and Rajurkar (1997); Mazurkiewicz *et al.,* (1989); Shetty *et al.,* (2006) (2007)] 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 to get good surface quality and dimensional properties, it is necessary to employ optimization techniques to find optimal cutting parameters and theoretical models to do predictions. Taguchi and response surface methodologies can be conveniently used for these purposes. [Suresh et al., (2002)] used the response surface method and genetic algorithm for predicting the surface roughness and optimizing the process parameters. [Kwak (2005)] has applied Taguchi and response surface methodologies for optimizing geometric errors in surface grinding process. The response surface method (RSM) is more practical, economical and relatively easy to use [Sahin and Motorcu (2004)].

In the present study, effect of cutting parameters on surface roughness on the machining of DRACs by pressured steam jet approach is evaluated and second order model is developed for predicting the surface roughness. The predicted and measured values are fairly close to each other. Their proximity to each other indicates the developed model can be effectively used to predict the surface roughness in the machining of DRACs.

2.0. MATERIALS AND METHODS

Al-SiC MMC work piece 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 40 mm 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 specimens were solution treated for 2h at a temperature of 540^{o}C in a muffle furnace, Temperatures were accurate to within ± 2 ^{o}C and quench delays in all cases were within 20 s. after solution sing, 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 SEM image of DRACs containing 6061 Al and 15vol. % SiC particles of 25µm. The chemical composition of specimens is shown in Table-1. Turning method as machining process was selected. The experimental study was carried out in PSG A141 lathe (2.2 KW) with different cutting speed, feed, steam pressure and constant depth of cut. The selected cutting tool was cubic boron nitride inserts KB-90 (ISO code), for machining of DRACs materials. The ISO codes of cutting tool insert and tool holder were shown in Table-2 respectively. Surface condition of machined work piece was observed using JEOL JSM-6380LA analytical scanning electron microscope. Surface roughness was measured using Taylor/Hobson surtronoic 3+ surface roughness measuring instrument (Figure-2). The steam generator and steam feeding system are developed in which jet flow parameters (pressure, flow rate) and cooling distance (it is the distance between nozzle and cutting zone) are controllable. Figure-3 shows the steam generator and steam feeding system.

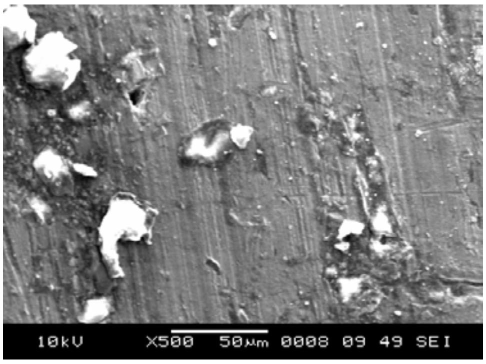

Figure-1. SEM image of DRACs (6061 Al/ 15% SiC 25p).

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

Elements	Cu	Mg	Si	Cr	Al
Weight percentage	0.25	1.0	0.6	0.25	Balance

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

Tool holder specification	STGCR 2020 K-16
Tool geometry specification	Approach angle: 91^0 Tool nose radius: 0.4mm Rake angle: 0^0 Clearance angle: 7^0
Tool insert CBN (KB-90) specification	TPGN160304-LS

Figure-2. Roughness measurement equipment layout.

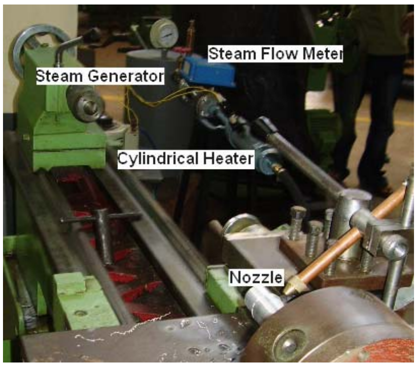

Figure-3. Steam generator and steam feeding system.

2.1. Response surface methodology

The surface finish of machined DRACs is important in manufacturing engineering applications which have considerable effect on some properties such as wear resistance, light reflection, heat transmission, coating and resisting fatigue. While machining, quality of the parts can be achieved only through proper cutting conditions. In order to know the surface quality and dimensional properties in advance, it is necessary to employ theoretical models making it feasible to do prediction in function of operation conditions [Sahin and Motorcu (2004)]. Response surface methodology (RSM) is a collection of mathematical and statistical techniques that are useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response [Montgomery (1991)].

In many engineering fields, there is a relationship between an output variable of interest ‘y’ and a set of controllable variables {x_1, x_2 . . . .x_n}. In some systems, the nature of the relationship between y and x values might be known. Then, a model can be written in the form:

$$y = f(x_1, x_2, ..., x_n) + \varepsilon \qquad (1)$$

where ε represents noise or error observed in the response y. If we denote the expected response be:

$$E(y) = f(x_1, x_2, ..., x_n) = \hat{y} \qquad (2)$$

then, the surface represented by

$$\hat{y} = f(x_1, x_2, ..., x_n) \qquad (3)$$

is called response surface. In most of the RSM problems, the form of relationship between the response and the independent variable is unknown. Thus the first step in RSM is to find a suitable approximation for the true functional relationship between y and set of independent variables employed. Usually a second order model is utilized in response surface methodology [Kwak (2005); Montgomery (1991)].

$$\hat{y} = \beta_o + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i} \sum_{j} \beta_{ij} x_i x_j + \varepsilon \qquad (4)$$

The β coefficients, used in the above model can be calculated by means of using least square method. The second-order model is normally used when the response function is not known or nonlinear.

2.2. Taguchi method

Taguchi techniques have been used widely in engineering design [Ross (1996) and Phadke (1989)]. 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 [Phadke (1989)]. 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 [Yang and Tarng (1998); Su *et al.*, (1999); Nian *et al.*, (1999); Lin (2002); Davim (2003); Ghani *et al.*, (2004)]. In particular, it is recommended for analyzing metal cutting problems for finding the optimal combination of parameters [Ghani *et al.*, (2004)]. Further depending on the number of factors, interactions and their level, an orthogonal array is selected by the user. Taguchi has used signal-noise [S/N] ratio as the quality characteristic of choice. S/N ratio is used as measurable value instead of standard deviation due to the fact that as the mean decreases, the standard deviation also deceases and vice versa. In other words, the standard deviation cannot be minimized first and the mean brought to the target. In practice, the target mean value may change during the process development. Two of the applications in which the concept of S/N ratio is useful are the improvement of quality through variability reduction and the improvement of measurement. The S/N ratio characteristics can be divided into three categories given by equations (5)-(7), when the characteristic is continuous.

Nominal is the best characteristic

$$\frac{S}{N} = 10 \log \frac{\bar{y}}{s_y^2} \qquad (5)$$

Smaller is the best characteristic

$$\frac{S}{N} = -10 \log \frac{1}{n}\left(\sum y^2\right) \qquad (6)$$

And larger the better characteristic

$$\frac{S}{N} = -\log \frac{1}{n}\left(\sum \frac{1}{y^2}\right) \qquad (7)$$

Where $\bar{y}$ is the average of observed data, s_y^2 the variation of y, n the number of observations, and y the observed data.

For each type of the characteristics, with the above S/N ratio transformation, the smaller the S/N ratio the better is the result.

3.0. EXPERIMENTAL DETAILS

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 29 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 Cutting speed m/min (A), the second column to Feed mm/rev (B), the fifth column to the Steam pressure bar (C) and remaining were assigned to interactions. The output to be studied was the surface roughness, further an analysis of variance (ANOVA) was carried out for surface roughness. The steps of our study of optimization are presented in Figure-4. The selected levels and factors in machining of DRACs are shown in Table-3.

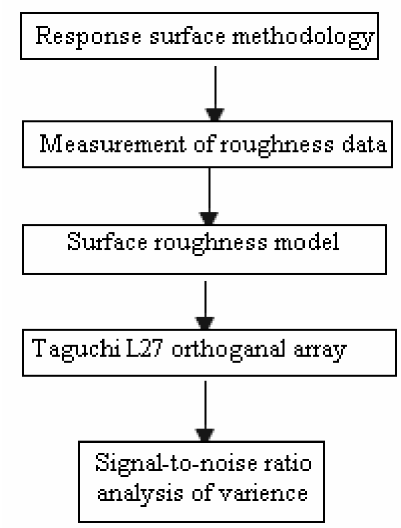

Figure-4. Steps of the optimization process.

Table-3. Levels and factors.

Level	**(A)** **Cutting speed** (m/min)	**(B)** **Feed** (mm/rev)	**(C)** **Steam pressure** (bar)
1	45	0.11	4
2	73	0.18	7
3	101	0.25	10

4.0. RESULTS AND DISCUSSIONS

Study of the surface roughness characteristics of DRACs requires more analysis due to the presence of hard reinforcement particles. Hence pressured steam jet approach helps in minimization of the surface roughness by preventing the impacted reinforcement particles from being embedded in the work piece matrix. Figure-5 shows the SEM image of tool wear observed on the CBN tool when machining the DRACs.

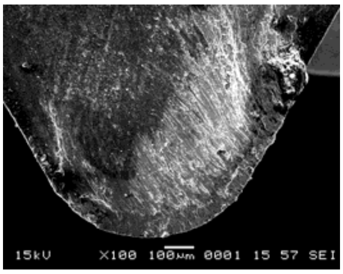

Figure-5. Typical wear pattern and material sediments observed on the CBN tool.

4.1. Effect of control parameters on surface roughness

In Taguchi method, the term “signal” represents the desirable value and "noise" represents the undesirable value. The objective of using S/N ratio is a measure of performance to develop products and processes insensitive to noise factors [Ross (1996)]. 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 shows the S/N ratios obtained for different parameter levels.

Table-4. Response table for Signal to Noise ratios Smaller is better (Surface roughness).

Level	**(A) Cutting speed** (m/min)	**(B) Feed** (mm/rev)	**(C) Steam pressure** (bar)
1	-10.379	-9.295	-10.768
2	-10.006	-9.915	-9.950
3	-9.579	-10.755	-9.247
Delta	0.800	1.460	1.521
Rank	3	2	1

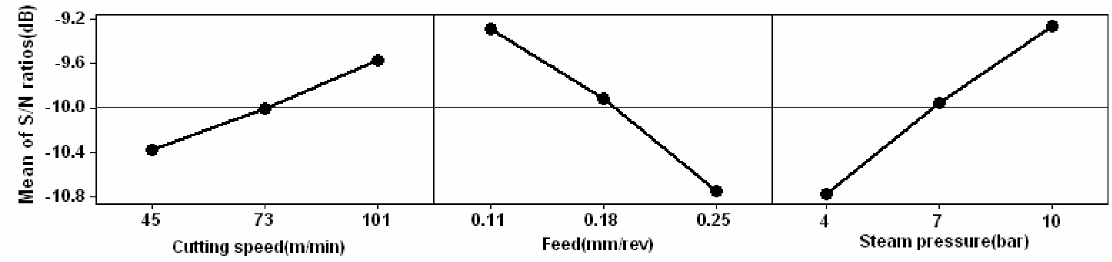

Figure-6. Mean S/N graph for surface roughness.

The calculated S/N ratio for three factors on the surface roughness in machining of DRACs for each level is shown in Figure-6. As shown in Table-4 and Figure-6 steam pressure is a dominant parameter on the surface roughness followed by feed. The cutting speed had a lower effect on the surface roughness. Lower surface roughness is always preferred. The quality characteristic considered in the investigation is smaller the better characteristics. In the present investigation, when the steam pressure is set at 10 bar is applied the surface roughness is minimized. Contrary to the steam pressure, feed had the maximum effect. The reason being, the increase in feed increases the heat generation and hence, tool wear, which results in higher surface roughness. The increase in feed also increases the chatter, and it produces incomplete machining of work piece, which led to higher surface roughness. The results shown prove that the roughness of the machined surface is highly influenced by the feed. Based on the above discussion and also evident from Figure-6, the optimum conditions for the surface roughness can be established at, Cutting speed (A): 101 m/min, Feed (B): 0.11mm/rev, Steam pressure(C): 10bar

Table-5. Analysis of variance for S/N ratios for surface roughness.

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**	**Percent P** (%)
(A) Cutting speed (m/min)	2	2.8850	2.8850	1.44249	24.60	0.000	11.98
(B) Feed (mm/rev)	2	9.6660	9.6660	4.83299	82.41	0.000	40.13
(C)Steam pressure(bar)	2	10.4317	10.4317	5.21584	88.94	0.000	43.31
AxB	4	0.3666	0.3666	0.09165	1.56	0.274	0.76
AxC	4	0.1337	0.1337	0.03342	0.57	0.692	0.28
BxC	4	1.7031	1.7031	0.42578	7.26	0.009	3.54
Residual Error	8	0.4692	0.4692	0.05864			
Total	**26**	**25.6552**					**100**

On the examination of the percentage of contribution (P%) of the different factors (Table-5), for surface roughness it can be seen that steam pressure has the highest contribution of about 43.31%, thus steam pressure is an important factor to be taken into consideration while machining DRACs followed by feed B (P = 40.13%), cutting speed A (P = 11.98 %). Interactions (A x B, A x C, B x C) do not present a statistical significance, nor a percentage of physical significance of contribution to the surface roughness.

4.2. Response surface analysis

The second order response surface representing the surface roughness (Ra) can be expressed as a function of cutting parameters such as cutting speed m/min (A), feed mm/rev (B), and steam pressure bar (C). The relationship between the surface roughness and machining parameters has been expressed as follows:

$$R_a = \beta_0 + \beta_1(A) + \beta_2(B) + \beta_3(C) + \beta_4(A^2) + \beta_5(B^2) + \beta_6(C^2) + \beta_7(AB) + \beta_8(AC) + \beta_9(BC) \qquad (8)$$

From the observed data for surface roughness, the response function has been determined in uncoded units as:

$$Ra = 4.97065 - 0.01817A - 0.08773B - 0.2661C + 0.00008A^2 - 2.3191B^2 + 0.00707C^2 + 0.0178571AB - 0.00017AC + 0.4047BC$$

Result of ANOVA for the response function surface roughness is presented in Table-6. This analysis is carried out for a level of significance of 5%, i.e., for a level of confidence of 95%. From the analysis of Table-6, it is apparent that, the F calculated value is greater than the F-table value ($F_{0.05,\,9,\,10} = 3.02$) and hence the second order response function developed is quiet adequate.

Table-6. ANOVA table for response function of the surface roughness.

Source	DF	Seq SS	Adj MS	F	P
Regression	9	1.81809	1.81809	25.70	0.000
Residual Error	10	0.07860	0.07860	0.007860	
Total	19	1.89670			

From equation (8) contours for each of the response surfaces at different steam pressure is plotted (Figure-7). These response contours can help in the prediction of the surface roughness at any zone of the experimental domain. It is clear from these Figures that the surface roughness falls with the increase of cutting speed and steam pressure; however, it increases with the increase of feed. Figure-8 shows the SEM images of machined surface under different steam pressure.

Figure-9(a-c) shows the effects of cutting speed at different steam pressure on the surface roughness. From the Figures it can be seen that at 10 bar pressure there is decrease in surface roughness value, this is because steam penetrates into the tool chip interface decrease the chatter between SiC particulate and the alloy matrix, and avoid seizing on the flank and resulting in lower the surface roughness value. From the Figure it is very clear that increase in cutting speed decreases the surface roughness value in all the cases, but increase in feed certainly increases the surface roughness.

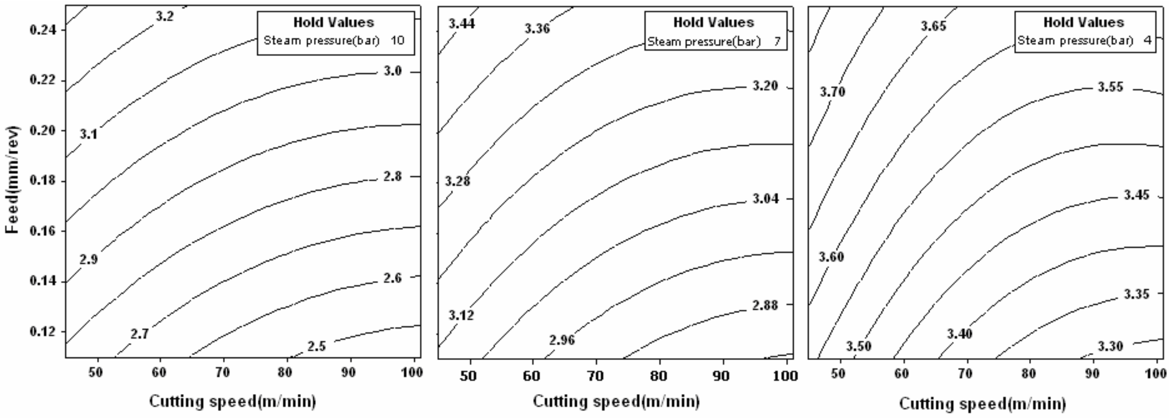

Figure-7. Surface roughness contours in cutting speed-feed planes at steam pressure of (a) 10bar; (b) 7 bar; (c) 4 bar.

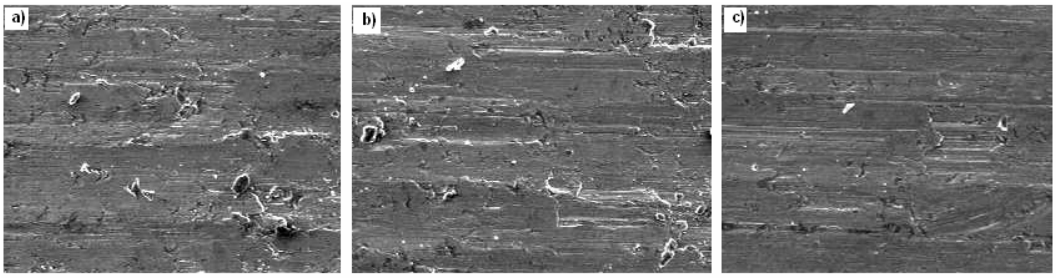

Figure-8. SEM images of machined surface under different steam pressure (a) 4bar; (b) 7bar; (c) 10 bar.

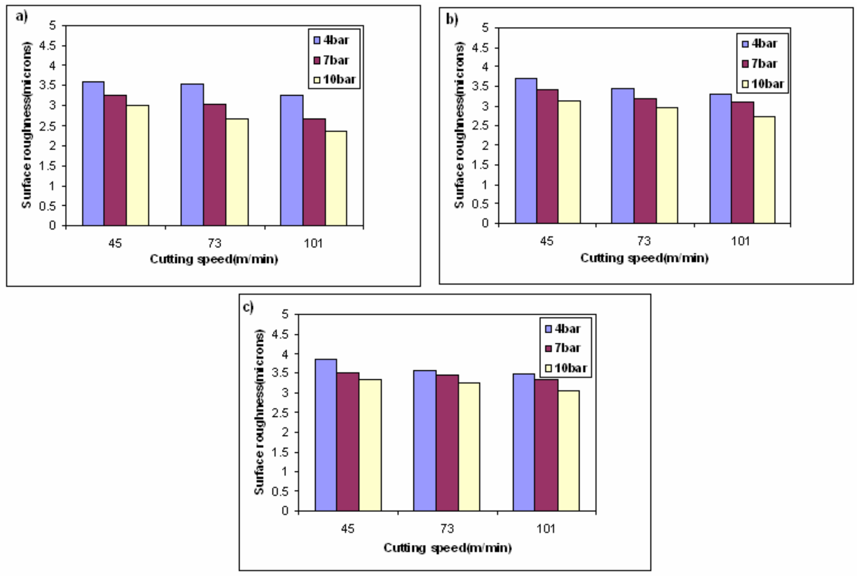

Figure-9. Effect of cutting speed at different steam pressure on surface roughness a) feed 0.11mm/rev; b) feed 0.18mm/rev; c) feed 0.25mm/rev.

5.0. CONCLUSIONS

The surface roughness in the turning process has been measured for machining of DRACs at different cutting conditions with a pressured steam jet approach using Taguchi's orthogonal array. Based on the experimental and analytical results, the following conclusions are drawn:

- The effect of machining parameters on the surface roughness has been evaluated with the help of Taguchi method and optimal machining conditions to minimize the surface roughness have been determined.
- The steam pressure is the dominant parameter for surface roughness followed by the feed. Cutting speed shows minimal effect on surface roughness compared to other parameters.
- For achieving good surface finish on the DRACs work piece, high steam pressure, high cutting speed and lower feeds are preferred.
- A second-order response surface model for surface roughness has been developed from the observed data. The predicted and measured values are fairly close, which indicates that the developed model can be effectively used to predict the surface roughness on the machining of DRACs with 95% confidence intervals. Using such model, one can obtain a remarkable savings in time and cost.

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