TOOL WEAR IN MACHINING OF HYBRID ALUMINIUM METAL MATRIX COMPOSITES

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ABSTRACT

This paper presents an experimental study in turning of hybrid aluminium metal matrix composites and its effect on tool wear when machined using a polycrystalline diamond (PCD) tool. The present study establishes the relationship between cutting conditions and machinability characteristics during the turning of hybrid MMCs. The investigation aims at determining the effects of cutting speed, feed rate and depth of cut on tool wear. The cutting tool wear was investigated and the experimental results showed that for reduced tool wear, feed rate and depth of cut should be minimum and the cutting speed should be either low or high, since at intermediate cutting speed the tool wear is more. Therefore there seemed to be a certain cutting speed which will cause the least tool wear.

Keywords: Hybrid Metal Matrix Composites, Machining, Turning, Polycrystalline Diamond Tool, Tool Wear

Nomenclature

S	Cutting speed in m/min
F	Feed rate in mm/rev
D	Depth of cut in mm
T_w	Tool Wear in mm

I. INTRODUCTION

Machining is a major manufacturing process in engineering industry. Performance of the product to a large extent is dependent on the accuracy and consistency of the machining processes used to produce the parts. General trend in machining include maximum material removal rate with optimum cutting parameters such as speed, feed and depth of cut. The cutting parameters are mainly dependent on machine tools and cutting tool materials. Traditional materials and processes are undergoing major changes to face the challenge and to provide manufacturing assistance to industry goals of quality, cost and delivery. Automotive, aerospace and defence industries are the leaders in development of these materials. Aluminium MMC are another new materials being developed for automotive application because of weight advantage. Brake rotors made of aluminium MMC may weigh less than half of cast iron brake rotor. MMC also offer high yield strength, good ultimate strength and excellent high temperature properties.[1]

A metal matrix composite (MMC) is a combination of two or more materials in which there exists two phases such as a matrix phase like aluminium or magnesium or any other metal and a reinforcing phase such as a ceramic like SiC or Al_2O_3. If there is only one matrix phase and one reinforcing phase, it is termed as non-hybrid metal matrix composite and if there are one matrix phase and two or more reinforcing phases, it is called as Hybrid metal matrix composite. The advantage of using one more reinforcer is to have a better and superior mechanical properties than that of individual elements constituting a metal matrix composite. Hybrid metal matrix composites (MMCs) posseses less weight, good strength, ability to operate at high temperatures and resistance to wear and tear than those of conventional materials. Due to these desirable properties it's usage is in several aerospace and automobile structures. Bearings, pistons, cylinder liners, connecting rods, turbo charger impellers, space structures, etc are some of the important applications of hybrid MMC. Poor machinability is the major issue which is a major hurdle in the popular use of hybrid MMCs. The reason is because of the relative hardness of the reinforcing materials like silicon carbide (SiC) and alumina (Al_2O_3).

Nowadays in the manufacturing industry, measurement of dimensional accuracy and surface finish is considered as the prediction of the machining performance [2]. Turning is the primary operation in most of the production processes that produces the components, which have critical features requiring specific surface finish. In the manufacturing industry, an improper cutting condition may cause high manufacturing costs and low product quality. Hence, the proper selection of cutting tools and process parameters is an important criterion for achieving high surface quality in the machining process [3].

Among the major cutting tool materials such as high speed steels (HSS), cemented carbides, cermets, ceramics, cubic boron nitride (CBN) and polycrystalline diamond (PCD), HSS possess best toughness characteristics whereas PCD possess best thermal hardness in that increasing order. [4,5,6] Today, PCD is extensively used for machining especially the abrasive silicon-aluminium alloys when surface finish and accuracy are criteria. Several researchers have indicated that PCD tools are the only tool materials that is capable of providing a useful tool life during the machining of SiC-Al hybrid MMCs. [7-15] PCD is harder than Al_2O_3 and SiC and does not have tendency to chemically react with the work piece material [16-18]. With the appearance of superhard tools, the possibility of precision machining applications has significantly widened. The PCD tool edge regenerates constantly during machining. Due to the pressure on the tool edge and the temperature, microcracks and microfractures develop, and fine sharp crystals emerging from the deeper layers of the flank of the tool ensure its continued sharpness and cutting ability. The resistance of the PCD tool to wear is high, because the micro cracks are shallow, and the grain boundaries localise them [19].

Experiments were conducted at various cutting speeds, feeds and depth of cuts and the tool wear was measured. The worn surface of the insert was examined, results were analysed and mathematical models were derived using surface response methodology (SRM). The interaction plots were made and are analysed.

II. EXPERIMENTAL SET UP

The Al6061 was cut into small pieces and melted in a graphite crucible. The required already preheated quantity of matrix material (wt.6%) was fed into the Furnace crucible and mixed thoroughly using a ceramic stirrer with the help of a motor. The temperature was raised above the liquidus temperature of the aluminium alloy that is above 890°C and then reduced slowly below liquidus temperature of the matrix so that the melt was kept between the solidus and liquidus temperature. Then the pre-heated mixtures of SiC and aluminium oxide particles were poured into the semi liquid melt. Again stirring was done with the help of the motor after keeping it in the furnace. The melt is heated again to above the liquidus temperature. Then for 30 minutes stirring was carried out at an average stirring speed of 350 rpm. The slurry was then poured into a preheated cast ion permanent mould. The solidified specimen casting is obtained after cooling. Now the specimen is used as the test material for performing turning operations. The experimental set up that was utilized in the manufacturing of hybrid MMC (Al6061-SiC-Al_2O_3) is shown in Fig. 1.

Fig. 1. Hybrid Metal Matrix Composites Experimental Setup

Fig. 2 shows the fabricated workpiece specimen after turning process is carried out by a PCD tool in a Lathe. The turning experiments were carried out at different cutting parameters of Cutting speeds 100, 200 and 300 m/min, Feed rates 0.10, 0.20 and 0.30mm/rev

Fig. 2. Turned Workpiece Specimen (Al6061-SiC-Al_2O_3) 6% wt.

and Depth of cuts 0.25, 0.50 and 0.75 mm. Simultaneously the Tool wear were measured for each cutting conditions and were recorded and the analysis of the results are discussed below.

III. RESULTS AND ANALYSIS

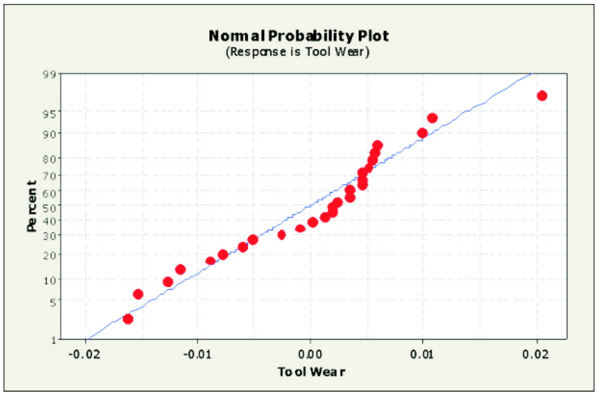

Fig. 3. Normal Probability Plot for Tool Wear

Fig. 3 shows the normal probability plot for tool wear in terms of percentage. The graph displays approximate 95% confidence intervals (curved blue lines) for the fitted distribution. These confidence intervals are calculated separately for each point on the fitted distribution. The data in the plot is spread almost close to the straight line which indicate that there is a correlation between the predicted values and the experimental data obtained.

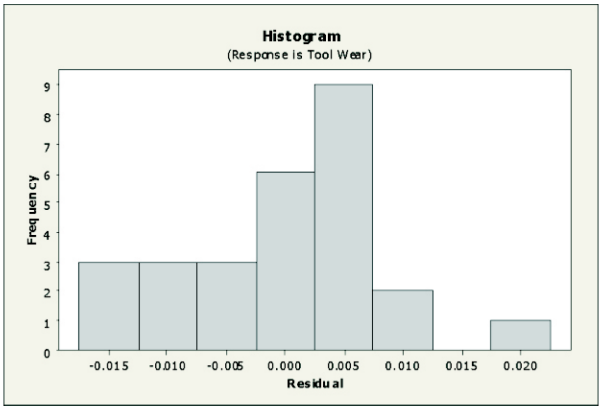

Fig. 4. Histogram of Residuals

Fig. 4 shows the histogram of the residuals. Histogram is used to examine the shape and spread of sample data. It divide sample values into many intervals called bins. Bars represent the number of observations falling within each bin (its frequency).

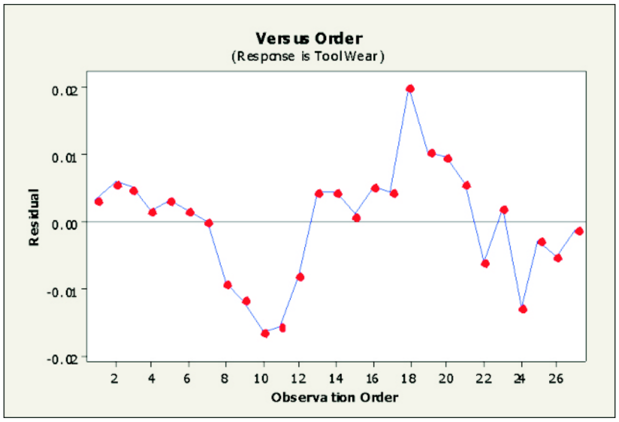

Fig. 5. Residual versus Order of Observation

Fig. 5 shows the residuals that were calculated against the order of experiment. From the figure it is very clear that there is a tendency to have runs of positive and negative residuals, indicating the existence of correlation between them.

Response Surface Regression: Tool Wear versus Cutting Speed, Depth of Cut and Feed

Table 1. Analysis of Variance for Tool Wear

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	0.057606	0.057606	0.006401	58.47	0.000
Linear	3	0.055456	0.002763	0.000921	8.41	0.001
Square	3	0.002033	0.002033	0.000678	6.19	0.005
Interaction	3	0.000117	0.000117	0.000039	0.36	0.786
Residual Error	17	0.001861	0.001861	0.000109		
Total	26	0.059467				

Table 2. Estimated Regression Coefficients for Tool Wear

Term	Coef	SE Coef	T	P
Constant	− 0.055556	0.033513	− 1.658	0.116
Cutting Speed (S)	0.000856	0.000193	4.442	0.000
Feed (F)	0.533333	0.192615	2.769	0.013
Depth of Cut (D)	0.040000	0.077046	0.519	0.610
$S*S$	− 0.000002	0.000000	− 4.292	0.000
$F*F$	0.000000	0.427156	0.000	1.000
$D*D$	0.026667	0.068345	0.390	0.701
$S*F$	− 0.000250	0.000302	− 0.828	0.419
$S*D$	0.000067	0.000121	0.552	0.588
$F*D$	0.033333	0.120818	0.276	0.786

$S =$ 0.0104631 PRESS = 0.00474448

$R-Sq = 96.87\%$ $R-Sq$ (pred) $= 92.02\%$ $R-Sq$ (adj) $= 95.21\%$

Mathematically, the Tool Wear Rate is expressed in terms of cutting speed S, depth of cut D and Feed F as:

Tool Wear, $T_W = -0.0555 + 0.000856\,(S) + 0.5333\,(F) + 0.04\,(D) - 0.000002\,(s^2) + 0\,(F_2) + 0.026\,(D^2) - 0.00025\,(S \times F) + 0.000067\,(S \times D) + 0.0333\,(F \times D)$

where S is Cutting speed, F is Feed and D is Depth of cut

Fig. 6 shows the Main Effects Plot for the Tool Wear, which plot the data means having multiple factors. The points in the plot are the means of the response variable at the various levels of each factor, with a reference line drawn at the grand mean of the response data. These plots are used for comparing magnitudes of main effects.

Fig. 7 shows the Interaction plot for the Tool Wear. Interactions Plot creates a single interaction plot

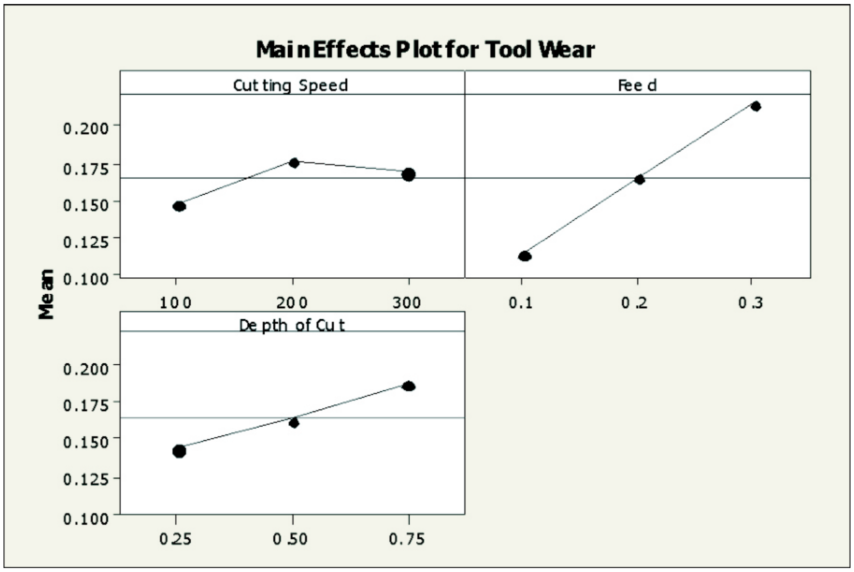

Fig. 6. Main Effects Plot for Tool Wear for different Cutting speed, Feed and Depth of cut

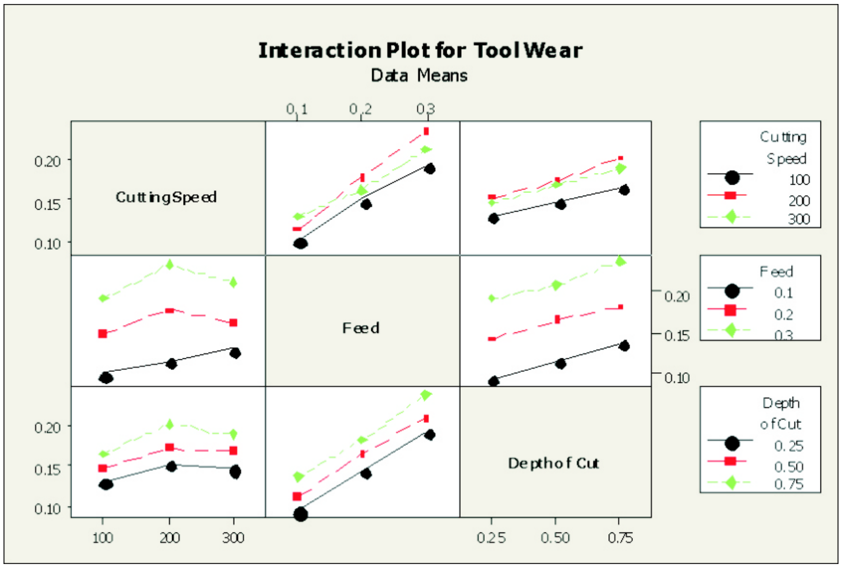

Fig. 7. Interaction Plot for Tool Wear at different cutting parameters

for two factors, or a matrix of interaction plots for three to nine factors. An interactions plot is a plot of means for each level of a factor with the level of a second factor held constant. Interactions plots are useful for judging the presence of interaction.

Interaction is present when the response at a factor level depends upon the level(s) of other factors. In the plot, the parallel lines indicate no interaction. The greater the departure of the lines from the parallel state, the higher the degree of interaction.

Fig. 8 shows the variation of the tool wear for different cutting speeds when the feed rates are taken to be 0.1, 0.2 and 0.3 mm/rev. The graph shows gradual increase in tool wear upto the cutting speed of 200 m/min and then decreases beyond that cutting speed, for feed rates of 0.20 and 0.30 mm/rev. But, for a feed rate of 0.10 mm/rev, the tool wear keeps on increasing gradually for all cutting speeds.

Fig. 9 shows the variation of the tool wear for different cutting speeds at different depth of cut such as 0.25, 0.50 and 0.75 mm. The graph shows gradual

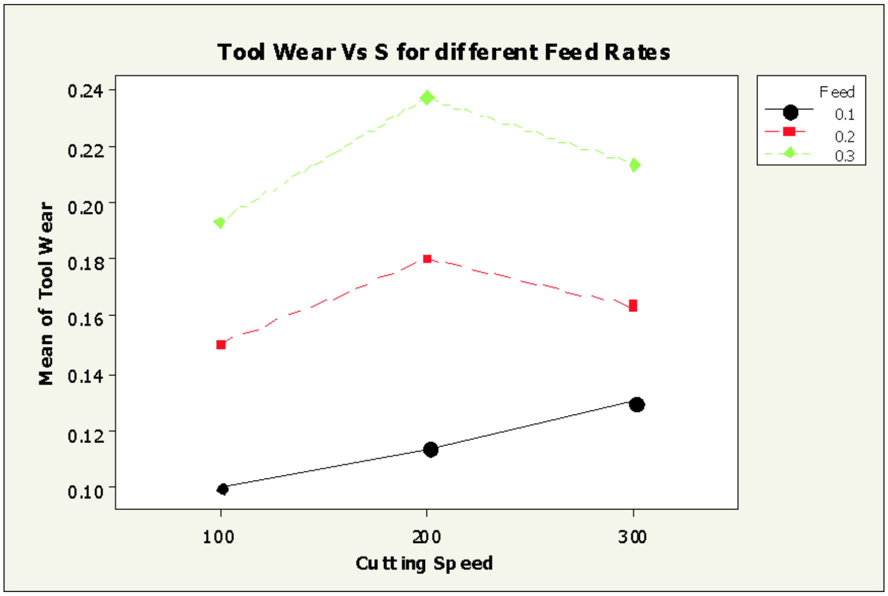

Fig. 8. Tool Wear Vs Cutting speed for different Feed Rates

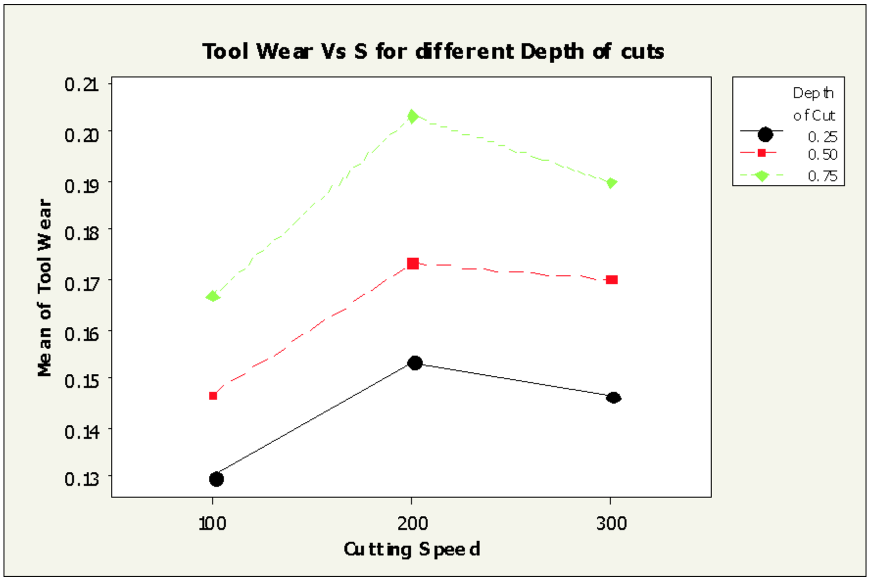

Fig. 9. Tool Wear Vs Cutting speed for different Depth of cut

increase in tool wear upto the cutting speed of 200 m/min and then decreases beyond that cutting speed, for all values of depth of cut.

Contour and surface plots are useful for establishing desirable response values and operating conditions.

A surface plot provides a three-dimensional view that may provide a clearer picture of the response surface.

Fig. 10 shows a 3D Surface plot for Tool Wear with respect to variations in Feed and Depth of cut. As the Feed increases, the tool wear increases and the tool wear is more for increasing depth of cuts. So, there is more tool wear for increasing values of feed and depth of cut.

Fig. 11 shows a 3D Surface plot for Tool Wear with respect to variations in Cutting speed and Depth of cut. As the Cutting speed increases, the tool wear increases initially and then gradually decreases. At the same time, as the depth of cut increases the tool wear goes on increasing. Therefore, the tool wear is less at

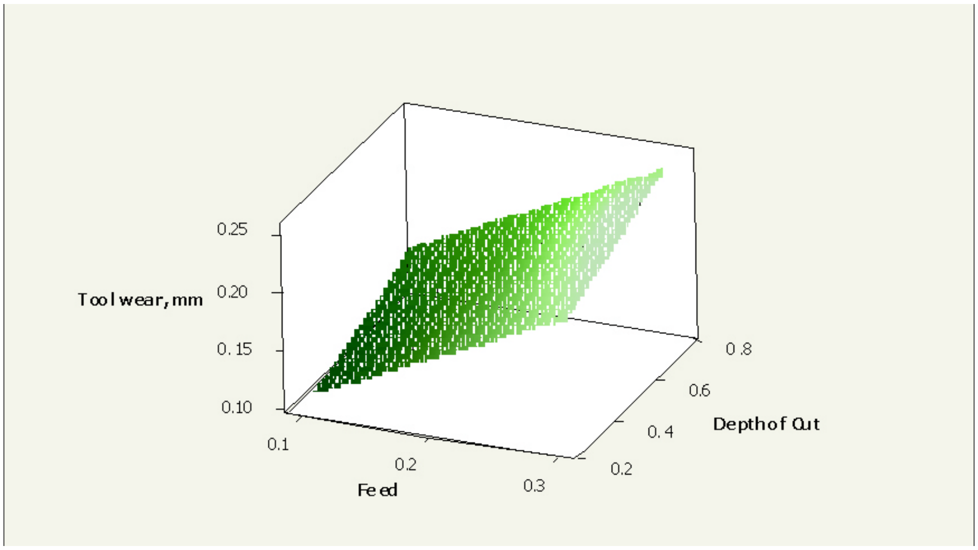

Fig. 10. Surface Plot for Tool Wear at various Feed and Depth of cut

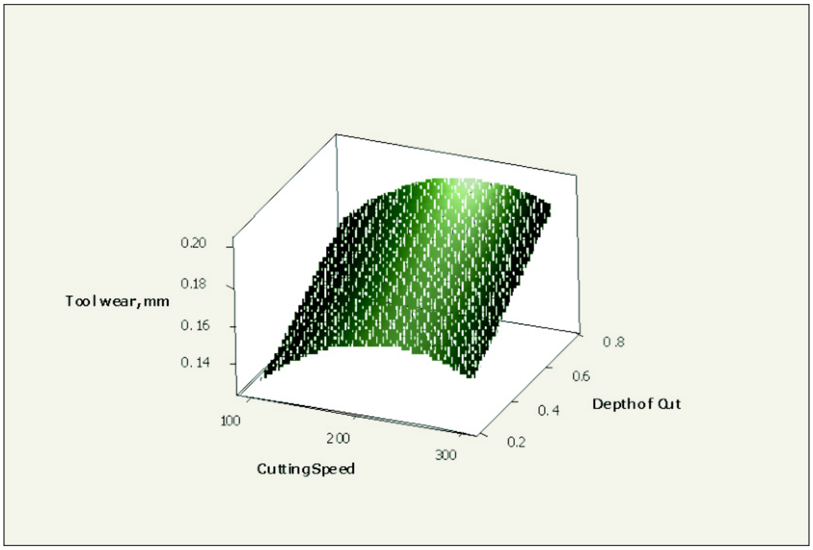

Fig. 11. Surface Plot for Tool Wear at various Cutting speed and Depth of cut

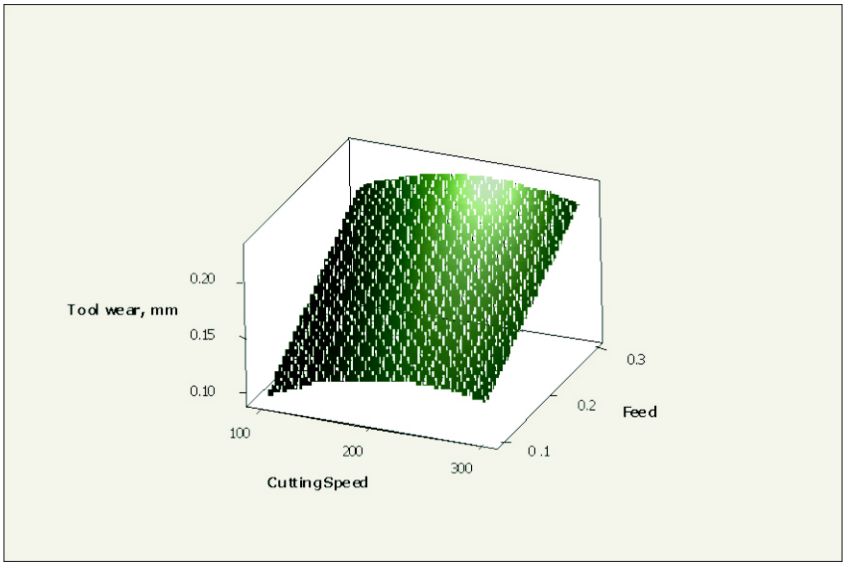

Fig. 12. Surface Plot for Tool Wear at various Cutting speed and Feed

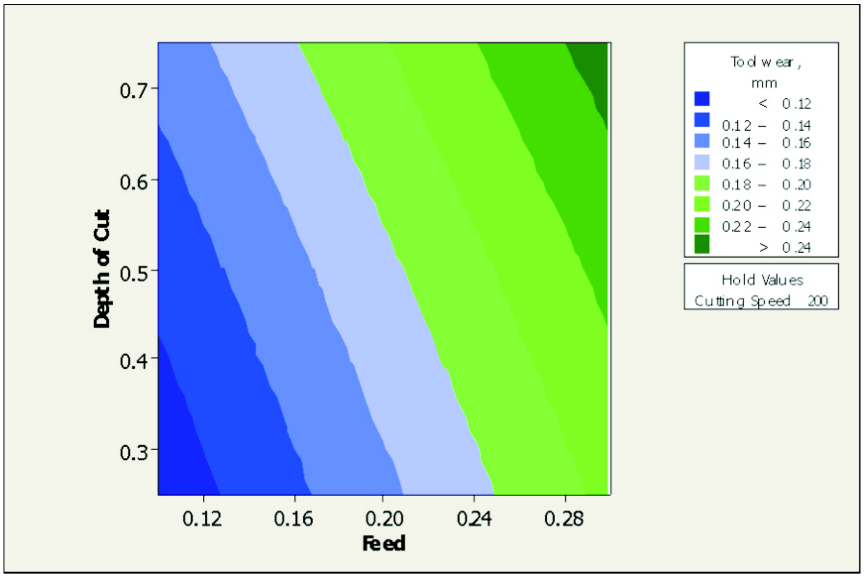

Fig. 13. Contour Plot for Tool Wear at different Feed and Depth of cut

lower and higher values of cutting speed and it is more at intermediate cutting speed. And also, tool wear is reduced for lower values of depth of cut and more for higher values of depth of cut.

Fig. 12 shows a 3D Surface plot for Tool Wear with respect to variations in Cutting speed and Feed. As the Cutting speed increases, the tool wear increases initially and then gradually decreases. Also, as the Feed increases the tool wear keeps increasing. Hence, for reduced tool wear, the cutting speed should be either less than or greater than 200 m/min. Also, tool wear can be reduced by selecting lower values of feed.

A contour plot provides a two-dimensional view where all points that have the same response are connected to produce contour lines of constant responses.

From Fig. 13, it is clear that the tool wear is more at higher values of Feed and Depth of cut. Hence reduced tool wear can be achieved by choosing minimum values of feed and depth of cut.

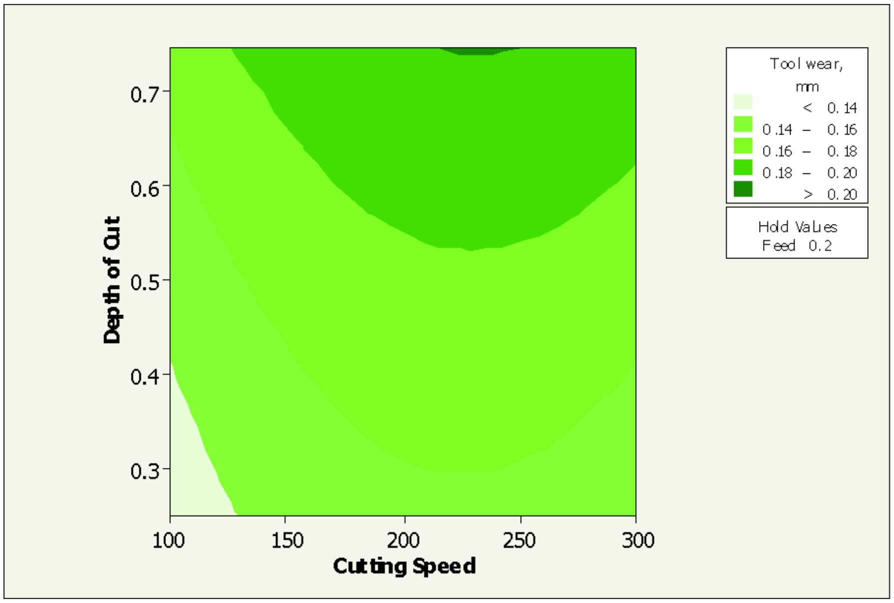

Fig. 14. Contour Plot for Tool Wear at different Cutting speed and Depth of cut

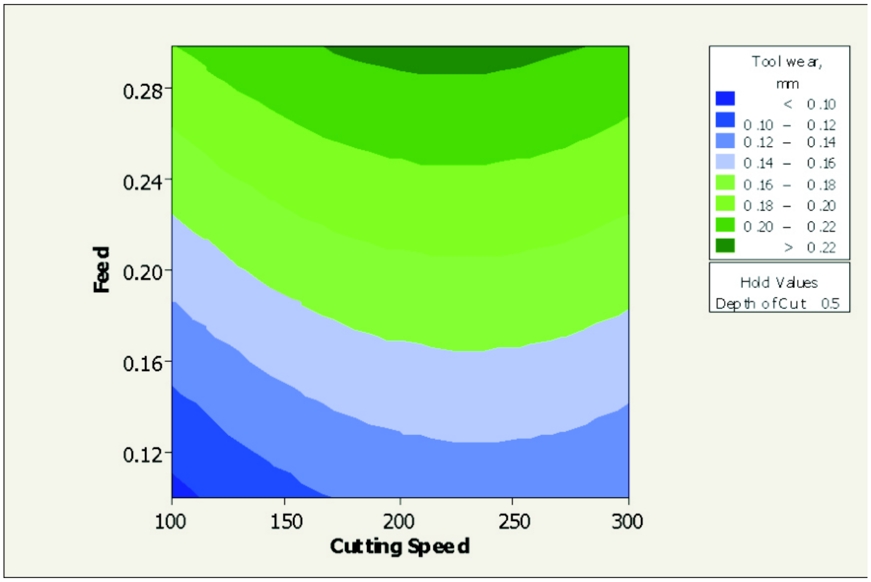

Fig. 15. Contour Plot for Tool Wear at different Cutting speed and Depth of cut

From Fig. 14, it is understood that the tool wear is more at higher values of Depth of cut and intermediate cutting speeds. Therefore reduced tool wear can be achieved by choosing minimum values of cutting speeds and depth of cut.

Fig. 15 clearly shows that the tool wear is more at higher values of Feed and intermediate cutting speeds. Therefore reduced tool wear can be achieved by choosing minimum values of cutting speeds and Feed.

IV. CONCLUSION

Turning of hybrid aluminium metal matrix composites and its effect on tool wear when machined using a polycrystalline diamond (PCD) tool was studied. The present study established the relationship between cutting conditions and machinability characteristics during the turning of hybrid MMCs. The investigation determined the effects of cutting speed, feed rate and depth of cut on tool wear. The cutting tool wear was investigated and the experimental results showed that for reduced tool wear, Feed rate and Depth of cut should be minimum and the cutting speed should be either low or high, since at intermediate cutting speed the tool wear is more. Therefore there seemed to be a certain cutting speed which will cause the least tool wear.

ACKNOWLEDGEMENT

The author express their sincere thanks to Sathyabama University for motivating us to do research and providing necessary help. The Madras Institute of Technology, Chennai provided their laboratory facilities for manufacturing the hybrid MMC and the authors wish to express sincere thanks to MIT, Chennai. The author thank Mrs. Sowdhamini Sasimurugan for her enduring support and encouragement in completing the experimental work. The author would also like to thank his friends, colleagues and his well wishers in successful completion of the present research work. Above all, a heartful thanks to the Almighty to make us what we are today.

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