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MATHEMATICAL MODEL FOR THE PREDICTION OF CHIP SERRATION FREQUENCY IN END MILLING OF STEEL AISI1020

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ABSTRACT
The present paper discusses the development of a mathematical model based on statistical analysis for predicting the chip serration frequency in end-milling operation of steel AISI1020 using coated TiN insert under dry conditions and full immersion cutting. A small CCD with 2 blocks and 5 replication of centre point in each factorial block was selected to design the experiments and each of the independent variables is considered up-to 5(five) levels in developing the chip serration models in terms of primary cutting parameters (Cutting Speed, Feed, Axial Depth of Cut). The experimental results indicate that the proposed mathematical models could adequately describe the performance indicators within the limits of the factors that are being investigated. The adequacy of the predictive model was verified using ANOVA at 95% confidence level.
KEYWORDS:
Chip serration frequency, end milling, response surface methodology

1. INTRODUCTION

In metal cutting, the present tendency is towards achieving increased material removal rates with very reliable machining processes, where the predictability of surface finish, work-piece accuracy, chatter and tool life are of prime importance. One of the restrictions limiting large material removal rates is the tendency of the machine tool to chatter. But to maintain stable machining, much attention must also be paid to the formation of the desired type of chip and chip controls to facilitate its easy removal. This is because the chip formation and breaking aspect is very significant in machining. Trent, Talantov, Amin and others [1-3] considered the formation of chips with serrated teeth to be the primary cause of chatter. Talantov and Amin have observed that chatter arising during turning is a result of resonance, caused by mutual interaction of the vibrations due to serrated elements of the chip and the natural vibrations of the system components, e.g. the spindle and the tool holder [2-3]. Much research work has been done on the chip formation in turning, drilling and face milling. Komanduri [4-5] has made some remarkable progress in the research of chip segmentation and instability in chip formation. Nevertheless it appears that very few works have been done to investigate the nature of chip formation in end milling because of its complexity and geometrical difficulty. Toenshoff [6] proposed the basic chip formation mechanism as "adiabatic shear" at high cutting speed. Changing speed during the machining process or finding an optimum speed are the commonest tactics to avoid chatter in milling.

Amin [7] earlier established that the instability of chip formation could be lowered by preheating the work material during turning. Yuan Ning *et al.* [8] indicates that chatter could be reliably recognized by analysis of the chips. Ekinovic *et.al* [9] mentioned in their work that cutting speed has significant effect on chip formation models.

Similar influence of the cutting speed on the chip structure and chip compression ratio was revealed in the experiments conducted by Tonshoff *et al.* [10]. As the chip formation process appears to be cyclic, its frequency is of interest. The frequency of chip formation can be measured by calculating the number of teeth produced in unit time as proposed by Talantov [11]. Astakhov *et al.* [12] studied the chip formation frequency of different work materials at the same cutting regimes and dimensions of the work-pieces. Amin [13] found that the root cause of chatter lies in the coincidence of the frequency of instability of chip formation and one of the natural frequencies of the machine-spindle-tool system. The instability of chip was found to be due to the formation of *cyclic chip,* widely known as the *serrated chips*. In this study the instability of the chip formation processes has been identified and calculated in terms of serration frequency and a mathematical model has been developed.

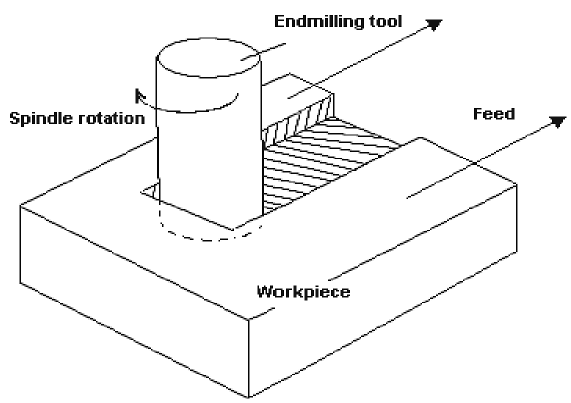


Figure 1 Experimental set up for end milling

Methodology: Experimental setup

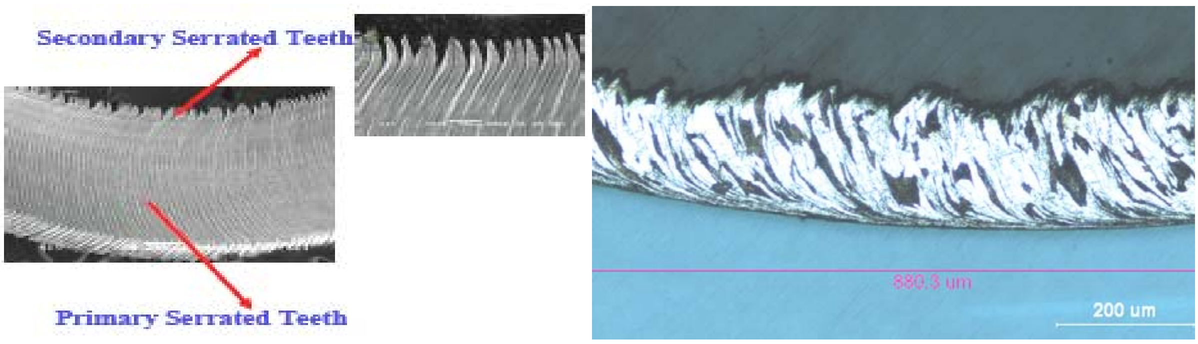
Cutting tests were conducted mainly on Vertical Machining Center (VMC ZPS, Model: 1060) powered by a 30 KW motor with a maximum spindle speed of 8000 rpm. Fig. 1 shows the experimental set up cutting test conditions on end milling for machining of steel AISI 1020 with TiN inserts.

2. CHIP ANALYSIS: IDENTIFICATION OF CHIP SERRATION & CALCULATION OF ITS FREQUENCY

In order to have a close look at the chip to identify its morphology and inspect the presence of the primary and/or the secondary serrated teeth and any other type of instability that might be present in the outer view of the chip, the latter was viewed under a Scanning Electron Microscope (SEM) and Optical Microscope for lengthwise sectional view (Fig 2(B)). A sample SEM view of the chip, shown in Figure 2(A), indicates the presence of the primary and secondary serrated teeth at different side of the chip.

The frequency of the primary/secondary serrated teeth formation, F_c, in the cases of milling operation was calculated knowing the length of the portion of the chip in the SEM pictures, L, the coefficient of chip shrinkage, K (determined by dividing the uncut chip length by the actual chip length), cutting speed, V m/min and the number of secondary serrated teeth, n, observed on the SEM picture; using the following formula [13]:

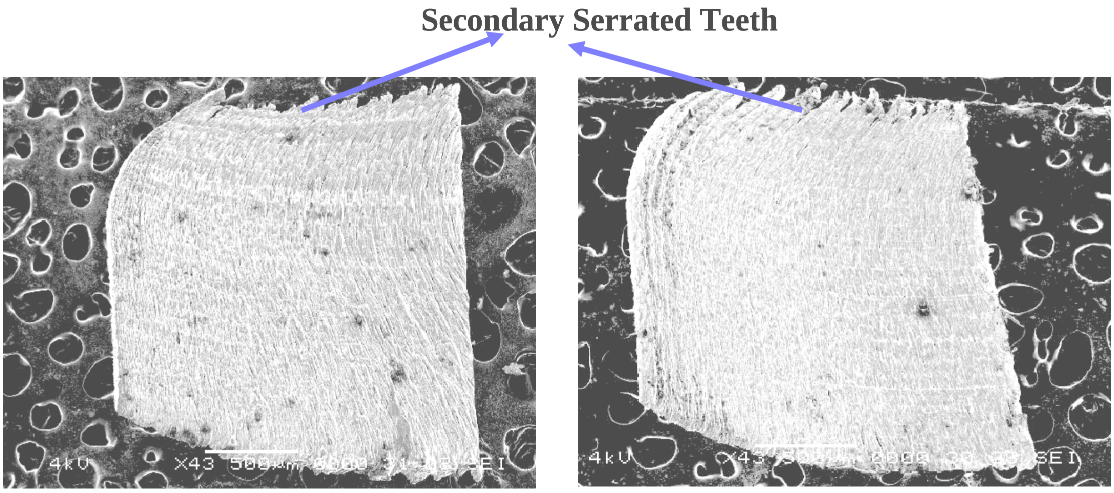
$$F_c = 1000\frac{nV}{60(LK)} \text{ [Hz]} \tag{1}$$



(A) (B)

Figure 2. Schematic of the chip: (A) SEM top view of the chip with the serrated element (B) length wise sectional view under optical microscope

The chip morphology at different cutting conditions is different. The secondary serrated teeth are observed under the scan electron microscope. A sample view of the chip (SEM) at different cutting conditions is shown in Figure 3.



(a) (b)

Figure 3. Sample SEM View of the AISI1020 chip at different cutting speed (a) CS 120m/min (b) CS 300 m/min with same Depth of Cut 1.59mm, feed: 0.089mm/tooth

3. MATHEMATICAL MODEL ON CHIP SERRATION

Chip Serration Frequency model for end milling in terms of the parameters can be expressed in general terms as:

$$f_c = D * V^x a^y f_z^z \qquad (2)$$

Where f_c is the predicted chip serration frequency (Hz), V is the cutting speed (m/min), f_z is the feed per tooth (mm/tooth), and a is the axial depth of cut (mm). D, x, y, and z are model parameters to be estimated using the experimental results. To determine the constants and exponents, this mathematical model can be linearized by employing a logarithmic transformation, and Eq. (2) can be re-expressed as:

$$\ln f_c = \ln D + x \ln V + y \ln a + z \ln f_z \qquad (3)$$

The linear model of Eq. 3 is:

$$f_c = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \qquad (4)$$

where y is the true response of Chip Serration Frequency on a logarithmic scale $x_0 = 1$ (dummy variable), x_1, x_2, x_3 are logarithmic transformations of speed, depth of cut, and feed, respectively, while β_0, β_1, β_2, and β_3 are the parameters to be estimated. Eq (4) can be expressed as:

$$\hat{f}_c = f_c - \varepsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 \qquad (5)$$

where $\hat{f}_c$ is the estimated response and f_c the measured Chip Serration Frequency on a logarithmic scale, ε the experimental error and the b values are estimates of the β parameters. The second-order model can be extended from the first-order model equation as:

$$\hat{f}_{2c} = f_c - \varepsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2 + b_{12} x_1 x_2 + b_{13} x_1 x_3 + b_{23} x_2 x_3 \qquad (6)$$

where, $\hat{f}_{2c}$ is the estimated response based on the second order model. Analysis of variance is used to verify and validate the model.

4. EXPERIMENTAL DETAILS

In this study, cutting tests were carried out for end milling in dry conditions on vertical machining centre with 20 mm diameter tool holder fitted with a single coated TiN insert with Full immersion. In this work, down milling method was employed in end milling due to some advantages like better surface finish, less heat generation, larger tool life, and better machining accuracy.

The independent variables at different levels were coded taking into considerations the limitation and capacity of the cutting tools. Levels of independent and coding identification are presented in Table 1, for experiment using Coated TiN inserts, respectively.

Table 1. Coding Identification for end milling using Coated TiN insert.

Level of coding	Lowest $-\sqrt{2}$	Low -1	Centre 0	High +1	Highest $+\sqrt{2}$
x_1 cutting speed, v m/min	120.0	137.25	190.0	262.5	300.2
x_2 axial depth of cut, mm	1.005	1.15	1.59	2.2	2.516
x_3 Feed, mm/tooth	0.039	0.05	0.089	0.16	0.204

The design of the experiments has an effect on the number of experiments required. Therefore, it is important to have a well-designed experiment to minimize the number of experiments which often are carried out randomly. In the experiment, small central composite design was used to develop the chip serration model. The analysis of mathematical models was carried out using Design-expert 6.0.8 package [14]. Cutting conditions in coded factors and the chip serration values obtained using TiN coated cemented carbide insert are presented in Table 2.

Table 2 Chip Serration Frequency results and cutting conditions in coded factors

Std No	Type	Level of Coding			Chip Serration Frequency, Hz
		x_1	x_2	x_3	
1	Fact	1	1	-1	8355,635
2	Fact	1	-1	1	16560,72
3	Fact	-1	1	1	5523,774
4	Fact	-1	-1	-1	2677,992
5	Centre	0	0	0	11358,23
6	Centre	0	0	0	12120,36
7	Centre	0	0	0	11530,32
8	Centre	0	0	0	12031,24
9	Centre	0	0	0	11444,28
10	Axial	-1.41	0	0	4655,282
11	Axial	1.41	0	0	11059,79
12	Axial	0	-1.41	0	6854,273
13	Axial	0	+1.41	0	6157,849
14	Axial	0	0	-1.41	13900,39
15	Axial	0	0	+1.41	12959,76

Cutting experiments were carried out in a block of AISI 1020. The work-piece material was clamped onto the machine table to provide maximum rigidity. The transforming equations of each of the individual variables are given below:

$$x_1 = \frac{\ln V - \ln 190}{\ln 262.5 - \ln 190};$$

$$x_2 = \frac{\ln a - \ln 1.59}{\ln 2.2 - \ln 1.59};$$

$$x_3 = \frac{\ln f_z - \ln 0.089}{\ln 0.16 - \ln 0.089}$$

The above relationships were obtained from the following transforming equation:

$$x_1 = \frac{\ln x_n - \ln x_{n0}}{\ln x_{n1} - \ln x_{n0}}$$

Where, x is the coded value of any factor corresponding to its natural value x_n. x_{n1} is the +1 level and x_{no} is the natural value of the factor corresponding to the base of zero level.

5. DEVELOPMENT SECOND ORDER MODEL USING CCD DESIGN

Fit and summary test in Table 3 summarizes that the quadratic model CCD models was more significant than linear model and it also proved that linear model has a significant lack of fit (LOF). Therefore, the quadratic model was chosen in order to develop the CCD model.

Table 3 Fit and Summary test of the second order CCD model

Sequential Model Sum of Squares						
	Sum of		Mean	F		
Source	Squares	DF	Square	Value	Prob > F	
Mean	1240.57	1	1240.57			Suggested
Block	0.016	1	0.016			
Linear	1.71	3	0.57	3.32	0.0651	
2FI	0.42	3	0.14	0.75	0.5578	
Quadratic	**1.30**	**3**	**0.43**	**480.35**	**<0.0001**	**Suggested**
Cubic	0.000	0				Aliased
Residual	3.604E-003	4	9.010E-004			
Total	1244.01	15	82.93			

The second order quadratic Chip Serration Frequency model is given as:

$$\hat{y}_2 = 9.39 + 0.31x_1 - 0.014x_2 - 0.025x_3 - 0.27x_1^2$$
$$-0.32x_2^2 + 0.041x_3^2 - 0.38x_1x_2 - 0.25x_2x_3$$

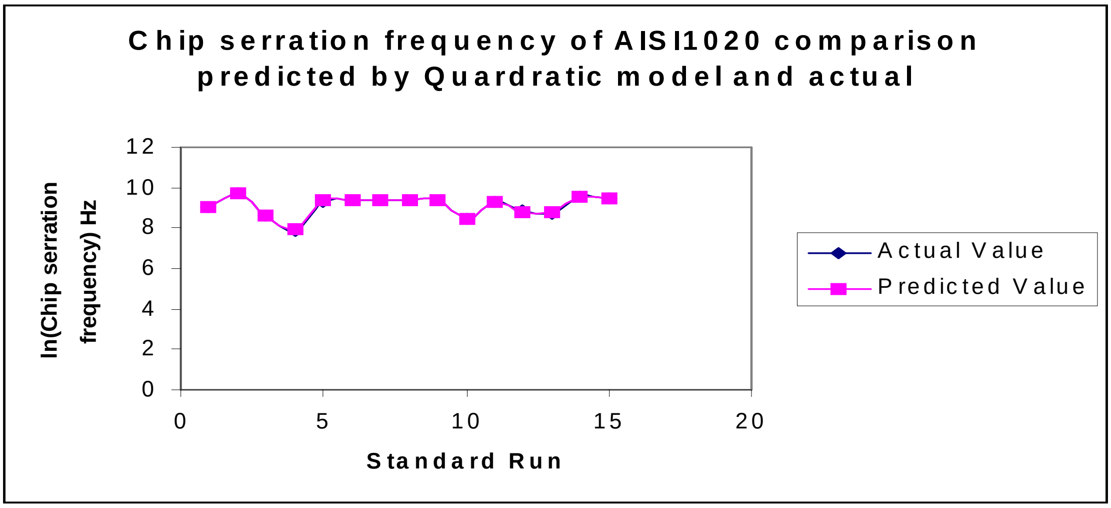


Figure 4. Chip Serration Frequency contours of experimental and quadratic CCD predicted values

Figure 4 shows the contours of actual results and the predicted values of quadratic CCD models. The graphs indicated that the quadratic model leads to closer results to the actual values.

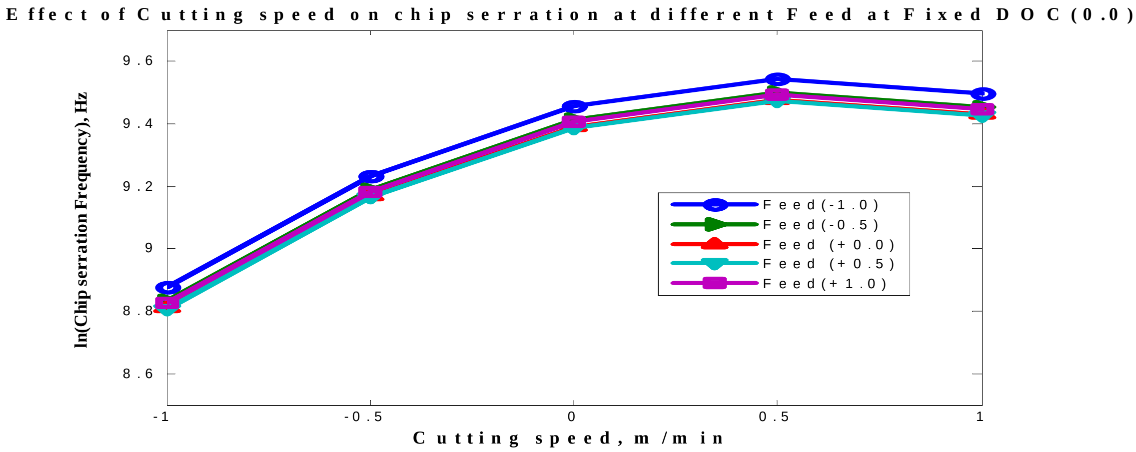
To verify the adequacy of the proposed second order CCD model, ANOVA was used and the results are shown in the Table 4. The quadratic CCD model shows that cutting speed has the most significant effect on chip serration frequency, followed by feed and axial depth of cut.

Table 4 Analysis of variance (ANOVA) of quadratic CCD model

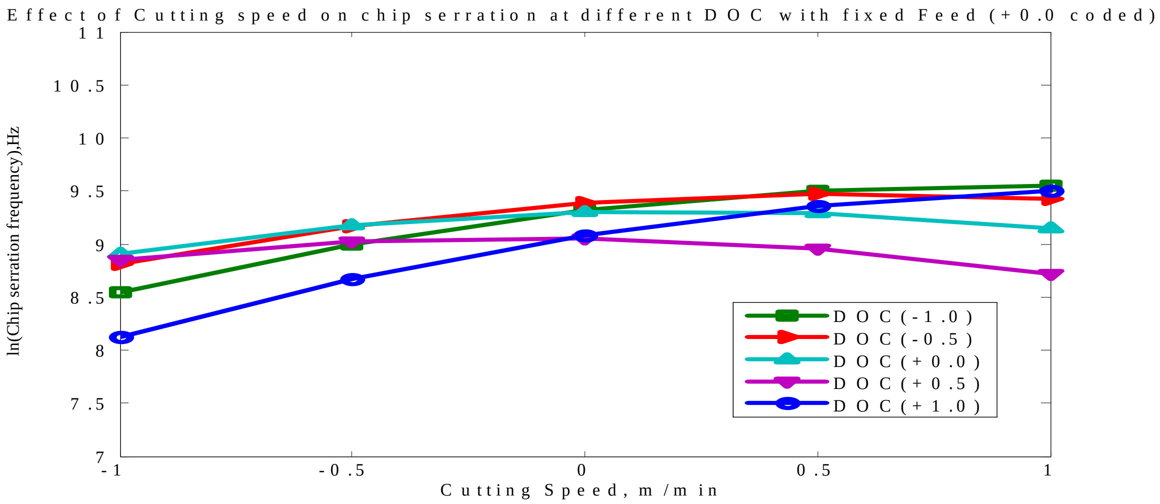
Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	Remarks
Block	0.016	1	0.016			
Model	3.42	8	0.43	261.34	<0.0001	significant
X_1	0.37	1	0.37	228.72	<0.0001	
X_2	1.558E-003	1	1.558E-003	0.95	0.3741	
X_3	2.455E-003	1	2.455E-003	1.5	0.2753	
X_12	0.56	1	0.56	339.29	<0.0001	
X_22	0.78	1	0.78	474.49	<0.0001	
X_32	0.013	1	0.013	7.7	0.0392	
$X_1 X_2$	0.28	1	0.28	173.47	<0.0001	
$X_2 X_3$	0.13	1	0.13	78.22	0.0003	
Residual	8.184E-003	5	1.637E-003			
Lack of Fit	4.580E-003	1	4.580E-003	5.08	0.0872	not significant
Pure Error	3.604E-003	4	9.010E-004			
Cor Total	3.45	14	3.45			

6. ANALYSIS OF MODEL

For the analysis of the developed quadratic model, Matlab software was used to represent the individual cutting parameters effects on chip serration frequency. Figure 5 (a) shows that with the increase of cutting speed the chip serration frequency increases and these trends follow for the other cases also but along with the increase of feed the chip serration also decreases.



(a)



(b)

Figure: 5 Effect of Cutting Speed on chip serration frequency at (a) Feed and (b) Depth of cut

Figure 5(b) shows that with the increase of cutting speed the chip serration frequency increases and these trends follow for the other cases also but along with the increase of depth of cut the chip serration also decreases.

Chip shrinkage coefficient is defined as the ratio of the uncut chip length by the actual chip length. It is defined as K. It has been observed from Figure 6 that with the increase of cutting speed the chip shrinkage coefficients for end milling of AISI 1020 decreases as result the chip serration frequency increases.

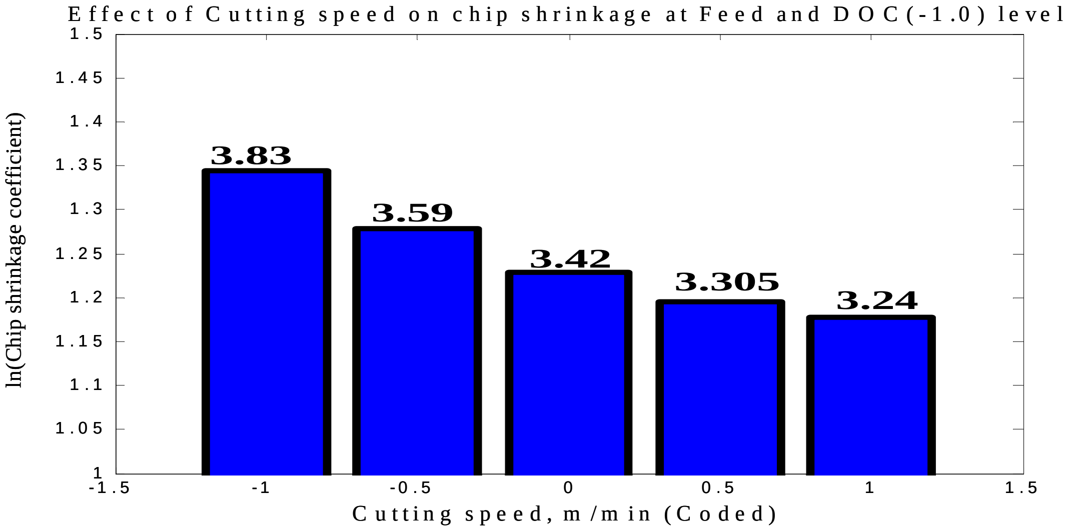


Figure: 6 Effect of Cutting Speed on chip shrinkage coefficient

7. CONCLUSIONS

This paper discussed the development of a mathematical model for the prediction of the chip serration (secondary) frequency. Based on the experimental findings a statistical model for the prediction of chip serration (secondary) frequency in end milling of AISI 1020 steel using coated TiN insert was developed.

The CCD model developed by RSM using Design Expert package are able to provide accurately predicted values of chip serration close to actual values found in the experiments. The equations are checked for their adequacy with a confidence level of 95%.

It has been observed that the cutting speed has positive effect on chip serration whereas the feed and depth of cut has negative effect on chip serration frequency. The effect of feed variation on chip serration frequency is not significant.

It has been observed that the chip shrinkage coefficient decreases with the increase of cutting speed, when the cutting speed is 138.25m/min the chip shrinkage coefficient is 3.83 whereas at 262.5m/min the chip shrinkage coefficient decreases to 3.24.

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