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UNIVERSITI TEKNOLOGI MARA

Journal of Mechanical Engineering

An International Journal

Volume 10 No. 1 Jun 2013 ISSN 1823-5514

JOURNAL OF MECHANICAL ENGINEERING (JMechE)

Journal of Mechanical Engineering (ISSN 1823-5514) is published by the Faculty of Mechanical Engineering (FKM), Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia.

Journal of Mechanical Engineering

An International Journal

Volume 10 No. 1 **Jun 2013** **ISSN 1823-5514**

Journal of Mechanical Engineering *Vol. 10, No. 1, 49-65, 2013*

Prediction of Cutting Forces Developed during Hard Turning of Hard Chrome Plated Surfaces on EN24 Substrate

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ABSTRACT

This paper investigates the development of cutting forces during the hard turning of hard chrome plated surfaces on EN24 substrate. The hard turning operation disproves the Merchant's theory of cutting force development during the machining as the hard turning is only a small stock material removal. Various forces produced such as cutting force, feed force and thrust force have been measured during the finish turning. The experimental results have indicated that the feed force is the predominant force out of three different forces developed. This is in good agreement with the available literature. The results obtained from the experimentation were used to predict the optimum cutting conditions in terms of cutting forces. The

ISSN 1823-5514

optimized cutting parameters are feed of 0.08mm/rev, cutting speed of 500rpm and depth of cut of 40μm. The developed mathematical model exhibited satisfactory goodness of the model fit in regression with different PcBN cutting tool inserts. A maximum of 5% variation in the experimental results of the cutting forces when compared with the mathematical model has been observed. This suggests that the developed mathematical model could be employed to predict the cutting forces during hard turning of hard chrome plated surfaces.

Keywords: *Hard turning, hard chrome plated surfaces, cutting forces, PcBN inserts, dynamometer.*

Introduction to Machining and Hard Turning

As humankind progresses towards implementing very tight precision standards, the total production concept needs re-assessment in its manufacturing practices, in particular finishing operations. The demand to maintain the very high accuracies of the components have resulted in selection of an appropriate manufacturing method required in finishing of the component. Currently, the most popular method of better finishing is the grinding operation. However, this operation has several shortfalls especially the finishing of the internal surfaces due to the fixture problem. Further, grinding requires enormous cutting fluid during machining, which is considered to be unhealthy to the green environment. All these problems associated with grinding made the researchers to think on the alternate methods to the grinding process [1,2].

One of the popular alternate solutions proposed by the researchers has been the hard turning. Hard turning is a simple turning operation which operates on the harder material having hardness above 45 HRc. The hard turning machines are normal CNC lathes with more rigid fixtures for the mounting of workpieces. With close cutting conditions, the hard turning operation produces the surfaces similar to the grinding operation. Hard turning can machine the complex workpieces in one step. It is less time consuming, more flexible and very cost-effective process. Although grinding is a typical finishing process employed in industry, in many cases hard turning is a better option for both internal and external finishing operations [3,4].

The increased demand for hard surface applications has resulted in the development of coated materials with hard substances. One such coated material is chrome plating. It is a method of electroplating a thin layer of chromium onto the base substrate. The thickness of chrome plating depends on the applications. Very thin coatings are normally called as the decorative coatings while the other type of chrome plating is the hard chrome also recognized as the industrial chrome or the engineered chrome. This type of coating increases wear and corrosion resistance with reduced friction. The hardness of the hard chrome plating is reported to be in the range of 62 – 70 HRc [5].

Finish machining remains the most important type of final forming. However, this method of production has changed significantly over recent decades, with the cutting process requirements becoming ever more stringent to meet the specified close tolerances. In achieving this, detailed knowledge of the cutting processes is indispensable. The optimized cutting forces and torques are the essential prerequisites for drawing the conclusions about the technology and the cutting parameters [6,7].

Experimentation

In this experiment, EN24 was selected as the base substrate owing to its high tensile strength and good compatibility with chrome plating. Table 1 reports the chemical composition of EN24 substrate.

Table 1 Chemical composition of EN24 substrate

Element	C	Si	Mn	S	P	Ni	Cr	Mo
Wt %	0.36	0.22	0.52	0.005	0.007	1.52	1.17	0.27

Hard chrome coating was deposited on EN24 base substrate by electro-deposition method. The electrolyte used was a mixture of chromic acid (CrO_3) and a catalytic anion in proper proportion. A current density of 50A/decimeter^2 and temperature of 55 – 60 ^{0}C has been adopted. Cylindrical samples of EN24 of diameter 50mm and height 70mm served as cathode for chrome plating. Coatings of thickness of 170µm have been deposited on all the substrates. Figure 1 shows the photographs of hard chrome plated EN24 cylindrical samples.

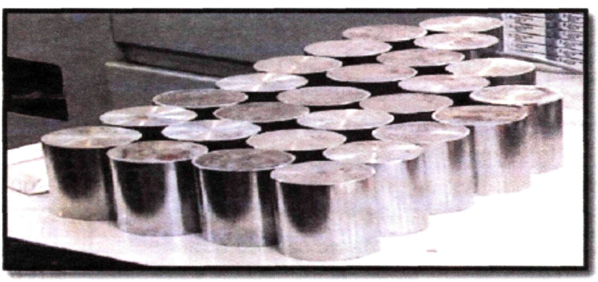


Figure 1 Photograph of chrome plated EN24 steel substrate

Machining of components with very hard surface requires better wear resistance properties of the cutting tool. To satisfy this requirement, normally coated CBN inserts are used in the machining of such components. TiN and TiAlN coated CBN inserts are the most sought after to achieve close tolerances of finished components. However, meager information is available as regards the use of TiAlN coated CBN inserts for finishing of very hard surfaces. Hence, TiAlN coated CBN inserts are being employed for finish machining in this work. MBC 020 grade of CBN inserts are used. The inserts used in the experiments were provided with a negative rake angle of 5^0. These were indicated with letter '*N*' in the insert designation. Negative rake angles in the cutting inserts are preferred during the machining of the hard components as reported by several researchers [8,9].

PcBN tool materials, with different grades and nose radii have been used to study the influence of the grade and nose radius. Series of experiments were conducted using CNGA (80^0 cutting edge angle) and DNGA (55^0 cutting edge angle) inserts. Table 2 shows the specification of the different TiAlN coated PcBN inserts used in the present investigation. The *'0404'* and *'0408'* in the specifications represent the thickness of the inserts and tool nose radii respectively. Cutting inserts of thickness of 4.76mm are used in the entire experimentation. The study on cutting forces with various levels of feed rate, cutting speed and depth of cut were analyzed as per the procedures adopted in our earlier work [10]. Table 3 reports the various levels and the factors involved in this experimentation, while Table 4 reports the factors of experimentation of L9 orthogonal array.

Table 2 Specifications of TiAlN coated PcBN inserts

Sl. No.	Insert	Cutting angle	Nose radius (mm)
1.	CNGA 120404	80^0	0.4
2.	CNGA 120408	80^0	0.8
3.	DNGA 150404	55^0	0.4
4.	DNGA 150408	55^0	0.8

Table 3 Cutting parameters and their levels

Parameters	Level 1	Level 2	Level 3
Cutting speed (rpm), *v*	300	400	500
Feed (mm/rev), *f*	0.04	0.06	0.08
Depth of cut (μm), *d*	40	80	120

Table 4 Levels and Factors of Experimentation (L9 OA)

Trail No.	Speed (rpm)	Feed (mm/rev)	DOC (μm)
1	300	0.04	40
2	300	0.06	80
3	300	0.08	120
4	400	0.04	120
5	400	0.06	40
6	400	0.08	80
7	500	0.04	80
8	500	0.06	120
9	500	0.08	40

Mazak Quick Turn Nexus 200 II - finish turning machine was used to turn the hard chrome plated cylindrical EN24 samples. Kistler piezoelectric dynamometer (Type 9129A) was loaded on the lathe to measure the cutting forces developed during the hard turning of hard chrome plated surfaces [11]. The averaged cutting force, feed force and the thrust forces have been measured and their output graphical displays are recorded using Data Acquisition Card (DAC) and FMS software at the end of each experiment. Measurement of these forces for the different cutting speed, feed and depth of cut for a length of cut of 5mm are obtained. Figure 2 shows the set-up of the Kistler piezoelectric dynamometer on the hard turning machine while Figure 3 illustrates the block diagram of the cutting force measurement technique.

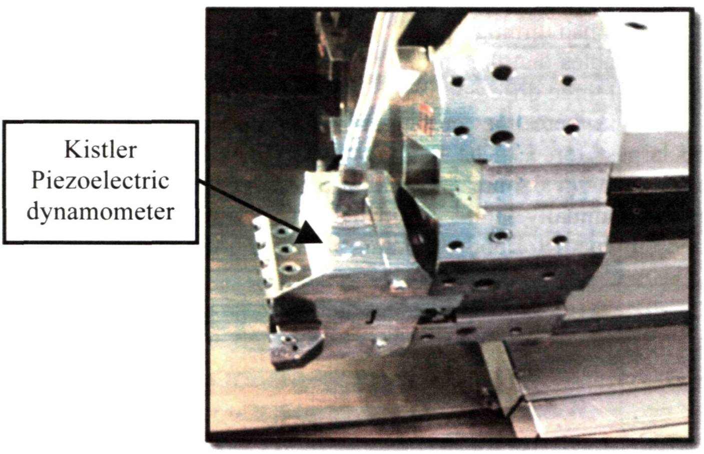


Figure 2 Set-up of the Type 9129A Kistler piezoelectric dynamometer

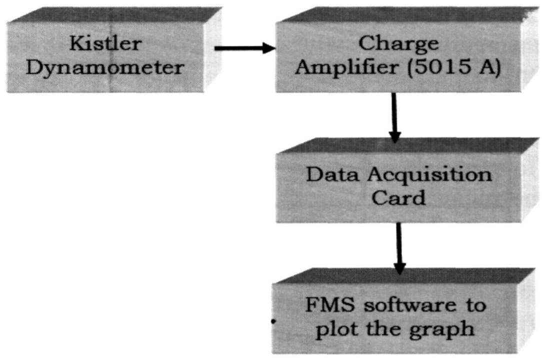


Figure 3 Block diagram of the cutting force measurement set-up

Minitab Version 15 software is used for the optimization of the various machining parameters. Analysis of Variance, Main effects plot for S/N ratio, Multiple linear regression analysis and Regression equations along with the normal probability plots have been generated for the analysis.

Results and Discussions

The FMS data analysis gathered the different cutting forces developed during the hard turning of hard chrome plated surfaces with different cutting inserts. Tables 5-8 report the forces recorded for the various cutting inserts. The forces F_x, F_y and F_z were the cutting force, feed force and the thrust forces respectively. The recorded experimental results revealed no relationship between the various cutting forces developed unlike that of a conventional metal cutting operation. This can be attributed to the smaller extent of material removal in the finish turning operation as reported in literature [2]. It is observed from these tables that the cutting force component (F_x) exhibited the least value among all three different forces. These observations do violate the Merchant's theory where the cutting force component has to be considered as the largest force. The feed force was maximal when hard turning was carried out with 0.4mm and 0.8mm nose radii cutting inserts. The thrust force was nominally higher when the depth of cut was 120μm. Similar observations are made for both 80^0 and 55^0 cutting edge angles.

Table 5 Values of cutting forces for CNGA 12 O4O4 MBC020 inserts

Tr. No.	Cutting speed (rpm)	Feed (mm/rev)	DOC (μm)	F_x (N)	F_y (N)	F_z (N)
1.	300	0.04	40	23.322	43.11	49.43
2.	300	0.06	80	37.989	85.12	96.05
3.	300	0.08	120	41.149	240.7	223.5
4.	400	0.04	120	43.944	191.1	202.3
5.	400	0.06	40	39.914	74.61	99.17
6.	400	0.08	80	21.907	64.81	46.74
7.	500	0.04	80	23.510	44.93	42.05
8.	500	0.06	120	40.435	222.8	207.5
9.	500	0.08	40	20.797	50.55	42.06

Table 6 Values of cutting forces for CNGA 12 O4O8 MBC020 inserts

Tr. No.	Cutting speed (rpm)	Feed (mm/rev)	DOC (μm)	F_x (N)	F_y (N)	F_z (N)
1.	300	0.04	40	44.272	113.7	107.3
2.	300	0.06	80	37.989	85.12	96.05
3.	300	0.08	120	40.712	229.8	186.7
4.	400	0.04	120	48.712	117.0	104.0
5.	400	0.06	40	39.914	74.61	99.17
6.	400	0.08	80	44.341	119.0	103.5
7.	500	0.04	80	39.914	96.77	94.90
8.	500	0.06	120	41.641	180.1	168.5
9.	500	0.08	40	39.412	77.75	91.15

Table 7 Values of cutting forces for DNGA 15 O4O4 MBC020 inserts

Tr. No.	Cutting speed (rpm)	Feed (mm/rev)	DOC (μm)	F_x (N)	F_y (N)	F_z (N)
1.	300	0.04	40	39.99	75.55	93.28
2.	300	0.06	80	42.13	118.9	94.48
3.	300	0.08	120	43.95	98.09	100.5
4.	400	0.04	120	39.42	112.6	104.5
5.	400	0.06	40	42.96	112.5	103.8
6.	400	0.08	80	38.67	96.46	93.07
7.	500	0.04	80	41.15	87.47	92.34
8.	500	0.06	120	44.27	103.4	109.4
9.	500	0.08	40	45.75	124.5	94.43

Table 8 Values of cutting forces for DNGA 15 O4O8 MBC020 inserts

Tr. No.	Cutting speed (rpm)	Feed (mm/rev)	DOC (μm)	Fx (N)	Fy (N)	Fz (N)
1.	300	0.04	40	46.25	118.6	103.0
2.	300	0.06	80	42.30	120.1	112.2
3.	300	0.08	120	42.16	217.8	174.3
4.	400	0.04	120	45.00	118.8	105.6
5.	400	0.06	40	43.78	116.8	106.1
6.	400	0.08	80	44.07	208.8	192.3
7.	500	0.04	80	41.96	119.3	108
8.	500	0.06	120	44.35	189.7	183.1
9.	500	0.08	40	45.05	117.4	95.25

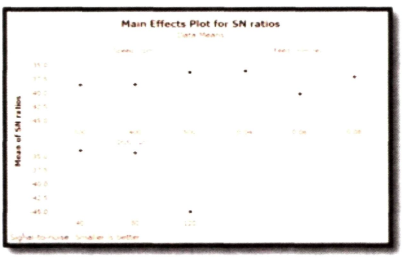
Optimization of cutting parameters

The optimization of the cutting forces recorded was carried out using Taguchi's Design of Experimentation (DoE). The cutting force is directly proportional to the power required for the cutting. It is evident that smaller the value of the cutting force better is the machinability. The optimization was focused on this issue.

According to the Taguchi quality design concept, an L9 orthogonal array has been used to determine the S/N ratio (d_B), analysis of variance (ANOVA) and '*F*' test values for indicating the effect of most significant parameters affecting the machining performance criteria, i.e. cutting force. The main purpose of the ANOVA is to investigate the design parameters and to indicate which parameters are significantly affecting the quality characteristics. This analysis contributes to determine the relative contribution of machining parameter in controlling the response of turning operation. Figure 4 shows the main effects of S/N ratio for the cutting force for different cutting inserts selected for the experiments. The cutting forces developed during the turning should be minimal to get the optimized results. Therefore the S/N ratios have been calculated for the optimum cutting forces as per "the smaller-the better" and this has been shown in equation 1.

$$\frac{S}{N} = -10\log_{10}\left[\frac{1}{n}\left(\Sigma y^2\right)\right] \qquad (1)$$

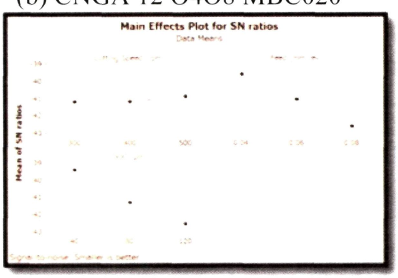
where y is the cutting force measured in N.



(a) CNGA 12 O4O4 MBC020

(b) CNGA 12 O4O8 MBC020

(c) DNGA 15 O4O4 MBC020



(d) DNGA 15 O4O8 MBC020

Figure 4 Main effects plot for SN ratios of cutting force with various inserts

The analysis of variance (ANOVA) tables were prepared from the results of each set of experiments to analyze the effects of cutting parameters on the response. The ANOVA was run using the General Linear Model (GLM) to determine the effects of each cutting parameter for each set of cutting tool insert. Tables 9-12 report the ANOVA data for different cutting inserts.

Table 9 Analysis of Variance using Adjusted SS for Tests for CNGA 12 O4O4 MBC020

Source	DOF	Seq SS	Adj SS	Adj MS	F	P
Cutting speed (rpm)	2	465.6	465.6	232.8	2.09	0.324
Feed (mm/rev)	2	1923.0	1923.0	961.5	8.62	0.104
Depth of cut (μm)	2	49842.8	49842.8	24921.4	223.48	0.004
Error	2	223.0	223.0	111.5		
Total	8	52454.4	52454.4			

Table 10 Analysis of Variance using Adjusted SS for Tests for CNGA 12 O4O8 MBC020

Source	DOF	Seq SS	Adj SS	Adj MS	F	P
Cutting speed (rpm)	2	2371	2371	1186	0.66	0.604
Feed (mm/rev)	2	1943	1943	972	0.54	0.650
Depth of cut (μm)	2	13370	13370	6685	3.70	0.213
Error	2	3614	3614	1807		
Total	8	21298	21298			

Table 11 Analysis of Variance using Adjusted SS for Tests for DNGA 15 O4O4 MBC020

Source	DOF	Seq SS	Adj SS	Adj MS	F	P
Cutting speed (rpm)	2	29.053	29.053	14.527	15.66	0.060
Feed (mm/rev)	2	77.794	77.794	38.897	41.92	0.023
Depth of cut (μm)	2	205.546	205.546	102.773	110.77	0.009
Error	2	1.856	1.856	0.928		
Total	8	314.250	314.250			

Table 12 Analysis of Variance using Adjusted SS for Tests for DNGA 15 O4O8 MBC020

Source	DOF	Seq SS	Adj SS	Adj MS	F	P
Cutting speed (rpm)	2	153	153	76	0.03	0.966
Feed (mm/rev)	2	5972	5972	2986	1.37	0.423
Depth of cut (μm)	2	5034	5034	2517	1.15	0.465
Error	2	4375	4375	2188		
Total	8	15534	15534			

The P values of less than 0.5 were considered as the predominant factors among three different cutting parameters. If the value of P is more than 0.5, that can be ignored as these parameters will have less influence on the output. From ANOVA tables, it is evident that the cutting speed contributes very marginally in all four type of cutting inserts selected for this experimentation. This observation is in line with earlier literature.

Mathematical model

The mathematical model was developed by means of multiple linear regression analysis for the optimal selection of machining parameters for the minimum cutting force. The normal probability (Residual) plot enables one to examine the goodness of model fit in regression. The regression equations for four different inserts are given in equations 2, 3, 4 and 5 respectively. The residual plots for cutting force for four different inserts are shown in figures 5- 8.

The regression equation for CNGA 12 O4O4 MBC020 is:

Fy(N) = -54 -0.084 Speed (rpm) +641 Feed (mm/rev) +2.03 DOC (µm) (2)

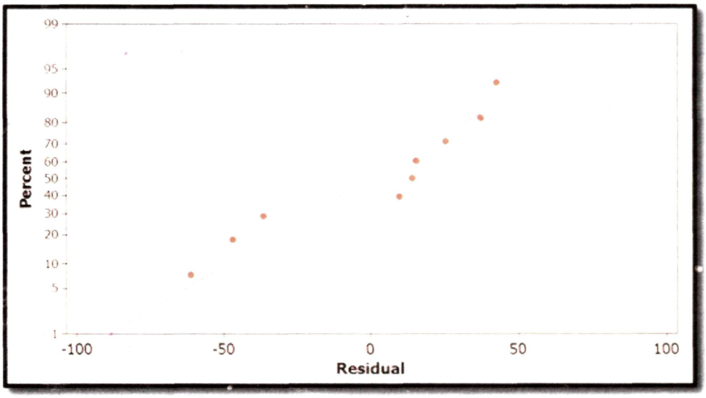


Figure 5 Residual plot of cutting force for CNGA 12 O4O4 MBC020

The regression equation for CNGA 12 O4O8 MBC020 is:

Fy(N) = 34.4 - 0.123 Cutting speed (rpm) + 826 Feed (mm/rev) + 1.09 DOC (µm) (3)

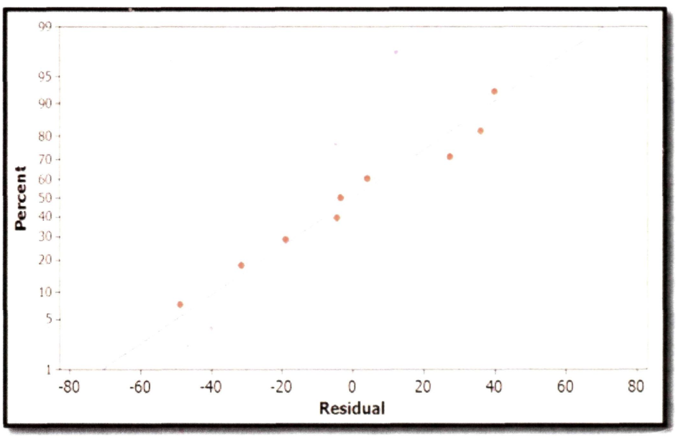


Figure 6 Residual plot of cutting force for CNGA 12 O4O8 MBC020

The regression equation for DNGA 15 O4O4 MBC020 is:

Fz (N) = 86.6 + 0.0132 Cutting speed (rpm) - 18 Feed (mm/rev) + 0.0954 DOC (μm) (4)

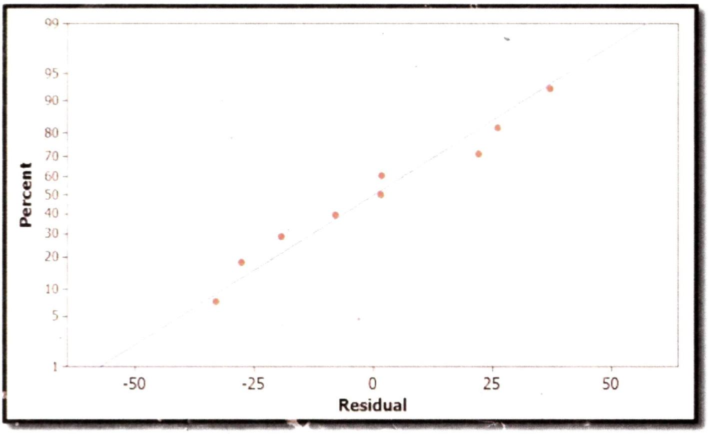


Figure 7 Residual plot of cutting force for DNGA 15 O4O4 MBC020

The regression equation for DNGA 15 O4O8 MBC020 is:

Fz (N) = 7.7 - 0.005 Cutting Speed (rpm) + 1210 Feed (mm/rev) + 0.661 DOC (μm) (5)

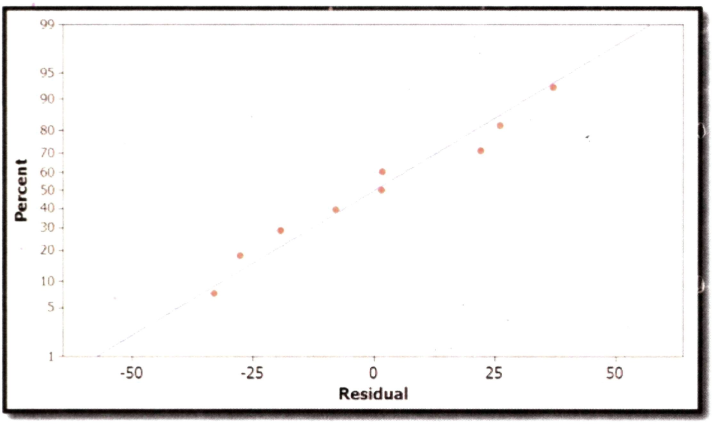


Figure 8 Residual plot of cutting force for DNGA 15 O4O8 MBC020

- It was very much clear from all normal probability plots for various inserts a satisfactory goodness of model fit in regression has been observed.

Comparative study of the cutting forces

A comparative study was carried out with the experimental results and the results obtained from the mathematical equation developed using the Minitab software. Figures 9-12 reports the comparison of experimental and predicted cutting forces from mathematical modeling.

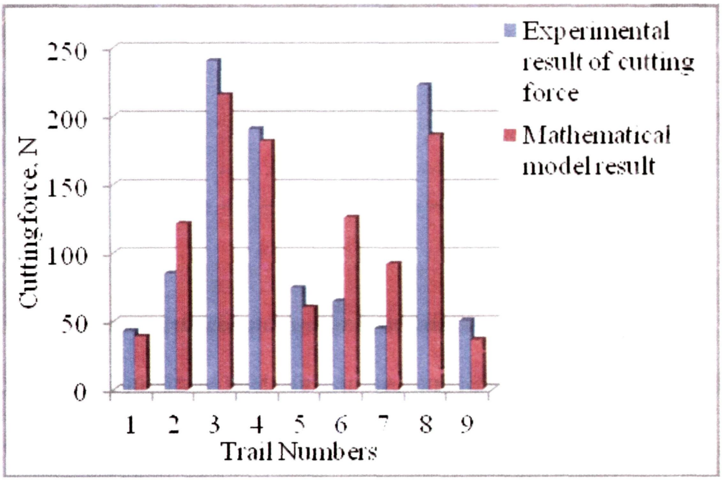


Figure 9 Comparison of the cutting forces on use of CNGA 12 O4O4 inserts

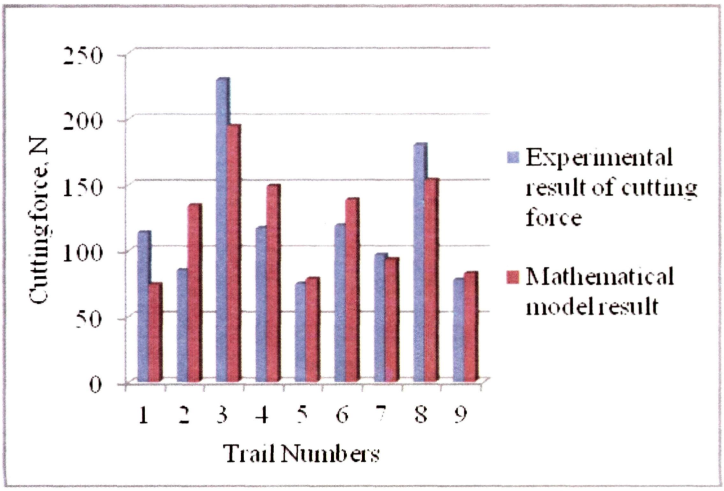


Figure 10 Comparison of the cutting forces on use of CNGA 12 O4O8 inserts

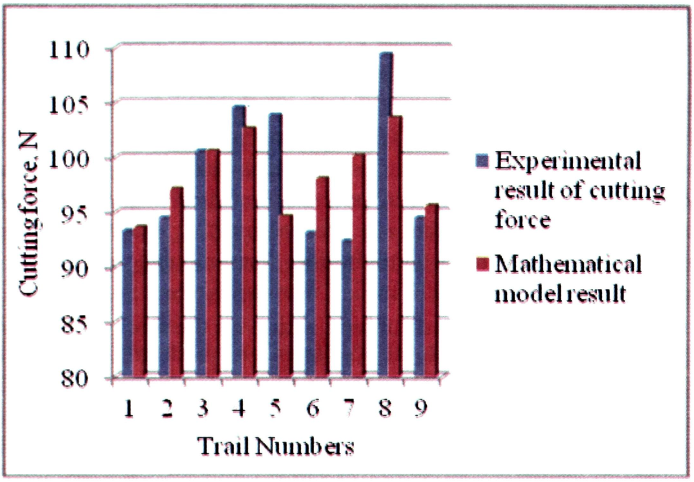


Figure 11 Comparison of the cutting forces on use of DNGA 15 O4O4 inserts

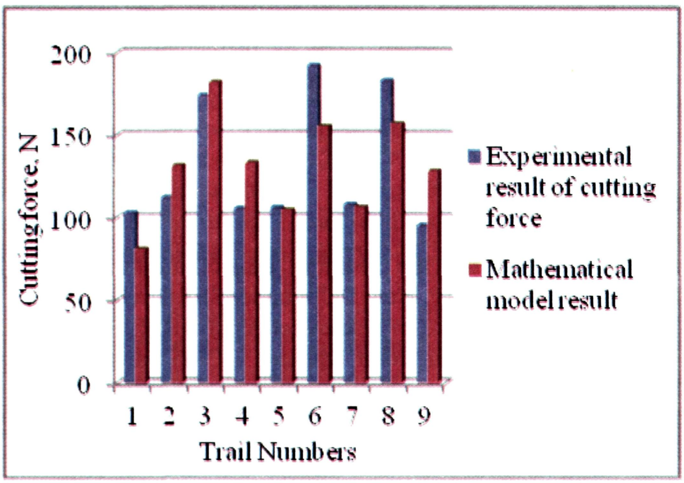


Figure 12 Comparison of the cutting forces on use of DNGA 15 O4O8 inserts

The above comparative study of the experimental results of the cutting forces with the mathematical models showed a variation of less than 5%. Hence, the mathematical model developed based on the experimental data could be employed to determine the cutting forces prior to finish machining operations. Both experiment and mathematical modeling demonstrated that at a cutting speed of 500rpm, feed of 0.08mm and a depth of cut of 40μm cutting force was least on use of all the four different cutting inserts.

Conclusions

On the basis of experimental results in terms of the minimum cutting force using Taguchi design concept, the following points can be concluded

- The major finding of the present work was the violation of the conventional machining when compared to the cutting force. Therefore the Merchant circle could not be used for force analysis for the finish turning of the components.
- Lower feed generated optimum cutting forces during machining of hard chrome plated surfaces.
- Lower depth of cut created rubbing action on the work surfaces because of which tool wear observed was more.
- The cutting force analysis demonstrated that the contribution of the cutting speed was significantly less when compared to the feed and the depth of cut.
- The developed mathematical model for prediction of cutting force was successfully proposed for the proper selection of the turning parameters.
- The developed model can aid directly to evaluate the cutting force value under different machining parameters combination during turning.
- The prediction of the cutting force by mathematical model results in minimizing experimentation required for the finish turning of hard chrome plated surfaces.

Acknowledgements

This work is a portion of the research project number: SR/S3/MERC-0113/2009 sanctioned by DST, New Delhi under SERC scheme.

The authors would like to acknowledge Mr. B.R. Satyan, Director – CMTI, Mr. P.V. Shashikumar, Joint Director – CMTI and Project guide of this DST sponsored project and authorities of DST for facilitating this research under the funding of DST. The authors acknowledge the authorities of DST for financial assistance for carrying out the research work.

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JOURNAL OF MECHANICAL ENGINEERING (JMechE)

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Contributions are invited from various disciplines that are allied to mechanical engineering. The contributions should be based on original research works. All papers submitted to JMechE are subjected to a reviewing process through a worldwide network of specialized and competent referees. To be considered for publication, each paper should have at least two positive referees's assessments.

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Paper Title in Arial 18-point, Bold and Centered

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ABSTRACT

The first section of the manuscript should be an abstract, where the aims, scope and conclusions of the papers are shortly outlined, normally between 200 and 300 words. TNR-10 italic

Keywords: maximum 5 keywords.

Title of First Section (Arial 11 Bold)

Leave one blank line between the heading and the first line of the text. No indent on the first para after the title; 10 mm indent for the subsequent para. At the end of the section, leave two blank lines before the next section heading. The text should be right and left justified. The recommended font is Times New Roman, 10 points. In 152 mm x 277 mm paper size, the margins are: left and upper: 22 mm each; right: 20 mm, lower: 25 mm.

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Tables and illustrations should be numbered with arabic numbers. Tables and illustrations should be centred with illustration numbers written one blank line, centered, after the relevant illustration. Table number written one line, centered, before the relevant table. Leave two blank lines before the table or illustration. Beware that the proceedings will be printed in black and white. Make sure that the interpretation of graphs does not depend on colour. In the text, tables and figures should be referred to as Figure 1 and Table 1.

The International System of Units (SI) is to be used; other units can be used only after SI indications, and should be added in parenthesis.

Equations should be typed and all symbols should be explained within the manuscript. An equation should be proceeded and followed by one blank line, and should be referred to, in the text, in the form Equation (1).

$$y = A + Bx + Cx^2 \quad (1)$$

Last point: the references. In the text, the references should be a number within square brackets, e.g. [3], or [4]–[6] or [2, 3]. The references should be listed in numerical order at the end of the paper.

Journal references should include all the surnames of authors and their initials, year of publication in parenthesis, full paper title within quotes, full or abbreviated title of the journal, volume number, issue number and pages. Examples below show the format for references including books and proceedings.

Examples of references:

[1] M. K. Ghosh and A. Nagraj, "Turbulence flow in bearings," Proceedings of the Institution of Mechanical Engineers 218 (1), 61-4 (2004).
[2] H. Coelho and L. M. Pereira, "Automated reasoning in geometry theorem proving with Prolog," J. Automated Reasoning 2 (3), 329-390 (1986).
[3] P. N. Rao, Manufacturing Technology Foundry, Forming and Welding, 2nd ed. (McGraw Hill, Singapore, 2000), pp. 53 – 68.
[4] Hutchinson, F. David and M. Ahmed, U.S. Patent No. 6,912,127 (28 June 2005).