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Effect of Tool Holder Angles on Cutting Force When Machining Aerospace Material

K.Kadirgama[1], M.M.Noor[1], M.R.M.Rejab[1], K.A. Abou-El-Hossein[2], Rosli A. Bakar[1], H.Ismail[4]

[1]Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26300 UMP, Kuantan, Pahang, Malaysia Phone: +609-5492233 Fax: +609-5492244. Emails: kumaran@ump.edu.my / muhamad@ump.edu.my
[2]Department of Mechanical Engineering, University of Pretoria, South Africa
[3]Department of Mechanical Engineering, University Tenaga Nasional[4]School of Material & Mineral Resources Engineering, Universiti Sains Malaysia, 14300 Pulau Pinang, Malaysia.

Abstract

Cutting force is one of the main factors to be considered in CNC milling machine. Prediction models and optimum values are very important for the machinist to save number of cutting tools and reduce machining time. This paper discussed the effect of the two different angles (90° and 70°) of tool holder on cutting force when machining aerospace material (Hastelloy C-22HS) in two different environments (dry and flood). The 90^o tool holder is suitable to be used in rough machining, milling casting part, internal facing with low accuracy and others. It can be used in the condition of high cutting speed, high feed rate and high axial depth. On the other hand, the 70^o tool holder is more suitable for milling operation of final machining component, hard material, etc. Response surface method (RSM) was used to minimize the number of experiments. First order models were developed to optimize the machining parameters (cutting speed, federate and axial depth) and obtain the optimum cutting force. It observed that low value cutting parameters need to be used for 70° tool holders, meanwhile for 90° tool holders high value cutting parameters can be used. Both angle of tool holder not suitable be used in dry cutting since the cutting force produced very high for machining purpose.

Keywords: Response surface method, tool holder, aerospace, dry

1. Introduction

Cutting fluids, usually in the form of a liquid, are applied to the chip formation zone in order to improve the cutting conditions. These improvements can take several forms, depending on the tool and work materials. Normally cutting fluid is used to reduce friction and wear (hence improving tool life and surface finish), to reduce cutting forces and energy consumption, to cool the cutting zone (thus reducing workpiece temperature and distortion), to wash away chips and to protect newly machined surfaces from environmental corrosion [1, 2].

Cutting fluid can be expensive and represents a biological and environmental hazard that requires proper recycling and disposal, thus adding to the cost of the machining operation. For these reasons dry cutting or dry machining has become an increasingly important approach; in dry machining no coolant or lubricant is used [1, 2].

Even though this approach suggests that higher temperature and more rapid tool wear will occur, some tool materials and coatings exhibit a reasonable tool life at higher temperature. Dry cutting, sometimes, is associated with high-speed machining, because higher cutting speed condition conveys a great amount of heat to the chip, which is a natural strategy to reduce the need for a coolant [3].

Large machining centers often have a coolant station that is very complex. The coolant station provides coolant through the tools in order to increase the amount of fluid for cutting operation. Coolant stations are usually made up of a series of filters to remove impurities and chips that have been carried in the coolant and pumps. Some coolant stations provide pressures of more than 1000 psi to the cutting operation. The relatively high pressure value allows good removal of chips, significant cooling, and better surface finish [4].

Alauddin et al. [5] have investigated the effect of cutting speed, feed rate and axial depth on the cutting force. According to them, cutting force decreases with the increasing of cutting speed, whereas cutting force increases with the increasing of feed rate and axial depth of cut. The F_x component is the highest in the up-milling mode, whilst in the down-milling mode the F_y component is the highest in the table system of cutting forces. Trent [6] has reported that the decrease in cutting force due to the increase of cutting speed is due to, partly, the softening of the workpiece under the condition of high temperature during cutting. According to Wuyi Chen [7], during the finishing operation of hardened steel, the radial thrust force (Fy) becomes the largest amongst the three cutting force components and it is very sensitive to the changes of cutting edge chamfer, tool nose radius and flank wear. Although an unchamfered tool with small nose radius generates low Fy and hence reducing the tendency to chatter, such geometry decreases the tool life.The mechanistic approach has been widely used for the force predictions and it has been also extended to predict the associated machine component deflections and form errors [8, 9].

This paper focuses on the optimisation of the cutting force with using tool holder 70° and 90° when machining aerospace material. Dry cutting also been performed to observe the effect of the lubricants towards cutting force.

2. Response Surface Method

Response surface method (RSM) is a collection of statistical and mathematical methods that are useful for the modelling and optimization of the engineering problems. In this technique, the main objective is to optimize the responses that are influencing by various parameters. RSM also quantifies the relationship between the controllable parameters and the obtained response. In modelling of the manufacturing processes using RSM, the sufficient data is collected through designed experimentation. In general, a second order regression model is developed because of first order models often give lack off fit [3]. The study uses the Box-Behnken design in the optimization of experiments using RSM to understand the effect of important parameters. Box-Behnken Design is normally used when performing non-sequential experiments. That is, performing the experiment only once. These designs allow efficient estimation of the first and second –order coefficients. Because Box-Behnken design has fewer design points, they are less expensive to run than central composite designs with the same number of factors. Box-Behnken Design do not have axial points, thus we can be sure that all design points fall within the safe operating. Box-Behnken Design also ensures that all factors are never set at their high levels simultaneously [10, 11]. The proposed linear model correlating the responses and independent variables can be represented by the following expression [10, 11]:

$$y = m \times Cutting\ speed + n \times Feed\ rate + p \times Axial\ \ depth + C \quad (1)$$

where y is the response, C, m, n, and p are the constants.

Equation (1) can be written as Equation (2):

$$y = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \quad (2)$$

where y is the response, x0 = 1(dummy variable), x1= cutting speed, x2 = feed rate, and x3 = axial depth. β0 = C and β1, β2, and β3, are the model parameters.

3. Experimental set-up

After the preliminary investigation, the suitable levels of the factors are used in the Minitab software to deduce the design parameters of 90^0 tool holders for Hastelloy C-22HS as shown in Table 1. The lower and higher speed values selected are 100 m/s and 180 m/s, respectively. For the feed, the lower value is 0.1 mm/rev and the higher value is 0.2 mm/rev. For the axial depth, the higher value is 2 mm and the lower value is 1 mm. In the case of radial depth, a value of 3.5 mm is selected for all experiments. Table 2 shows the selected values for the variables. The design parameters of 70^0 tool holders for Hastelloy C-22HS are shown in Table 3. The parameters values are different from the 90^0 tool holder because high values of cutting speed, feed rate and axial depth are not suitable to be used with 70^0 tool holder. From the preliminary experiments, the entire cutting tools are damaged when the parameters of 90^0 tool holder are used. The lower and higher speed values selected are 25 m/s and 100 m/s, respectively. For the feed, the lower value is 0.1 mm/rev and the higher value is 0.3 mm/rev. For the axial depth, the higher value is 1 mm and the lower value is 0.4 mm. In the case of radial depth, a value of 1 mm is selected for all experiments. Table 4 shows the selected values of the design variables. In order to develop the first-order model, a total of 15 experiments are carried out.

Table 1: The values selected for the variables (90^0 tool holders for Hastelloy C-22HS).

Factors/Coding of Levels	**-1**	**0**	**1**
Speed, V_c (m/min)	100	140	180
Feed, f (mm/rev)	0.1	0.15	0.2
Axial depth, a_d (mm)	1	1.5	2

Table 2: Design values obtained from the Minitab (90^0 tool holders for Hastelloy C-22HS).

Experiment Number	**Cutting speed, V_c (m/min)**	**Feed rate, f (mm/rev)**	**Axial depth, a_d (mm)**
1	140	0.1	2
2	140	0.2	1
3	100	0.15	1
4	100	0.15	2
5	140	0.15	1.5
6	100	0.1	1.5

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7	180	0.1	1.5
8	180	0.15	2
9	180	0.2	1.5
10	140	0.2	2
11	180	0.15	1
12	140	0.15	1.5
13	140	0.1	1
14	100	0.2	1.5
15	140	0.15	1.5

Table 3: The values selected for the variables (70^0 tool holders for Hastelloy C-22HS).

Factors/Coding of Levels	**low**	**mid**	**high**
Speed, V_c (m/min)	25	62.5	100
Feed, f (mm/rev)	0.1	0.2	0.3
Axial depth, a_d (mm)	0.4	0.7	1

Table 4: Design values obtained from the Minitab (70^0 tool holders for Hastelloy C-22HS).

Experiment Number	**Cutting speed, V_c (m/min)**	**Feed rate, f (mm/rev)**	**Axial depth, a_d (mm)**
1	100	0.3	0.7
2	25	0.3	0.7
3	62.5	0.3	0.4
4	62.5	0.2	0.7
5	100	0.1	0.7
6	100	0.2	0.4
7	100	0.2	1
8	62.5	0.1	1
9	25	0.1	0.7
10	62.5	0.3	1
11	62.5	0.2	0.7
12	25	0.2	0.4
13	62.5	0.1	0.4
14	62.5	0.2	0.7
15	25	0.2	1

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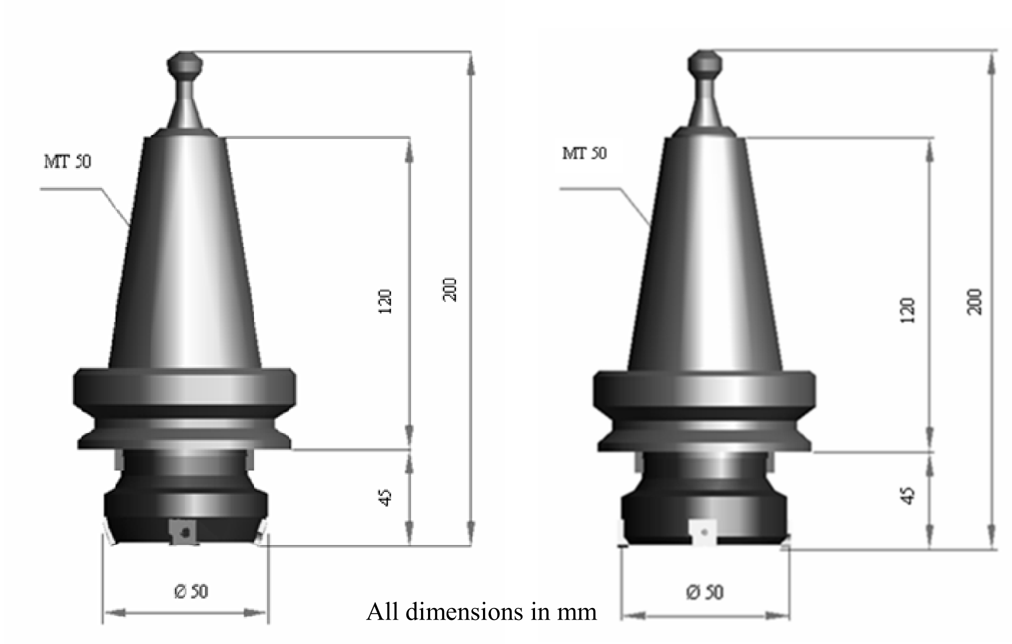
The tool holders used in this study are shown in Figure 1 (a) and 1 (b).



(a) **(b)**

Figure 1: (a) Tool holder 70^0, (b) Tool holder 90^0

4. Result & Discussion

4.1. Development of first and second order of cutting force model using RSM

After conducting the first pass (one pass is equal to 85 mm length) of the 15 cutting experiments, the cutting force readings are used to find the parameters appearing in the postulated first-order model Equation. (1). In order to calculate these parameters, the least square method is used with the aid of Minitab. The first-order linear equation used to predict the cutting force is expressed as:

$$\text{Force'} = -785.89 - 1.88x_1 + 5706.03x_2 + 578.33x_3 \quad (3)$$

with tool holder at 90° with coolant

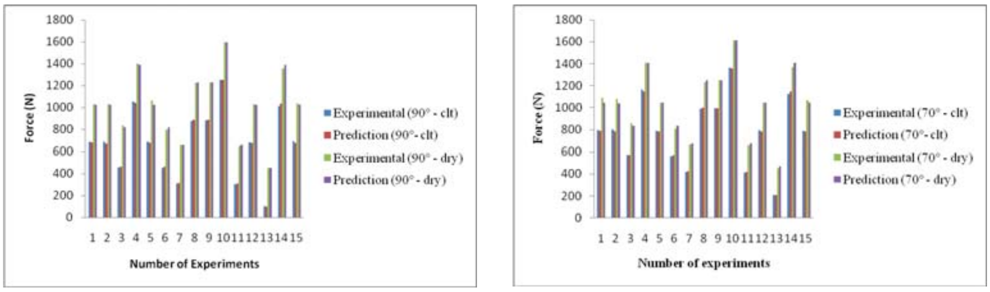
$$\text{Force'} = -333.17 - 2.0x_1 + 2853.01x_2 + 963.88x_3 \quad (4)$$

with tool holder at 70° with coolant

From this linear equation, one can easily notice that the cutting force is affected significantly by the feed rate, followed by axial depth and cutting speed for all the models. According to Saylam *et al.* [12] the increase in feed rate and axial depths will cause the cutting force to become larger. On the other hand, the decrease in cutting speed will slightly cause a reduction in cutting force [13, 14]. Basically, the forces are very high when dry cutting is performed with both 70^0 and 90^0 holders. The dry cutting is not suitable for machining Hastelloy C-22HS with the current parameters. Due to the fact that it is not suitable to be used, the analysis of dry cutting is not performed. Since nickel based alloys are harden rapidly, once the milling cutter starts to operate, it is more difficult to perform machining due to the hardening effect. As the cutting edge is not sufficiently sharp, the metal is pushed instead of cut. This will result in higher cutting force and higher temperature [15]. At relatively high cutting speeds (150 m/min), the energy input to the system and the stresses are correspondingly higher and lead to increased heat generation. The generated heat in the shear zone helps to plasticise (soften) the workpiece material, reducing the forces required to cut the material. At lower cutting speeds (100 and 125 m/min), less heat is generated and the temperature-induced softening of the workpiece is hence reduced, giving rise to higher cutting force [16].

Figure 2 (a) shows the measured cutting force values and the respective values predicted by the first-order model for 90^0 tool holder, meanwhile Figure 2 (b) shows the experimental and predicted values for 70^0 tool holder. It is clear that the predicted values are in good agreement with the experimental readings. This indicates that the obtained linear model is useful to predict values of cutting forces. The cutting tool conditions are shown in Figure 3 and 4 at high cutting force operation, respectively, at first pass of the experiment for the 90^0 and 70° tool holder with coolant. The cutting tool used in high cutting force operation is severely damaged. The cutting tool used in low cutting force operation can be further used, while this condition does not apply for cutting tool used in high cutting force operation owing to the fact that it is already damaged at the first pass. Figure 5 shows the cutting tool condition at dry cutting, where the inserts suffers with high breakage.

The adequacy of the first-order model is verified using the analysis of variance (ANOVA). At a level of confidence of 95%, the model is checked for its adequacy. As shown in Table 5 (a), and 5 (b), the probability (P) value is not significant with the lack-of fit (>0.05). Meanwhile F-statics for both models are 13.16 and 14.06. This implies that the model could fit and it is adequate [17, 18]. The developed linear model Equation (4) is used to plot the contours of the cutting force at different values of axial depths. Figures 6 (a), 6(b), 6 (c) show the cutting force contours at three different axial depths (lowest "-1", middle "0", and highest values "+1"). Due to the fact that the trend for the cutting force is identical for all the models, only one contour plot deduced from one model that is tool holder 90^0 with coolant, is shown. It is obvious that the reduction in cutting speed and increase in feed rate will cause the cutting force to increase dramatically. From Figure 6(c), the cutting force reaches its highest value when all cutting conditions, except for cutting speed, are at their maximum values. In this case, the cutting speed is at its smallest value (100 m/min).



(a) (b)

Figure 2: Experiment result and prediction result for first order cutting force model: (a) Tool holder at 90^0 with coolant and dry (b) Tool holder at 70^0 with coolant and dry

Table 5: Variance analysis for first order cutting force model: (a) Tool holder at 90^0 with coolant and dry (b) Tool holder at 70^0 with coolant and dry

Source	**Degree of freedom**	**F**	**P**
Regression	3	2545.23	0
Linear	3	2545.23	0
Residual Error	11		
Lack-of-Fit	9	13.16	0.073
Pure Error	2		
Total	14		

(a)

Source	**Degree of freedom**	**F**	**P**
Regression	3	3157.22	0
Linear	3	3157.22	0
Residual Error	11		
Lack-of-Fit	9	14.06	0.068
Pure Error	2		
Total	14		

(b)

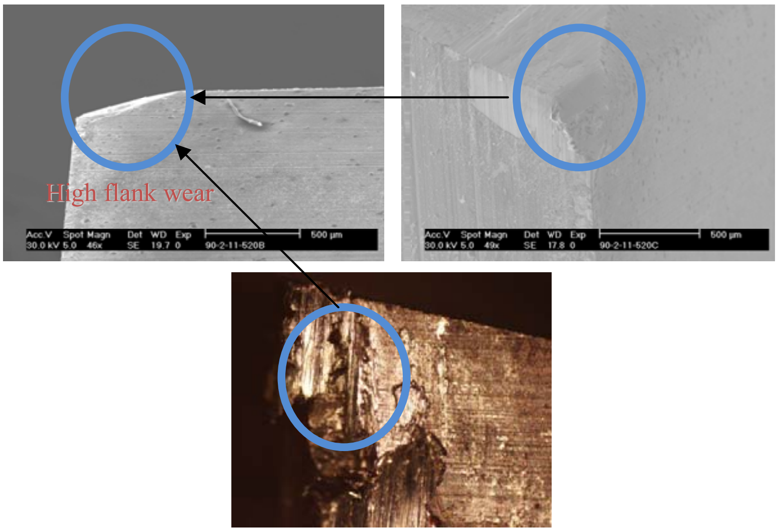


Figure 3: SEM and Microscopy picture for cutting condition: Cutting speed 100 m/min, Feed rate 0.15 mm/rev, axial depth 2 mm with 90^0 tool holder and coolant.

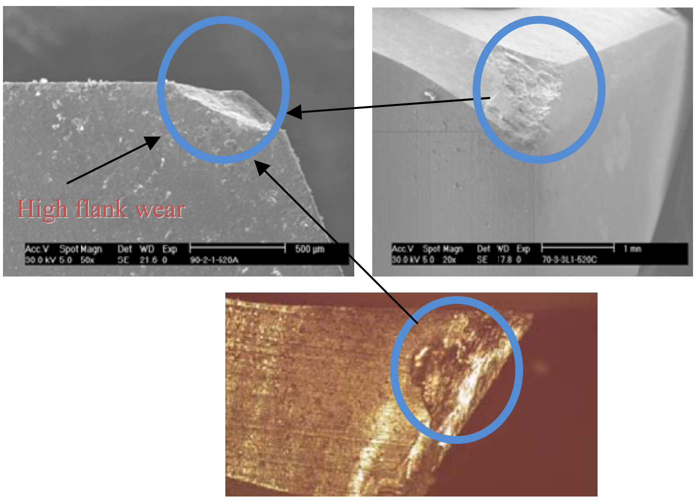


Figure 4: SEM picture for cutting condition: Cutting speed 25 m/min, Feed rate 0.2 mm/rev, axial depth 1 mm with 70^0 tool holder and coolant.

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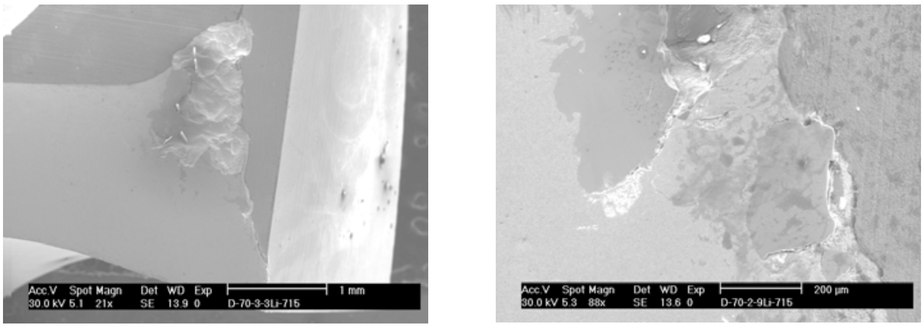

Figure 5: SEM picture for dry cutting condition

Cutting Force (N) Cutting Force (N) Cutting Force (N)

(a) (b) (c)

Figure 6: Cutting force contours in the cutting speed-feed rate plane for (a) axial depth 1 mm, (b) axial depth 1.5 mm, (c) axial depth 2 mm.

4.2. Optimization of the cutting force value

Ideally, the main goal of the current work is to minimise the cutting force with a correct combination of variables. This goal can be achieved using Minitab. Optimization approach employed in Minitab, each response is transformed using a specific desirability function. The weight defines the shape of the desirability function for each response. For each response, a weight can be selected from 0.1 to 10 to emphasise or de-emphasise the target. A weight

- less than one (minimum is 0.1) places less emphasis on the target
- equal to one places equal importance on the target and the bounds
- greater than one (maximum is 10) places more emphasis on the target

The optimum value for cutting force for tool holder 90^0 with coolant is 100.17 N, which corresponds to design variables: Cutting speed (m/min) =180, Feed rate (mm/rev) = 0.1053 and Axial depth (mm) = 1.0783. The optimum for cutting force for tool holder 70º with coolant) is 123.04 N, which corresponds to design variables: Cutting speed (m/min) = 100, Feed rate (mm/rev) = 0.10 and Axial depth (mm) = 0.4. For the dry cutting condition, the optimum force value is very large and it is not suitable to be used.

5. Conclusion

The cutting forces increase with increasing of federate and axial depth. On the other hand, the decrease in cutting speed will slightly cause a reduction in cutting force. The forces, for the dry cutting are very high and not suitable to be use. The optimum cutting condition (cutting force - 90° holder) for all the cutting tools are; cutting speed 180 m/min, feedrate 0.1 mm/rev and axial depth 1 mm. At this condition the material removal rate (MRR) is 401.02 mm^3/min. The optimum cutting condition (cutting force - 70^0 holder) for all the cutting tools are; cutting speed 100 m/min, feedrate 0.1 mm/rev and axial depth 0.4 mm. At this condition the material removal rate (MRR) is 25.46 mm^3/min. The parameters value for 70° tool holder must be low due to its sliding angles which cause high penetration to the workpiece. Meanwhile for 90° tool holder, higher parameters values can be used.

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References

1. Metal cutting theory and practice by David a. Stephenson and John S.Agapiou, publish by Marcel Dekker, Inc, 1997
2. Metal Cutting Mechanics by Viktor P.Astakhov, publish by CRC press, 1999
3. Manufacturing Process and Systems, Ninth Edition; by Philip F.Ostwald and Jairo Munoz, publish by John Wiley & Sons
4. Workshop Technology Volume 2; by HS Bawa;publish by Tata McGraw-Hill;1995
5. M.Alauddin, M.A.Mazid, M.A.EL Baradi,M.S.J.Hashmi,"Cutting forces in the end milling of Inconel 718",Journal of Materials Processing Technology",77(1998),pp 153-159
6. E.M. Trent, Metal Cutting, 3rd ed., Butterworth-Heinemann, 1991.
7. Wuyi Chen,"Cutting forces and surface finish when machining medium hardness steel using CBN tools", International Journal of Machine tools and Manufacture, 40(2000), pp 455-466
8. Koenigsberger F, Sabberwal A J P, "An investigation into the cutting force pulsations during milling operations", International Journal of Machine Tool Design and Research 1 (1961) 15–33.
9. Budak E, Altintas Y, "Peripheral milling conditions for improved dimensional accuracy", International Journal of Machine Tool Design and Research 34/7 (1994) 907–918.
10. Budak E, Altintas Y, "Modeling and avoidance of static deformations in peripheral milling of plates", International Journal of Machine Tool Design and Research 35 (3) (1995) 459–476.
11. Technology of Machine Tools,Fourth Edition; by Krar.Ostwald ;publish by McGraw – Hill;1995
12. Haci Saylam, Suleyman Yaldiz, Faruk Unsacar," The effect of tool geometry and cutting speed on main cutting force and tool tip temperature", Materials and Design, Article in press (2005).
13. Abou-El-Hossein K A, Kadirgama K, Hamdi M, Benyounis K Y, "Prediction of cutting force in end-milling operation of modified AISI P20 tool steel", Journal of Materials Processing Technology, 182 (2007) 241-247
14. K.Kadirgama, K.A.Abou-El-Hossein. (2005),'Torque and Cutting force prediction model by using Response Surface Method', International Journal of Applied Mathematics and Statistics, IIT India 4(6): 11-30

15. Li H Z, Zeng H, Chen X O, "An Experimental study of tool wear and cutting force variation in the end-miliing of Inconel 718 with coated carbide inserts," Journal of Materials Processing Technology," Article in press (2006)
16. Abhijeet S. More, Wenping Jiang , Brown W D, Ajay P. Malshe, " Tool wear and machining performance of cBN–TiN coated carbide inserts and PCBN compact inserts in turning AISI 4340 hardened steel", Journal of Materials Processing Technology, Article in press (2006)
17. K.Kadirgama, K.A.Abou-El-Hossein. (2005), 'Force Prediction Model for Milling 618 tool Steel Using Response Surface Methodology', American Journal of Applied Sciences 2(8): 1222-1227, 2005
18. K.Kadirgama, K.A.Abou-El-Hossein. (2005),'Torque and Cutting force prediction model by using Response Surface Method', Accepted for publication in International Journal of Applied Mathematics and Statistics, IIT India