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Prediction of Temperature Induced on SAE 5160 Steel Shaft during a Face Milling Operation

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Abstract: *Several researchers studied the temperature produced during machining of a workpiece by using different machining parameters and workpiece. In this study, SAE 5160 steel shafts were face milled under dry conditions and the temperatures induced were measured using infrared thermometer. Machining parameters considered in this study were cutting speed, depth of cut and feed rate and the experimental design method employed was 2^3 factorial. Each shaft was milled at a length of 55 mm. The induced temperatures were analysed using Minitab 19.0 Statistical software. Depth of cut was found to be the most significant parameter followed by cutting speed and feed rate. A mathematical model was generated and was found to be valid in predicting the induced temperature since its percentage error (+0.2) fell within the standard percentage error (±5.0). The optimal machining parameters were found to be at lower depth of cut (1 mm), lower cutting speed (180 rpm) and higher feed rate (1.5 mm/rev).*

Keywords: *Temperature, SAE 5160 Steel, Shaft, Face Milling, Operation.*

I. Introduction

Machining process is controlled by different variables such as spindle speed, feed rate, depth of cut, cutting tool and others. Using these parameters to produce a component with good quality depends on the skills and experience of the technician. The cutting tool and workpiece are in contact during milling which results in heat generation and this heat is found in the cutting zone [1]. Temperature at the cutting zone can have significant effects on the roughness of the workpiece produced and the cutting tool lifespan can be affected [2]. Factors that influence temperature produced during milling are cutting speed or spindle speed, feed rate and depth of cut. *Patel et al.* [3] reported that depth of cut is the most significant (64% significance) milling parameter on temperature produced during milling. A study was conducted by Shah e*t al.* [4] on the influence of machining parameters on temperature variation in milling process for S45C carbon steel. The factorial design method was employed to study the temperature generated in the milling process and the milling parameters chosen in this work were spindle speed, depth of cut, feed rate and direction of cut. The experiment was conducted using MANFORD MF-450VS conventional vertical turret milling machine with a carbide cutting tool of 10 mm diameter which is coated with Aluminium Titanium Nitride (AlTiN). S45C carbon steel block with 60 mm in height, 10 mm wide and 160 mm in length was milled under arid conditions and the temperatures were recorded at five different points along the workpiece utilizing TI FLUKE 400 thermal imaging camera. The milling process was done for up milling and down milling with varying milling parameters. Fluke Smart View Software was used to extract the temperatures from the thermal images. Increasing feed rate and spindle speed was found to have an increase on temperature in both up milling and down milling. It was found that depth of cut was the most significant parameter causing temperature rise in the milling process. Finite difference method was used by Denkena *et al.* [5] to study the process stability and heat generation in milling of thin aluminium (Al-Li 2196) workpiece. The heat generated from the process was measured using thermal imaging camera and emissivity spray was used at the back of the workpiece to enhance the reading of the camera to obtain accurate readings. Cylindrical rod made of mild steel was used in a turning experiment by Akhil *et al.* [6] to determine the temperature produced on the tip of the cutting tool. The machining parameters used were cutting speed, feed rate and depth of cut. Cutting speed and feed rate were turned at three levels while depth of cut was at four levels. An assembly of a K-type thermocouple with a multi-meter was used to measure the temperature produced. The thermocouple was inserted into the shank of the cutting tool such that it touches the cutting tool tip. It was concluded that, temperature rise during turning is related to cutting speed. Cutting speed have higher effect on the temperature followed by feed rate and depth of cut. Simulation technique was used by Uzorh and Nwufo [7] to describe heat generation in the tool-chip, chip-work piece and tool-work piece interfaces. The cutting parameters used were speed and feed rate. A thermal model was generated using the transient three-dimensional heat diffusion equation for the tool holder assembly. The model was solved using the finite difference method under a control volume. Simulation was done using different materials. Cutting speed was found to be the most influencing factor in heat generation and models were generated to help machinist select suitable speed and feed. Pittalà and Monno [8] developed a model to predict the temperature of Ti-6Al-4V workpiece in a face milling operation. They utilized infrared camera to quantify the workpiece temperature and they eventually developed a rheological model and calibrated utilizing different milling experiments. Richardson, Keavey and Dailami [9] generated a model for induced temperatures on a workpiece during dry milling. Information from temperature distribution in a workpiece is relevant due to the serious consequences of severe local heat produced during machining which could influence the heat treatment or artificial aging properties, hardness and residual stresses of the material, which eventually influence the structural integrity of the member [10]. Different techniques have been employed for thermal mapping of cutting tools, work piece and chips for example: analytical methods [11], experimental and numerical (simulation) methods [12], hybrid techniques and heat source methods. The main goal for this work is to generate a mathematical model to predict the temperature induced on SAE 5160 steel shaft during a face milling operation using a 2^3 factorial design technique. The mathematical model is validated and optimized.

II. Material

SAE 5160 Steel was selected as the test material because of its availability, low cost, and extensive usage in industry. It is remarkably strong and durable. It also has high resistance to fatigue, ductility, and has good spring qualities useful for applications which requires flexibility. SAE 5160 steel is used for the production of coil and leaf springs [13], [14]. The chemical composition is shown in Table 1.

Table 1: Chemical Composition of SAE 5160 Steel

Element	C	Si	Mn	P	S	Cr
Content %	0.59	0.22	0.96	0.016	0.018	0.86

Source: [15]

III. Method

3.1 Experimental Design

The 2^3 factorial design method was used in this paper. A 2^3 factorial design method is one which makes use of three variables each having two levels. The variables used in this experiment were cutting speed, depth of cut and feed rate. A total of 8 experiments ($2^3 = 8$) with varying parameters were performed. The first eight pieces were milled with varying parameters and the temperatures were recorded. The experiments were repeated on the remaining 8 pieces to confirm the values recorded. Figure 1 shows the Geometrical view of the 2^3 Factorial Design technique employed in this research.

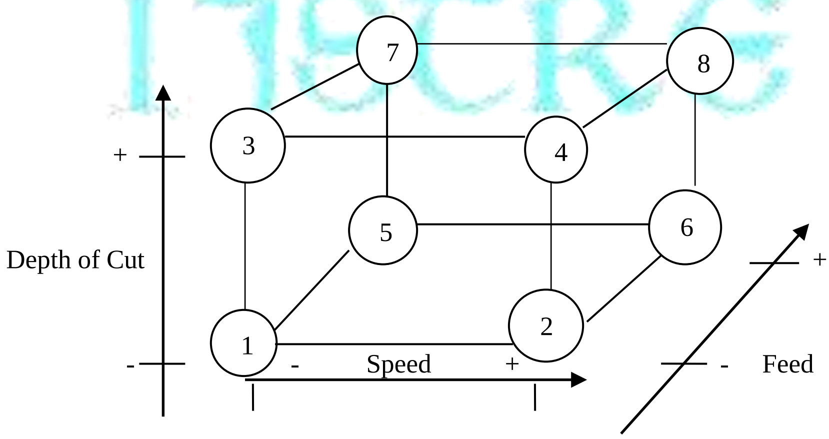

Figure 1: 2^3 Factorial Design

3.2: Experimental Set-up

Facing was done at one end of each shaft and after that each shaft was slightly centre drilled. A drill was fixed into the tailstock and advanced into the workpiece to drill. The facing was done to make the side flat for proper drilling and this was done to enable firm grip of the tailstock on the milling machine. The three jaw chuck assembly and the tailstock assembly were mounted on the worktable of the milling machine to hold the workpiece firmly during the milling process. The cutting tool used was a high speed steel with a diameter of 95 mm. The cutting tool was fixed on the tool holder and was made to face the side of the shaft. The milling process was done on a conventional milling machine. Each of the workpiece was milled at a length of 55 mm. The milling variables for this experiment are displayed in Table 2.

Table 2: Face Milling Parameters

Variables	Low (-)	High (+)
Speed (rpm)	43	77
Feed Rate (ins/rev)	0.53	1.40
Depth of cut (mm)	1	2

After the face milling was done on the shafts, the temperatures were measured using an industrial infrared thermometer version 320-EN-00 7160320015 A0 with a range of -50°C to 400°C. The initial and final temperature of each workpiece was measured by pointing the laser on the workpiece. Figure 2 shows the experimental set-up

Figure 2: Experimental Set-up

IV. Results And Discussion

4.1 Experimental Results

The experimental results for this research with varying cutting parameters are shown in Table 3. From the table, it can be observed that the highest temperature (31.4°C) was recorded at a speed of 77 rpm, at a feed of 1.40 ins/rev and at a depth of cut of 2 mm. It can also be observed that the lowest temperature (21.8°C) was recorded at a speed of 43 rpm, at a feed of 1.40 ins/rev and at a depth of cut of 1 mm. The symbols N, D and F represent cutting speed, depth of cut and feed rate respectively. T_o is the initial temperature of the workpiece and T_f represents the final temperature. The temperature difference was calculated and represented as ΔT.

Table 3: Table of experimental results

S/N	N	D	F	N (rpm)	D (mm)	F (ins/rev)	T_o (°C)	T_f (°C)	ΔT (°C)
1	-	-	-	43	1	0.53	30.2	55.8	25.6
2	+	-	-	77	1	0.53	30.0	53.3	23.3
3	-	+	-	43	2	0.53	29.7	56	26.3
4	+	+	-	77	2	0.53	30.1	60.3	30.2
5	-	-	+	43	1	1.40	28.8	51.4	22.6
6	+	-	+	77	1	1.40	31.3	53.5	22.2
7	-	+	+	43	2	1.40	29.3	55.9	26.6
8	+	+	+	77	2	1.40	29.8	61.2	31.4
9	-	-	-	43	1	0.53	28.6	53.5	24.9
10	+	-	-	77	1	0.53	29.8	52.9	23.1
11	-	+	-	43	2	0.53	31.7	58.7	27.0
12	+	+	-	77	2	0.53	28.5	60.5	32
13	-	-	+	43	1	1.40	31.4	53.2	21.8
14	+	-	+	77	1	1.40	28.7	51.5	22.8
15	-	+	+	43	2	1.40	30.3	56.4	26.1
16	+	+	+	77	2	1.40	27.3	57.8	30.5

4.2 Analysis of Variance

ANOVA was utilized to determine the effects of the machining parameters on the induced temperature. The significance level was 0.05 and thus, with a confidence level of 95%. A machining parameter or combination of parameters is/are considered significant if the associated p-value is less than 0.05. Table 4 shows the analysis of variance. From the table, all the factors were significant except the two-way interactions of Speed and Feed. The three-way interactions of Speed, Depth of Cut and Feed was also found to be insignificant.

Table 4: Analysis of Variance (ANOVA)

Source	DF	Adj SS	Adj MS	F-value	P-value	Interpretation
Model	7	172.290	24.613	62.31	0.000	Significant
Linear	3	137.635	45.878	116.15	0.000	Significant
N	1	13.323	13.323	33.73	0.000	Significant
D	1	119.902	119.902	303.55	0.000	Significant
F	1	4.410	4.410	11.16	0.010	Significant
2-Way Interactions	3	33.445	11.148	28.22	0.000	
N*D	1	29.160	29.160	73.82	0.000	Significant
N*F	1	1.562	1.562	3.96	0.082	Insignificant
D*F	1	2.723	2.723	6.89	0.030	Significant
3-Way Interactions	1	1.210	1.210	3.06	0.118	
N*D*F	1	1.210	1.210	3.06	0.118	Insignificant
Error	8	3.160	0.395			Significant
Total	15	175.450				Significant

4.3 Generation of Mathematical Model

An uncoded model was generated to predict the temperature that will be induced on SAE 5160 steel shaft during a face milling operation. The model is a function of the machining parameters chosen in this study. The mathematical model can be utilized to predict the temperature that is likely to be induced on an SAE 5160 steel shaft during a face milling operation. Minitab 19.0 Statistical Software was used to generate the mathematical model. The mathematical model is shown as:

Temperature Induced, (ΔT) = 41.70 – 13.28 F – 0.3330 N – 10.19 D + 0.2306 (N×D) 0.1538 (F×N) + 6.36 (F×D) – 0.0744 (F×N×D) (1)

Where F, N and D represent feed rate, cutting speed and depth of cut respectively. The R^2 value for the response was found to be 98.20% which means that the model for vibration fits the data well. The R^2 (pred) was also found to be 92.80 % which implies that the model can be used to predict the variability in temperature induced.

4.4 Validation of Mathematical Model

The mathematical model was validated by comparing the experimental values with the predicted values. The predicted values were calculated using Microsoft Excel. For the model to be valid, the average percentage error should fall within ± 5.00. The average percentage error was calculated based on the percentage error of each experiment. Percentage error of each process and average percentage error were calculated using equation (2) and equation (3) respectively. Table 5 shows the comparison of experimental values with predicted values.

$$\text{Percentage error} = \frac{Experimental\ Value - Predicted\ Value}{Experimental\ Value} \times 100\% \quad (2)$$

$$\text{Average percentage error} = \frac{\sum_{n=1}^{n} P_e}{n} \quad (3)$$

Where n = number of percentage errors and P_e = percentage error. The total percentage error of the experiment was calculated by adding all the percentage errors. The total percentage error was divided by the total number of experiments which was 16 to get the average percentage error.

Table 5: Comparison of experimental values with predicted values

S/N	Experimental Value	Predicted Value	Percentage Error
1	25.6	25.2	1.45
2	23.3	23.2	0.53
3	26.3	26.6	-1.17
4	30.2	31.1	-2.84
5	22.6	22.1	2.02
6	22.2	22.4	-1.08
7	26.6	26.2	1.36
8	31.4	30.8	1.80
9	24.9	25.2	-1.32
10	23.1	23.2	-0.33
11	27.0	26.6	1.45
12	32	31.1	2.95
13	21.8	22.1	-1.57
14	22.8	22.4	1.58
15	26.1	26.2	-0.53
16	30.5	30.8	-1.10

$$\text{Average percentage error} = \frac{\sum_{n=1}^{n} P_e}{n} = \frac{3.2}{16} = 0.2$$

The average percentage error was calculated to be 0.2 which falls within the standard percentage error (± 5.00). This implies that the mathematical model is valid and can be used to predict the temperature produced during milling of SAE 5160 steel shaft with varying machining parameters.

4.5 Optimization of Induced Temperature

Temperature generated during machining is dependent on the machining parameters chosen and the cutting conditions. This temperature can have significant effects on the workpiece and cutting tool. The workpiece roughness, tolerance, corrosion resistance and the microstructure can be affected and can cause rapid tool wear, build-up-edge formation which can reduce the cutting tool lifespan. Figure 3 shows the optimization plot of the machining parameters during face milling of SAE 5160 steel shaft under dry condition.

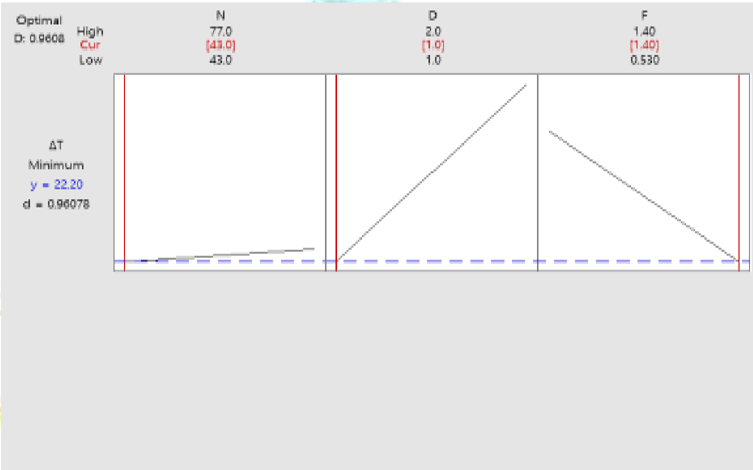

Figure 3: Optimization Plot

The aim of the optimization is to minimize the temperature generated during face milling of SAE 5160 steel shaft. From Figure 3, the optimum machining parameters are high feed rate, low cutting speed and low depth of cut. To achieve low temperature in the workpiece, the feed rate should be set to 1.40 ins/rev, cutting speed should be set to 43 rpm and depth of cut should also be set to 1 mm as indicated in red numbers on the optimization plot. Reducing the temperature will improve the quality of the workpiece and extend the lifespan of the cutting tool. The composite desirability is 0.96078.

V. Conclusion

Depth of cut was found to be the most relevant machining parameter in temperature generation, cutting speed was the second significant parameter and feed rate was found not to have much influence on the temperature produced during face milling of SAE 5160 steel shaft. Increasing depth of cut will cause a significant increase in temperature. High cutting speed and low feed rate will also cause temperature to rise. The combined effects of the machining parameters were found to have effects on the temperature generated. A mathematical model was generated to predict the temperature induced on SAE 5160 steel shaft during face milling. The R-square was 98.42% and R-square (predicted) was 93.67% which shows that the model fitted well for the values used in this research. The model was validated using the experimental and predicted values. The average percentage error for the model was found to be 0.2 which fell within the assumed standard percentage error of ±5.0. The average percentage error (0.2) showed that the model was valid to predict the temperature induced on SAE 5160 steel shaft during a face milling operation. It was revealed in the optimization plot that to obtain minimum temperature induced on the workpiece, depth of cut should be 1 mm, feed rate should be 1.4 ins/rev and cutting speed should be 43 rpm. The composite desirability was 0.96078.

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