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Design of Laboratory Apparatus for Temperature Prediction in Turning Process

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Abstract

To illustrate heat generation in turning processes for “Manufacturing Processes” course, an experimental apparatus including hardware, software and experiment protocol was designed and integrated. Cutting parameters’ effects on temperature rising in turning process were examined. Design of experiment and embedded thermocouple measurement were applied to cover the cutting parameters and collect the experimental data. After collecting temperature data with full factorial experiment, statistical analysis including analysis of variance (ANOVA), main effect, interactive effect and regression analysis was conducted. This experiment trains students on machining, sensors, data acquisition, and statistical analysis. It identified that all the three cutting parameters positively affected the temperature rising. Linear mathematic models mapping the temperature rising and cutting parameters were deducted with an R^2 value of 0.78. The results were analyzed statistically and graphically. The model of predicting chip-tool temperature can satisfactorily map temperature rising and cutting parameter settings within the considered range in turning process. This temperature prediction approach can be extended to other machining processes such as milling, drilling etc.

Keywords: Experiment design, Turning, Temperature prediction, Embedded thermocouple, Cutting parameters

1. Introduction

Turning operation is the process of producing cylindrical parts. Precise estimation of temperature rising in turning is critical on preventing thermal deformation on work piece, reducing tool wear and increasing tool life. Due to the complexity of machining mechanics, it's hard to predict the intensity and distribution of the heat sources in turning operation. The properties of materials used in machining vary with temperature; the mechanical process and the thermal dynamic process are tightly coupled with cutting parameters including cutting depth, spindle speed, and feed rate. In order to help students better understand the effects of cutting parameters on temperature rising in turning process, an experiment apparatus was designed for the “Manufacturing Processes” course. Two undergraduate research interns went through the experiment procedures in the summer. It illustrated that the experiment procedure is clear and is feasible for the undergraduate level classes. This experiment apparatus can be applied to train students on machining, sensors, data acquisition, and statistical methods.

The rest of this paper is organized as follows: Section 2 surveys related experimental methods to measure the tool, chip or work-piece temperature and their distribution. Section 3 discusses about the proposed methodology based on the embedded thermocouple measurement and design of experiment to cover cutting parameters and collect the experimental data. Section 4 presents the results and discusses statistical analysis including analysis of variance (ANOVA), main effect, interactive effect and regression analysis. Section 5 concludes the research and outlines the future direction.

2. Literature review

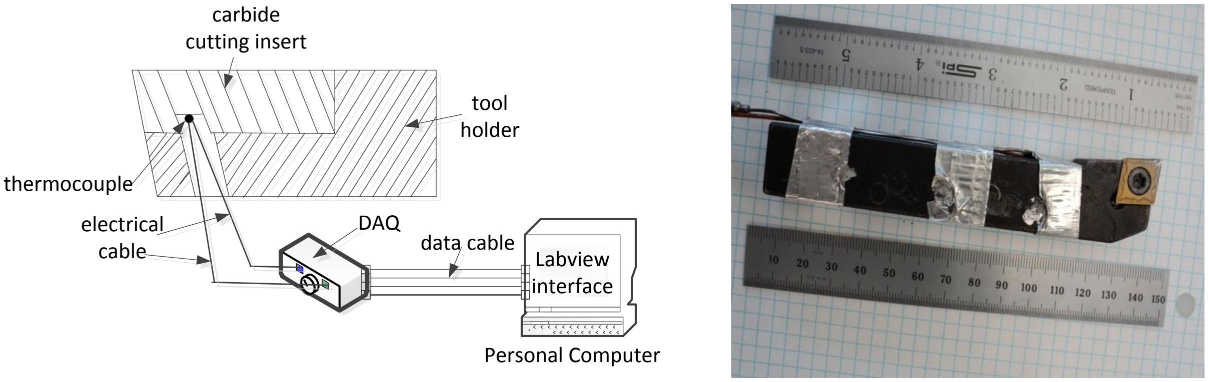
The experimental study of temperature rise during machining goes back to around 1900 by F.W. Taylor [1], who discovered the relationship between cutting speed and tool life. Since then researchers worked both on analytical and experimental methods to evaluate temperature rising. Trigger and Chao [2] were the pioneers of using analytical methods to predict temperature by taking to account the plastic deformation energy and friction between tool and chips. With the advances in numerical analysis, researchers used finite difference methods (Usui et al. [3] and finite element methods (Kardirgama et al. [4]) to evaluate temperatures with considering more parameters affecting temperature. Experimental methods also have been used with researchers for many years to find correction between cutting parameters and temperature rise. On [5], researchers have summarized experimental methods on measuring the tool, chip or work-piece temperature and their distributions. Different techniques such as calorimetric, thermocouple, radiation thermometry, and thermal paints have been used in the past [6]. However, all of these temperatures methods except thermocouple are not simple neither reliable enough for routine test. The embedded thermocouple technique is widely used for measuring the average chip-tool interface temperature, because it avoids generation of parasitic electromotive force (emf) and electrical short circuit. The other methods suffer from various disadvantages such as slow response indirectness and complications in measurement. Most of the researchers have embedded thermocouple into work piece. Sivasakthivel and Sudhakaran [7] reported a research of drilling a 1-mm hole into work-piece specimen and placing a K-type thermocouple 4-mm below the matching surface. Although the method successfully predict the temperature rise, it is not practical to be used for turning operation. Another thermocouple method is tool-work method. In this method, the tool temperature measurement employs the tool and the work material as the two element of a thermocouple. The thermoelectric emf generated between the tool and work piece during metal cutting was calculated by measuring voltage [8]. The difficulty with this method is on measurement calibration that varies with the tool type and the work piece material. Enlightened by this, we designed the experiment based on the embedded thermocouple measurement.

3. Experiment Methodology

3.1 Hardware setup

The hardware used in the experiments included a lathe, carbide cutting insert with embedded thermocouple, National Instrument (NI®) data acquisition (DAQ) board, personal computer, laser temperature meter and digital camera.

A precision lathe was the machining test bed of the experiment. By changing the gear box setting, different cutting parameters could be selected. An embedded thermocouple was applied for to measure the temperature rising of the cutting tool. It was embed in the tool holder and attached to the cutting tool as shown in Figure 1. The DAQ collected the temperature readings from thermocouple and sent them through to the computer.



(a) (b)

Figure 1. Embedded thermocouple technique for temperature measuring, (a) schematic and (b) cutting insert cutting tool with thermocouple

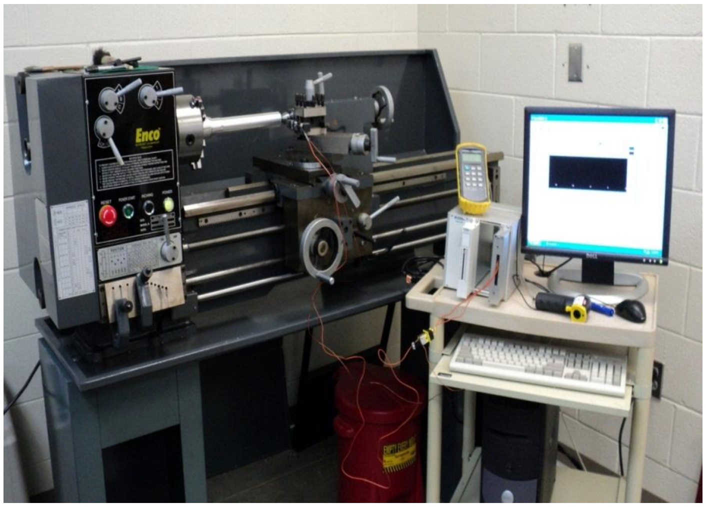
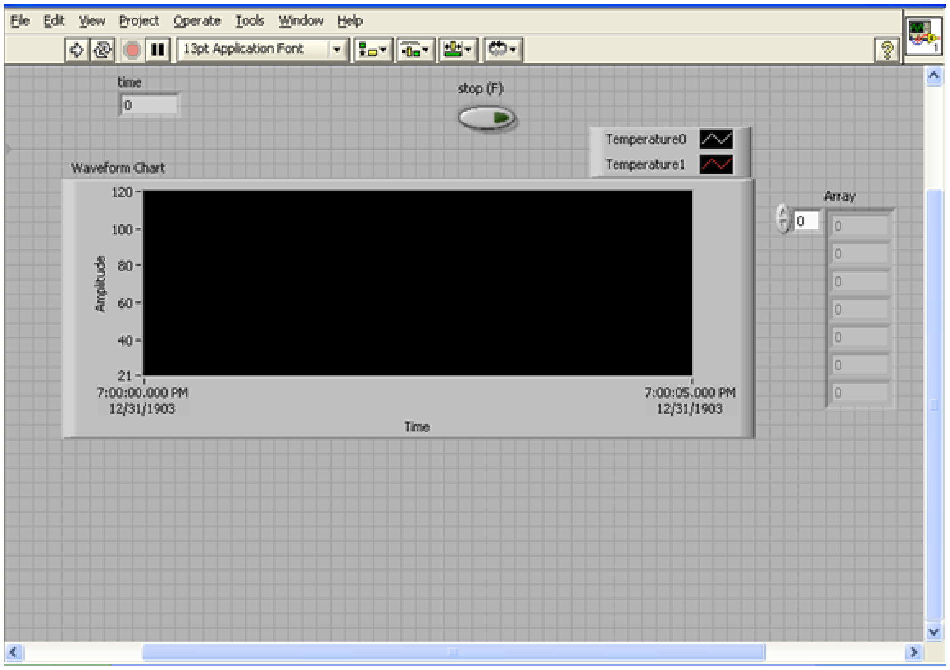


Figure 2 Experiment setup for measuring temperature rising in turning processes with embedded thermocouple

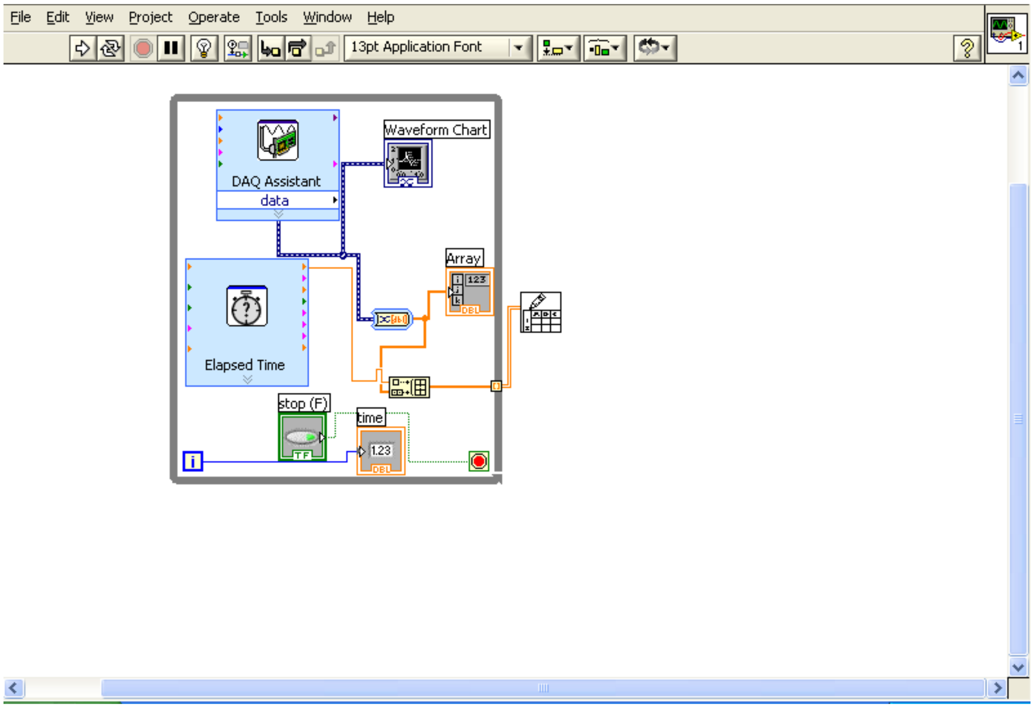
Finally, the whole experiment setup is illustrated as Figure 2: the lathe (to the left), thermocouple (copper wires attached to the cutting tool), DAQ (white box in the middle), computer (to the right) and Labview interface program (on the computer screen). In this experimental setup, one end of a low carbon steel bar was mounted on a three jaw chuck, and the other end of the bar was mounted with the lathe center.

3.2 Software setup

Labview interface was designed to collect information from the thermocouple and data acquisition card. The front panel and block diagram for the data acquisition are shown in Figure 3 (a) and (b) respectively. This Labview program has the capability of displaying multi-channel temperature data in real time, saving temperature file for later analysis etc.



(a)



(b)

Figure 3 Labview interface for the data acquisition (a) front panel, (b) block diagram

3.3 Design of Experiment

The objective of this study was to understand cutting parameters' effects on raising temperature during the turning process. Among the three factors, maybe a relatively small number of them play vital role. Are they indeed different? How different are they? With the experiment objective, we need to select the experiment design for this study. There are five categories of experimental problems according to their objectives: 1) treatment comparisons, 2) variable screenings, 3) response surface exploration, 4) system optimization, and 5) system parameter robustness [9]. Our problem falls into the categories of treatment comparison and variables screening. Factorial design is an experimental methodology which permits researchers to study behaviors under conditions in which independent variables vary simultaneously, so the researchers can investigate the joint effect of two or more factors on a dependent variable. The factorial design also facilitates the study of interactions, illuminating the effects of different conditions of the experiment on the identifiable subgroups of subjects participating in the experiment. Based on that, full factorial design was selected for this study. To study the objective, $3\times3\times3$ factorial experiments were designed to cover three independent factors including cutting depth (d), spindle speed (v) and feed rate (f). The levels of factors used in the experimental design are listed in Table 1. Twenty seven experiments were conducted for the study, using three variables each at three levels (Table 2). The experiments follows the randomization principle, since that the more experimental runs are arranged randomly; the more insurance one has against extraneous factors possibly affecting the results.

Table 1 Levels of factors used in the experimental design

Cutting parameter	Symbol	Level		
		Low (-1)	Medium (0)	High (+1)
Spindle speed (r/min)	v	525	950	1550
Feed rate (in/rev)	f	0.001	0.005	0.01
Depth of cut (in)	d	0.001	0.005	0.01

3.4 Experiment Protocol

Before the experiment, the temperature measurement devices were calibrated. Then the experiments were started according to the below procedures: 1) record the room temperature and tool, work-piece temperature; 2) conduct the experiments as the Table 2's setup on spindle speed, cutting depth, and feed rate; 3) let the lathe and Labview program simultaneously run for fifteen seconds to acquire the temperature readings, then proceed to save the data in Labview, 4) collect the cutting chips; 5) wait for the cutting tool to cool back to room temperature , then start the next run of experiment. Following this protocol, two sophomore level undergraduates implemented the experiment during a six-week of summer research. These two students major in electronics technology, without background on machining, sensors, data acquisition, and statistical analysis etc. They were trained on those knowledge in the first three weeks, then they spent two weeks on carrying out the experiment. The data analysis and report were finished in the last week.

4. Results and Discussions

4.1 Collected Data and Analysis of Variance (ANOVA) Results

The raw data collected from the experiments were extracted to performance measurements and summarized in Table 2. The ANOVA models on cutting parameters' effects on the temperature rising are shown below as Table 3. This table illustrates that all the three parameters are important factors with small p-values ($p<0.05$) that will influence the temperature rising.

Table 2 Experiment design and temperature rising for cutting steel

Standard Order	Run Order	Cutting Depth (in)	Spindle Speed (r/min)	Feed Rate (in/rev)	Temperature Rising (°C)
1	7	0.001	525	0.001	9.78
2	25	0.001	525	0.005	12.66
3	21	0.001	525	0.01	17.82
4	12	0.001	950	0.001	6.01
5	4	0.001	950	0.005	14.07
6	23	0.001	950	0.01	23.51
7	24	0.001	1550	0.001	8.08
8	26	0.001	1550	0.005	15.09
9	6	0.001	1550	0.01	54.96
10	22	0.005	525	0.001	9.25
11	1	0.005	525	0.005	12.24
12	15	0.005	525	0.01	33.00
13	19	0.005	950	0.001	8.18
14	3	0.005	950	0.005	29.67
15	18	0.005	950	0.01	56.03
16	9	0.005	1550	0.001	21.66
17	11	0.005	1550	0.005	22.11
18	2	0.005	1550	0.01	44.65
19	8	0.01	525	0.001	12.12
20	16	0.01	525	0.005	17.62
21	17	0.01	525	0.01	47.46
22	5	0.01	950	0.001	17.26
23	20	0.01	950	0.005	14.33
24	10	0.01	950	0.01	48.12
25	27	0.01	1550	0.001	22.75

26	13	0.01	1550	0.005	33.55
27	14	0.01	1550	0.01	53.49

Table 3 ANOVA results on cutting parameters’ effects on temperature rising

Analysis of Variance for Temperature rising, using Adjusted SS for Tests						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Feed rate	2	4295.08	4295.08	2147.5	38.47	0.000
Spindle Speed	2	608.69	608.69	304.35	5.45	0.013
Cutting Depth	2	646.56	646.56	323.28	5.79	0.010
Error	20	1116.61	1116.61	55.83		
Total	26	6666.94				
S = 7.47199 R-Sq = 83.25% R-Sq(adj) = 78.23%						

In this table, the abbreviations are noted as following. DF, degree of freedom; SS, sum of squares; Seq.SS, the sequential sum of squares, which is the sum of the sums of squares for all indicator variables corresponding to the variable listed, given all terms corresponding to variables previously listed; Adj.SS, the adjusted sum of squares, which is the sum of the sums of squares for all indicator variables corresponding to the term, given all the other terms; F, F ratio test; P probability.

4.2 Regression Model

Following the ANOVA, an initial analysis of the data in Table 2 was performed by fitting a regression model. Table3 presents the estimated regression coefficients for temperature rising. In Table3, there are three highlighted terms which have large p-values (greater than 0.10) indicating that they are not statistically significant within its preset range. Thus, they were removed and a revised model was re-fitted.

Table 4 Estimated regression coefficients for temperature rising in turning

Term	DF	Seq SS	Adj SS	Adj MS	F	P
Cutting Depth	2	646.56	646.56	323.28	3.76	0.071
Spindle Speed	2	608.69	608.69	304.35	3.54	0.079
Feedrate	2	4295.08	4295.08	2147.54	24.95	0.000
Cutting Depth*Spindle Speed	4	206.98	206.98	51.74	0.60	0.673
Cutting Depth*Feedrate	4	95.24	95.24	23.81	0.28	0.885
Spindle Speed*Feedrate	4	125.73	125.73	31.43	0.37	0.827
Error	8	688.67	688.67	86.08		
Total	26	6666.94				

After taking away the insignificant terms, the following revised model was obtained as below. As shown below, R^2 was 0.78, indicating that the model as fitted explained 78% of the variability in temperature rising in the turning process with the cutting parameters.

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Temperature rising=-11.1713+1267.13*Cutting Depth+0.0112894*Spindle Speed+3314.21*Feed rate

Term              Coef  SE Coef         T      P
Constant        -11.17    5.057  -2.20903  0.037
Cutting Depth  1267.13  415.135   3.05233  0.006
Spindle Speed     0.01    0.004   3.10578  0.005
Feedrate       3314.21  415.135   7.98343  0.000

Summary of Model
S = 7.94201      R-Sq = 78.24%        R-Sq(adj) = 75.40% PRESS = 1988.57  R-Sq(pred) = 70.17%
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Figure 4 is the residual analysis for the cutting parameters on temperature rising. The Normal probability plot illustrates that all the residual points are along a straight line, with no abnormalities observed in the plot. The histogram shows the shape of a Normal distribution, and there is no outlier found on the residual plots. Thus, the experiments fit a Normal distribution. This implies that the experiments are valid.

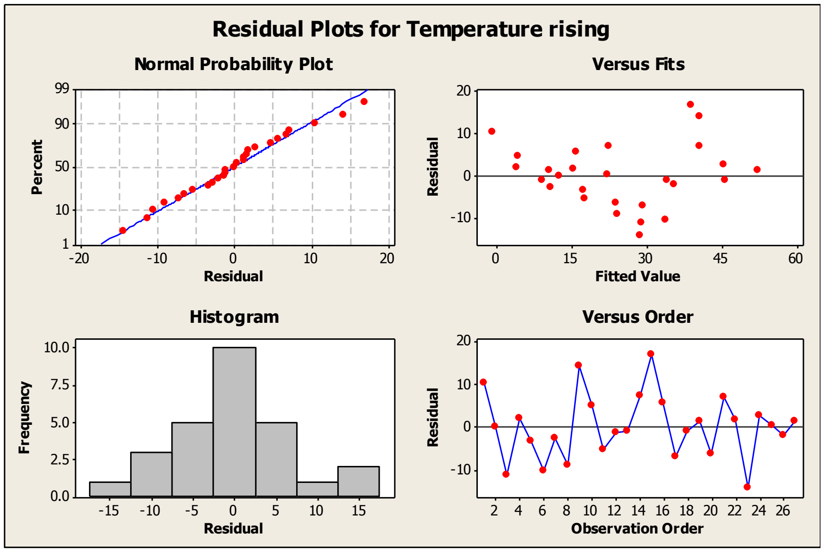


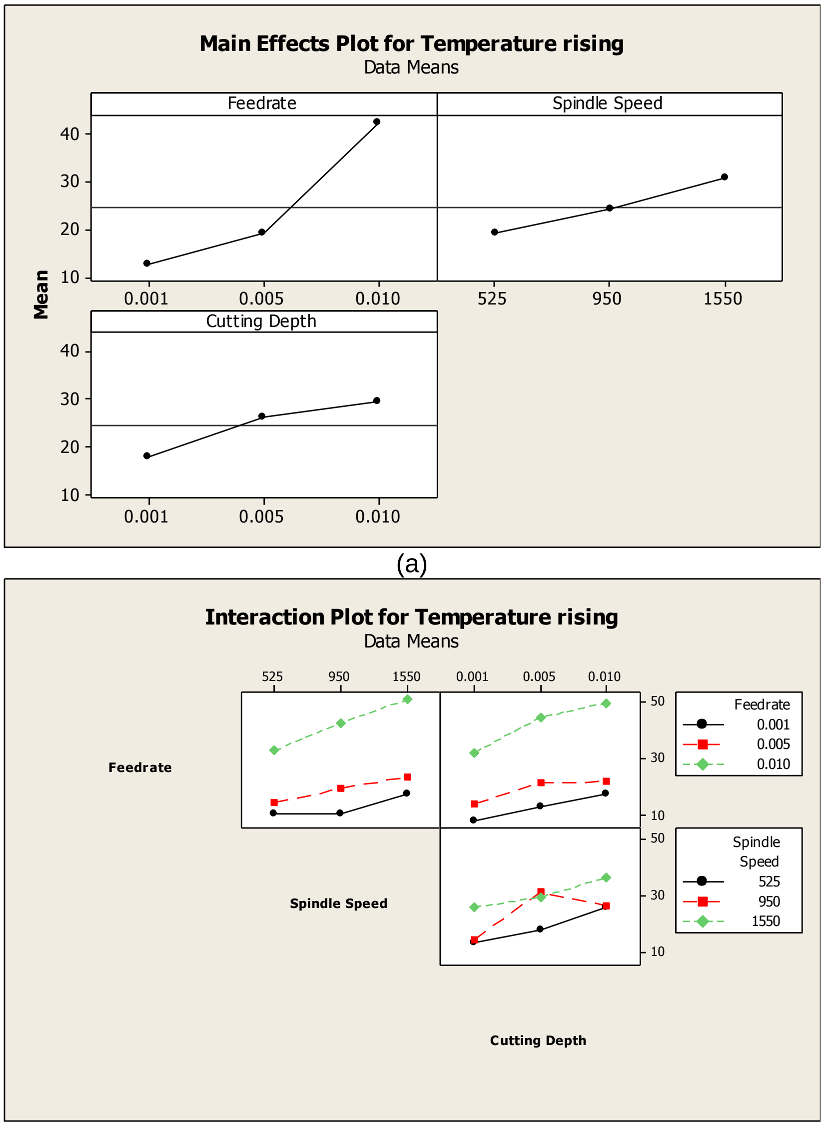
Figure 4 Residual plots temperature rising with regression model

4.3 Main effects and interaction effects plots

Based on the data collected in Table 2, plots of the main effects of cutting depth, spindle speed, and feed rate on temperature rising are presented in Figure 5. These plots show that all the three parameters have positive impacts on temperature rising.

Figure 5 (a) is the main effect plot for the cutting parameters with the considered range. On the main effect plot of feed rate, it shows the steepest slope. the mean temperature rises from 12.78 °C at the feed rate of 0.001 in/rev to 42.11 °C at the feed rate of 0.01 in/rev. On the main effect plot of spindle speed, the mean temperature rises from 19.10 °C at the spindle speed of 525 rev/minute to 30.7 °C at the spindle speed of 1550 rev/minute. On the main effect plot of cutting depth, the mean temperature rises from 17.99 °C at the cutting depth of 0.001 inch to 29.63 °C at the cutting depth of 0.01in.

Figure 5 (b) is the interaction plot for the cutting parameters with the considered range. On the interaction plot of feed rate and spindle speed, the mean temperature rises from 10.38 °C at the combination of (feed rate of 0.001 in/rev and spindle speed of 525 rev/min) to 51.02 °C at the combination of (feed rate of 0.01 in/rev and spindle speed of 1550 rev/min). On the interaction plot of feed rate and cutting depth, the mean temperature rises from 7.9 °C at the combination of (feed rate of 0.001 in/rev and cutting depth of 0.001 in) to 49.68 °C at the combination of (feed rate of 0.01 in/rev and cutting depth of 0.01 in). On the interaction plot of spindle speed and cutting depth, the mean temperature rises from 13.42 °C at the combination of (spindle speed of 525 rev/min and cutting depth of 0.001 in) to 36.59 °C at the combination of (spindle speed of 1550 rev/min and cutting depth of 0.01 in).



(a)

(b)

Figure 5 Main effects plot (a) and interaction plot (b) for temperature rising

5. Conclusion and future direction

This study aimed at developing an experimental apparatus to illustrate heat generation in turning processes for "Manufacturing Processes" course. Experimental hardware, software and experiment protocol were successfully designed and integrated to examine the effects of cutting parameters, including cutting depth, spindle speed, and feed rate, on the temperature rising on turning process. Design of experiment and embedded thermocouple measurement were applied to cover the cutting parameters and collect the experimental data. After collecting temperature data with full factorial experiment, statistical analysis including ANOVA, main effect, interactive effect and regression analysis was conducted. This experiment trains students on machining, sensors, data acquisition, and statistical analysis. It identified that all the three cutting parameters positively affected the temperature rising. Linear mathematic model mapping the temperature rising and cutting parameters were deducted with an R2 value of 0.78. Analysis on the cutting chips also identified the effect of cutting parameters on the temperature rising. The suggested models of chip-tool interface temperature can be satisfactorily applied on convenient mapping between temperature rising and cutting parameter settings within the range of cutting conditions considered in turning process. This temperature prediction approach can be extended to other machining processes such as milling, drilling etc.

When designing an experiment, three fundamental principles, randomization, replication, and blocking, need to be considered [9]. The more experimental runs are arranged randomly; the more insurance it has against extraneous factors possibly affecting the results. By replication, the estimation of magnitude of experimental error variance against the differences among treatments is judged. Increasing the number of replications, it will decrease the variance of treatment effect estimation and provide more power for detecting differences in treatments. By effective blocking, the within-block variation is much smaller than between-block variation. By comparing the treatment in the same block, the block effects are eliminated in the comparison of treatment effects, thus making effect more efficient. The deficiency of this current design is that it did not observe the replication principle when running the experiment. Replication allows an estimation of the random error; also allows a more precise estimate of the factor's effect in the experiment, since a reasonably large replication times will reduce the experimental error [9]. When applying this laboratory design in course, this deficiency shall be avoided.

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