Experimental investigations to evaluate the effects of cutting parameters on cutting temperature and residual stresses during milling process of the AISI 1045

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Abstract. Today major metal cutting companies in industrial countries, looking to gain time and reduce manufacturing costs while respecting the environment. There are many phenomena which affect the quality and production costs of the product, including cutting efforts, cutting temperature, residual stresses, etc. A better understanding of these phenomena will reduce production costs and maximize productivity.

The aim of this work is to analyze the effect of machining conditions (cutting speed, feed speed and cutting depth) on cutting temperature and residual stresses, during the milling operations using the response surface method. A good accuracy between predicted and measured values of the cutting temperature was found, the cutting speed and the depth of cut are parameters whose effect is most sensitive to the residual stresses and the cutting temperature. However, little influence has been registered in the case of an increase of the feed rate.

The percentage of error is 4.57%, indicating that the numerical approach can accurately predict the cutting temperature of the AISI 1045.

1. Introduction

Product quality has always been one of the most important elements in manufacturing operations. In view of the present global economy and competition, continuous improvement in quality and the production costs decrease has become a major priority, particularly for major corporations in industrialized countries, [5-13].

Cutting is one of the most important and common manufacturing processes in industry. Machining is not an easy process to study and to model, due to the inherent difficulty to know exactly what happens in the region around the tool type, [2]. Milling is the most feasible machining operation for producing slots and keyways with a well defined and high quality surface, [6].

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The heat generated in cutting process is one of the most important issues in the metalworking industry. High temperature in metal cutting dramatically degrades the tool life, surface integrity, size accuracy and machining efficiency, [4-10].

Thermal consideration of hard machining processes is very important for tool wear mechanisms and heat penetration into the subsurface layer, which leads to the formation of the white layer and define the diffusion of residual stresses [3]. The temperature in the machining not only affects the tool wear,
but also directly influences the residual stresses [12]. It is well known that machining processes create residual stresses on the surface of machined components [1]. Residual stresses can be defined as tensile and compressions that exist in the material following a manufacturing process. Residual stresses induced by material removal have a major influence on the life time of machined pieces especially in its corrosion resistance and fatigue life [1-14]. Residual stresses can cause part distortion especially in the case of large components such as structural parts in industry, [15,17]. Nowadays, the generation mechanism of the machined residual stress is still an uncompleted explored scientific problems [16]. Thus, it is necessary to understand the profile of the residual stress in the machining [10].

Many studies used the surface response method to solve problems in the field of machining, especially to study the influence of cutting parameters on the surface finish of manufactured parts, cutting force or the life of cutting tools. M. Subramanian et al (2014), [8], have studied the surface quality when milling aluminium (AL 7075-T6), using the response surface method. From their results, the Surface roughness increases with the increase in cutting feed rate and the surface roughness increases with the decrease in cutting speed. A comparison is made between the predicted results and the experimental results and has been found that the deviation is well within the limit of 95 % confidence level. Confirmatory test has been conducted to ensure the validity of the model, and the error is within 5 %.

Pardeep Kumar et al (2015), [9] are used this technique to conduct a study of the effect of cutting parameters on the surface quality of the workpiece, cutting forces and cutting temperature. Tests were conducted in machining by turning, the material is an AISI H13, the cutting tool material is CBN. They found that the cutting forces influence the hardness of the pieces after machining and increase in hardness of work material resulted in better surface roughness as well as increase in tool tip temperature.

Hamed Hassanpour and al (2016) [8], Studied the effects of cutting parameters on roughness, topography, microhardness, white layer thickness and surface chemical composition through Response Surface Methodology. They was found that increasing cutting speed has a significant influence in the reduction of surface defects. Furthermore, all the cutting parameters increased microhardness and white layer thickness.

M. Kamruzzaman et al (2016), [11], used the response surface method and artificial neural network to study the temperature interface - piece tool -chip and tool life, when turning of the C-60 steel, 17CrNiMo6 steel, and 42CrMo4 steel by uncoated SNMG and SNMM carbide inserts. The control of cutting temperature and residual stresses, us to monitor the milling operation that directly affect the product quality and production costs. This study examines the effects of cutting speed, feed rate and cutting depth on cutting temperature and residual stresses in milling process of the carbon steel, using the response surface method.

2. Experimental procedure

The machine used in this research work was a Knuth Rapmill 700 CNC milling machine, which has the ability to linear and circular interpolation on three axes, programmable in ISO format for SI and English units). The spindle rotational speed is 12000 rot / min and the diameter of the cutting tool is 50 mm with 5 inserts 0.025 mm of the edge radius. the Orthogonal cut in the milling operation was performed on prismatic parts with the flowing dimensions 250 mm in length, 110 in width and 50 mm in thickness. Cutting temperature and residual stress are investigated by considering some affecting factors, cutting speed, feed rate and cutting depth. The experimental set-up is shown in Figure 1.

The milling tests were performed at five different cutting speeds (100, 150, 200, 250 and 300 m/min) and four feed rates (0.09, 0.12, 0.15 and 0.18 mm/rev) while the depth of cut was (0.25, 0.5 and 0.75 mm).

The uncoated commercial carbide insert Sandvik Coromant (490R-08T308E-ML H13A) was used under dry condition. The main chemical components of Sandvik inserts and cutting parameters used in tests are shown in Tables 1 and 2, respectively.
### Table 1. The cutting conditions.

| Name                  | Number of levels                          |
|-----------------------|-------------------------------------------|
| Cutting speed (m/min) | (100, 150, 200, 250 and 300)              |
| Depth of cut (mm)     | (0.25, 0.5 and 0.75)                      |
| Feed rate (mm/tooth)  | (0.09, 0.12, 0.15 and 0.18)               |

### Table 2. Dimensions of the used insert.

| S (mm) | RE (mm) | LE (mm) | IC (mm) |
|--------|---------|---------|---------|
| 3.3    | 0.8     | 5.6     | 8.5     |

![Figure 1. Experimental setup of measuring cutting temperature and residual stresses.](image)

### 2.1. Work piece material
The work material used as the test specimen was AISI 1045, medium carbon steel that is widely used in industry aerospace, automotive, mechanical etc. The chemical composition of the material is presented in Table 3.

### Table 3. Chemical composition of AISI 1045.

| Elements | Fe   | C    | Mn   | Si   |
|----------|------|------|------|------|
| %        | 97.35| 1.35 | 0.77 | 0.45 |
Figure 2. EDS analysis of work piece and a microstructure of the steel used obtained by Leica type DMI5000 – optical microscope.

The EDAX module with possibility of EDS analysis and crystallographic recognition provides simultaneous presentation of secondary electrons images and of spread electrons on every way of work. Maximum acceleration voltage for electron and ion beam is 30KV

2.2. Work piece material
Various experimental techniques (thermocouple, infrared system, etc.) have been developed to evaluate the cutting temperature during machining operations. [5] For monitoring the temperature field in the surface of the workpiece an infrared thermal camera was chosen. This technique was preferred because it is easy to calibrate, it has a quick response time and a good repeatability during experiments.

Or the temperature measurement an IR camera Flir A325 was used, having an InSb Detector, and 320 x240 pixel, microscope lens giving 10 microns spatial resolution and +/- 2 degrees C temperature resolution for measurement of the used range. The setting up of the Infrared camera was similar to the high speed camera. The videos were recorded with duration of seven seconds and 100 frames per second.

In general, the measurement methods of residual stress using a variety of techniques range are the strain gage, drilling method, X-ray technology, etc. [7]

In this work to measure the residual stress in the surface layer at a depth of 0.8 mm, the hole drilling technique was used. The measurements were performed using a RESISTANCE mechanism, consisting of a SIN-2t drill, a SINT 1 electronic assembly, a SPIDER 8 digital recorder and a computer (Figure 1) The strains were measured using a strain gauge rosette, type SEA-06-062UL-120, glued to the surface of the piece, the latter sends the signals to the computer by the acquisition system of data.

The results obtained were treated with the integral calculation method. Initial measurements were made on materials to determine the initial residual stress distribution.

3. Response surface methodology
The RSM is a procedure used to determine the relationship between the independent process parameters with the desired response and exploring the effect of these parameters on responses, [19].
The experimental results of the measurement of the cutting temperature as a function of different cutting parameters are illustrated in the table 4.

**Table 4.** Experimental results for the cutting temperature.

| Run | Cutting speed (Vc) (m/min) | Feed (B) (mm/rev) | Depth of cut (C) (mm) | Cutting temperature (T ) (°C) |
|-----|----------------------------|-------------------|----------------------|-----------------------------|
| 1   | 100                        | 0.18              | 0.75                 | 100                         |
| 2   | 100                        | 0.18              | 0.5                  | 83                          |
| 3   | 100                        | 0.18              | 0.25                 | 80                          |
| 4   | 100                        | 0.15              | 0.25                 | 80                          |
| 5   | 100                        | 0.15              | 0.5                  | 82                          |
| 6   | 100                        | 0.15              | 0.75                 | 102                         |
| 7   | 100                        | 0.12              | 0.25                 | 78                          |
| 8   | 100                        | 0.12              | 0.5                  | 85                          |
| 9   | 100                        | 0.12              | 0.75                 | 103                         |
| 10  | 100                        | 0.09              | 0.5                  | 100                         |
| 11  | 100                        | 0.09              | 0.75                 | 90                          |
| 12  | 100                        | 0.09              | 0.25                 | 77                          |
| 13  | 150                        | 0.18              | 0.5                  | 82                          |
| 14  | 150                        | 0.18              | 0.25                 | 84                          |
| 15  | 150                        | 0.18              | 0.75                 | 115                         |
| 16  | 150                        | 0.15              | 0.25                 | 84                          |
| 17  | 150                        | 0.15              | 0.5                  | 98                          |
| 18  | 150                        | 0.15              | 0.75                 | 118                         |
| 19  | 150                        | 0.12              | 0.5                  | 98                          |
| 20  | 150                        | 0.12              | 0.75                 | 118                         |
| 21  | 150                        | 0.12              | 0.25                 | 82                          |
| 22  | 150                        | 0.09              | 0.75                 | 120                         |
| 23  | 150                        | 0.09              | 0.5                  | 98                          |
| 24  | 150                        | 0.09              | 0.25                 | 84                          |
| 25  | 200                        | 0.18              | 0.75                 | 120                         |
| 26  | 200                        | 0.18              | 0.5                  | 100                         |
| 27  | 200                        | 0.18              | 0.25                 | 85                          |
| 28  | 200                        | 0.15              | 0.5                  | 100                         |
| 29  | 200                        | 0.15              | 0.75                 | 118                         |
| 30  | 200                        | 0.15              | 0.25                 | 90                          |
| 31  | 200                        | 0.12              | 0.75                 | 125                         |
| 32  | 200                        | 0.12              | 0.25                 | 95                          |
| 33  | 200                        | 0.12              | 0.5                  | 100                         |
| 34  | 200                        | 0.09              | 0.5                  | 105                         |
| 35  | 200                        | 0.09              | 0.75                 | 110                         |
4. Results and discussion

4.1. Residual stress

Figure 3 shows the evolution of residual stress versus measuring depth, for the initial measurement and for the flowing cutting condition (Vc = 100 m/min, 300 m/min and f = 0.09 mm/tooth, 0.18 mm/tooth and a = 0.25 mm, 0.5 and 0.75 mm).
Figure 3. Evolution of residual stress versus measuring depth for initial measuring and cutting parameters.

The residual stress after machining with the cutting condition (Vc=100 m/min and f= 0.09mm/tooth, 0.18mm/tooth) were tensile excepting the interval of depth between 0.1 to 0.2 mm for the feed rate equal 0.18 mm/tooth, were the residual stress are compressive, this is because of the increase in the cutting temperature during milling operation. The mechanical loadings (e.g. cutting force) generally introduce compressive stresses due to contact pressure, whereas thermal loading is generally associated with tensile stresses [18-21]. By against for initial measurements the stresses in both directions are compressive excepting the interval of depth between 0.7 to 0.8 mm were the residual stress are tensile. By against for initial measurements the stresses in both directions are compressive excepting the interval of depth between 0.7 to 0.8 mm were the residual stress are tensile. For a feed rate of 0.18 mm/tooth, the cutting velocity increases from 100 m/min to 300 m/min and depth of cut increases from 0.25 mm to 0.75 mm. Residual compressive stresses in both directions increase due to the increase in cutting temperature, under the effect of the increase of the cutting speed and the cutting depth. It is concluded that the residual stresses in the cutting and feed directions are influenced by the cutting speed and the depth of cut from the results obtained in this work.

4.2. Cutting temperature
The influence of cutting parameters (cutting speed, feed / tooth and depth of cut) on the temperature field were designed dry milling without lubrication. The results of the variation of the temperature as a function of the cutting parameter for the tested inserts are illustrated in Figure 4.
The influence of the cutting speed on the temperature field was studied for feed rate \( f = 0.09 \text{ mm/tooth}, 0.12 \text{ mm/tooth}, 0.15 \text{ mm/tooth}, \) and the depth of cut \( (ap = 0.75 \text{ mm}) \), Figure 2, us allows to generally observe an increasing trend of more or less rapid temperature.

We find that the cutting temperature increases with increasing depth of cut regardless of the cutting speed and feed rate.

However, little influence has been registered in the case of an increase of the feed rate.

**Figure 4.** Evolution of cutting temperature versus the cutting parameters.
4.3. **ANOVA Analysis**

ANOVA is useful to figure out the influence of given input parameters from a series of experimental results by the method of design of experiments for machining processes and it also allows to supply an interpretation output data. It essentially consists of partitioning the total variation in an experiment into components ascribable to the control factors and generated errors [20]. Table 5 shows the results of ANOVA model for cutting temperature.

| Source     | Squares   | Sum of df | Square   | Mean Value | F Prob > F | p-value |
|------------|-----------|-----------|----------|------------|------------|---------|
| Model      | 10058.21  | 9         | 1117.58  | 36.08      | < 0.0001   | significant |
| A-Cutting speed | 73.37    | 1         | 73.37    | 2.37       | 0.1301     | significant |
| B-Feed rate     | 36.57    | 1         | 36.57    | 1.18       | 0.2824     | significant |
| C-Depth of cut  | 459.94   | 1         | 459.94   | 14.85      | 0.0003     | significant |
| AB          | 40.04     | 1         | 40.04    | 1.29       | 0.2610     | significant |
| AC          | 30.01     | 1         | 30.01    | 0.97       | 0.3297     | significant |
| BC          | 53.05     | 1         | 53.05    | 1.71       | 0.1966     | significant |
| A²          | 306.72    | 1         | 306.72   | 9.90       | 0.0028     | significant |
| B²          | 24.07     | 1         | 24.07    | 0.78       | 0.3823     | significant |
| C²          | 99.01     | 1         | 99.01    | 3.20       | 0.0799     | significant |
| Residual    | 1548.73   | 50        | 30.97    |            |            |         |
| Cor Total   | 11606.93  | 59        |          |            |            |         |

The final equation of the cutting temperature that connects the input and output parameters is modeled by a quadratic regression and represented as follows, Eq 1.

\[
T = 37.56000 + 0.38869 \times Vc + 130.66667 \times f + 2.64000 \times \text{ap} - 0.34444 \times Vc \times f - 0.049000 \times Vc \times \text{ap} + 137.33333 \times f \times \text{ap} - 5.40476E-004 \times Vc^2 - 703.70370 \times f^2 + 43.60000 \times \text{ap}^2
\]  

The fig. 5 shows a comparison of the cutting temperature as a function of test number, obtained by the experimental and numerical approaches. It can also be seen that the prediction results and experimental results are consistent, showing its accuracy and the feasibility of predicting with the surface response method.

![Figure 5. Comparison between measured and predicted values for cutting temperature.](image-url)
The figure 6 report the effect of the interaction of cutting parameters (cutting speed, feed / tooth and depth of cut) on the cutting temperature, in 3D obtained by response surface method after the optimization. As observed from figure the feed rate has a negligible effect on the cutting temperature, by against the cutting temperature sharply increases with the increases in the cutting speed and depth of cut.

5. Optimization of cutting condition
The optimal solutions are presented in Table 6. Values of optimal cutting parameters are found to be as follows, \( V_c = 103.04 \text{m/min}, \ f=0.14 \text{ mm/tooth} \) and \( a_p= 0.25 \text{mm} \). The optimized cutting temperature is \( T= 76.9184167^\circ \).

| Number | Cutting speed, m/min | Feed rate, mm/tooth | Depth of cut, mm | Temperature | Desirability |
|--------|----------------------|---------------------|------------------|-------------|--------------|
| 1      | 103.04               | 0.14                | 0.25             | 76.9184167  | 1 Selected   |
| 2      | 111.34               | 0.18                | 0.28             | 76.5122538  | 1            |
| 3      | 101.84               | 0.18                | 0.25             | 73.2866831  | 1            |
| 4      | 101.57               | 0.16                | 0.26             | 75.3998076  | 1            |
| 5      | 101.77               | 0.15                | 0.28             | 76.7622265  | 1            |
6. Conclusion
The aim of this work is to analyze the effect of machining conditions (cutting speed, feed speed and cutting depth) on cutting temperature and residual stresses, during the milling operations using the response surface method.

The tests of the cutting temperature, residual stresses and numerical prediction of the cutting temperature allowed us to get out with the following conclusions:
- The cutting temperature increases as the cutting speed increases and the depth of cut;
- However, little influence has been recorded in the case of an increase in feed rate on the cutting temperature field;
- It is concluded that the residual stresses in the cutting and feed directions are influenced by the cutting speed and the depth of cut from the results obtained in this work;
- The residual stresses in both directions are generally compressive;
- A good agreement between the predicted and measured cutting temperature was found in this study;
- The percentage of error is 4.57%, indicating that the numerical approach can accurately predict the cutting temperature of the AISI 1045 in milling operations.

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