Kerbala Journal for Engineering Science

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# Experimental, Finite Element and Statistical Analysis of Temperature Generated in AISI 304 Stainless Steel during Drilling Operation

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**Received: 03 July 2021; Revised: 10 January 2022; Accepted: 20 April 2022, ; Published: 30 June 2022**

***Abstract:***

The drilling operation was found in the early time of modern technology due to the importance of this operation in manufacturing. The drilling operation was developed to meet the requirements of modern industry. The study of factors that influence the drilling operation is very important to develop and enhance the performance of drilling tools and machining. The objective of this study is to prove the closeness between experimental and FE works to measure the temperature in a specified point on the workpiece. This closeness will be evidence of the reliability of FE temperatures to extract the linear and nonlinear expressions in the SPSS program. For experimental work, a 10mm diameter drill bit of 118$^{\circ}$ point angle was used to make three drilling operations by using a radial drilling machine. Three cutting speeds of (100-200-300) rpm, with fixed feed rate and drilling depth as 0.15mm/rev, and 3mm, respectively. The experimental operations are included in the FE study for validation. For numerical study, 3D simulations based on the FE method by using Deform-3D Ver.11 commercial software were executed to explain the influence of drilling parameters as well as drill bit point angle on the temperature generated in the workpiece material in dry drilling of AISI 304 stainless steel. Two drill bits of HSS have been used in this study with 10mm diameter and these tools are different in point angle of 110° and 118°, respectively. The drill bits are imported from a specific website in the format of STL. The workpiece modeling shape is cylindrical with a diameter of 50mm and 5mm thickness. The cutting parameters include three cutting speeds as (100, 200, and 300) rpm, and three feed rates as (0.15, 0.25, and 0.35) mm/rev, and the depth of drilling is constant for all operations as 3mm. The results provided a good closeness between experimental and their FE operations and the decision was to assume the FE temperatures reliable, and qualified to be used in SPSS work. The results showed that the temperature generated in the machined models increased with speed for both tools and the temperature generated by the tool of 118° point angle is higher than the temperature generated by the tool of 110° point angle. The influence of feed rate was also investigated. There was a good closeness between FE temperatures and nonlinear regression ones which indicated to consider the temperature variation as nonlinear in this study.

**Keywords:** Machining, Drilling, FEM, DEFORM-3D, Simulation, High-Speed Steel, Stainless Steel AISI 304, Statistical Analysis, SPSS

## 1. Introduction

Drilling operation is very important in manufacturing and modern technology owing to the importance of this process to make circular holes in the products and it's usually implemented at the final steps of manufacturing. Many researchers attempted to study the factors that influence this operation. One of the important factors that influence the performance of drilling operations is the heat generated during drilling. This heat influences the tool lifetime, properties of machined material and integrity of produced holes. The amount of heat generated in drilling operation depends on many factors such as cutting parameters (speed, feed and depth of hole), the geometry of drill bit, materials of workpiece and cutting tool, and thermal and mechanical properties of cutting tool and workpiece materials. B. Ozcelik and E. Bagci [1] studied the influence of cutting parameters on drill bit temperature in dry drilling of AISI 1040 by using coated carbide tool. Jian Wu and Rongdi Han [2] studied the effect of drilling parameters on the workpiece temperature in dry drilling of Ti6Al4V and AISI 1045 by using HSS drills. R. Muhammad et al. [3] investigated the effect of drilling parameters on the heat generated in drilling of AISI 1010 by using WC cutting tool. S. Kilikevičius et al. [6] did experimental work with numerical simulation in drilling and threads tapping of DC-06, AISI304, and Ti-6Al-4V alloy by using HSS and WC cutting tools. Jolene S. Vas et al [7] investigated the temperature generated on the high speed steel drill bits of different point angles as 82°, 100° and 118° during dry drilling of austenitic stainless steel and the temperature was recorded by infrared thermometer. M.S. Nagaraj et al. [8] investigated the influence of drill point angle on the heat generated on the cutting tool experimentally by using tungsten carbide coated tools of different point angles of 118°, 135° and 140° during dry drilling of Nimonic C-263 and numerically by using Deform-3D software. Erkan and Yucel [9] tried to study the influence of cutting speed and feed rate on the temperature generated in the workpiece material of AISI304 by using the FE method based on Deform-3D software and the cutting tool is HSS with 5mm diameter. They found out a significant influence of speed on temperature compared with the influence of feed rate, because the workpiece temperature increased with speed and dropped with feed rate. K. Thirukkumaran et al. [10] studied the influence of using different point angles cutting tools on the heat generated in cutting tool and workpiece materials in dry drilling of Al-5%SiC composite as machined material and 5mm diameter high speed steel as cutting tools with different point angles as 90°, 118°, and 135°. Sharma and Pradhan [11] investigated the influence of tool point angle on the heat generated in dry turning of AISI 1045 by using carbide cutting tools of different point angles as 118°, 135° and 140°. Nagaraj et al. [12] tried to study the heat generated in dry drilling of Nimonic C-263 alloy experimentally by using tungsten carbide cutting tools of different point angles as 118°, 135° and 140° and the simulations have been carried out for validation by using Deform-3d software. Ahmadi and Mohammadi [13] tried to study the influence of cutting conditions such as cutting speed, feed rate, and cooling on the heat generated in teeth implantation numerically by using Deform-3D software and different point angles cutting tools as 70°, 90°, and 118° degrees and different helical angles of 20°, 23°, and 30° and the simulation work is validated experimentally under the same drilling conditions. Luo et al. [14] did an experimental and FE study on the influence of spindle speed and feed rate on axial force, tool temperature, and torque in dry drilling of 7075-T6 aerospace aluminum alloy by using many values of speeds and feed rates and the comparison between experimental and FE simulations was also executed.

Based on the mentioned studies, the present study includes FE simulations by Deform-3D software in dry drilling of stainless steel AISI 304 to investigate the influences of drilling conditions as well as point angles of 10mm diameter high speed steel cutting tools on the temperature generated in the workpiece material. The experimental work is carried out to prove that the FE temperatures are very close to the real temperatures of experimental work. They are reliable and qualified to be used in measuring the temperatures of linear and nonlinear regressions. The statistical work by SPSS software is based on extracting two equations for measuring temperature by using linear and nonlinear regressions according to the quantitative data of cutting parameters, point angle, and FE temperatures that we already simulated.

## 2. Materials of the study

### 2.1. Workpiece Material

The workpiece material which has been used in this study is stainless steel AISI 304 which is hard to machine material and has over 18% of chromium and 8% nickel installed around a composition of iron [4,7], see Table 1. AISI 304 stainless steel is involved in a lot of manufacturing processes owing to its good corrosion resistance and easy machinability [9].

Stainless steel 304 is needed in manufacturing due to its low corrosion and high mechanical properties (ultimate tensile strength is more than 590 Mpa). This alloy has FCC atomic structure and considered as non-magnetic alloy. The mechanical properties of AISI 304 are mentioned in Table 2.

**Table 1 Chemical composition of AISI 304 [4].**

| Element | C | Mn | P | S | Cr | Ni | Si | Mo | Fe |
|---|---|---|---|---|---|---|---|---|---|
| Percentage % | 0.081 | 1.74 | 0.018 | 0.019 | 19.04 | 7.93 | 0.368 | 1.24 | Remaining |

**Table 2 Mechanical properties of workpiece [6].**

| Material | Ultimate Tensile Strength, Mpa | Ultimate Yield Strength, Mpa | Elongation at break, % | Elastic Modulus, Gpa |
|---|---|---|---|---|
| AISI 304 | 515-708 | 205-340 | 40 | 193 |

## 2.2. Cutting Tool Material

These tools are considered high speed steel have the same diameter but differ in one parameter which is the point angle, one is 110° and the other is 118° point angles. High speed steel tools are characterized by high working hardness, high wear resistance, and excellent toughness. Table 4 explains the material characteristics of high speed steel. High speed steel is developed to improve the performance of the cutting tools by adding some important metals to resist the rapid wear and temperatures that occur in the tools during machining operations. The high speed steel DIN 338 tool which is used in the experimental work has been developed by adding 5% cobalt to the chemical composition to enhance the surface hardness, see Table 3. Cobalt plays an important role in protecting the tools from wear and keeps the dimensional accuracy of the tools. The geometry specifications of this tool are mentioned in Table 5.

**Table 3 Chemical composition of high speed steel DIN 338 [5].**

| Element | Percentage [%] | Element | Percentage [%] | Element | Percentage [%] |
|---|---|---|---|---|---|
| Carbon | 0.85 | Sulfur | 0.002 | Vanadium | 1.75 |
| Silicon | 0.3 | Chromium | 3.87 | Tungsten | 6.09 |
| Manganese | 0.2 | Molybdenum | 4.72 | Cobalt | 5 |
| Phosphor | 0.002 | Nickel | 0.18 | Ferrous | Remaining |

**Table 4 Material properties of HSS cutting tools [6].**

| Property | Unit | HSS |
|---|---|---|
| Young’s Modulus | GPa | 233 |
| Poisson’s Ratio | - | 0.28 |
| Density | $\mathrm{Kg/m^3}$ | 7.6 |
| Thermal Expansion Coefficient | $\mathrm{K^{-1}}$ | $12.6\mathrm{X}10^{-6}$ |
| Thermal conductivity | $\mathrm{W/m.K}$ | 20.2 |
| Specific heat | $\mathrm{J/kg.K}$ | 0.42 |

**Table 5 Geometrical parameters of the experimental work drill bit.**

| Parameter | Specification |
|---|---|
| Material | HSS DIN 338 |
| Diameter | 10 mm |
| Drill type | Twist drill bit |
| Total length | 135 mm |
| Point angle | 118° |
| Helix angle | 32° |
| Flute length | 90 mm |
| Shank length | 45 mm |
| Shank type | Cylindrical |

## 3. Experimental setup and procedure

Three drilling experiments were performed on a radial drilling machine by using a high speed steel drill bit of 10 mm diameter. The temperature of the workpiece model was measured by using a thermal infrared camera, which has a measuring range of -10 °C to 500 °C. The thermal camera is fixed on a suitable fixture so as to prevent any expectable movement in the camera while measuring the temperatures, see Figure 1. The procedure of experimental work is to apply the infrared laser of the thermal camera on a specified point on the workpiece and monitor the temperatures in this point on the workpiece material which is close to the edge of the cutting tool. This point is the visible point of the machined workpiece that acquires the highest temperature during drilling among the rest of the visible parts of the machined workpiece, see Figure 1. The infrared laser of the thermal camera is focused on this point during the cutting process and then monitoring the temperature readings that appear on the screen of the camera. When the time of each operation gets finished, the highest temperature that appeared on the screen will be recorded. The workpiece material is AISI 304, which has a shape of a hallow disc with internal and external diameters of 170 mm and 265 mm, respectively, with 20 mm thickness. The cutting parameters of the experimental work are shown in Table 6. The cutting time of each operation is measured according to equation 1, and this time is needed to know how the time of monitoring the temperatures of each operation.

$$T_m = \frac{t + 0.5Dtan(90 - 0.5\theta)}{f\ N} \tag{1}$$

Where, $T_m$ is the cutting time (min), $t$ is the drilling depth (mm), $D$ is the diameter of the tool (mm), $\theta$ is the point angle of the drill bit, $f$ is the feed speed (mm/rev), and $N$ is spindle speed (rpm).

**Table 6 Cutting parameters and machining time of each operation.**

| Experiment | Speed (rpm) | Feed rate (mm/rev) | Drilling depth (mm) | Cutting time (s) |
|---|---|---|---|---|
| 1 | 112 | 0.15 | 3 | 24 |
| 2 | 200 | 0.15 | 3 | 12 |
| 3 | 300 | 0.15 | 3 | 8 |

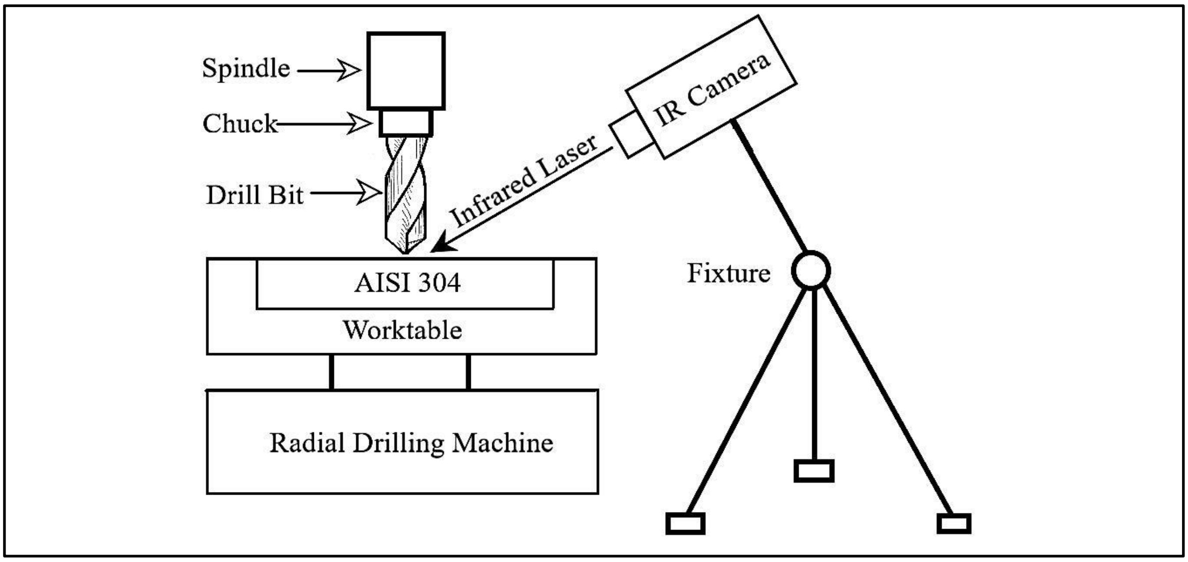


**Figure 1 Experimental set up.**

## 3. 3D FE Analysis for Temperature Measurement

The 3D drilling operations are performed by using the finite element method based on Deform-3D software. The FE simulations are divided into two groups. The first group includes three processes to validate the result of experiments and the second group includes eighteen FE operations conducted by two different point angle tools by using different cutting parameters. The first group, which is needed for experimental validation, is included in the second group by using the tool of 118° point angle and the same cutting parameters of the experimental setup.

### 3.1 Cutting Parameters

Three spindle speeds of (100, 200, and 300) rpm with three feed rates of (0.15, 0.25, and 0.35) mm/rev were used in these simulations. The depth of drilling is the same for all operations as 3mm penetration of the drill bit into the workpiece material. Each speed was used with each feed rate to make nine drilling simulations by each tool. Therefore, eighteen simulation processes have been done by both tools. The levels of cutting parameters are shown in Table 7.

**Table 7 Cutting parameters and their levels in simulations.**

| Factors | Unit | Levels of cutting parameters | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| Speed | rpm | 100 | 200 | 300 |
| Feed rate | mm/rev | 0.15 | 0.25 | 0.35 |

 ISSN: 2709-6718

### 3.2 Initial Conditions

The initial conditions are representing the atmosphere conditions around the cutting area such as the environmental temperature, and air convection coefficient as well as some important factors at tool-workpiece interface such as shear friction factor, and heat transfer coefficient, see Table 8. The selection of such values referred to dry drilling simulations because the convection coefficient of air is 20 w/m².C, and the temperature of the air around the drilling area is standard 25°C.

**Table 8 Initial conditions of FE modeling.**

| Process Condition | | | |
|---|---|---|---|
| **1. Environment** | | **2. Tool-Workpiece Interface** | |
| Temperature | 25 ºC | Shear friction factor | 0.6 |
| Convection Coefficient | 0.02 N/sec/mm/C | Heat transfer coefficient | 45 N/sec/mm/C |

### 3.3 Modeling of cutting tools

Two cutting tools of the same diameter and different point angles, one is 110° point angle, and the other is 118° point angle, see Figure 2. These tools are imported from specific website and then inserted into the program in a format of STL during the modeling of cutting tools. The geometrical parameters of these tools were measured accurately by means of special technique in the program, see Table 9. In the modeling of the cutting tools, the temperature of the tool before drilling was not selected and ignored which means there is no ability to specify the material of the tools and no meshing technique for the cutting tools because the neglecting of tool temperature selection leads to consider the tool as high-speed steel and this step is useful in reducing the time of the simulation.

**Table 9 Geometrical parameters of cutting tools.**

| Tool No. | Diameter | Total length | Working length | Shank length | Shank diameter | Helix angle | point angle | Type of material | Flutes |
|---|---|---|---|---|---|---|---|---|---|
| Tool 1 | 10 mm | 100 mm | 56 mm | 44 mm | 10 mm | 28° | 110° | Rigid | 2 |
| Tool 2 | 10 mm | 150 mm | 100 mm | 50 mm | 10 mm | 30° | 118° | Rigid | 4 |

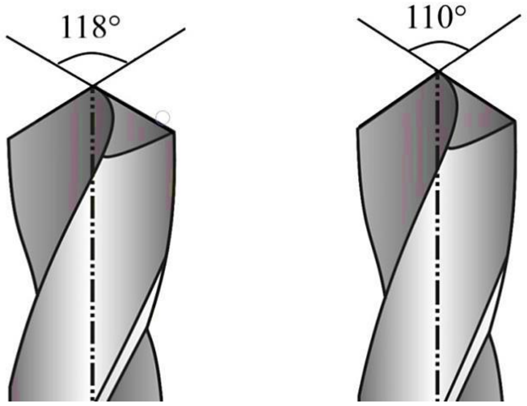


**Figure 2 The point angles of both cutting tools.**

### 3.4 Modeling of Workpiece

The work samples are made as a cylindrical shape with a diameter of 50mm and 5mm thickness. In the boundary condition, the speed of the side and bottom surfaces of the workpiece in the x, y, and z directions is taken as zero to ensure that the workpiece is stationary and fixed during drilling. The constraint illustrations for these simulations are shown in Figure 3. The material type of the work models is considered as plastic; see the modeling assumptions of the workpiece in Table 10.

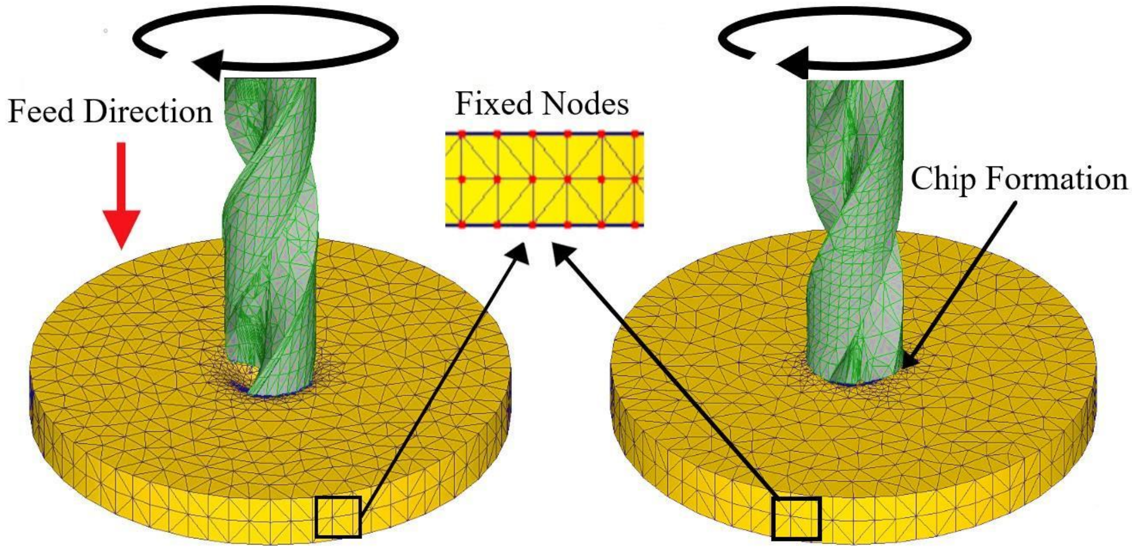


**Figure 3 Constraints of the workpiece model showing the mesh model of tool and workpiece.**

**Table 10 The modeling parameters of the workpiece.**

| Shape | Diameter | Thickness | Mesh | No. of Nodes | Element | Mesh size ratio | Surface Polygons | Type | Temp. |
|---|---|---|---|---|---|---|---|---|---|
| Cylinder | 50 mm | 5 mm | 12000 | 2121 | 8872 | 5 | 2346 | Plastic | 20 °C |

### 4. Statistical Analysis for Temperature Measurement

The SPSS analytical software was used to make statistical analysis to the quantitative data initiated from cutting parameters as well as the point angle of the tool and the specified temperature of FE analysis. Statistical analysis is known as a process through which data related and related to scientific research are collected and processed in order to analyze and study these data and then extract results from it. In this part of the study, the quantitative data of speed, feed rate, point angle of the tool, and specified FE temperature that occurred on the machined models will be analyzed according to the multiple linear regression and nonlinear regression.

### 4.1 Multiple Linear Regression

Multiple linear regression is one of the developed statistical methods that ensure the reliability of inference in order to enhance the results of the study through the optimal use of data in finding casual relationships between the phenomena of the topic of research. Multiple linear regression is about finding a mathematical expression that expresses the relation between two variables or more and is used to estimate past values and predict future values. It is also a regression of the dependent Y on many independent variables $X1 + X2 + \cdots + Xk$. Therefore, it's used in predicting changes in the dependent variables. Thus, multiple linear regression is used to explain the relationship between a continuous dependent variable and two or more independent variables. The speed, feed rate and drill bit point angle were assumed as independent variables, whereas the FE temperature is assumed as a dependent variable. The following expression is expected from linear regression analysis:

$$Y = \alpha + \beta_1 X_1 + \beta_2 X_2 + \cdots\cdots + \beta_K X_k \tag{2}$$

Where the $Y =$ dependent variable, $\alpha =$ constant value, $\beta_1 =$ the slope of the regression y on the first independent variable, $\beta_2 =$ slope of the regression y on the second independent variable, $X_1 =$ the first independent variable, and $X_2 =$ is the second independent variable.

### 4.2 Non-Linear Regression

Nonlinear regression is a form of regression analysis in which data is fit to a model and then expressed as a mathematical function. The nonlinear regression connects the two or more variables in a nonlinear (curved) relationship. The goal of the model is to make the sum of R squares as small as possible. Sum of squares is a measure that tracks how much the observations of Y differ from the nonlinear (curvilinear) function used to predict Y. The nonlinear regression can be carried out as following:

1. The curve estimation regression is conducted three times between each independent variable, speed, feed or point angle of the tool, and the other is dependent variable (temperature) obtained from FE simulations. This regression is carried out between two variables only, one is independent, and the other is dependent, taking into consideration 11 different curve estimation regression models. The goal of curve estimation regression is to select which model provides a higher R square than other models.
2. The model of higher R square will be considered as a nonlinear mathematical expression to be inserted in the model expression in the nonlinear regression. The constant variables of the nonlinear expression are existed in the tables of curve estimation regression.
3. Defining the mathematical model of nonlinear relationship in the nonlinear regression with the constant values that are already existed in this model.

4. Two values of temperature, predicted and residual. Only predicted temperatures will be enough as a nonlinear regression values.

## 5. Results and discussions

### 5.1 The experimental and FE results of the validation

Table 14 shows the measured temperature from experimental and FE simulations in at a specified point on the workpiece. It’s noted that the temperatures increased significantly with an increase of cutting speed in both experimental and FE studies. The error between experimental and FE studies can be calculated from the below equation:

$$Error = \left(\frac{Experimental - Simulated}{Experimental}\right) 100\% \tag{3}$$

**Table 11 Calculated errors between temperatures of FE and experimental work.**

| Process No. | Speed | Experimental temperature °C | FE temperature °C | Absolute Error % |
|---|---|---|---|---|
| 1 | 100 | 110 | 128 | 16.36 |
| 2 | 200 | 152 | 176 | 15.78 |
| 3 | 300 | 178 | 211 | 18.5 |

Also there is a good closeness between experimental and FE as it’s noted in Table 13, which refers to a maximum error as 18.5% whereas the minimum error as 15.78%. Thus, the maximum error didn’t exceed 20%. This is very acceptable values of deviation and. It can be said that the FE results are qualified and reliable to be used as the dependent variables in measuring the temperatures of linear and nonlinear regressions of SPSS software.

### 5.2 The results of workpiece temperature by FE simulations

The values of FE temperatures were measured at specified points on the work model as in the case of the  experimental study. The location of this point is very close to the contact between the tool and the workpiece, see Figure 4. The temperature circled in red is required. Table 12 show the results of FE simulations and the cutting conditions of each operation. The results of specified temperatures will be investigated according to the influence of cutting parameters and the point angle of the tool.

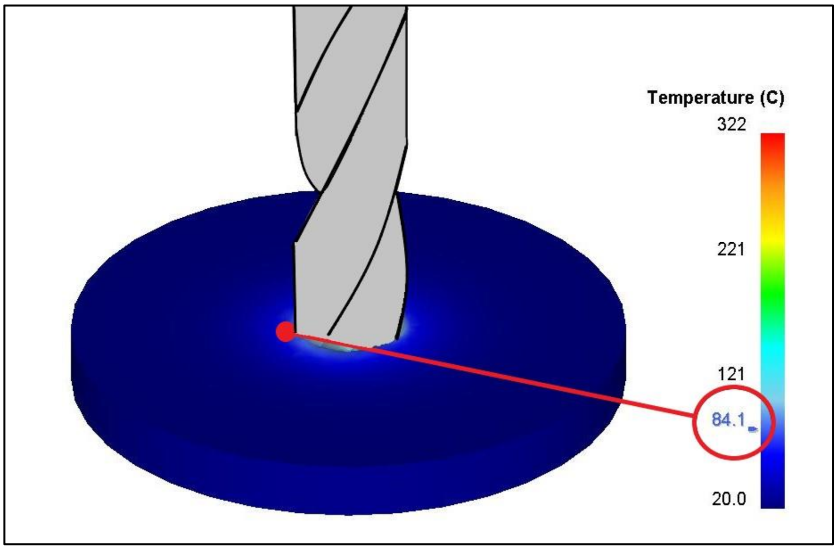


**Figure 4 Location of the specified point on the work model.**

**Table 12 Specified FE temperatures of the workpiece for each operation.**

| Process No. | Speed rpm | Feed Rate mm/rev | Specified workpiece temperature °C | |
|---|---|---|---|---|
| | | | The tool is 110° point angle | The tool is 118° point angle |
| 1 | 100 | 0.15 | 84.1 | 128 |
| 2 | 100 | 0.25 | 118 | 170 |
| 3 | 100 | 0.35 | 104 | 129 |
| 4 | 200 | 0.15 | 145 | 176 |
| 5 | 200 | 0.25 | 172 | 219 |
| 6 | 200 | 0.35 | 155 | 166 |
| 7 | 300 | 0.15 | 184 | 211 |
| 8 | 300 | 0.25 | 202 | 246 |
| 9 | 300 | 0.35 | 217 | 249 |

### 5.2.1. The influence of cutting speed on workpiece temperature

Figures 5, and 6, discuss the variations of specified temperature recorded on the workpiece model with respect to cutting speed at all feed rates for both tools separately. It's noted that the workpiece temperature increased significantly with increasing cutting speed at different feed rates and tool point angles. This result is agreed with the result reported by Jolene S. Vas et al [7], Rahul Sharma, and Swastik Pradhan [11]. The increase of cutting speed led to an increase in temperatures owing to the increase of friction between the cutting tool and workpiece, also the increase of internal friction between atoms that resulted in plastic deformation of the machined material. The higher temperature when using 118° point angle tool is 249°C, at a speed of 300, 0.35 mm/rev feed rate. The lower temperature when using 118° point angle tool is 128°C at a cutting speed of 100 rpm, and feed rate of a 0.15 mm/rev. The higher temperature when using 110° point angle tool is 217°C, at a speed of 300, 0.35 mm/rev feed rate. The lower temperature when using 110° point angle tool is 84.1°C at a cutting speed of 100 rpm, and a feed rate of 0.15 mm/rev. Thus, the higher temperatures occurred at the highest cutting speed and the lower temperatures occurred when lower cutting speed was used, regardless of the value of feed rate, which means that the cutting speed is a significant parameter in controlling the machined model's temperature in the drilling operation.

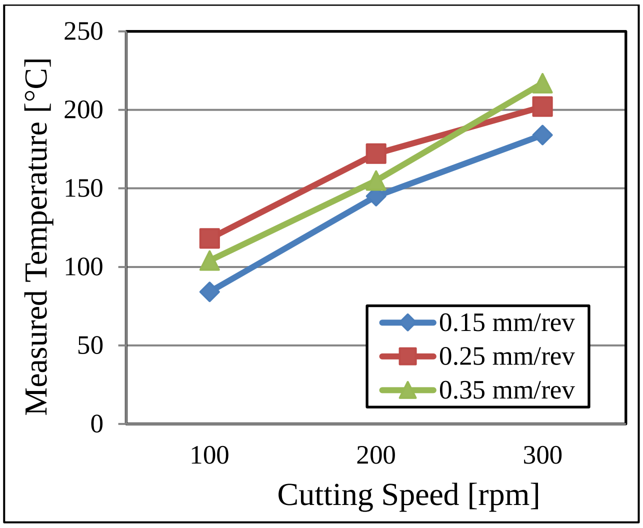


**Figure 5 The variation of temperature with respect to cutting speed at tool of 110° point angle.**

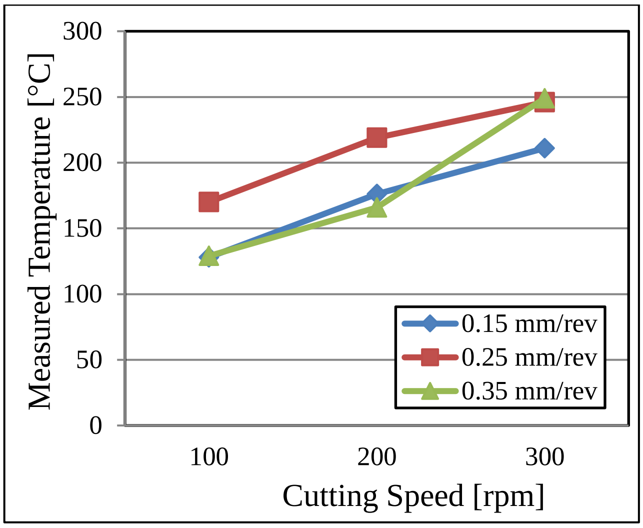


**Figure 6 The variation of temperature with respect to cutting speed at tool of 118° point angle.**

### 5.2.2. The influence of feed rate on workpiece temperature

Figures 7, and 8, showed the variations of specified workpiece temperatures with respect to feed rates at all cutting speeds for both tools separately. The temperature situation showed an increase in temperature when transferring from 0.15mm/rev to 0.25mm/rev, but most of the operations provided a noticeable decrease in temperature at feed of 0.35mm/rev. From this study, we can conclude that the feed rate has not a significant influence on the temperature initiated on the workpiece compared with the influence of cutting speed. The increase of feed rate leads to an increase in the chip thickness that contact with a cutting tool at the tool-chip interface, which causes a high heat at this zone and a considerable part of this heat will be transferred to the machined models. That’s why it noted an increase of workpiece temperature with increase of feed rate from 0.15mm/rev to 0.25mm/rev. Also, the increase of feed rate leads to high friction at the tool-workpiece interface, which causes the higher temperature in the workpiece. Sometimes the increase of feed rate leads to a decrease in the temperature due to decrease the cutting time of the process and this reduces the frictional time at tool-workpiece and tool-chip interfaces. The results of temperature vs. feed rates are agreed with references [7,8, and 9].

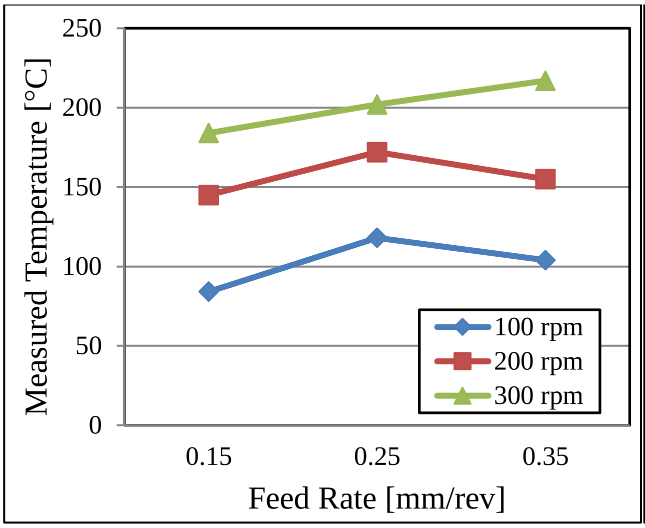


**Figure 7 The variation of temperature with respect to feed rate at tool of 110° point angle.**

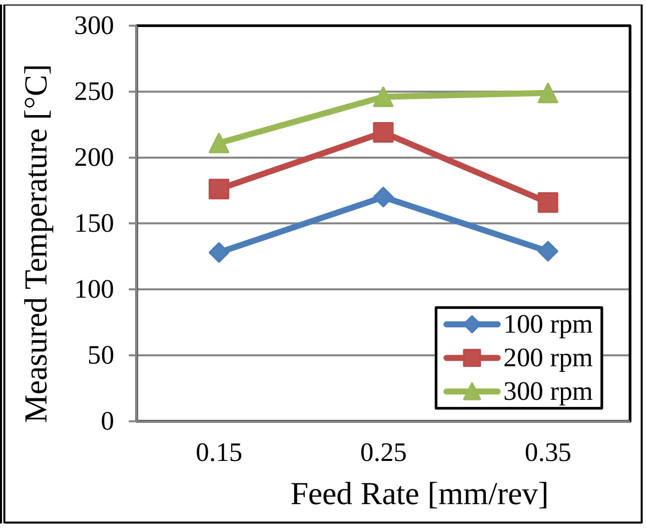


**Figure 8 The variation of temperature with respect to feed rate at tool of 118° point angle.**

### 5.2.3 The influence of tool point angle on workpiece temperature

From Figure 9, and 10, the larger point angle tool produced high temperatures in the machined models whereas the smaller point angle tool produced low temperatures in the machined models. The explanation for that is the increase of drill bit point angle led to an increase in the cross-sectional area of deformation which means wider frictional contact at the tool-workpiece interface and thus higher temperatures were generated in the machined models. It can also be noted an important observation that the deviation between the workpiece temperatures that caused by booth tools becomes lower when using a higher feed rate. This is maybe because the higher feed rate caused the workpiece to be rubbed strongly with the tool during the drilling operation, and thus, the temperatures which are produced through high feed rate will be high and close to each other. The results of the influence of tool point angle are agreed with the references [7, 8, 10, 11, 12, and 13]. The deviation of temperatures owing to various point angles is calculated as:

$$\text{Percentage } (\%) = \left( (T_{hp} - T_{lp}) / T_{lp} \right) 100\% \tag{4}$$

Where, $T_{hp}$ is the temperature at high point angle, and $T_{lp}$ is the temperature at low point angle.

**Table 13 The deviation between temperatures due to the change of point angle**

| Process No. | Speed rpm | Feed Rate mm/rev | Specified workpiece temperature °C | | Deviation (%) |
|---|---|---|---|---|---|
| | | | 110° point angle | 118° point angle | |
| 1 | 100 | 0.15 | 84.1 | 128 | 52.2 |
| 2 | 100 | 0.25 | 118 | 170 | 44 |
| 3 | 100 | 0.35 | 104 | 129 | 24 |
| 4 | 200 | 0.15 | 145 | 176 | 21.4 |
| 5 | 200 | 0.25 | 172 | 219 | 27.3 |
| 6 | 200 | 0.35 | 155 | 166 | 7.1 |
| 7 | 300 | 0.15 | 184 | 211 | 14.6 |
| 8 | 300 | 0.25 | 202 | 246 | 21.7 |
| 9 | 300 | 0.35 | 217 | 249 | 14.7 |

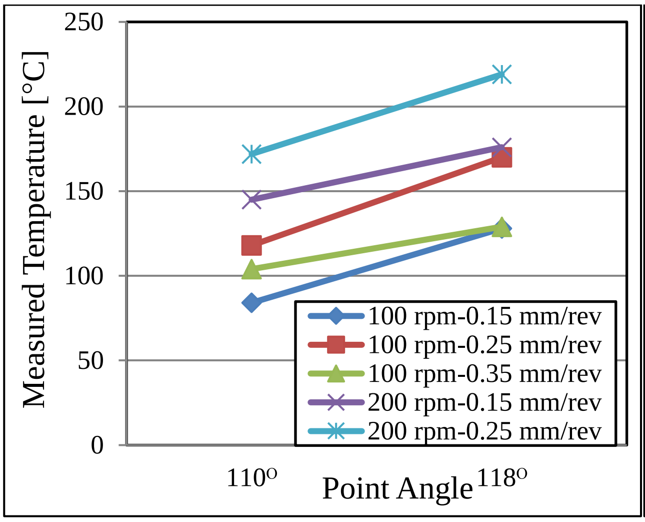


**Figure 9 The variation of temperature with respect to point angle for five FE operations.**

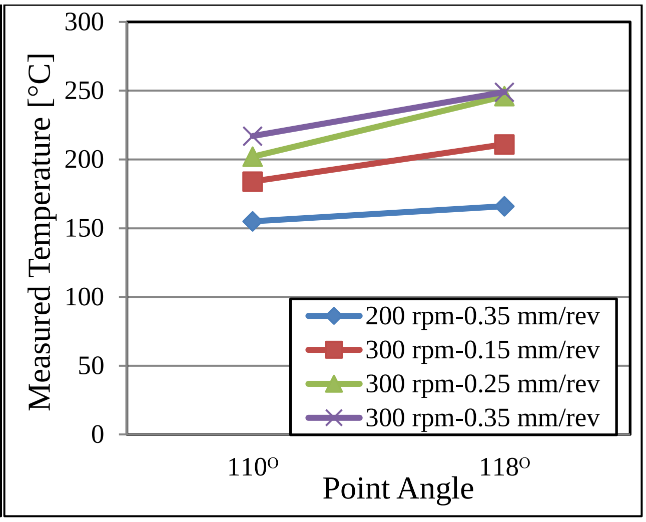


**Figure 10 The variation of temperature with respect to point angle for four FE operations.**

### 5.3. The statistical results

A multiple linear regression model was used in which the quantitative data of speed, feed rate, and tool point angle were considered as independent variables and the specified workpiece temperature from FE simulations as the dependent variables. The results of regression showed there is a significant relationship between speed, feed, and drill point angle. This can be known from the F value and its significance which are (34.849), (0.000), respectively. From F value and its significance value, it may be said that the model is valid and there is a strong correlation between the temperature and the independent variables. Therefore, the null hypothesis is refused and the alternative hypothesis is accepted. The results of linear regression are listed in Table 14.

**Table 14 Results of linear regression.**

| | |
|---|---|
| R Square | 0.882 |
| F Value | 34.849 |
| F (Significance) | 0.000 |
| Constant Value ($\alpha$) | -439.715 |
| Beta of Speed ($\beta_1$) | 0.48 |
| Beta of Feed ($\beta_2$) | 76.583 |
| Beta of Point Angle ($\beta_3$) | 4.346 |
| VIF factor | 1.000 |

The linear regression equation is observed from the beta of speed, feed rate, and point angle is:

$$Y_1 = -439.715 + 0.48\,(S) + 76.583\,(F) + 4.346\,(P) \tag{5}$$

Where, $Y_1$ is the prediction of temperature by linear regression method, S is the cutting speed, F is the feed rate, and P is the point angle. In the nonlinear regression model, the cutting parameters and point angle were considered as independent variables, whereas temperature was considered as dependent variable. To perform a nonlinear regression according to the quantitative data, there is an obligation to do a curve estimation regression between each independent variable such as speed, feed, and point angle and the dependent variable of temperature, separately, taking into consideration about 10 nonlinear models. The target of making this step before nonlinear regression is to find out which model gives the higher values of R square for the purpose of adopting its mathematical formula to be inserted in model expression of nonlinear regression. The "Cubic" model provided higher R square than other nonlinear models; thus the decision was to use its nonlinear formula as a model expression in nonlinear regression. The results of the curve estimation regression are concluded in Table 15.

**Table 15 The important results of nonlinear regression.**

| **Parameter** | **Curve Estimation between** | | |
|---|---|---|---|
| | **Speed-Temp** | **Feed-Temp** | **Point Angle-Temp** |
| Total Cases | 18 | 18 | 18 |
| R | 0.85 | 0.294 | 0.377 |
| R Square | 0.722 | 0.086 | 0.142 |
| Adjusted R square | 0.685 | -0.036 | 0.088 |
| Standard Error of the Estimate | 26.647 | 48.306 | 45.322 |
| F Value | 19.473 | 0.708 | 2.648 |
| F (Significance) | 0.000 | 0.508 | 0.123 |

The final nonlinear expression for predicting temperature is:

$$Y_2 = (B0 + B1 * S + B2 * S^2 + B3 * S^3) + (B4 + B5 * F + B6 * F^2 + B7 * F^3) + (B8 + B9 * P + B10 * P^2 + B11 * P^3) \tag{3}$$

Where $Y$ is the temperature extracted by nonlinear regression, S is the cutting speed, F is the feed rate, and P is the point angle of the cutting tool. The constant parameters from B0 to B11 should be defined quantitatively in modeling of nonlinear regression and these parameters are very easily to be taken from the curve estimation regression results, see Table 16.

**Table 16 The constant parameters in nonlinear regression model.**

| B0 | B1 | B2 | B3 | B4 | B5 | B6 | B7 | B8 | B9 | B10 | B11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 70.21 | 0.523 | 0.324 | -3.32E-7 | 9.365 | 1351.167 | -2549.167 | 1 | -324.59 | 4.346 | 1 | 1 |

The results of nonlinear regression provided the high value of R square which is resulted from the sum of R squares that gained from each curve estimation regression as 95% variations in temperatures. Thus, the model is valid and there is a strong correlation between the independent variables and the dependent variable. The final step for linear and nonlinear regressions is to predict the Y parameter which is the temperature by linear and nonlinear regressions. This can be achieved by applying equations 5 and 6 to the quantitative data of each operation, see Table 17.

**Table 17 Temperatures of FE analysis and predicted ones from SPSS software.**

| Operation | Speed (rpm) | Feed Rate (mm/rev) | Point angle | FE temperature °C | SPSS Temperature °C | |
|---|---|---|---|---|---|---|
| | | | | | Linear Regression | Nonlinear Regression |
| 1 | 100 | 0.15 | 110° | 84.1 | 97.81 | 88.64 |
| 2 | 100 | 0.25 | 110° | 118 | 105.46 | 121.80 |
| 3 | 100 | 0.35 | 110° | 104 | 113.12 | 103.96 |
| 4 | 200 | 0.15 | 110° | 145 | 145.80 | 138.63 |
| 5 | 200 | 0.25 | 110° | 172 | 153.46 | 171.78 |
| 6 | 200 | 0.35 | 110° | 155 | 161.11 | 153.94 |
| 7 | 300 | 0.15 | 110° | 184 | 193.79 | 184.63 |
| 8 | 300 | 0.25 | 110° | 202 | 201.45 | 217.78 |
| 9 | 300 | 0.35 | 110° | 217 | 209.11 | 199.94 |
| 10 | 100 | 0.15 | 118° | 128 | 132.57 | 123.41 |
| 11 | 100 | 0.25 | 118° | 170 | 140.23 | 156.56 |
| 12 | 100 | 0.35 | 118° | 129 | 147.89 | 138.73 |
| 13 | 200 | 0.15 | 118° | 176 | 180.56 | 173.39 |
| 14 | 200 | 0.25 | 118° | 219 | 188.22 | 206.54 |
| 15 | 200 | 0.35 | 118° | 166 | 195.88 | 188.71 |
| 16 | 300 | 0.15 | 118° | 211 | 228.56 | 219.39 |
| 17 | 300 | 0.25 | 118° | 246 | 236.21 | 252.54 |
| 18 | 300 | 0.35 | 118° | 249 | 243.87 | 234.71 |

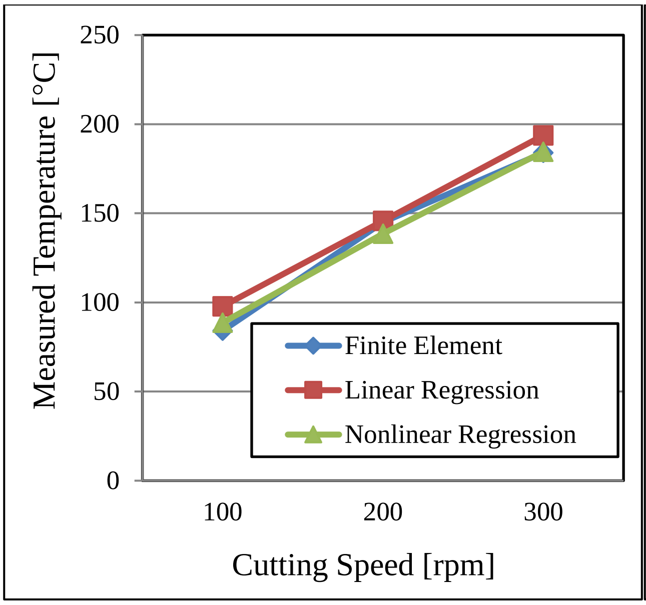


**Figure 11 The variation of temperature vs. cutting speed for feed of 0.15 mm/rev, tool 110º.**

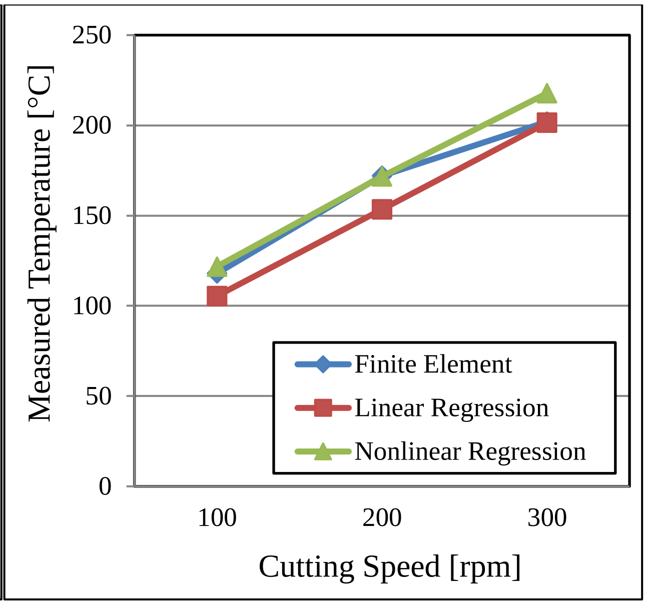


**Figure 12 The variation of temperature vs. cutting speed for feed of 0.25 mm/rev, tool 110º.**

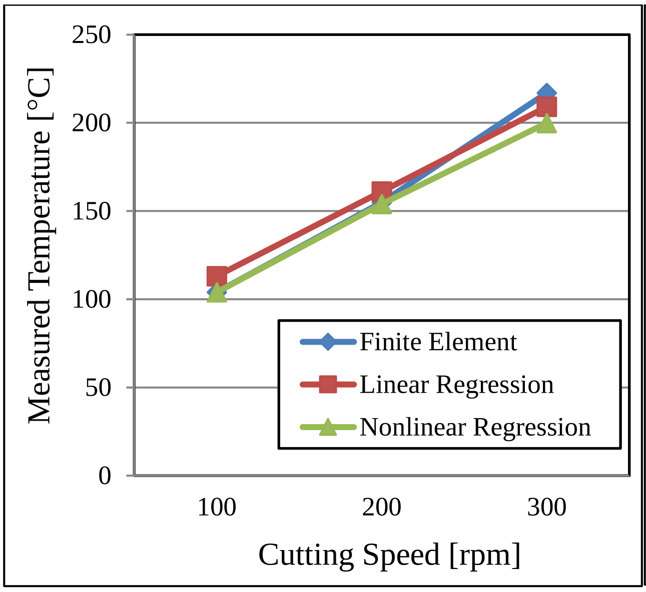


**Figure 13 The variation of temperature vs. cutting speed for feed of 0.35 mm/rev, tool 110º.**

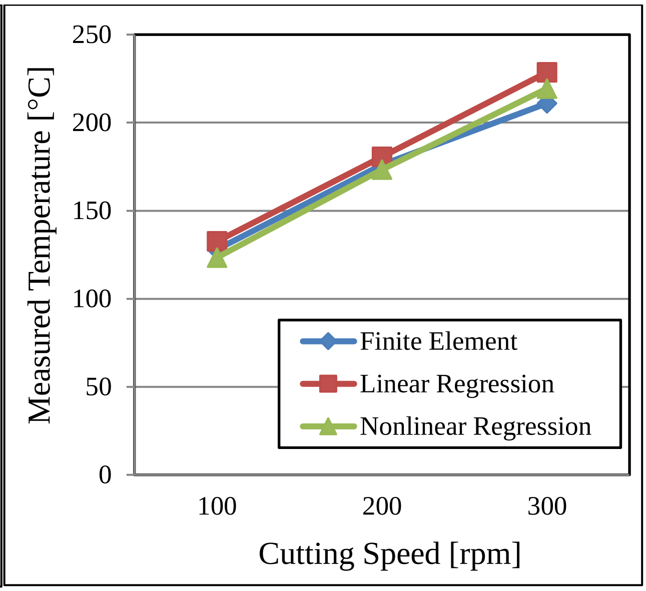


**Figure 14 The variation of temperature vs. cutting speed for feed of 0.15 mm/rev, tool 118º.**

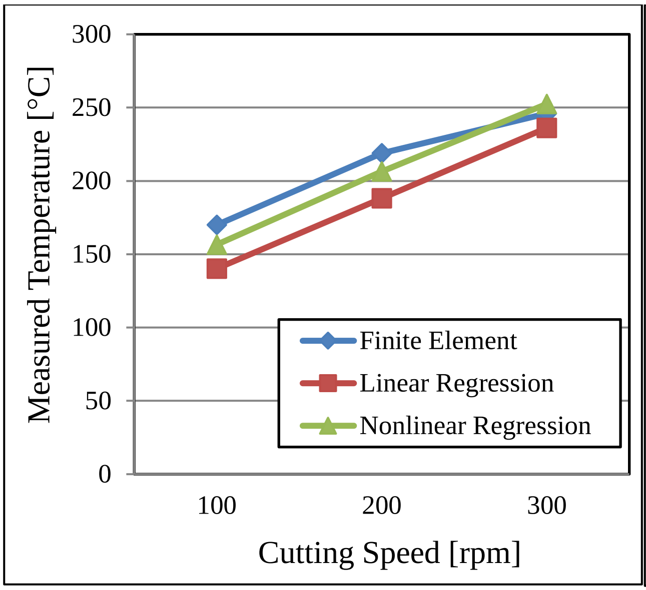


**Figure 15 The variation of temperature vs. cutting speed for feed of 0.25 mm/rev, tool 118$^{O}$.**

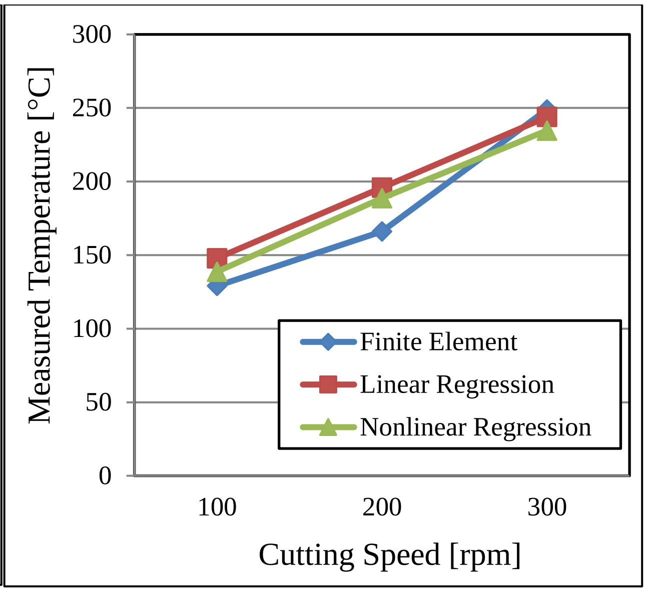


**Figure 16 The variation of temperature vs. cutting speed for a feed of 0.35 mm/rev, tool 118$^{O}$.**

Figures (11-12-13) indicate that there is a good closeness between the readings when the tool has a 110$^{O}$ point angle, unless Figure 12 which is the less closeness between the operations of 110$^{O}$ point angle. Figure 14 showed the best closeness when the tool is 118$^{O}$ point angle and the closeness became poor at figures 15 and 16. But in general all the figures showed a temperature elevation with an elevation of speed. The closeness between FE temperatures and SPSS temperatures can be investigated as below equation:

$$Deviation\ \% = ((T_{FE} - T_{SPSS})/(T_{FE}))100\ \% \tag{7}$$

Where, $T_{FE}$ is the FE temperature and $T_{SPSS}$ is the linear or nonlinear regression temperature.

From Table 18, the higher and lower deviations between FE and linear regression are 17.5% and 0.27%, respectively, whereas the higher and lower deviations between FE and nonlinear regression are 13.68% and 0.038%, respectively. From that it can be said that the closeness between FE and nonlinear regression is better than the closeness between FE and linear regression. From that it can also be said that the nonlinear regression is considerable in this study. To check the results of the experimental and its FE validation with the quantitative temperatures of linear and nonlinear works, see Figure 17. The figure provides evidence about the closeness between experimental, FE and SPSS temperatures, and this leads to consider the study is valid to use the FE temperatures in the statistical analysis of this program.

Table 18 The deviation percent between FE temperatures and the ones predicted by SPSS software.

| Operation No. | Point angle | Temperature °C | | | Absolute Deviation (%) Between: | |
|---|---|---|---|---|---|---|
| | | FE Temperature | Linear Regression | Nonlinear Regression | FE-Linear Regression | FE-Nonlinear Regression |
| 1 | 110° | 84.1 | 97.81 | 88.64 | 16.3 | 5.39 |
| 2 | 110° | 118 | 105.46 | 121.80 | 10.62 | 3.22 |
| 3 | 110° | 104 | 113.12 | 103.96 | 8.77 | 0.038 |
| 4 | 110° | 145 | 145.80 | 138.63 | 0.55 | 4.4 |
| 5 | 110° | 172 | 153.46 | 171.78 | 10.78 | 0.128 |
| 6 | 110° | 155 | 161.11 | 153.94 | 3.9 | 0.684 |
| 7 | 110° | 184 | 193.79 | 184.63 | 5.32 | 0.342 |
| 8 | 110° | 202 | 201.45 | 217.78 | 0.27 | 7.8 |
| 9 | 110° | 217 | 209.11 | 199.94 | 3.63 | 7.86 |
| 10 | 118° | 128 | 132.57 | 123.41 | 3.57 | 3.6 |
| 11 | 118° | 170 | 140.23 | 156.56 | 17.5 | 7.9 |
| 12 | 118° | 129 | 147.89 | 138.73 | 14.6 | 7.5 |
| 13 | 118° | 176 | 180.56 | 173.39 | 2.6 | 1.48 |
| 14 | 118° | 219 | 188.22 | 206.54 | 14 | 5.69 |
| 15 | 118° | 166 | 195.88 | 188.71 | 18 | 13.68 |
| 16 | 118° | 211 | 228.56 | 219.39 | 8.3 | 3.97 |
| 17 | 118° | 246 | 236.21 | 252.54 | 3.98 | 2.65 |
| 18 | 118° | 249 | 243.87 | 234.71 | 2 | 5.73 |

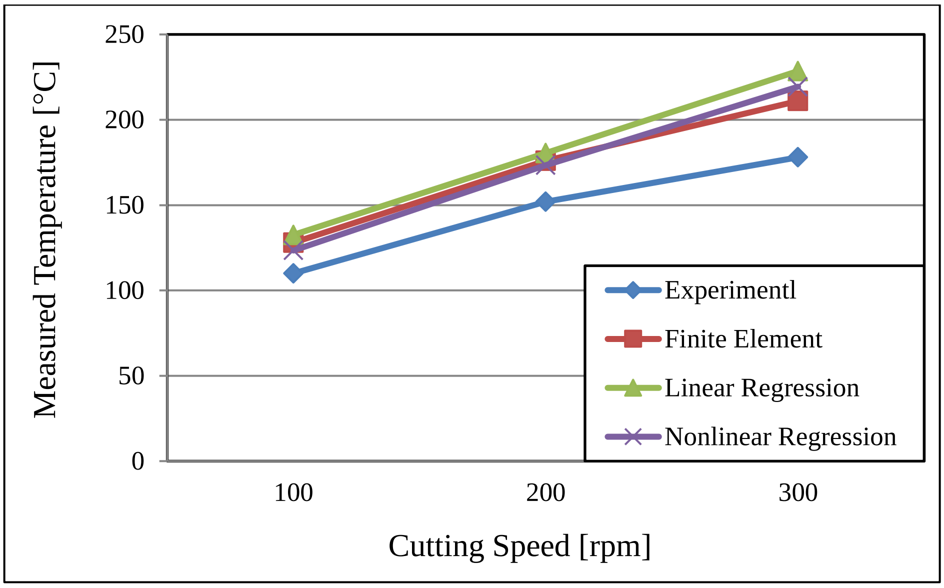


**Figure 17 Variation of temperature vs. cutting speed for experimental, its FE validation and SPSS.**

## 5. Conclusions

The present study includes an experimental investigation with FE validation to measure the workpiece temperature in at a specified point. The second part of this study includes FE simulations to study the effect of cutting parameters and tool point angle on the heat generated in the workpiece material in dry drilling of stainless steel AISI 304. The temperature results of these simulations are then used in predicting the workpiece temperature in both linear and nonlinear regressions by using SPSS software. The following conclusions have been summarized from this study:

1. The maximum error between experiments and their FE simulations didn't exceed over 20%, and this is the suitable situation for validation. This was the main reason for considering the FE results of temperatures in predicting the temperatures of linear and nonlinear regressions.

2. The higher experimental temperature occurred when 300 rpm cutting speed was used. Also, the FE simulations that were executed for validation purpose, recorded higher temperatures at a speed of 300 rpm. Therefore, speed is a significant factor in controlling the workpiece temperature in both experimental and numerical simulations.

3. The influence of cutting speed on FE temperature of the machined model was very noticeable and significant. The higher rise in temperature (249$^{O}$C) was recorded when the speed of 300rpm was used, and the lower rise in temperature (84.1$^{O}$C) was recorded when the speed of 100rpm was used.

4. The influence of feed rate was not clear enough because sometimes the temperature was dropped significantly with the increase of feed rate and sometimes the temperature was increased with the increase of feed rate. Only one speed (300) rpm, kept a noticeable increase in temperature with increase of feed rate at all cutting tools of different point angles.

5. The influence of drill point angle on the machined model's temperature was very significant. The tool of 110$^{O}$ point angle produced lower workpiece temperatures compared with the tool of 118$^{O}$ point angle. The maximum deviation in temperature between both tools of different point angles is more than 52% and this value exceeded fifty percent.

6. After predicting the temperatures by linear and nonlinear regressions, there was a high closeness between FE and nonlinear regression temperatures because the higher deviation was only 13.68 %, whereas the higher deviation between FE and linear regression temperatures was 17.5%. This indicated that the nonlinear assumption is considerable in this study because the

higher R square was recorded in the results of nonlinear regression as 95 %, whereas the R square of linear regression is 88.2%, but in anyway both regressions were valid to predict the workpiece temperatures because the very small difference between their results.

## Nomenclature

| | |
|---|---|
| $T_m$ | Machining time (min) |
| $t$ | Drilling depth (mm) |
| $D$ | Diameter of the tool (mm) |
| $\Theta$ | Point angle of the drill bit |
| $f$ | Feed speed (mm/rev) |
| $N$ | Spindle speed (rpm). |
| $Y$ | The predicted temperature by linear or nonlinear regressions |
| $\alpha$ | Constant value |
| $\beta_1$ | Slope of the regression y on the first independent variable |
| $\beta_2$ | Slope of the regression y on the second independent variable |
| $\beta_K$ | Slope of the regression y on the k independent variable |
| $X_1$ | The first independent variable |
| $X_2$ | The second independent variable |
| $X_k$ | The k independent variable |
| $T_{hp}$ | The temperature caused by high point angle tool |
| $T_{lp}$ | The temperature that caused by low point angle tool |
| $Y_1$ | The temperature predicted by linear regression |
| $Y_2$ | The temperature predicted by nonlinear regression |
| $S$ | The cutting speed (rpm) |
| $F$ | The feed rate (mm/rev) |
| $P$ | Tool point angle |
| $B0\ to\ B11$ | Definable constant parameters in nonlinear regression |
| $T_{FE}$ | The maximum workpiece temperature by FE analysis |
| $T_{SPSS}$ | The predicted temperature value by linear or nonlinear regressions |

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## دراسة عملية ونظرية وتحليلية لدرجة الحرارة المتكونة في الصلب المقاوم للصدأ 304 خلال عملية التثقيب

***الخلاصة:*** *تم اكتشاف عملية التثقيب في وقت مبكر من التكنلوجيا الحديثة نظرا لاهمية هذه العملية في الصناعة. هذه العملية تم تطويرها لتلبية متطلبات الصناعة الحديثة. دراسة العوامل التي تؤثر في عملية التثقيب مهمة جدا لتطوير وتحسين اداء ادوات القطع والعملية بصورة عامة. الغرض من هذه الدراسة هو اثبات التقارب في قياس درجة حرارة معينة على سطح قطعة العمل بين العملي باستخدام الة تثقيب واداة تثقيب والنظري باستخدام برنامج تشوه- ثلاثي الابعاد. هذا التقارب يعتبر دليل على موثوقية درجات الحرارة النظرية في ايجاد معادلتين احداهما خطية والاخرى غير خطية لقياس درجة الحرارة باستخدام البرنامج الاحصائي. للجزء العملي تم استخدام اداة ذات قطر 10 ملم وذات زاوية اداة قدرها 118 درجة وتمت عمليات التثقيب باستخدام الة تثقيب نصف قطرية. ثلاث سرعات قطع وهي (100-200-300) دورة/دقيقة وسرعة التغذية ثابتة وقدرها 0.15 ملم/دورة وعمق التثقيب هو 3 ملم. العمليات التطبيقية موجودة من ضمن العمليات التي تمت بالبرنامج. الجزء النظري (البرنامج) والذي يعتمد على طريقة العنصر المتناهي الصغر حيث تم اجراء دراسة تأثير سرعة القطع والتغذية وزاوية النقطة للأداة على درجة حرارة القطعة ولهذه الدراسة تم استخدام اداتين ذات قطر ثابت 10 ملم و زاوية نقطة مختلفة احداهما 110 درجة والاخرى 118 درجة والاداتين تم تنزيلهما من موقع الكتروني مجاني. شكل قطعة العمل اسطواني ذات قطر 50 ملم وسمك 5 ملم. السرعات هي 100- 200- 300 دورة/دقيقة وسرعة التغذية 0.15-0.25-0.35 ملم/دورة وعمق قطع ثابت لكل العمليات 3 ملم. النتائج اثبتت تقارب قوي بين الجزء العملي والنظري الخاص به ولهذا السبب يمكن اعتبار نتائج العمليات النظرية موثوقة لغرض استخدامها في الدراسة التحليلية. السرعة اثرت بشكل ملحوظ على درجة الحرارة حيث ازدادت الحرارة بازدياد السرعة كذلك الاداة ذات زاوية النقطة*

*الاكبر ادت الى حصول حرارة اكبر في قطعة العمل. الحرارة الناتجة من الدراسة التحليلية اثبتت تقارب قوي بين درجات الحرارة الناتجة من البرنامج والانحدار اللاخطي الذي نتج من استخدام البرنامج الاحصائي وبذلك يمكن اعتبار التغير الذي حصل في الحرارة في هذا البحث هو تغير لا خطي.*