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Prediction of cutting temperature in carbide cutting tool using finite element method

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ABSTRACT

This study demonstrated the effectiveness of the finite element method in predicting the cutting temperature in carbide inserted cutting tool. A three-factor Box-Behnken design, making seventeen cutting tests of a cylindrical mild steel bar with 200 mm length by von mises diameter was employed to study the numerical and the experimental predictions. The data obtained from the tool tests was compared and statistically analyzed using the reliability plots. On comparison, both the experimental and finite element method (FEM) analysis by ANSYS® readings were in close agreements, with the minimum and maximum error of 0.010% and 0.895%, respectively. In conclusion, the research clearly shows that ANSYS® is a very efficient expert tool for modeling and predicting the cutting temperature of carbide insert cutting tool in dry turning operation using mild steel.

1. Introduction

Machining process like the metal cutting operation is a plastic deformation process that has been found to generate more heat than the simple manual tools due to the sliding friction of the chip on the rake face. The heat generated during the cutting operation brings about a rise in the temperature of the tool, chip and the work-piece. As the temperature increases, it adversely impairs the cutting tool, chips and weakens the mechanical properties of the machined surface. The magnitude of the cutting temperature depends on quite a number of factors like the tool geometry parameters, cutting conditions (wet or dry), type of material of the cutting tool/work piece and the process parameters [1]. However, the major effect of the increased cutting temperature in Von Mises stress, which inevitably is induce on the cutting tool due to high strains. The produced Von Mises stresses are the major cause of tool fracture, fatigue and failure; a situation resulting from loses of bindings within the crystals of the tool materials [2]. This makes the prediction of the tool's temperature an important undertaking, as it will optimally adjust the various cutting parameters before-hand for an improved machinability. Ostafieu et al. [3] examined tool heat transfer in orthogonal metal cutting under steady state. The iterative procedure was used to determine the temperature distributions on the cutting tool. Thereafter, the heat flux model with its conditions was analyzed. Their results showed agreement with the experimental results; meaning that the chosen heat flux model was appropriate. Grzesik [4] studied the influence of the tool-work interface temperature when machining AISI 1045 and AISI 304. The researcher employed the use of a standard K-type thermocouple to measure the interface temperature of the work piece. Dewes et al. [5] developed a temperature prediction model which they applied under transient conditions. It was done by a fixed-point iteration process in quasi-steady energy partitioning to improve on Stephen's model. Chaudhary et al. [6] addressed the tribology in metal cutting in treating the thermal issues, they developed an analytical model that was used to determine the temperature distributions in the chip, the tool and the work piece material using the combined effect of two heat sources, namely; the nature of the apparent heat partition in the shear plane and the variable heat partition at the chip-tool interface. The researchers were

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able to justify the empirical model using a wide range of pellet numbers available in the experimental data obtained from literature. Miller et al. [7] carried out a study on cutting tool temperature measurement using a new experimental technique known as modern digital infrared imaging technique. This device was able to overcome many problems associated with past experimental techniques during orthogonal machining operations. The device was effective as it successfully displaced the temperature distributions on the cutting tool. Abhang and Hameedullah [8] carried out a study on EN-31 steel alloy with tungsten carbide insert using the tool-work thermocouple technique to research the tool-chip interface temperature. Their results showed agreement with the shaw's non-dimensional model. In addition, the work was able to ascertain that increasing cutting speed, feed rate and depth of cut can bring about increase in the cutting temperature of the tool. Ranc et al. [9] also studied temperature prediction in orthogonal cutting of Al/SiCp composites with a k-20 carbide cutting tool using a thermocouple. This was to measure the temperature along the cutting tool edge at various cutting speeds and depths of cut while the feed rate was kept constant. The temperature distributions at the cutting edge, shear zone and the interface region were estimated from the analysis of the steady state heat transfer carried out by the researchers. Nasr et al. [10] confirmed that when they studied the turning process during metal cutting. They agreed on the fact that the metal cutting process is the biggest part of the manufacturing sector which in turn represents the biggest energy consumers in the world. Their results showed that the cutting temperature increases with increase in the spindle speed, feed rate and depth of cut.

This study focused on expert modeling and prediction of cutting temperature in carbide insert cutting tool using finite element method (ANSYS).

2. Materials and Methods

2.1 Workpiece Material

The workpiece material that is used in the cutting tool test was a cylindrical bar mild steel (American Iron and Steel Institute, AISI 1010). This choice is the result of sustainability in a wide variety of automotive applications such as axles and spline shafts [11]. The mild steel (workpiece) was first planed to a uniform dimension of 200 mm in length and 44 mm in diameter, respectively.

2.2 Tool material

The tool material used in this study is a triangular and removable coated carbide insert P(10). In this study, it was selected since it performs better than the uncoated carbide tool when turning steel. Thomas et al. [12] founded that it can reduce tendency to built up edges, less heat generation and increase tool life thanks to reduced friction, fewer thermal cracks and most importantly the wear pattern which is recognized easily by the yellow tin layer [13].

2.3 Experimental Method

The Box Behnken Design (BBD) The 3 factors Box Behnken Design BBD is a response surface design that is suitable for exploiting quadratic response surfaces, thereby helping to generate a second-degree polynomial model that is used for optimising the process. It is also advantageous for three factors taken at different levels because it requires fewer numbers of runs but for four or more factors this advantage disappears. Hence it has been adopted for this study because it was used to determine the process relationship between the independent variable (spindle speed, federate and depth of cut) and dependent variable (Cutting temperature which is ordinary difficult with direct straight line experimental method. Some other characteristics of BBD are good lack of fit detection, suitability for blocking, minimum number of treatments. combinations, good graphical analysis through simple data patterns, very cost effective, good distribution of variance of the produced response(s) through the design region and internal estimate of error. It was developed using the design expert (software). While the experimental runs is determined by the number of the input parameters using Equation (1) below:

$$N = K^2 + K + C_p \tag{1}$$

where N = number of experimental runs, K= Factors number which is 3 in this case, Cp= number of replications at the centre point which is 5 in this case.

In this study, the experimental cutting test included the dry cutting of a cylindrical mild steel bar is 200 mm length by 44 mm diameter by using the industrial Lathe machine. For the machining operation, carbide inserts single-point cutting tool was used. The three-factors BBD of experiment was adopted. The parameters of cutting that are the feed rate, depth of cut and the spindle speed are shown in Table 1. 7^{th} experiment were performed as given in Table 1. For the cutting tool tests, The 2060 Electronic numerical controlled (ENC) model lathe situated at Prototype Engineering Development Institute (PEDI), Ilesa, Osun state, Nigeria was used.

Interpretation and evaluation of result is expressed in this stage. Seventeen experiments were conducted for the cutting temperatures in carbide insert tools while machining AISI 1010 mild steel under dry condition. The cutting tool tests were based on the three factors Box-Behnken design generated by the Design Expert. During, the experimental test, the K-type digital multi- meter thermometer was used to measure the tool's temperature.

The carbide inserts cutting tool test was conducted based on the three factors Box Behnken's experimental design on a 2060 CNC industrial lathe under dry condition using cylindrical mild steel of 200 mm long. Before the experiments, the work piece was first plain for uniform diameter of 44 mm in the university of Benin Production laboratory.

The plain work piece was then taken to the lathe for machining where it was supported between the three chucks of the rotating center of the tail stock while the carbide inserts cutting tool was mounted on the righthand tool holder. And at different times, the cutting tool was automatically fed based on the selected values and levels of the cutting parameters. The researcher's application of the three factors Box Behnken Design is to determine the optimum values of the cutting parameters that will enable effective functioning of the cutting tool when using mild steel. The cutting parameters were chosen at different levels of spindle speed ranging from 200-600 rpm and federate from 0.05-1.5 mm/rev.

The configuration is based on the experimental designed matrix of seventeen runs was used. The tool work piece thermocouple (k-type digital thermocouple GM 1312) was used to measure the cutting temperature of the cutting tool. During the experiment three readings were taken at every 5 minutes and their average was adopted measured data so as to minimize experimental error. And after each single test the carbide tool was replaced, this was to eliminates the defects of temperature and possible tool wear on the tool and responses.

2.4 Numerical Method

The finite element method (FEM) which is an expert tool was used for simulating the behavior of the cutting tool during machining. Furthermore, commercial FEM software such as ANSYS® was used to analyze finite element problem in three steps namely: preprocessing, solution and post processing according to Etin-osa and Achebo [14].

Governing equation and bounding conditions of heat transfer:

The governing equation for temperature variation in the carbide insert cutting tool is derived from energy conservation and fourier law as showed below; Energy in-Energy out +Energy generation=Energy stored.

Table 1. Cutting parameters and corresponding levels [15]

Tools Type		Cemented Carbide inserts		
Workpiece materials		Mild Steel		
Cutting parameters	Symbols/ Units	Low (-1)	Medium (0)	High (+1)
cutting speed	n, rpm	200	400	600
Feed rate	f, mm/rev	0.05	0.1	0.15
Depth of cut	d, mm,	0.5	1.0	1.5

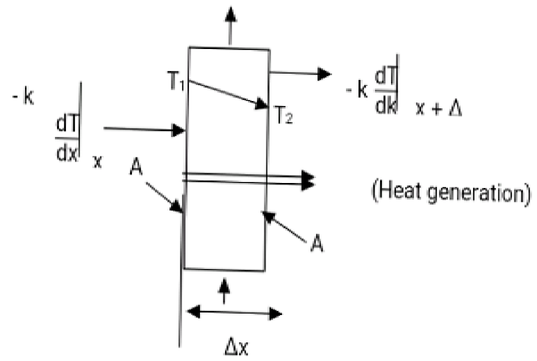

Figure 1. Control volume showing energy inflow and outflow by conduction through the carbide insert cutting tool.

From Figure 1, the basic description of the process is using the first law in control volume form (steady flow energy equation as given in Equation (2) below:

$$Qx = -K\left(\frac{AdT}{dx}\right)x \quad (2)$$

Taking the limit as dx approaches zero, we have:

$$\frac{dQ(X)}{dx}=0 \quad (3)$$

or

$$\frac{d}{dx}\left(KA\frac{dT}{dx}\right) = 0 \quad (4)$$

Equation (4) is the temperature field for quasi-one dimensional steady state heat transfer. Where K is constant, Equation (4) reduces to

$$\frac{d}{dx}\left(A\frac{dT}{dx}\right) = 0 \quad (5)$$

The term $\frac{dT}{dx}$ is called the gradient, which is the slope of the temperature curve with length x.

The temperature conditions for the cutting tool from Equation (4) where A is constant is:

$$\frac{d^2T}{dx^2} = 0 \quad (6)$$

When Equation (5) is integrated, it becomes:

$$\frac{dT}{dx} = 0 \quad (7)$$

and

$$T = cx + d \quad (8)$$

Equation (8) is the expression for the temperature field where c and d are constants of integration. For second order equation such as Equation (6), 2-boundary conditions are needed to determine c and d. One of such set of boundary conditions can be specification by the temperatures at both sides of the tool as:

$$T_{0} = T_1 \; and \; T_L = T_2$$

$$or$$

$$T = T_1 \text{ at } x = 0 \quad (9)$$

$$T = T_2 \text{ at } x = L \qquad (10)$$

so T_1=d , T_2=cL +d. Therefore,

$$T = \frac{T1 - T2}{L} x + T_2 \qquad (11)$$

When surface temperature is specified, $T \big|_{x=0} = T_S$.

Therefore, the Fourier equation for steady conduction in a limiting case where Δx tends zero for the cutting tool is written in differential form. This includes the geometrical properties defining of the problem, the element connectivity (mesh the model), the element types to be used, the material properties of the elements, the physical constraints (boundary conditions) and the loadings. Figure 2 shows the basic model of the carbide single point cutting tool. The AutoCAD Inventor was used for the design and exported into ANSYS for the temperature analysis [15].

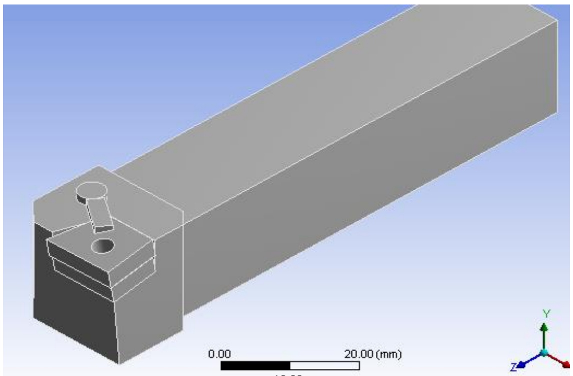

Figure 2. Carbide Insert Single Point Cutting Tool

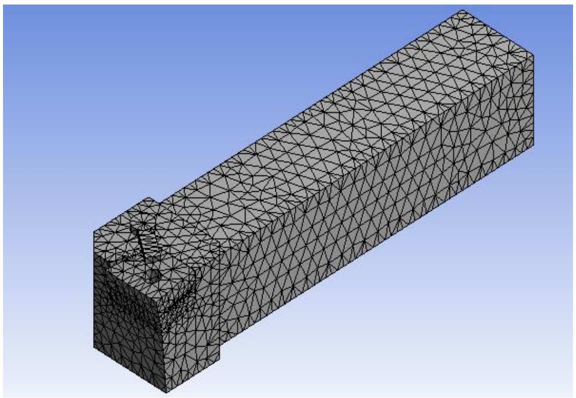

Figure 3. Meshing of Carbide Tool

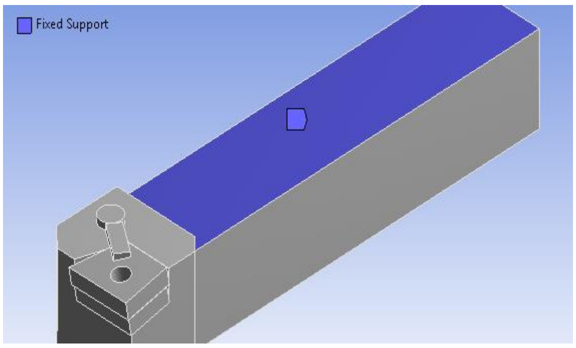

Figure 4. Fixed Support

Table 2. The coded and actual levels for the box-behnken experimental design

Process parameters	Symbols	Coded and Actual Levels		
		-1	0	+1
Spindle speed (rpm)	X_1	200	400	600
Feed rate (mm/rev)	X_2	0.05	0.10	0.15
Depth of cut (mm)	X_3	0.5	1.0	1.5

After the geometry modelling using AutoCAD, the geometry was exported to ANSYS® tool. The surface mesh for the specimen is shown in Figure 3. The fine was selected as the center relevance at the detail mesh section. 46407 and 28437 were the numbers of nodes and elements, respectively. They were generated for the meshed cutting tool. Finally, the analysis of the settings was carried out, where the boundary conditions such as applied force, fixed support, pressure etc. are specified. The fixed support for the cutting tool is shown in Figure 4, the top and bottom part are movement restricted. To find the induced temperature on the cutting tool, the values of the spindle speed, feed rate and depth of cut as given in Table 2 were attributed to tool of ANSYS®.

Solution:

In this step, the features like numerical integration, equation solving and matrix manipulation are performed automatically by the tool of software. The governing algebraic equation in matrix form, computation of the unknown values of the primary field and assembling was automatically done. The details of the discritization of the solution domain carried out for the FEM analysis and thus used by the expert system for the generation of the results are 46407 and 28437 for the nodes and the elements, respectively. The analysis was performed with the same design matrix at varying spindle speed, feed rate and depth of cut for seventeen different runs. The cutting tool was modeled using inventor 2019 and simulated using the commercial FE-ANSYS 16.0 expert, a finite element based software. The effect of the cutting temperature on the cutting tool is characterized with their maximum value at the fixed end of the tool in the FEM distributions field of this study and was then adopted in prediction of the concerned response simply to validate the experimental results.

3. Results

3.1 Results Obtained from the Experiment

Table 2 shows the coded and the actual levels for the Box-Behnken experimental design, while Tables 3 and 4 shows the experimental and numerical results obtained for carbide insert tool. Table 5 shows the experimental, FEM predicted and absolute percentage error for carbide cutting temperature.

Table 3. Experimental data for carbide tool while machining mild steel

Experimental runs	Spindle speed (rpm)	Feed rate (mm/rev)	Depth of cut (mm)	Average cutting temperature °C
1	200	0.15	1.00	141.10
2	400	0.05	1.50	161.11
3	600	0.10	1.50	340.60
4	400	0.10	0.50	72.10
5	600	0.05	1.00	154.40
6	400	0.05	0.50	74.90
7	600	0.10	0.50	135.00
8	600	0.15	1.00	311.60
9	400	0.10	1.00	177.79
10	200	0.05	1.00	80.00
11	400	0.15	1.50	330.52
12	400	0.10	1.00	177.79
13	400	0.10	1.00	177.77
14	400	0.10	1.00	177.79
15	400	0.10	1.00	177.78
16	400	0.15	0.50	130.00
17	200	0.10	1.50	152.99

Table 4. FEM Predicted results for carbide cutting tool

Run No.	Spindle speed, n (rpm)	Feed rate, f (mm/rev)	Depth of cut, ap (mm)	FEM Predicted cutting temperature, T (^{0}C)
1	200	0.15	1.0	142.22
2	400	0.05	1.5	162.73
3	600	0.10	1.5	342.33
4	200	0.10	0.5	72.658
5	600	0.05	1.0	155.02
6	400	0.05	0.5	75.576
7	600	0.10	0.5	135.44
8	600	0.15	1.0	312.41
9	400	0.10	1.0	178.57
10	200	0.05	1.0	80.351
11	400	0.15	1.5	330.00
12	400	0.10	1.0	178.57
13	400	0,10	1.0	178.57
14	400	0.10	1.0	178.57
15	400	0.10	1.0	178.57
16	400	0.15	0.5	131.33
17	200	0.10	1.5	153.97

Figure 5 and 6 shows the prediction of carbide cutting temperature using FEM while Figure 7 shows the reliability plots showing comparison between experimental and predicted carbide cutting temperature.

3.2 Discussion of Results

Table 2 was used by the selected design Expert 7.0 version to generate the randomized design matrix for the experimental and numerical study. The experimental matrix consists of three independent variables namely; spindle speed (rpm), feed rate (mm/rev) and depth of cut (mm). The response for this study is the cutting temperature. The data in Table 3 above shows that as spindle speed of machining mild steel with carbide tool increased from 200rpm to 600rpm while other input parameters are kept constant, the tool's cutting temperature increased from 72.10^{0}C to 340.60^{0}C. This is because the spindle speed determines the movement of the cutting tool; therefore, its variation causes a rise in the tool's temperature. This was found to be in line with past researchers like Grzesik et al. and Ozel and Altan [4, 16] who stated that increased in cutting speed and feed rate brought about increased in cutting zone temperature when they machined AISI 1045 and AISI 304 with carbide insert tool. Figure 5 shows the prediction that was obtained for carbide cutting temperature at varying process parameters using the finite element expert system. From Figure 5, the result shows that the predicted carbide cutting temperature is 142.22^{0}C when a spindle speed of 200rpm, feed rate of 0.15mm/rev and depth of cut of 1.0mm were applied. Figure 6 shows the prediction that was obtained for carbide cutting temperature at varying process parameters using the finite element expert system. From Figure 6 the result shows that the predicted carbide cutting temperature is 162.73^{0}C when a spindle speed of 400rpm, feed rate of 0.05mm/rev and depth of cut of 1.5mm were applied. The same predictive approach was used for experiment numbers 7-17. Table 4 shows the result of the FEM predicted values for carbide cutting tool while machining mild steel. From the result obtained, it can be deduced that as the spindle speed increased from 200rpm to 600rpm, there was an increased in the tool's cutting temperature from 142.22 ^{0}C to 342.33 ^{0}C.

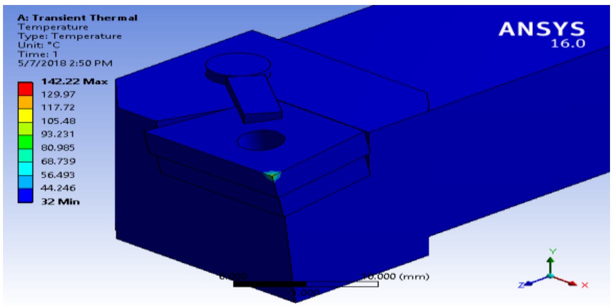

Figure 5. Prediction of carbide cutting temperature Using FEM

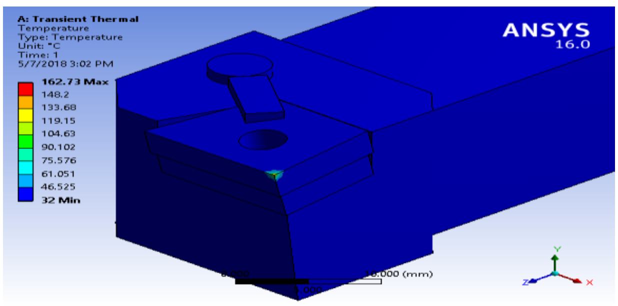

Figure 6. Prediction of carbide cutting temperature using FEM

Table 5. The experimental, FEM predicted and absolute percentag error for carbide cutting temperature

Run No.	Cutting temperatures (°C) Experimental (E)	Cutting temperatures (°C) FEM Predicted (P)	Absolute percentage error (%)
1	141.10	142.22	0.02381
2	161.11	162.73	0.01006
3	340.60	342.33	0.50793
4	72.10	72.658	0.76283
5	154.40	155.02	0.40155
6	74.90	75.576	0.89453
7	135.00	135.44	0.32593
8	311.60	312.41	0.25995
9	177.79	178.57	0.43872
10	80.00	80.351	0.43750
11	330.52	330.00	0.15733
12	177.79	178.57	0.43872
13	177.77	178.57	0.43876
14	177.79	178.57	0.43872
15	177.78	178.57	0.44437
16	130.00	131.33	0.01023
17	152.99	153.97	0.69980

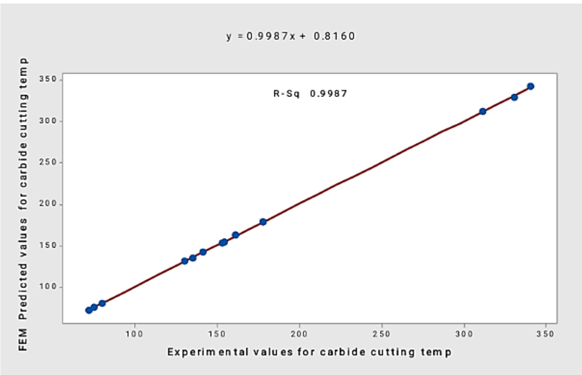

Figure 7. Reliability plots showing comparison between experimental and predicted carbide cutting temperature

It was also observed, that the increase in depth of cut from 0.5 mm to 1.5 mm generated a corresponding increase in the tool's cutting temperature from 72.658^{0}C to 330.99^{0}C. The same applied to the feed rate as it is increased from 0.5mm/rev to 0.1mm/rev, the tool's tip response also increased from 162.73^{0}C to 342.33^{0}C. Hence, it is suggested that the cutting parameters (n, f and ap) should be controlled in such a way as to have the optimum cutting temperature, as this will guarantee minimum tool wear and prolonged tool life for a better machining economy. This is also in line with the work of Elbestawi et al. [17]. The predicted result of Table 5 when compared with the experimental result shows a mean absolute error of 0.3936%. This value is small and below the maximum error of 10% recommended by Lazoglu and Altintas [2]; Olodu [18], respectively. Hence, the value is satisfactory and show good predictability of the model and its adequacy to predict the carbide cutting temperature. The carbide prediction inserted cutting tool cutting temperature when machining mild steel using dry orthogonal cutting process was executed by using the finite element method and experiment. This is to know-how accurate the FEM can predict the temperature on the tool. Finally, a comparison between the FEM and experiment was perfomed as presented in Table 5. It can be seen that both experimental and FEM (ANSYS®) reading were in close agreements, with the minimum and the maximum errors as 0.010 and 0.895, respectively in this table. From the FEM closeness pattern of the experiment (in Figure 7), it shows clearly that ANSYS® is a very useful predicting tool, that can be used for a cutting tool temperature simulation analysis.

4. Conclusion

In this study, an approach using FEM for predicting carbide insert cutting temperature has been successfully and effectively demonstrated. Based on the results and discussions presented in the preceding sections, the following conclusions have been drawn;

- All the three selected process parameters (spindle speed, feed rate and depth of cut) have significant effects on the tools' cutting temperature. However, the spindle speed has the most significant influence, followed by the depth of cut and then the feed rate. So, when a lower cutting temperature is desired for longer tool performance, the values of the process parameters should be set at considerably low levels.
- The experimental test shows that the chip formations are continuous type at lower process parameters.
- The FEA results show that the maximum cutting temperature is at the top of the cutting tool, which is the cause of tool failure.

Therefore, from the obtained results, it has been shown that the FEM predictions of the tool's temperature can improve the cutting tool service life as well as the machined components integrity. Therefore, the metal cutting industries should endeavor to use FEM simulated means like the ANSYS®, to predict their tool's cutting temperature for a specified cutting process, in order to prolong the service life of the cutting tools and to avoid exceedance of their yield points; a cause which leads to tool failure and wear when machining mild steel with carbide inserts cutting tools.

Declaration

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The authors also declared that this article is original, was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

Author Contributions

M. Ozakpolor developed the methodology and performed the analysis. C. Aliyegbenoma assisted in data collection, and D.D. Olodu improved the study.

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