Global Scientific JOURNALS

GSJ: Volume 7, Issue 1, January 2019, Online: ISSN 2320-9186
www.globalscientificjournal.com

EXPERT MODELLING AND PREDICTION OF VON MISES STRESSES IN CARBIDE INSERT CUTTING TOOL USING FEM (ANSYS)

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Abstract

Metal machining operation results in irreversible stripping of a work piece material in order to achieve a predefined geometry. It comes with various adverse effects on the cutting tool such as abnormal thermal gradient in the form of von mises stresses. These effects can lead to regrinding of the cutting edges, untimely tool's failure as well as poor surface finish on the work piece. These and many others are cost ineffective to the manufacturing firm. In this research, we aim to show how robust the Finite Element (ANSYS) method is, by comparing its predictive strength to the experimental machining operation.

To achieve our goal, we carried out an experimental cutting test using the dry cutting of a cylindrical mild steel bar of 200mm length by 44mm diameter. Carbide insert single point cutting tool was used for the machining operation. The Box-Behnken Design (BBD) of experiment was adopted for this work and seventeen (17) experimental tests were generated for the research. The experimental values were compared with the ANSYS simulated values.

At the end, both the experimental and FEM (ANSYS) readings were in close agreements, with the maximum and minimum error being 0.761 and 0.123 respectively. This research clearly shows that ANSYS is a very robust expert tool that can be used to model and predict von mises stress in carbide cutting tool.

Keywords: BBD, insert, FEM, Cutting tool, Von-mises stress.

1. Introduction

The metal cutting process is known to be a deformation process where cutting tool removes unwanted material from workpiece in form of chip to achieve a specified geometry. Associated with the followability of these chips from the cutting zone is some resistances on the cutting tool in the form of induced stresses. Literature has shown that these resistances are majorly caused by uncontrolled cutting parameters. Lawani et al (2008) carried out experimental investigations on the process parameter of a cutting tool and its influence on cutting forces and surface roughness for a finished Hard turning operation using MDN250 steel, the experimental operation involved cutting speed, depth of cut and feed rate as control variables, while feed force, surface roughness and the thrust force were taken as response parameters. During the experiment, the flank wear was measured with the tool maker's microscope. And at the end, the work was able to prove that good surface appearance in material can be attained when cutting speed, depth of cut are set close to their high level of (93m/min and 0.2mm respectively) while feed rate at low level of 0.04mm/rev. Ozel and Zeren (2004) also presented a methodology for the determination of work piece flow stress and the friction at the chip-tool interface during the high-speed cutting at high deformation rates due to the high cutting temperatures of the cutting zone. Their results were used to stimulate the high-speed machining using the finite element analysis based program. The flow stress model based on process dependent parameters like the stain, strain-rate and temperature were used together with the friction model so as to enable them to determine the unknown parameters of the flow stress and the friction model.

Shui-sheng et al (2001) proposed a material model using AL 606L-T6 over a wide range of strain rate between $10^{-4}S^{-1}$ to $10^{4}S^{-1}$ in order to evaluate the efficiency of the component of Johnson-cook (JC) material and the damage model.

Yen et al (2004) postulated that the most commonly used method for the determination of flow stresses are the tension, uniform and torsion tests.

Outeiro et al (2008) analyzed the residual stresses induced by dry turning on difficult-to- machined materials. Their focus was on the effects of cutting process parameters on the machining performance (residual stresses) and surface integrity while turning Inconel 718 and Austentic stainless steel AISI 318L under dry condition with coated and uncoated carbide tools. A three-dimensional predictive finite element model was developed and on comparing both the predicted and experimental result, according to the authors a new knowledge on surface integrity in terms of residual stresses was developed.

Marahao and Davim (2011) examined the role of flow stresses and friction coefficient on machining using finite element analysis. In the review work, the coulomb friction model was cited as the commonly used technique in most finite element method while the Johnson-cook constitutive law was presented as a prerequisite predictive model.

Altan and Semiatim (2012) stated that the quantitative analysis of the flow stress constitutes one of the most important inputs to the simulation of a metal forming process. And that the flow stress of a metal may be quantified in terms of its dependence on strain, strain-rate and temperature. They further stressed that the flow stress can also be based on the internal state variables such as the dislocation, density, gain size, phase formation, strain- rate and temperature.

Grzesik and Wanat (2006) investigated the influence of tool wear on surface roughness in hard turning using differently shaped ceramic tools. The surface roughness was determined by the macroscopic tool geometry at certain levels of feed rates. Others that have studied on similar research issue were Chou et al 2002, Benga and Abrao (2013), Grzesik and Wanat (2006).

The work piece material used in the cutting tool test is a cylindrical bar mild steel. Its American iron and steel institute, AISI is 1010. Its choice of selection is as a result of its sustainability in wide variety of automotive applications like in axle, and spline shaft, Aberg & Green (1996). The (mild steel) work piece was first plained for a uniform dimensions of 200mm in length and 44mm in diameter.

The tool material used is a triangular and removable coated carbide insert P(10). It choice of selection in this study is because it has been shown to perform better than the uncoated carbide tool when turning steel, Thomas et al. (1997). It has also be found to reduce the tendency to built-up edges, less heat generation and increase tool life owing to reduced friction, less thermal cracks and most importantly the wear pattern that is easily recognized with the yellow tin layer, Walter (1996). The insert was rigidly mounted on a right hand style tool holder, designated by ISO as MCLNR 2525 M12.

2. Experimental Method

The experimental cutting test in this work, involved the dry cutting of a cylindrical mild steel bar of 200mm length by 44mm diameter using the industrial 2026 ENC model Lathe machine. Carbide insert single point cutting tool was employed for the machining operation. The Box-Behnken Design (BBD) of experiment was adopted for this work, table 1 shows the cutting parameters which are the spindle speed, depth of cut and feed rate. From table 1, seventeen (17) experimental tests were generated for the research. While, Table 2 shows the generated BBD matrix for the three process parameters as well as the response obtained after experiment.

***Table 1**: Cutting parameters and their corresponding levels.*

Tools Types		Cemented Carbide insert		
Work piece materials		Mild Steel		
Cutting parameters	Symbols/ units	Low (-1)	Medium (0)	High (+1)
Spindle 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

***Table 2:** Experimental data for cemented carbide insert cutting tool while machining mild steel*

Experimental runs	Spindle speed (rpm)	Feed rate (mm/rev)	Depth of cut (mm)	Von mises stresses(Y2) N/mm^2
1	200	0.15	1.00	995.10
2	400	0.05	1.50	590.00
3	600	0.10	1.50	934.50
4	400	0.10	0.50	365.15
5	600	0.05	1.00	370.09
6	400	0.05	0.50	195.65
7	600	0.10	0.50	310.45
8	600	0.15	1.00	847.60
9	400	0.10	1.00	661.09
10	200	0.05	1.00	435.56
11	400	0.15	1.50	1346.54
12	400	0.10	1.00	661.10
13	400	0.10	1.00	661.09
14	400	0.10	1.00	661.10
15	400	0.10	1.00	661.12
16	400	0.15	0.50	450.02
17	200	0.10	1.50	1100.53

The 2060 Electronic numerical controlled (ENC) model lathe situated at Prototype Engineering Development Institute (PEDI), Ilesa, Osun state, Nigeria was used for the cutting tool tests. Fig.1 shows the experimental set-up, where a strain meter connected to a single electrical strain gauge was used to take reading from which the induced equivalent stresses were obtained.

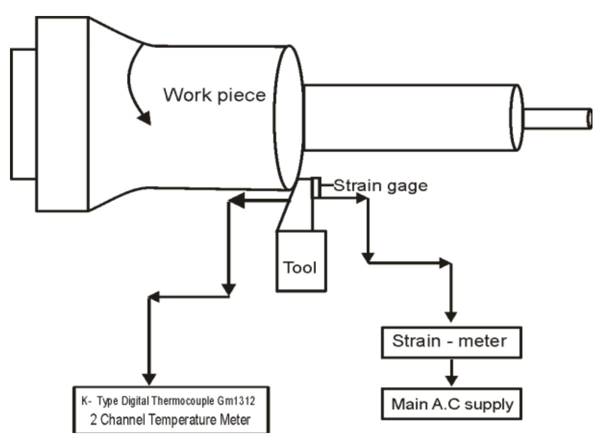

***Fig. 1:** Experimental set-up*

2.1 FEM simulation

The finite element method is an expert tool used for simulating the behavior of the cutting tool during machining. Commercial FEM software such as ANYSY; analyzes finite element problem in three steps namely: preprocessing, solution and post processing (Etin-osa and Achebo, 2017) as explained below.

2.1.1Preprocessing:

This includes defining the geometrical properties of the problem, the element types to be used, the material properties of the elements, the geometrical properties of the elements (length, area etc.), the element connectivity (mesh the model), the physical constraints (boundary conditions) and the loadings.

Fig. 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 stress analysis.

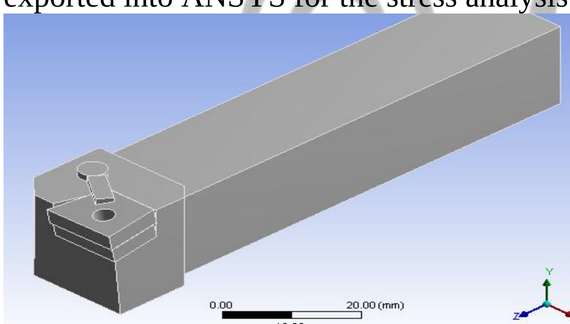

Fig. 2: *Carbide Insert Single Point Cutting Tool*

After the geometry modelling using AutoCAD, we exported the geometry to ANSYS. The surface mesh for the specimen is shown in Fig. 3. We selected fine as the center relevance at the detail mesh section. 46407 and 28437 were the numbers of nodes and elements generated for the meshed cutting tool.

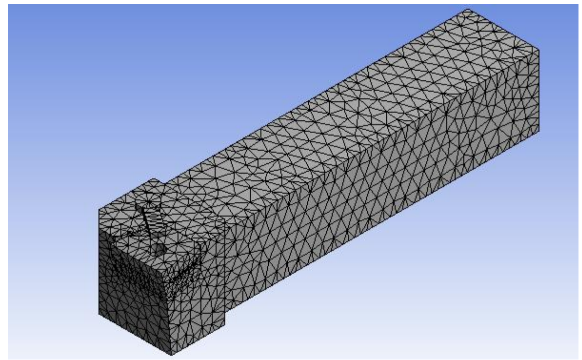

Fig. 3: *Meshing of Carbide tool*

Thirdly, we proceed to analyzed settings, where the boundary conditions such as fixed support, applied force, pressure etc. are specified. The fixed support for the cutting tool is shown in fig. 4 the top and bottom part are movement restricted.

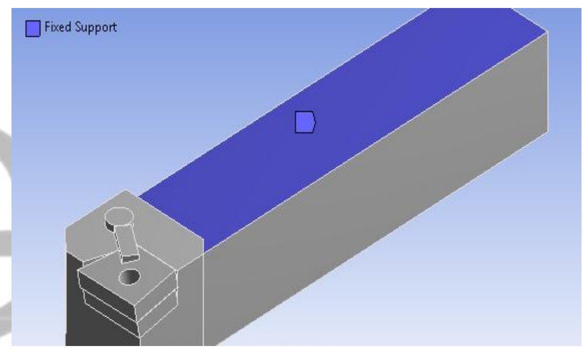

Fig. 4*: fixed support*

To find the induced stresses on the cutting tool, the cutting force should be known. The various applied forces are determined from the spindle speed, feed rate and depth of cut values as given in table 2. The values were imputed to ANSYS. Using equation (1) the force in table 3 was determined. The force depicted in table 3 is the force reaction coming from the workpiece which is equal and opposite to the actual cutting force applied.

For turning operation using carbide tipped tool, the below relation holds $F_c = Cd^x f^y V^n, kgf$ (1)

Where

F_c = cutting force, N

f = feed, mm/rev

d = depth of cut, mm

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ISSN 2320-9186

V = cutting speed, m/min
With $\alpha = +10^0, \lambda = 45^0, R = 2mm, i = 0^0, C = 10^0$, without lubrication

For work material such as steel and steel castings, with tensile strength of $75\, kgf/mm^2$ and for feed less than or equal to $0.75\, mm/rev$ take $C = 300, x = 1.0, y = 0.75, n = -0.15$ (Sharma, 1982)

Table 3: *Summary of cutting tool force*

S/N	Spindle speed (rpm)	Feed rate (mm/rev)	Depth of (mm)	Forces (N)
1	200	0.15	1.00	43.94772225
2	400	0.05	1.50	26.06346724
3	600	0.10	1.50	41.24686998
4	400	0.10	0.50	16.21204987
5	600	0.05	1.00	16.35035708
6	400	0.05	0.50	8.687822414
7	600	0.10	0.50	13.74895666
8	600	0.15	1.00	37.27075435
9	400	0.10	1.00	29.2222349
10	200	0.05	1.00	19.27948506
11	400	0.15	1.50	59.41185751
12	400	0.10	1.00	29.2222349
13	400	0.10	1.00	29.2222349
14	400	0.10	1.00	29.2222349
15	400	0.10	1.00	29.2222349
16	400	0.15	0.50	19.8039525
17	200	0.10	1.50	48.63614962

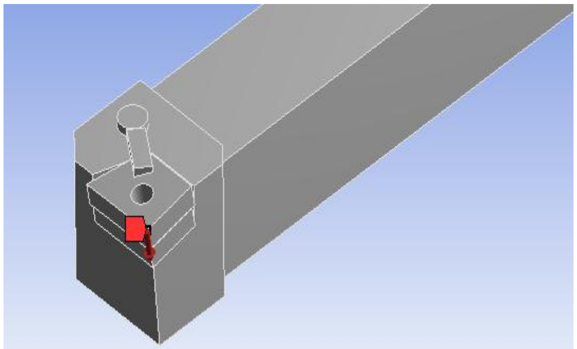

***Fig. 5**: cutting force reaction on carbide tool*

Solution: The features in this step such as matrix manipulation, numerical integration, and equation solving are carried out automatically by the software. The governing algebraic equation in matrix form, computation of the unknown values of the primary field and assembling was done automatically.

3. Results and discussion

3.1 Results

Post processing: Interpretation and evaluation of results is expressed in this stage.

For a turning operation with spindle speed of 200 rpm, feed rate of 0.15 mm/rev and a depth of cut of 1 mm, the stress of 997.32 N/mm^2 was generated on the cutting tool. Fig. 6 shows the induced stress from minimum to maximum during the turning process, when a cutting force of 43.9477 N was applied.

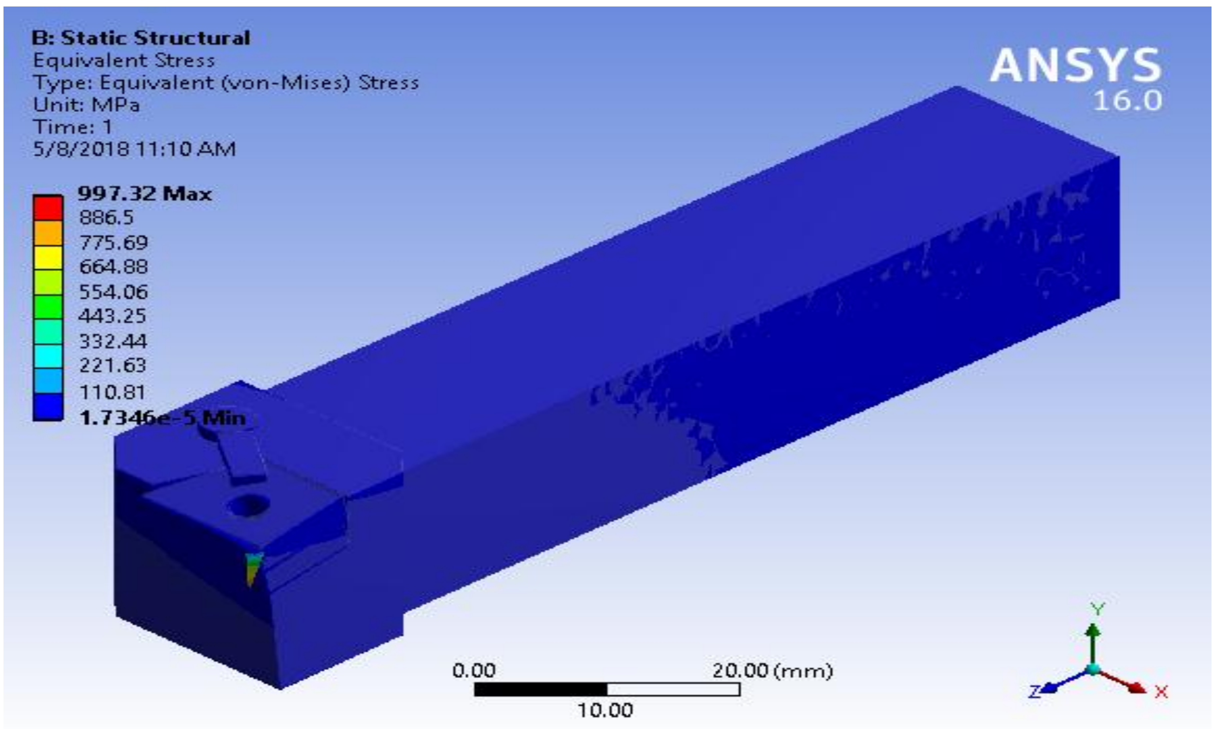

***Fig. 6:** von-mises stress for cutting force of 43.9477 N*

For a turning operation with spindle speed of 400 rpm, feed rate of 0.05 mm/rev and a depth of cut of 1.50 mm, the stress of 591.46 N/mm^2 was generated on the cutting tool. Fig. 6 shows the von mises stress from minimum to maximum during the turning process, when a cutting force of 26.0635 N was applied.

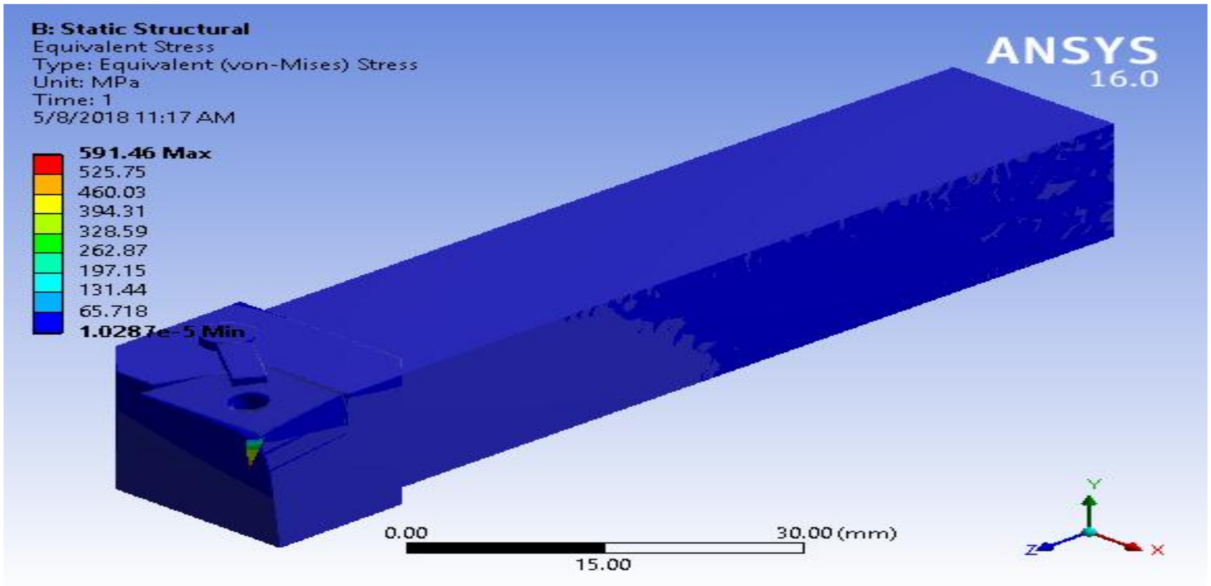

Fig. 7: *von-mises stress for cutting force of 26.0635 N*

For a turning operation with spindle speed of 600 rpm, feed rate of 0.10 mm/rev and a depth of cut of 1.50 mm, the stress of 591.46 N/mm^2 was generated on the cutting tool.

Fig. 6 shows the stress von mises stress from minimum to maximum during the turning process, when a cutting force of 41.2469 N was applied

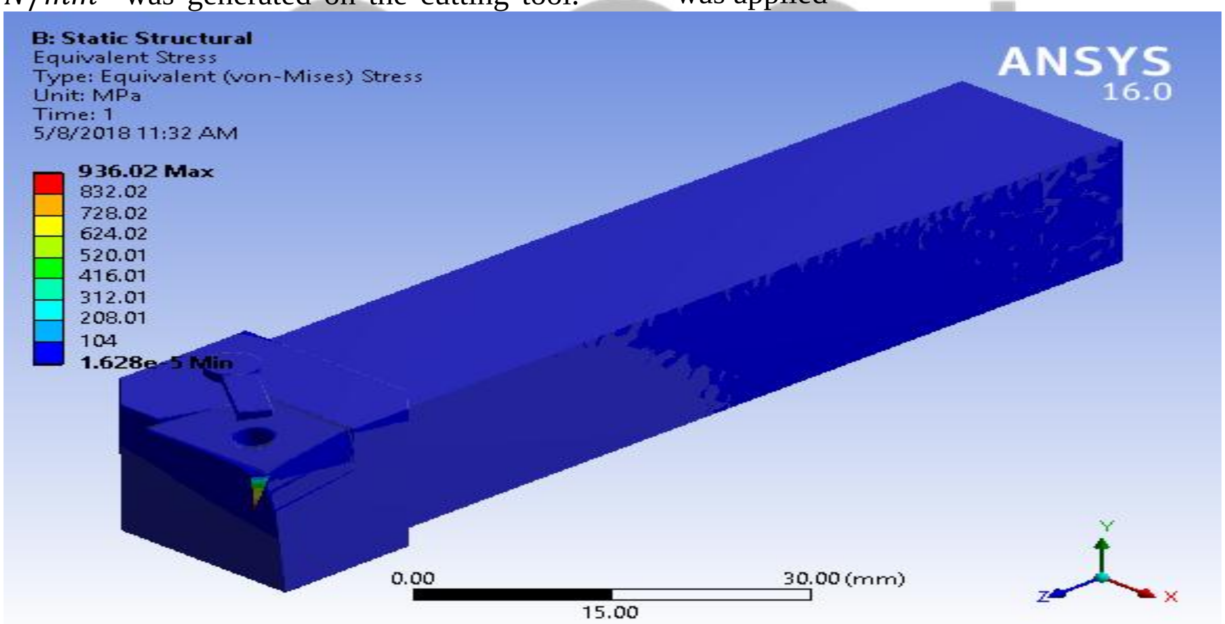

Fig. 8: *von-mises stress for cutting force of 41.2469 N*

Summary of the ANSYS generated maximum Von-mises stresses obtained for the BBD design of experiment are given in table 4.

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ISSN 2320-9186

Table 4: *Summary of ANSYS generated Von-mises Stresses*

S/N	Spindle speed (rpm)	Feed rate (mm/rev)	Depth of (mm)	Max Von Mises Stress N/mm^2
1	200	0.15	1.00	997.32
2	400	0.05	1.50	591.46
3	600	0.10	1.50	936.02
4	400	0.10	0.50	367.9
5	600	0.05	1.00	371.04
6	400	0.05	0.50	197.15
7	600	0.10	0.50	312.01
8	600	0.15	1.00	845.79
9	400	0.10	1.00	663.15
10	200	0.05	1.00	437.51
11	400	0.15	1.50	1348.2
12	400	0.10	1.00	663.15
13	400	0.10	1.00	663.15
14	400	0.10	1.00	663.15
15	400	0.10	1.00	663.15
16	400	0.15	0.50	449.42
17	200	0.10	1.50	1103.7

3.2. Discussion

Table 5: *FEM comparative prediction of von-mises stresses and experimental reading.*

S/N	Max Von Mises Stress N/mm^2 (experimental)	Max Von Mises Stress N/mm^2 (FEM)	Percentage error %
1	995.10	997.32	0.222596559
2	590.00	591.46	0.246846786
3	934.50	936.02	0.162389693
4	365.15	367.9	0.74748573
5	370.09	371.04	0.256037085
6	195.65	197.15	0.760841998
7	310.45	312.01	0.499983975
8	847.60	845.79	0.214001111
9	661.09	663.15	0.310638619
10	435.56	437.51	0.445704098
11	1346.54	1348.2	0.123127132
12	661.10	663.15	0.309130664
13	661.09	663.15	0.310638619
14	661.10	663.15	0.309130664
15	661.12	663.15	0.306114755
16	450.02	449.42	0.133505407
17	1100.53	1103.7	0.287215729

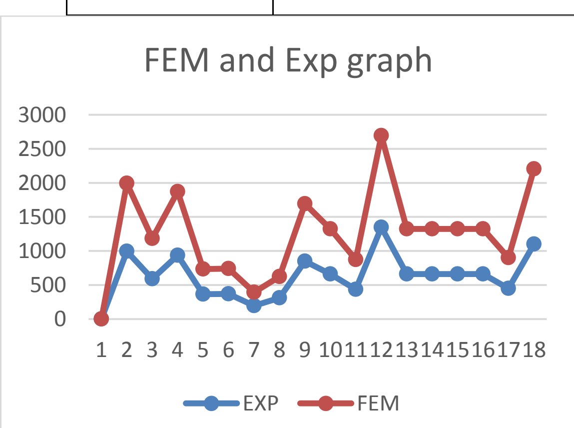

Fig. 9*: Graph of Experimental and Finite element modelled plot*

The prediction of carbide insert cutting tool von mises stresses when machining mild steel using dry orthogonal cutting process was carried out, using the experimental and the finite element method. This is to know how accurate the FEM could predict the stresses generated on the tool. The Box-Behnken's experimental design with the aid of the Design Expert 7.00 was used to generate the design of experiment (DOE) for the matrix as shown in table 2. The von-mises stresses obtained in table 2 is the experimental values. To get the FEM stress values, the forces gotten from table 3 using equation (1), were employed to generate the FEM von-mises stresses in table 4. At the end, a comparative analysis between the experimental and FEM was carried out as shown in table 5.

From table 5, it can be seen that both experimental and FEM (ANSYS) reading were in close agreements, with the maximum and minimum error as 0.761 and 0.123 respectively. From the FEM mimicking pattern of the experimental in fig. 9, it clearly shows that ANSYS is a very robust predicting tool, which can be used for stress simulation analysis in a cutting tool.

4. Conclusion

The present research study focused on predicting cemented carbide insert at various cutting parameters while machining mild steel under dry condition. The experimental design was conducted by the three factors Box-Behnken design. During, the experimental tests, the strain gauge connected to an A.C supply strain meter was used to measure the induced strain from which the stress was calculated. The FEM software was used to verify the test results. In all, the following conclusions have been drawn;

1. The FEA result shows that the von mises stress are found at the tip of the cutting tool.

2. The experimental test shows that the chip formations were found to be a continuous type at lower spindle speed and feed rate. This is in accordance with Ozel et al (2000) findings'.
3. As depth of cut increases from 0.5 to 1.5mm there is a sudden rise in tools' von mises stresses. This is the major reasons for tools' failures, instabilities and wears due to increased deformations

From the obtained results, it has been showed that the predictions of the von mises stress of a cutting tool can improve the service life of the cutting tool as well as the integrity of the machined components. Hence, it is recommended that the metal cutting industries should endeavor to use FEM simulated means such as ANSYS, to predict the tool's von Mises for a specified cutting process, in order to prolong the service life of the cutting tools and avoid exceedence of their yield points; a cause that leads to tool wear and failure while machining mild steel with carbide insert cutting tools.

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