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DEVELOPMENT OF MATHEMATICAL MODEL FOR THE PREDICTION OF CUTTING FORCE ON AISI STEEL USING TAGUCHI DESIGN AND FINITE ELEMENT METHOD

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Abstract

Finite Element Analysis consists of computer model or design that is stressed and analyzed for specific results. It is used in the design of new products and refinement of the existing product. A great focus was made on developing a mathematical model for the prediction of cutting force on AISI steel using Taguchi Design and Finite element method (FEM). A total of nine experiments were conducted using Taguchi Orthogonal Array Design of Experiment. The cutting force for each experiment was measured using a Dynamometer. The results from the comparisons revealed that the differences in the experimented and predicted values lie between 0.4% and 0.9%. The developed mathematical equation was adjudged to be adequate from a coefficient of determination (R^2) and adjusted R^2 values which were determined to be 96.8% and 87.1% respectively. In the Finite Element Analysis, a total of 2207 elements and 6454 nodes were involved in the penetration of the tool into the work piece. A maximum equivalent (Von mises) stress and total deformation of 496250Mpa and 0.6025mm respectively were exerted on the workpiece on the application of cutting force of 10000N.

Keywords: Taguchi Design, Design of Experiment Finite element Method and Cutting force

1.0 Introduction

The production of industrial components for design and manufacturing purposes requires precise machining of parts to desirable dimensions [1]. It has to do with removal of unwanted material from a work piece so as to attain specified geometrical dimensions and surface finishing [2]. Machinability has a major objective of producing components economically. There are considerable amount of research deployed to develop metal cutting processes.

Machine turning tools are used on lathes for cutting or finishing the outside diameter of a work piece. Turning tools can be used to produce cylindrical parts. In its form the turning processes are typically carried out on a lathe, which is considered to be the oldest of machine tools and can be of different types such as straight turning, taper turning, profiling or external grooving [3]. Those types of turning process can produce various shapes on material. The objective of metal turning is to establish productive theory that will enable us to predict cutting performance such as chip formation, cutting force, cutting temperature, tool wear, and surface finish[4]. The ultimate objective of the science in turning process is to solve practical problems associated with efficient material removal in metal cutting process. To achieve this, the principle governing the turning process should be understood. A knowledge of this principle makes it possible to model, simulate and thereby predict the practical results off cutting process and thus to select the optimum cutting conduction for each particular case.

One of the greatest efforts made in manufacturing engineering is in the application of Design of experiment computer simulation for the preparation of production processes so as to be geared towards the prediction of the power requirement, cutting forces, chip formation and equivalent stress using numerical models [5]. The Taguchi Orthogonal design method is highly recommendable in efficient production process. This computational model would have great value in increasing the understanding of the cutting process and in the reduction of the number of experiments which traditionally are used for tool design, process selection, machinability evaluation and chip breakage investigation [6].

In recent years, Finite Element Methods (FEM) has become widely used in research and industrial applications because of the advancements in computational efficiency and speed [7]. FEM is a useful tool for the analysis of metal cutting process where this method provide better prediction of process variables whereas interaction of the tool and the chip

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can also be examined. The understanding of interactions during the cutting process is a fundamental task where this knowledge enables tool makers to evaluate the performance of the cutting tool design [8]. Besides, it also enables the users of cutting tools to evaluate the effects of the working conditions on tool life and on the quality of the final part [9]. Hence, FEM is an effective method as it would decrease experimentation and reduce cost. In addition, much cutting force models have been developed to predict machining parameters. As for FEM simulation of machining, the main problem is to determine the boundary conditions at the tool-chip interface [10]. It is expected that at the end of this work, a good agreement is obtained between simulation and experimental data to indicate that the simulation is capable of predicting cutting force and optimizing machine parameters.

Finite element simulations are considered a widespread and strong tool in the study of metal cutting. Due to its comprehensive ability, finite element simulations take into account large complexities that come upon metal cutting [11]. Till late 1990s, the majority of researchers generated their own FEM codes to use in their studies. Due to the long computational hours of simulations and high memory capacity needed, the use of FEM was limited and if used, 2D simulations were dominant [12]. However, over the last 20 years, developments in technology (hardware and FE codes) dramatically increased, overcoming to an extent the limitations faced in modelling and computational difficulties [12]. FEM based simulation models focus on conventional machining, prediction of chip formation, distributions of strain, temperatures and stresses on the tool cutting edge. An investigation of heat generation in cutting tool performed by [13] examined cutting parameters of suitable cutting tool geometry and the experimental results revealed that the main factors of the increasing cutting temperature are cutting speed, feed rate and depth of cut. In the same vein, an investigation into the effect of machining parameters on residual stresses in orthogonal cutting was carried out by [14]. The study concluded that the maximum tensile residual stresses increased with increasing the cutting speed and feed rate. Similarly, an investigation on the influence of the cutting parameters on the residual stress induced in turning of AISI 316L steel was conducted by [15]. Specifically focusing on cutting forces, cutting speed and the process feed rate.

A paramount significance of this study is that Taguchi Design and Finite element analysis will give better prediction of turning variables such as cutting forces, feed rate, cutting speed and equivalent stress which is essential to the optimization of cutting tool design and cutting conditions such that product quality and tool life are considerably enhanced. This study is aimed at developing a mathematical model for the prediction of cutting force on AISI steel work piece using finite element method.

2.0 Materials and Methods

A titanium made turning tool was applied on the AISI 1045 steel workpiece. A stop clock was used to take record of the timing for the experiment. A total of nine experiments was conducted using Taguchi Orthogonal Array Design of Experiment. The cutting force for each experiment was measured using a Dynamometer. The obtained values from the design of experiment were analysed using ANOVA, Signal to Noise ratio, Multiple Linear Regression and Finite Element Method.

The data matrix shown in Table 1 involves the cutting parameters and various levels applied in this study. Cutting parameters used are cutting speed, feed rate and depth of cut.

Table 1: Cutting parameters and their levels

Factor	Level 1	Level 2	Level 3
Cutting speed	200	300	400
Feed rate	0.05	0.075	0.1
Depth of cut	0.1	0.2	0.3

The chemical composition and the mechanical properties of AISI structural steel are shown in Tables 2 and 3 respectively.

Table 2: Chemical Composition of AlSl Structural Steel [16]

Element	%
Sulphur	0.04
Carbon	0.16 to 0.18
Magnesium	0.70 to 0.90
Silicon	0.40
Phosphorous	0.04
Iron	96.78

Table 3: Mechanical Properties of AISI Structural Steel [16]

PROPERTIES	METRIC
Density	2.700kg/m^3
Young's modulus	2e+11pa
Poisson's ratio	0.3
Bulk modulus	1.6667e+11pa
Shear modulus	7.6923e+10pa
Isotropic secant coefficient of thermal expansion	1.2e-051/^{0}c
Compressive ultimate strength	0pa
Compressive yield strength	2.5e+08 pa
Strain-life parameters	0.0e+01.0e+1-5.4e+0-6.6e-
S-n curve	Log(10)1.0e+06.0e=0pa Log(10)7.9e+09.6e+0
Tensile ultimate strength	4.6e+08pa
Tensile yield strength	2.5e+08pa
Isotropic thermal conductivity	60.5w/m^{0}c
Specific heat constant pressure	434j/kg^{0}c
Isotropic resistivity	1.7e-07 ohm.m
Isotropic relative permeability	10000

3.0 Result and Discussion

3.1 Modelling of the cutting assembly

The isometric drawing and orthographic projection of the tool and work piece assembly is shown in Figures 1 and 2 respectively

Fig. 1: Isometric drawing of cutting tool and workpiece

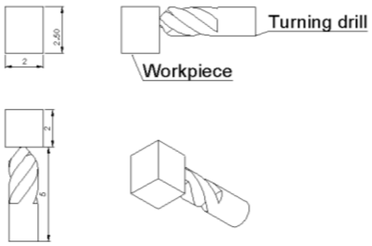

Figure 2: Orthographic projection of the assembly

3.2 Taguchi Design

Design of experiment Taguchi Design conditions was used to conduct the cutting force experiment. The result of the experiment is shown in Table 4.

Table 4: Design of Experiment result for the cutting force

No. of experiment	Cutting speed, A (rad/s)	Feed rate , B(mm/s)	Depth of cut, C (mm)	Experimental Cutting force (N)	Predicted cutting force	%error
1	200	0.05	0.10	10200	10122.2	0.763
2	200	0.075	0.20	10500	10572.2	0.688
3	300	0.01	0.30	10600	10605.6	0.052
4	300	0.05	0.20	9880	9885.5	0.055
5	300	0.075	0.30	9990	9912.22	0.779
6	300	0.10	0.10	10300	10372.2	0.701
7	400	0.50	0.30	9500	9572.22	0.760
8	400	0.075	0.10	10020	10025.6	0.056
9	400	0.10	0.20	10560	10482.2	0.737

In order to ascertain the magnitude of error in this experimentation a comparison was drawn between the experimental and predicted values. The comparison was carried out using equation (1).

$$Error = \frac{exprimental\ value - predicted\ value}{exprimental\ value} \qquad (1)$$

The results from the comparisons shown in Table 4 reveal that the differences in the experimented and predicted values lie between 0.4% and 0.9%. This goes to show that the magnitutude of the error is not large.

The Signal to Noise ratio result obtained in this study is shown in Table 5. The result showed from the ranking that feed rate is the most important parameter followed by cutting speed.

Table 5: Signal to Noise ratio result

Level	A	B	C
1	80.37	79.87	80.15
2	80.05	80.14	80.26
3	80.02	80.41	80.02
Delta	0.35	0.54	0.25
Rank	2	1	3

The Multiple linear Regression analysis applied to Table 4 developed the mathematical model as given in Equation (2).

$$F = 9986 - 2.033A + 12533B - 717C \qquad (2)$$

Where F=Cutting force
A= Cutting speed
B= Feed rate
C= Depth of cut

The developed mathematical equation was adjudged to be adequate from a coefficient of determination (R^2) and adjusted R^2 values which were determined to be 96.8% and 87.1% respectively. Furthermore, the statistical values obtained from the Analysis of Variations analysis shown in Table 5 reveals that cutting speed (A) and feed rate(B) are significant with p-values of 0.048 and 0.010 respectively using a significant level of 0.05.

Table 6: Analysis of Variance(ANOVA) of experimented results

Source	DF	Adj SS	Adj MS	F-value	P-value
Regression	3	867950	289317	7.88	0.024
A	1	248067	248067	6.76	0.048
B	1	589067	589067	16.04	0.010
C	1	30817	30817	0.84	0.402
Error	5	183606	36721		
Total	8	1051556			

To further buttress the adequacy of the developed mathematical model a Normal Probability Plot shown in Figure 3 was created. The plot reveals that the residual points lie very close to the ideal diagonal distribution line.

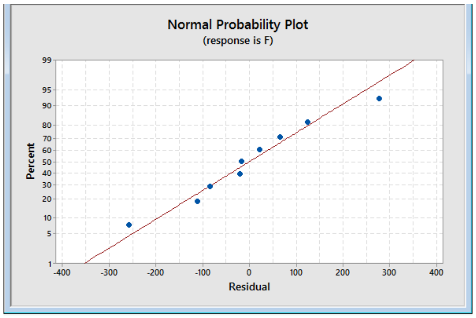

Figure 3: Normal probability plot

3.3 Finite Element Analysis

The Titanium cutting tool and steel workpiece assembly was meshed by 1mm element size as shown in Figure 4. A total of 2207 elements and 6454 nodes were involved in the penetration of the tool into the workpiece

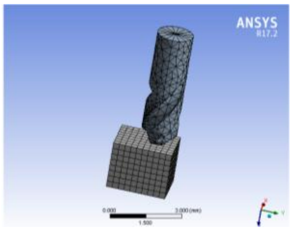

Figure 4: Meshed tool and workpiece in ANSYS

The average experimental and predicted force of 10000N was applied to the top surface of the workpiece in the ANSYS static structural analysis systems as shown in Figure 5.

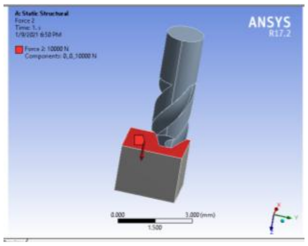

Fig. 5: Application of cutting force in ANSYS

The finite element analysis yielded a maximum equivalent (Von mises) stress value of 496250Mpa and a minimum equivalent (Von mises) stress on the work piece on the application of cutting force of 10000N as shown in Figure 6. The result obtained was found to be similar to that of [15]. The equivalent stress increases with time progressively as shown in Figure 7.

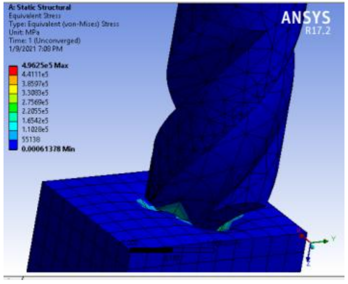

Figure 6: Equivalent (Von mises) stress in ANSYS

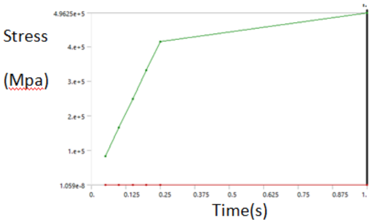

Figure 7: Plot of Equivalent stress (Mpa) with time (s)

The result of the total deformation is shown in Figure 8. It reveals the level of deformation exerted by the tool on the workpiece. A total deformation of 0.6025mm was exerted on the workpiece on outright penetration at the top surface of the workpiece. The total deformation showed increment with time as shown in Figure 9.

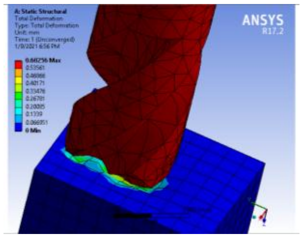

Figure. 8: Total deformation result in ANSYS Workbench

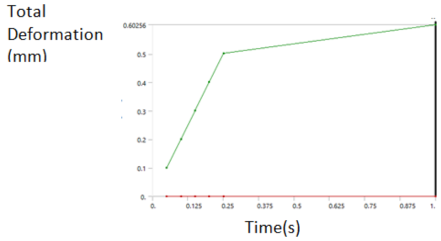

Figure. 9: Plot of Total deformation (mm) with time (s)

4.0 Conclusion

The study showed that an increase in cutting force leads to a reduction of cutting speed. Cutting parameters used in the experiments were found to be very significant as confirmed by their p-values and f-values. The developed mathematical model was adequate with R^2 and adj R^2 values of 92.7% and 82.1% respectively. The prediction error between experimental and predicted values was found to be 1.2%. Graphical results from ANSYS workbench showed that at the predicted cutting force of 10000N incursion into workpiece surface begins to gather great momentum with deformation of the work piece becoming visible.

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