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Experimental Investigation and FE Simulation of the Effect of Variable Control on Temperature Distribution in Orthogonal Metal Cutting Process

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Abstract

The study aimed at building a 3-Dimensional finite element simulation to monitor orthogonal machining process under a dry machining environment. The study was conducted in two stages of experimentation and finite element modelling and simulation (FEMS). The purpose of the experimentation was to obtain data which will be used to validate the FEMS result. The FEMS was carried out with a commercially available solver. The workpiece material employed for the study was mild steel in the form of round bar of solid shaft having 45 mm diameter and length of 500 mm. Mild steel was selected due to its wide range of applications in the fields of manufacturing tools and mould industry. The tool material used was tungsten carbide of DIN4980R 20 mm x 20 mm, with cutting angle of 80-degree tool steel, which was modelled in the FEMS as a rigid body. Various cutting conditions such as speed, feed rate and depth of cut were considered to obtain the tool chip temperature. Different values of temperature were recorded at interval of 10 seconds and ranged from 10 to 100 seconds. The FEMS was carried out by making one of the conditions vary while the others were constant. The temperature values measured with a digital thermocouple were used to validate the FEMS data obtained. The result show that the cutting temperature predicted by the FEMS is within 20% of the real experimental value and followed the same trend. It was discovered that the values of temperature obtained from simulation were also much higher than that of experimentation. Therefore, the experimental value might not be accurate, due to some experimental errors and environmental effects like partial contact between the measuring device and the cutting tools, fluctuation in the magnitude of air flow around the surrounding which may affect the cutting temperature, room temperature and pressure effect. Generally, with an increase in the cutting speed, feed rate and depth of cut, the tool temperature also increased

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and the cutting speed was found to be the most effective parameter when consideration is given to temperature effects, especially in high range of cutting conditions.

1. Introduction

Metal cutting is an irreversible process that is associated with thermomechanical processes. Large plastic deformation resulting in a thermal diffusion and high strain rates occurs during metal cutting process. The increasing temperature within the cutting zone, between the chip and the tool, has a great impact on the machining process and also the machined product. It has various effects on the tool life, cutting forces, and the surface integrity of the work piece. It is reported that higher cutting temperature decreases both the yield strength of the work piece material and the cutting forces [1]. It however affects tool wear, integrity and surface finish of the machined parts, mechanism of chip formation, thermal deformation of cutting tool and tool life. It also has direct effects on the corrosion resistance, service life and machining distortions of the machined parts [1-4]. Various methods and approaches have however been adopted to study the phenomenon of cutting temperature on work pieces. These methods include the use of experiments [4-6], finite element [5] and finite difference [7] methods and analytical modelling [8-10]. The use of experiments has limitations in accuracies due to certain factors which include experimental design flaws and difficulty in measuring the temperature around the cutting zone. Huang and Yang [2] reported that research results from O'Sullivan and Cotterell [11] and Cotterell and O'Sullivan [12] showed that the temperature measurements were taken in the neighbourhood of the cutting zone where very high temperature variation occur instead of very close to the work piece. This experimental design flaw limits the general application of the result. More experimental design flaws associated with other research studies are x-rayed in Huang and Yang [1].

The use of the finite element and finite difference methods and analytical modelling has gained good applications in determining the tool-chip temperature, residual stresses, plastic strain and strain rate, cutting force effects, tool wear and other machining phenomena. The suitability, accuracies and performance of these methods depends greatly on the exactness of the models developed to represent the actual cutting process which include the description of the behaviour of the work piece material under machining conditions [13]. Comparative studies carried out to determine the degree of convergence by different analytical methods show a disparity of results [13]. Moreover, the essence of all the different methods is partly to be able to determine the best combination of cutting parameters that will deliver a good product. This the method of simulation offers. It is able to give the platform that encourages optimisation and innovation. With simulations, the effects of changing cutting variables on both work pieces and cutting tools can be easily determined without recourse to repeated experimentation and laborious modelling procedures which at the long run may not be accurate. This is the focus of this study. It aimed to provide a pathway to enable finite element simulation for predicting the phenomena of machining and to observe the degree of convergence of the results with those of experimentation.

2. Materials and Methods

2.1. Experimental work

The essence of the experiment was to generate data points that were used to test if the FE Simulation (FES) results converged to the experimental results. Gear Head Precision Lathe machine (GH 1440-A, with three jaw chuck) was employed with Tungsten Carbide (DIN4980R 20 mm x 20 mm, with cutting angle of 2º, end relief angle 7º) as cutting tool to machine mild steel solid shaft of 45 mm diameter and 1000 mm length. The variables considered were, cutting speed (v mm/s), feed rate (f mm/rev) and depth of cut (d mm). While each variable was used to determine its effect on tool temperature, others were kept constant. Prior to operation, the cutting tool was

prepared so that each of the tool features will be clearly identified as shown in Fig. 1. The cutting parameters are shown in Table 1 and the machine specifications are displayed in Table 2.
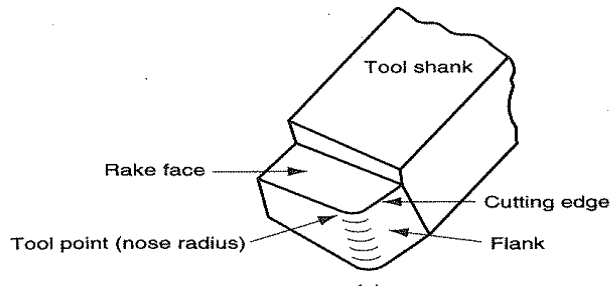

Fig. 1: Detail component of a cutting tool [14]

Table 1: Cutting parameters employed for the experimentation

Parameters	Unit	Experimental Level				
		1	2	3	4	5
Depth of cut	mm	0.5	1	1.5	2	2.5
Cutting feed	mm/rev	0.2	0.5	0.75	1	1.25
Cutting speed	mm/s	90	140	215	330	510

Table 2: Machine Specification

Manufacturer	WARCO
Power machine extra equipment	5.7KVA
Spindle speed	1,800 mm/s
Center length	1000 mm
Feed rate	mm/rev.

The schematic of the cutting operation is shown in Fig. 2. During cutting, the tool's cutting edge was positioned such that the initial work surface corresponds to the thickness of the chip prior to chip formation, t_o. Thus, as the chip forms along the shear plane, its thickness increases from t_o to t_c. The combination of the cutting conditions gives sixteen matrix points, and the experiments were carried out for all the sixteen combinations of speed, feed, and depth of cut. A digital thermocouple was used to measure the temperature changes.
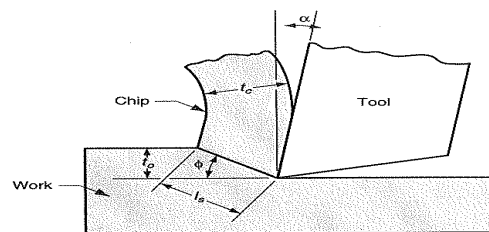

Fig. 2: The orientation of the cutting operation [14]

2.2. Finite element modelling (FEM)

The FEM was carried out in three sets of procedures of preprocessing, solving and post processing. The preprocessing involves the geometric model creation, material and boundary condition definitions and the descretisation. The solver generates results from the preprocessed data and the post processing plot the outcome for interpretation. Based on the aforementioned, a 3-D model of the orthogonal metal cutting with plane strain condition was developed with assumptions made to represent as much as possible the cutting operations. These assumptions include that cutting takes place at constant specified parameters (speed, feed rate and depth of cut), the nose radius of the tool was constant at 50 microns, the tool is rigid and that tool wear is negligible, to reduce the complexity and runtime. Other assumptions include that the room temperature was 30°C, the machining took place under dry condition and the materials property is homogenous. The FEM was done using an FEM solver and the results obtained were compared with that of the experimental work. A hexagonal type of mesh with a total of 535 and 9800 elements, 480 and 78400 nodes were employed for the cutting tool and work piece respectively. Figs. 3 to 5 give the model view of the cutting tool, work piece and assembly.
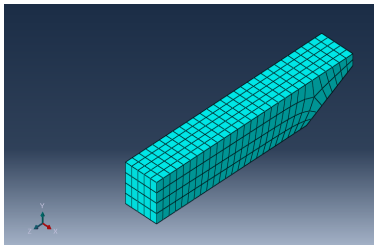
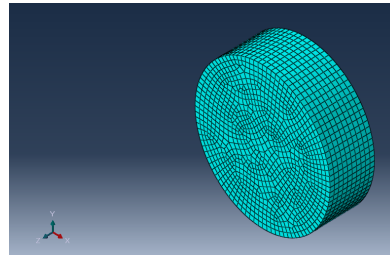Fig. 3: The meshed model of the cutting tool   Fig. 4: The meshed model of the work piece
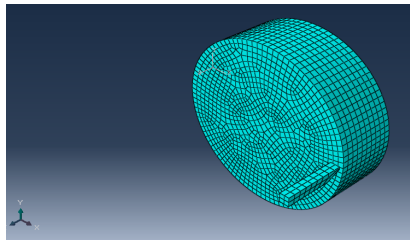
Fig. 5: Mesh image of the cutting tool and work piece assembly

3. Results and Discussion

3.1. Experimental Results

Figs. 6 to 8 presents the results of the effects of cutting speed, feed rate and depth of cut on the tool temperature respectively.
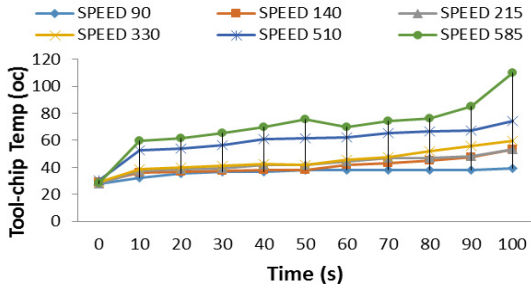
Fig. 6: The graph of cutting temperature against cutting speed
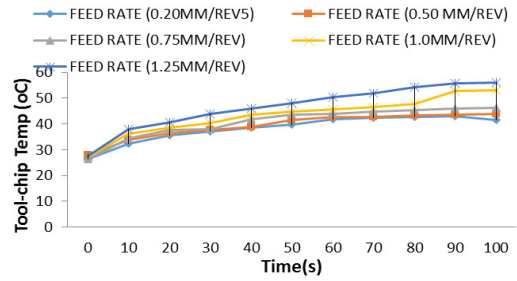

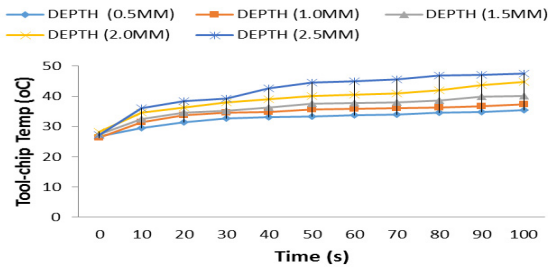Fig. 7: The graph of cutting temperature against feed rate

Fig. 8: The graph of cutting temperature against depth of cut

Figs. 6 to 8 showed that there is almost direct relationship between cutting speed, feed rate and depth of cut with tool temperature. Moreover, the feed rate produced a lower effect than the cutting speed while the depth of cut produced the least temperature values and gradients.

3.2. FEM Results

Results from the FEM are presented in Figs. 9 to 11. Fig. 9 shows that cutting speed varies with tool temperature. Moreover, while the temperature increases with speed from 90 to 585 mm/s, the values dipped at 330 mm/s and then picks again. This trend was consistent throughout except for minor drops at speed 215 mm/s at 100 s and 585 mm/s at 70 s where the temperature values drops by 0.22% and 0.33% respectively. Fig. 10 shows that at constant machining time below 100 s, the tool temperatures were the same irrespective of the values of the feed rate, while Fig. 11 shows that at each machining time, apart from 20 s, the increase in depth of cut brought about increase in tool temperature.
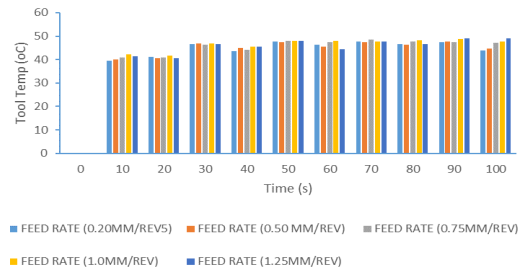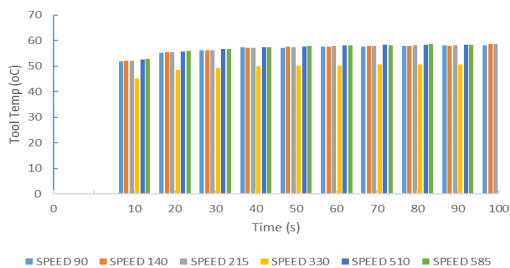
Fig. 9: FEM results of the effects of cutting speed on tool temperature   Fig. 10: FEM results of the effects of feed rate on tool temperature
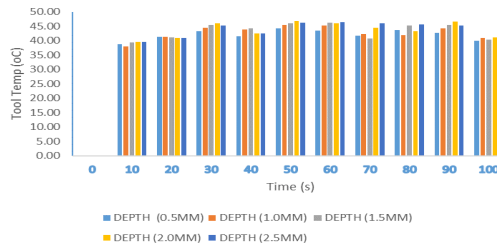
Fig. 11: FEM results of the effects of depth of cut on tool temperature

3.3. Comparison between the experimental and FEM results

Fig. 12 to 14 presents the results of comparison between the values obtained from experiments and that from FEM. The figures show similar trends. Moreover, Fig. 12 shows higher values of tool temperatures from the experiments throughout the machining periods for each cutting speed, while Figs. 13 and 14 show that as the time progressed, the effects of increasing feed rate and depth of cut as predicted by the FEM resulted in higher values than the experiments. The difference in the results can be adduced partly to uncontrollable environmental conditions which are associated with practical processes and errors in measurements. Despite this, the FEM results followed the same trend with those of the experiment, and, were able to mimic the experimental conditions. Thus, showing that, the simulation results can be relied upon to determine the optimal cutting conditions without recourse to experimentation. It is cheap and flexible.
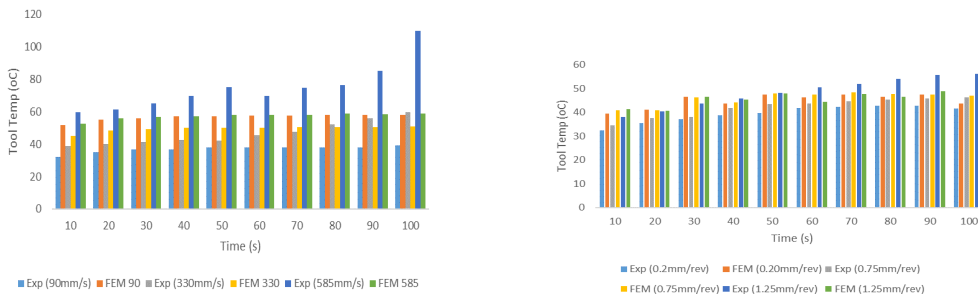
Fig. 12: Comparison of results of experiments with FEM for cutting speed Fig. 13: Comparison of results of experiments with FEM for feed rate
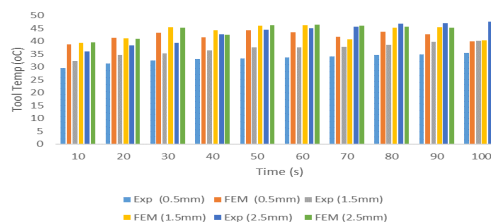
Fig. 14: Comparison of the results of experiments with FEM for depth of cut

4. Conclusion

The study carried out both experimental investigation and finite element simulation of dry cutting of a mild steel sample using a lathe machine and carbide tool cutter. The outcome showed that results from the experiment validate the finite element simulation. Both processes predicted that cutting speed produces the highest tool chip temperature while the depth of cut produced the least. Based on the results therefore, finite element models, if well developed with appropriate assumptions, can be employed for the analyses of the phenomenon of dry cutting in metal machining process without the need for experimentation.

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