SSRG International Journal of Mechanical Engineering
ISSN: 2348 – 8360 /doi:10.14445/23488360/IJME-V8I11P101

Volume 8 Issue 11, 1-7, Nov, 2021
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Original Article

Experimental Analysis of Cutting Forces and Finite Element Simulation in Milling Operations

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Received Date: 05 October 2021
Revised Date: 07 November 2021
Accepted Date: 18 November 2021

Abstract *- In this study, the effects of cutting parameters on cutting forces were investigated experimentally in machining. Experiments were carried out by drilling holes with a TiAIN-coated hard carbide cutting tool using a finger milling machine on a CNC vertical machining center. Drilling was performed with AISI 140 as the workpiece material. During the cutting tests, the depth of cut was kept constant at 1 mm and three cutting speeds (100, 120, and 150 m/min) and four different feed rates (0.1, 0.2, 0.3, and 0.4 mm/rev) were used. A Kistler 9333-A force sensor was used to measure the cutting force on the horizontal axis during the machining process. The variation of the cutting force values depending on the cutting parameters was analyzed graphically. The effects of the cutting force values obtained from the experiments on the tools were determined using ANSYS software, and the total deformation and vonMises stresses at the tooltips were compared.*

Keywords - *ANSYS, cutting force, cutting speed, depth of cut, feed rate, finite element method*

I. INTRODUCTION

In the industrial sector, experimental research to study metal cutting processes is expensive and time-consuming, and the relationship of the parameters to the cutting process is usually based on theoretical knowledge only. Therefore, in order to select the best tools for each process, alternative methods are needed to analyze the cutting process and determine the process parameters. Computer simulation using the finite element method (FEM) is one of these techniques [1, 2]. In order to examine the effects of cutting forces in machining, experimentally obtained data are compared with those obtained via FEM analyses. Many studies have been conducted on this subject [3, 4, 5, 6]. In Kurt's (2006) study, tools with different geometries were used with different cutting parameters. Inconel 718 and AISI 1117 were chosen as the workpiece materials. A 9257B (Kistler) dynamometer was used to measure the cutting forces during the machining process, and the stresses on the cutting tool were analyzed in the ANSYS program. It was concluded that when the depth of cut and feed rate was increased at the applied cutting speed, the cutting forces also increased, and therefore, all stress components were increased [7]. Apaydın (2009) investigated experimentally and numerically how the resulting cutting forces in turning and chip removal changed depending on the cutting parameters. In the study, AISI 4340 was chosen as the workpiece material. Experiments were carried out under vertical cutting conditions using both coated and uncoated cutting tools. The cutting force values generated during the chip removal process were measured with a 9257B Kistler dynamometer. The experiments showed that with the increase in the feed rate, the cutting force increased, and accordingly, the pressure acting on the cutting tool also increased. It was concluded that as the cutting speed increased, the cutting forces decreased [8]. Aydın (2014)examined cutting forces and dimensional errors resulting from the cutting force distribution in chip removal using an end milling cutter. In the study, an effective simulation method was presented to analyze the dimensional surface defects caused by cutting tool deflection in the milling process and to determine the cutting coefficients required for modeling cutting forces [9].

In the study of Jadhav and Ramgir (2015), the vertical metal cutting process was analyzed using the FEM. This study focused on the effect of friction between tool and workpiece and the effect of the rake angle on cutting forces in vertical metal cutting. The Johnson-Cook model was used to initiate the machining process during the analyses. Four different tool tilt angle values between 20° and 30° were used for the simulation. For the coefficient of friction, three different values between 0.05 and 0.15 mm were used. The cutting tool material was AISI 4340 steel, and AISI 1045 steel was used as the workpiece material. For the processing of the AISI 4340 steel in the analysis phase, ABAQUS/Explicit 6.11 was successfully applied using the FEM. The chip removal process was simulated in accordance with dry friction conditions. As a result of the study, it was concluded that for the displacement value at the fixed tooltip, the cutting forces had increased due to the increase in the friction coefficient between the tool and the workpiece [10]. In the study of Gökçe and Çiftçi (2019), the cutting forces in the milling process were investigated by both experimental and FEM techniques. A Kistler 9272-A piezoelectric-based dynamometer capable of measuring the force component in three axes (Fc, Ff, and Fr) simultaneously was used to measure the cutting forces during machining. In the analysis, the feed force (Ff), which had the greatest value, was taken into account. The experiments demonstrated that with the increase of cutting speed, the cutting forces also increased and that there was a direct proportionality between the feed rate and the cutting forces. It was concluded that the cutting forces obtained from the experimental studies and the FEM analysis results were 90% consistent [11].

In this study, the effects of cutting parameters on cutting forces in machining were investigated experimentally. The experiments were carried out by drilling holes with a CNC vertical machining center using TiAlN-coated hard carbide cutting tools. Drilling was performed on a workpiece of AISI 1040 material. A Kistler 9333-A force sensor was used to measure the cutting force on the horizontal axis during the machining process. The effects of the cutting force values obtained from the experiments on the tools were determined using ANSYS software, and the total deformation and von Mises stress at the tooltip were compared.

II. EXPERIMENTAL PROCEDURES

A. Test Sample and Cutting Tools

In this study, AISI 1040 steel, which is widely used in machine manufacturing, was used as the workpiece material. The force sensor was attached to it (Fig. 1), and the CATIA program was used for designing the test sample. No heat treatment was applied to the surface of the test sample to be chipped. Table I shows the chemical composition of AISI 1040 steel.

The study used a 10-mm diameter TiAlN-coated hard carbide end mill cutting tool that is in wide use industrially. The cutting tool was scanned using reverse engineering, and all dimensions were extracted via the scanning process. Experiments were carried out on a Quaser MV203II/10 CNC vertical machining center.

Table I. Chemical Composition of AISI 1040

Carbon (C)	Manganese (Mn)	Phosphorus (P)	Sulfur (S)
0.38-0.40	0.69	0.017	0.04-0.05

B. Force Measurement System

The cutting force values obtained from the tests were measured during chip removal by the force sensor connected to the sample (Fig. 1) and to the test setup. The Kistler-9333A, shown in Figure 2, was the force sensor used in the experiments. The force sensor can measure the force value in the compression direction. For this reason, during the designing of the experimental setup, the force sensor was horizontally connected to the test sample, as seen in Figure 1. The experimental setup was designed to measure the force in the x (horizontal) direction (fx) during the cutting process and chip removal from the workpiece surface.

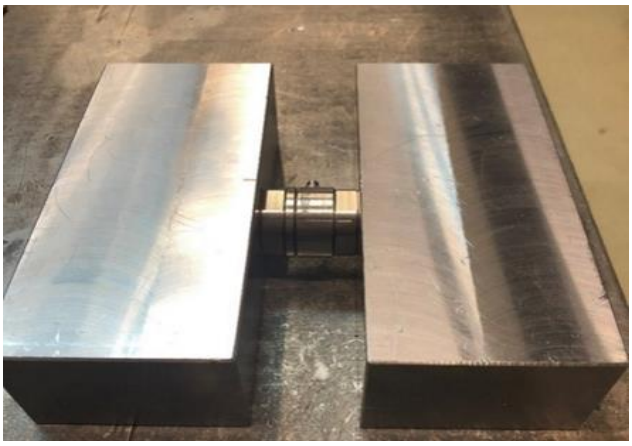

Fig. 1: Force sensor attached to the workpiece

The cutting force data generated during the experiments were taken using the Kistler-9333A force sensor and transferred to the Kistler-5877B0 amplifier and then to the computer with the data- reading card and VNC program. The devices/hardware used to obtain/measure data during and after the experiments, and their features are shown in Table II.

Table II. Devices/Hardware Used in the Experiments and Their Features

Devices/Hardware	**Special Feature**
Force sensor	Kistler-9333A
Amplifier	Kistler-5877B0
Software	VNC-Maxymos

C. Force Measurement Sensor

The Kistler force sensor was attached to the AISI 1040 workpiece(160 × 70 × 50 mm), as seen in Figure 1. In order to fix the force sensor, the sensor was also attached to a piece from the back. During the experiments, the workpiece and, therefore, the force sensor attached to it were kept stable, and the necessary motion for cutting was provided by the cutting tool.

Fig. 2: Force measurement sensor used in experiments

As seen in Figure 3, the force sensor was connected to the Kistler data converter device with a special cable in order to receive the cutting force data generated at the time of cutting from the force sensor connected to the workpiece. The VNC program was installed on the computer in order to read the cutting forces in N during the cutting process. The converter device was connected to the computer to be used with an Ethernet cable. Finally, the converter was connected to the power device and started working when the power supply was activated.

After the setup in Figure 3 was installed, the workpiece on which the force sensor was attached to the workbench was shown in Figure 4. A fresh unused insert was used for each experiment. No coolant was used in the experiments. The cutting parameters used for each experiment were entered on the screen of the CNC machine in accordance with the experimental design. Before starting the cutting process, the VNC program was opened from the computer, and necessary adjustments were made. When the cutting process was started, manual data recording was run in order to monitor the cutting force from the VNC program simultaneously. The readings were recorded on a USB stick connected to the converter. Cutting force values were automatically plotted according to the cutting time using the Maxymos program. The same procedure was repeated for each experiment.

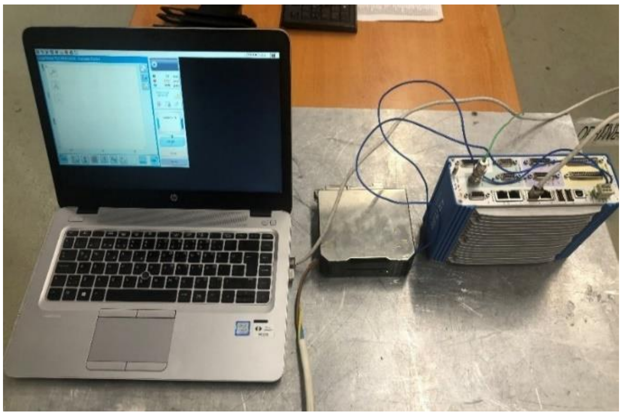

Fig. 3: Experimental setup for receiving data

D. Experimental Setup

In the experiments, the depth of the cut was determined as 1 mm and kept constant. Three different values for cutting speed (100, 120, and 150 m/min) and four different values for feed rate (0.1, 0.2, 0.3, and 0.4 mm/rev) were used. In total, 15 different experiments were carried out with 15 TiAlN-coated hard carbide inserts.

Fig. 4: Experimental setup

E. Finite Element Method

The cutting tools that perform the cutting process in machining are very expensive products, so maximum tool life is desired [12]. Optimum cutting parameters should be used for each cutting tool and workpiece material in order to achieve maximum tool life while cutting at the desired level of quality [13, 14]. Since it is a costly process to determine these optimum cutting parameters experimentally, the FEM is widely used in engineering and mathematical models. By using this method, the designs and strength analyses of the machine elements can be carried out in minimum time, instead of by way of expensive and long-term experiments.

In addition, FEM is widely used to solve the problems that arise during the cutting process. The information obtained by examining previous studies in the literature shows that the results from the analyses can confirm the results from the experiments to a high degree.

In this study, an analysis was carried out to investigate how the cutting forces generated during the experiments affected the tool. The ANSYS Static Structural module was used while performing stress analysis. The modeling of the tool was performed in the CATIA program and transferred to ANSYS. The cutting tool is normally TiAIN coated; however, because the yield strength value of this coating could not be reached, the titanium alloy in the ANSYS library was defined as the cutting tool material. As seen in Figure 5, a 1-mm mesh was applied to the tool.

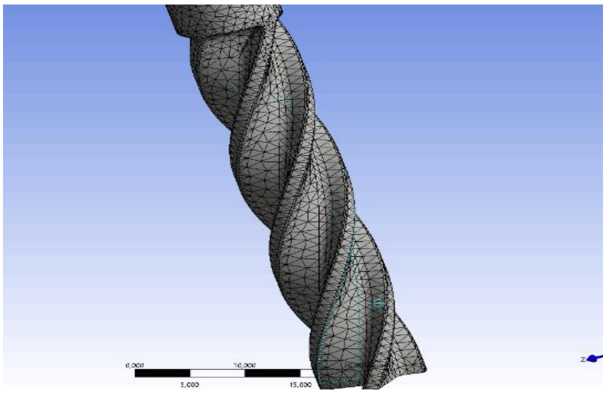

Fig. 5: Mesh applied onto the cutting tool

Sharp corners were slightly rounded in order to get as far away from a divergence as possible during the analysis and to obtain a more accurate result. The cutting force value measured at the end of each test was applied to the tool in the horizontal direction, as shown in Figure 19. Since the cutting tool removes 1 mm of chips from the surface of the workpiece, 1 mm of the cutting edge was selected, and the force was applied in that way. Experiments were taken into account when deciding on the direction of application of the force. During the tests, the cutting tool moves towards the part in the -x direction. For this reason, the force on the tool was applied in the x-direction, as shown in Figure 6. In order to better simulate the experimental setup, the upper part of the tool, which is connected to the workbench, was fixed in the analysis.

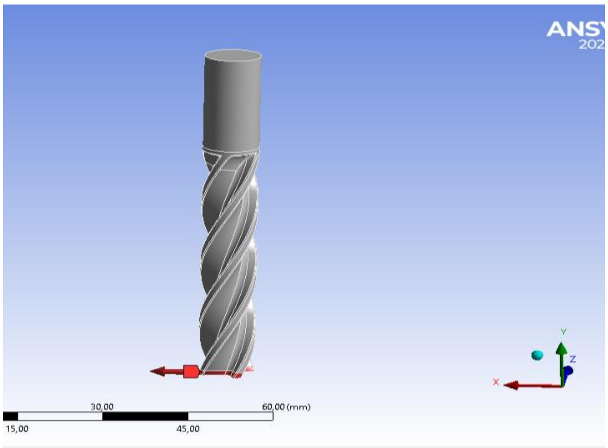

Fig. 6: The cutting force applied to the cutting tool

During the analyses, the temperature was assumed to be 22ºC, and at the same time, gravity in the -y-direction (Fig. 6) was also taken into account.

In addition to the von Mises stresses of the measured cutting force value in each experiment, the total deformation of the tool was also examined. With the effect of the cutting force on the cutting tool, the total deformation distribution in the cutting tool was also investigated.

III. RESULTS AND DISCUSSION

The horizontal cutting force measured in the experiments was transferred to the VNC program with the Kistler transducer, and the force-time graphs seen in Figures 7 and 8 were obtained using the same program.

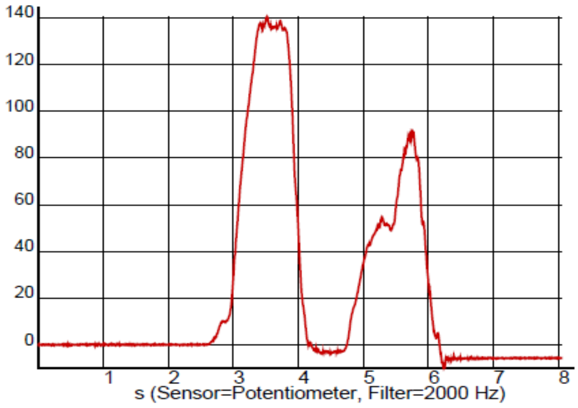

Fig. 7: force-time graph

The distribution of von Mises stresses formed on the cutting tool by the cutting forces measured as a result of the experiments is shown in Figure 9, in which the cutting force value obtained from the first experiment was used in order to provide an example image. The highest von Mises stress value was observed where the tool was attached to the workbench. In the remaining eleven experiments, the stress distribution was similar but with different values.

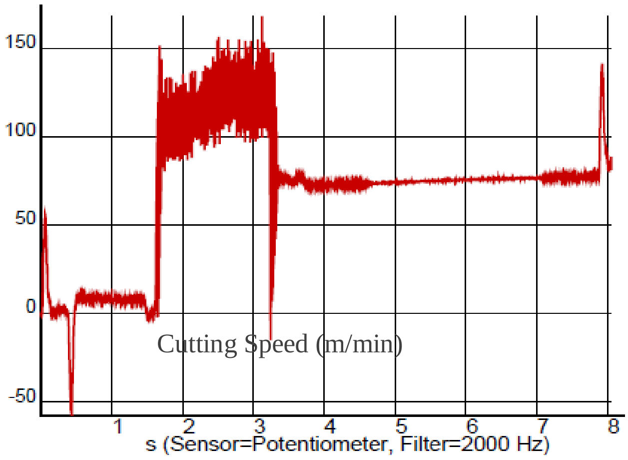

Fig. 8: force-time graph

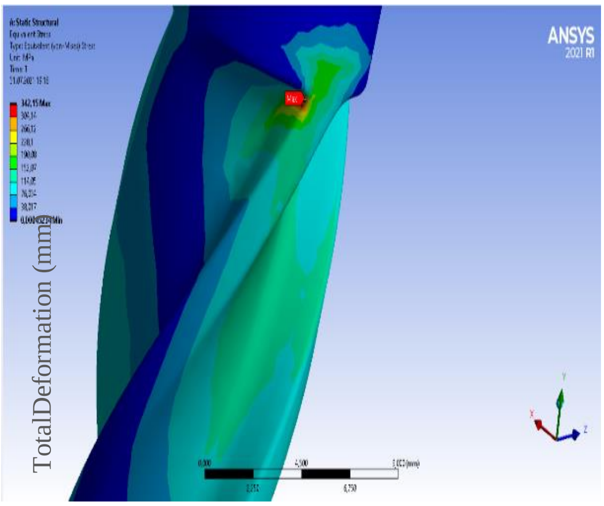

Fig. 9: Distribution of von Mises stresses

The total deformation distribution created by the cutting forces measured as a result of the experiments performed with the cutting tool is as shown in Figure 10, in which the deformation is in the +x direction where the force was applied. Figure 10 shows the cutting force values obtained from the experiments.

According to the experimental data, the cutting force increased when the feed was kept constant, and the cutting speed was increased. Likewise, the cutting force increased when the cutting speed was kept constant, and the feed increased.

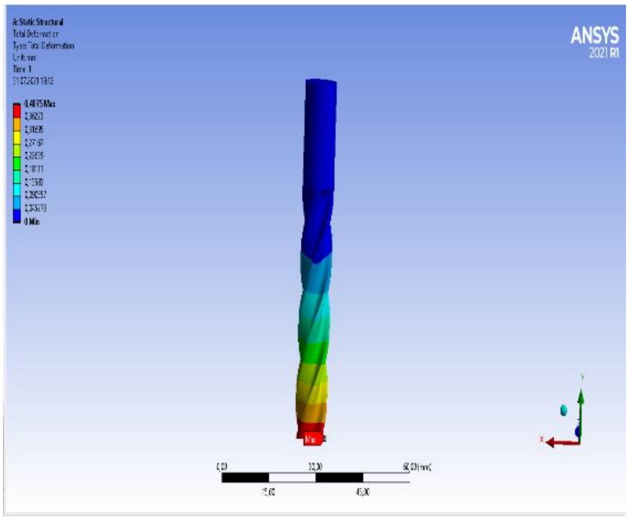

Fig. 10: Total deformation distribution

The graph showing the relationship between the feed rate and cutting force according to the test results is shown in Figure 11.

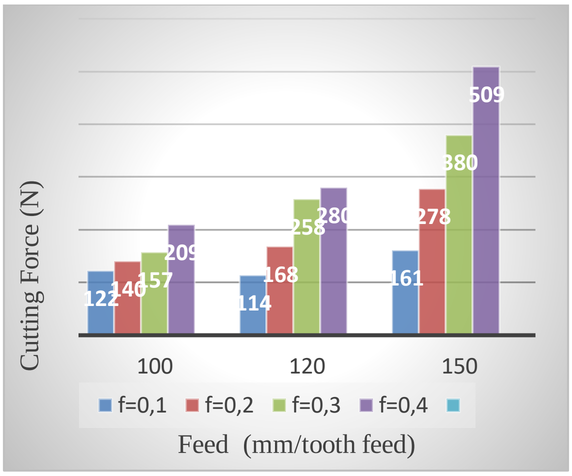

Fig. 11: Cutting force-feed rate graph showing experimental results

Examination of the experimental data showed that when the cutting speed was kept constant, and the feed rate increased, the measured cutting force value also increased. Only in the third experiment did the measured cutting force value decrease slightly, compared to the second experiment, although the feed rate value was increased. The graph showing the relationship between the cutting speed and cutting force according to the test results is shown in Figure 12.

The data obtained as a result of the analyses were examined and compared with each other, showing that the value of the von Mises stress formed in the tool increased as the cutting force applied to the tip of the tool increased. When the value of the applied cutting force decreased, the value of the von Mises stress formed in the tool also decreased.

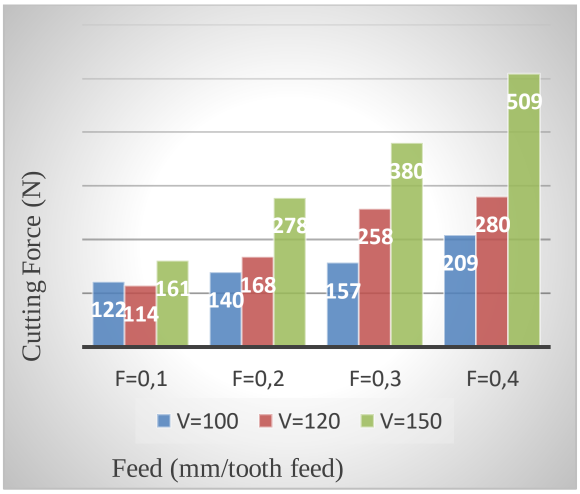

Fig. 12: Cutting force-cutting speed graph showing experimental results

The graph showing the correlation between the cutting force-von Mises stress values according to the results of the analyses is shown in Figure 13.

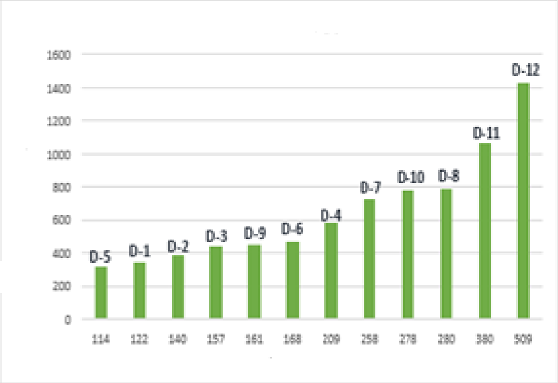

Fig. 13: Cutting force and von Mises stress analysis

The data resulting from the analyses were examined and compared with each other, showing that as the cutting force applied to the tip of the tool increased, the total deformation at the tip of the cutting tool increased in the same way. When the value of the applied cutting force decreased, the value of the total deformation at the tip of the cutting tool also decreased.

The graph showing the correlation between the cutting force-total deformation values according to the results of the analyses is shown in Figure 14.

According to the experimental data, in the first experiment, when the feed rate was 0.1 mm/rev and the cutting speed was 100 mm/min, the measured cutting force value was 122 N. In the fifth experiment, when the cutting speed was increased to 120 mm/min at the same feed rate, the measured cutting force value had inversely fallen to 114 N. In the ninth experiment when the cutting speed was increased to 150 mm/min at the same feed rate, the measured cutting force value was 161 N, indicating that the cutting force had increased.

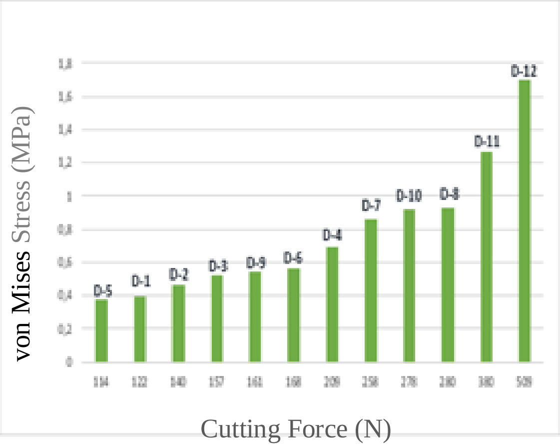

Fig. 14: Cutting force-total deformation graph

In the second experiment, when the feed rate was 0.2 mm/rev and the cutting speed was 100 mm/min, the measured cutting force value was140 N. In the sixth experiment, when the cutting speed was increased to 120 mm/min at the same feed rate, the measured cutting force value had risen to 168 N. In the tenth experiment, when the cutting speed was increased to 150 mm/min at the same feed rate, the measured cutting force value was 278 N, indicating that the cutting force had increased.

In the third experiment, when the feed rate was 0.3 mm/rev and the cutting speed was 100 mm/min, the measured cutting force value was 157 N.When the cutting speed was increased to 120 mm/min at the same feed rate in the seventh experiment, the measured cutting force value had risen to 258 N. In the eleventh experiment, when the cutting speed was increased to 150 mm/min at the same feed rate, the measured cutting force value was 380 N, indicating that the cutting force had increased.

In the fourth experiment, when the feed rate was 0.4 mm/rev and the cutting speed was 100 mm/min, the measured cutting force value was 209 N.In the eighth experiment, when the cutting speed was increased to 120 mm/min at the same feed rate, the measured cutting force value had risen to 280 N. In the twelfth experiment, when the cutting speed was increased to 150 mm/min at the same feed rate, the measured cutting force value was 509 N, showing that the cutting force had increased.

Examination of all the data showed that when the feed rate was kept constant, and the cutting speed was increased, the measured cutting force also increased. Only in the sixth experiment a slight decrease was observed in the measured cutting force value, compared to the first experiment, although the feed rate was kept constant and the cutting speed was increased.

IV. CONCLUSION

The effects of cutting speed and feed rate on the cutting force were investigated in machining on a vertical cutting model using experimental and finite element methods. Analyses were conducted for the total deformation, and von Mises stresses formed on the tools due to the effect of the cutting forces. The effect of the cutting parameters on the total deformation and stress in the tools was determined. The experiments demonstrated that the cutting forces increased in parallel with increasing cutting speed and feed rate during chip removal. The analyses revealed a direct correlation between the cutting forces and both the total deformation of the tool and the von Mises stresses. From this, it was possible to conclude that increasing the cutting speed and feed rate during chip removal would increase the total deformation of the tool. Likewise, it was observed that increasing the cutting speed and the feed rate would also increase the von Mises stresses in the tool.

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