Effect of changing turning parameters on the cutting forces

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Abstract: This paper deals with the effect of changing turning parameters on the cutting forces while machining AISI 1020 steel. Experimental results reveal that the increase in depth of cut (*d*) influenced the cutting forces more when compared to changing the feed rate (*f*) and cutting speed (*v*). Also, within the selected range of variables, an optimum material removal rate (*MRR*) is also recommended.
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Keywords: Turning, Material removal rate, cutting forces, depth of cut, feed rate, cutting speed

Introduction

Machining is a widely used type of material removal process where a single point or multi-point tool is used to remove material from the workpiece thus giving it the desired shape. There are many types of machining processes and turning is one of them. In turning operation, the workpiece is held in the chuck and is rotated at certain speed while a fixed single point cutting tool is brought into contact with it, thus removing metal. In case of external turning, the diameter of the workpiece is reduced, whereas in case of internal turning, the diameter of a hole is enlarged. Many researchers (Ahmed, et al. 2006,Muhammad, et al. 2012,Muhammad, et al. 2010,Muhammad, et al. 2011,Stoll, et al. 2006,Ahmed 2014,Atta and Ahmed 2014,Silberschmidt, et al. 2014,Ahmed 2013,Zafar and Ahmed 2013) have contributed towards force assessment during machining.

In (Avila and Abrao 2001), the performance of three types of cutting fluids were compared to dry cutting when continuous turning hardened AIS 4340 steel using mixed alumina inserts. Tool life, surface finish, tool wear mechanism and chips formed were evaluated. The authors concluded that the application of a cutting fluid based on an emulsion without mineral oil results in a longer tool life compared to dry cutting. When performing finish cutting at high cutting speeds, the use of cutting fluid was responsible for reducing the scatter in the surface roughness values. Gradual wear was reported mainly due to diffusion and abrasion. Chipping and catastrophic failure were frequent when rough turning was performed.

The chip light emission and morphology, cutting forces, surface roughness and tool wear in turning Zr-based bulk metallic glass material were investigated in (Bakkal, et al. 2004). Chip morphology showed that the light emission was correlated to melting of BMG chip. For the BMG chip without light emission, the serrated chip with adiabatic shear band and void formation was observed. Cutting forces and specific cutting energy of BMG was compared with those of AI6061 and SS304. High cutting speed significantly reduced the forces for BMG machining due to thermal softening. Roughness of machined BMG surfaces was generally better than the other two work materials.

The influence of cutting speed on tool wear and roughness was investigated in (Korkut, et al. 2004). Determination of optimum cutting speed was aimed when turning AISI 304 austenitic stainless steel using cemented carbide cutting tools. A decrease in tool wear was observed with increasing the cutting speed upto 180 m/mi. Surface roughness was also decreased with increasing the cutting speed. Correlation was made between the tool wear/surface roughness and the chips obtained at three cutting speeds.

The influence of rake angle, cutting feed and cutting depth on residual stresses in hard turning was analyzed in (Dahlman, et al. 2004). Face turning was performed with constant speed in AISI 52100. Cutting feed and depth of cut were investigated. A greater negative rake angle gave higher compressive stresses as well as a deeper affected zone below the surface. The depth of cut did not affect the residual stresses whereas an increase in feed rate generated significantly higher compressive stresses.

The evolution of descriptive parameters during time when machining a hard material with a cubic boron nitride was evaluated in (Remadna and Rigal 2006). The paper aimed at studying the turning of hard materials with CBN inserts, the correlation between wear evolution and the direction of cutting forces during high-speed machining. Based on the experimental results, it was concluded that the geometry of the cut evolves considerably relative to the lifetime of a CBN tool. Cutting forces increased gradually with the increase of the cutting distance and the tool flank wear.

Numerical simulations of high-speed orthogonal machining were performed to study the finish hard-turning process as a function if cutting speed, feed, cutter geometry and workpiece hardness in (Qian and Hossan 2007). Feed force appeared to be a larger force component than the cutting force in the hard turning. Cutting force and feed force increase with increasing feed, tool edge radius, negative rake angle and workpiece hardness.

Tests were conducted in (Isik 2007) in order to determine the machinability of tool steels where the effects of tool material, types of coolant on the insert and cutting parameters that affect the machinability were taken into consideration. The cutting force data used in the analyses were gathered by a tool breakage detection system that detected the variations of the cutting forces measured by a three-dimensional force dynamometer. During the experiments cutting forces, flank wear and surface roughness were measured throughout the tool life and the machining performance of the tool steels was compared. It was concluded that the cutting speed was the most influential parameters on tool life. In turning operation, feed rate was the most influential parameter on surface roughness, cutting depth second most important and the cutting speed least influenced parameter.

The development of the first and second order models for predicting the cutting forces produced in end-milling operation of modified AISI P90 tool steel were discussed in (Abou-El-Hossein, et al. 2007). The first and second order cutting forces equations were developed using the response surface methodology to study the effect of four input cutting parameters (cutting speed, feed rate, radial depth and axial depth of cut) on cutting force. The cutting force contours with respect to input parameters were presented and the predictive models analyses were performed with the aid of statistical software. The received second order equations showed that the most influential input parameter was the feed rate followed by axial depth and radial depth of cut and finally the cutting speed.

The effect of cutting parameters on cutting forces and surface roughness in finish hard turning of MDN250 steel were investigated using coated ceramic tool in (Lalwani, et al. 2008). The machining experiments were conducted based on response surface methodology and sequential approach using face centered composite design. Depth of cut was declared as the most dominant contributor to the feed force. In the thrust force, feed rate and depth of cut contributed 46% and 49% respectively. In the cutting force, feed rate and depth of cut contributed 52% and 41% respectively. In case of surface roughness, it was also concluded that the feed rate provided primary contribution and influenced most significantly.

Experimental studies of wear, cutting forces and chip characteristics were analyzed in (Katuku, et al. 2009) when dry turning ASTM Grade 2 austempered ductile iron (ADI) with polycrystalline cubic boron nitride (PcBN) cutting tools under finishing conditions were carried out. A depth of cut of 0.2 mm, a feed rate of 0.05 mm/rev and cutting speeds ranging from 50 to 800 m/min were used. Flank wear and crater wear were the main were nodes within this range of cutting speeds. Cutting speeds between 150 and 500 m/min were fund to be optimum for the production of workpieces with acceptable tools life, flank wear rate and lower dynamic cutting forces.

The effects of cutting speed, feed rate, workpiece hardness and depth of cut on surface roughness and cutting force components in hard turning were experimentally investigated in (Aouici, et al. 2012). Results showed that the cutting force components were influenced principally by the depth of cut and workpiece hardness; on the other hand, both feed rate and workpiece hardness had statistical significance on surface roughness. The best surface roughness was achieved at the lower feed rate and the highest cutting speed.

The effect of cutting speed, feed, tool nose radius, geometry of the tool chip breaker and coating of the cutting tool were studies in (García Navas, et al. 2012) AISI 4340 steel. As feed increased, residual stresses were noted to be more tensile due to an increase in cutting temperature. As cutting speeds increased, the residual stresses tend to be less tensile. An increase in tools nose radius implied higher tool-workpiece contact area, thus resulted in higher temperature due to friction and less plastic deformation leading to more tensile surface residual stresses although the surface roughness improved for such cases.

An attempt to developed a force prediction model during finish machining of EN31 steel using hone edge uncoated CBN tool was presented in (Bartarya and Choudhury 2012). A combination of the machining parameters for better performance within a selected range of machining parameters was also analyzed. A full factorial design of experimental procedure was used to develop the force and surface roughness regression models, within the range of parameters selected. The model showed that the dependence of cutting forces and surface roughness on machining parameters were significant. Depth of cut was found to be the most influential parameters affecting the three components of forces followed by the feed rate. The cutting speed was the least influential factor affecting the cutting forces.

The influence of cutting speed, feed rate, depth of cut and machining time on machinability characteristics such as machining force, surface roughness and tool wear suing response surface methodology based on second order mathematical models during turning of AISI 4340 using coated carbide inserts was analyzed in (Suresh, et al. 2012). From the parametric analysis, it was revealed that the combination of low feed rate, low depth of cut and low machining time with high cutting speed was beneficial in minimizing the machining force and surface roughness.

In (Sivaraman, et al. 2012), a multiphase microalloyed steel was turned to study the effect of machining parameters such as cutting speed, feed and depth of cut on cutting forces. The mechanical properties of the multiphase microalloyed steels were analogous to the quenched and tempered steel. The analysis of variance was performed to identify the significance of machining parameters. The results showed that feed and depth of cut influenced more on cutting forces than cutting speeds. The optimal cutting conditions to machine the multiphase microalloyed steel were identified as cutting velocity of 80 m/min, feed rate of 0.05 mm/rev and depth of cut of 0.1 mm.

Material removal is accomplished through shearing operation (Muhammad, et al. 2012). The tool pushes the material or the workpiece, thus creating the primary shear done. Material, in the form of plates, slip along this shear plane and thus a chip is formed. Figure 1 presents the forces acting along the tool-workpiece interaction zone and the shear zone.

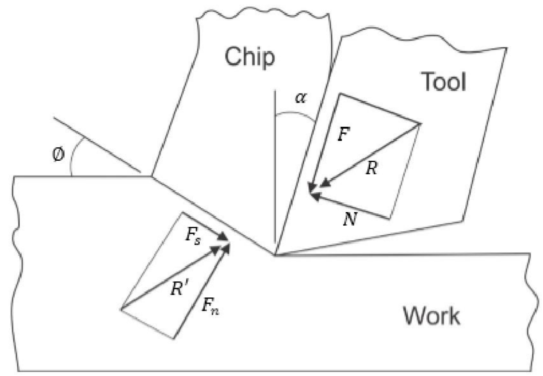

Figure 1: Forces acting on the chip in orthogonal cutting (after (Groover 2010))

$$F = F_c sin\alpha + F_t sin\alpha \quad (1)$$

$$N = F_c cos\alpha - F_t sin\alpha \quad (2)$$

$$F_s = F_c cos\emptyset - F_t sin\emptyset \quad (3)$$

$$F_n = F_c sin\emptyset + F_t cos\emptyset \quad (4)$$

None of these forces are measurable using the force dynamometer. The force dynamometer rather measure another set of forces that is along the x-axis and y-axis (Figure 2).

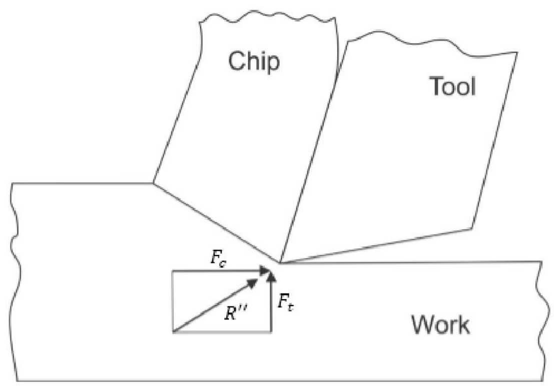

Figure 2: Forces acting on the tool that can be measured (after (Groover 2010))

Since the resultant of all these forces is common, these can be related using the Merchant's circle diagram, Figure 2.

The three variables they control the turning operation are the cutting speed (v), feed rate (f) and the depth of cut (d). The product of these three is called the material removal rate (MRR).

$$MRR = v\ f\ d \quad (5)$$

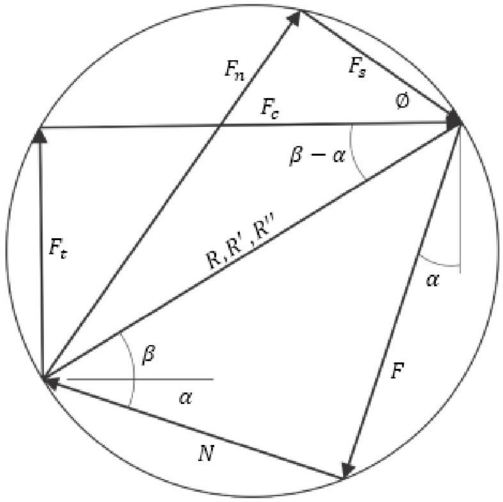

Figure 3: Mohr's circle for linking various types of machining forces (after (Groover 2010))

Experimental Procedure

A 32 mm diameter AISI 1020 steel rod was selected as a starting material. It was machined down to 30 mm and heated to 0.75 of the melting point and furnace cooled to remove the effects of any residual presence that might have developed during shipping and handling. Pinacho S-90/165 lathe was used to conduct the experiments. The lathe machine was equipped with a digital readout that provided better control in setting up the values of depth of cut and feed rate. A Kistler type 9129AA force dynamometer was used to measure the forces along the *x*, *y* and *z*-axis. The dynamometer was connected to computer using the Multichannel Charge Amplifier type 5070 and DAQ for DynoWare type 5697. The way the dynamometer was setup, the forces along x-axis corresponded to the cutting forces, F_C whereas the forces along z-axis corresponded to tangential forces, F_T. Table 1 presents the set of variables selected for the experimentation.

Table 1: Set of variables selected for experimentation

Variable name	Values	Units
Speed, *N*	360, 700, 1400	rpm
Feed rate, *f*	0.05, 0.1, 0.2	mm/rev
Depth of cut, *d*	0.25, 0.5, 0.75, 1	mm

Various combinations of variables were developed using the data presented in the table 2. The case name contains the information like type of turning (conventional turning), feed rate, depth of cut and speed.

Figure 4: Experimental Setup

Table 2: Final list of cases developed for experimentation

Case Name	Speed, rpm	Feed, mm/rev	Depth of Cut, mm
CT_0P25_0P05_360	360	0.05	0.25
CT_0P25_0P05_700	700	0.05	0.25
CT_0P25_0P05_1400	1400	0.05	0.25
CT_0P25_0P1_360	360	0.1	0.25
CT_0P25_0P1_700	700	0.1	0.25
CT_0P25_0P1_1400	1400	0.1	0.25
CT_0P25_0P2_360	360	0.2	0.25
CT_0P25_0P2_700	700	0.2	0.25
CT_0P25_0P2_1400	1400	0.2	0.25
CT_0P5_0P05_360	360	0.05	0.5
CT_0P5_0P05_700	700	0.05	0.5
CT_0P5_0P05_1400	1400	0.05	0.5
CT_0P5_0P1_360	360	0.1	0.5
CT_0P5_0P1_700	700	0.1	0.5
CT_0P5_0P1_1400	1400	0.1	0.5
CT_0P5_0P2_360	360	0.2	0.5
CT_0P5_0P2_700	700	0.2	0.5
CT_0P5_0P2_1400	1400	0.2	0.5
CT_0P75_0P05_360	360	0.05	0.75
CT_0P75_0P05_700	700	0.05	0.75
CT_0P75_0P05_1400	1400	0.05	0.75
CT_0P75_0P1_360	360	0.1	0.75
CT_0P75_0P1_700	700	0.1	0.75
CT_0P75_0P1_1400	1400	0.1	0.75
CT_0P75_0P2_360	360	0.2	0.75
CT_0P75_0P2_700	700	0.2	0.75
CT_0P75_0P2_1400	1400	0.2	0.75
CT_1_0P05_360	360	0.05	1
CT_1_0P05_700	700	0.05	1
CT_1_0P05_1400	1400	0.05	1
CT_1_0P1_360	360	0.1	1
CT_1_0P1_700	700	0.1	1
CT_1_0P1_1400	1400	0.1	1
CT_1_0P2_360	360	0.2	1
CT_1_0P2_700	700	0.2	1
CT_1_0P2_1400	1400	0.2	1

Results and Discussions

The force results for various cases are presented in this section. Figure 5 presents the forces for various cutting speeds and feed rates at a constant depth of cut of 0.25 mm.

Figure 6 presents the force results for various cutting speeds and feed rates at a constant depth of cut of 0.5 mm.

Figure 7 presents the force results for various cases of feed rates and cutting speeds at a constant depth of cut of 0.75 mm. Figure 8 presents the results for various feed rates and cutting speeds at a constant depth of cut of 1 mm.

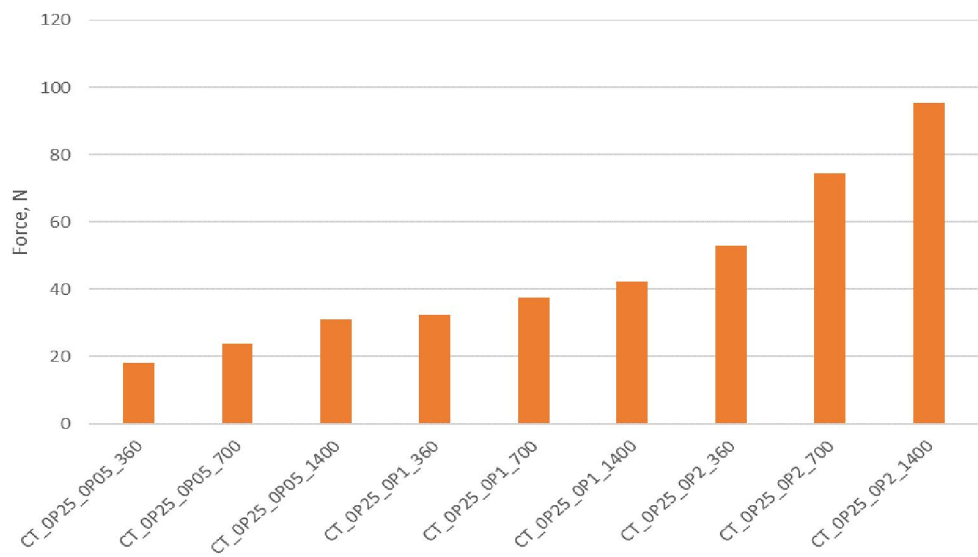

Figure 5: Machining forces as recorded by the force dynamometer for *d* = 0.25 *mm*

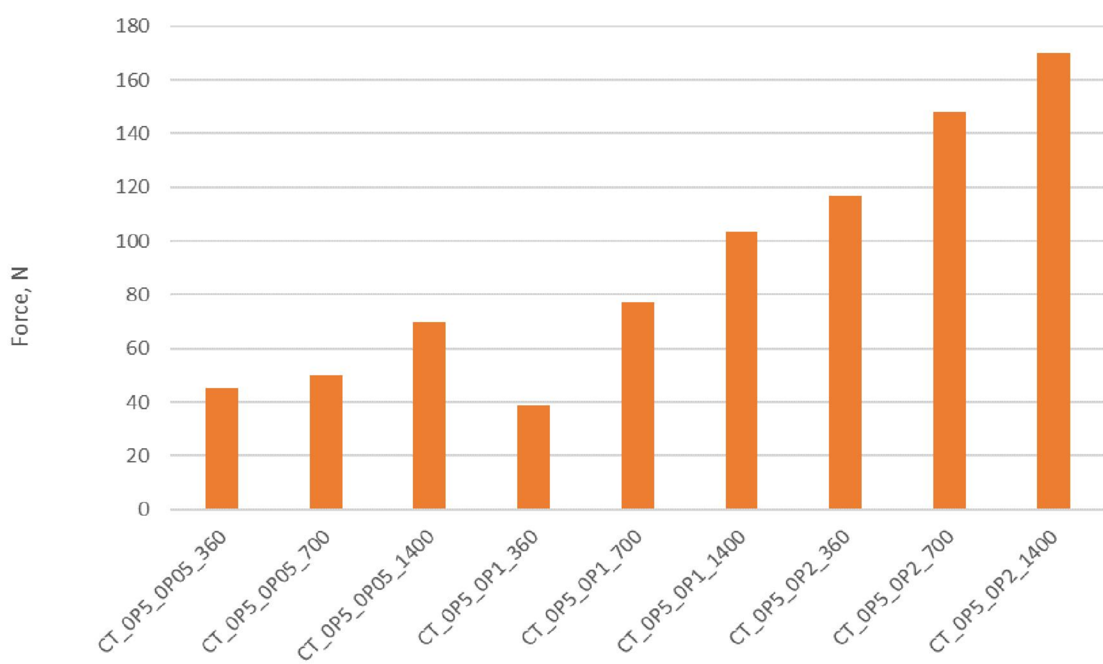

Figure 6: Machining forces as recorded by the force dynamometer for *d* = 0.5 *mm*

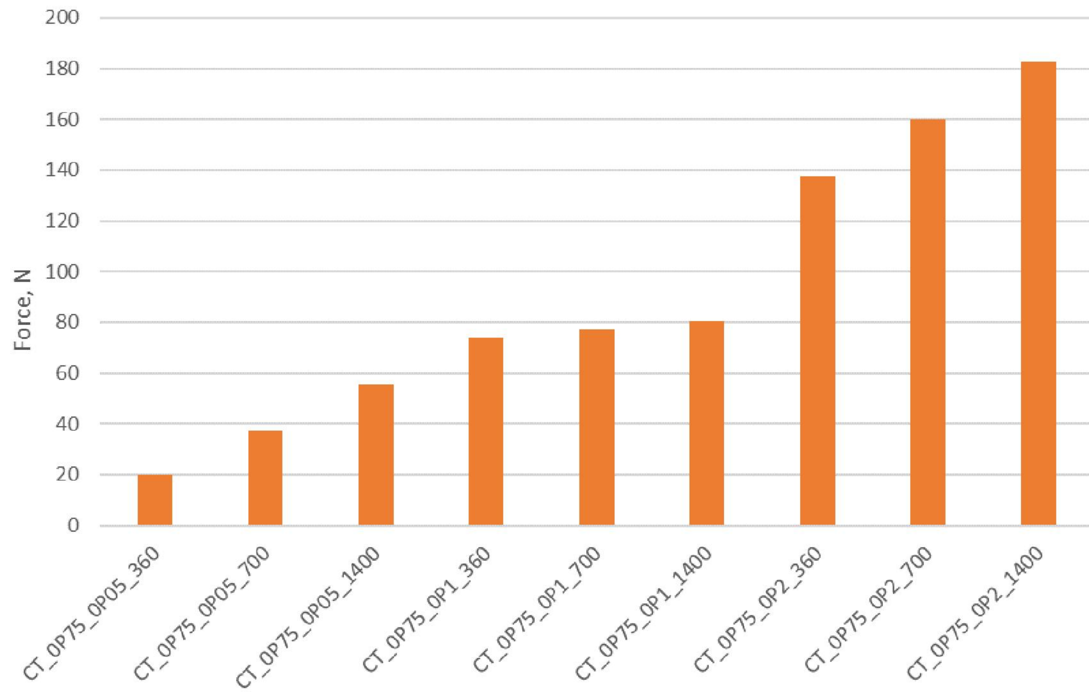

Figure 7: Machining forces as recorded by the force dynamometer for $d = 0.75$ *mm*

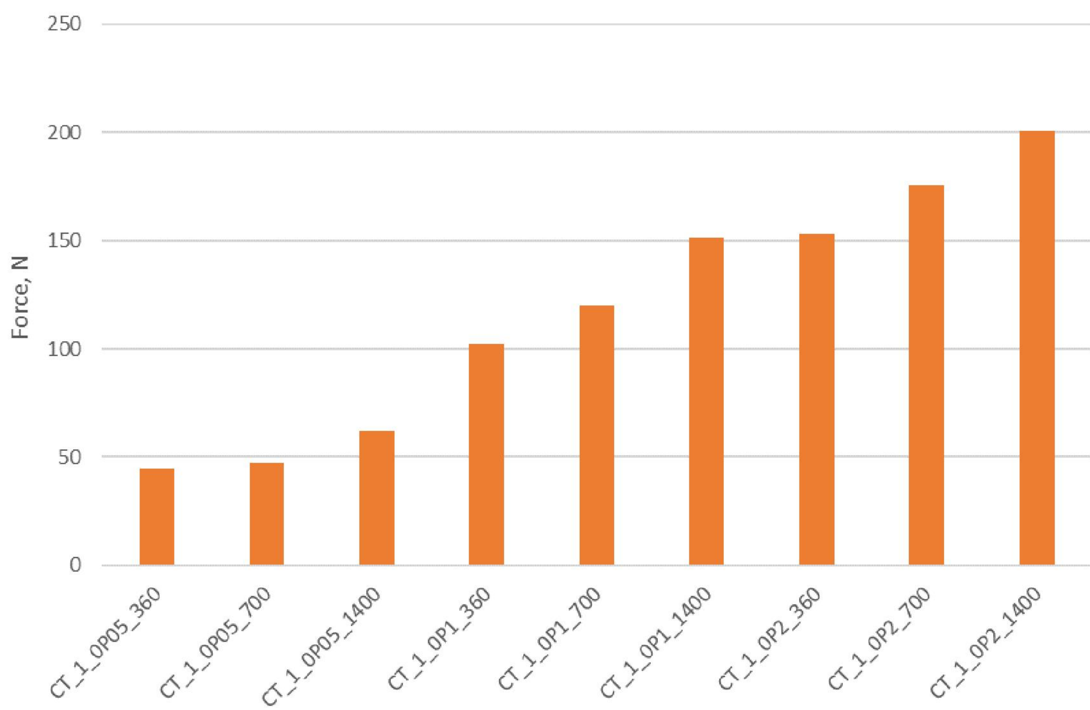

Figure 8: Machining forces as recorded by the force dynamometer for $d = 1$ *mm*

From the above figures, it can be seen that the effect of depth of cut is the most dominant, whereas the effect of cutting speed is least affecting the cutting forces. Also it was observed that the relationship between increasing the material removal rate and cutting forces was not linear. At higher material removal rates, the cutting forces were not changing much. Two combinations were identified as optimum; a cutting speed of 1400 rpm, with a depth of cut of 1 mm and a feed rate of 0.2 mm/rev and a cutting speed of 1400 rpm, depth of cut of 0.75 mm and a feed rate of 0.1 mm/rev.

Conclusion

This paper presents the effect of changing turning parameters on the cutting forces while machining AISI 1020 steel. Experimental results revealed that the increase in depth of cut *d* influenced the cutting forces more when compared to changing the feed rate *f* and cutting speed *v*. Also, within the selected range of variables, an optimum material removal rate *MRR* is also recommended. Two combinations were identified as optimum; a cutting speed of 1400 rpm, with a depth of cut of 1 mm and a feed rate of 0.2 mm/rev and a cutting speed of 1400 rpm, depth of cut of 0.75 mm and a feed rate of 0.1 mm/rev.

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