

Investigating the Performance of Coated Carbide Insert in Hard Steel Helical Milling

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Abstract: Helical milling is an alternative hole-making machining process which presents several advantages when compared to conventional drilling. In the helical milling process, the tool proceeds a helical path while rotates around its own axis. Due to its flexible kinematics, low cutting forces, tool wear, and improved borehole quality may be achieved. In this study, a new helical milling process to create holes in hardened steel with a hardness of HRC 52 was used. Carbide inserts with PVD TiN coating were applied. Input parameters including cutting speed and feed rate were considered in 4 and 2 levels, respectively. In order to increase the reliability of the results, experiments were repeated 4 times and the total of 32 tests were performed. Other cutting parameters, such as axial and radial depth of cut were constant. Machining process was performed in dry state and without any lubricant. Output characteristics were tool wear, surface roughness, cutting force, machining time and material removal rate. Tool wear, surface roughness and forces, were measured by tool maker microscopy, roughness tester and dynamometer, respectively. The results showed that increasing the cutting speed on this type of hardened steel, decreases the surface roughness, machining forces and machining time. However, increasing the cutting speed and the feed rate enhances the tool wear and material removal rate considerably. Cutting speed and Feed rate of 50 m/min and 0.05 mm/tooth, offered the best mechanical properties of the Machining.

Keywords: Coated Carbide Tool, Hard Steel, Helical Milling, High Performance Machining

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1 INTRODUCTION

In recent years, the machining of hard parts as a desirable and effective technology has been a substituted for polishing operations such as grinding. Hard material machining has the advantages of reducing the time and cost of machining, eliminating the payment of operations, improving the health and reducing the distortion caused by heat treatment [1], [2].

One of the challenges ahead for machining the parts in hard mode is the performance of cutting tools. In order to deal with the limitations of this method, robust tools should be used to improve the quality of the work piece while improving the life of the tools and carbide tools, while having the appropriate cost, acquire higher hardness, low thermal expansion, elasticity coefficient and high thermal conductivity. Hence, these tools are considered as the most commonly used tools for machining steels and castings alloys [3], [4]. However, carbide tools have lower wear resistance compared to advanced tools such as CBN and ceramics and hence they can not only be used as a tool for machining hard materials.

Therefore, in order to improve wear resistance, they cover carbide tools with abrasion-resistant materials. The higher hardness and temperature of the coating, the greater wear resistance will result. These coatings also have a lower friction coefficient, which reduces friction between tools and work-pieces, and improves important applications, such as dry machining [5], [6]. In machining hard materials, titanium base coatings are considered as the most common coating for improving wear resistance and machining of carbide tools. In addition to the material of coating, thickness and coating method is also very important. Cutting tools coating are carried out in a variety of ways, including chemical vapor deposition (CVD) and physical vapor deposition (PVD) [7].

The Helical milling method is considered as one of the new processes for the production of high-quality holes that can be used in a hard-hole drilling. One of the prominent features of this technique is its high flexibility in the production of holes of any diameter and the integration of the production process. This means that by using a machine tool and a cutting tool, it possible to perform different processes, such as milling and drilling [8].

Compared to conventional drilling, this method, due to having more movement space during the helical movement, creates less contact between the tool and the work-piece surface which leads to less wear on the instrument. Hence, the use of helical milling in the development of parts used in various industries, including aerospace, power engineering and molding is expanding.

2 BACKGROUND

In the following, some studies which have been carried out on helical milling will be indicated [9]. Eyre et al. [10], examined the cutting conditions by using different processes of drilling and helical milling on hard steels and reported that for economic and environmental reasons, it would be better to operate the machining process on these steels in a dry state without any lubricant. They also found out that using a helical milling could make a hole with a surface roughness close to polishing, which prevents the use of polishing operations such as reaming. Lee et al. [11] studied the quality of the hole in milling the Ti6Al4V alloy using a carbide tool, and stated that the poorest quality of the hole production in drilling will be resulted by worn out tool. This is due to the high temperature of the tool. They also said that with increasing time of machining and wear, the surface of the hole production would be of lower quality.

Veldius et al. [12] studied tribology compatibility and improvement of the machining efficiency on the hard steel. In their study, they used various coatings and carbide ball nose tools, and they stated that the type of coating is effective on the hardness of the machining process. They also found that, if a high tribology capability was achieved between tools and work-pieces, then tool life and surface integrity in hard drilling would be improved. Lee and Liu [11] studied topography and surface roughness of the hole production with the help of a helical milling and reported that there is an inverse ratio between the surface roughness and the feed. In such a way, if the feed rate is lower, better surface quality is obtained.

Brainsheimer et al. [13] stated that during the machining process of helical milling, the BUE decreases, which reduces the machining temperature and plastic deformation. This reduction in temperature reduces the friction coefficient in the cutting region and, in addition, reduces adhesion between the tool and the work-piece. Rack and Mussan [14] studied the effects of cutting speed and feed rate on hard machining of hardened gears. Their results showed that cutting speed is the main effect on wear and residual stress of the work-piece. They also stated that the feed rate is the most decisive parameter on the surface roughness. Okada and colleagues [15] investigated the performance of carbide tools with a various coating in hard milling of hardened steels.

They reported that by controlling tool wear, surface roughness, machining forces and cutting temperature machining performance can be improved. Carbide Cutting tools versus CBN (cubic Bern Nitrate) cutting tools have more tool-wear and therefore have a shorter life. Instead, carbide tools can create a suitable surface roughness regarding the proper price. They stated that

with decreasing wear, it can be concluded that the resulting temperature of the tool and the workpiece is a steady state, which itself prevents thermal shock. This way, these thermal shocks, due to the creation of micro-tracks, have an adverse effect on the sudden failure of the tool. Aslan [16] investigated the performance of milling carbide tools in hardening of X210 Cr12 steel. His aim was to test the wear of TiB, TiCN + TiAlN coatings. He argued that carbide tools with TiAlN are better than TiCN coatings. As a result, the wear of carbide tools with TiCN + TiAl coating is equal to 0.72 mm, for TiCN coating equal to 0.79 mm, and for TiAlN coating equal to 0.55 mm. Robinovich et al. [17] studied on coatings of cutting-tools and stated that the TiAlN coating causes the formation of a protective layer of alumina between the tool and the stainless steel, which reduces friction, cracks and wear of tools, and ultimately improves tool life. The investigations show that, despite the extensive studies in the helical milling, a report on the performance of the high-speed steel helical milling operation has not been published using the insert tool. For this purpose, helical milling on hardened steel AISI D2 with a hardness of 52 HRC was investigated experimentally and the tool wear and surface roughness of the hole production, machining force, machining time and cutting rate per unit time in this process was reviewed.

3 PREPARATION AND TESTING

The work-piece used in this study is AISI D2 steel (ASTM A681), heat treated with a hardness of 52 ± 52 HRC. The original chemical composition of AISI D2 hard steel is given in "Table 1". In order to achieve the hardness, the work-piece is heat treated. Vacuum heat treatment is a process in which the austerite of the steel is carried out in vacuum and quenched with a neutral gas such as nitrogen or argon.

Table 1 Chemical compositions of hardened AISI-D2 steel

Chemical elements	Weight percent %
Chrome	12.1
Carbon	1.6
Vanadium	0.8
Molybdenum	0.71
Silicon	0.5
Manganese	0.3
Nickel	0.2
Iron	Based

This method has advantages such as hardness from the surface to the core of the piece, the reduction of residual stress and the distortion resulting from heat treatment and increased toughness. In order to achieve abrasion resistance, carbide inserts (LC 08, 8026) with PVD

coating of material TiN were used. All experiments were carried out in dry and without lubrication for economic and environmental reasons. The inserts are firmly on the K2-CLC holder. The diameter of the cutting tool is 8 mm after the insertion of the tool in the holder. The tools and inserts used are shown in "Fig. 1 & Fig. 2", respectively.



Fig. 1 Tool holder used in the experiment.

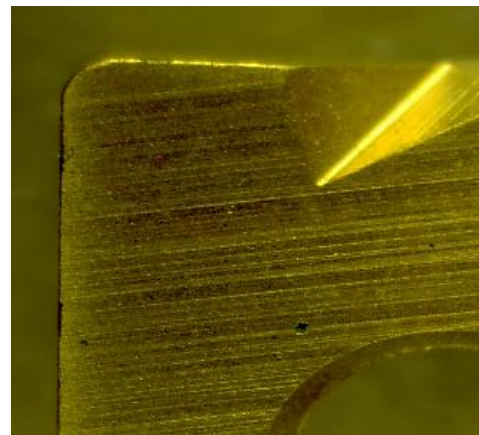


Fig. 2 Insert used in the experiment.

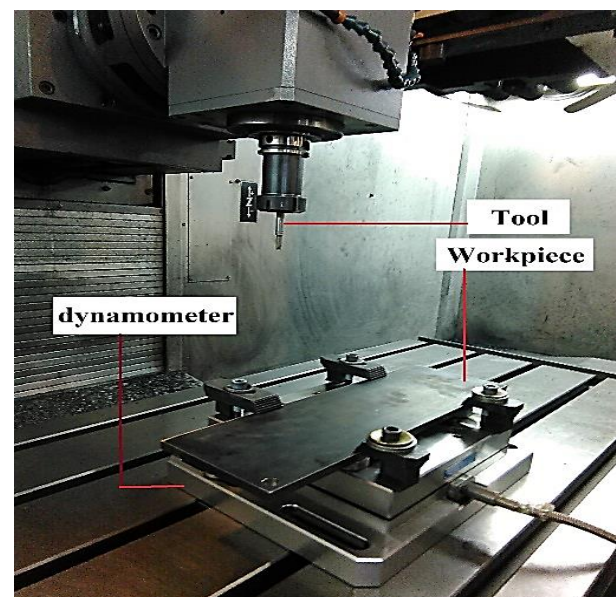


Fig. 3 View of the experiment and its layout.

The experiments are planned by a milling machine with three-axis numerical control of the FSO model for the CME Company with Hidenhain controller. The maximum revolution of the machine is 18,000 rpm. Figure 3 shows an overview of the testing equipment layout. Wear on cutting tools has different criteria, each of which is due to its own reasons. Regarding the dominance of the free edge wear mechanism at high velocities, in this study, free-rim wear was measured and reported. In order to measure the inserts wear the VMM-CMM device with EV-4030 model was utilized. The inserts were first placed under a microscope, and then, using the software, the edge-wound curve of the tool was determined and the values of the wear were determined by measuring the curvature distance (line perpendicular to the curve). The microscope instrumentation used is shown in Figure 4.



Fig. 4 Image measuring device for wear.

The experimental design used in this study is a full factorial method. Prior to designing the test, the range of machining parameters were determined by performing some set of initial tests. Input parameters of the cutting speed (V_c) and feed rate (F_z) were considered as test variables in 4 and 2 levels respectively. Tests were performed randomly with four replications and a total of 32 experiments were conducted. Data obtained from Experiments were analyzed by Minitab 16 software. In “Table 2”, the test parameters and their levels were determined. Machining forces were also measured using a dynamometer. The dynamometer used is the 9255B Kistler type, whose range in X and Y directions is from -20 KN to 20 KN and in Z direction from -10 KN to 40 KN. The PS1 model was used to measure surface roughness. Surface roughness has been reported based on Ra criterion, which is equal to the roughness curve integral obtained over the measured length. The surface roughness of each hole was measured in three different paths and the mean of these three numbers was considered as roughness.

Table 2 Test variable parameters along with the levels

Parameters	Levels			
Cutting (V_c) m/min speed	50	100	150	200
Feed rate (F_z) mm/tooth	0.05	0.1	-	-
Depth of cut (a_p) mm	0.1	-	-	-

4 RESULT

In “Table 3”, the values of the input parameters and the average outputs of the experiments are presented including tool wear, surface roughness, cutting forces, machining time and MRR. These outputs are examined separately in the following.

Table 3 Test variable parameters and outputs

Test	Cutting speed m/min	Feed rate mm/tooth	Wear mm	Ra μ m	MRR mm^3/min	Machining time sec
1	50	0.05	0.087	0.896	0.209	315
2	50	0.1	0.081	0.431	0.417	152
3	100	0.05	0.103	0.672	0.418	155
4	100	0.1	0.244	0.317	0.836	75
5	150	0.05	0.110	0.693	0.627	99
6	150	0.1	0.260	0.358	1.253	57
7	200	0.05	0.180	0.623	8.778	69
8	200	0.1	0.246	0.299	17.556	56

4.1. Surface Roughness

The measurement results of the surface roughness of the hole production indicates that the best and worst surface roughness is 0.299 μ m and 0.896 μ m, respectively. Figure 5 shows the diagram corresponding main effects of parameters on the surface roughness of the produced

hole. According to this figure, with an increase in cutting speed from 50 m / min to 200 m / min, surface roughness improved by about 200%. Also, with increasing cutting speed, by far the roughness of the production hole has been reduced.

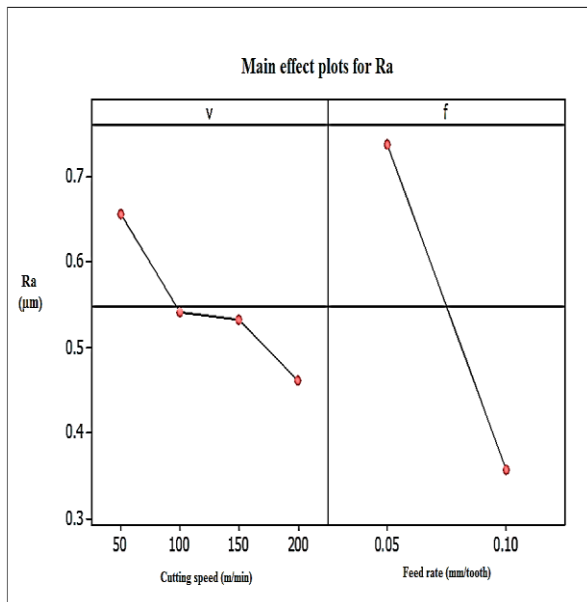


Fig. 5 Graph of the effect of cutting speed and feed rate on surface roughness.

This can be due to the reduction of cutting forces and softening of the material due to the increased temperature in the cutting area. As a result, plastic deformation is easily done and, consequently, the surface roughness of the hole has been improved. Additionally, with increasing cutting speed from 100 m / min to 150 m / min, roughness decreased with lower slope. This slope reduction is due to the process stability and vibration reduction of the machine tool in this interval of cutting speed [19]. On the other hand, as feed rate proceeded, surface roughness improved dramatically.

This improvement can be justified by the exceeding of the feed rate from the radius of the tool. In order to better understand the effect of cutting parameters, in “Fig. 6”, the contour of the interaction between the cutting speed and the feed rate on the surface roughness has been shown. As shown in the figure, surface roughness has been improved by simultaneously increasing both parameters (cutting speed and feed rate). Also, as seen, the effect of the feed rate on the surface roughness was greater than the cutting speed.

4.2. Tool Wear

In the present study, since the cutting speeds are located in the high speed machining area, the flank wear is the main mechanism of disability of the instrument in the area, and this wear was measured and reported. In the process of helical milling, due to the kinematics of the process, the method of cutting, reducing the clash and contact of the tool with the work-piece, a slight wear has been observed.

Nonetheless, the flank wear values in “Table 3 and Fig. 7” show that with increasing cutting speed, wear

increases significantly. Cutting speed and machining temperatures that are directly related to each other are among the main reasons for tool wear. As cutting speed increases, the machining force is concentrated on the tip of the tool and the temperature of the cutting area increases.

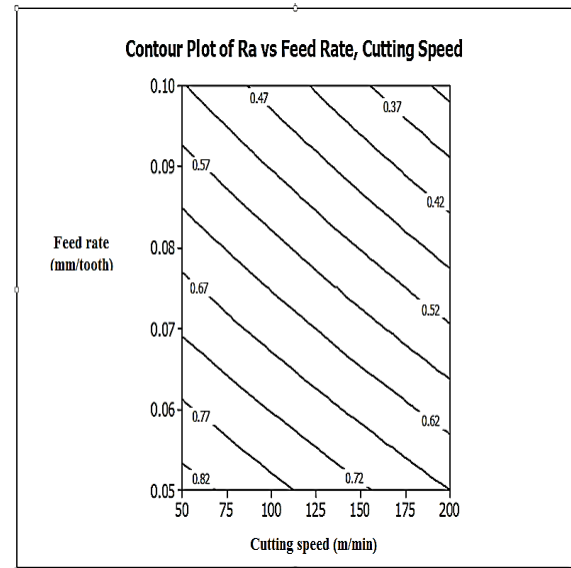


Fig. 6 Graph of the effect Contour plot of cutting speed and feed rate on surface roughness.

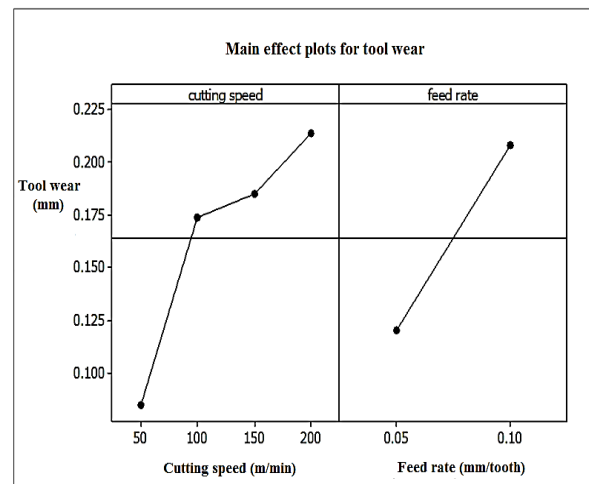


Fig. 7 Graph of the effect of cutting speed and feed rate on tool wear.

On the other hand, as the force and temperature increase between the tools and the work-piece, the tool is slightly softened and the plastic deformation possibility can be increased. Also, with increasing cutting speed, the MRR is increased, which results in increased fracturing of the tool and eventually more severe wear on the tool. By increasing the cutting speed, tool wear is also reduced due to reduced heat transfer to the environment and

higher filing rates, hence the tool life will be diminished. As shown in “Fig. 8”, the rate of wear is increasing at cutting speed of 100, 150 and 200 m / min, with a feed rate 0.05 to 0.1 mm per toe. But at a speed of 50 m / min, as the feed rate advance, the wear rate is almost constant. Therefore, the optimal speed for the life of the tool will be 50 meters per minute.

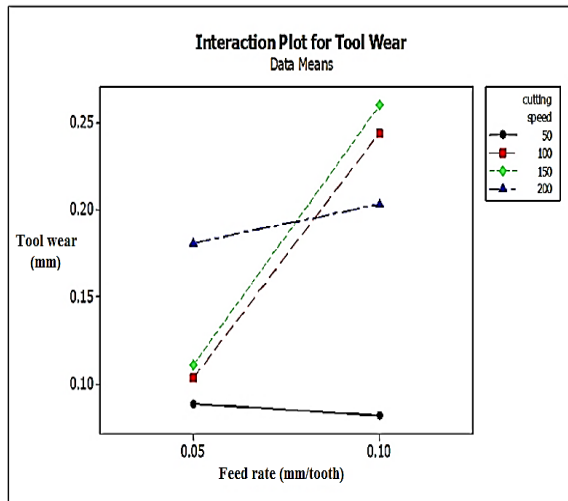
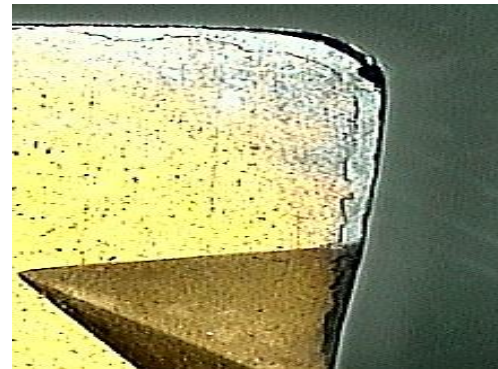
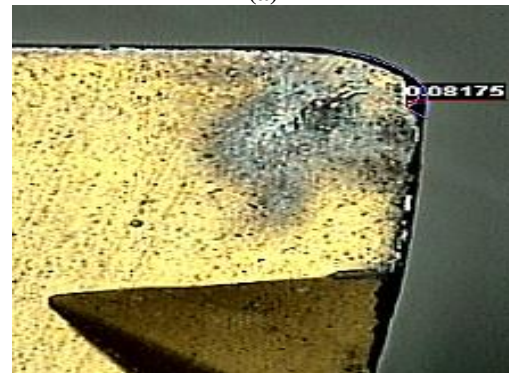


Fig. 8 Graph of cutting speed and feed rate interaction on tool wear

In “Fig. 9 and 10”, the amount of abrasion in different cutting rates and feed rate is shown. In addition, as shown in “Fig. 8”, the tool wear at cutting rate of 200 m / min (with respect to 100 m/s and 150 m / min) has less variation, which results in stability and improvement of the process. The contour of the interaction between the cutting speed and the feed rate on the surface roughness has been shown in “Fig. 11”.



(a)



(b)

Fig. 10 Tool wear in 50 m/min: (a): Feed rate 0.1 mm/tooth and (b): Feed rate 0.05 mm/tooth.



(a)



(b)

Fig. 9 Tool wear in 200 m/min: (a): Feed rate 0.1 mm/tooth and (b): Feed rate 0.05 mm/tooth.

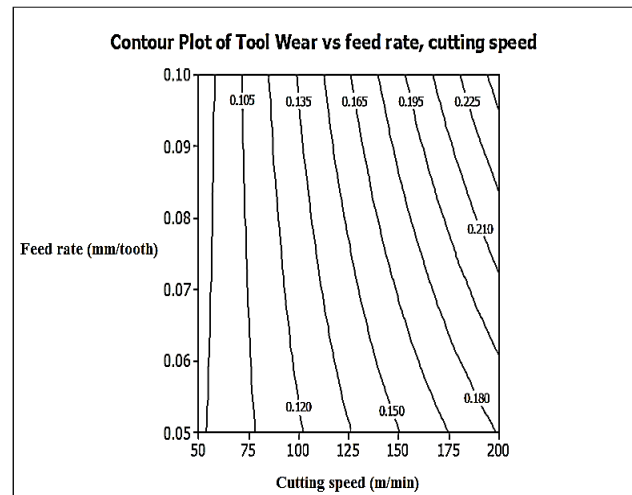


Fig. 11 Graph of the effect Contour plot of cutting speed and feed rate on tool wear.

4.3. Machining Force

In the helical milling, the material removal is in cut off form, so that the cross-sectional area follows the sinusoidal changes. For this reason, the level of tool contact and material removal is constantly changing and is much less than ordinary drilling. By increasing the cutting rate, the machining force was reduced due to the change of material removal process (“Fig. 12”). In addition, by increasing the cutting speed, due to the smaller cutting area, less energy was used for material removal and consequently reduces cutting forces [19]. On the other hand, with declining feed rate, power is declined. This reduction in force can be attributed to the reduction of the friction coefficient and the uneven distribution of stress in the cutting plane. As a result, by increase of cutting speed and decreasing feed rate (in the permitted range) cutting speed diminishes and machining efficiency is improved [20].

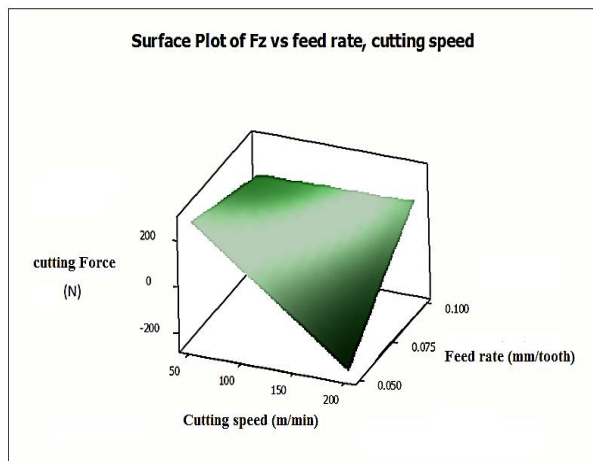


Fig. 12 Surface plot of cutting force on the cutting speed and feed rate.

4.4. Machining Time and Material Removal Rate

If the helical milling process is carried out at low speeds and rates, machining time gets higher in comparison to other ordinary processes like drilling. The reason for this increase is the long pathway in the helical milling. But if the helical milling process is carried out at higher speeds and higher rates, machining time is improved and it can compete with other process of holes production. Also, using a helical milling process, different holes can be created without changing the tool, which reduces non-machining time and dimensional errors associated with tool replacement.

In this study, time is measured using power-mill software, it only measured the net time of the machining process, in which other times related to closing tools, work-pieces were not considered. With increasing speed and feed, the machining time was reduced. Such that

with increasing speeds and rate from 50 m / min and 0.05 mm / d to 200 m / min and 0.1 mm / d / d, time required has diminished more than 5.71 times (“Fig. 13”).

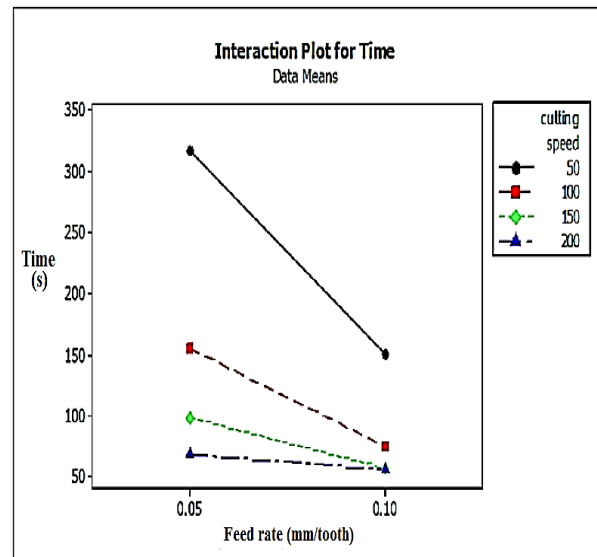


Fig. 13 Graph of cutting speed and feed rate interaction on machining time.

Regarding the time, the material removal rate was similar to the machining time. Except the fact that, it grew at a speed of 150 m / s with a slight gradient and suddenly soared after this speed. So, when speed from 50 meters per minute increase to 150 meters per minute and from 150 meters per minute to 200 meters per minute, the filing volume reduction rate per unit time becomes 2 and 14 times, respectively (“Fig. 14”).

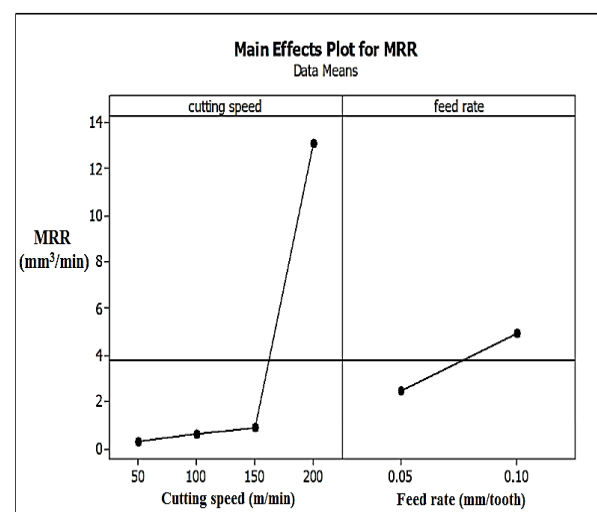


Fig. 14 Graph of the effect of cutting speed and advance on Material removal rate.

5 CONCLUSION

In this study, the helical milling process with various cutting speed and feed rate in hard steel AISI D2 with a hardness of 52 HRC was investigated. The results of this study are briefly summarized as follows:

1- By increasing the cutting rate and the feed rate, surface roughness has been improved by reducing the friction between the tool and the machined surface. So that the best surface finishes at a speed of 200 m/min and a feed rate 0.1 mm/tooth at 0.299. However, it can be concluded that the surface roughness of the hole produced by the helical milling process is such that it reduces the need for use of finishing processes or eliminates in wide variety of cases.

2- With a cutting rate increase from 100 m / min to 150 m / min, roughness decreased with a slighter slope. This slope reduction is due to the process stability and vibration reduction in this range of cutting rates.

3- Unlike surface roughness with increasing cutting speed and feed rate, the wear of tool has increased. Also, at the cutting speeds of 100, 150 and 200 m/min, the wear increased with a feed of 0.05 to 0.1 mm per tooth, but the wear rate was almost constant at a speed of 50 m / min.

4- By increasing the cutting rate in this type of hard steel, roughness, machining forces and machining time were reduced. But on the contrary with increasing cutting speed and feed rate, tool wear and material removal rate have increased dramatically. However, at a rapid speed of 50 m /min and a feed rate of 0.05, more improved conditions can be achieved.

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