Effect of Feed Rate and Depth of Cut on Cutting Forces and Surface Roughness when End Milling of Mild Steel using NOVIANO Cutting Tool

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Abstract

In this paper, a series of milling tests were carried out in order to identify the effects of feed rate and depth of cut on cutting forces and surface roughness while end milling the mild steel using NOVIANO and conventional cutting tools. Slot-milling operations were conducted. The cutting forces and surface roughness in a wide range of feed rate (value according to manufactured of cutting tool) and depth of cut were discussed. Results showed that the cutting forces for the Fx and Fy increase with the increase of feed rate for both cutting tool. Further increasing the speed of feed rate, the surface roughness also improves for both cutting tool. However, the comparison between both cutting tool, it was found that the cutting force and surface roughness much better for NOVIANO.

Keywords
Cutting force, surface roughness, depth of cut, feed rate, NOVIANO cutting tools

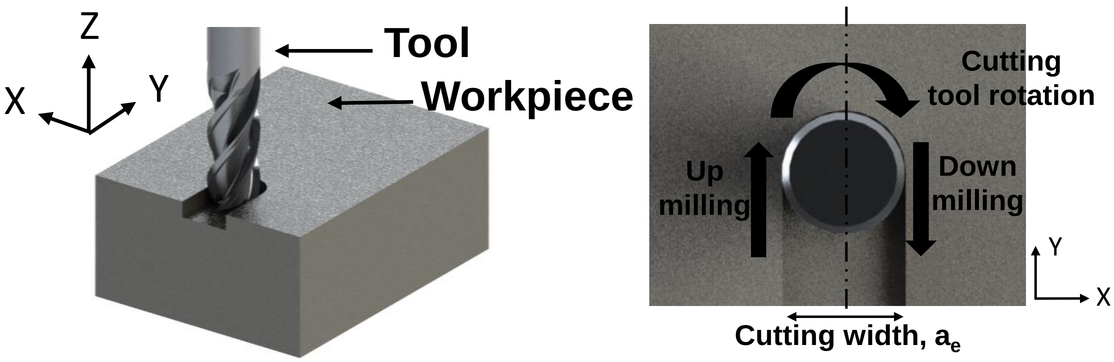
1. Introduction

In the current industrial scenario, the slot milling process has been extensively study not only to improve the manufactured part's performance but also to reduce manufacturing costs. The development of cutting tool materials have been orderly increased in order to machine more difficult material such as toughness, hardness and wear resistance (Liew et al. 2008). Carbon steel was used as a first cutting tool material and nowadays after a lot of discussion and studies, many researcher used carbide as a cutting material in the industry (Klocke and Eisenblätter 1997).

A manufactured part's performance quality is determined in part by its surface quality and integrity resulting from the manufacturing process. All machines have some flexibility in their structure. Force generated from conventional machining process will cause machine tool system to vibrate and consequently will affect the surface being produced (Grossi et al. 2015). Nevertheless, the present of vibration during cutting process also can improve the cutting performance (Rasidi et al. 2014). During the cutting process, cutting force is one of the most important issues and an efficient and precise cutting force model is therefore crucial for the selection of machining parameters such as feed rate and spindle speed (Rahim et al 2016). Furthermore, cutting temperature could impair the surface integrity of the machined surfaces (Rahim and Sasahara 2009). In addition, the capability of the CNC milling machine to make batch production would be a noteworthy advantage for machining. However, for more accurate and precise machining, the cutting force should be reduced as this force partially defines the surface quality and affects the appearance function and reliability of the products. So far, many researches have been conducted to predict cutting force under given machining conditions (Wang et al. 2015).

Furthermore, a good surface finish, which is indicate by low surface roughness, not only assures quality, but also reduces manufacturing cost (Dudzinski et al. 2004). There are many types of roughness parameters, which include surface roughness R_a, R_q, R_z and R_{sk}. The most used international parameter and universally recognized for roughness as it can be easily measured by graphical process is R_a. Low surface roughness is vital in term of tolerance, as it reduces assembly times and avoids the need for secondary operations and leads to overall cost reduction (cutting force reduction and surface quality). According to (Rahim and Sasahara 2011), low cutting force contributed to the better surface finish. Besides, lower surface roughness or smoothness of the machine surface is particularly important to improve the fatigue strength, corrosion resistance and creep life of materials (Tian et al. 2013). Surface roughness also has important effect on stress corrosion resistance and creep strength of the machined surface, which in turn affects the service-life of components, so it is a crucial factor in predicting the capability of machining performance (Field et al. 1989).

As shown in Figure 1(a), in the slot cutting process using the end mill, the cutter generally rotates on an axis vertical to the work piece. Cutting teeth are located on both the end face of the cutter and the periphery of the cutter body. The trajectory of the tool path depends on the spindle speed and feed rate relative to the work piece. The spindle speed is the important part as it carries the tool tip edge to the round shape, but it is different and shape changing when the feed rate starts to move (Rasidi et al. 2015).



(a) (b)

Figure 1. (a) Geometry of end milling process (b) Top view of slot cutting

2. Experimental Set up

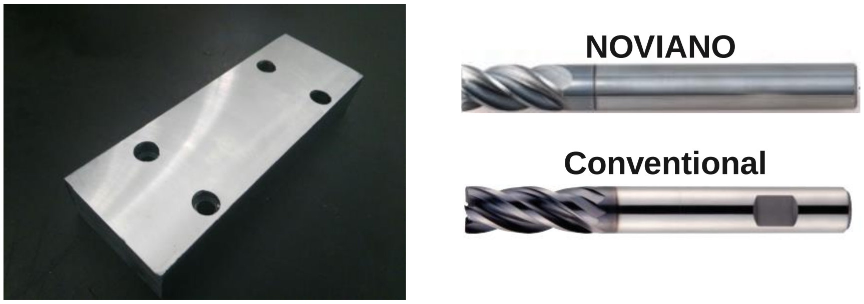
The applicable cutting parameters of the experiment have been considered prior starting the machining operation. The machine parameter is set according from the manufactured as shown in Table 1. In order to discuss the effects of the relationship between depth of cut and feed rate on the cutting force and surface roughness features, two experiments was conducted with two type of different cutting tool as shown in Table 2.

Table 1. Cutting tool terminology

Terminology	Conventional	NOVIANO
Tool Diameter (mm)	6	6
Tool Length (mm)	50	57
Length of cut (mm)	16	13
Number of Teeth	4	4
Helix angle (^{o})	35	40
Tool Material	Micro Grain Carbide	Solid carbide (tungsten carbide)
Type of shank	Plain	Plain
Coating	Coated	Coating material = TiSi Based - Multilayer Microhardness (HV 0,05) = 3600 Max application temperature (°C) ≤ 1200 Friction coefficient = 0,3

Table 2. Process variable for experiment

Process Variable	Unit	Conventional	NOVIANO
Spindle Speed	n(min^{-1})	4750	6450
Feed Rate	mm/min	140, 280, 560	178, 355, 710
Depth of Cut	mm	0.1, 0.2, 0.3	0.1, 0.2, 0.3

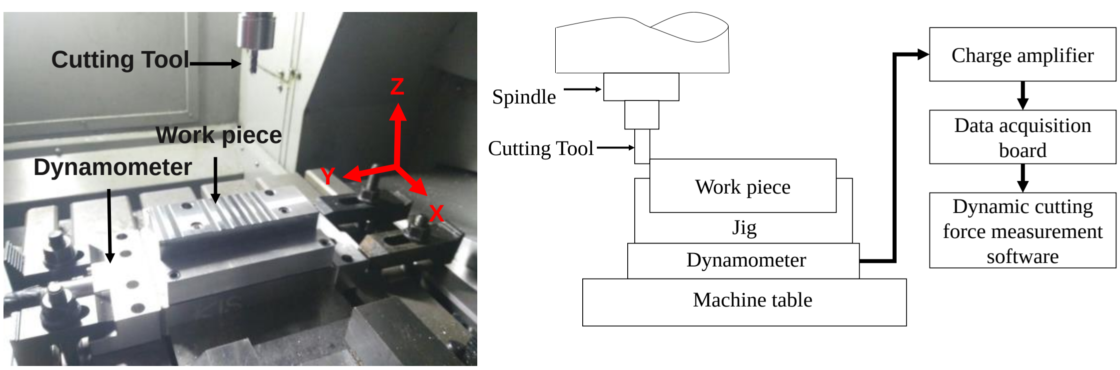


(a) (b)

Figure 2. (a) Work piece; (b) Cutting tool

Mild steel with 35 mm width and 100 mm length was used as the work piece as shown in Figure 2(a). To facilitate the investigation of the cutting force variation and to improve cutting efficiency, the conventional cutting tool (experiment 1) and an end mill manufactured by NOVIANO (experiment 2) was chosen. The NOVIANO cutting tool composes a four-flute cemented carbide tool with TiSi multilayer coating, helix angle 40^0, max application temperature (°C) ≤ 1200 and 6mm in diameter as shown in Figure 2(b). The meaning of NOVIANO is "No vibration and noise" which apply at it special geometry of the cutting tool makes it anti-vibration. While, the conventional cutting tool composes a four-flute micro grain carbide, helix angle 35^0, and 6mm in diameter as shown in Figure 2(b). It designed for general purposes to machine carbon steels, tool steels, alloy steels and stainless steels for both cutting tool.

A Kistler Type 9257B dynamometer used to measure the three orthogonal components of the cutting force as shown in Figure 3(a). It has a good rigidity and high natural frequency. The block of work piece mild steel mounted on the jig and attached to dynamometer through a fixture. The dynamometer connected to a multi-channel charge amplifier, and a high-speed DAQ card in a computer acquired the output signal. The sampling rate was set as 1000 Hz. The system of measuring milling force dynamically is show in Figure 3(b).



(a) (b)

Figure 3. (a) Experimental set up; (b) The measuring system

The system of measuring milling force dynamically was show in Figure 4. For a correct signal analysis, it is important to have a good understanding of different coordinate systems involved, which include the machine tool coordinate system and sensor coordinate system. A schematic view of the coordinate system of the dynamometer for cutting force measurement was show in Figure 4. The dynamometer produces force readings in the X, Y and Z-axis directions. In the cutting testing, the feeding was along the –X direction of the dynamometer

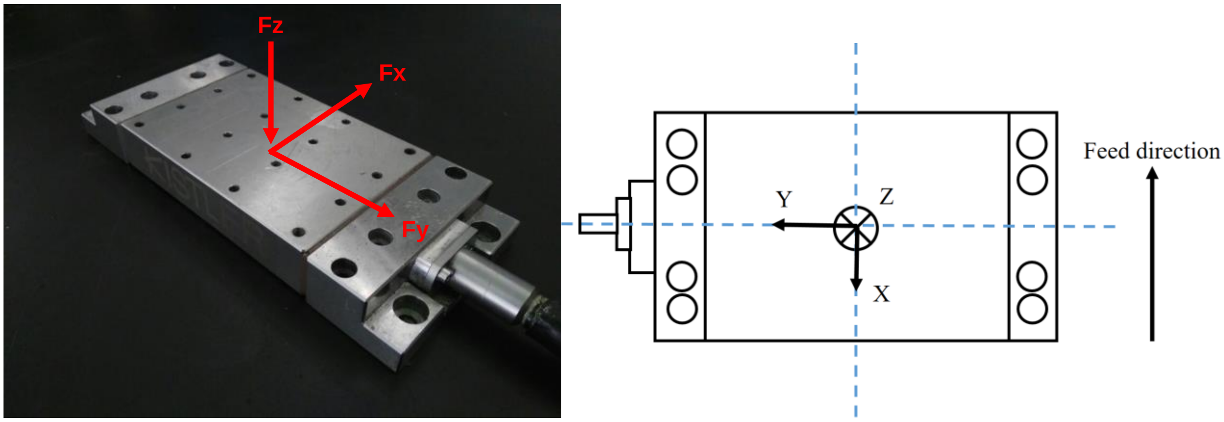
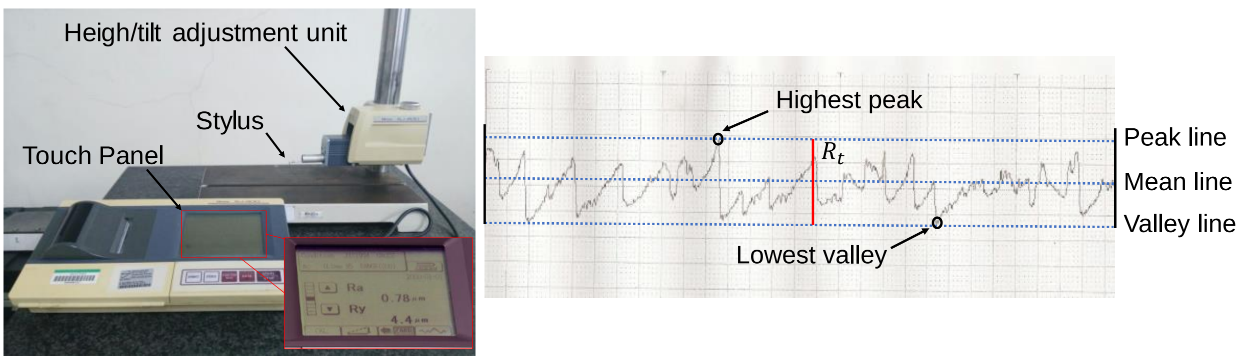


Figure 4. Coordinate system of dynamometer

Surf test SJ-400 as show in Figure 5(a) whereas R_a is measured using roughness tester equipped under a magnification of ×10, in accordance to the JIS B 0601 (1994) standard with a 0.6 mm cut off distance. Surface roughness measurements were performed and repeated at three different spots for each samples. After each cut, the surface roughness is measure on the surface table using stylus profilometer. Three fixed spots were chosen for each milled surface, whereby one in the middle and the other two on the edge, were used to measure the surface roughness of the cut. Following this, the mean of the three readings is recorded. Figure 5(b) show the example of the result for surface roughness, R_a from the surf test SJ-400.



(a) (b)

Figure 5. (a) Surf test SJ-400 (b) Result for surface roughness, R_a reading

3. Result and Discussion

3.1 Cutting Force

The slot-milling test is carried out to investigate the cutting force reduction and the surface quality improvement of the machined mild steel using conventional and NOVIANO cutting tool. To have an understanding of the cutting force variation patterns, a global view of the force waveforms is shown in Figure.6.

To examine the force pattern in more detail, a smoothing method was apply with window size of 500 given in Figure 7. The waveforms show the cutting force variation from entering to exiting the cutting for a whole cutting length of 20 mm. When the cutter stated engaging to exiting the cutting, there were significant variations of the force amplitudes. This might be caused by the intermittent cutting process. This was followed by a stabilized cutting period where the peak forces were evenly distributed, until the cutter started to exit the cutting.

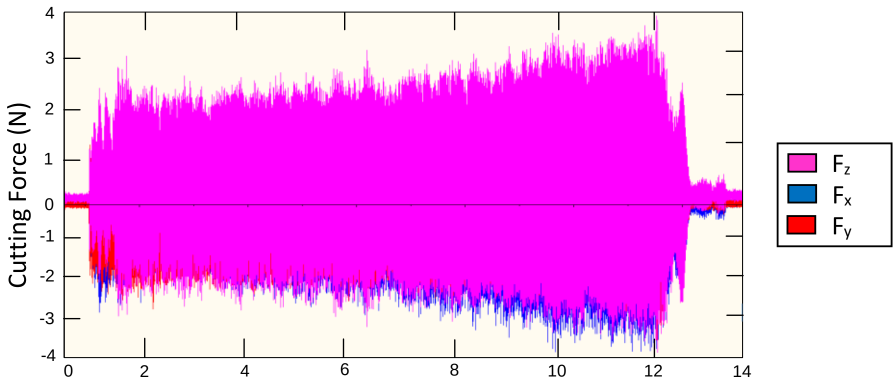
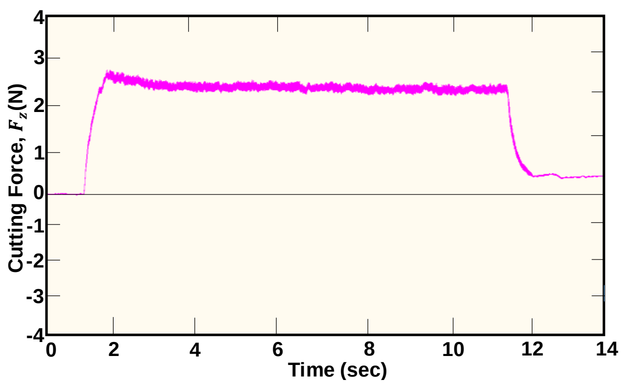
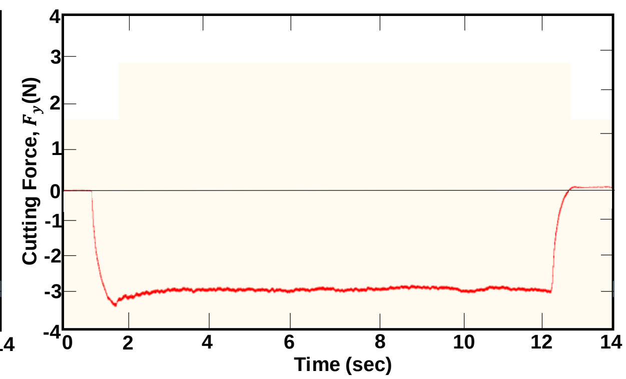


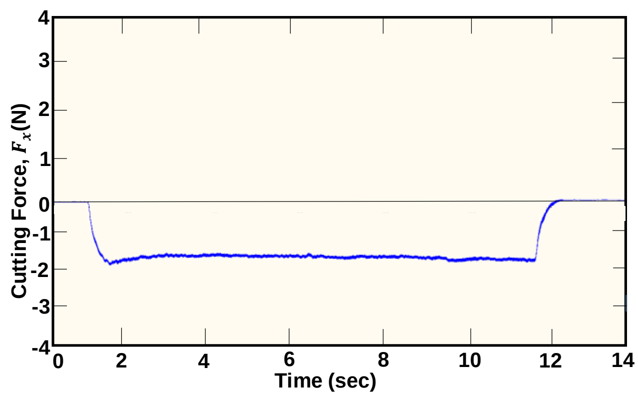
Figure 6. Global view of the force waveforms



(a) F_z



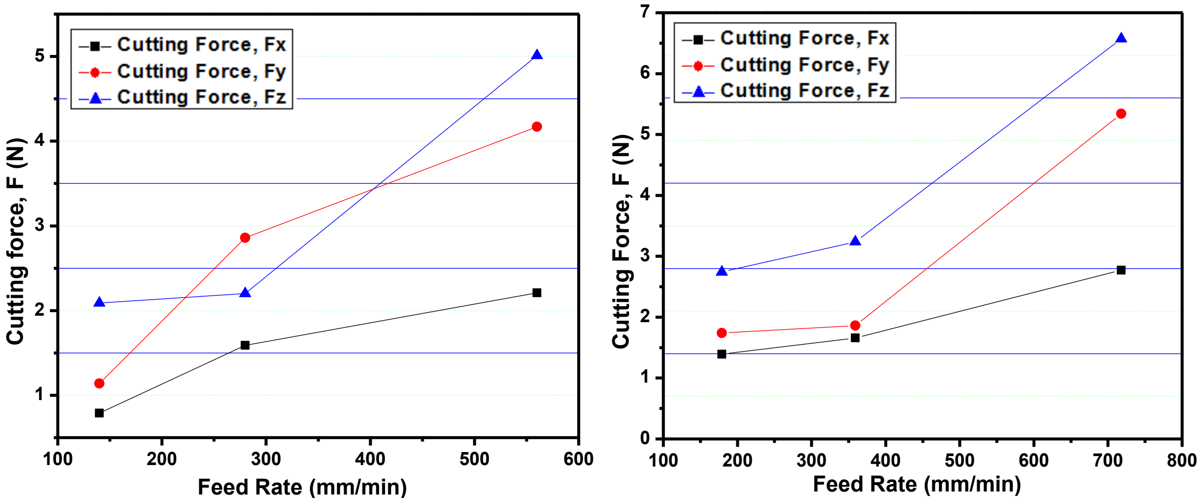
(b) F_y



(c) F_x

Figure 7. Cutting force waveforms

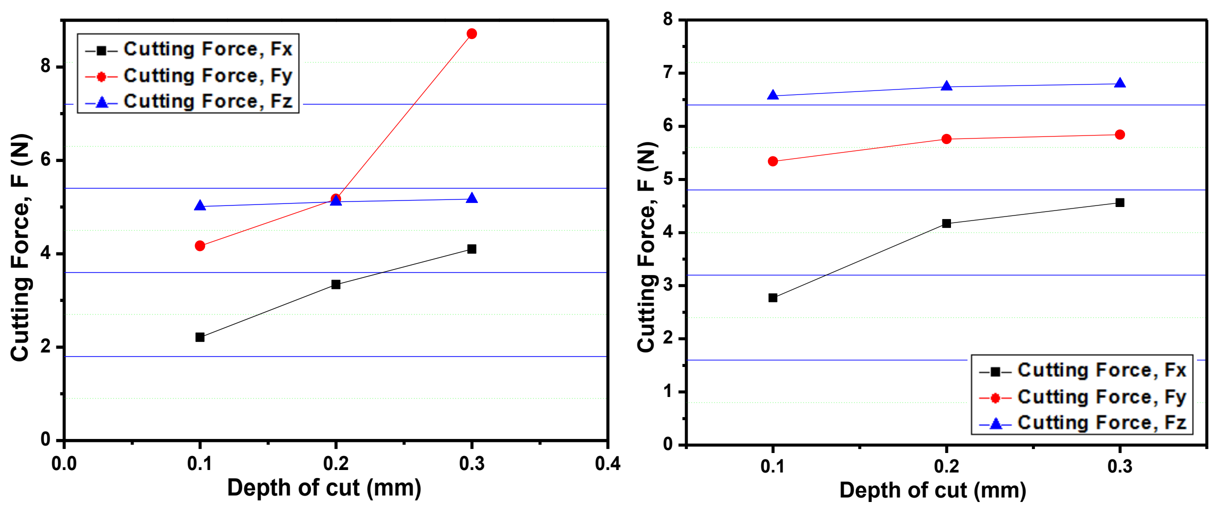
Since the measured cutting forces are in a complex waveform, the selection of suitable forces values for investigation is important. The potential values can be the root-mean-square (RMS), the peak amplitude (p), the peak to peak (PTP) values. However, there exist some problems with theses parameters. For instance, the values of peak force amplitude can be affected by some disturbances such as tool-work piece vibration. In this study, we propose the use of an averaged mean value as the representative parameter. The determination method for this parameter is to firstly select a stabilized cutting period or in a steady condition, for example approximately in between 2 seconds until 11 seconds of cutting. Then find the peak force in each reading and finally calculate the mean value between stabilized times.



(a) (b)

Figure 8. Cutting force (N) XYZ under different feed rate (mm/min) (a) Conventional ;(b) NOVIANO

Figure 8, shows the cutting forces Fx, Fy and Fz for cutting tool conventional and NOVIANO under different feed rate. Obviously, the principal of cutting forces state that Fz, to be the highest among the three cutting forces (Tian et al. 2013). The averaged peak force components in the X-Y-Z directions corresponding to different feed rates are illustrated under the depth of cut 0.1 mm. It is shown among the three force components, the averaged peak force for Fz is the largest, followed by Fy which is slightly smaller than Fx. From the graph, it shows that with an increase in the feed rate, the cutting forces also increase accordingly.



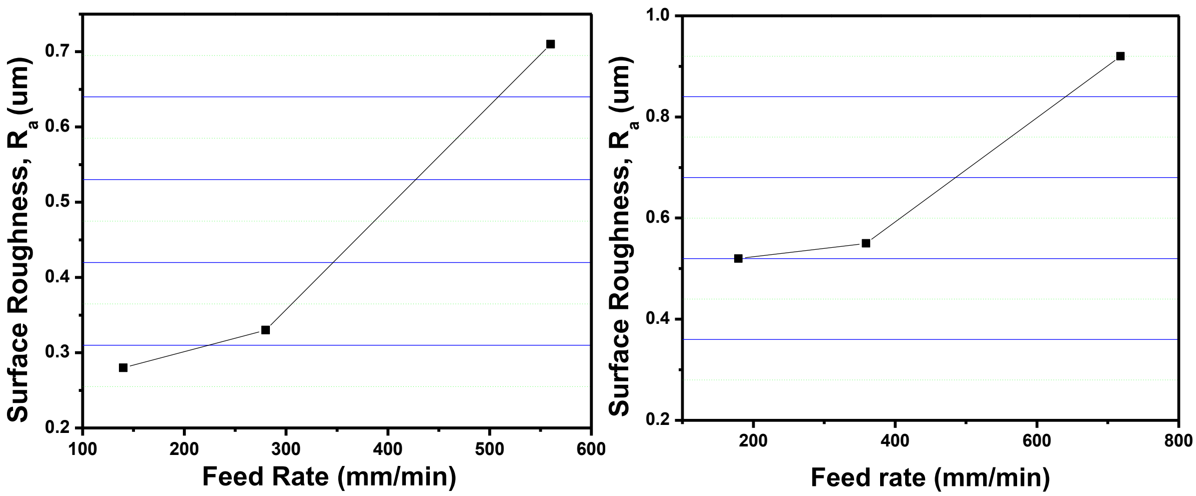
(a) (b)

Figure 9. Cutting force (N) XYZ under different depth of cut (mm) (a) Conventional (b) NOVIANO

The same explanation is also observed during machining under different of depth of cut. Figure 9 shows the influence of depth of cut on the cutting force. The general trend is similar with machining under different of feed rate. It can be seen that the peak forces also increase comfortably as result of increase in depth of cut. This is due to the fact that an increase in the chip load increases the cutting forces need to remove the material. Based on the cutting force components in the X-Y-Z values for both conventional and NOVIANO, although the cutting force produced on the NOVIANO slightly higher than conventional, NOVIANO cutting tool is able to machine more productively at almost 30% higher feed rate.

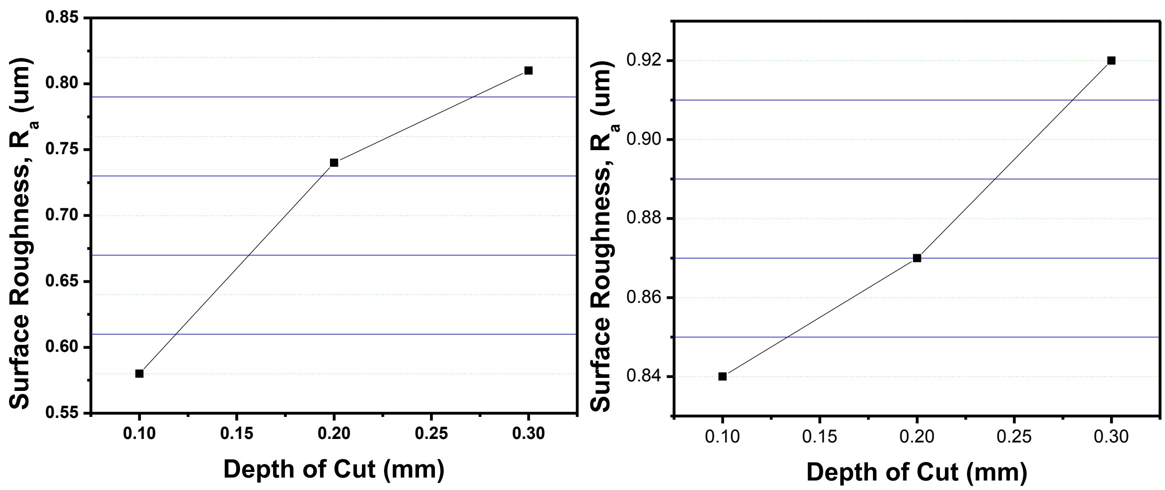
3.2 Surface Roughness

The surface quality after machining processes correlates very closely with the cutting parameters and the tool geometries. These machining processes will only deteriorate the surface quality if the inappropriate parameters are used, such as dull tools, too high feed speeds or depth of cut, improper cutting speeds, coolant or lubrication, or incorrect tool hardness. Hence, the cutting parameters were chosen from the value suggestion according to manufactured of cutting tool.



(a) (b)

Figure 10. Surface roughness, R_a (μm) under different of feed rate (mm/min) (a) Conventional (b) NOVIANO



(a) (b)

Figure 11. Surface roughness, R_a (μm) under different of feed rate (mm/min) (a) Conventional (b) NOVIANO

Figure. 10 and 11 shows the influence of feed rate and depth of cut on the arithmetic average of the roughness profile, R_a on the machined surface. At the variation of feed rate, the roughness profile for both cutting tool increase when the feed rate increase. The feed rate of (718 mm/min) with the depth of cut (0.1 mm) produce the highest value of roughness profile for the NOVIANO cutting tool. However, the value of roughness profile for both cutting tool almost the same, this explained when the cutting speed reach it maximum speed, the softening of the material due to increased cutting temperature results in a smoother finish and so lower surface roughness (Arunachalam et al. 2004).

At the variation of depth of cut, the roughness profile for both cutting tool shows a same pattern which is when the depth of cut increase the roughness profile also increases. The feed rate of (718 mm/min) with the depth of cut (0.3 mm) produce the highest value of roughness profile. The interaction between feed rate and axial depth of cut has also a significant effect on the measured surface roughness. The surface roughness value increases with the increase feed rate and the axial depth of cut (Moola et al. 2012).

The graphs for surface roughness at different feed rates and depths of cut show the NOVIANO tool to produce higher roughness (R_a) values. This is related to the rake Angle of the NOVIANO tool which is +2°. The less positive rake Angle also explains the slightly higher cutting force and surface roughness values produced by the NOVIANO cutting tool as compared to the conventional cutting tool. However, the NOVIANO cutting tool can machine more productively at higher cutting parameters than conventional tools on Mild Steel material while achieving the maximum tool life.

Based upon the cutting parameter provided from the manufactured, the axial depth of cut is found to be most significant factor affecting surface roughness, followed by variation of feed rate. The lower depth of cut (0.1mm), with lower feed rate (140 mm/min) and higher spindle speed (4170 min^{-1}), are determined to be the best choices for obtaining the lowest value of surface roughness for conventional cutting tool. However, the lower axial depth of cut (0.1mm), with lower feed rate (179 mm/min) and higher spindle speed (5640 min^{-1}), are determined to be the best choices for obtaining the lowest value of surface roughness for NOVIANO cutting tool. As compared to the conventional cutting tool, the SE45 Noviano end mill was able to machine at 30% higher feed rate and spindle speed.

The surface roughness produced in milling operation depends on the feed rate and depth of cut. The use of cutting parameter for selecting the best levels of combination for surface roughness (Ra) value suggests the use of low value of feed rate and depth of cut in order to obtain good finish. The greater the feed rate and depth of cut the larger the cross-sectional area of the uncut chip and the volume of the deformed work piece. Consequently, the larger is the resistance of the work piece to chip formation and the greater is the cutting force leading to an interaction overload between the cutting tool and the work piece creating bad surface quality. Further, it can be seen that the surface roughness decreases with the increase in cutting speed. So, the temperature rise softens the material aiding grain boundary dislocation and thus reducing the surface roughness (Zhang et al. 2007).

Conclusion

A series of milling tests while end milling the mild steel were carried out with NOVIANO and conventional cutting tools. The cutting forces and surface roughness were analyzed to identify the effect of feed rate and depth of cut and the following conclusion can be made.

1. It can be seen that the cutting forces will increase steadily as result of increase in depth of cut. . This is due to the fact that an increase in the chip load increases the cutting forces need to remove the material.

2. At the variation of depth of cut, the roughness profile for cutting tool shows a pattern which is when the depth of cut increase the roughness profile also increases. Since the feed rate and depth of cut is increase, the larger the cross-sectional area of the uncut chip and the volume of the deformed work piece. Thus, the larger is the resistance of the work piece to chip formation and the greater is the cutting force leading to an interaction overload between the cutting tool and the work piece creating bad surface quality.

3. It was observed that, all analysis techniques delivered similar results such that the depth of cut is found to be most significant factor affecting surface roughness, followed by feed rate.

4. Based on the comparison for both conventional and NOVIANO cutting, although the value of cutting force and surface roughness produced on the NOVIANO slightly higher than conventional, NOVIANO cutting tool is able to machine more productively at almost 30% higher feed rate and reducing machining time.

Acknowledgements

The authors would like to express their appreciation to the Office for Research, Innovation, Commercialization and Consultancy Management (ORICC), Universiti Tun Hussein Onn Malaysia for the financial support via (Vot U596). This work also a collaboration with manufactured cutting tool HPMT Industries Sdn Bhd.

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Biography

Dr. Mohd Rasidi bin Haji Ibrahim has earned a Diploma in Tool and Dia Technology, Production Technology from German Malaysian Institute, Kuala Lumpur Malaysia. He is pursuing his education in Manufacturing Engineering degree from Leeds Metropolitan University, United Kingdom, Great Britain. He has over 5 years of industrial experience working for well-known companies in the Malaysia and United Kingdom in engineering design and manufacturing specializing in the design and machine building in finite element analysis. He also had working and research experience in advance machining and precision machining focused on the miniature and high precision high-Tech part. Upon returning home to Malaysia in 2012, Mohd Rasidi was promptly hired by Universiti Tun Hussein Onn Malaysia (UTHM) as a senior lecturer and being responsible in machining department as a full-time researcher. He also supervises 4 PhD students, 3 master students and plenty of undergraduate students currently. His research is focused on an Advance and Precision Manufacturing machining and appointed as a researcher in Precision Machining Center (PREMACH) in UTHM.

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Charles Prakash Edward Peter has earned a B.S. in Mechanical Engineering from Tri-State University in Angola, Indiana in the USA and also a Master in Business Administration degree from Indiana Wesleyan University in Marion, Indiana in the USA. He has over 20 years of industrial experience working for well-known companies in the USA in engineering design and manufacturing specializing in the design of hydraulic, pneumatic and injection molding presses from concept to completion. Apart from this, he also has five years' working experience with an international company in the USA designing and manufacturing thermocouple sensors and thermal analysis systems used by several companies in the steel making industry. Upon returning home to Malaysia in 2009, Charles was promptly hired by HPMT Industries Sdn. Bhd. which is a solid carbide cutting tools manufacturer in Shah Alam, Selangor in Malaysia as a pioneering tool test engineer to manage and run the newly-formed Research and Development department's tool testing division. Since its inception, he has conducted and managed numerous tool tests many of which have successfully improved the company's existing cutting tool products as well as contributed to the development of completely new types of twist drills and end mills to add to the company's existing product offerings.