A STUDY OF THE EFFECTS OF CUTTER PATH STRATEGIES AND CUTTING SPEED VARIATIONS IN MILLING OF THIN WALLED PARTS

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ABSTRACT

Selection and application of tool path strategies and tool orientations in the process of milling is an important issue in machining of thin wall parts such as blades and airfoils. Proper selection can lead to substantial savings in machining time, improvement of workpiece surface quality and improvement in tool life, thereby leading to overall cost reduction and higher productivity. In this paper, the effects of cutter orientation used to machine curvature surface of thin aluminum parts (7075) with a 3-axis ball end-milling were investigated to improve geometric accuracy and surface integrity and the most optimal range of machining forces.

The experiments were performed using four cutter directions such as transversal outward, transversal inward, longitudinal outward, and longitudinal inward directions. During milling, machining forces were measured in different directions and machining surface texture was evaluated by optical microscopy and the finished roughness of machined samples was measured.

In addition, in this study, for machining the aluminum (7075) blocks as the workpiece, a relatively wide range of cutting speeds (spindle speeds) for milling is used and the effects of cutting speed variations on the amplitude of machining forces, machined surface quality and surface roughness are studied to select appropriate and optimal speed range.

KEYWORDS: Cutter orientation, Thin- wall parts, 3- Axis milling, Surface texture, Machining forces, Cutting speed.

1. INTRODUCTION

Free-form machining with ball-end milling is vastly used in manufacturing processes for machining complex surfaces in several industries such as automobile, aerospace, die and mold industries .The main reason for using these kinds of tools in milling of curvature surfaces is as the result of having the ability to adapt geometrically and easily on 3-D surfaces [1].

In this paper, the effects of cutter orientation used to machine turbine blades with a 3-axis high speed ball end-milling were investigated to improve geometric accuracy and surface integrity. Since there is a possibility for changing the inclined angle of a tool in 5-Axis milling, the surface roughness is better than that of a surface produced by 3-axis milling. In addition, 5- axis milling due to the flexibility in tool orientation and the ability to make an extra angle to workpiece surface can be applied in machining of complex surfaces while for 3-axis milling is not possible to choose such an angle during machining [2].

Due to lack of access to 5- Axis CNC milling, tool path strategies machining tests on curvatured surface of thin aluminum parts; have been done with CNC 3-axis milling. Surface texture affects the performance of machined part, during the dynamic loading cycle, so when the machined surface defects are too much, these areas act as sites of stress concentration and weaken workpiece against dynamic loading and failure or rupture of workpiece. On the other hand Cutting forces are important in determining workpiece tolerances. Low cutting forces, ideally in the direction of the cutter axis are essential for high workpiece dimensional accuracy. In addition reducing the cutting forces, increases machine tool life and reduces tool wear rate (TWR) and consequently reduces overall machining costs [3].

Cutting speed is one of the most important parameters in machining that has a great effect on machining efficiency and quality of machined surface and the total machining time. Among the most effective and efficient modern manufacturing technologies, high speed machining (HSM) is employed to increase productivity and reducing manufacturing costs. Although one of the disadvantages of HSM is the high surface defects and reduced quality of machined surface texture depending on work and tool materials as well as tool life requirements, the cutting speed used in HSM is changing but often 2–50 times higher than those employed in traditional (relatively low speed) machining. Due to its high material removal rate and short product cycle time, HSM has received steadily growing applications in recent years in many industrial sectors, such as aerospace, aircraft, automotive, and die and mold making.[4]

2. MILLING STRATEGIES

Raster and offset cutter path strategies have their own advantages and disadvantages. Although raster milling has generally been found to produce a shorter cutter path, scallop marks that are left on the walls of a machined pocket can not be completely removed. With offset strategy, scallop marks are removable and a smooth surface is produced. Figure1. depicts an illustration of raster milling at cutting orientation angle of 60° and the graph determines the result of cutting length and tool wear area per length based on cutting angle orientation. In general, tool wear and cutting length increases with increasing orientation angles. The results indicating that cutting angle orientation and cutting length have significant effect on the tool wear [3]. Fry et al proved that, raster milling parallel to the longest dimension of workpiece by selecting the appropriate starting point, leads to shortest cutting path [5].

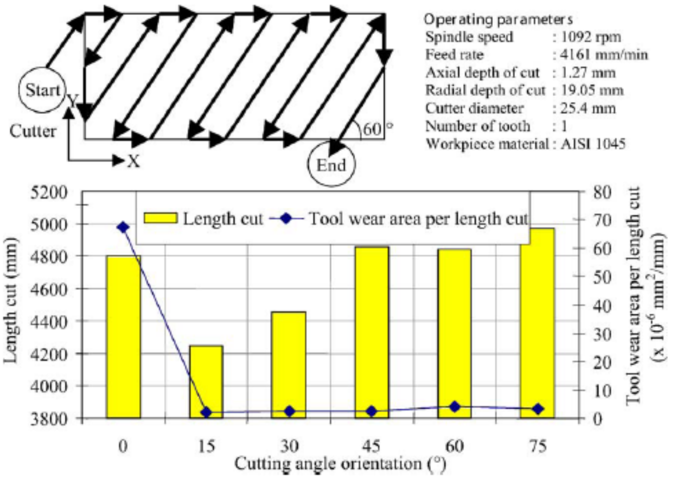


Figure 1: Effect of cutting angle orientation on cutting length and tool wear area per length cut [5].

Cutter path strategies for milling thin walled parts have to be investigated by some aspects. High speed milling of thin walled parts has been applied successfully by Smith and Dvorak [6] although for aluminum workpiece material it was concluded that cutter paths should be chosen such that the machining areas be supported by a maximum non-machined material as possible and the direction of cutting should proceed from the least supported area to the best-supported area. When milling thin walled sections, appropriate selection of cutting speed, feed rate and axial depth of cut in order to avoid distortion of workpiece is so important. Lower amplitude of cutting forces, cutting temperature and tool chatter are particularly necessary for reducing structural distortion. With low cutting forces, cutter deflections can be reduced, which in turn reduces the distortion of the finish part. Reduction of cutting temperatures, decreases the thermal strains induced in the workpiece [7] .

During ball-end milling on free formed surfaces, the tool–chip contact area varies significantly when using different cutter path orientations [3].

3. EXPERIMENTAL SET UP AND CONDITIONS

All experimental works were carried out to evaluate the effects of cutter orientations with a vertical 3-axis CNC milling machine (VMC) with FANUC-18 M controller, which has maximum spindle revolution of 6000 rpm. First, aluminum blocks of Al-7075 were prepared by dimensions of 30 × 30 × 80 mm. In rough and finish milling processes, 10 blocks was used to perform the desired tests. The tools that were used for roughing operations made by Korloy company and coated carbide with diameter of 20 mm and two inserted edges. For finishing operations four carbide ball-end mill coated tools with two k-2 grade, edges and diameter of 6mm made by YG Company were used. To ensure accuracy of test results after each run, ball-end mill tools were replaced. In order to investigate the surface texture resulting from machining and comparing that, an optical microscope (Struerz with maximum magnification of 1000 X) has been used, It should be noted that tests were performed by magnification of 50 X.

Figure 2: The picture of optical microscopy that used in tests

4. TESTS OF CUTTING TOOL ORIENTATIONS DURING MILLING

To evaluate four overall orientations of milling cantilevered surfaces such as blades and air foils and selecting optimum machining parameters that produce the lowest amplitude of machining forces and on the other hand having the best surface quality, some test plans are designed.

In the case of milling of aluminum 7075 alloy, experiments were performed using four kinds of cutter directions during milling such as Longitudinal Outward, Longitudinal Inward, Transversal Outward, and Transversal Inward directions (Figure 3)

In this paper, all cutter conditions are down milling and defined as follows:

- Longitudinal inward: feed direction from free side of machined workpiece to supported side (cantilevered) through the length of the surface.
- Longitudinal outward: feed direction from supported (cantilevered) side of machined workpiece to free side through the length of the surface.
- Transversal inward: feed direction from free side of machined workpiece to supported (cantilevered) side through the width of the surface.
- Transversal outward: feed direction from supported (cantilevered) side of machined workpiece to free side through the width of the surface. Four cutter directions that will be investigated are indicated in Figure 3.

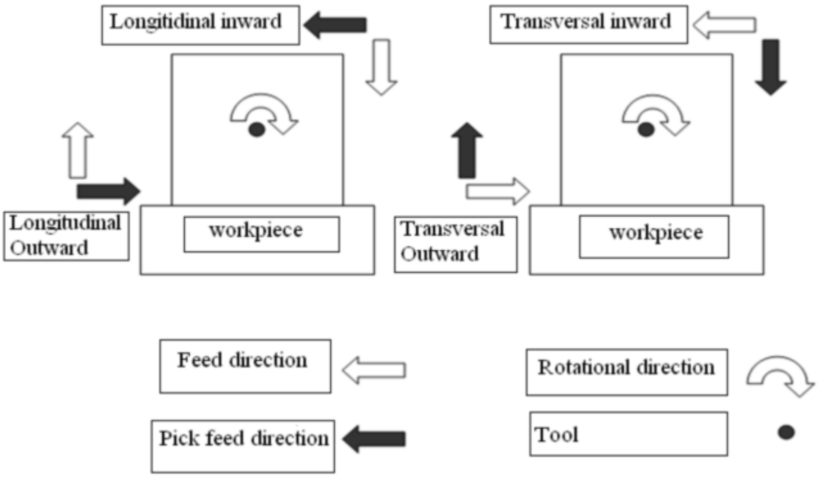


Figure 3: cutter orientations used in tests

Due to lack of access to 5-axis CNC milling for performing the tool orientation (direction) tests, a conventional 3-axis milling is used. In order to be capable of performing these tests in a way that workpiece to become as a short blade in the 5- axis CNC milling machine, that is clamped only from one side, CAD model of the desired sample is prepared in Mechanical Engineering software. The CAD model is a curved surface with concave form with length of 50 mm and width 30 mm and maximum thickness of 8 mm and amount of curvature in surface is 3 mm. The CAD model of workpiece is shown in Figure. 4. For rough milling, one side of aluminum blocks are fastened in a clamp and the clamp is also fastened on the surface of dynamometer that is located on the table of milling machine. Workpiece in finishing operations, is machined in the form of cantilevered beam, the supported side of workpiece is clamped with a M12 bolt in a threaded hole on the surface of dynamometer (kistler Model 9255B), that is used to measure cutting forces. Since workpiece is clamped, only one surface is milled because in 3-axis milling machine, the inclination angle of tool towards work surface can not be changed, and tool axis is always perpendicular to the machined surface, whereas in 5 -axis CNC milling machine, workpiece is enable to rotate during machining. In order to adapt tool with machined surface, the ball-end mill tool is used. It should be noted that CAM modeling of the workpiece was performed with Mastercam software and by using RS 232 port, NC generated code files of CAM, are sent to the CNC machine controller. In figure 5, a picture of rough milling operation is shown. Table 1, shows the rough cutting conditions in these experiments.

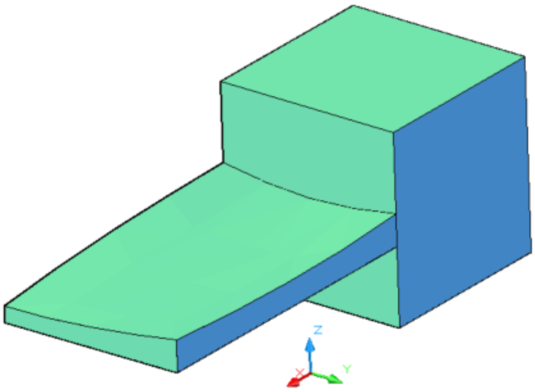


Figure 4: CAD model of workpiece for milling

Table 1: Cutting conditions for rough milling

Milling time	Milling orientations	Cooling condition	Pick feed (mm)	Depth of cut (mm)	Feed rate (mm per tooth)	Spindle speed	Machining strategies
15':25"	Down milling	With cooling	0.8 mm	0.4 mm	0.35 mm/tooth	1750 rpm	spiral

Figure 5: picture of workpiece during rough milling

5. FINISHING OPERATIONS IN TESTS OF CUTTING TOOL ORIENTATIONS

After rough milling on four aluminum blocks, to study the effects of cutter path directions and orientations, four kinds of cutter orientations such as Transversal inward, Transversal outward, Longitudinal inward, and Longitudinal outward directions according to Figure.3 and based on cutting parameters in Table 2, are tested.

Table 2: Cutting conditions for Finish milling in experiments

	Condition One	Condition Two	Condition Three	Condition Four
Milling Orientation	Transversal inward	Transversal outward	Longitudinal inward	Longitudinal outward
Milling Strategy	Single direction raster	Single direction raster	Single direction raster	Single direction raster
Type of Milling	Down Milling	Down Milling	Down Milling	Down Milling
Cooling Condition	dry cutting	dry cutting	dry cutting	dry cutting
Spindle Speed	1000 rpm	1000 rpm	1000 rpm	1000 rpm
Feed rate (mm per tooth)	0.1	0.1	0.1	0.1
Radial Depth of Cut (mm)	0.5	0.5	0.5	0.5
Pick Feed (mm)	0.8	0.8	0.8	0.8
Tool Overhang (mm)	35	35	35	35

Figures 6, show pictures of the longitudinal outward and transversal inward milling, and also the method of clamping workpieces on the dynamometer during the experiments, is shown.

The Longitudinal Outward milling

The Transversal Inward milling

Figure 6: picture of longitudinal outward and transversal inward milling

For different cutting strategies and orientations such as Transversal inward, Transversal outward, Longitudinal inward and Longitudinal outward directions that are presented in table 2, cutting forces in X and Y axes and surface roughness were measured and also machined surface texture was evaluated by an optical microscopy. Figures 7 and 8 show the measured forces in the x and y directions by means of dynamometer during milling operations related to two conditions (Transversal inward and Longitudinal outward) from four different machining orientations, these images are milling force spectrums which have been selected as typical examples of the total measured force range during milling. Figure 9, shows the surface texture images related to different tool orientations and with considering these results, in conclusion section the best cutting strategy for machining turbine blades with a 3-axis milling is recommended. In order to assess the machined surface roughness, the roughness tester probe trajectory, was perpendicular to feed direction during milling, or in other words, roughness assessment was performed for each sample in Pick feed machining directions.

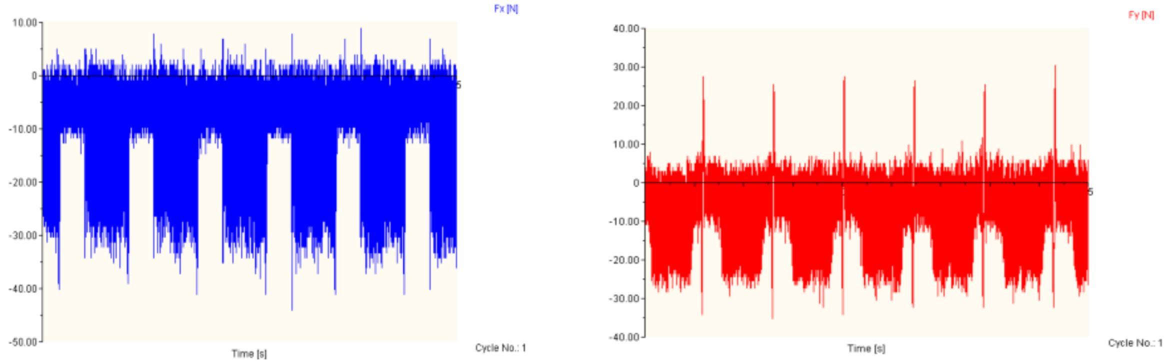


Figure 7 : cutting forces in x and y direction for the transversal inward milling

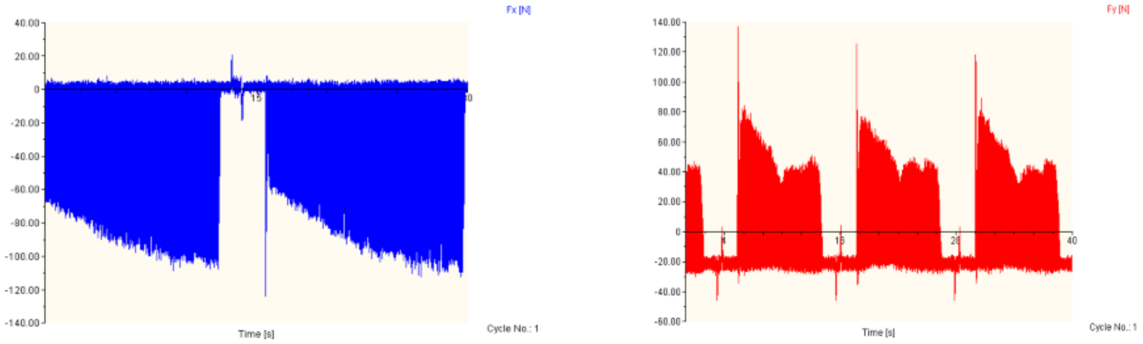
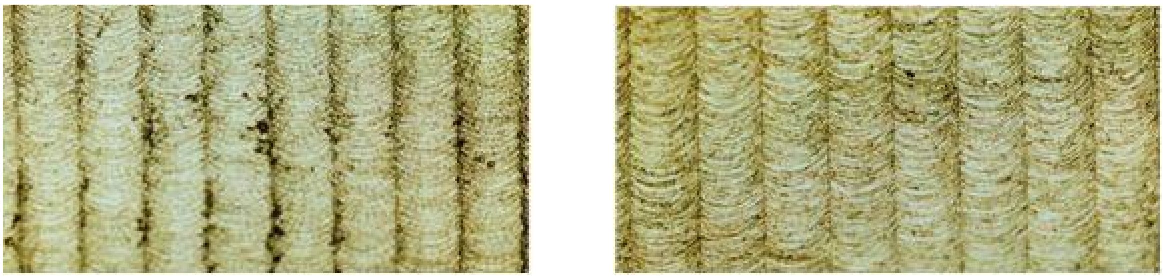


Figure 8: cutting forces in x and y direction for the longitudinal outward milling



transversal outward milling

transversal inward milling

longitudinal outward milling

longitudinal inward milling

Figure 9: Surface textures of machined samples

6. CONCLUSION OF TOOL ORIENTATIONS (DIRECTIONS) IN THIN WALLED PARTS MILLING

In this study the effects of cutting tool orientations (directions) and cutting speed changes on the machinability of aluminum parts (AL-7075) by 3-axis milling was evaluated. Workpiece has a free-form surface; therefore ball-end mill tools are used in this study. The main reason for using this tool in machining of curvature surfaces is to have the ability of adapting easily on 3-D surfaces. This research was carried out in order to find the optimal cutter orientation, which could have an effect on surface roughness, machining forces and surface integrity. During milling operations, cutting forces in x, y and z axes were measured by means of dynamometer and then with optical microscopy, surface texture of machined parts, with magnification of 50X were investigated and after that roughness assessment was performed on samples and the surface roughness (Ra) resulting from each type of milling operation was measured respectively. Finally, using data from cutting forces, surface texture, roughness profiles and surface roughness (Ra), the optimum conditions were selected. In milling of cantilevered surfaces, four different cutting strategies and orientations such as transversal inward, transversal outward, longitudinal inward, and longitudinal outward directions were tested that the results of average measured forces and surface roughness for them are shown in table 3. According to table 3, it can be determined that increase of machining forces cause an increase in surface roughness and also reducing the quality of surface texture. Dark areas in images of surface texture are valleys, and bright spots in the images are prominence, results show that an increase in average machining forces leads to increase of non-uniformity in surface texture, therefore increases the amount of surface roughness (R_a) or the surface quality is going to be worse.

Table 3: results of experiments for cutting forces and surface roughness

Condition	Average Machining Forces (N)	Surface Roughness (R_a) (μm)
Transversal Inward	42.5	2.662
Transversal Outward	103	3.314
Longitudinal Inward	74	3.093
Longitudinal Outward	141	3.973

In these experiments, with attention to the results of cutting forces, surface texture and surface roughness, it is specified that for ball end milling of cantilever-shaped thin plates, the best cutting condition is obtained with a Transversal Inward orientation, and the worst cutting condition is obtained with a Longitudinal Outward orientation. The best conditions of cantilever-shaped thin plates milling in terms of priority includes:

1- Transversal Inward
2- Longitudinal Inward
3- Transversal Outward
4- Longitudinal Outward

The reason of this matter in ball end milling on free-form surfaces with curvature is that, tool–chip contact area varies significantly when using different cutter path orientations and directions. Increasing of tool-chip contact area due to inclination angle towards the machining surface has a significant effect on cutting forces [3]. Kim et al. declared that average cutting forces in transversal direction of tool paths are less than average cutting forces in longitudinal direction of tool paths. Although they have not expressed clear reasons for it, but it seems, the main reason is the tool–chip contact area. High speed milling of thin walled parts has been performed successfully by Smith and Dvorak [6], for aluminum workpiece material, it is concluded that cutter paths should be chosen in such a way that machining areas to be supported by maximum non-machined material as possible and the direction of cutting should proceed from the least supported area to the best supported area.

7. TESTS OF CUTTING SPEED VARIATIONS

This research was carried out in order to find the optimal cutting speed, which could have an effect on surface roughness, machining forces and surface integrity. In this section, to evaluate 6 different cutting speeds, 6 blocks are used to perform the desired tests. The rough cutting process conditions of aluminum blocks is similar to process that is used in tests of the cutting tool orientations. Table 4 shows the cutting conditions for finishing process in these experiments. The tools used in finishing of these samples are the same as used previously for tool orientation tests.

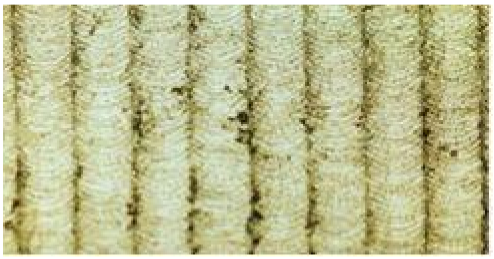
Table 4: Cutting conditions for finish milling.

Milling orientations	Machining strategies	Milling type	Spindle speed (rpm)	Depth of cut radial (mm)	Depth of cut axial (mm)	Feed rate (mm per tooth)	Cooling condition	Tool Overhang (mm)
Transversal Inward	Single direction raster	Down milling	2000	0.5	0.8	0.1	Dry	35
			2800					
			3600					
			4400					
			5200					
			6000					

For all different cutting conditions that presented in table 1, cutting forces in X and Y axes are measured by the dynamometer (Kistler 9255B) and the machined surface texture is evaluated by optical microscopy with magnification of 50 X. Then surface roughness assessment is performed on samples and the surface roughness (Ra) resulting from each type of milling is measured respectively. Finally, using data from cutting forces, surface texture, roughness profiles and surface roughness (Ra), the optimum cutting speed are selected. Surface textures for different cutting conditions are shown in Figure 10.

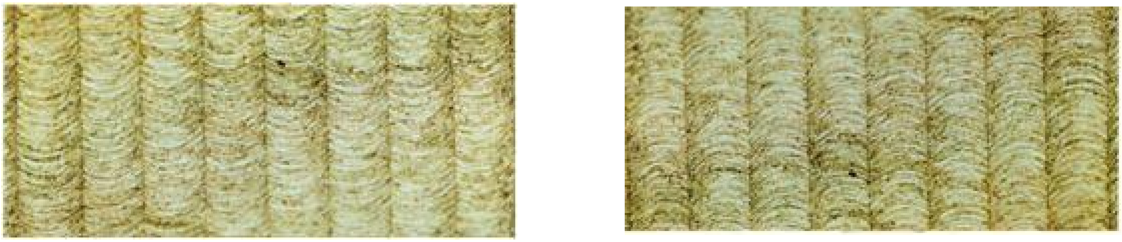
2800 rpm

2000 rpm



4400 rpm

3600 rpm



6000 rpm

5200 rpm

Figure 10: surface texture for different cutting speeds

With attention to the results of measured machining forces, surface roughness and surface texture variations related to the tests of cutting speed variations, the results are presented graphically in Figure 11 and Figure 12. It is clear from Figure 12 that surface roughness of machined part reduces up to spindle speed of 2000 rpm. With increasing the spindle speed, surface roughness increases to its highest level in 3600 rpm and then by increasing the spindle speed, reduces again. This variation of surface roughness (Ra) is shown in Figure 12. from force-spindle speed diagram, is concluded that with increasing spindle speed up to 3600 rpm, average of machining forces increases and then by increasing the spindle speed to about 6000 rpm the machining forces reduces. It should be noted that maximum possible spindle speed of this 3-axies CNC milling that is used in experiments, is 6000 rpm. It is clear that increase of machining forces has a significant effect on the increasing of surface roughness and maximum amount of cutting forces in 3600 rpm leads to highest level of surface roughness (Ra), or the worst machined surface texture. This issue is completely verified by images of surface texture in Figure 10.

Also machining forces in spindle speeds of 2000 rpm, 5200 rpm and 6000 rpm are less, compared to the other cases that are tested. Roughnesses of machined surface in these cases are lower respectively. This issue is completely verified by images of surface texture in Figure 10.

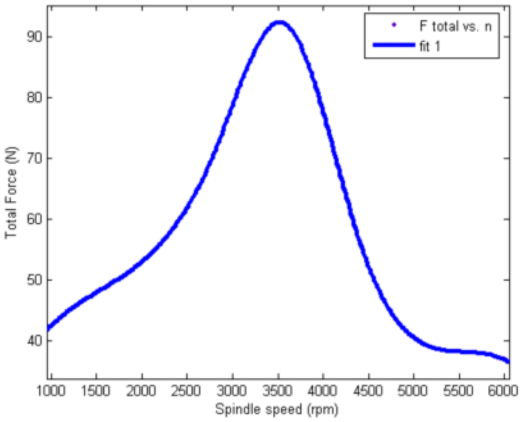


Figure 11 :Diagram of average resultant forces versus different spindle speeds

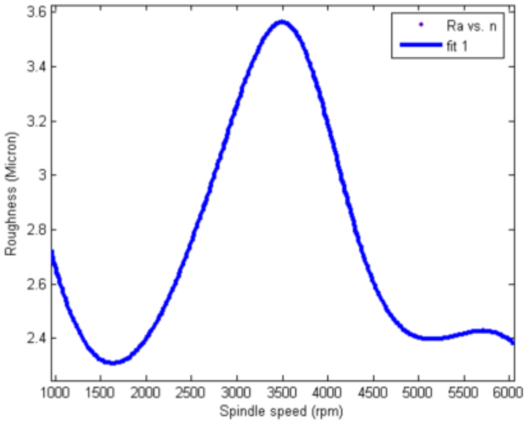


Figure 12 :Diagram of surface roughness versus different spindle speeds

The reason of rising machining forces with increasing cutting speed up to 3600 is that momentum of energy corresponding to square of cutting speed is increased and hence momentum forces during the milling process increase and then the total machining forces increase. After spindle speed 3600 rpm, increasing the cutting speed, leads to rising of temperature in the tool–chip contact area, and causes the softening temperature of workpiece material, which lets the chips deform more easily, and average of machining forces reduce and finally milling (cutting) operation will be performed easier [8]. In addition, the temperature rise in tool–chip interface can also cause the friction force to decrease, consequently by increasing the spindle speed after a certain value (which in this study related to the condition of workpiece, cutting tool and milling machine it is 3600rpm.). The factors such as temperature rising in the tool–chip interface, softening temperature of the workpiece and decreasing the friction force overcome to the momentum force which is resulted from the cutting speed rising, and causes decrease of machining forces after the cutting speed of 3600 rpm.

8. CONCLUSION OF CUTTING SPEED VARIATIONS IN THIN WALLED PARTS MILLING

In generally, since cutting speed increases from a certain value and temperature increases in the tool–chip interface, in addition to reduction of machining forces, surface roughness decreases. This phenomenon is due to Flattening Effect, which may be attributed to intensive heating of the material being machined. An increase in cutting speed causes an increase of temperature in cutting edges [9]. The effect of this phenomenon can be observed in Figure 11 and Figure 12, such that flattening effect leads to reduction of cutting forces and surface roughness after the cutting speed of 3600 rpm. With all above results it can be concluded that the best and most efficient condition for milling of aluminum blocks, that simultaneously satisfy the low roughness (Ra), high quality and also produces the minimum cutting forces, is the cutting speed of 2000 rpm, also the cutting speed of 2000 rpm has better conditions than 6000 rpm, although in milling with cutting speed of 6000 rpm, the machining forces and surface roughness are lower, the reason for this selection is that, in cutting speed of 6000 rpm, tool wear rate is higher than tool wear rate in 2000 rpm, and in addition the depreciation rate of machine tools is higher in higher spindle speed. During milling of a free-formed shaped thin plate, deflection and chatter vibration of the workpiece due to low stiffness has negative effect on the surface integrity, geometric and dimensional accuracy [10], therefore, it is necessary to select optimal cutting speed with consideration of these effects.

Finally and with regarding the results of these tests and other similar studies, it is concluded that after a certain range, with increasing the cutting speed, cutting force reduces in the rigid workpiece and otherwise surface roughness increases with increasing the cutting speed in the workpiece due to low stiffness.

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