Research concerning optimum cutting parameters according with tool path strategy for finishing procedures

A E Pena¹, F D Anania¹ and M Zapciu¹
¹Politehnica University of Bucharest, Department of Machine Tools and Manufacturing Systems, Spl. Independentei, No. 313, sector 6, 060042, Bucharest, Romania

E-mail: andra.pena@upb.ro

Abstract. Optimization of cutting parameters in NC milling needs to be studied because of its influence on machining time and cost. Today, any CAM software offers many tool path strategies to milling free form geometries. However, the users must have the know-how to choose the strategies according to geometry complexity, cutting tool geometry and its contact on the machined surface. Choosing the right strategy with the right cutting parameter is a rather difficult task to do on the machine tool. In this paper we try to take into account the influence of the toolpath over the surface quality for finishing operation. The main goal is to establish a direct link between machining parameters and toolpath in order to obtain the same surface quality for different trajectories. The first step consist in making a series of experiments for standards toolpaths (which can be found in any CAM software) like one-way, zig-zag, spiral from outside to inside, zig-zag at 45 dgr on a milling center. Based on the results, a correction coefficient for the feed rate was established.

1. Introduction

Generally, the handbook or human experience is used to select convenient machine parameters in manufacturing industry. In process planning of conventional milling, selecting reasonable milling parameters is necessary to satisfy requirements involving machining economics, quality and safety.

The machining parameters in milling operations consists of cutting speed, depth of cut, feed rate and number of passes. These machining parameters significantly impact on the cost, productivity and quality of machining parts. The effective optimizations of these parameters affect dramatically the cost and production time of machined components as well as the quality of final products. [1]

Several researches have also addressed the influence of cutter path on surface roughness, although few studies focus on the impact of tool path strategies on surface texture [2, 3, 4]

The tool path has always been the weak link in the chain –machine tool; cutting tool; CAM software, typically forcing the use of cutting parameters that are on the side of caution rather than productivity. These cautionary tool parameters are detrimental to the tools performance and fate.[5]

One of the main goals in finishing operations is to achieve a very low workpiece surface roughness. However, surface irregularities, which are always present in all machined parts, depend on several factors. In milling operations, surface quality improves at higher cutting speeds. Depth of cut indirectly affects surface quality, since the cutting force, vibration and cutting temperature increase with an increase in the depth of cut. Other factors that influence surface roughness are feed, tool nose radius, tool wear, cutting strategy, the tool’s trajectory during cutting, workpiece material,
cooling/lubrication system and the dynamic parameters of machining, such as cutting force, tool deflection, vibration and several thermal phenomena [6].

In general, it is found that surface roughness increases with an increase in the feed rate and depth of cut and a decrease in cutting speed.

The focus of numerous and extensive studies that evaluate surface finish is usually centered on the effect that machining parameters (speed, feed, depth of cut, etc.) have on the surface quality. They do not take into account the influence of the cutting toolpath on the surface quality.

Most of the commercial CAM software today offers several possibilities of algorithms of distributing the tool path in the domain of the designed part. Ones of the commonly used tool path are: One way curves; Zig-zag or raster curves; Helix curves; Spiral curves; Contour curves; Radial curves; Sequential curves.

2. Experimental research

In this paper is presented a way to take into account the different toolpath trajectories as a factor in the calculus of machining parameters. The research is starting with a finishing operation in milling process for basic toolpath trajectories existing in Cimatron E CAM software.

Some machining tests were made and roughness influenced by the type of trajectories was taking into account.

The proposed work investigates the efficiency of the different toolpath strategy for finishing milling.

3. Equipment and materials

The toolpaths evaluated were (figure 1) standard toolpaths from the software CimatronE 11 as follows:

- **One way** - is used climb milling to obtain a good surface quality.
- **Zig-zag** – both climb and conventional milling is used.
- **Helix curves** – the tool trajectory is from outside to inside with corner radius over the trajectories;
- **Radial** – is similar to helix curves from the tool trajectory point of view, but with sharp corner.
- **Zig-zag at 45 degree** – the tool trajectory is inclined relative to X direction with 45 degree (the linear movement is obtained by interpolation of the two axis of the machine (x and y). This trajectory type is used by some mold makers because they obtain a good quality surface.

The material used was 6061 aluminum, one of the most common alloys of aluminum for general purpose use. This is a precipitation hardening aluminum alloy, containing magnesium and silicon as its major alloying elements. The main mechanical properties are: Density 2.7 [g/cc]; Hardness: Brinell 95; Rockwell A 40; Tensile Yield Strength 276 [MPa]; Modulus of Elasticity 68.9 [GPa]; Poisson's Ratio 0.33; Fatigue Strength 96.5 [MPa]; Fracture Toughness 29 [MPa-m½] Shear Modulus 26 [GPa];
Shear Strength 207 [MPa].

The experiments were made on a 3 axis machining center First MCV300 that has a max. spindle speed of 8000rpm, spindle motor power 7.5kW and a maximum cutting federate of 10000 mm/min. The cutting tool is an end mill with 12 mm diameter with 3 flute. It is uncoated, solid fine grain, carbide tool from Iscar. All cases investigated were carried out without coolant.

In order to evaluate the surface quality, for the roughness measurement was used a Mitutoyo Surftest SJ210 instrument that has a measuring range (on X axis) of 17.5mm and a measuring speed of 0.25mm/s, 0.50mm/s, 0.75mm/s. The cut off length and the sampling length is 0.08mm, 0.25mm, 0.8mm, 2.5mm (figure 2).

![Figure 2. Experimental equipment.](image)

### 4. Experimental studies and calculus

A number of experimental cutting tests were made in order to identify and quantify the influence of the tool trajectories over the machining parameters.

In the first step the cutting regime for the initial tests was calculated according to the basic formulas for milling (equation (1)).

$$V_c = \frac{\pi \cdot D \cdot n}{100} \text{[m/min]} \quad F = n \cdot f_z \text{[mm/min]}$$  \hspace{1cm} (1)

Where: $D$ – the tool diameter in mm; $n$ – spindle speed in rpm; $F$ – feed rate in mm/min; $z$ – no. of flutes; $f_z$ – feed/tooth

The cutting regime parameters were kept for all studied trajectories at the same values $F=420$[mm/min], $n=350$[rpm], $V_c=132$ [m/min] and $f_z=0.04$ [mm/tooth]. The feed/tooth was chosen according to the cutting tool manufacturer’s recommendations; and for the preliminary tests the decision was to use the minimum value. The depth of cut was 0.3mm for all tests.

In order to have good results a series of 5 tests were made for each type of tool trajectory. For each test the roughness was measured in 3 points on 2 directions (x and y). Averages were calculated for each direction of measurement (equation (2)).

$$R_{aj}^x = \frac{\sum_{i=1}^{n} R_{aij}^x}{n} = \ldots R_{aj}^y = \frac{\sum_{i=1}^{n} R_{aij}^y}{n}$$  \hspace{1cm} (2)

where $i=1..3$ -measurement number;

$n$- number of measurements (3- for our study case).

$j=1..5$ -number of test for each type of tool trajectories
$R_{aj}^x$ - Average roughness in x direction for each cutting test for the same trajectories type;

$R_{aj}^x$ – roughness in X direction for each measurement;

$R_{aj}^y$ - Average roughness in Y direction for each cutting test for the same trajectories type;

$R_{aj}^y$ – roughness in Y direction for each measurement;

An average roughness was established for each cutting test (equation (3))

$$R_{aj}' = \frac{R_{aj}^x + R_{aj}^y}{2}$$  \hspace{1cm} (3)

where $j=1..5$ - number of test for each type of tool trajectories;

$R_{aj}'$ – average roughness for each cutting test for the same trajectories;

The measurements results are presented in table 1.

### Table 1. Measurements results/

| No | Tool trajectory type (t) | Tests | $R_{aj}^x$ [μm] | $R_{aj}^y$ [μm] |
|----|--------------------------|-------|----------------|----------------|
| 1  | One way                  | 1     | 0.13          | 0.10          |
|    |                           | 2     | 0.08          | 0.09          |
|    |                           | 3     | 0.12          | 0.13          |
|    |                           | 4     | 0.17          | 0.12          |
|    |                           | 5     | 0.12          | 0.11          |
| 2  | Zig-zag                  | 1     | 0.10          | 0.12          |
|    |                           | 2     | 0.10          | 0.11          |
|    |                           | 3     | 0.12          | 0.12          |
|    |                           | 4     | 0.15          | 0.13          |
|    |                           | 5     | 0.13          | 0.11          |
| 3  | Helix                    | 1     | 0.11          | 0.11          |
|    |                           | 2     | 0.11          | 0.13          |
|    |                           | 3     | 0.11          | 0.12          |
|    |                           | 4     | 0.13          | 0.12          |
|    |                           | 5     | 0.25          | 0.37          |
| 4  | Spiral                   | 1     | 0.11          | 0.14          |
|    |                           | 2     | 0.19          | 0.11          |
|    |                           | 3     | 0.16          | 0.11          |
|    |                           | 4     | 0.32          | 0.18          |
|    |                           | 5     | 0.18          | 0.17          |
| 5  | Inclined 45              | 1     | 0.13          | 0.20          |
|    |                           | 2     | 0.22          | 0.1          |
|    |                           | 3     | 0.09          | 0.33          |
|    |                           | 4     | 0.22          | 0.23          |
|    |                           | 5     | 0.14          | 0.16          |

In order to have an accuracy results an average roughness was calculated for each tool trajectories type (equation (4)) and the results are in table 2.

$$R_{aj}' = \frac{\sum_j^m R_{aj}'_j}{m}$$  \hspace{1cm} (4)

where $j=1..5$ - number of each test for each type of tool trajectories;

$m$ - number of test made for a certain tool trajectories (5 in our study case)

$R_{aj}'$ – reference roughness for each trajectories type;

$R_{aj}'$ – average roughness for each cutting test for the same trajectories type;

### Table 2. Surface quality.

| No | Tool trajectory type (t) | Tests | $R_{aj}$ [μm] | $R_{aj}'$ [μm] |
|----|--------------------------|-------|----------------|----------------|
| 1  | One way                  | 1     | 0.13          | 0.11          |
|    |                           | 2     | 0.13          | 0.10          |
|    |                           | 3     | 0.10          | 0.11          |
|    |                           | 4     | 0.10          | 0.11          |
|    |                           | 5     | 0.11          | 0.10          |
| 2  | Zig-zag                  | 1     | 0.11          | 0.12          |
|    |                           | 2     | 0.14          | 0.11          |
|    |                           | 3     | 0.11          | 0.11          |
|    |                           | 4     | 0.13          | 0.14          |
|    |                           | 5     | 0.12          | 0.16          |
| 3  | Helix                    | 1     | 0.12          | 0.10          |
|    |                           | 2     | 0.12          | 0.18          |
|    |                           | 3     | 0.25          | 0.20          |
|    |                           | 4     | 0.20          | 0.15          |
|    |                           | 5     | 0.16          | 0.16          |
| 4  | Spiral                   | 1     | 0.23          | 0.21          |
|    |                           | 2     | 0.23          | 0.19          |
|    |                           | 3     | 0.14          | 0.16          |
|    |                           | 4     | 0.16          | 0.18          |
|    |                           | 5     | 0.13          | 0.18          |

To calculate the correction factor for machining parameters a constant reference value was established as minimum of $R_{aj}'$ calculated (equation (5)).
Figure 3. Average roughness($R_a$) according with trajectory type.

$$R_{a}^{ref} = \min(R_a^t) \quad \text{where} \ t=1..5$$

$t =$ tool trajectories with the fallow value: 1 - one way; 2 - zig-zag; 3 - spiral; 4 - helix; 5 - 45 dgr inclined.

5. Experimental studies and calculus
As it can be seen from table 3, the value for roughness differs from one toolpath to another. Based on this data was calculated a correction coefficient that takes into account the tool trajectory. The coefficient was calculated as a rapport between the surface roughness for each trajectory type and the reference. The correction factor was established for each tool trajectories based on formula 6 and the results are presented in table 3.

$$C_{Ra}^{t} = \frac{R_a^t}{R_a^{ref}}$$

Where $t = 1..5$ - tool trajectories with the fallow value: 1 - one way; 2 - zig-zag; 3 - spiral; 4 - helix; 5 - 45 dgr inclined

$R_a^{ref}$ - reference roughness for each trajectories type;

$R_a^t$ - constant reference value

| Tool trajectory | One way | Zig-zag | Helix | Spiral | 45 dgr |
|-----------------|---------|---------|-------|--------|--------|
| Correction factor | 1       | 1.15    | 1.37  | 1.41   | 1.60   |

A formula for the feed rate calculus was established by taking into account the correction factor (equation (7))

$$F = \frac{f_n z}{C_{Ra}^{t}}$$

6. Test and validation
In order to validate the correction coefficient another series of tests were made. The validation test was made for maximum feed per tooth supported by the tool ($f_z = 0.11 \text{mm/tooth}$ and $0.3 \text{mm cutting depth}$).

In first step the cutting regime was calculated according with classic formula (equations 1, 2) and in the second step the calculus was made by using correction factor according with value from (table 4).

For each test the average roughness and cutting time was measured on the machining center. The
results are presented in table 4 and figure 4 and 5.

| Tool trajectory | One way | Zig-zag | Helix | Spiral | 45 dgr |
|------------------|---------|---------|-------|--------|--------|
| Clasic          |         |         |       |        |        |
| \( F = f_{n_Z} \) | Feed rate [mm/min] | 1155 |       |        |        |
|                  | Cutting time [min]  | 11   | 5     | 5      | 3      |
|                  | Roughness Ra [μm]   | 0.30 | 0.36  | 0.40   | 0.50   | 0.41   |
| Corrected       | Feed rate [mm/min]  | 1155 | 1004  | 843    | 820    | 722    |
| \( F = \frac{f_{n_Z}}{c_{R_z}} \) | Cutting time [min]  | 11   | 6     | 7      | 4      | 3      |
|                  | Roughness Ra [μm]   | 0.30 | 0.31  | 0.25   | 0.23   | 0.22   |

**Figure 4.** Time variation.  
**Figure 5.** Validation results.

If it is applied this coefficient on the standard formula for calculating the feed rate it can be observed that the feed rate is reduced depending on the cutting tool trajectory in order to obtain similar surface quality for all trajectories. (see equation 7)

It is well known that reducing the feed rates while keeping the spindle speed up lightens the chip load and leads to a nicer surface finish. But lighten the feed rate too much, the tools will start to rub, and tool life will go way down due to the excess heat generated by the rubbing.

In order to evaluate the productivity, during the machining the time was monitored to evaluate the efficiency of applying the coefficient that reduce the feed. As it can be see from table 4 the machining time does not increase significantly although the feed rate is reduced. So we can say that from the point of view of productivity the process is not too much affected, but the surface quality is improved and so the use of this approach is useful.

**7. Conclusions**
This is the first step for developing an easy to use, fast calculus software for the milling cutting parameters. The difference from the other similar software is that we take into account (besides a number of other factors experimentally or analytically determined) the type of cutting tool trajectories.

Machining parameters are typically adjusted according to the instructions in the tools catalogues and/or handbooks without regard to the roughness requirements and geometrical tolerances of the surface to be machined. Incorrect adjustment of the machining parameters, feed rate and depth of cut lead to tool deflection and consequently reduced surface quality. With increasing feed rate and depth of cut, the tool deflection is increased.

The theory says that the best surface quality is obtained when using climb milling, but we do not always have the possibility to machine in such a manner. Using the method that we propose, to use a coefficient that reduce the feed rate in order to improve the surface quality based on the tool trajectory, but not to affect the productivity, is the right way to approach this problem.
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