CLASSIFICATION OF THE FEED-RATE OPTIMIZATION TECHNIQUES: A CASE STUDY IN MINIMIZING CNC MACHINING TIME

M. Sedighi   &   M. Noorani Azad

Abstract: *Along with increasingly development of CAD/CAM software and their application in various industries, minimizing of the machining time is found to be more important. In this paper, firstly the concerning subjects are discussed regarding classification of the optimization techniques. These are programming techniques, high speed machining techniques and feed rate optimization techniques. As a case study, an NC code was generated for machining of a plastic die by means of a dedicated software and the die was machined conventionally. Then the workpiece was machined using optimization techniques. Finally times taken for two approaches have been compared. The result shows machining time after optimization has been reduced considerably (64%).*

1. Introduction

On the early times of appearing the CAD/CAM technology in producing of complicated parts, most industrialists were seeking only to produce part. However, nowadays CAD/CAM software and related industries are being increasingly developed in a more competitive business world. So the production of complicated parts are not the sole target, but increasing the geometrical accuracy and the quality of final product, as well as minimizing the machining time, come in to the list of goals.

New processes and methods in the field of machining and CAD/CAM technologies have been developed to achieve such goals. One of these new methods that result in reduction of machining time is feed rate optimization. Determination of optimized machining feed-rate is difficult task due to the continuously changing geometry of the cut. For example, in the conventional machining procedure of a sculpture surface, feed rate will be set at a constant value for whole tool paths based on the worst case of the cut geometry. This provides a conservative cut, but it will increase the machining time and cost which subsequently reduces the efficiency. But if the feed rate is specified on the basis of cut width and depth at any

motion, a safe cutting could be provided while time saving has been also achieved.

Recently many studies have been carried out in this area. Some of the first work on feed-rate planning was done by Wang [1], where he used a Z-buffer representation of the workpiece and a simple volumetric model to relate cutting force to the metal removal rate (MRR). Takata [2] utilized a Z-buffer approach for the workpiece/cutter geometry description and combined this with the mechanistic model of Kline [3] to investigate the process. Altan [4] has developed a process planner that keeps the chip load constant during sculptured surface finish machining by adjusting both the feed-rate and spindle speed. Jerard and his co-workers [5,6,7] have performed most of their studies on feed rate optimization as a series of practical works. In advance CAM software, feed rate optimization has been used as a routine procedure in recent years. In these software, optimization of feed rate is carried out by simulating of cutting process and accurate estimation of feed in any machining step. Metacut [8] and Vericut [9] are two of these software.

Unfortunately, a few studies are available for comparison of commercial CAD/CAM software in this regards. Further more in the user manuals of this software only the procedure of data input/output have been expressed and the software doesn't say any things about the logics and algorithms of optimization. This lack of information might be due to a rivalry policy between the software providers. In this paper, it has been tried to explain and compare the optimization logics in CAD/CAM commercial software.

So, the principles and procedures of optimization are described in three sections. It has also been tried to present a total picture of existing optimization techniques and their goals. In the case study section, a dedicated software has been used for feed rate optimization. To examine these procedures, two similar dies were machined, one using conventional method and the other one using optimization method.

2. Classification of Optimization Techniques

There are several factors that may affect the machining conditions. These factors include: accuracy, minimizing time, finish quality, tooling maintenance and eliminating the polishing time.

Generally, the final goal in tool path optimization is to achieve the condition with the best possible value of the mentioned factors. Tool path optimization can be discussed both experimentally and theoretically. The optimization techniques can be classified in the following classes:

1- Using programming techniques for practical optimization
2- Using the new technology of High Speed Machining (HSM) [10]
3- Feed rate optimization.

The first class has three subdivisions which are:
  a) Using known principles of machining process
  b) Using preform blocks
  c) Converting small linear motions to arc or curve motions.

Figure (1) presents optimization techniques (left column) and general goals of optimization (right column).

Among those items the most applicable method is feed rate optimization technique for which many researches have been carried out. Nowadays, these techniques are being developed by means of new software. The details of the feed rate optimization classes will be described briefly in the following sections.
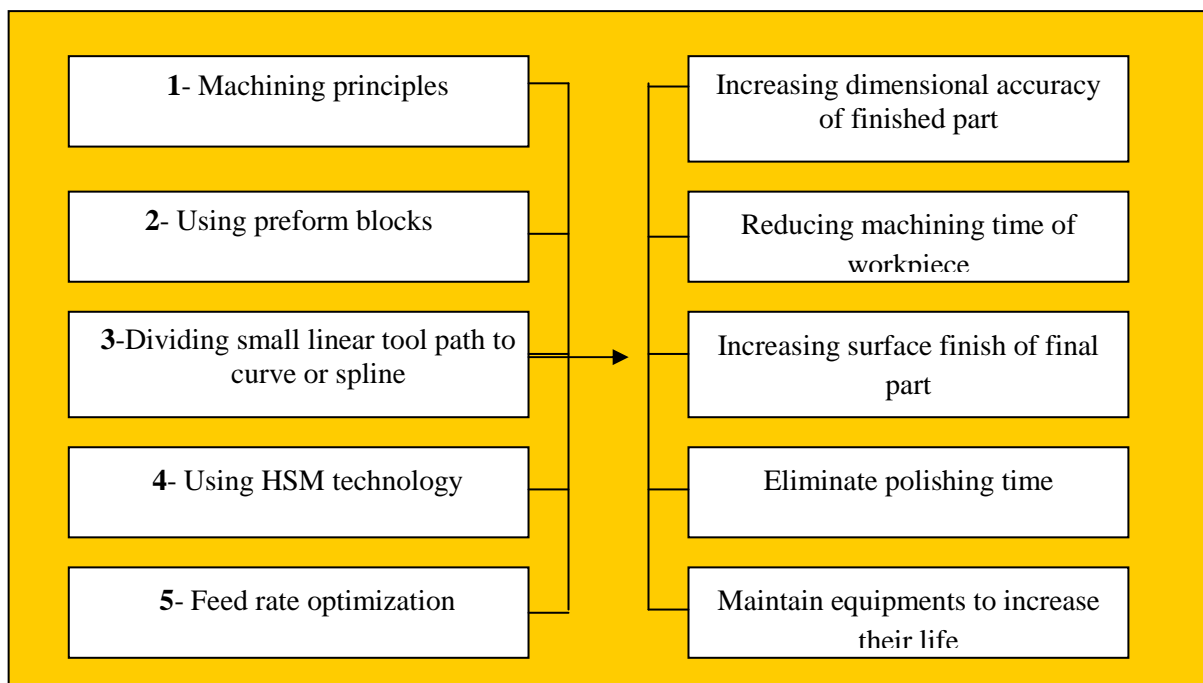

Fig. 1. Classification of optimization techniques and their goals

2-1. Simulation of Cutting Process
Simulation plays an important role in all engineering practices. It is usually used prior to actual CNC machining to check any errors that may be encountered in the process. Moreover simulation has other advantages like specifying machining time and feed rate. Computer simulation of cutting process is performed in two ways: Solid Modeling method and Z-Map method [11].

In solid modeling method, the volume generated by tool itself is subtracted from the volume of raw workpiece. In fact, the simulation is performed by boolean functions. Simulation time is proportional

(with the power four) to the number of tool motions [11]. As shown in figure (2) in the Z-MAP method, the workpiece surface is fitted using a series of spaced points at XY plane, in the form of two-dimensional arrays.

Then an upward vector extends from each of these points to the surface of raw material. These vectors are called directional vectors or ZDV. The extension of these vectors to the surface of raw material makes them crossed the workpiece surface and Z coordinates of the intersection is assumed as a base point. According to figure (3) the volume created by rotation of the tool at any given motion is considered as a pocket. The pocket

intersection with ZDV is calculated and is compared with previous coordinates of the same ZDV. If the new Z coordinates is less than the old one, the length of ZDV is reduced as much as the difference of them. This algorithm continues to the end of final step.
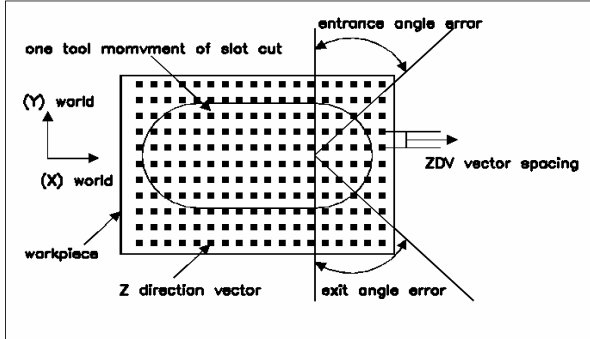

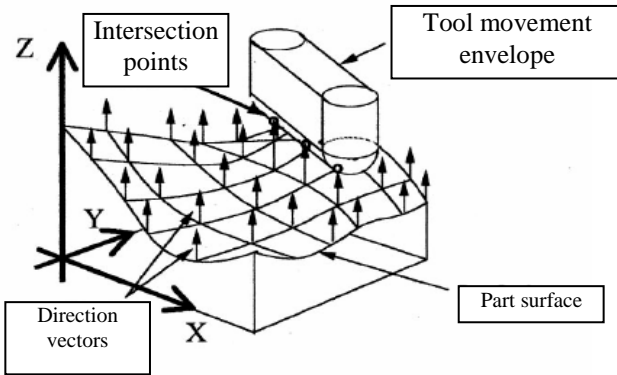**Fig. 2. Schematic presentation of Z- MAP method [6]**

Fig. 3. Intersecting Z-MAP vector with the pocket resulting from tool rotation[6]

As shown in figure (4), a solid tetragonal (dexel) can be imagined in the spaces between ZDVs, so those vectors of ZDV are at the center of these tetragonals.
The measurement of the material removal rate is estimated by intersection of the volume generated from tool rotation and the volume created by tetragonal. The speed of Z-MAP method is higher because the speed of simulation in this method is proportional to the number of tool motions (N).
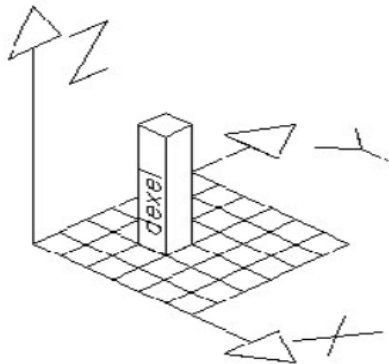

Fig. 4. Setting the solid tetragonal between Z vectors

2-2. Using Volumetric Method to Specify Feed Rate

Volumetric method is one of the methods used to determine feedrate [11]. In this method, optimized feed is determined according to relations governing the material removal rate. Material removal rate, is the removed volume of material (V_R) per time unit and can be calculated by equation-1:

$$M.R.R = \frac{V_R}{T} = \frac{V_R}{\frac{L}{f}} = \frac{V_R \times f}{L} \tag{1}$$

Where

L = Length of motion, f = Feed rate,

The volume of removed material can be obtained by using Z-MAP method as presented in equation-2:

$$V_R = \sum_{i=1}^{n_d} \left\{ (z_b - z_a)_l . A_i \right\} \tag{2}$$

Where

A_i = Area of ZDV,

Z_b = Magnitude of vector before touching the tool,

Z_a = Magnitude of vector after touching the tool,

n_d = Number of vectors touched the tool during tool motion.

In this method, firstly a certain base material removal rate is assigned by the user. Then the volume of removed material (V_R) at any length of motion (L) is calculated using Z-MAP method. Finally, the proper feed rate for tool motion will be obtained by substituting these values in equation-3:

$$f = \frac{(MRR).L}{V_R} \tag{3}$$

2-3. Using Force Vector Method to Obtain Feed Rate

Another method for obtaining optimized feed rate is mechanical method or force vector method [6]. In this method the optimized feed is determined using governing equations for cutting forces. In the cutting process, the force acting on the tool tooth is proportional to the thickness of the chip. Tangential and radial components of this force are shown in equation -4 and 5 respectively:

$$\Delta F_t = K_t . h (\phi, z) \tag{4}$$

$$\Delta F_r = K_r . \Delta F_t \tag{5}$$

Where Kt , Kr is constant parameters and h is the chip thickness.

Chip thickness depends on the angle of tool rotation (α) and the feed rate f, ($h = f \sin\alpha$).

So equation-6 is used for calculating the chip thickness at any location:

$$h(\phi, z) = \frac{f(\phi, z).Ns(\phi, z)}{n_t.N} \qquad (6)$$

Where

$f(\phi, z)$ = Feeding vector,

$Ns(\phi, z)$ = Vector perpendicular to tool surface,

n_t = Number of tool tooth

N = Number of spindle rotation,

The value of the constant K_t depends on material property, tool geometry (chip angle), cutting speed (V), chip thickness (h), tool wear and material temperature. The dependency of K_t to many factors makes the estimation of the cutting force more difficult.

3. Using Commercial Software to Minimize Machining time

As explained in section 2, one of the optimization techniques is to determine the machining conditions (feed rate and spindle speed) regarding the cutting conditions (width and depth of feed). This method, which has been integrated in the most of the commercial software, not only minimizes machining time but also increases tool and machine life.

Optimization by software is carried out in two ways:

- Force vector method
- Volumetrical method

The first method is based on the forces acting on the tool and the second method is based on material removal rates (M.R.R) which were discussed in section 2 and section 3. Due to the dependency of the first method to many variables, it is mostly a research method. But the second method is used in many software.

Among the popular CAM software, the PS-Opti Feed module of Powermill software and High-Feed module of Mastercam software are capable of optimizing the feed rate. Metacut and Vericut are another two types of such software that make feed rate optimization possible.

The steps of feed-rate optimization in such software are based on the following three principles:

1- Specifying maximum removable volume of material by the user: This volume is obtained by assigning the values for tool step-over (width) and depth of cut (step down) and is considered as a base value.
2- Estimation of the material removal for each step of tool motion: In this step the tool path is divided into smaller paths. Based on the accuracy specified by the user (resolution), the amount of removal volume is calculated.
3- Comparing steps 1 and 2, to specify proper feed rate: In this step, the new feed rate is determined by comparing the values obtained in previous steps. Then the determined value is filtered by user using specified constraints and is extracted if desired.

4. Experimental Case Study

As a case study, a plastic moulding die has been selected. Figure (5) shows the preform block prior to the CNC machining.
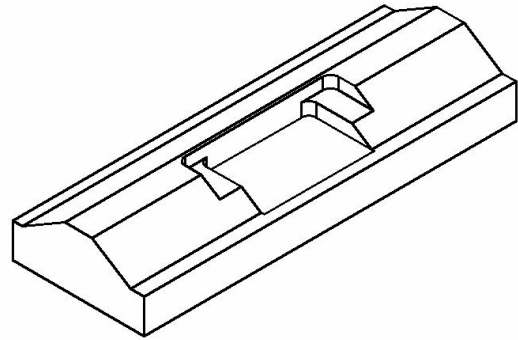

Fig. 5. Preform block of the die

Figure (6) present the details of the final machined die. As shown, there are different depths of material removal at different sections of the die. This could cause a remarkable increase in machining time if an optimization process was not carried out on the NC file generated for the specimen.
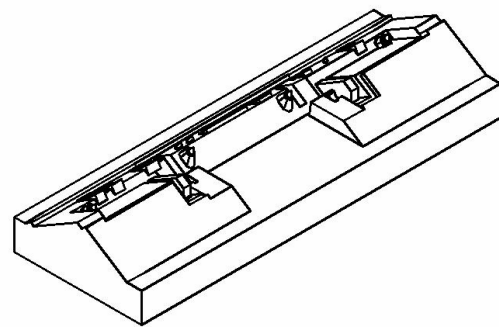

Fig. 6. The machined

If the constant feedrate as shown in table (1) is used, the machining time will take 780 minutes.

Tab. 1. Machining Conditions

Tool Type	Mat.	Depth. Cut	Step Over	Feedrate
Dia. 24	H13	1 mm	18 mm	100 mm/min

For the optimization of this case, Vericut software which works volumetrically is used to optimize

feedrate[11]. Since the cutting geometry is changed during machining process, some sections may be machined with higher feed rate. while in rough machining stage orientation and magnitude of cutting loads are not important, For assigning optimized feed rate, volumetric method is used.

After optimizing the feed rate, machining time of the die was reached to 292 minutes. Thus a reduction equal to 64% of machining time was achieved in comparison to the ordinary machining method. Figure (7) shows a part of the NC program generated by using optimized feed rate. The feed rate between 50-300 m/min can be observed while the nominal feed rate was equal to 100 m/min.

```
N2643 X252.951Y-34.04F3000
N2644 Z-9.915
N2645 Z2.
N2646 X97.96Y33.899
N2647 Z-9.922
N2648 G1Z-11.915F50
N2649 X93.682Y31.698F180
N2650 X80.849Y25.096F150
N2651 G3X79.992Y28.452I-26.918J-5.087F280
N2652 G1X78.039Y31.614F300
```

Fig. 7. A part of NC program generated based on optimized feed rate

5. Conclusion

In this paper, the principles and the methods of the machining time optimization were discussed. Different optimization techniques were described and compared. Then by using these techniques in a practical case study, it was shown that the optimization technique can minimize the machining time remarkably.

References

[1] Wang, K.K., *''Solid Modeling for optimizing Metal Removal of Three-Dimensional NC End Milling,''* J. Manuf. Syst., **7**, No. 1, 1988, pp. 57–65.

[2] Takata, S., Tsai, M.D., Inui, M., Sata, T., ``*A Cutting Simulation System for Machinability Evaluation Using a Workpiece Model,*'' CIRP Ann., 38/1, 1989, pp. 417–420.

[3] Kline, W.A., DeVor, R.E., Lindberg, J.R., *''The Prediction of Cutting Forces in End Milling with Application to Cornering Cuts,''* Int. J. Mach. Tools Manuf., 22, No. 1, 1982, pp. 7–22.

[4] Altan, T., Shatla, M., Yen, Y., Akgerman, N., *''High Performance Machining for Die/Mold Manufacturing- R&D in Progress'',* International Conference on Sculptured Machining, Nov 11, 1998, Chrysler Technology Center, MI, Kluwer Academic Publishers, 1998, pp. 293–314.

[5] Jerard, R.B., Fussell, B.K., Ercan, M., *"On–Line Optimization of Cutting Conditions for Nc Machining*" NSF Design, Manufacturing Industrial Innovation Research Conference, Tampa, Florida, 2001.

[6] Hemme, J.G., Fussell, B.K., Jerard, R.B., *"Robust Feedrate Selection for 3-axis Machining Using Discrete Models",* J. Manu. Sci. Eng. Vol 123 pp214-224, 2001.

[7] Jerard, R.B., Fussell, B.K., Hemmett, J.G., Ercan, M.T., *"Tool path Feedrate Optimization: A Case Study*" Proc. Ins. Design. Manu. Jan 3-6, Vancouver, 2000.

[8] Elliot, B., *'Technical Discussion of MetaCut Tool path Optimization*", Northword Design, 2002.

[9] www.cgtech.com, 2004.

[10] Unigraphics Solutions *"High Speed Machining (HSM) Using NURBS Technology"*. Unigraphics Inc., 2003.

[11] Choi, B., Jerard, R., *Sculptured Surface Machining - Theory and Applications*, Chapman & Hall, May 1998,ISBN 0-412-78020 - 8.