A Long-term Control Scheme of Cutting Forces to Regulate Tool Life in End Milling Processes

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Abstract:
Numerous researches have been reported in the literature on the cutting force control in end milling processes. There have been, however, very few practical applications actually employed in commercial products. In this research, as a practically feasible and effective cutting force control scheme, we propose a long-term cutting force control strategy with a particular focus on the regulation of the tool life. First, the cutting force is monitored only at every "check point" set on the tool path. Since it does not require continuous full-time monitoring of cutting forces, a "cheaper" estimation scheme of cutting forces can be potentially employed. During actual cutting, the feedrate profile is updated at every check point, such that the cutting force is regulated along the target profile. The target profile is given such that the desired cutting distance can be machined before reaching the end of tool life. The effectiveness of the present approach is experimentally investigated by cutting experiments of hardened steel.

Keywords: cutting force control, end milling, tool life, intelligent machining, cutting force monitoring

1. Introduction

In early '90s, a sintered carbide end mill with an (Al, Ti)N coating was introduced into the manufacturing of dies and molds, which made it possible to directly machine pre-hardened steel of the hardness up to HRC60. By first performing heat treatment on raw steel and then machining it by using this tool, die/mold making process can be significantly simplified, eliminating the needs for grinding or EDM (electric discharging machining) processes after the heat treatment. Particularly in the machining with such a tool, very careful process planning is crucial to perform safe, and productive machining. For example, if machining conditions are not adequately set, the tool damage such as the chipping can easily occur. If machining conditions are set too conservatively to avoid tool damages, the machining productivity will be significantly sacrificed. Furthermore, in die and mold machining, it is often required to finish the entire machining process by using one tool only, since the tool exchange often deteriorates the machining accuracy. In today's industry, process planning relies to a high extent on expert machine operators' experience and knowledge. Even for such an expert operator, process planning for the high-productive machining of hardened steel is quite difficult.

In order to perform safe, and high-productive machining by fully utilizing the potential of recent high-speed machining centers, it is important to develop a support system that can autonomously monitor the machining process, and optimize machining conditions adaptively. From this viewpoint, numerous research efforts have been devoted on "intelligent" control of machining processes. In particular, the control of cutting forces in end milling processes have been extensively studied for years. A majority of works found in the literature is on the subject of adaptive feedback control techniques (for example, [1, 2]). There have been, however, very few practical applications of such an approach actually employed in commercial products. A critical issue with the actual implementation of such a control approach is the cost of installing a sensor to monitor cutting forces; reliable, high-accurate sensors to measure cutting forces, such as a dynamometer, is expensive.

In this research, as a practically feasible and effective cutting force control scheme, we propose a long-term cutting force control strategy with a particular focus on the regulation of the tool life. First, the cutting force is monitored only at every "check point" set on the tool path. Since it does not require continuous full-time monitoring of cutting forces, a "cheaper" estimation scheme of cutting forces, such as the estimation from spindle or servo motor current, can be employed. The feedrate profile is scheduled in advance based on a prediction model of cutting forces. During actual cutting, the feedrate profile is updated at every check point, such that the cutting force is regulated along the target profile. The target profile is given such that the desired cutting distance can be machined before reaching the end of tool life.

The effectiveness of the present approach is experimentally investigated by cutting experiments of hardened steel. Throughout this paper, we consider a roughing process of hardened steel, JIS SKD61 (HRC53), which is commonly used in die and mold manufacturing, by using an (Al, Ti)N coated sintered carbide straight (radius) end mill.

2. Overview of Control Scheme

2.1 Overview of Control Scheme

As a scheme to autonomously determine machining conditions, the control of cutting forces have been long studied. In most of them, the feedrate is used as a control variable, since it is easy to manipulate. In most of past researches, the objective of cutting force control can be described as follows: when the cutting force is higher than the target level, to avoid the tool damage, the feedrate must be reduced; when the cutting force is lower than the target level, to enhance the productivity, the feedrate must be increased.

Cutting force control schemes found in the literature can be roughly categorized into the following two: 1) feedback control schemes based on the real-time monitoring of cutting forces (e.g. [1,2]), and 2) model-based off-line feedrate scheduling schemes based on the prediction of cutting forces (e.g. [3,4]). As has been discussed in Section 1, a critical issue with the practical implementation of feedback control schemes is the reliability and the cost of cutting force monitoring. On the other hand, model-based feedrate scheduling schemes optimize feedrate profiles in priori such that the "predicted" cutting force is regulated at the given desired level. Considering practical implementation, simpler model-based approaches, which can be seen as a feedforward control approach, are more feasible and practically effective than feedback control approaches.

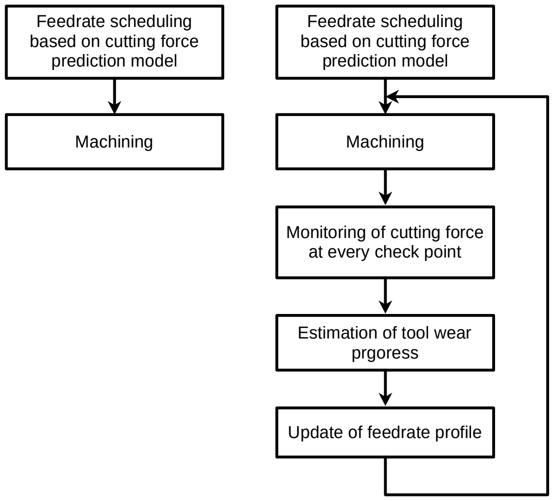
Since model-based feedrate scheduling schemes do not monitor the actual machining process, its control performance completely depends on the accuracy of the cutting force prediction model. Another inherent issue with model-based feedrate scheduling schemes is that it is impossible to adapt to the change in machining process. One of critical changes in machining processes is caused by the progress of the tool wear. Generally, the cutting force increases as the tool wear progresses. If the cutting force is controlled constant ignoring the progress of tool wear, the machining productivity would be critically sacrificed.

Considering the drawbacks of both schemes, in this study, we propose the following combination of both schemes: the variation of cutting forces in short term is suppressed by applying a model-based feedrate scheduling scheme. The cutting force is monitored only at "check points" on the tool path. The cutting force prediction model is updated at every check point, and the feedrate profile is re-calculated in order to regulate the progress of tool wear, and consequently, to regulate the tool life. Figure 1 illustrates the concept of the proposed approach.

To this goal, this paper presents the following schemes:

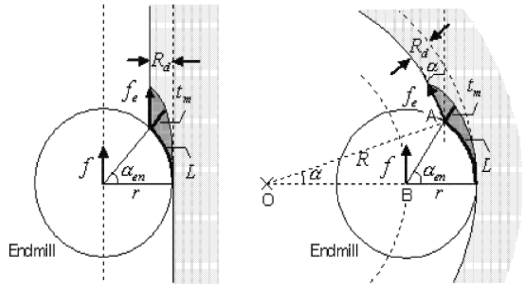
(1) Estimation of tool wear progress by monitoring cutting forces at check points:
A scheme to estimate the progress of tool wear, and to predict the tool life, by monitoring cutting force at every check point is proposed.

(2) Feedrate control to regulate the tool life:
Based on the estimated tool life at every check point, a scheme to modify the feedrate profile is presented such that the desired cutting distance is obtained before the end of tool life is reached.



(a) Conventional feedrate scheduling approach (b) Proposed approach

Figure 1: Concept of the proposed control scheme



(a) On a straight path (b) On a circular path

Figure 2: Schematics of end milling process

2.2 Cutting Force Prediction Model

In this paper, we employ the cutting force prediction model proposed by Kakino el al. [5] for the feedrate scheduling. This section briefly reviews this model.

Figure 2(a) and (b) depict the schematics of end milling process on straight and circular paths, respectively. In the figures, t_m and L respectively denote the maximum undeformed chip thickness and the arc length of cutting engagement. Kakino et al. proposed a simple model to predict the cutting force by using these two variables:

$$F = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{12} X_1 X_2 \quad (1)$$

where X_1 and X_2 respectively represent the variables, t_m and L, normalized by given central values. $\beta_0 \sim \beta_{12}$ are constant coefficients. From the geometry shown in Fig. 2(a), the following equations can be derived:

$$\alpha_{en} = \arcsin\left(\sqrt{1-\left(\frac{(R-R_d)^2-(R-r)^2-r^2}{2\cdot(R-r)\cdot r}\right)^2}\right) \quad (2)$$

$$L = r \cdot \alpha_{en} \quad (3)$$

$$t_m = f_z \cdot \sin(\alpha_{en}) \quad (4)$$

where f_z: the feed per tooth at the tool center, α_{en}: the engagement angle, R: the arc radius, R_d: the radial depth of cut, and r: the tool radius.

3. Estimation of Tool Wear Progress by Monitoring Cutting Forces

3.1 Monitoring of Cutting Forces at Check Points

In practical implementation, it is difficult from the viewpoint of the reliability and the cost to continuously monitor the cutting force, and to apply a feedback control scheme based on it. It is much more practically feasible to implement a scheme to monitor cutting forces only at "check points," which can be set at the region where the estimation of cutting forces is relatively easy. For example,

Table 1: Major machining conditions

Machine	Vertical machining center
Tool	(Al, Ti)N coated sintered carbide radius end mill (diameter: 6mm, 6 flutes)
Workpiece	JIS SKD61 (HRC53)
Coolant	Oil mist
Cutting direction	Down cut
Tool extension	18 mm
Axial depth of cut	6 mm

Table 2: Machining conditions in tool wear tests (S1: Standard condition, C1~C4: Conditions 1~4)

Name	Spindle speed, min^{-1}	Cutting speed, m/min	Radial depth of cut, mm	Feedrate, mm/min	Feed per tooth, mm/tooth
S1	16,000	301.6	0.3	11,520	0.120
C1	16,000	301.6	0.5	7,680	0.080
C2	8,000	150.8	0.3	2,900	0.060
C3	8,000	150.8	0.3	3,781	0.079
C4	8,000	150.8	0.4	2,900	0.060

it has been well known that cutting forces can be estimated by observing the armature current of servo motors for feed drives [6]. In practice, the servo motor current is influenced by many other disturbances such as the friction, and thus it is in general difficult to estimate the cutting force in high reliability. It is especially difficult under non-steady-state motion of the machine, where the effect of the friction on servo motor current significantly varies [7]. By setting check points on the region where the machine's motion is in steady state (e.g. a straight line), the estimation of cutting force based on servo motor currents becomes more practically feasible.

3.2 Estimation of Tool Wear Progress

In end milling processes, it is well known that the cutting force generally increases as the tool wear progresses [8]. Needless to say, the cutting force is also dependent on machining conditions or tool path geometries. This section first presents a scheme to estimate the tool wear progress from the cutting force.

At every check point, the cutting force in the XY plane, F_{xy}, is measured. Assuming that the variables X_1 and X_2 are given at this check point (these variables are given by the geometry of tool path and machining conditions), the coefficient β_0 in Eq. (1) is re-calculated by using the measured cutting force. All the other coefficients, $\beta_1 \sim \beta_{12}$ are assumed to be the same as original values.

Notice that the coefficient β_0 corresponds to the estimated cutting force when X_1=X_2=0. Refer the machining condition corresponding to X_1=X_2=0 as the "standard condition." Although the values of X_1 and X_2 may vary at every check point, by observing the estimated β_0, one can evaluate the increase of cutting force due to the progress of tool wear virtually in the same "standard" condition. In this paper, the estimated $\hat{\beta}_0$ is referred to as the "tool

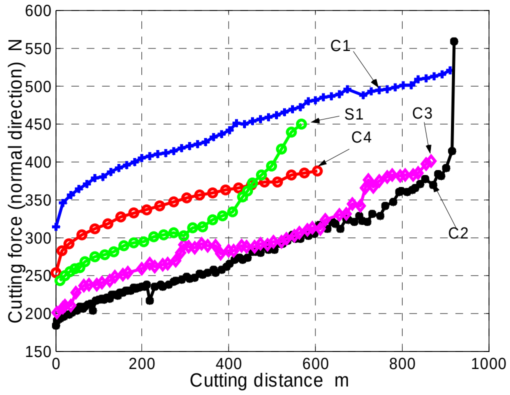


Figure 3: Measured cutting forces (in the direction normal to the feed direction) until the end of tool life.

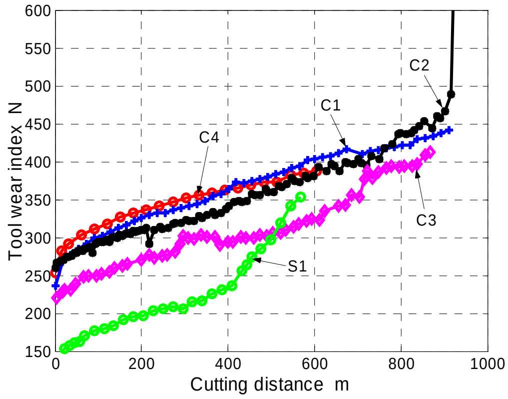


Figure 4: Estimated tool wear indices, $\hat{\beta}_0$, computed from measured cutting forces shown in Fig. 3

wear index" hereafter.

3.3 Experimental validation

To demonstrate the estimation scheme of tool wear progress presented above, simple cutting experiments are conducted. Table 1 summarizes common machining conditions. In this experiment, the cutting force is measured by using a three-component dynamometer (Kistler's 9257B).

Tool wear tests are conducted by repeating straight side cutting in the same machining condition, until the end of tool life is reached. Total five different machining conditions are tested as shown in Table 2. At every 10 to 30 meters, the cutting force is measured by using the dynamometer. The end of tool life is judged by considering the cutting force, the cutting noise, and the observation of tool damage by using a tool microscope.

Figure 3 shows the comparison of measured cutting forces in total five conditions. Note that, in this figure, the cutting force component in the direction normal to the feed direction is plotted, since the effect of tool wear progress is more significant in this direction than in the feed direction under such machining conditions.

In all the cases, the cutting force keeps increasing until the end of tool life is reached. However, naturally, the level of the cutting force when the end of tool life is reached is quite different for different cutting conditions.

Therefore, it can be easily seen that the end of tool life cannot be judged by simply observing the cutting force.

Then, as presented in Section 3.2, the tool wear index, $\hat{\beta}_0$, is computed at each check point. Figure 4 shows the comparison of tool wear indices in five cases. It can be observed that the variation in the tool wear index, β_0, for different machining conditions is much smaller than that in the measured cutting force. The end of tool wear is reached when the tool wear index, $\hat{\beta}_0$, reaches about 350~450 N in all the cases. Therefore, these experimental results validate that by introducing the tool wear index, the estimation of tool wear progress and the end tool life becomes much easier.

4. Cutting Force Control to Regulate the Tool Life

4.1 Determination of Target Profile of Cutting Force Control

Generally, the cutting force increases as the tool wear progresses. If the cutting force is controlled constant ignoring the progress of tool wear, the machining productivity would be critically sacrificed. To avoid it, the target level of cutting force control must be modified as the tool wear progresses.

In this paper, we propose a scheme to determine the target profile of cutting force control such that the given desired distance can be machined before the end of tool life is reached, with the minimum machining time.

Figure 5 illustrates the concept of the present control scheme. Assuming that the machining starts with a new tool, the first some distance is machined by using the initial feedrate profile. By measuring the cutting force at every check point, the rate of the increase in the cutting force can be estimated by using e.g. a simple linear extrapolation. When the estimated level of the cutting force to reach the end of tool life is given from some database or preliminary experiments, the cutting distance that can be machined before reaching the end of tool life can be estimated.

In the case of Fig. 5, the rate of the increase in the cutting force is estimated from cutting forces measured over the cutting distance 100m ~ 200m. The first 100m is ignored, considering that a rapid increase of cutting force is often observed when the tool is really new. Assuming that the end of tool life is reached when the cutting force reaches 400N, we can estimate that the end of tool life will be reached at the cutting distance of about 700m. Suppose that the control objective is to machine the cutting distance of 1000m. In this case, the target profile of cutting force control can be given as illustrated in Fig. 5, as a line connecting current and final levels of cutting force.

4.2 Feedrate Regulation for Cutting Force Control

As has been stated in Section 2.1, the proposed scheme assumes that the feedrate profile is scheduled such that the (predicted) cutting force is regulated constant by using the initial model given in Eq. (1). This feedrate profile is updated at every check point, where the updated β_0 and the new target of cutting force are given. To simplify the control law, we adopt the simplest modification of the feedrate profile: the entire feedrate profile is increased or decreased by a constant value. The detailed algorithm is given as follows:

(1) At the k-th check point, measure the cutting force, $F(k)$.
(2) Evaluate $\hat{\beta}_0(k)$ from $F(k)$ and given $X_1(k)$ and $X_2(k)$ by solving Eq. (1).
(3) Estimate $\hat{\beta}_0(k+1)$ at the (k+1)-th check point.
(4) For the target cutting force, $\widetilde{F}(k+1)$, evaluate the feedrate by solving Eq.(1) with $\hat{\beta}_0(k+1)$, $X_1(k+1)$ and $X_2(k+1)$.
(5) Compare the computed feedrate with the original one. Increase or decrease the entire feedrate profile between the k-th and (k+1)-th check points by this difference.

4.3 Experimental Validation

To demonstrate the effectiveness of the present feedrate control scheme, it is applied to simple straight cutting tests. Major machining conditions are the same as the one shown in Table 1. Other machining conditions are: the spindle speed is 16,000 min^{-1} (cutting speed: 301.6 m/min), the radial depth of cut is 0.3mm. The initial feedrate is 11,520 mm/min.

The straight side cutting is repeated until the end of tool life. The first 210m is machined by using the initial feedrate above. The check point is set at every 30m. At the cutting distance 210m, the feedrate control presented above is activated.

As a preliminary experiment, the same straight side cutting is repeated without activating the feedrate control (i.e. under a constant feedrate). As shown in Fig. 6 ("constant federate"), in this case, the tool reaches the end of tool life at the cutting distance of 619.4m.

Then, two tests are conducted. In the first test (referred to as Case 1), the target cutting distance is set at 1,000m. The target profile of cutting force control is determined by assuming that the tool reaches the end of tool life when the cutting force reaches 400N. Fig. 6 compares measured cutting forces with and without the feedrate modification. It can be observed that in Case 1, the tool life was extended to 875.9m. The error between target and measured cutting forces was at maximum 19 N, which shows good control performance of the present feedrate regulation scheme.

In Case 2, the target cutting distance is set at 400m, shorter than the constant feedrate case. The intension is to shorten the machining time as much as possible by increasing the feedrate, under the condition that the required cutting distance is safely machined. Fig. 6 also shows measured cutting forces in this case. The tool reached the end of tool life at the cutting distance of 695.2m. Although it was longer than expected (the cutting force finally reached about 500N), the target cutting distance, 400m, was easily cleared.

Figure 7 shows feedrate profiles in all the cases. In the constant feedrate case, the material removal rate was 20.7 cc/min. In Case 1, the overall material removal rate was 19.2 cc/min. By applying the feedrate regulation, the tool life was extended by about 250m, without sacrificing the machining efficiency significantly. In Case 2, the

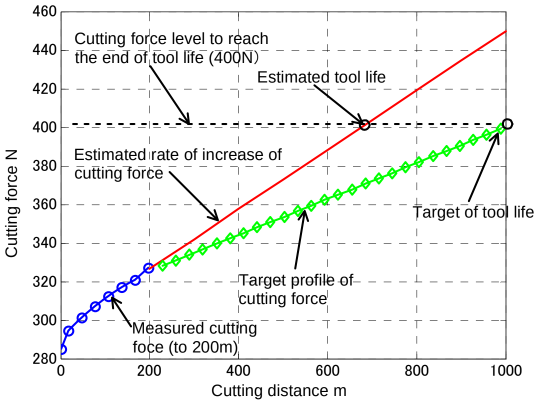


Figure 5: Concept of the determination of target profile of cutting force control

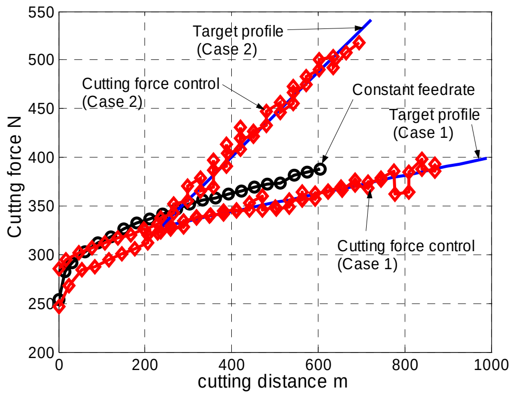


Figure 6: Measured cutting forces with and without feedrate regulation

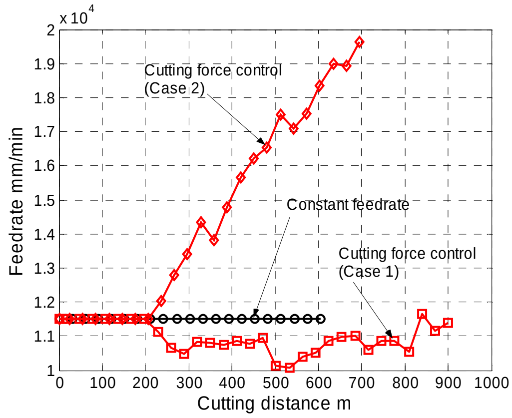


Figure 7: Feedrate profiles (corresponding to Fig.6)

overall material removal rate was 25.6 cc/min, significantly larger than the constant feedrate case.

5. Case Study

5.1 Experimental Description

The effectiveness of the present scheme is experimentally investigated in its application to the machining of more complex geometries.

Figure 8 shows tool paths used in this case study (Note that, to make the paths easily viewable, only 1/5 of the paths are drawn in this figure; the actual step-over distance is 0.3 mm, while this figure is drawn with the step-over distance of 1.5 mm). From the outermost path to the innermost path of contour parallel paths, the workpiece of the initial size of 150 mm × 66 mm is machined. The total cutting distance to remove one layer is 36 m. This is repeated to the following layers until the end of tool life.

Figure 9 shows the location of check points, as well as the curvature of the path where each check point is set. The check points are set on three tool path cycles on each layer. The cutting distance to reach each tool cycle is respectively about 13 m, 23 m, 33m, from the start point of one layer (each cycle is referred to as the tool path cycle 1, 2 and 3).

Major machining conditions are the same as those shown in Table 1. Other machining conditions are: the spindle speed of 8,000 min^{-1} (the cutting speed of 150.8 m/min), the tool extension of 18 mm, the axial depth of cut of 6.0 mm, and the step-over distance of 0.3 mm.

The cutting force in the XY plane, F_{xy}, is measured at each check point. In this case study, in order to show the feasibility of the present scheme in practical applications, where it is often difficult to install a dynamometer due to cost or geometric restrictions, we employ a lower-cost estimation scheme of cutting forces that has been presented by one of the authors [9]. In this scheme, four displacement sensors are installed near a front bearing of a spindle, such that the displacement of the spindle in X- and Y- directions can be measured, and then the cutting force imposed on the tool can be estimated. The estimation accuracy of this scheme has been experimentally studied by Sarhan et al. [9].

Until the cutting distance of 36 m, the machining is conducted under the initial feedrate profile. The initial feedrate profile is scheduled by using the initial prediction model of cutting forces, such that the cutting force is regulated constant throughout the entire path.

At the cutting distance of 36 m, the tool life is estimated by applying the scheme presented in Section 3. In this case study, it is estimated by assuming that the end of tool life is reached when the average cutting force reaches 400 N. The control objective is to reach the target cutting distance, 200 m. The target profile of cutting force control is determined as presented in Section 4.1. The feedrate profile is modified as presented in Section 4.2 at each check point. The machining continues until the end of tool life.

5.2 Experimental Results

Figure 10 shows cutting forces measured at the tool path cycle 1, 2 and 3 at each layer. On each tool path cycle, the cutting force is measured at 5~10 check points (as illustrated in Fig. 9), and their average is plotted in Fig. 10. When the feedrate regulation is not activated (i.e. when the initial feedrate profile is used until the end of tool life), the end of tool life is reached at the cutting distance of 108 m.

When the feedrate regulation is activated to modify the feedrate profile at each check point, the end of tool life is reached at the cutting distance of 226 m. It is over the target, 200 m, and the tool life is extended about twice compared to the case without the feedrate regulation.

6. Conclusion

In this research, we propose a long-term cutting force control strategy to regulate the tool life. The present scheme can be summarized as follows:

(1) The cutting force is monitored only at every "check point" set on the tool path. Since it does not require continuous full-time monitoring of cutting forces, a "cheaper" estimation scheme of cutting forces can be employed.

(2) During actual cutting, the feedrate profile is updated at every check point, such that the cutting force is regulated along the target profile. The target profile is given such that the desired cutting distance can be machined before reaching the end of tool life.

The effectiveness of the present approach is experimentally investigated by preliminary cutting experiments of hardened steel. More practical applications of the present scheme will be studied in our future research.

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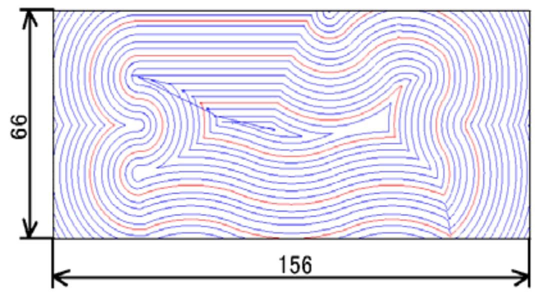

Figure 8: Tool center trajectories (red ones indicate the paths where check points are set)

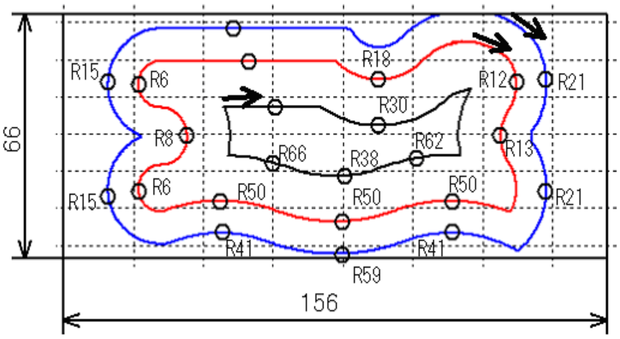

Figure 9: The location of check points (○ marks)

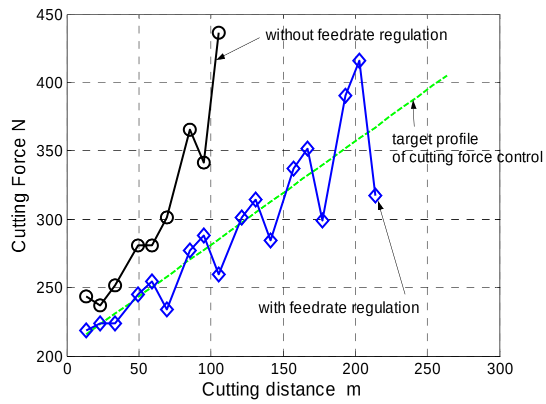

Figure 10: Comparison of cutting forces measured at check points with and without the feedrate regulation