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Constant Engagement Tool Path Generation to Enhance Machining Accuracy in End Milling

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Summary

During end milling with contour-parallel (CP) offset tool paths, the tool experiences a varying engagement with the workpiece, which leads to a variation in cutting forces. In a finishing process, such variation of cutting forces causes the degradation of machining accuracy and surface finish. Presented in this paper is to propose an algorithm to generate a new offset tool path generation scheme, which regulates a constant cutting engagement with workpiece in 2.5D end milling. By maintaining cutting engagement constant, the cutting force can be regulated approximately constant, thus minimizing the variation of tool deflection, and improving machining accuracy. The validity of the proposed tool path generation scheme is realized experimentally when is applied to a semi-finishing path in pocket milling. Potential benefits revealed from the experimental results include far less variation of cutting forces, and consequently enhanced machining accuracy without increasing the machining time.

Key words: Contour-parallel tool path, Offset, Constant engagement, Cutting force, Machining accuracy, End milling

1. Introduction

Contour-parallel (CP) offset tool path is extensively used in the machining of dies and molds. In practical machining with CP offset tool paths, when the basic mechanism of cutting is taken into account, it has been found that the cutter experiences a significantly varying engagement with the workpiece. As illustrated in Fig. 1, the cutter engagement can be defined by the parameter, the engagement angle, α. It can be easily realized that this varying cutter engagement, an inevitable consequence of CP offset tool paths, leads to a variation in the cutter load/chip load. Especially in a finishing process, such variation of cutter engagement causes an unavoidable fluctuation of cutting forces and tool deflection that may result in degradation of dimensional accuracy and surface quality of the workpiece to be machined [(1)].

To overcome such an inherent problem with CP offset tool pats, several efforts have been previously made. For instance, many researchers such as Terang et al.[(2)] introduced an adaptive feed rate control scheme to maintain a constant material removal rate in pocket milling. Most recently, some commercially available CAM software also adopt a simple feed rate optimization scheme so as to regulate the material removal rate at a constant level. In practice, however, the fruitfulness of these approaches relies solely upon the performance of a CNC machine that must ensure a high feed rate control performance in response to a frequent and quick change of feed rate. Even with the latest CNC machines, it is often the case that a desired control performance of cutting forces under an adaptive feed rate control scheme cannot be obtained due to a control error in feed rate. On the other hand, there has been relatively little or no initiative offered to explicitly modify the tool path itself to avoid the extreme variation of cutting forces in pocketing.

Iwabe et al.[(3)] proposed an idea that insertion of an additional circular arc at a convex corner can help keep cutter engagement below the prescribed limit. Yamaji et al.[(4)] introduced a tool path planning scheme to remove critical cutting regions by trochoidal grooving. These approaches are, however, more effective to avoid an excessive tool load mainly in rough cutting. Recently, Stori and Wright [(5)] proposed a unique approach, where an offset tool path is modified such that the engagement is always kept constant. However, their method can be applied only to convex contours. Furthermore, when it is applied to a spiral-out tool path, the proposed algorithm leaves leftover material, resulting in a further need of additional machining to remove excess corner material. Therefore, this approach may be justified in the application of rough cutting where efficient material removal is of the primary interest; it is, however, practically impossible to apply this scheme to a finishing process.

Keeping the possible drawbacks of the above approaches in mind, this research work introduces a new tool path modification scheme, which regulates a constant cutting engagement such that the final workpiece geometry to be machined can be preserved. Unlike the algorithm proposed by Stori and Wright [(5)], we propose to modify a semi-finishing path prior to a finishing path such that a constant engagement is maintained in the finishing path, while the geometry of the finishing path itself is preserved. Another attractive feature of the proposed algorithm is that it can be applied to any kind of two-dimensional contours comprising of convex and concave corners, whenever there exists a solution that geometrically meets the constant engagement requirement. The effectiveness of the proposed constant engagement tool path generation scheme is experimentally realized when it is applied to the pocket milling with a radius end mill.

2. Algorithm for constant engagement tool path generation

Given an initial planar curve representing the final contour geometry of the pocket to be machined, and an original contour-parallel (CP) tool path to achieve the desired contour, the main aim of the algorithm is to compute a new adjacent inner tool path such that the engagement angle can be regulated at a desired level on the machining along the final contour-parallel tool path. Figure 2 depicts the basic working principle of the proposed algorithm.

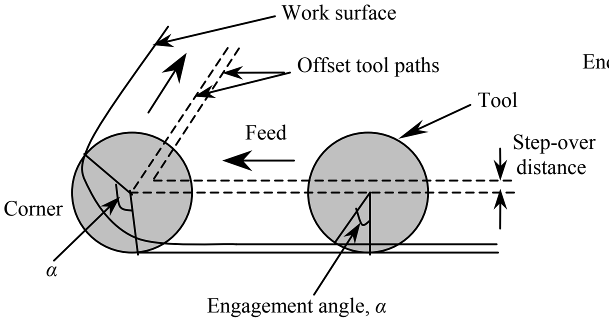

Figure 1 Definition of the engagement angle

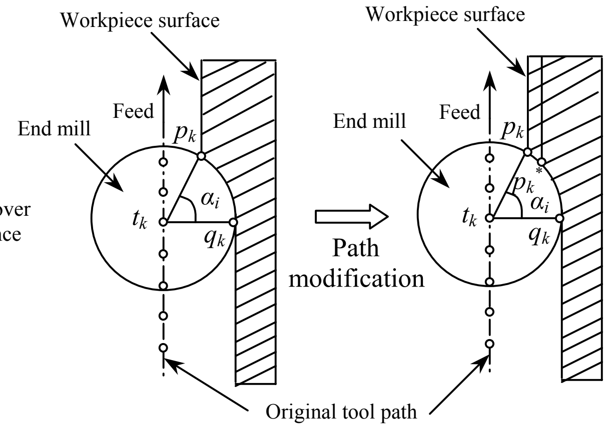

Figure 2 Concept of algorithm for constant engagement too path

Suppose that a trajectory of the tool center location in the finishing path, $t_k(i) \in R^2$ $(i=1,...,N_k)$, is given by offsetting the workpiece contour to be machined. Unlike the algorithm proposed by Stori and Wright, we do not modify this finishing path to preserve the workpiece contour to be machined. As illustrated in Fig. 2, the engagement angle, α_i, is defined by the tool center, $t_k(i)$, the intersection point of the tool circumference with the newly generated offset surface, q_k, and the intersection point of the tool circumference with the previously cut surface, p_k. The intension of the proposed algorithm is to modify the location of the intersection with the previously cut surface, p_k, to regulate the engagement angle. Since this "precut surface" is generated by the previous inner path (referred to as the semi-finishing path hereafter), the modification of p_k can be done by the modification of the trajectory of the tool center location in the semi-finishing path, $t_{k-1}(i) \in R^2$ $(i=1,...,N_{k-1})$. The detailed algorithm of the computation of $t_{k-1}(i)$ is given as follows.

- (a) For the given tool center location, $t_k(i)$, compute the intersection point of the tool circumference with the newly generated offset surface, $q_k \in R^2$ (see also Fig. 2).
- (b) Compute the intersection point of the tool circumference with the previously cut surface, $p_k^* \in R^2$, such that the engagement angle, α_i can be maintained at the given desired value.
- (c) Set $i=i+1$ and repeat the steps (a) and (b) till $i=N$.
- (d) Now by offsetting p_k^* $(i=1,...,N_k)$ toward the inside by the tool radius, the inner tool path $t_{k-1}(i) \in R^2$ $(i=1...N_{k-1})$ can be computed.

3. Experimental conditions

In this study, a series of machining tests was carried out to justify the effectiveness of the constant engagement (CE) offset tool path, developed by the proposed algorithm. In order to compare explicitly the performance of the proposed CE modified tool path with those of other conventional machining processes used in a finishing path, the whole machining tests are categorized into several machining strategies. The strategies are illustrated in the sections 4.1 and 4.2.

A pocket with different circular arc geometries shown in Fig. 3 was machined. A three-axis vertical high-speed machining center was used for the machining tests. Carbon steel (S50C, size: 70mm×40mm×20mm) without any hardening was used as work piece material. Throughout the experiments, an (Al, Ti) N-coated sintered carbide radius end mill (diameter: 10 mm, 4 flutes) was used. Down cut milling with oil mist as the coolant was carried out on the workpiece while the spindle speed, 2800 rpm and the axial depth of cut, 10 mm are maintained throughout the machining experiments. It is to be noted that before the semi-finishing path, contour parallel tool paths with the step-over distance (Std) of 0.5 mm were used in all the tests for rough machining. The proposed algorithm is applied only to the semi-finishing path (i.e. the second path from the outermost). During each cutting test, the cutting force was monitored and measured by using a three-component dynamometer. After the finishing path, the geometric error of the final workpiece contour with respect to reference workpiece surfaces was also measured by a coordinate measuring machine (CMM).

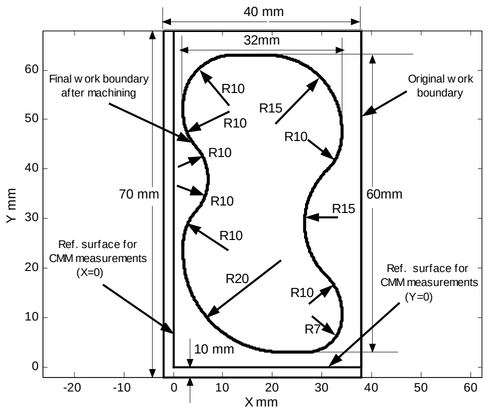

Figure 3 Geometry of the pocket to be machined

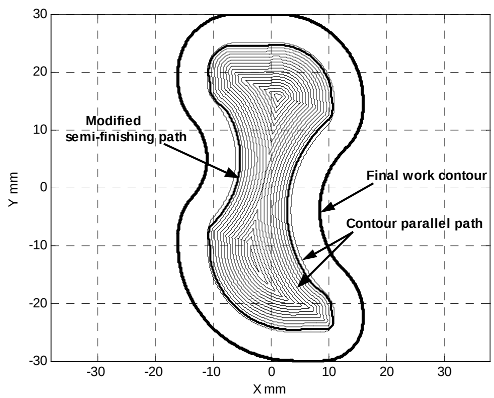

Figure 4 Modified constant engagement tool path

4. Experimental validation

4.1 Experimental comparison I (cases where the step-over distance is constant throughout the entire path)

Strategy 1 (CP, no finish) represents the case where original CP tool paths are applied throughout the entire machining. The step-over distance (Std) is 0.5 mm throughout. Strategy 2 (Modi CE) features the case where the proposed CE tool path generation scheme is applied to modify the semi-finishing path prior to the finishing path. Note that all the paths except for the semi-finishing path are the same as those in strategy 1. Fig. 4 shows tool paths used in Strategy 2, where the modified semi-finishing path is drawn in a thicker line. Notice that in concave corners, the semi-finishing path is modified to go “closer” to the finishing path, which results in a smaller engagement in the machining of the finishing path. On the contrary, in convex corners, it goes “further” from the finishing path, indicating a larger tool engagement in the finishing path. The proposed tool path generation scheme controls the engagement angle at a constant level in the finishing path by modifying the previous path. Finally, in strategy 3 (FR control (force)), an original CP path with variable feed rate is applied to the finishing path, while the feed rate is varied such that the cutting force is maintained constant throughout the finishing path. The feed rate profile is optimized based on the cutting force prediction model proposed by Otsuka et al. [(6)]. Note that the feed rate is constant at 1000 mm/min in strategies 1 and 2 throughout the entire path.

Figure 5 depicts a comparison of cutting forces for Strategies 1, 2 and 3. It can be distinctly observed that by applying modified constant engagement tool path (Strategy 2), the cutting force variation is significantly reduced. Notably, a greater reduction in maximum cutting force variation of about 75% and 40% can be revealed at the very sharp arc (indicated by “6” in Fig. 5) when compared with those in contour parallel path (Strategy 1) and feed rate control scheme (Strategy 3) respectively. Also, an approximately constant cutting force level except few peaks at transition points between circular arcs shown in Fig. 5 is visible.

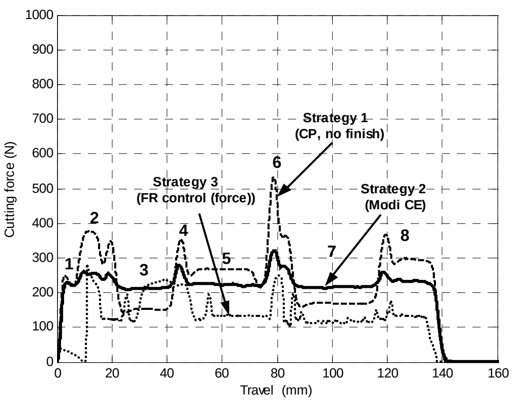

Figure 5 Comparison of cutting forces for Strategies 1, 2 and 3

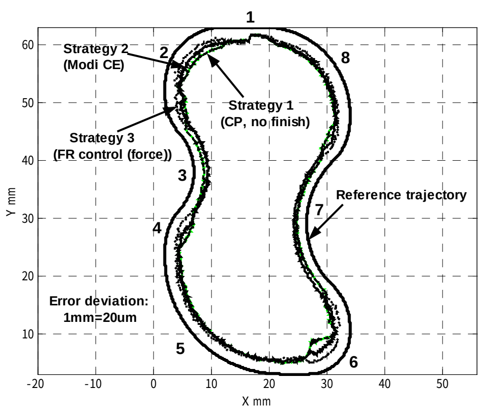

Figure 6 Machined surface trajectories measured by a CMM for Strategies 1, 2 and 3

Figure 6 illustrates geometric error profiles of machined workpieces with respect to the reference surface trajectory measured by a CMM. Figure 7 shows the same profiles drawn with the distance along the workpiece surface from the starting point indicated by “1” in Fig. 6. It is seen that in terms of variation of machined surface error, modified constant engagement tool path (Strategy 2) shows improved machining accuracy compared to that in contour parallel path. The variation in machined surface error is significantly less while contour parallel path and feed control scheme reveal a distinct variation over the cutting length as is observed in Fig. 7. The mean value of the surface error over each of six arcs is shown in Fig. 8. The numbers on the top of graphs indicate the corner name, corresponding to those in Fig. 6. By applying constant engagement path (Strategy 2) a remarkable reduction in mean surface error can be observed at concave corners of smaller radius of curvature (as indicated by "2" and "6" in Fig. 8) while comparing with that for contour parallel path (Strategy 1). It is also found that maximum variation of surface error along the whole workpiece contour is reduced by approximately 70% when comparing with that for contour parallel path (Strategy 1).

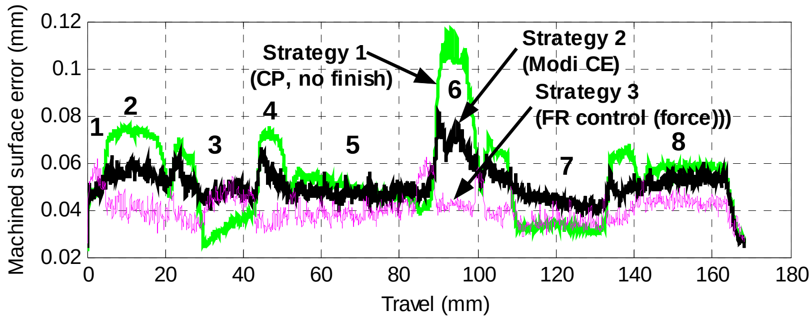

Figure 7 Machined surface error measured by a CMM for Strategies 1, 2 and 3

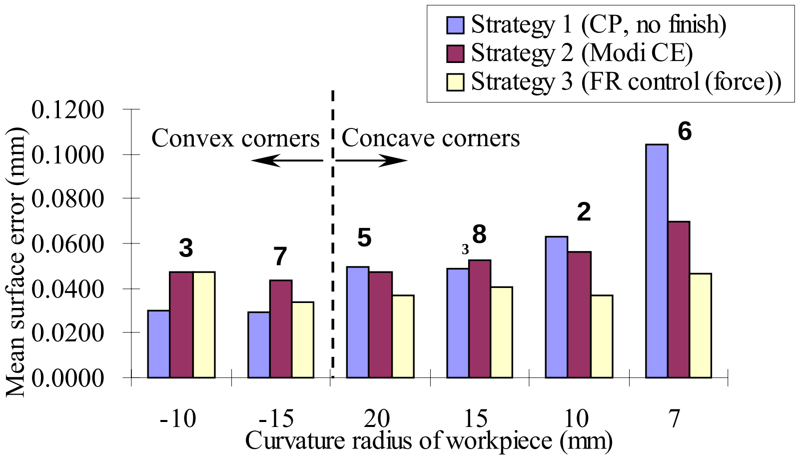

Figure 8 Variation of mean surface error with curvature radius of workpiece for Strategies 1, 2 and 3

On the other hand, as is also shown in Figs. 7 and 8, machining accuracy and variation of surface error can apparently be improved by feed rate control scheme (Strategy 3). However, it provides a significantly longer machining time as is shown in Fig. 9. Hence, by applying constant engagement tool path, the total machining time can be shorten by about 16.40% compared to feed rate control scheme.

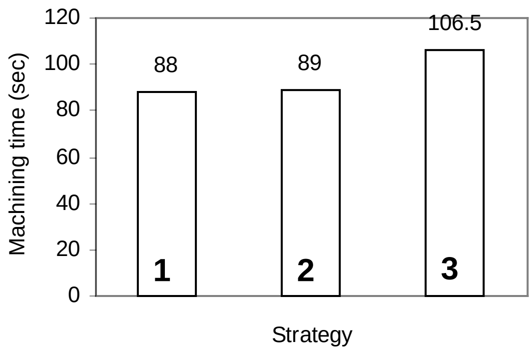

Figure 9 Total machining time for Strategies 1, 2 and 3

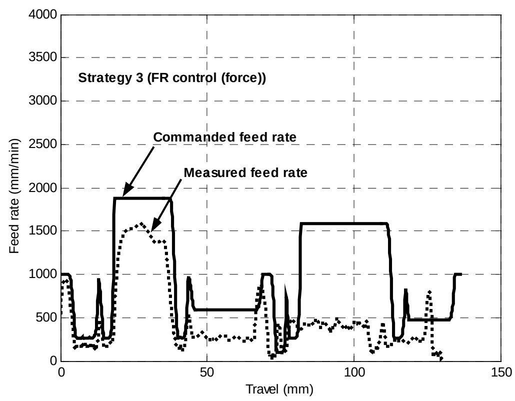

Figure 10 Comparison between commanded and measured feed rate for Strategy 3

The machining accuracy obtained by the feed rate control scheme totally depends on the feed rate control performance of the machine's servo controller. From the cutting test with feed rate control scheme, it is found that there is more distinct difference between commanded feed rate and measured feed rate as is shown in Fig. 10, which could also result in sort of uncertainty in achieving desired machining accuracy. Therefore, it can be inferred that the proposed tool path modification scheme can improve the machining accuracy in a more stable manner without sacrificing the machining time.

4.2 Experimental comparison II (cases where the step-over distance is smaller in the finishing path)

In this section, the proposed tool path modification scheme is applied to a contour parallel path where the step-over distance is smaller in a finishing path than previous roughing paths. Strategy 4 (CP, Std=0.1) corresponds to the case where an original CP path is applied to a finishing path with step-over distance (Std) of 0.10 mm. Note that the step-over distance for all the paths prior to the finishing path is 0.5 mm. Strategy 5 (Modi CE, Std=0.1) represents the case where the proposed tool path modified scheme is applied to the semi-finishing path in Strategy 4. The feed rate is constant at 1,000 mm/min throughout the entire path in Strategies 4 and 5. And, a CP tool path with variable feed rate is applied to the finishing path in the case of Strategy 6 (FR control (cut point)) where step-over distance is set as 0.1 mm. The feed rates are optimized in a way such that the feed per tooth at actual cutting point is kept constant [7].

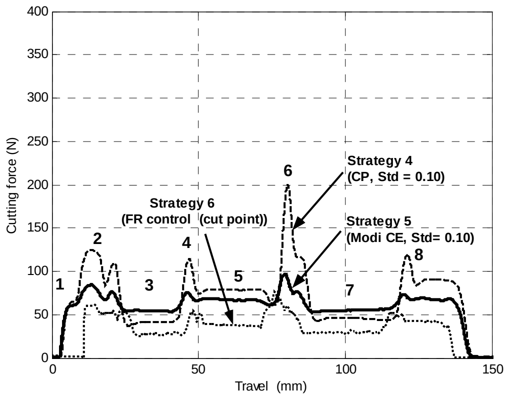

Figure 11 Comparison of cutting forces for Strategies 4, 5 and 6

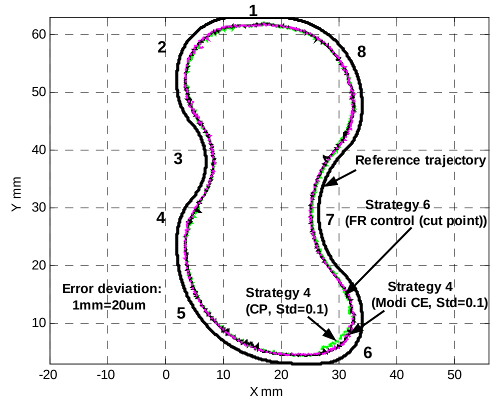

Figure 12 Machined surface trajectories measured by a CMM for Strategies 4, 5 and 6

Shown in Fig. 11 is the cutting force characteristic for Strategies 4, 5 and 6. From Fig.11, it is seen that lesser variation in cutting force along the tool travel-distance can be achieved by applying modified constant engagement path to a semi-finishing path prior to the finishing path with smaller step-over distant (Std=0.1mm). Again, maximum cutting force variation is reduced by about 75% at concave sharp corner (indicated by **6** in Fig. 11) compared to Strategy 4. This indicates that a steady state cutting operation may be maintained by applying modified constant engagement path in the finishing process.

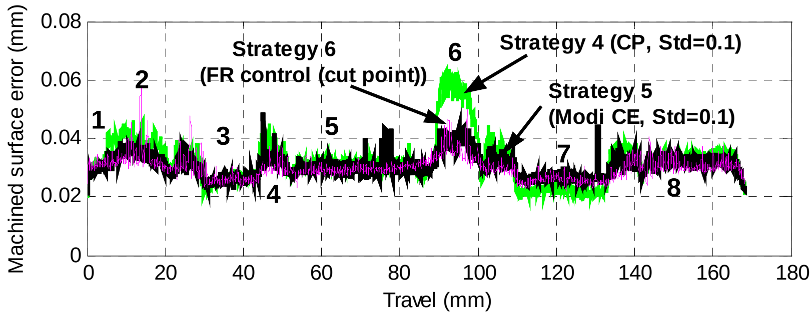

Figure 13 Machined surface error measured by a CMM for Strategies 4, 5 and 6

The comparison of geometric error profiles between the strategies, shown in Figs. 12 and 13, reflects that Strategy 5 provides improved machining accuracy, and gives almost as same machining accuracy as that in Strategy 7. However, by applying Strategy 5 (Modi CE, Std=0.1), a notable reduction of about 20μm in machined surface error can be achieved at the sharp concave corner (as indicated by “6” in Fig. 13) compared to Strategy 4 (CP, Std=0.1). Furthermore, Fig. 14 quantitatively describes a clear comparison of variation of mean machined surface error with respect to curvature radius of workpiece for the strategies. Comparing with Strategy 4, mean surface error becomes smaller for Strategy 5 (Modi CE, Std=0.1) when the tool approaches concave arcs of smaller radius of curvature (as indicated by “8”, “2” and “6” in Fig. 14). Additionally, about 62% reduction in maximum variation of machined surface error is obtained while comparing with that for Strategy 4 (CP, Std=0.1).

On the other hand, although feed control scheme (Strategy 6) seems to have as improved machining accuracy as that in Strategy 5 (shown in Figs. 13 and 14), its total machining time is, however, 12% longer than that for Strategy 5, similarly as the results presented in section 4.1. Furthermore, the feed rate control scheme is tremendously affected by the feed rate control performance of the machine tool, thus showing a drastic variation between commanded feed rate and measured feed rate values. Hence, the machining result described above manifests that by applying constant engagement tool path in the semi-finishing path prior to a finishing path with a contour parallel path with smaller step-over distance (= 0.1 mm), the machining accuracy of final work contour could be improved with shorter machining time.

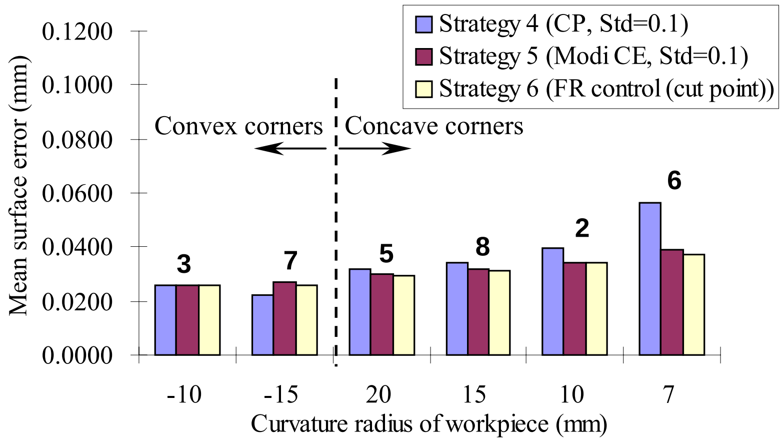

Figure 14 Variation of mean surface error with curvature radius of workpiece for Strategies 4, 5 and 6

5. Conclusions

In this study, an algorithm to generate a semi-finishing path such that a constant engagement angle is maintained through a finishing path is proposed. By applying the proposed scheme, the cutting force in the machining of finishing path can be maintained at a desired constant level, which naturally improves the geometrical machining accuracy in pocket milling. From the cutting tests with the proposed scheme along with different machining strategies, the following conclusions can be drawn:

a) Comparing with contour parallel path, using modified constant engagement tool path, the maximum variation of the cutting force in the machining of finishing path is significantly reduced (by 75%), which results in the significant reduction in machining accuracy (by 62%-70%). A similar result is obtained in both cases where the step-over distance is constant throughout the entire path, and where the step-over distance is smaller in the finishing path.

b) A critical problem with a feed rate control scheme for constant cutting force regulation is that it is often the case that a sufficient feed rate control performance cannot be achieved due to the performance limitation of servo controllers. Therefore, in practice, it is difficult to apply a feed rate control to a finishing process. Furthermore, any feed rate control scheme may significantly extend the machining time, while delivering little improvement in machining accuracy.

Acknowledgements

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