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Enhanced pocket milling strategy for improved quality

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Abstract

Computer aided part programming applications, available within state-of-the-art CAD/CAM systems, fail to generate high quality part programmes, in most cases due to a poor understanding of shopfloor operation and constraints. Usually, there is lack of manufacturing culture and expertise in these systems. The development of applications that implement sound machining practices and provide manufacturing expertise to part programmers is a key issue, if robust part programmes, requiring no editing at the shopfloor level and enabling the use of high material removal rates, are to be achieved. This paper presents an enhanced rectangular pocket machining strategy, based on the data derived from an experimental work on the effect of machining strategies and parameters on the quality of machined parts.

Keywords

CAD/CAM, computer aided part programming, milling, pocket machining

1 INTRODUCTION

High productivity and high quality milling, as measured through the machining time, set-up time, part programme editing time, rework cycles, scrap rates and achievable dimensions and tolerances, is determined mostly during the part programming phase, either manual or computer assisted.

L. M. Camarinha-Matos (ed.), *Re-engineering for Sustainable Industrial Production*

One of the most common operations in NC milling, is pocketing, both of rectangular or complex shaped contours, with or without islands. Pocketing operations are carried out with end mill/drills and require axial feeding and both, full immersion and non-full immersion cutting passes. This procedure is repeated several times until the full depth is attained. The number of passes is dependent on the allowable axial depth of cut. It follows that, together with tool geometry and material, cutting speed and feedrate, axial and radial depths of cut are key parameters that have to be defined before NC programme generation. While cutting speed and feedrate can be optimised / tuned by machine-tool operator, axial and radial depths of cut determines the actual structure of NC programme. The resultant toolpath is highly difficult to be edited at the shopfloor. Editing of an improperly generated part programme can be a time consuming operation, prone to errors and inconsistent part quality.

The work by Tarng (1993) has shown that during pocketing operations, radial depth of cut changes with cutting direction, traveling paths and position of path. To take that fact into account, and produce dynamically acceptable toolpaths in order to avoid chatter, conservative machining parameters are selected and the material removal rate reduced. A system was developed where feedrate is automatically adjusted to compensate for variable radial depth of cut. It was showed that a 20% decrease in pocket machining time could be achieved with this feed optimisation procedure. A chatter-free toolpath planning strategy to be used in CAD/CAM systems was also proposed by Weck (1994). Stability charts which contain chatter-free axial and radial depths of cut at practical cutting speed range are used to implement dynamically correct toolpath for pocketing.

Tlusty (1990) showed that internal corners change (increase) radial depth of cut, which has a strong effect on stability, reducing the quality of the part. Consequently, it is argued that pocketing strategies with internal corners should be avoided.

It can be concluded that, together with the above mentioned machining parameters, the machining strategy, as defined through the toolpath or distribution of machining passes required to clear out the material, in order to produce even a simple rectangular pocket, is of paramount importance.

Kline (1982) have shown that in end milling process, the cutting forces during machining produce deflections of cutter and workpiece which result in dimensional inaccuracies or surface errors on the finished component.

Milling mode (up or down-milling) is also an important parameter and has a key effect on part quality. Budak (1994) stated that in up-milling mode, cutting tool is pushed into the part side wall, increasing pocket width / length due to the end mill deflection, while in down-milling, tool deflection shifts the tool axis away from the pocket wall, which relieves the cut and decreases pocket width / length. However, during finishing operations the effect of the ploughing forces cannot be omitted. Consequently, even in the case of up-milling, when the radial depth of cut is very light, tool can deflect away from the pocket surface. One concludes that milling mode can affect part quality, particularly in finishing operations.

Commercial pocket cycles, available within state-of-the-art Numerical Controls and Computer Assisted NC programming systems can be classified into four broad categories: spiral-out, spiral-in, zig-zag, linear. In all these cycles, axial and radial depths of cut are fixed and cannot be modified during the elemental passes required to machine each pocket. Cutting speed and feedrate cannot be modified either, to accommodate for changes in radial depth of cut which arise at the end of each elemental pass required to enlarge the pocket. Toolpaths are distributed according to particular algorithms that consider only geometry-related constraints, such as, pocket geometry, tool diameter and specified stepover. They are considered as geometry-oriented pocketing cycles being not process-oriented and not technologically optimised. It was this understanding that induced the work of Tarng (1993), Weck (1994), and Tlustly (1990) above mentioned.

Our research work had a twofold objective: primarily to identify the effect of several machining parameters and pocketing strategies on part quality; secondarily to propose an enhanced and technology-oriented pocketing cycle to be implemented in a commercial CAD/CAM package.

2 EXPERIMENTAL WORK

The objectives of the experimental work were, the assessment of the effect of machining parameters and pocketing strategies on part quality and machining time. The standard *Mastercam* pocketing strategies were used in order to determine:

1. Influence of roughing milling strategy on machining time and dimensional accuracy.
2. Influence of finishing milling method on machining time and dimensional accuracy.

The machining tests were carried out on a CNC Hermle milling machine with a 12 mm diameter, 40 degrees helix angle, 3 fluted high-speed steel end mill. The work material was a 7079-T651 aluminium alloy. Machining parameters were determined from tool manufacturer machinability databases.

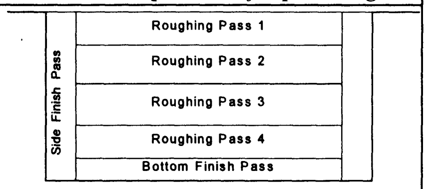
The pocketing strategy efficiency assessment is based on the comparison of pocket machining times and achieved dimensional accuracy. This experiment included the machining of a series of rectangular pockets, carried out with identical machining parameters, using the following *Mastercam* roughing strategies: one-way conventional (Owcv), spiral-in (Spi), spiral-out (Spo) and zig-zag (Zz). The sequence of operations to machine these pockets and the used geometrical machining parameters for each operation are presented in Table 1.

Table 1 *Mastercam* pocket strategies and elemental operations for pocketing

Machining parameters for each operation

Elemental Operations	*no.of passes*	*depth (mm)*	*radial depth (mm)*
pocket roughing	4	4.875	8
pocket bottom finishing	1	0.5	8
pocket side finishing	1	20	0,5
pocket dry passes	1	20	

Elemental operations for pocketing



Dimensional analysis was carried out on a DEA coordinate measuring machine (CMM) in order to reduce measuring time and to achieve a suitable measuring accuracy. Dimensions were taken both in the straight sections of the pockets and at the corners. The results are presented in this section.

Roughing milling strategy analysis

Figure 1 presents the effect of pocketing strategies on machining time. As expected, zig-zag strategy is the fastest strategy, being the lowest material removal rate achieved with the one way strategy.

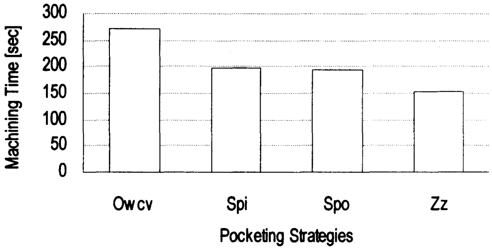


Figure 1 Influence of pocketing strategies on machining times (60x40x20 mm pockets).

Figure 2, displays the simulated *Mastercam* pocketing cycles, presents the geometries generated by roughing passes as calculated by the routines, and quantifies both the maximum stock values left for finishing passes and the dimensional deviations that were found in the corners of the pockets, for each one of the pocketing strategies.

Figure 2.a presents the stock geometry left for side finishing passes with the one way strategy. Maximum stock values of 6.07 mm (which greatly overlaps the programmed value of 0.5 mm) occur at the top right corner (TRC) and bottom right corner (BRC). These corners correspond to the ones where the tool retracts at the end of the extreme end straight cuts. The algorithm used by this *Mastercam* pocketing cycle seems not to be able to handle properly the situation. A suitable compensation is not carried out since the routine offsetted the pocket x side in the y direction with no change the endpoint x coordinate for the first and last moves. Similar error occurs in the zig-zag strategy, but since tool is interpolated along the BRC and top left corner (TLC), the material left by the improperly offsetted function, is removed. Identical limitation was found with the Heideinhain TNC 425 controller zig-zag strategy.

As a result, this error is propagated during the finishing operation. One can observe in figure 2.e and 2.f, that the highest dimensional deviations, with values ascending to 350 to 400 microns, can be found in TRC and BRC for the one way strategy, and BLC and TRC for the zig-zag strategy. It is shown that the highest dimensional deviations occur in the corners where the biggest stocks arise. These deviations can be explained as follows:

- The cutting forces have a direct influence on cutter and workpiece deflection and the resulting surface error, and are directly associated to the radial immersion. It is expected that higher radial immersion ratios will produce higher cutting forces and cutter deflections, and result in larger dimensional deviations. Therefore, the largest is the material stock left for the side finishing cutting pass, the largest will be the cutting forces, together with the tool deflection. It is believed that, to a certain extend, the geometrical deviations that were found in the machined pocket corner profiles can be associated to the stock geometry left for the side finishing pass by the roughing passes. In fact, in the pockets produced by zig-zag or one way strategies, the stock geometry left for the finish pass is not regular with peak stock values exceeding 10 times the defined value.

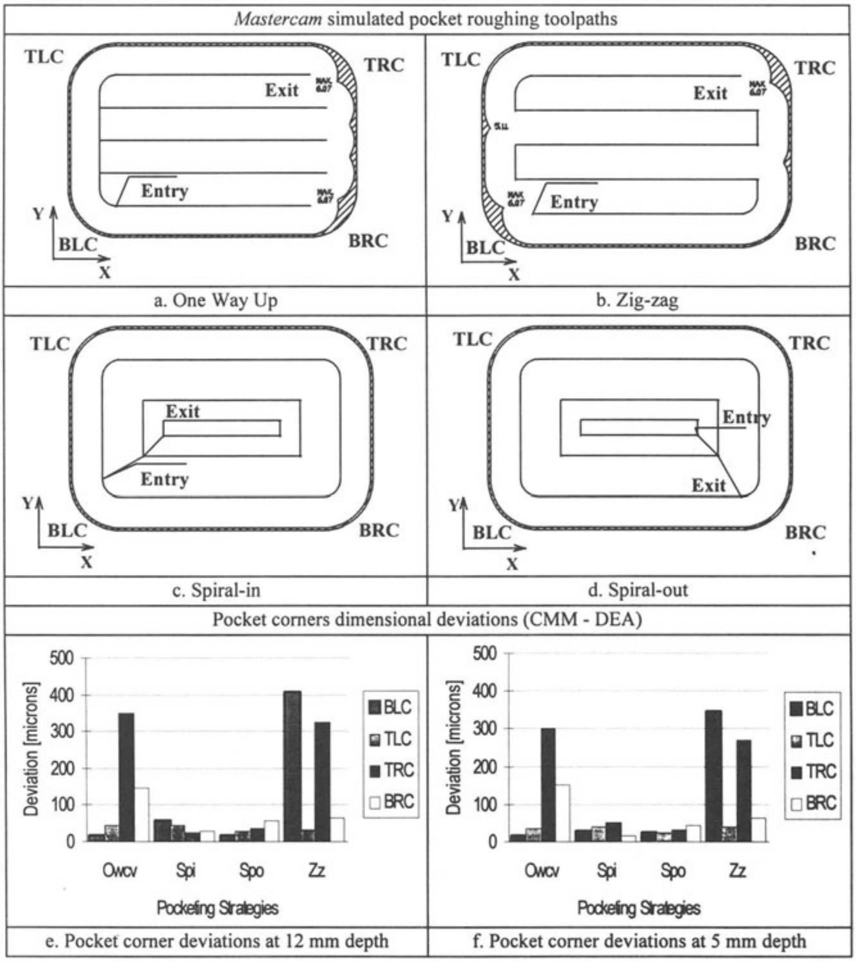


Figure 2 *Mastercam* pocketing roughing strategies and pocket accuracy analysis.

A good correlation can be established between the stock geometry left for the side finishing pass, the maximum stock values locations and the highest dimensional deviations observed in the pockets after the finishing operation.

For both spiral strategies, the stock left for the finishing passes is very homogeneous following the desired pocket contour. Consequently, the dimensional deviations after the finishing pass are the lowest among all pocketing strategies.

The comparison of the *Mastercam* roughing pocketing strategies, considering the criteria machining time and dimensional accuracy, allows the extraction of the following information:

1. The zig-zag strategy presents, as expected, the lowest machining time of all strategies.
2. The spiral strategies, can produce the pockets with higher dimensional accuracy, due to improper tool path compensation in the corners when the zig-zag strategy is used.
3. The maximum deviations observed in the areas close to the pocket corners are critical in the dimensional accuracy comparison, once these values are generally 8 to 10 times higher than those observed in the pocket basic dimensions.
4. A good correlation can be established between the finishing stock geometry left for the finishing pass and the final machined surface accuracy. The maximum deviations occur where the highest stock values left for finishing stock arise.

Finishing milling method analysis

The objective of this set of machining tests is the comparison of the finishing pass methods: up-milling method, and; down-milling method, and its influence on the final pocket dimensional accuracy and pocket surface quality. This experiment included the machining of a series of rectangular pockets, carried out with identical cutting machining parameters, except the milling method used in the finishing pass.

Figure 3 presents the influence of milling method on dimensional deviation. One can observe that lower dimensional deviations can be achieved if up-milling is used in the finishing pass.

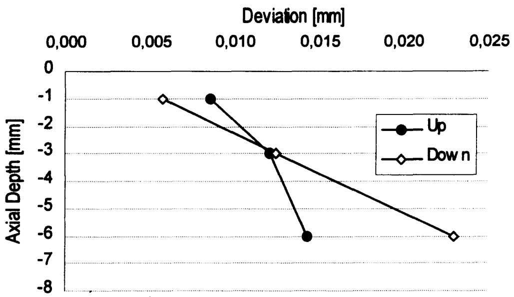


Figure 3 Influence of milling method on dimensional deviation.

The explanation for this behavior can be found once again on the effect of the cutting forces. During down-milling operations, the cutting forces produce cutter and workpiece deflection that shifts the cutter away from the nominal surfaces. Theoretically, these deflections result in pockets with smaller dimensions than desired, with the larger dimensional deviations being at higher axial depths. Usually, for roughing cuts, the opposite is equally true for up-milling.

For the down-milling experiments, the obtained surface profile error, along the axial depth, is as predicted. The pocket is smaller than desired and the larger errors occur at higher axial depths. However, in the up-milling method experiments, the observed surface error profiles have not the expected slope. This can be explained by the combined effects of the cutting forces and ploughing forces on the resulting cutter deflection:

- The interference between the tool flank and the machined surface results in the generation of ploughing forces acting in the radial and tangential directions, pushing the tool away from the surface. In down-milling, the effects of these ploughing forces are added to the ones derived from the cutting forces, deflecting the cutter and producing a surface with a high slope. In up-milling, the forces are applied in opposite directions. For light radial immersions, the ploughing forces effects are probably stronger than the cutting forces effects, which results in inverted cutter deflections and justifies the surface error profile found. The magnitudes of the dimensional errors in down-milling are larger than in the case of up-milling due to: the above mentioned combined effects of the ploughing and cutting forces; the magnitudes of the radial cutting force which are larger in down-milling; and finally, because in up-milling the tool is pushed into the material, which resists the deflection, while there is no resisting contact stiffness in down-milling, since the tool deflects away from the workpiece toward the air.

The analysis of the pocket dimensions that were obtained with the finishing pass methods, up-milling and down-milling, gave the following indications:

1. Higher dimensional accuracy is achieved if up-milling is used in the finishing operation.
2. For the range of feedrates considered (0.11 - 0.173 mm/tooth), the milling method had no influence on the pocket walls surface quality.
3. As expected, the milling method (up/down) have shown no influence on the pocket machining time.

As a conclusion of the experimental work, one can derive the following rules to be applied:

1. Spiral-in and spiral-out strategies will produce the "best" roughing quality with a marginal increase in machining time, when compared with zig-zag pocketing.
2. Spiral-in and spiral-out strategies create the best conditions for a smooth finishing operation and enable the control of roughing milling mode (up/down).
3. Up-milling mode should be used for finishing the pocket side walls.

However, if we take into consideration the work by Tlusty (1990), the spiral-out strategy should be discarded, since systematic internal cornering is present. This fact determines that even if we select, for the cuts preceding the corner, one half-immersion pass, there will be a time during the corner where the tool is slotting. Since radial immersion has a strong effect on stability, one should avoid systematic changes from non-full immersion to full immersion conditions (Budak,1994).

The spiral-in strategy seems to be the best strategy for rectangular pocketing. In its very basic structure, spiral-in includes a frame cut followed by several offsetted contouring cuts (towards pocket center). The first frame cut is carried out in full immersion mode (slotting) and the remaining contouring cuts in non-full immersion as determined by the specified and controllable stepover. This structure of the spiral-in routine, as implemented in CAD/CAM systems, entails a strong disadvantage. A unique axial depth of cut and feedrate has to be programmed for both full immersions and non-full immersion cuts. It follows that, to avoid chatter, conservative parameters are used in pocket machining. The improvement of both, quality and productivity pocket milling can be achieved if we split the cycle in two different routines, one for slotting (the outside frame) and the other for spiral-in in non-full immersion cutting, each one with a different set of machining parameters, which are dependent of tool diameter and workpiece material.

3 ENHANCED POCKET MILLING CYCLE

As a result of the limitations of the existing strategies, that were found in the experimental work, a new Enhanced Pocket Cycle was developed for *Mastercam* software environment, enabling the manufacture of the pocket using the following sequence of machining operations: 1. Pocket Framing; 2. Pocket Roughing; 3. Pocket Finishing; 4. Pocket Additional Finishing (optional), and; 5. Pocket Bottom Finishing.

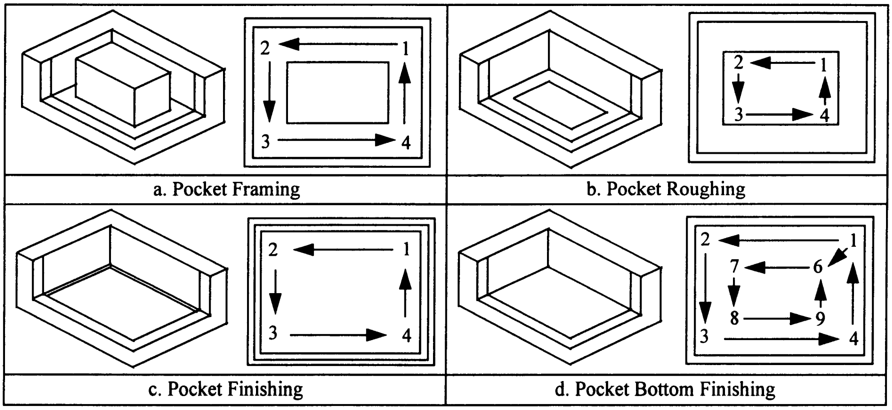


Figure 4 Enhanced sequence of operations for pocketing (passes at the final depth).

The new enhanced strategy is independent of tool diameter and workpiece material.

Pocket framing operation consists in slotting the periphery of the pocket in as many passes as required. The tool passes through the positions marked 1, 2, 3, 4 and 1 along the pocket periphery, as shown in Figure 4.a. The suitable cutting parameters for this specific operation (the most restrictive case) are used.

Considering that full immersion cuts are carried out, axial depth of cut can be reduced, only for this section of the pocket. This operation is followed by pocket roughing, which consists in machining the central area in as many passes as required, using a spiral-in strategy. If up-milling is the suitable method, clockwise direction is required and the tool passes through the positions marked 1, 2, 3, 4 and 1, as shown in Figure 4.b. Otherwise, the cutter follows these positions in the reversed order. The pocket dimensions determine the number of cutter motions required at each depth. The optimised cutting parameters for this operation can be used. Radial immersion can be half of the tool diameter in order to avoid the simultaneous use of up and down-milling methods. Axial depth of cut can be increased (comparing with the one used in the preceding frame cutting), decreasing the required number of passes.

The pocket finishing operation aims the finishing of the pocket side walls. The suitable milling method determines the direction (CW/CCW) in which the finishing pass is performed. The passes along the pocket boundaries follow the toolpath as shown in Figure 4.c. If up-milling is the suitable method, clockwise direction is required and the tool passes in order through the positions marked 1, 2, 3, 4 and 1. Otherwise, the cutter follows the positions marked in the reverse order. The optimised cutting parameters for this specific operation can be used also.

Additional finishing operation (dry passes) can be used for further improvement of the pocket side walls accuracy. The direction (CW/CCW) in which the dry passes are performed is similar to the finishing passes direction. This machining operation is optional, and the suitable number of dry passes (0, 1 or 2) are performed, as determined by shopfloor expertise built-in the system.

Finally, pocket bottom finishing operation is carried out in order to finish the pocket bottom, using the spiral-in strategy and the optimised machining parameters (Figure 4.d).

The enhanced rectangular pocketing cycle was implemented in the *Mastercam* milling package. The new cycle included both, the new operations sequence, partially driven by CAD data and complemented by on-line user input, and an optimised spiral-in toolpath. With this enhanced cycle, CNC programmes can be generated with "local" optimisation of machining parameters for several elemental machining passes which are required to complete the full cycle.

The developed application, although implementing a complexer toolpath, through the splitting of the initial spiral-in cycle, still guarantees a reduced effort in the user input. Machining expertise is also provided to the user, since it is built-into the system. A programmer with a lower process knowledge can use the system and still providing improved quality part programmes.

4 CONCLUSION

An enhanced rectangular pocket cycle was proposed. The improvements achieved with the new cycle can be summarised as follows:

1. Use of only one routine to apply an optimised sequence of operations to produce a pocket (framing, spiral-in roughing, finishing, additional finishing and spiral-in bottom finishing).
2. Use of a complete optimised set of machining parameters for each one the elemental operations, automatically determined by the system.
3. Use of an optimised spiral-in machining strategy for pocket roughing operation and pocket bottom finishing operation.

4. The reduction of pocket machining time can be achieved together with the control of chatter.

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6 BIOGRAPHY

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