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Title

Scalability of Tool Path Planning to Micro Machining

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Abstract: Micromachining applications have received increased emphasis in recent years with the advent of new precision manufacturing applications which have stringent requirements for surface and edge finish. One of the main concerns in micromachining is burr formation which can incur high production costs due to time-consuming deburring operations. Although deburring operations are commonly carried out in macroscale milling, in micro machining they can be difficult to use. Deburring processes can destroy delicate microfeatures and are usually unfeasible at the micro scale. For this reason, the utilization of burr minimizing machining tool paths is desirable. Optimum tool paths minimize burr formation while satisfying surface quality requirements, dimensional tolerances, and cycle time constraints. A new concept for micro end milling tool paths is developed. An integrated performance index using the Taguchi method is introduced to optimize the main microscale end milling process outputs: surface quality, edge accuracy, burr formation, and time constraints. In addition, the concept is applied to macroscale milling and its scalability down to the micromilling scale is studied.

TOOL PATH PLANNING CONCEPT

In the past, different theories and methods to reduce burr formation in the face milling process were developed in the Laboratory for Manufacturing Automation at the University of California at Berkeley. In this research, the basic approach of the tool path planning concept is to divide the pocket milling problem into three separate problems:

1. Outer contour following pass
2. Inner material removal
3. Inner features

All three parts of the pocket machining process are interrelated by the cutting time, which is a very important parameter since it determines the manufacturing productivity. It is assumed that, except for the cutting time, the three tasks are independent, meaning that the parameter setting of inner material removal does not influence the top burr size. Since different characteristics (each requiring different parameter settings) have to be optimized in each part, it is possible to adjust the parameters specifically for respective characteristics. For example, if a certain cutting speed results in the least amount of top burr formation, but a different cutting speed produces the best roughness of the bottom surface, the inner material will be removed with a different cutting speed than the outer contour pass uses. In order to keep the investigation manageable, the cutting process is not divided into rough or finishing operations, since it is not practical for the machining of micro features.

A. INNER MATERIAL REMOVAL

The inner material of a pocket is the one that is removed neither by the outer contour pass nor by a possible window framing cut for inner features. The volume of the inner material is in most cases larger than the material volume that is removed in the other passes, meaning that it has the biggest influence on cutting time. On the other hand, inner material

removal has no influence on side walls or edges of the pocket. Burr formation, as well as the edge finish and dimensional accuracy on the sides of the pocket, do not need to be considered. Only two attributes are to be taken into account during the planning of the tool path for the inner material removal: Surface roughness (precision) and dimensional accuracy regarding the depth of the pocket.

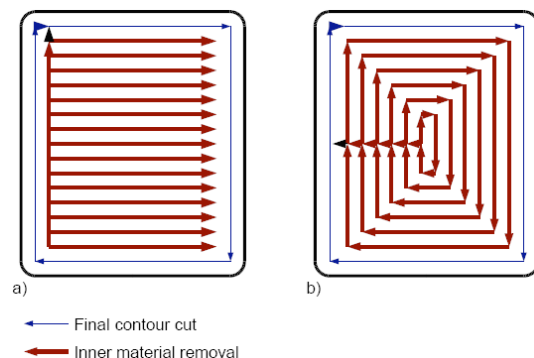


Fig. 1 Inner and outer tool paths: a) direction parallel (zig) path, b) contour parallel tool path

A relatively large number of parameters are available for optimizing the attributes. One of the most interesting parameter regarding the tool path planning is the milling strategy or type of tool path. Several different strategies exist, the most important ones being: Direction parallel (zig-zag); direction parallel, uniform orientation (zig); contour parallel (contour following), out; contour parallel (contour following), in; and spiral paths.

The tool paths investigated in this research are the direction parallel with uniform orientation (Fig. 1 a) and contour parallel from the inside to the outside (Fig. 1 b). The zig tool path has the advantage of reduced changes in the feed direction. During those changes, the radial tool engagement or radial depth of cut increases significantly, which can cause tool deflection and deterioration in the bottom surface [1].

The contour following tool path has the advantage that few (if any) tool retractions are necessary. In contrast to this, a tool retraction is necessary in zig cutting after every direction parallel cut, because the cutter has to be moved to the starting point of the next direction parallel pass. On the other hand, zig toolpaths are easier to generate while contour parallel paths have to be computed using either of the three approaches: pixel-based, Voronoi diagram, or pair-wise offset approaches [2].

B. OUTER CONTOUR FOLLOWING PASS

The outer contour following pass is the final pass along the contour of the pocket, as depicted in Fig. 1. During this final pass, the side walls of the pocket are generated. The attributes influenced in this phase are the top burr, the dimensional accuracy, the surface finish of the side wall, and the bottom surface. In normal pocket milling two types of burr can occur: Top and bottom burr. Only the top burr is influenced by the final contour pass.

The dimensional accuracy and edge finish are difficult to measure, and therefore neglected in this research. However, it is obvious that for instance a high width of cut and high chip load would result in a stronger displacement of the tool due to the high forces, and therefore, less accuracy. The tool path planning concept provides a feasible means of improving those attributes as well. The bottom surface generated during this phase is usually small compared to that generated during the previous cutting operation.

C. INNER FEATURES

In some cases, pre-existing holes are in the workpiece; when a workpiece was casted, for example. When the cutter machines over the edges of these holes, the burr formation mechanism is similar as in a face milling operation and bottom burrs occur on these edges. Similar burr minimization techniques as developed for face milling can be applied. The basic approach of this concept is to use an inverted window framing cut. A small amount of material is removed first such that subsequent passes don't produce any burrs. In the original window framing concept, exits of the cutting edge during tool engagement are avoided by moving the cutter along the outer edges of the workpiece during the first pass using only down-milling [3]. Furthermore the tool uses a rotational entrance and by doing so avoids exits of the cutting edge during the tool entrance.

In the inverted window framing cut, the tool enters the workpiece from inside the hole using a rotational tool entrance, as displayed in Fig. 2. It then traverses along the edge of the hole, removing a certain amount of material. When the tool reaches the entrance point again, it starts to remove the inner material. Since the cutting edge does not exit the workpiece during tool engagement, exit burrs are avoided in all subsequent passes.

D. INTEGRATED PERFORMANCE INDEX

With the integrated performance index the Taguchi Method provides a useful tool to integrate different characteristics into one statistical value for optimization. The integrated

performance index is the sum of the signal to noise ratios of the different characteristics for the different parameter settings by using weights to specify the importance of each of them.

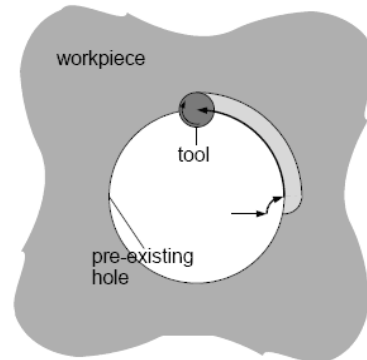


Fig. 2 Inverse window framing cut

To assess parameter settings, the integrated performance index of the Taguchi Method is used. The signal to noise ratios η of the different characteristics (e.g. cutting time, surface roughness, top burr height, and bottom burr height) are weighted and summed [4]. The performance index which – when minimized – leads to the best parameter combination with given weights is expressed as

$$\xi_i = \alpha\eta_{time,i} + \beta\eta_{roughness,i} + \gamma\eta_{topburr,i} + \delta\eta_{bottomburr,i} \quad (1)$$

To find the best parameter setting it is feasible to use a table with all possible parameter combinations to calculate the estimated values of the different characteristics. These values are combined with the help of equation (1). The result is a table containing the parameter permutations, the signal to noise ratios and the performance index.

The parameter optimization concept developed in the previous sections can be applied on any pocket end milling process. It is valid regardless of the size of the cutter, as long as the pocket is large enough to distinguish between inner material removal and outer contour passes. In micro machining the focus on the requirements is usually different. This can be adjusted by using the weight ratios of the integrated performance index.

In conventional pocket machining, sometimes deeper pockets are machined using a rough and finishing cut. In those cases, this concept (with some alteration) can still be applied. The inner material removal and the inverted window framing cut of this concept would be used in the finishing operation, while the rough cutting operation could remain the same.

EXPERIMENTAL RESULTS

In order to verify the applicability of the tool path planning concept and to get further insight into the process of micro machining, experiments were conducted to investigate the influence of different parameters on the surface roughness and the burr formation in conventional milling, as well as in

micro machining. For the evaluation of the surface roughness the ISO ten point height parameter R_z is used. Because of the high variability of burrs there is no standardized method of burr measurement available. In this research the burrs are measured optically using an optical coordinate measurement machine (OCMM).

E. SURFACE ROUGHNESS IN CONVENTIONAL CUTTING

Fig. 3 shows the roughness results from the conventional experiment. Error bars are included into the diagram. They indicate a confidence interval of 70% calculated assuming Gaussian normal distribution of the results. The specific cutting method had the strongest impact on the surface finish. With higher feed rates, the surface roughness becomes rougher as well, as seen in Fig. 3. On one hand, this is due to the higher chip load, which results in higher forces and a higher tool deflection. On the other hand, each cut of the cutting edge produces a small groove because of spindle deflection, misalignment, and the non-straightness of the minor cutting edge. Larger distances between two cuts result in deeper grooves. No significant interaction between the cutting method and the feed rate can be observed, but the surface produced with up milling is better than with down milling.

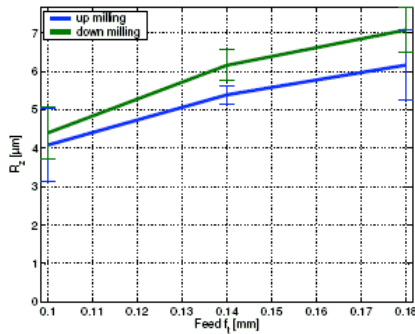


Fig. 3 Influence of feed per tooth on surface roughness in conventional up and down milling

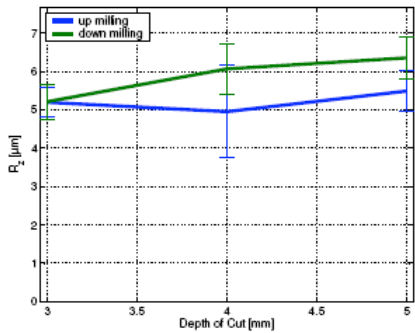


Fig. 4 Influence of the depth of cut on surface roughness in conventional up and down milling

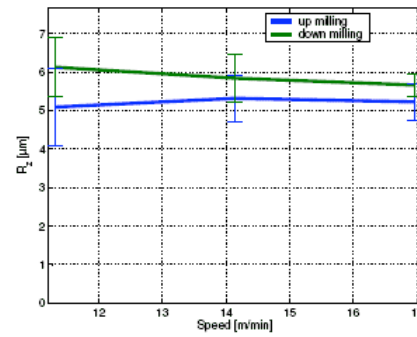


Fig. 5 Influence of cutting speed on surface roughness in conventional up and down milling

A higher depth of cut results in a higher surface roughness (Fig. 4), which is probably due to tool deflection from higher cutting forces. For up milling, no significant difference can be seen. The roughness at 4 mm depth of cut is smaller than for the other two levels, but the large deviation of this value, represented by the error bars, shows that this result could be due to an outlier. The influence of the cutting speed is very small (Fig. 5).

For down milling, higher cutting speeds result in a slightly better surface finish. In up milling no such influence can be seen. Furthermore, a multiplicative model similar to the models by Adams and Boer [5] and Tipnis et al. [6] is calculated. This model includes all interactions calculated using the Taguchi orthogonal array.

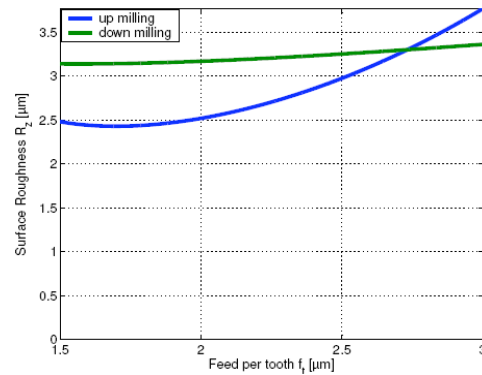


Fig. 6 Influence of feed per tooth on the surface roughness in micro milling

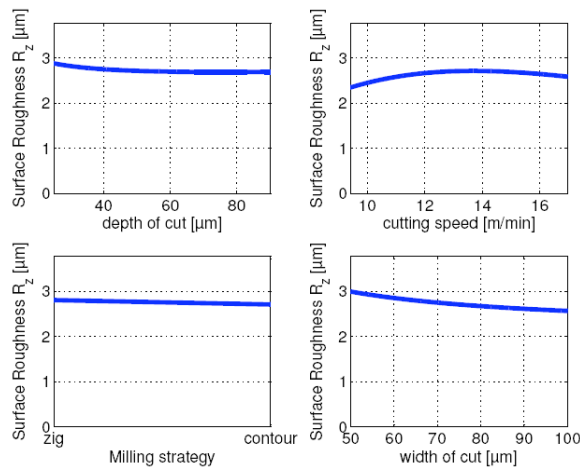


Fig. 7 Influences of the depth of cut, cutting speed, milling strategy, and the width of cut on the surface roughness in micro machining

F. SURFACE ROUGHNESS IN MICROMACHINING

For the investigation of the surface roughness in the micro experiment, a model was formulated. The model is based on the multiplicative models by Adams and Boer [5] and Tipnis et al. [6].

The influence of the feed and its interaction with the cutting method are displayed in Fig. 6. The feed has a far stronger influence on the surface roughness during an up milling operation, while in a down milling operation almost no influence can be seen. The intersection between the two lines is at higher values, meaning that up milling generally leads to a better surface finish. The depth of cut does not seem to have a large influence on the surface roughness, as can be seen in Fig. 7. No significant difference between zig cutting and contour parallel cutting can be observed. The cutting speed has a higher influence. It shows a maximum roughness at about 14 m/min. Also the width of cut has an influence that is not negligible. It is interesting to note that with a higher radial tool engagement, the surface roughness is lower.

Since the width of the cut has no influence on the chip load, it does not affect the cutting force. On the other hand a higher width of cut leads to less passes of the tool. In return this leads to fewer steps on the surface.

Lee and Dornfeld [7] achieved similar results regarding the influence of the feed. But in that work, no distinction between up and down milling could be made, because only slots were milled. Therefore up and down milling occur at the same time. The surface finish in that research was about two to three times better than here. This can be explained by the increase in machining steps due to the subsequent passes. In slot milling the whole slot is machined in one single pass. Therefore, tool elongation and machine accuracy do not influence the roughness. Wang et al. [8] did micro machining experiments with regard to the surface roughness. They determined that the feed had a strong influence, but the influence of the cutting speed and the interaction of both is even

stronger. In some cases, a small feed per tooth even had a negative influence on the surface roughness. In their experiments, the feed per tooth used was below 1 μm while the spindle speed was above 60000 rpm. Small feeds can cause a transition from cutting to plowing where no chip is formed, hence increasing the surface finish.

G. COMPARISON OF SURFACE ROUGHNESS IN MICROMACHINING AND CONVENTIONAL CUTTING

The feed per tooth has a similar effect in micro machining as in macro machining. Thus a small feed per tooth usually results in a better surface finish. This is commonly explained by the smaller distance between two pitch marks, which results in a smaller depth of the pitch marks. Also, the influence of the feed is stronger in up milling than in down milling in both micro and conventional machining. In both cases the roughness value decreases as the width increases. This may be due to the machine tool accuracy between passes, because a smaller width of cut means more passes of the tool and therefore more steps. The milling strategy does not have a strong influence in the micro nor in the macro milling process.

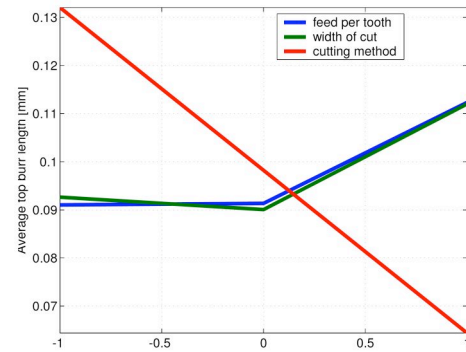


Fig. 8 First order effects of the feed, the cutting method, and the width of cut on the top burr formation in the conventional experiment

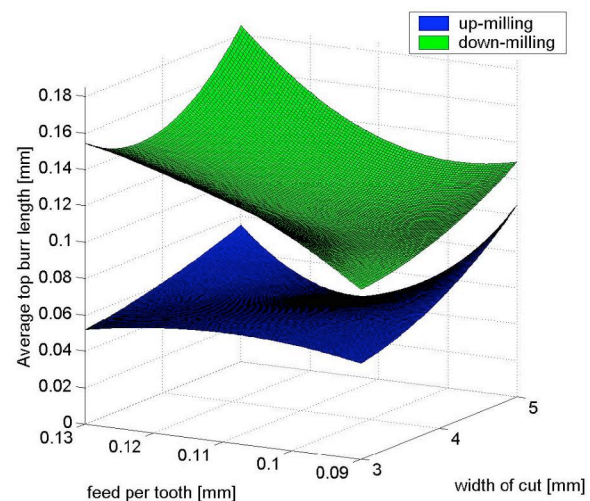


Fig. 9 Top burr of conventional experiment: Influences of feed, width of cut, and cutting method

H. BURR FORMATION IN CONVENTIONAL CUTTING

The low number of parameters for the conventional burr ex-

periment permits a full factorial analysis, meaning that all permutations of parameter levels are investigated. Fig. 8 displays the first order effects of each parameter. This means that interactions are neglected in the diagram. The cutting method has the strongest influence in this investigation (1: up milling, -1: down milling). To explain the influence of the cutting method the difference between up milling and down milling regarding the burr formation has to be explained.

In down milling the cutting edge enters the workpiece with a large radial depth of cut. As the edge proceeds through the material a chip forms, which flows to the top because of the helix angle of the cutter. The burr which results from this chip flow increases as the cutting edge proceeds through the material. When the cutting edge exits the material on the side wall of the finished workpiece a large chip is generated, which can stick to the top edge of the workpiece. In contrast to this, in up milling the cutting edge enters the workpiece on the surface which will remain as the side wall of the pocket. A chip is generated as the cutting edge removes material on its pass. But the chip at the entrance is quite small. It is biggest when the tool exits the workpiece. Therefore, the burr at the tool entrance is quite small and the big burr at the tool exit will be removed in the subsequent cut.

As seen in Fig. 9, a strong interaction exists between the feed and the cutting method. With down milling, a high feed results in large burr formation, while with up milling, no big influence of the feed rate can be seen. To explain this, the difference between the two cutting methods has to be taken into account. In down milling the size of the chip is strongly dependent on the feed per tooth; therefore the top burr gets bigger with higher feed per tooth. In up milling, the top burr, which will remain after subsequent cuts, is generated when the cutting edge enters the workpiece. Since the actual chip load at the beginning is very small, effects of the feed are small, too. And this burr is not as dependent on the feed per tooth as the top burr generated by a down milling operation.

I. BURR FORMATION IN MICROMACHINING

As mentioned above, a model as proposed by Tipnis et al. [6] and Adams and Boer [5] was calculated to analyze the influence of different parameters.

Fig. 10 displays the influence of the feed per tooth and the width of cut on the top burr formation. The depth of cut and the speed in this diagram are $40\ \mu\text{m}$ and $13\ \text{m/min}$, respectively. It is interesting to notice that the feed has a negative slope, especially with respect to up milling. This means that at higher feeds the top burr gets smaller. The reason for this is the plowing effect associated with Poisson bulging of the material, which takes place with a small uncut chip thickness, since the top burr is not generated by shearing, but by material which is pushed to the top. Therefore a Poisson burr occurs. Especially in up milling, the uncut chip thickness is very small at the beginning. During this first cutting phase the final top edge of the pocket is generated. When plowing instead of cutting takes place, the material is strongly compressed. Furthermore, it can be seen in Fig. 10 that in down

milling the width of the cut has a strong influence. This is due to the cutting edge entering with a high chip load in down milling operations. As the cutting edge proceeds through the material, a chip is formed which in the end hinges at the top edge. In down milling the burr produced in the end is the final top burr, meaning that as the chip formation time increases, the burr size increases as well. Therefore, a larger width of cut results in a larger burr.

Fig. 11 displays the influences of the depth of cut and the cutting speed on the top burr formation. The feed per tooth and the width of cut are kept constant in this figure at $2.25\ \mu\text{m}$ and $50\ \mu\text{m}$ respectively. The cutting speed has no significant influence on the burr height. A higher depth of cut leads to a smaller top burr. Especially in down milling, the burr size increases when the depth of cut decreases.

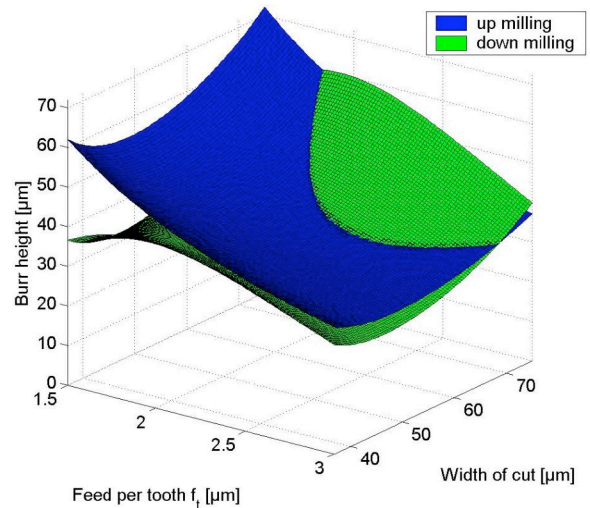


Fig. 10 Influence of feed per tooth and width of cut on the burr height in micro machining

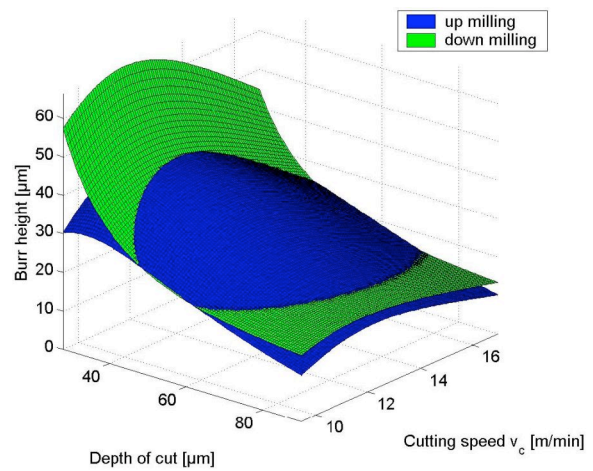


Fig. 11 Influence of the depth of cut and the cutting speed on the burr height in micro machining

J. COMPARISON OF THE BURR FORMATION PROCESS

With respect to the depth of cut, the burrs in the micro experiment are much larger than the burrs in the conventional experiment, and the burr formation process seems to be more different. The parameter with the highest influence in

the conventional experiment is the cutting method. Down milling results in far larger burrs than up milling. But in micro machining this depends very much on the other parameters. Furthermore, in conventional machining the burr size increases with higher feeds, while in micro machining smaller feeds lead to larger burrs, especially with up milling. This is explained by the plowing effect, which takes place at very small uncut chip thicknesses. In micro machining the feed per tooth is only a few micrometers. Therefore, plowing is the dominant material removal process, especially during up milling where the cutting edge enters with a very small angle hence an extremely small uncut chip thickness. Also, in the conventional experiment, it could be observed that in up milling the smallest feed value results in a larger burr than the intermediate value. The depth of cut (which has no significant influence on the top burr formation in the conventional cutting process) with increasing values leads to a decrease of the burr height in the micro machining process. But in both processes the speed has no significant influence on the burr formation.

CONCLUSION

In this research a new tool path planning concept for the end milling of pockets was developed. This concept aims at minimizing different characteristics such as surface roughness, top burr formation, and – in the case of bottom edges – bottom burrs. If inner pre-existing pockets occur, an inverted window framing cut is used to avoid tool exits and therefore exit bottom burrs. Furthermore, to optimize other characteristics the pocket machining is divided into several parts: The inner material removal, the outer contour pass, and – if applicable – the inverted window framing cut. For each part of the pocket, different parameter settings are used in order to optimize the characteristic which is most important for the respective part. A special open pocket experiment was designed for micro and macro machining to find the optimal parameter setting, and to determine influences in the different cutting processes. From experiments with the open pockets models were calculated, which can be applied to other workpiece geometries.

Additionally the influences in the conventional and in the micro milling experiment were determined using the Taguchi method for experimental design such that the two processes could be compared. Factors with the highest impact on the surface roughness have similar influences in micro and macro machining, meaning that the surface finish improves at a lower feed per tooth. Furthermore, the impact of the feed is stronger with up milling than with down milling. The influences on the top burr formation are different in conventional and micro milling. In conventional milling higher feeds result in a larger top burr formation, while in micro machining smaller feeds produce a larger burr. This is due to the plowing mechanism instead of shearing which takes place with a small uncut chip thickness. The bottom burr formation was negligible in both experiments and even not reliably measurable in the micro experiment. This is due to the inverted window framing concept, which avoids exit burrs, and entrance burrs are in most cases secondary burrs

and therefore negligible.

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