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# Generation of micro fins using ultraprecision diamond skiving

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**Abstract**
The fabrication of thin-walled structures has shown to be challenging with conventional machining techniques, especially due to the dynamics of high rotational tools. As structures continue to shrink in size, high aspect ratio features like micro fins become harder to generate due to the scale of the machining dynamics compared to the feature size. To avoid this, skiving presents itself as an ideal process to produce such thin and intricate features. The process creates the fins by "slicing" into the material without removing it, increasing the surface area of the material with a finite volume. However, fabrication of thin fins less than 50 um using conventional CNC tools, proves to be challenging due to limitations in both the machine and materials. As such, skiving using a diamond tool on an ultraprecision machine is proposed. Using a single setup, these micro fins can now be directly produced on the surface of the substrate, ensuring minimal geometrical deviations. In this paper, the fabrication of micro fins is discussed, along with the accompanying limitations and challenges.

Ultra-precision, Diamond, Micromachining

## 1. Introduction

Thin-walled structures have always posed a myriad of challenges in terms of fabrication. In machining, these are usually associated with the low rigidity of the features, leading to deformation and vibrations which inherently affect the overall precision and finishing of the parts [1]. This is especially critical when the features machined are scaled down in size, not only reducing the overall tolerances of the features, but also lowering the rigidity due to the thinness of the material. These result in sensitive features that can be easily damaged. As such, alternative manufacturing processes are required to produce such intricate features.

To create high aspect ratio fins, skiving has been the de facto technique widely used in the production of heat radiators. These fins are produced on a specialized 3-axis machine that can slice into the substrate material to form the newly sliced material at an angle away from the base of the substrate without removing it. This allows for extremely thin fins to be formed very close to each other with minimal material wastage. Thus, this technique circumvents the dynamic issues present in alternative machining processes.

However, traditional skiving processes are unable to generate more intricate fins thinner than 50 µm due limitations in terms of the accuracy and compliance of the machines used, as well as the sharpness of the tools used to slice into the substrate.

To address these issues, the proposed diamond micro skiving processes serve as an interesting alternative to produce micro fins tenths of microns in thickness. Using a unique setup on a 5-axis Ultra Precision Machine (UPM), a flat edged diamond tool is used, allowing the process to overcome the physical limitations present in conventional skiving processes [2].

In this study, the generation of micro fins are investigated using two forms of diamond skiving. This is followed by the experimental results and an analysis, as well as a discussion on the various factors affecting the diamond skiving process.

## 2. Diamond skiving

Diamond skiving employs the use of a diamond tool to selectively slice a layer of material without removing it. This leaves a sliver of material on the desired surface, creating micro features which are difficult to directly produce using conventional material removal techniques. To enable this on the UPM with a controlled rake angle, the tool is set upon the machine as shown in Figure 1, with the rake face of the tool parallel to the Y- axis, facing the -X direction.

The mechanics of the feature generation by skiving is akin to that of material flow in conventional machining processes. However, as only a sliver of material is required to be left upon the surface, there are a couple of strategies which can be adopted to generate the desired features on the surface of the workpiece depending on the geometry of the features, as shown in Figure 2.

The first technique involves entry of the material surface at an angle, at which the front clearance of the tool does not affect the subsequent features, for the thickness of the fin. After which, the tool travels horizontally along the surface of the substrate to create the micro fin. This process is straight forward and can be initiated at any point on the surface. It also does not require thick stock material to create taller fins. However, the drawback is that the density of the fins will be affected as the subsequent fins have to be sufficiently spaced from the initial fin.

The next technique only requires the entry motion of the tool into the surface of the workpiece at an angle which is sufficient to not interfere with the front clearance of the tool. This allows for the micro fins to be densely packed with smaller inter-fin spacing. The height of the fins is directly related to the depth of the tool plunge, while the fin thickness depends on the period of the tool entry. For dense micro fins with high aspect ratios, a combination of the two processes can be executed to produce the features.

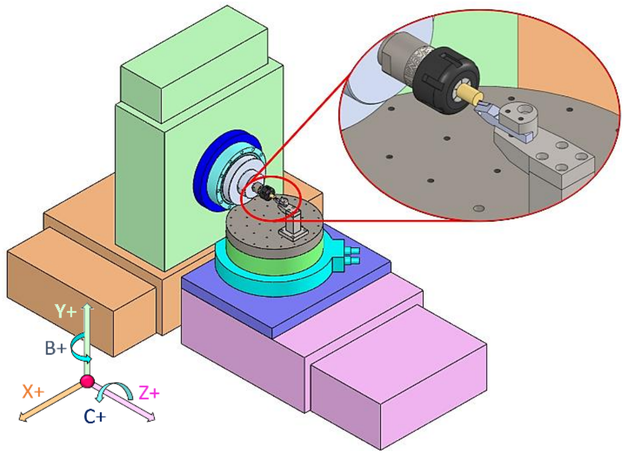


**Figure 1.** Setup of the tool and workpiece for the diamond skiving process, with the tool rake facing the X- direction.

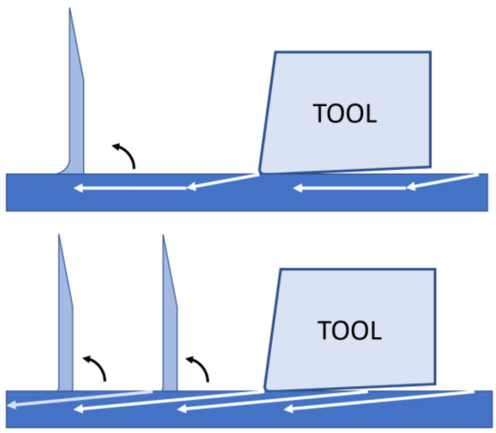


**Figure 2.** Various ways to skiv micro fins using diamond tools with the fins generated from left to right. (Top) Surface skiving and (Bottom) Diagonal skiving.

## 3. Experimental verification

To verify the feasibility of the process, a single crystal diamond tool with a 200 µm flat end, 15 degrees front clearance and an included angle, also known as the nose angle, of 20 degrees was used. This tool was selected to create fins with rectangular profile compared to the tools used in conventional turning processes. The tool was positioned on the B-stage of the 5-axis ultra-precision machine with the rake face facing the X-direction, as seen in Figure 3. This allows for the precise control of the tool's rake angle using the rotation of the B-stage, due to the tight angles involved, especially when the front clearance of the tool geometrical restricts this specific setup.

The workpiece used in this verification process was a cylindrical brass rod, measuring 10 mm in diameter, with the features being formed on the circular end of the rod in a hexagonal pattern. This was to ensure that observations and measurements of the profile of the formed fins were easily accessible, without the need to focus through the other formed features. Brass was also chosen due its ductility and low wear rates when using diamond tools. Moreover, a flood coolant was used, increasing the lubrication while reducing friction and wear.

For this experiment, the rake angle of the tool was set at a positive 12 degrees. With an approaching angle of 2 degrees, the remaining available front clearance of the tool was 1 degree. This was so that the tool had sufficient clearance so as not to unintentionally chafe the surface of the unformed material.

For the surface skiving, the experiment consists of having various penetration depths, along with various skiving lengths. This allows for the understanding of the parameters to enable the micro fins to be formed. For the investigation of the diagonal skiving parameters, variations in the depth of the slice and the spacing of the fins were examined. Details of the parameters using in this study have been tabulated in Table 1 and Table 2, while the description schematic of the is provided in Figure 4 and Figure 5 respectively.

The surface of the workpiece was prepared by facing the workpiece using the flat tool to ensure the alignment of the Z-coordinate before the experiments were executed. As for the positioning of the tool, the established parameters provide a basis upon which the point cloud can be based. The feed of the tool was set at 50 mm/min, with a 0.3 second dwell time at the base of the fin before retracting and indexing to the next plunging location.

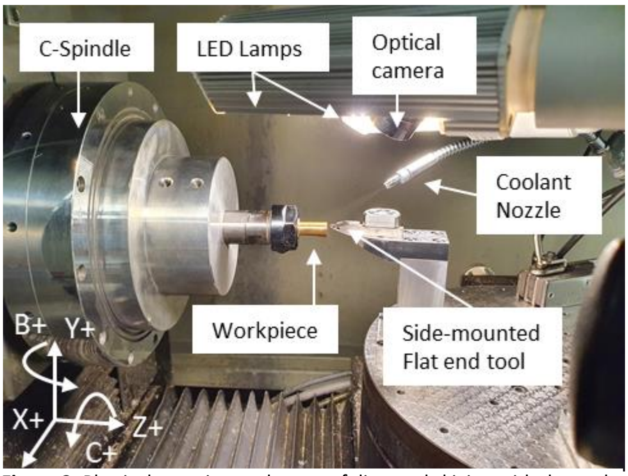


**Figure 3.** Physical experimental setup of diamond skiving with the tool facing the X- direction.

## 4. Results and discussion

Using the flat nose diamond tool, micro fins were successfully generated on the surface of the brass workpiece with surface skiving and diagonal skiving, as shown in Figure 6 and Figure 7 respectively. These were taken using an optical microscope with a 1000x objective. Used a datum reference, the images also possess a reflected image from the face of the brass workpiece.

For surface skiving, the generation of micro fins using 1 µm depth of cut was unsuccessful. This can be attributed to the insufficient depth of cut (DoC) to overcome the compliance of the material with the edge radius of the tool, resulting in the material not being engaged and sheared by the tool [3,4]. Furthermore, the tool edge radius effect becomes more prominent as the DoC approaches the dimension of the tool edge radius, causing a negative effective rake angle. Instead, the surface is being rubbed and burnished. While it may be possible to identify the minimum DoC required to engage the material, the result would be specific for this tool and/or the edge radius.

As for the 5 µm and 10 µm DoC surface skiving experiments, the micro fins were successfully generated, as seen in Figure 6. All the micro fins possess a characteristic curl, with more prominence as the fins are generated with longer lengths. They also have a higher curvature at the tips of the fins due to the thinner profile of the cross-section. This fin profile is akin to that of conventional chip formation in traditional machining models. Due to the shear angle of the material, the shear bands can be seen building up in the inner side of the curl. This results in the fin possessing one shorter side and one longer side, causing the fin to curl inwards towards the shorter side of the fin. This is further corroborated with the increase in the fin thickness, with an average of 6.75 µm and 14.2 µm, from the unformed chip thickness of 5 and 10 µm respectively, provided by the penetration depth.

*__Table 1.__ Parameters for surface skiving of micro fins on brass*

| No | Penetration Depth (µm) | Unformed fin Length (µm) | Inter-fin Spacing (µm) |
|---|---|---|---|
| 1 | 1 | 30 | 20 |
| 2 | 1 | 60 | 50 |
| 3 | 1 | 90 | 80 |
| 4 | 1 | 120 | 110 |
| 5 | 5 | 150 | 100 |
| 6 | 5 | 300 | 250 |
| 7 | 5 | 450 | 400 |
| 8 | 5 | 600 | 550 |
| 9 | 10 | 300 | 200 |
| 10 | 10 | 600 | 500 |
| 11 | 10 | 900 | 800 |
| 12 | 10 | 1200 | 1100 |

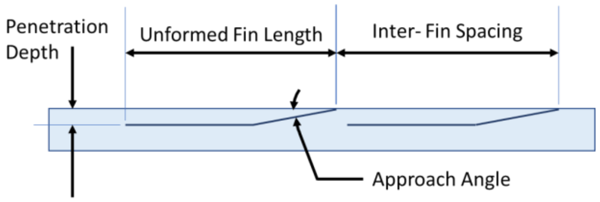


**Figure 4.** Parametric definition of surface skiving parameters.

*__Table 2.__ Parameters for diagonal skiving of micro fins on brass*

| No | Penetration Depth (µm) | Unformed fin Length (µm) | Fin Spacing (µm) | Thickness (µm) |
|---|---|---|---|---|
| 1 | 5 | 143.27 | 29 | 1.0 |
| 2 | 5 | 143.27 | 143 | 5.0 |
| 3 | 5 | 143.27 | 286 | 10.0 |
| 4 | 5 | 143.27 | 573 | 20.0 |
| 5 | 10 | 286.54 | 29 | 1.0 |
| 6 | 10 | 286.54 | 143 | 5.0 |
| 7 | 10 | 286.54 | 286 | 10.0 |
| 8 | 10 | 286.54 | 573 | 20.0 |
| 9 | 15 | 429.81 | 29 | 1.0 |
| 10 | 15 | 429.81 | 143 | 5.0 |
| 11 | 15 | 429.81 | 286 | 10.0 |
| 12 | 15 | 429.81 | 573 | 20.0 |

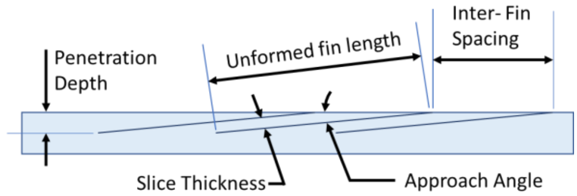


**Figure 5.** Parametric definition of diagonal skiving parameters.

The diagonal skiving experiments also successfully generated micro fins, albeit with interesting patterns, as seen in Figure 7. For the micro fins formed using a 5 µm penetration depth, the lower fin height resulted in smaller side profile aspect ratios compared to the other longer fins. This allowed for a less prominent curve of the micro fins, allowing them to stand relatively perpendicular to the substrate surface.

The micro fins with the 10 µm DoC and shorter fin spacing on the other hand resulted in an unstable micro fin formation. Whilst these fins have a straight formation profile, the direction at which they point in fluctuates for each fin. This disparity may be caused by various factors including, but not limited to, the acceleration and deceleration of the tool, structural stability, and the residual stresses.

This instability also is also observed the fins formed with the 15 µm DoC. However, there are periodic moments at which the fins form a full curl, creating a corrugated surface with a cross-sectional profile akin to mini pipes (See Figure 7 – bottom left). The larger unformed fin thicknesses for both 10 and 15 µm DoC created consistent and uniform micro fins with the characteristic curls.

To address the curls and create straighter micro fins, the ideal rake angle of the tool must be set perpendicular to the shear angle of the material. This allows the tool to slice through the substrate without much change to the uncut chip thickness to form the micro fins and avoids the formation of the shear bands. However, due to the geometrical limitations of the diamond tool, this is not possible. Comparing the surface skiving to diagonal skiving, the curls in the surface skived fins are more prominent. This is due to the relative rake angle between the tool and the workpiece, as there is an increase in the resultant rake angle for the diagonal skived fins.

The fin thicknesses of the diagonal skiving fins have also been plotted against the average measured thickness, as seen in Figure 8. From the plot, the fin thicknesses for both the 5 and 10 µm DoC processes taper out after a certain point, compared to the theoretical fin thickness, T, derived from the geometries as follows:

$$T = S \tan \vartheta \qquad (1)$$

Where S is the inter-fin spacing and ϑ is the approaching angle. This results in fins that are generated without interaction with the material removed from the previous cuts. This theoretical limit can be determined by the length of the unformed fin length, L, which can be determined as follows:


**Figure 6.** Results of micro fins formed by surface skiving. (Top row - from left to right) 5 µm deep micro fins with increasing unformed fin length. (Bottom row - from left to right) 10 µm deep micro fins with increasing unformed fin length. Arrow scales are with 50 µm markings.

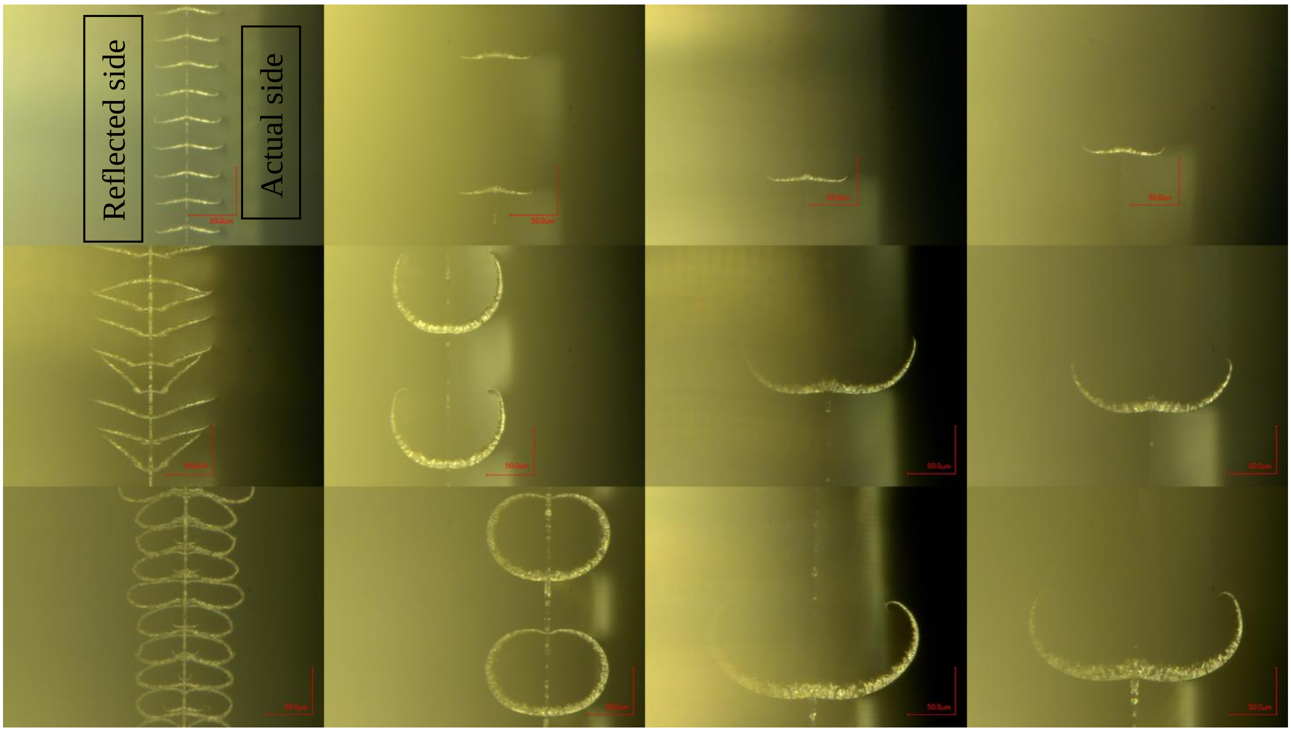


**Figure 7.** Results of micro fins formed by surface skiving. (Top row - from left to right) 5 µm deep micro fins with increasing inter fin spacing. (Middle row - from left to right) 10 µm deep micro fins with increasing inter fin spacing. (Bottom row - from left to right) 15 µm deep micro fins with increasing inter fin spacing. Arrow scales are with 50 µm markings.

$$L = \frac{DoC}{\sin\vartheta} \qquad (2)$$

Thus, the depth of cut provides a limit to the maximum unformed chip thickness of the micro fins, with more interactions of material when the inter fin spacing is smaller.

## 5. Conclusion

The successful generation of micro fins using ultraprecision diamond skiving has shown promise in the fabrication of thin-walled structures. Using two separate techniques, namely surface skiving and diagonal skiving, these high aspect ratio features were generated using a flat edge diamond tool. The motion of the tool leaves a sliver of material at the end of each pass without removing it, resulting in micro fins of various geometries. With a unique setup of the tool, control of the rake angle was possible without the need for additional axes to be added in the 5-axis UPM. This was done by placing the tool on its side and setting it upon the B-stage, with the rake facing in the -X direction.

These fins were generated using depth of cuts of more than 5 µm. By varying the process parameters, such as the inter-fin spacing and penetration depth, the resulting cross-sectional profile of the micro fins change accordingly, with a characteristic curl due to the shear bands within the fin. Longer and thinner fins have shown to curl more, and in some cases creating micro pipes. An understanding on the interaction of parameters in diagonal skiving have also been discussed, allowing for the design of the fin length and thickness.

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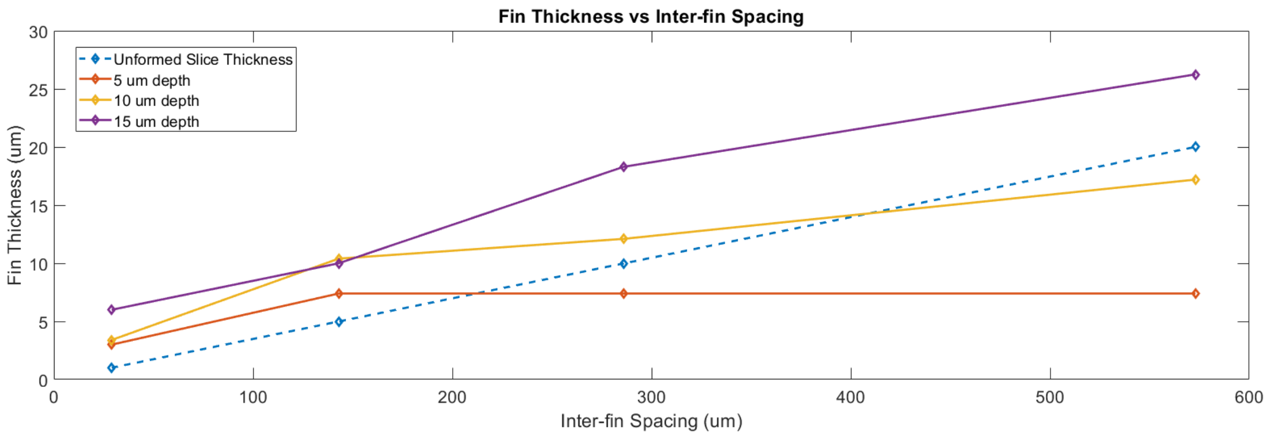


**Figure 8.** Diagonal skiving fin thickness variation between the various inter-fin spacings and the fin thickness for the various