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Procedia CIRP 77 (2018) 332–335

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8th CIRP Conference on High Performance Cutting (HPC 2018)

# Interdependence Between Tool Misalignment and Cutting Forces in Ultraprecise Single Point Inverted Cutting

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## Abstract

Ultraprecise single point inverted cutting (USPIC) is a microfabrication technique that has been recently developed for the generation of micro-optical microstructures with sharp concave geometries. Among the multiple challenges encountered during the micromachining process, tool alignment represents one of the critical factors affecting the overall accuracy of the microstructure that in turn affects its optical functionality. Since none of the presently available tool alignment techniques was found to perform well in the particular context of the diamond insert used in USPIC, an in-depth analysis of its mechanics was used in this study to provide insight on the interdependence between cutting tool misalignment and cutting forces. For this purpose, an experimental setup was devised to record the 3D cutting forces generated during the fabrication of two representative concave geometries delimited by planar facets. The first test geometry represents an instance of an isolated right triangular prism (RTP) whose quality and optical functionality will be significantly affected by diamond insert misalignment, particularly due to the undesirable contact to occur between the secondary/lateral cutting edges of the tool and the optically nonfunctional RTP facets. By contrast, the second test geometry had both lateral facets removed, such that the cutting conditions obtained in this case could be regarded as similar with that of the classical orthogonal cutting setup. Direct comparisons of the cutting force profiles obtained for the two cutting scenarios enable unequivocal identifications of tool misalignment direction and magnitude, such that targeted corrective actions could be performed to address the issue.

*Keywords:* microfabrication, high precision diamond cutting, optical microstructures, tool alignment, cutting forces

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## 1. Introduction

All state-of-the-art automotive retroreflectors that exist on the market are invariably based on corner-cube geometries. This is primarily a consequence of the conventional pin-bundling technology that is used to fabricate them. However, the use of microcutting technologies in retroreflector fabrication has practically unlocked the design and/or geometry of the retroreflective microstructures to be embedded in some of the mandatory illumination/safety components of a vehicle.

In this context, the novel right triangular prismatic (RTP) microstructure is characterized by a high degree of fabrication difficulty due to its elevated surface quality requirements as well as its concave shape. The task of RTP fabrication has prompted the development of a new manufacturing technique termed Ultraprecise Single Point Inverted Cutting (USPIC) [1-4] that relies on a high precision micromachining center in combination with a monocrystalline diamond tool. Additionally, the determination of USPIC tool path trajectory/strategy is of vital importance, particularly since

10.1016/j.procir.2018.09.028

none of the existent computer aided manufacturing (CAM) systems can be used for this purpose.

After the prototypical USPIC trials have validated the feasibility of the new technique, the emphasis of the research has shifted towards machining aspects that would allow further improvements in the RTP quality [5]. Along these lines, it became soon apparent that tool alignment and tool path trajectory play a significant role on structure accuracy and tool life, particularly since it is known that tool misalignment is one of the major contributors to tool wear [6]. Furthermore, ultraprecise machining of optical structures was shown to be significantly affected by any type of form errors [7].

In an ideal/theoretical USPIC operation, the symmetry plane of the diamond insert is perfectly aligned with the Z-axis of the machine tool whereas the primary cutting edge of the tool is parallel with the X-axis of the machine tool. However, none of these two conditions can be met in practice, partly because of the imperfect tool holder construction, partly because of a difficult to control setting/orientation of the diamond insert on the shank. Of note, while the alignment of the shank can be corrected – to a large extent – through a time consuming process involving the use of a high precision digital indicator, this method is of little use to the diamond insert that is attached to the shank.

On the other hand, while precise diamond alignments are routinely performed in a different context, such is for instance, the case of atomic force microscope (AFM) measurements [8, 9], there is no uncomplicated/obvious way to implement these laser-based techniques in the USPIC environment.

Since tool misalignments will undoubtedly and unequivocally affect the functionality of the RTPs to be generated through USPIC, the main objective of the current study was to identify a relatively simple method that is capable to verify the presence of the tool misalignment, such that appropriate corrective actions can be performed prior to the launch in fabrication of a large array of RTPs.

## 2. Experimental Setup and Cutting Scenarios

To better understand the effect of tool alignment on cutting forces, two machining experiments were performed on aluminum 6061 samples in order to accurately capture the characteristics of the USPIC mechanics (Figure 1). For this purpose, tool geometry, fixturing, cutting cycle and parameters were kept identical among the two cutting trials.

The critical dimensions of the tool are the 50° angle included between rake and clearance face as well as the cutting-edge length/tool width of approximately 1 mm. The tool was mounted such that the clearance angle was 3° relative to a negative Z-axis motion, while A-axis was set to +45°. This tool-workpiece relative positioning is equivalent with an instance of a positive 37° rake angle while plunging and a negative 53° while ploughing. Here, plunging motion is defined as the negative Z-axis motion used to approach/enter the RTP structure and create the length of the chip (red arrows in Figure 2). By contrast, ploughing motion is defined as the negative Y-axis motion used to shear the chip from the lower facet and evacuate the chip (orange arrows in Figure 2).

The tool path trajectory for fabricating an RTP has an inherent repetitive nature such that material removal occurs over multiple sequential cuts. However, although the overall USPIC strategy might be complicated, one complete cutting cycle – consisting of approach, plunge cut, plough cut, and retract motions - is in fact sufficient to detect the presence of the tool misalignment.

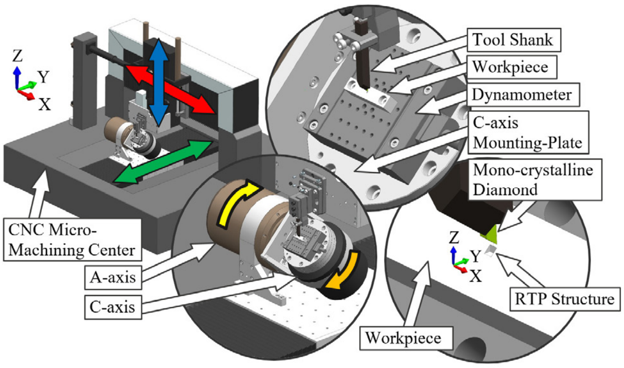

**Figure 1.** Experimental setup: five-axis micromachining center, tool, dynamometer, and workpiece

The first experiment conducted has involved the fabrication of an isolated RTP structure by means of the USPIC unidirectional strategy. A more detailed description of this technique can be found in [5]. The term “isolated” indicates that the RTP structure was cut in virgin material (Figure 2a). Of note, cutting tool is fully engaged across its entire cutting edge in this scenario. Furthermore, RTP width coincides with the length of the primary cutting edge.

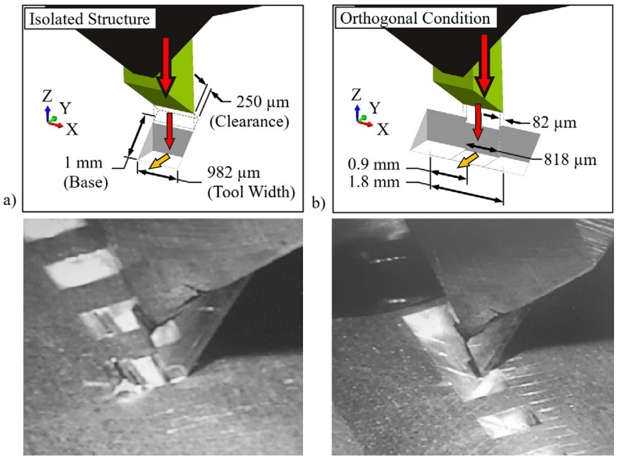

**Figure 2**. Cutting scenarios: a) isolated, and b) orthogonal

By contrast, the RTP cut in the second experiment is neighbored by two adjacent RTPs that were cut in advance (Figure 2b). The tool used in the experiments was characterized by the width of the primary cutting edge of 982 µm. The midpoint of the two precut structures were positioned 1.8 mm apart in the X-direction, thus leaving 818 µm between them. This arrangement leads to an 82 µm overlap between the two precut structures and the one positioned between them. Because of this positioning, the contact between the two endpoints of the primary cutting edge and the workpiece material was avoided, such that no optically nonfunctional RTP facets were generated in this case. The overall setup of this second scenario resembles that of a conventional orthogonal cutting condition.

Overall, in addition to the change in cutting configuration (*i.e.*, isolated vs. orthogonal), the second scenario is also characterized by a reduction in cutting width (from 0.982 to 0.818 mm or 16.7% decrease). Depth of cut in both scenarios was set at 5 µm.

## 3. Diamond Insert Misalignment

Evidently, the critical difference between the two scenarios is that the orthogonal cutting configuration precludes any interaction between the secondary cutting edges of the tool and the workpiece. Because of this, all cutting forces to be generated in the second scenario are solely dependent on the contact between the primary cutting edge of the tool and the workpiece material.

As such, by assuming that the tool is – for instance – misaligned with respect to Y-axis, it can be inferred that unanticipated X-axis forces will be generated during plunging motion. To exemplify this concept, Figure 3 depicts a simplified case in which the tool is misaligned by +5°. Clearly, as the tool travels downward along the RTP facet, the right side of the tool will engage more with the workpiece, such that positive $F_x$ component of the component will be present. This imbalanced contact between the tool and workpiece will likely cause an excessive tool deflection as well as an increased stress on the adhesive connection between diamond insert and tool shank. Finally, the RTP structure to be generated in this scenario will likely deviate from the desired quality and/or functional requirements.

## 4. Cutting Force Results

Figure 4 shows the temporal variation of the cutting forces for both investigated scenarios. The correlation of the graph with cutting motion kinematics suggests that the initial $F_z$ spike appears immediately after the tool engages the workpiece surface. The magnitude of the initial $F_z$ component was -1.57 N and -1.29 N for the isolated and orthogonal scenarios, respectively. This corresponds to a 17.8% difference, that is comparable to the change in chip load/primary cutting edge width that was mentioned at the end of Section 2. At this incipient position of the plunging motion, the tool is not engaged deep into the RTP structure and therefore the lateral forces caused by diamond misalignment in the isolated cutting scenario would be minimal at this point.

The next peak of $F_z$ occurs at root of the cut (*i.e.*, RTP apex) where plunging motion concludes. The respective forces are -5.34 and -4.06 N (isolate vs. orthogonal). This 24.0% difference is larger than the change in chip load and it can be thus attributed to the lateral frictional and impingement forces acting on the right flank of the diamond insert. As the tool engages deeper into the RTP structure, a quasi-linear increase in the $F_z$ component seems to be present in the isolated cut scenario. This type of variation for $F_z$ connects the two aforementioned peaks. By contrast, the quasi-linear increase in $F_z$ is not present in the orthogonal cutting scenario and this confirms that the steady increase in the isolated RTP case is caused by the lateral contact of the tool that in turn is a consequence of the misaligned diamond insert.

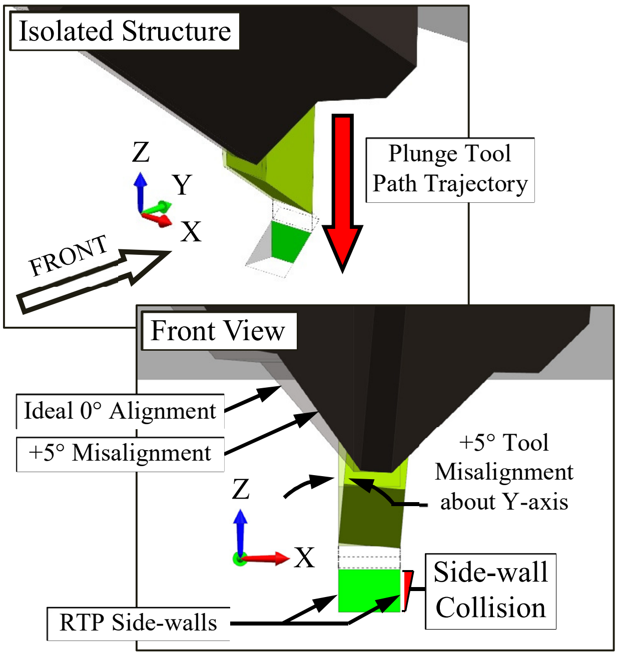

**Figure 3** Tool misalignment example

Since the plunging motion happens strictly along Z-axis, the main effect of the lateral frictional force will exert on $F_z$ whereas $F_y$ will remain virtually unaffected. However, once plunging concludes and ploughing starts, it can be noticed that the lateral contact starts to affect more $F_y$. More specifically, after the 0.1 seconds dwell between the motions, it can be seen that the peak $F_y$ for the isolated structure is -3.33 N while for the witness orthogonal configuration reaches only -1.73 N. This behavior can be interpreted as a direct consequence of the ploughing motion direction that is confined to –Y. Because of this, the lateral contact on the tool will oppose the direction of the ploughing motion and therefore increase the $F_y$ component that before the chip is dislodged from the bulk material of the workpiece. Furthermore, the chip that has accumulated during plunging will continue to grow a bit further before its detachment and this will lead to additional (*i.e.*, non-misalignment related) $F_y$ increases. This phenomenon can be distinctively observed in the orthogonal cutting scenario.

Finally, unequivocal comparisons can be made with respect to the X component of the measured cutting force. Obviously, the lack of lateral contact in the orthogonal scenario determines $F_x$ to remain at quasi-null values. Nevertheless, this is not the case of the isolated RTP cutting scenario in which $F_x$ exhibits a continuous growth for the entire duration of the cutting cycle, practically supporting the hypothesis that in addition to the aforementioned friction-dependent effects on $F_y$ and $F_z$, the lateral contact caused by the tool misalignment will also generate an impingement force to essentially translate into $F_x$. One important observation to be made here is that while $F_x$ has a relatively low importance in the overall context of USPIC

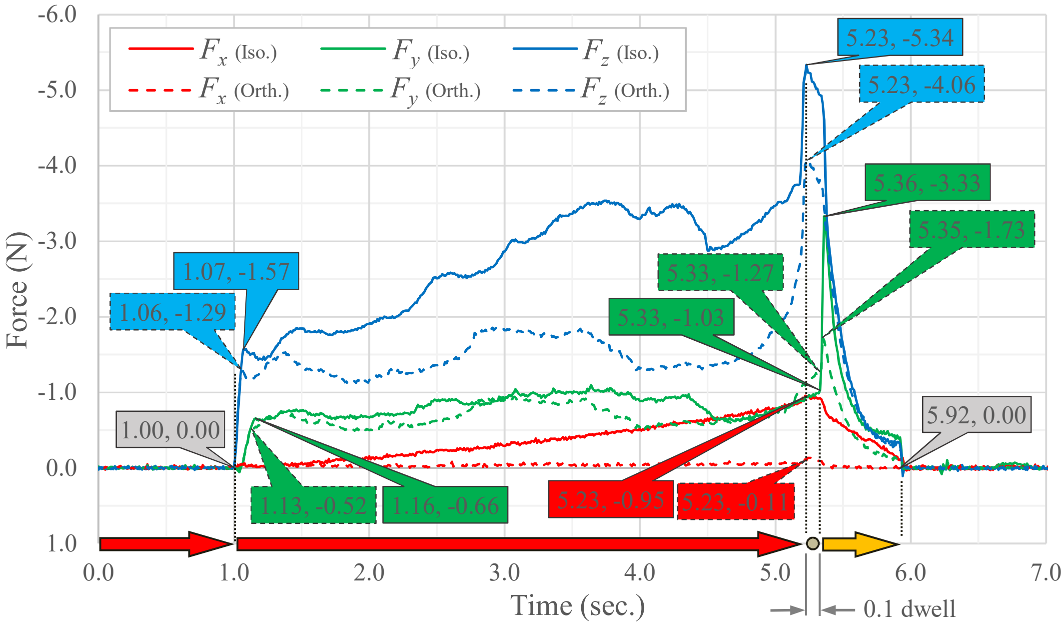

**Figure 4.** Comparative Cutting mechanics of the unidirectional strategy in isolated and orthogonal configurations

cutting mechanics, its role in tool misalignment monitoring/detection is quite significant.

## 5. Conclusions

In this study, two parallel cutting scenarios were used to investigate the effect of diamond insert misalignment on the cutting forces generated in USPIC-based RTP fabrication. The experiments performed have indisputably proved that the lateral contact between the secondary cutting edge of the tool and the workpiece – that is in fact a consequence of the inappropriate tool orientation – is responsible for the generation of cutting force components that would be inexistent in the ideal/practically unattainable case of a perfect tool alignment.

While from the USPIC mechanics perspective it was already known that the main cutting forces will occur along Z and Y axes (*i.e.*, principal cutting directions for plunge and plough motions) this study has also demonstrated that the analysis of $F_x$ profile can also provide important information, particularly with respect to tool misalignment. Because of this, it can be assumed that real-time monitoring of this tertiary force might be also important for other types of machining applications. Furthermore, while the presence of $F_x$ provides clear indications with respect to the direction of the misalignment correction, the magnitude of the corrective action remains to be established by means of iterative calibration techniques.

In the particular case of USPIC, in which other tool alignment systems proved to be difficult to implement, future work will attempt to add displacement sensors on the tertiary direction in an effort to better quantify/monitor the magnitude of tool misalignment. The severity of the misalignment will have a direct impact on the magnitude of the measured cutting forces and, based on appropriate calibration routines, the amount of misalignment could be inferred and then corrected.

The reduction of misalignment-induced components of the cutting forces will allow an even distribution of the chip load with positive effects on both the quality/optical functionality of the fabricated RTP structures as well as on the durability of the relatively expensive USPIC monocrystalline diamond tool.

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