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Experimental Investigation of Friction Stir Processing Scallop Removal Utilizing Complex Toolpaths

Tyler Grimm
Clemson University

Laine Mears
Clemson University

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Background

Friction Stir Processing

Friction stir processing (FSP) is a novel material strengthening process derived from friction stir welding (FSW). These processes drive a non-consumable, rotating tool through the parent metal. This produces significant strain on the material's microstructure, causing substantial grain refinement. Furthermore, the frictional heat generated by the rotation of the tool is not large enough to cause the rapid grain growth commonly seen during hot forging operations. FSW and FSP are distinguished by their primary objective: FSW is used to join materials with an additional benefit of material strengthening, whereas FSP is explicitly used to strengthen a continuous workpiece.

Errors in Machining

Two types of errors may occur during freeform surface machining: scallop formation and gouging. Gouging occurs when material is cut past the desired surface and scallops are formed when material remains outside of it. Advancements in computer-aided manufacturing (CAM) software has eliminated gouging through the implementation of several monitoring techniques such as feasibility cone checking[1], C-space modeling[2,3,4], and the rolling ball method[5]. Scallops cannot be eliminated when machining complex surfaces; however, they should be minimized.

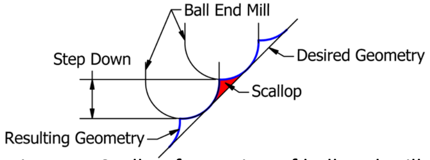


Figure 1: Scallop formation of ball end mill

Methodology

A significant advantage may be realized if a scallop removal process can be coupled with material enhancements. By combining the use of a complex toolpath with friction stir processing, the surface variability of the final part may be improved, as well as the surface's strength. A "curly" toolpath was used to reduce the size of scallops. These paths were created using the following parametric equation:

$$X = t + \cos\left(\pi t \times \frac{L}{D}\right) \times D \times P \times \frac{\pi}{2}$$

$$Y = \sin\left(\pi t \times \frac{L}{D}\right) \times \frac{S}{2}$$

Where t is the parameter, L is the total linear distance of the path, D is the loop distance, and P is the overlap parameter. An example of this toolpath can be seen in Figure 2.

Motivation

Computer numerical control (CNC) developments have enabled machinists to create geometries that were previously not possible with manual mills. This technology has rapidly advanced; however, manufacturers must face an inevitable dilemma. The machining of complex curves with simply shaped tooling results in excess material which cannot be cut, causing inaccuracies to develop between the CAD model and the resulting workpiece.

Traditional toolpaths make passes at discrete and sequential Z-steps. The distance between these steps is known as the step size. This type of toolpath forms scallops which result from the curvature of the tool. The size of these scallops may be reduced by decreasing the step size. However, this is at the cost of longer toolpaths. Because of this drawback, manufacturers would significantly benefit from processes which minimize processing time while maintaining a high degree of part accuracy.

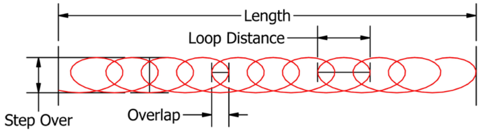
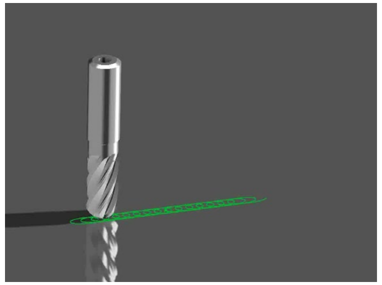


Figure 2: Complex path designations

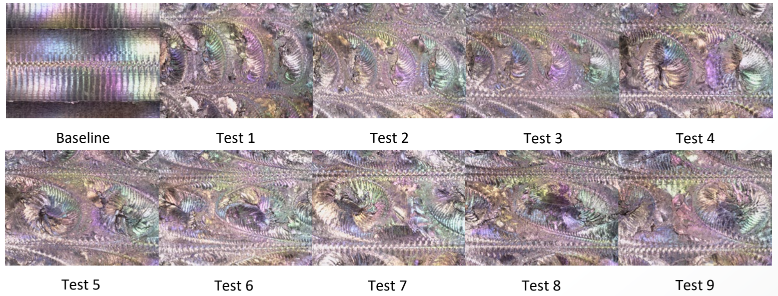
Cutting passes were performed utilizing a 0.375" diameter TiCN coated carbide ball end mill with a feed rate of 3,048 mm/min, a spindle speed of 10,000 RPM, and a depth of cut of 0.5 mm. Passes were performed with a stepover of 4 mm, which produced a scallop height of 0.43 mm. FSP passes were performed utilizing the same end mill with similar feeds and speeds; however FSP passes were performed with a counter-clockwise tool rotation. This caused the material to act as a solid tool, rather than an end mill cutter. FSP paths were positioned such that the scallop ran through the center of the curls.

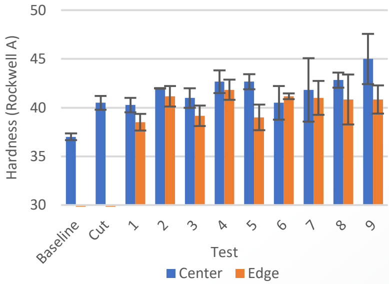


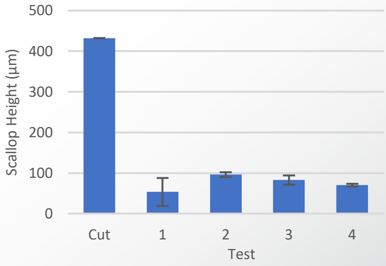
Test Parameters

Test #	Loop Distance (mm)	Overlap
Baseline	-	-
1	1.6	0.5
2	1.6	1
3	1.6	1.5
4	3.2	0.5
5	3.2	1
6	3.2	1.5
7	4.8	0.5
8	4.8	1
9	4.8	1.5

Results







Conclusions

Scallops were effectively reduced utilizing the method described herein. Surface variability was reduced by a maximum of 80%. Additionally, an increase in hardness was experienced through an FSP effect. However, hardness measurements were produced with low repeatability. This suggests that the surface hardness resulting from the complex path is non-uniform. Therefore, additional care must be taken when selecting this toolpath, as this effect may hinder the part's performance during use. Additionally, future studies must be conducted in order to determine the additional processing time required to perform such complex paths relative to reductions in step size and subsequent surface hardening.

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