Workpiece surface flatness improvement by tool length compensation in micromilling

ICOMM 2014 No. 107

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Abstract

Micromilling quality improvement requires an accurate management of all the involved resources (machine tool, tool, fixture, workpiece). Specific attention has to be paid, comparing to macro operations, also to machining strategies and tool and workpiece measuring strategies. The extreme workpiece accuracy requires to reinterpret some procedures, already applied in the macro world, with the purpose to minimize errors. It is the case of the tool length compensation, which plays a strong role on the micromilling overall performance. In order to demonstrate the importance of factors affecting tool length, as machine spindle thermal transients and tool wear assessment, the present paper takes the workpiece flatness deviation as a case study and presents a manufacturing and measuring strategy able to meet a challenging flatness constraint.

Keywords: micromilling, accuracy, flatness.

1. Introduction

Four fundamental resources (machine tool, tool, fixture and workpiece) are involved in every machining operation as shown in the lower layer of Fig. 1. When dealing with micromilling, they have to count on specific features:

- machine tool: the thermal and dynamic stability ensures high accuracy; low CNC sampling times reduce chord errors [1-5];
- tool: tool geometry (e.g., a low cutting edge radius is useful to reduce the minimum uncut chip thickness), tool material (ultrafine hard metal grains are typically required), coating (able to reduce friction and built-up-edge also when ploughing occurs) [1-3];
- fixture: only one fixturing operation is often allowed in a working cycle to reduce errors. This fact requires ad hoc fixtures able to let five workpiece faces free for working and measuring operations;
- workpiece: homogeneous materials are required, at least at a mesoscale, to simplify process parameters selection [1-2].

When machining at the microscale, also machining strategies [6-8] (D in Fig. 1) and tool and workpiece measuring instruments and related strategies [4] (higher layer of Fig. 1) play a fundamental role and have to be added to the aforementioned resources (Fig. 1) as they strongly affect machining operations.

The described set of involved resources, in particular D and E in Fig. 1, should manage a couple of important factors, as thermal transients and tool wear, playing a strong role on the micromilling overall performance.

Thermal transients affect both machine tool and onboard measurement instruments [4]. This way, they are responsible for machine components dimensional changes (e.g. spindle axial deformations) and fictitious dimensional changes, wrongly acquired by measurement instruments as onboard tool presetting systems. Both in case of spindle deformations and wrong tool presetting acquisitions, tool length experiences fictitious variations.

Tool wear assessment along a machining cycle is important to allow compensating real tool length variations. Tool measurement not only is useful to correctly refer the tool to the workpiece at the beginning of a working operation, but, if correctly integrated in the machining cycle, it allows to accurately measure and correct tool wear.

It is clear how an accurate tool length compensation approach along a machining cycle is particularly critical when very strict tolerances are required on the workpiece surface. Tool length compensation has to be robust to both fictitious and real tool length variations.

The aim of the present paper is to demonstrate the importance of machine spindle thermal transients and tool wear assessment on the final workpiece quality through a simple but industrially significant case study. An accurate plane surface with a strict flatness deviation has been manufactured on a quite large workpiece.

This kind of tolerance requires high accuracy in tool length assessment when obtained by an endmill, so it represents an interesting challenge to prove tool length compensation effectiveness in general.

2. Objectives

The case study of this paper is manufacturing a flat surface (Fig. 2) with a strict flatness deviation on a Cu-Ni12Zn30Pb1 copper-nickel zinc alloy.

Tool diameter and process parameters are specifically selected to imply high machining time. This fact makes tool length assessment critical due to both machine spindle thermal transient and tool wear occurring during machining operations.

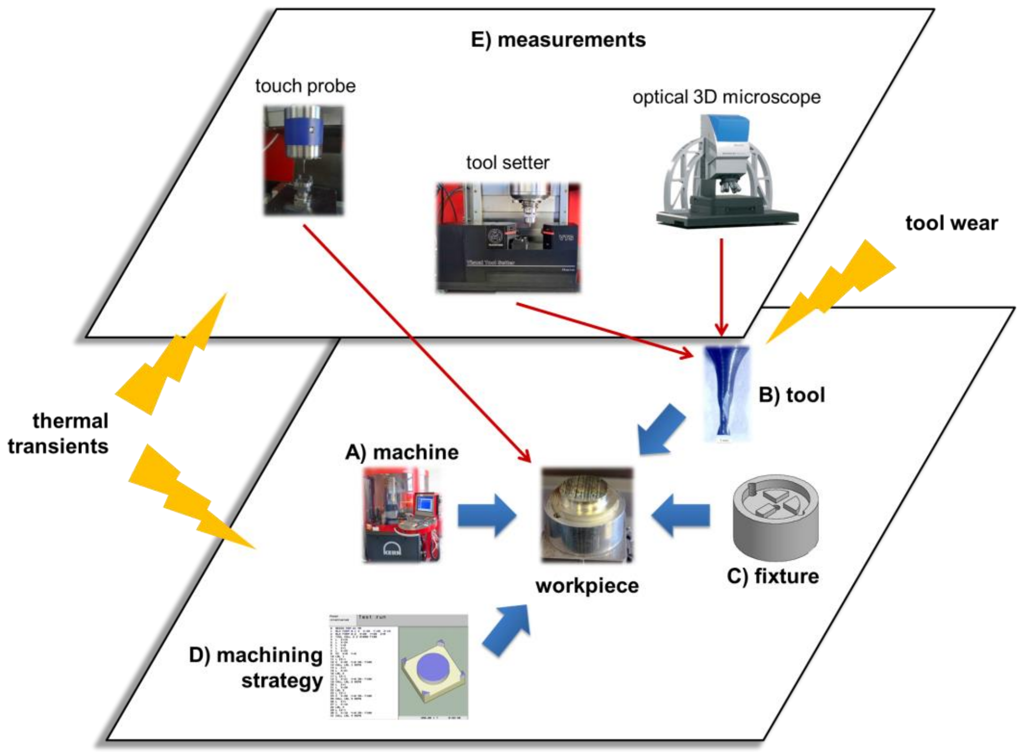


Fig. 1. Resources involved in a micromilling operation.

A small tool diameter compared to the machined surface diameter (1 mm vs. 29.5 mm) has been selected. The surface dimensions with respect to the tool diameter make the required flatness constraint challenging.

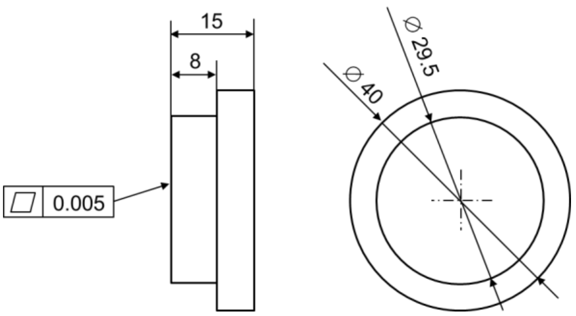


Fig. 2. Case study.

The selected case study makes sense for molds machining. Even if the workpiece surface is flat in the present study while the mold surfaces are usually sculptured, the part has to be finished ensuring a uniform allowance in both cases. In case of molds, it is useful for the following polishing phase.

The present study aims at defining methods able to manage long machining times meeting workpiece quality constraints. Looking for optimal machining parameters is not the purpose of this paper.

3. Experimental setup

This Section presents the resources involved in the research and the employed constant cutting parameters.

Micromilling tests were performed on the Kern EVO ultra precision 5-axis machining center (A in Fig. 1) available at the "MI_crolab", mechanical micromachining laboratory of Dipartimento di Meccanica of Politecnico di Milano (nominal positioning tolerance = ± 1 µm, precision on the workpiece = ± 2 µm).

Table 1. Tool characteristics and constant cutting parameters.

			Roughing	Finishing
Tool	Tool manufacturer		Sandvik Coromant	Seco Tools
	Code		R216.12-06030-BS07P	512010Z2.0-SIRON-A
	Tool material		coated carbide	cemented carbide
	Flute number		2	2
	Diameter		6 mm	1 mm
	Helix angle		35°	20°
	Rake angle		12°	10°
	Max. axial engagement		7 mm	2 mm
Cutting parameters	Axial depth of cut (mm)	a_p	0.1	0.04
	Radial depth of cut (mm)	a_e	5	0.02
	Feed per tooth (mm/rev)	f_z	0.03	0.004
	Cutting speed (m/min)	v_c	116	157
	Spindle speed (rpm)	n	6185	49780

As concerning tools (B in Fig. 1), Table 1 shows the employed roughing and finishing endmill characteristics and the selected cutting parameters. Prior to machining, each new tool was cleaned by ethanol to remove any residual oil. Ethanol was also used to clean the clamping collet before and after mounting the tool. Surface milling was performed with no coolant and using pure air to remove chips.

A proper fixture (C in Fig. 1) was needed to hold the workpiece during milling operations. Fig. 4 depicts the fixture that was especially designed for the required workpiece (Fig. 2) and machined on the Kern EVO machining center. In this fixture, the workpiece was placed on three small flat surfaces and was held in position by the lateral cylindrical surface with the addition of cyanoacrylate adhesive. Three screws at the bottom helped to remove the workpiece at the end of machining operation.

Fig. 4. Workpiece fixture.

Regarding the machining strategy (D in Fig. 1), the roughing and finishing operations were performed by parallel passes at constant Z level, respectively, along the machine X and Y axes. Machining along different directions allows reducing surface waviness. In case of both roughing and finishing (Fig. 5), down-milling was always applied by performing all passes, respectively, along the X and Y positive direction.

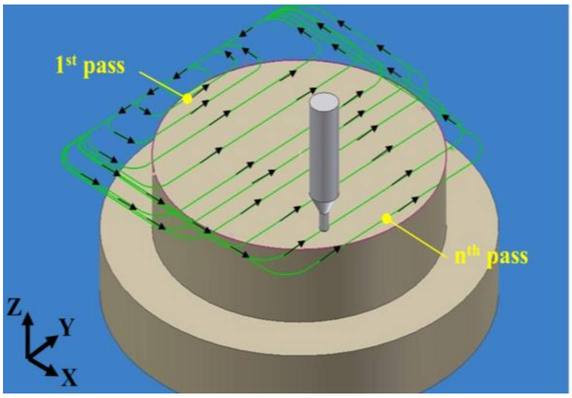


Fig. 5. Finishing tool path.

As concerning measurements (E in Fig. 1), a 3D optical measuring system (Alicona Infinite Focus©) was used prior to machining to determine the fresh tool geometry (Fig. 6a) and its effective outer diameter (Fig. 6b) (measurement parameters: 10x magnification, exposure time = 51.5 ms, anular light, estimated vertical and lateral resolutions = 0.06 μm and 4 μm). Table 2 summarizes the obtained results for the cross sections in Fig. 6b.

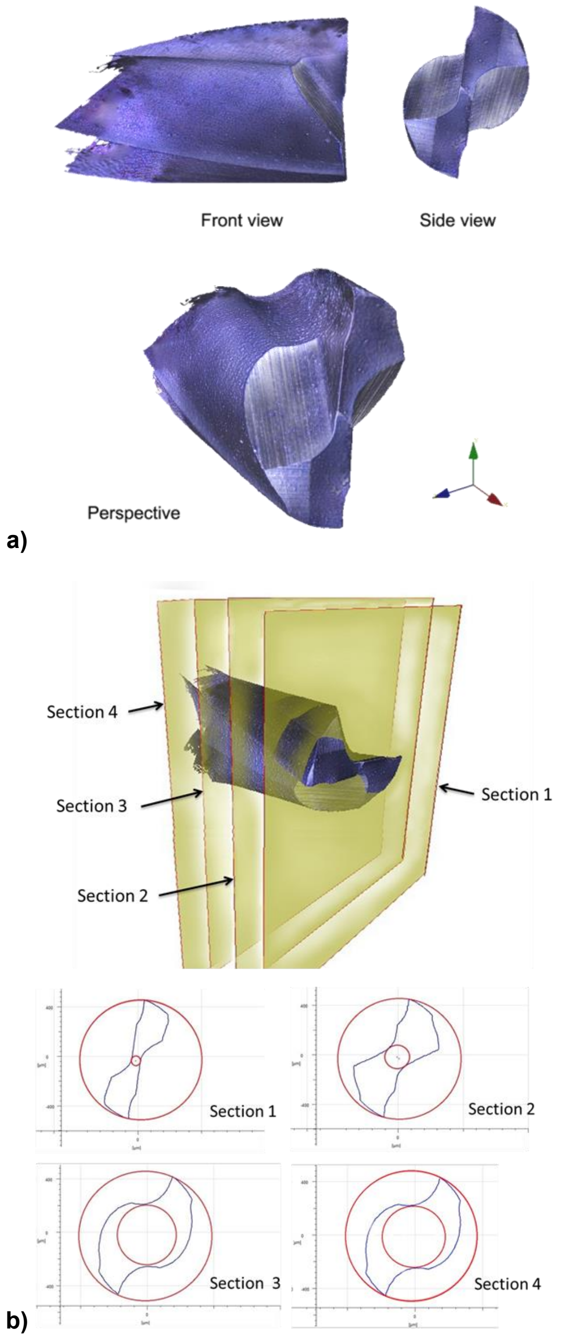


Fig. 6. Fresh finishing tool acquisition by Alicona Infinite Focus: a) 3D view and b) cross sections.

Table 2. Fresh tool measurement results.

Section	Distance from tool tip (mm)	Outer circle radius (μm)	Inner circle radius (μm)
1	0.08	243.3	482.0
2	0.14	258.7	463.3
3	0.30	100.4	489.4
4	0.50	39.3	485.3

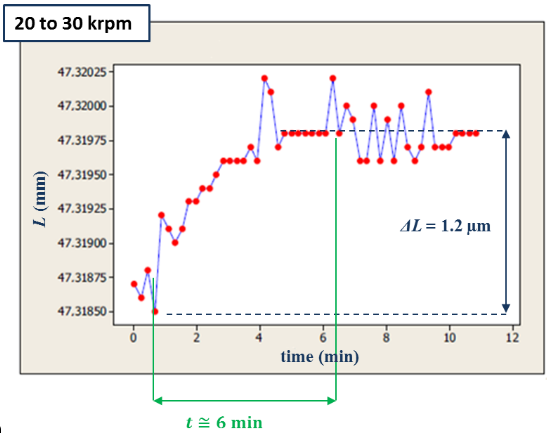
Onboard tool measurements (E in Fig. 1) were carried out by means of the Marposs VTS© (Visual Tool Setter) having a resolution of 0.1 μm and a repeatability of 0.2 μm (2σ). The VTS© thermal transient is managed by a proper warm-up strategy which is performed before machining. Prior to VTS© measurements the tool was carefully cleaned to remove chips that can affect tool length measurements.

Workpiece height measurements (E in Fig. 1) were performed by means of the m&h 32.00-MINI infrared touch probe with which the Kern EVO machining center is equipped. Workpiece flatness is then evaluated by the workpiece height variation throughout its surface.

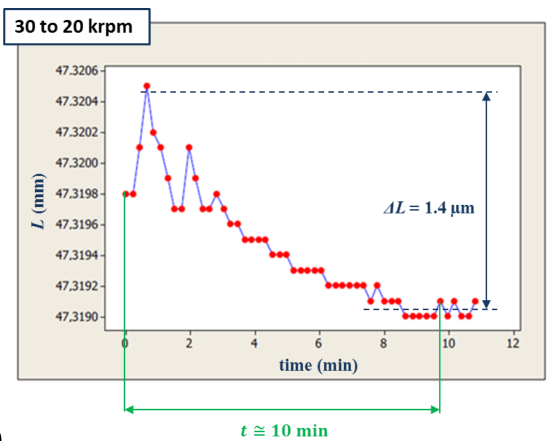
4. Experiments

Experiments carried out in the frame of this study have been divided in two parts. The first part (Section 4.1) deals with the machine spindle thermal transient when changing its rotational speed and the way to minimize its effect on the workpiece final accuracy by means of proper warm-up procedure before machining. The second part (Section 4.2) deals with the procedure applied to compensate other real or fictitious tool length variations along the machining cycle.

4.1. Machine spindle warm-up



a)



b)

Fig.7. Acquired tool length variation caused by a step change of spindle speed regime: a) increasing spindle speed, b) decreasing spindle speed.

Thermal transients affect the machine spindle depending on its rotational regime, thus the tool length acquired by the VTS© fictitiously varies because of spindle thermal deformations. Tool length value becomes stable only after a certain time from the spindle speed step variation. Fig. 7 depicts tool length measurements carried out after a spindle speed variation from 20000 rpm to 30000 rpm and vice versa. The graphs show how the tool length stabilization requires a few minutes.

The idea applied in this study has been to minimize fictitious tool length variations as much as possible before machining. In order to try to overcome spindle thermal transient issues, the spindle was warmed-up for 20 minutes at each one of the steps applied to achieve the working speed (10000 rpm, 20000 rpm and 50000 rpm). This procedure was carried out prior to each machining operation.

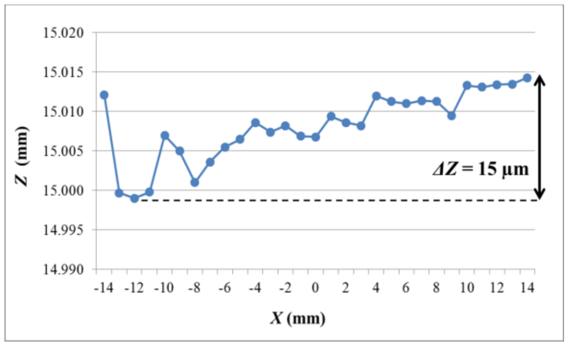
4.2. Tool length variation compensation

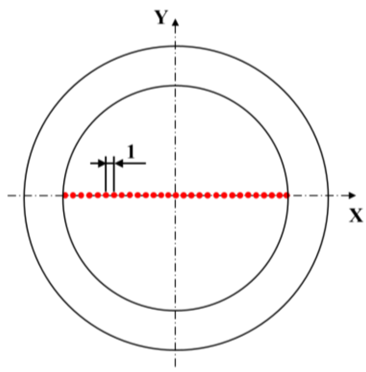
This Section presents tool length variation effects on workpiece flatness deviation and shows the effectiveness of two implemented tool length compensation methods, called “basic approach” and “advanced approach”.

4.2.1. Basic approach

The whole surface was machined uninterruptedly after the initial tool length measurement. Fig. 8a shows the results of the height measurements performed by the touch probe along the X direction at a distance of 1 mm from each other (Fig. 8b).

a)





b)

Fig.8. Surface height measurements: a) results, b) measurement positions.

The graph shows that surface height increases with the milling passes and the achieved surface height variation is about 15 µm. This effect is probably due to a real or fictitious tool length variation during machining, which lasted 3 hours and 15 minutes. Real tool variations depend on tool wear while fictitious ones depend on spindle thermal deformations.

4.2.2. Advanced approach

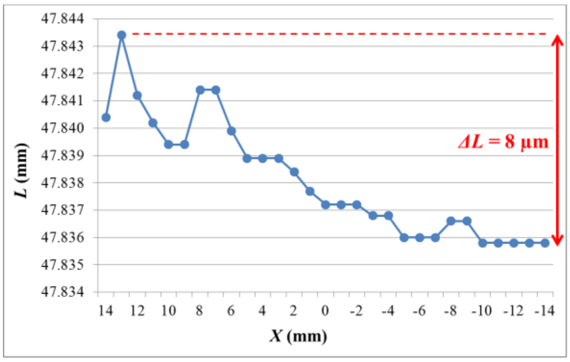
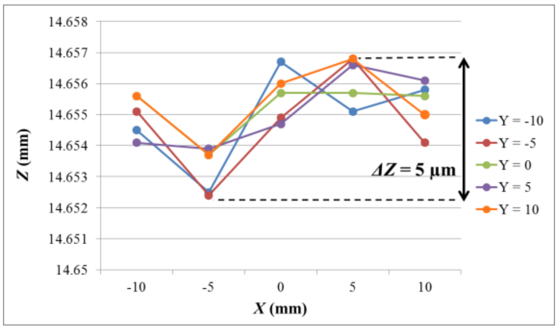
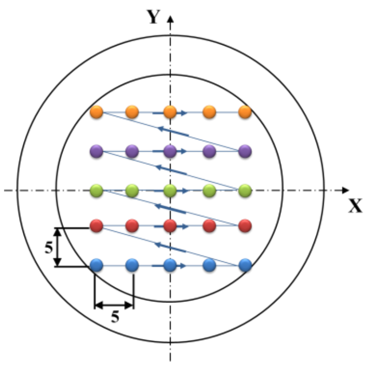


Fig. 9. Tool length variation acquired by the VTS© as required by the advanced tool length compensation approach.

In order to compensate tool length variations, a new machining strategy has been designed and a new finishing mill of the same kind was used for the experiment: after the mill moved 1 mm in X direction (i.e. every 50 passes), its length was measured by the VTS© (measurement results in Fig. 9) and the new tool length was provided to the machine tool NC.

a) 



b)

Fig.10. Surface height measurements: a) results, b) measurement positions.

The final surface height (Fig. 10a) was measured at the positions indicated in Fig. 10b to better describe the achieved results. Absolute surface height corresponds to the final workpiece thickness that is not coherent with the drawing of Fig. 2. In fact, a complete machining cycle composed of roughing and finishing was applied on the same workpiece for both the basic and advanced approach without removing it from the fixture. This fact reduced the workpiece thickness. In any case, only the workpiece flatness deviation was important for the purpose of this study.

As it can be noticed in Fig. 10a, the improved tool length compensation approach allowed to achieve a lower surface height deviation. This fact would prove that such an approach is able to face tool length variations (Fig. 9) both in case they are real (depending on tool wear) and fictitious (depending on spindle thermal deformations).

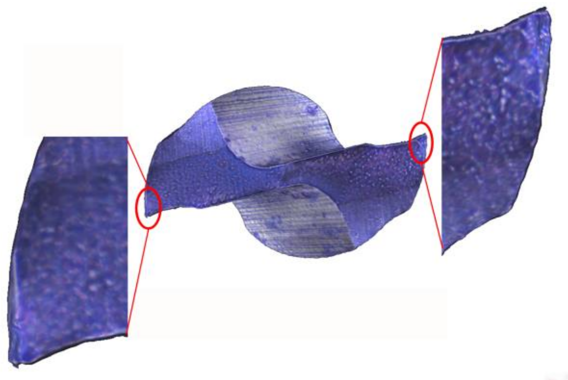


Fig. 11. Alicona Infinite Focus acquisition of tool after machining with the advanced compensation approach.

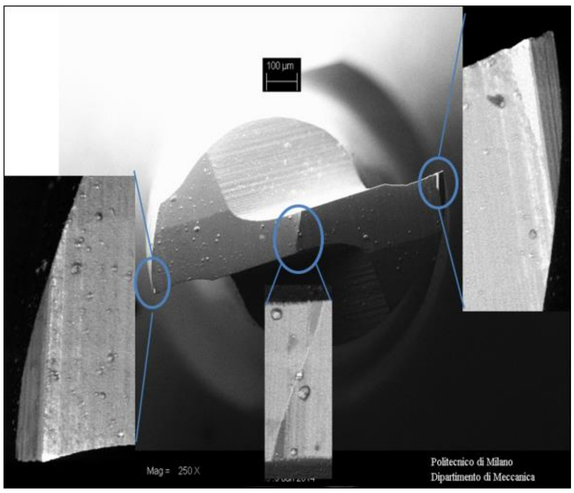


Fig. 12. SEM picture of tool after machining with the advanced compensation approach.

Regarding tool wear, Fig. 11 shows the Alicona Infinite Focus acquisition of the finishing tool after machining with the advanced tool length compensation approach. It seems that no wear occurred as qualitatively confirmed by a SEM picture (Fig. 12) of the same tool. Tool wear should not be the cause of the acquired tool length variation

(Fig. 9), so only spindle thermal deformations seem to play a fundamental role, in this case, being responsible of fictitious tool length variations. The proposed advanced approach is able to tackle this issue.

The drawback of the achieved workpiece quality improvement is the machining time increase: the machining cycle was 4 hours and 10 minutes long against a 3 hours and 15 minutes duration for the basic approach.

It is clear how a residual surface height error still remains due to non considered factors. For example, some machine spindle instabilities are likely to occur due to the required high rotational regime, at the limit of its allowed range.

5. Conclusions and future developments

The present study demonstrates how machine spindle thermal transients and tool wear assessment play a fundamental role on the final accuracy of a micromilling operation.

Flatness deviation on a large workpiece area was used as a quality indicator and appropriate procedures were applied to reduce the effects of the machine spindle thermal transients and compensate tool length variations due to wear.

Final results achieve a 5 μm height variation on the workpiece surface.

As a residual surface height error still remains after applying a tool length compensation strategy, further studies are needed to determine and compensate other factors acting on the final workpiece.

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