Geometrical quality improvement of high aspect ratio micromilled pins

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ABSTRACT
Mechanical micromachining is a reference process for producing 3D complex microparts and specifically tools for other processes as molds for micro injection molding and males for microextrusion. High aspect ratio features as bars, ribs, pins, etc. are very common in these cases and their quality strongly affects the final plastic part quality. This paper focuses on high aspect ratio steel pins, since they are one of the most challenging features to be manufactured on microextrusion males. The pin geometrical quality has been defined according to the standards and a suitable measurement procedure has been set up with the aim to study the micromilling process parameters effects on the most representative pin quality characteristics. The statistical analysis results point out some criteria for selecting the best process parameters.

KEYWORDS
Micromilling, pin, geometrical quality, out of straightness, ANOVA

INTRODUCTION

Micromilling is one of the most versatile tooling processes in the microfield since it is able to effectively manufacture 3D features on molds and dies (Figure 1). The final quality achieved by micro injection molding and micro extrusion is strongly affected by the micromilling performance. This is the reason why it is crucial to correctly select micromilling parameters in function of the target feature geometry.

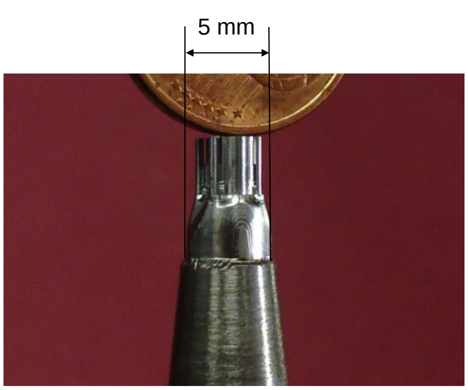

Figure 1. High AR pins in a microextrusion male manufactured by micromilling in the frame of the MuProD European project (references in the Acknowledgement Section)

Typical and challenging features in micromilled parts are high aspect ratio (AR) ones, such as bars, ribs and pins [1-2]. In particular, pins are very critical since they are one of the less rigid features, where micromilling forces tend to produce deformations or breakage. This means that micromilling process parameters should be carefully designed and pin milling strategies have to be reconsidered to control the micropin geometrical accuracy.

Literature survey

Only a few studies dealing with micropin milling can be found in the literature and they simply aim at demonstrating the process capability to machine high aspect ratio pins, without investigating the best machining conditions to obtain good quality pins. Pin quality definition itself lacks in the literature.

The study of Bang et al. [3] describes the design and testing of a selfmade PC-based 5-axis micromilling machine. The authors machined several features, such as thin walls, high AR pins, micro impellers and micro blades to validate their machine design. Regarding pins, they obtained 30 μm diameter pins with a height of 650 μm (AR = 21.6) on brass. The pins were machined by rotating them along their axis, hence using the milling machine as a lathe. However, the authors did not point out the relationship between process parameters and workpiece quality.

Bordatchev et al. [4] used brass as target material and machined pins with a maximum AR of 30 (diameter = 200 µm; height = 6 mm). No different process parameter sets were investigated and no detailed workpiece quality measurements were performed in this study.

Specific literature do not provide knowledge helping to select the process parameters and to identify quality outcomes in pin micromilling. Moreover, no systematic approaches exist dealing with relationships between process parameters and workpiece quality.

Previous studies [5-6] by the present authors pointed out the process parameters effect on workpiece quality and cutting forces in case of thin wall manufacturing. A similar approach is considered in the present study taking into account high AR micropins manufacturing.

OBJECTIVES AND DEFINITIONS

The main aim of the present study is to improve the current knowledge on micropin milling. The present paper presents an approach to identify the relationships between process parameters (axial depth of cut a_p, radial depth of cut a_e, feed per tooth f_z and milling strategy) and workpiece geometrical quality with the purpose to achieve some useful process parameter selection criteria.

This Section describes quantities, procedures and conventions applied in this study to achieve the defined objective.

Workpiece and fixture geometry, machining center and working operation definition

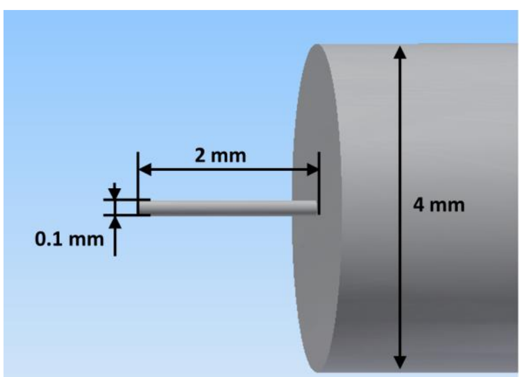

Figure 2. Target feature.

The target feature of the present study (Figure 2) is a pin with AR equal to 20 (diameter = 100 µm, height = 2 mm) made of 0.4 % Carbon steel (C40). A single pin configuration has been considered, where no constraints exist on the mill dimensions. Multiple pin configurations (pin matrixes) will be studied as a future development.

The Kern EVO ultra precision 5-axis machining center available at the "MI_crolab" of Dipartimento di Meccanica of Politecnico di Milano (nominal positioning tolerance = ± 1 µm, precision on the workpiece = ± 2 µm) has been used to machine the studied pins.

Pins have been obtained from 12 mm long and a 4 mm wide previously turned rough cylindrical workpieces (Figure 2) held by a properly designed fixture (Figure 3), where two grains act along the *X* and *Y* machine axes to steadily maintain the work position. This fixture is held by a clamping system fixed on the machine table.

The machine touch probe touched the rough cylinder to accurately acquire the position of its axis and top surface and consequently define the reference system for the following machining operations.

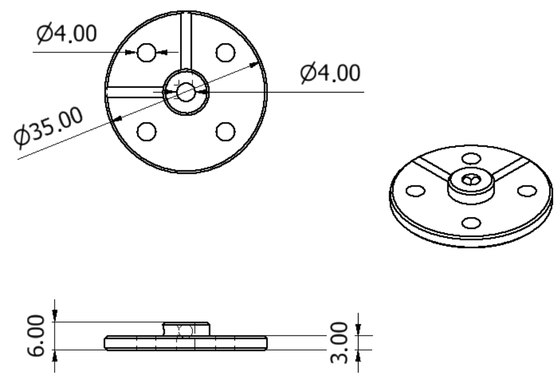

Figure 3. Workpiece fixture.

As the final pin quality is the relevant feature, process parameter have been varied only for the finishing operation while roughing milling operations have been performed with constant parameters before each run using a specific roughing tool. All machining operations have been performed by Sandvik CoroMill Plura carbide end-mills, whose characteristics are summarized in Table 1.

Regarding the pin manufacturing cycle, first of all a 6 mm diameter mill has been used for face milling the top workpiece surface; then, a 2 mm diameter mill has been used for pin roughing, i.e. for reducing the rough cylinder diameter to a value defined by the radial depth of cut a_e required by the finishing operation of each single run.

Eventually, a helicoidal tool path (Figure 4b) has been designed for pin finishing. Similarly to the "step support" tool path (Figure 4a) used in thin wall milling [5-7], the helicoidal tool path allows to partially support the pin when milling the opposite side.

A 2 mm diameter mill has been selected for the finishing operation in order to count on a rigid tool and consider all deflections as belonging to the pin.

Table 1. Roughing and finishing mill characteristics.

Operation	Mill				
	Code	Cutting diameter	Teeth number	Helix angle	Radial rake angle
		D_c	z	θ_h	γ_f
Face milling	R216.12-06030-BS07P	6 mm	2	30°	10.5°
Pin roughing	R216.32-02030-AC60P	2 mm	2	30°	10.5°
Pin finishing					

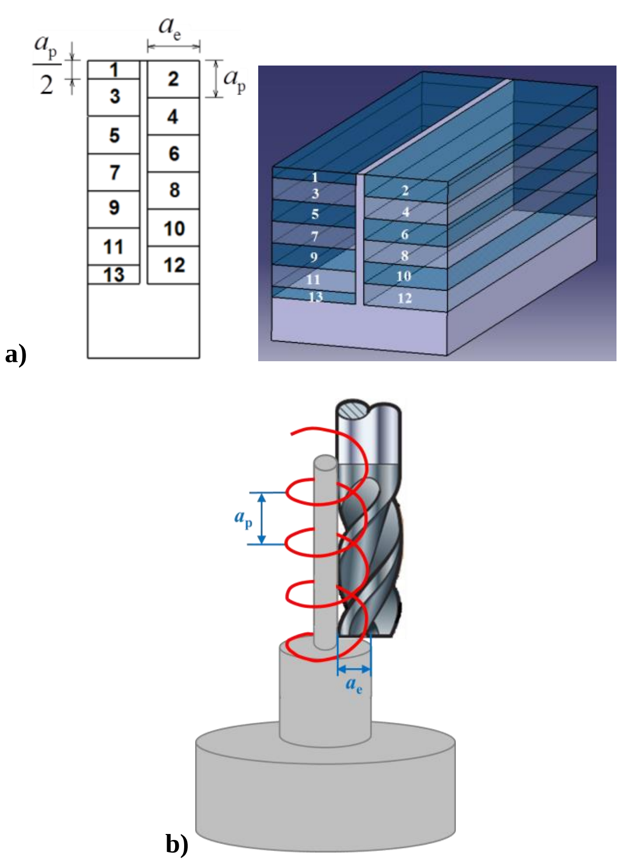

Figure 4. a) step support and b) helicoidal tool paths.

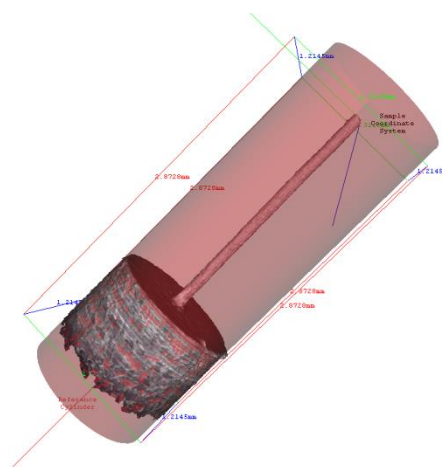

Figure 5. Pin geometry acquired by Alicona Infinite Focus.

Pin measurements

Pin geometrical quality has been evaluated in terms of three quality characteristics, namely the diameter absolute error, the taper ratio and the axis "out of straightness" [8-11].

Pin measurements have been acquired by the focus variation technique implemented in the Alicona Infinite Focus optical 3D measuring system (outcome example in Figure 5) available at the MI_crolab.

Starting from the measured point clouds, all the quality characteristics of interest are computed as follows.

First of all, points at the top and at the bottom of each pin are not included in the analysis because defects like burrs at the top and striations at the bottom greatly affect repeatability at these two extreme zones of the pin. Blue planes shown in Figure 6 are thus used as thresholds to get rid of the extreme unstable zones.

Then a reference Cartesian Coordinate System was computed for each pin. As a matter of fact, geometric form tolerances (as the axial straightness or the cylinder diameter) are used to place constraints on the difference between the actual shape and the ideal one. By definition, this difference should not be affected by the location of the shape of interest [8, 11]. The least-square cylinder (Figure 7) was firstly computed starting from the point cloud acquired on the pin surface.

The diameter D_{eff} of this least-square cylinder is used as reference to represent the pin diameter and is used to compute the diameter absolute error *err* as:

$$err = D_{\text{eff}} - D_{\text{nom}} \tag{1}$$

where D_{nom} represents the pin nominal diameter (100 µm).

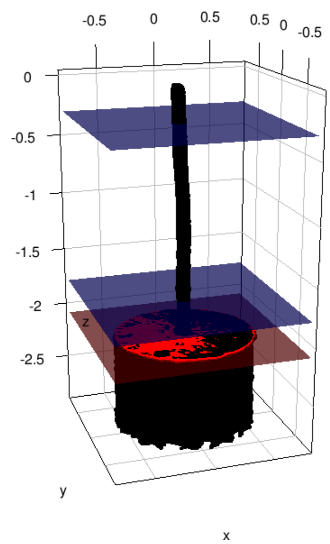

Figure 6. Pin point cloud selection discarding the highest and the lowest part.

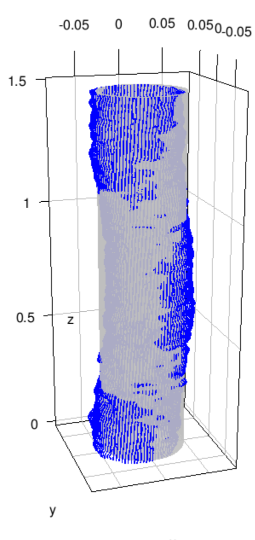

Figure 7. Least squares cylinder (grey) approximating the pin point cloud (blue).

The axis of the least-square cylinder is used as reference *Z* axis for each cylinder. In order to compute the out of straightness and the taper ratio, the cylinder is sliced (Figure 8) considering a set of planes orthogonal to the *Z* axis. According to the standards [8], the axis is the locus of the centers obtained by sectioning the cylinder at different heights [8-11].

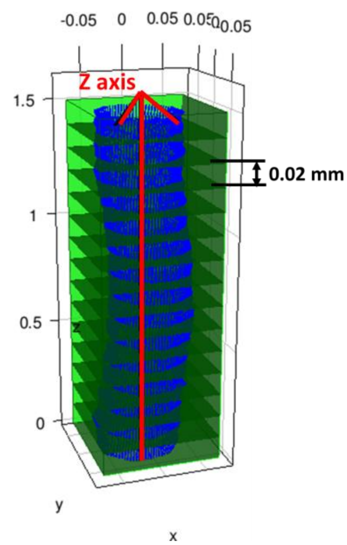

Figure 8. Pin segmentation.

All the points between two slices are assumed as lying (approximately) at the same Z-height and are thus used as reference to fit a least-square circle. The radius of each least-square circle is then used as reference to compute the taper ratio index t_r. This ratio should represent an increase (or decrease) of the cylinder radius as a function of the cylinder height and is hence computed as the slope of the straight line fitting the radius of the least-square circle computed on each slice as a function of the Z-position of the slice itself (Figure 9).

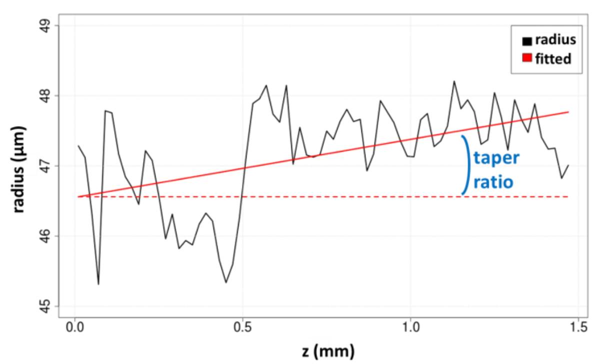

Figure 9. Taper ratio t_r calculation.

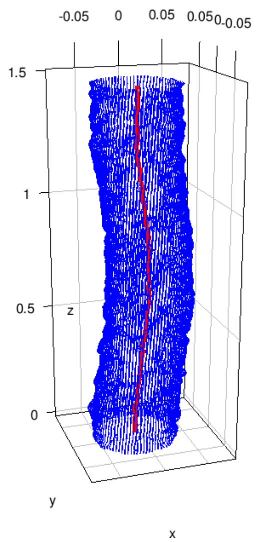

Figure 10. Pin point cloud (blue) and axis (red).

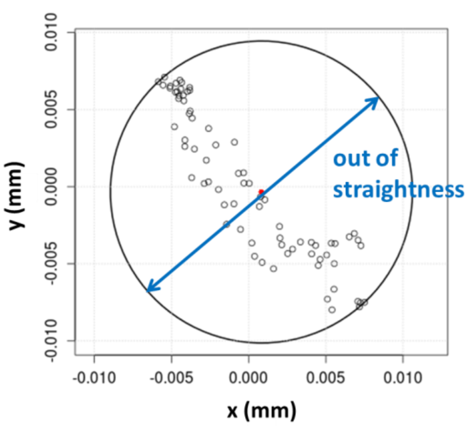

Figure 11. Out of straightness *oos* calculation basing on axis points (top view).

Eventually, the centers of all the sliced circles are used to compute the pin axis, which was clearly not a straight line (Figure 10). The straightness form error of this axis, called "out of straightness" *oos*, is eventually computed as the diameter of the minimum circumscribed circle containing all the pin axis points. .Figure 11 shows all the axis points projected on the XY plane and the corresponding *oos* value (diameter of the circle including all the points).

All the computations were carried out using the C++ library *Point Cloud Library* (PCL) [12] and in particular the RANdom Sample Consensus (RANSAC) algorithm [13] and the Eigen library [14].

EXPERIMENTAL DESIGN

A proper factorial experimental design has been prepared in order to point out the effects of the selected process parameters (axial depth of cut a_p, radial depth of cut a_e (Figure 4), feed per tooth f_z and milling strategy) on the pin geometrical quality characteristics.

A 2^4 factorial design, replicated three times, has been defined. Some central points have been added to the plan for all the factors, with exception of the strategy (a central point makes no sense for the strategy). In particular, 6 central points have been added for both the strategy levels, for a total of 12 central points. Therefore, the whole experimental design has consisted of 60 runs, which have been completely randomized.

The experimental design in summarized in Table 2. The selected factor levels have been determined in a preliminary experimental campaign based on the mill manufacturer manual.

Table 2. Experimental design summary.

Factor	*Symbol*	*Uncoded levels (coded levels)*
axial depth of cut	a_p	0.066 (-1), 0.133 (0), 0.2 (1) mm
radial depth of cut	a_e	0.2 (-1), 0.5 (0), 0.8 (1) mm
feed per tooth	f_z	12.5 (-1), 18.5 (0), 24.5 (1) μm/rev
strategy		up-milling, down-milling

EXPERIMENTAL RESULTS

The first result has pointed out as up-milling strategy has been clearly not suitable for pins since all runs performed by the up-milling strategy caused a pin breakage.

Only down-milling runs is thus in the following and a three factors (a_p, a_e and f_z) complete model has been analyzed.

The analysis of variance (ANOVA) results on the pin geometrical quality characteristics have been summarized in Table 3**.**

As concerning t_r, the variance homogeneity hypothesis is not satisfied, hence a weighted ANOVA has been performed.

Table 3. ANOVA p-values (dark grey = significant factor, grey = nearly significant factor, confidence level α = 1%.

		Factors						
		Axial depth of cut (a_p)	Radial depth of cut (a_e)	Feed per tooth (f_z)	a_p*a_e	a_p*f_z	a_e*f_z	$a_p*a_e*f_z$
Response	Diameter absolute error (*err*)	**0.0000**	0.4347	0.0988	0.6517	0.5715	0.1182	0.1512
	Taper ratio (t_r)	**0.0053**	0.0272	**0.0013**	**0.0006**	0.0180	0.3926	0.1645
	Out of straightness (*oos*)	**0.0000**	**0.0000**	**0.0068**	0.0354	**0.0016**	0.6875	**0.0061**

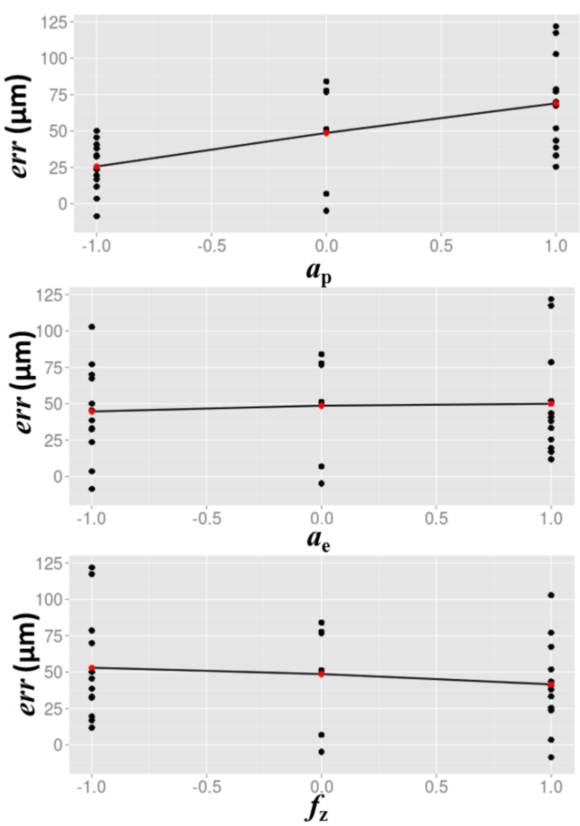

Figure 12. Interval plot of the diameter absolute error *err* against factors (the black line connects mean values).

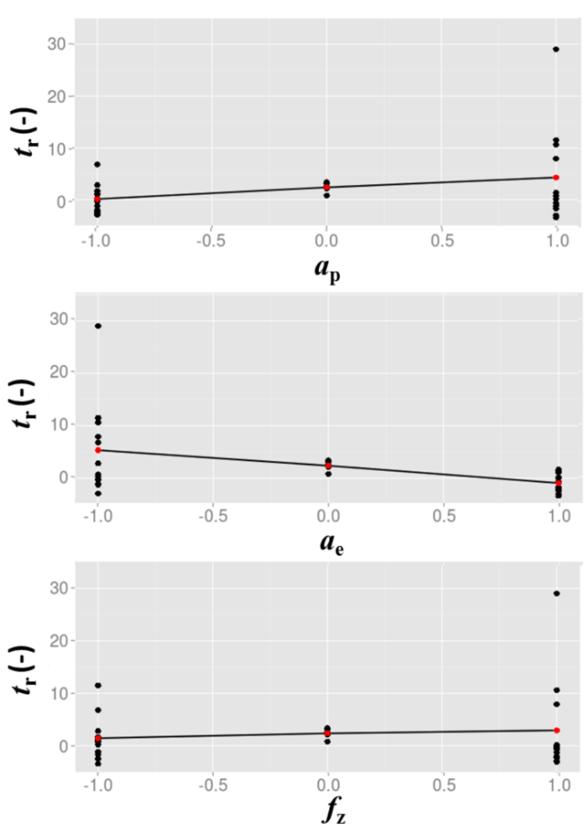

Figure 13. Interval plot of taper ratio t_r against factors (the black line connects mean values).

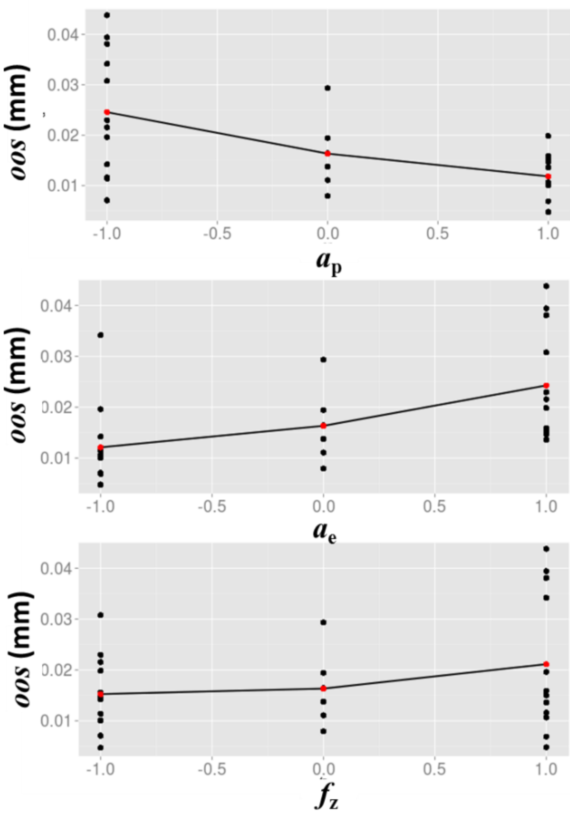

Figure 14. Interval plot of the axis out of straightness *oos* against factors (the black line connects mean values).

The ANOVA p-values show how all the considered factors affect the pin geometrical quality.

In particular, the taper ratio t_r (Figure 13) increases as the a_p increases: the higher force values produced by high a_p probably cause larger pin deflections and hence a lower effective a_e with consequent higher final local diameters. This consideration is also supported by the diameter absolute error *err* results (Figure 12) that point out how the pin diameter is higher at high values of a_p. On the other hand, the out of straightness *oos* (Figure 14) reduces as a_p increases: this effect could be due to a higher and more homogeneous elastic recovery after the pin deflection.

Moreover, the t_r (Figure 13) decreases as a_e increases, probably because higher a_e mean stiffer pins at the finishing pass, i.e. more support to the pin on the opposite side of the mill.

Summarizing the a_p and a_e effects, it seems that it is convenient to apply higher a_p to obtain more straight pins and to compensate the undesired pin taper by using higher a_e, paying attention to the negative a_e effect on pin straightness.

Finally, as can be seen in Figure 13 and 14, a lower f_z improves the pin geometrically quality in terms of t_r and *oos* because it makes the cutting force lower, even if attention has to be paid to the minimum chip thickness effect, according to which it is convenient not to use too small values of f_z to avoid high thrust forces that could deflect the pin.

According to the mentioned results, the best factor combination, as a compromise among the different errors, has been: $a_p = 1$, $a_e = 0$ and $f_z = 0$ (coded levels).

If only the pin straightness is the manufacturing target, the parameter combination $a_p = 1$, $a_e = -1$ and $f_z = -1$ (coded levels) should be applied as demonstrated by the low value of *oos* obtained in this case.

These results are useful criteria to choose the correct parameters combination to obtain the best pin geometrical quality in case of high AR pin micromilling (Figure 15).

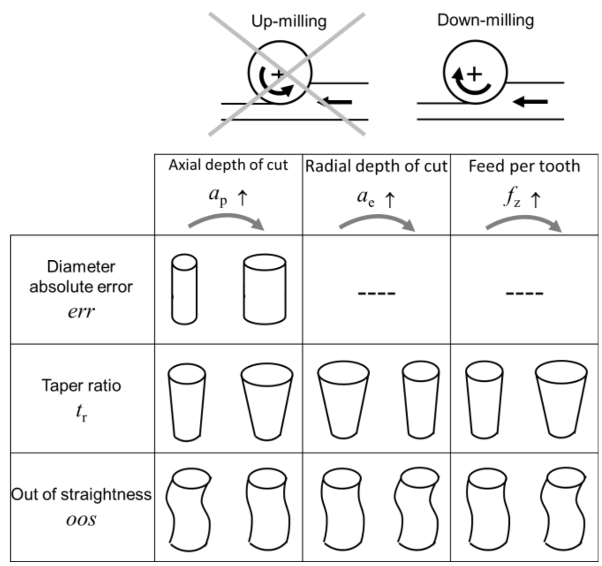

Figure 15. High AR micromilling parameters selection rules

CONCLUSIONS AND FUTURE DEVELOPMENTS

The present paper has investigated the effect of the typical micromilling process parameters (axial depth of cut a_p, radial depth of cut a_e, feed per tooth f_z and milling strategy) on the geometrical quality of high aspect ratio pins. The studied pin quality characteristics have been the diameter absolute error, the taper ratio and the straightness deviation, able to capture the main pin geometrical characteristics.

The objective to point out some selection rules for the micromilling process parameters in function of the main pin accuracy target has been achieved.

Future developments of the presented research will validate the obtained results on different pin materials and dimensions. Pin matrixes will be also considered, with their constraints on the mill dimensions.

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