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Enhancing machined surface quality through optimized CAD/CAM interpolations and tolerance adjustments

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ABSTRACT

The VP50 steel, characterized by its bainitic/martensitic microstructure, poses significant machining challenges, including elevated cutting forces and heat generation. These factors directly impact surface roughness, as hardened surfaces tend to exhibit greater irregularities when cutting parameters or tools are not properly optimized. The objective of this study is to critically analyze the quality of machined surfaces using CAD/CAM programming tools during the milling of VP50 steel cavities with spherical-tip carbide inserts. The analysis focuses on the influence of two types of interpolations (linear and circular) and tolerances (0.05 mm and 0.1 mm), which define the tool path during the machining of a three-dimensional cavity. Surface roughness and geometric accuracy were selected as the primary responses due to their crucial role in determining the functional performance and quality of machined components. These indicators are widely used in the literature as key metrics for evaluating the efficiency of machining strategies and the impact of CAD/CAM parameters on the final product quality. The results indicate that circular interpolation with a 0.1 mm tolerance is the most effective option for minimizing shape deviations and enhancing process accuracy.

Keywords: VP50 Steel; Bainitic/Martensitic Microstructure; Machining Surface Quality; CAD/CAM Programming; Circular Interpolation.

1. INTRODUCTION

In machining operations, the primary objective is to produce components that maximize functionality and interchangeability, while minimizing costs and ensuring high productivity [1]. This requires that every part or assembly of a final product adhere to strict specifications regarding dimensions, shape and surface finish [2, 3]. In milling, quality and surface integrity are of paramount importance, as they directly influence the product's appearance, functional performance and dimensional stability [4]. These quality attributes are affected by various factors, including feed rate, cutting speed, depth of cut, machining time, tool radius and angle, workpiece geometry, material hardness, machine stability and the use of cutting fluids, among others [5]. Additionally, dimensional accuracy is critical to ensure that the manufacturing process consistently meets the required product specifications [6].

In this context the CAD/CAM platform has become a significant factor in manufacturing, especially on complex surfaces parts, mainly because of surface quality, reliability and product competitiveness [7–9].

After manufacturing a component, it is essential to measure the dimensions of the finished part and evaluate any deviations from the dimensions specified by the designer [10]. These deviations must fall within defined tolerances, which determine the suitability of the part for its intended function [11, 12].

During the manufacturing process, the shape and relative positioning of geometric elements often deviate from their ideal configurations. If such deviations impact the functionality of the part, the application of tolerances becomes necessary [13]. These tolerances, which account for deviations in shape, orientation, position and runout are collectively referred to as geometric tolerances. When analyzing surface quality and dimensional deviations, it is crucial to consider all stages of the manufacturing process [14, 15].

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The choice of interpolation type (linear or circular) and tolerance directly affects the accuracy, surface finish and efficiency of the machining process for three-dimensional cavities. Linear interpolation, although widely used, can create discontinuities in the tool movement, increasing vibrations and wear. In contrast, circular interpolation enables smoother trajectories, improving surface quality and reducing mechanical stress. Regarding tolerances, a smaller one ensures higher precision and better surface finish but increases processing time, while a larger one speeds up machining but may compromise geometric accuracy. The optimal choice should balance precision, machining time and tool integrity according to project requirements [16–18].

AMIN *et al.* [19] examined factors influencing mold and die manufacturing in milling operations by varying interpolation methods to assess surface finish. Their findings indicated that linear interpolation resulted in unsatisfactory surface quality, attributed primarily to operational vibrations. Silveira (2002) conducted a study on the surface roughness of ABNT H13 steel using a toroidal cutter with a 12 mm diameter [20]. COELHO *et al.* [21] explored the roundness and roughness of hardened AISI H13 steel (52 HRC) in end milling operations, producing 50 mm diameter cylindrical cavities through circular interpolation. DE SOUZA[22]analyzed the surface roughness of AISI P20 steel (30 HRC) during end milling with 6 mm diameter ballnose cutters in the finishing stage. KORKUT *et al.* (2007) investigated surface roughness in tangential milling of AISI 1020 and AISI 1040 steels [23]. KESAVALU and SUBRAMANIAN [24] optimized surface roughness values during the machining of stainless steel alloys based on a Taguchi L27 orthogonal array. The results indicated that the feed rate significantly influenced the outcomes. MARTINS *et al*. [25] studied the influence of different machining strategies on the surface roughness, residual stresses, and fatigue life of tempered and quenched AISI 4140 steel (40 HRC). The greatest influence on surface roughness was due to variations in feed, which resulted in higher roughness values for higher feed rates.

In another study, DE SOUZA *et al*. [26] analyzed the effect of interpolation methods (linear and polynomial) on the surface finish of the Ti6Al4V alloy during down milling operations. The experiments utilized P10 carbide tools coated with TiAlN and applied cutting fluid. Similarly, MESQUITA *et al.* [27] conducted an experimental investigation on the influence of end milling on AISI 1020 steel, employing carbide cutters with rounded tips (32 mm in diameter) coated with TiN. Furthermore, NUNES *et al.* [28] developed CAM programs with linear and polynomial interpolation methods, as well as tolerances of 0.001 mm and 0.025 mm, to examine the surface roughness behavior of the 7050-aluminum alloy during end milling. The study used spherical carbide end mills with a diameter of 10 mm. THO [29] investigated that the increase in machining forces leads to higher surface roughness, consequently reducing the quality of the manufactured part. EL-MIDANY *et al*. [30] concluded that optimizing the tool path depends on both the geometry of the surface boundaries and the cutting conditions. CASTANHEIRA *et al*. [31] investigated the influence of two different milling strategies on the quality of a convex surface in two types of materials. Surface quality was evaluated using various roughness parameters, which were correlated with the perceived gloss and analyzed alongside the characteristics of each material, such as hardness and microstructure.

This study aims to evaluate the impact of interpolation type and tolerance settings in the TopSolid CAM program on the quality of parts produced through end milling. The material utilized in the experiments was VP 50 steel and the output variables analyzed included surface roughness, curvature radius and line shape deviation. This type of milling investigation holds significant practical relevance, particularly in the manufacturing of injection mold cavities, as it facilitates the optimization of machining parameters, minimizes tool wear and enhances surface finish quality, thereby improving overall process efficiency and functionality. Moreover, such research contributes to advancements in sustainability and technological innovation in manufacturing. To support the analysis of the results, the statistical tool Analysis of Variance (ANOVA) was employed.

2. EXPERIMENTAL METHOD

The material utilized in this study was VP 50 tool steel, characterized by a bainitic/martensitic microstructure. As noted in [27], this is a precipitation-hardened steel with a hardness of approximately 40 HRC. Unlike tempered steels, this treatment provides advantages such as reduced distortions, ease of production, and simplified mold maintenance. The test specimens were rectangular, with dimensions of 218 × 210 × 25 mm.

The experiments were conducted on a CNC Machining Center, model Discovery 760, manufactured by Romi, featuring an 11-kW power output and a maximum rotational speed of 10000 rpm. The machine is equipped with a Siemens Sinumerik 810D CNC, offering high processing capability and 2.5 Mbytes of available memory for program storage.

For the tests, GC-1010 (H10) ballnose carbide inserts coated with TiAlN via the PVD technique were utilized. These inserts, measuring 4 mm in thickness and 20 mm in length, were selected for their high wear resistance, thermal stability and spherical tip geometry, which enable precise machining of three-dimensional

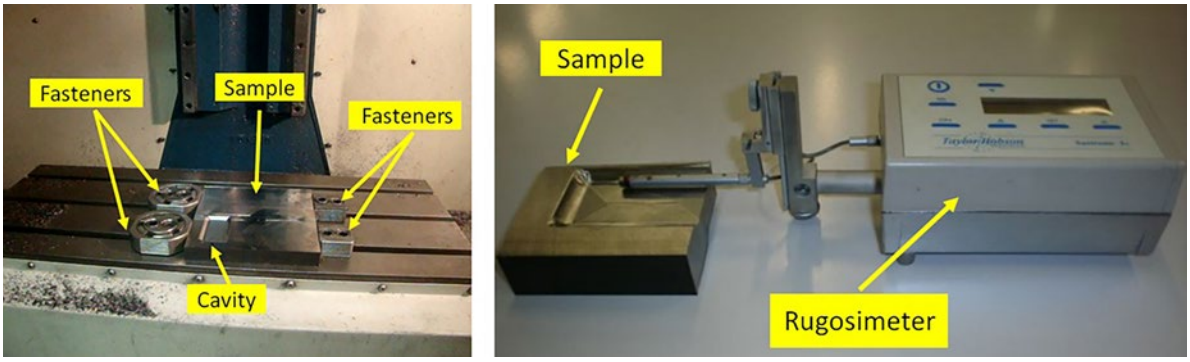

Figure 1: (a) Post-machining sample: (b) Surface roughness measurement.

and complex surfaces. Their reliability and versatility across different materials make them ideal for detailed and consistent analyses of machining processes [32]. The choice of this tool was driven by its spherical tip geometry, compatibility with the workpiece material, performance under key parameters such as speed and feed rate, cost-effectiveness, market availability, and suitability for the specific application.

As noted in [32], the geometry and grade of the tool are typical for end milling operations involving hardened steels with hardness exceeding 36 HRC. This tool is designed to meet a wide range of machining requirements, from roughing to finishing tasks. It is well-suited for operations that involve generating profiles or cavities with three-dimensional shapes (sculptured surfaces). Additionally, it offers high resistance to plastic deformation, thermal cracking and excellent wear resistance under severe machining conditions. The cutter, manufactured by Sandvik Coromant, accommodates two inserts and is specified as R216-20T1020, with a diameter of 20 mm and a length of 185 mm.

The roughness parameters were measured using a Surtronic3+ portable roughness meter (model 112/1590) manufactured by Taylor Hobson. To facilitate the measurements, the part was sectioned to allow better access for the roughness meter to the target region, as illustrated in Figure 1. For each machining condition, tests were conducted in duplicate, with roughness measured on each surface. The final value was determined as the average of three measurements. Both Rz and Rq parameters are crucial in the manufacturing of injection mold cavities, as they directly impact process efficiency, the quality of the final part, and the longevity of the mold. Controlling these parameters is vital to meet the technical and economic demands of the industry.

The tests were conducted using a 2^k factorial design, where k equals 2, representing the type of interpolation (linear or circular) and the dimensional tolerances (0.10 mm and 0.05 mm). During the experiments, the cutting speed (v_a = 200 m/min), feed per tooth (f = 0.15 mm/tooth), axial depth of cut (a_p = 0.45 mm) and lateral step-over (1.0 mm) were kept constant. These values were selected based on pre-experiments specifically aimed at optimizing surface roughness and ensuring machining stability. The definition of these cutting conditions was informed by a combination of technical literature, equipment and material limitations, and iterative adjustments during preliminary trials. By maintaining these parameters constant, the study ensured that the influence of CAD/CAM interpolation type and tolerance level could be accurately isolated and analyzed.

Following the machining process, the samples were prepared for shape error measurements. For roughness evaluation, measurements were taken in directions both parallel and perpendicular to the tool's advance marks, beginning at the position where the tool completed its cutting operation. For radius measurement, the contour line was used as the reference (Figure 2).

The radius of curvature and shape deviations of the machined parts were measured using a three-coordinate measuring machine (CMM) of the movable bridge type, manufactured by Mitutoyo (model BR-M443), with a resolution of 1 µm and a working volume of 400 × 400 × 300 mm for the x, y and z axes, respectively (Figure 3). A single probe with a 2 mm diameter ruby sphere was utilized during the measurements.

3. RESULTS AND DISCUSSION

3.1. Roughness

Figure 4 presents the roughness results measured in both the parallel and perpendicular directions. The roughness parameter Ra in the parallel direction ranged between 0.91 and 1.16 µm, while the Rq parameter varied from 1.18 to 1.38 µm, and the Rz parameter ranged from 4.78 to 5.71 µm. Although the variations in Ra and Rq

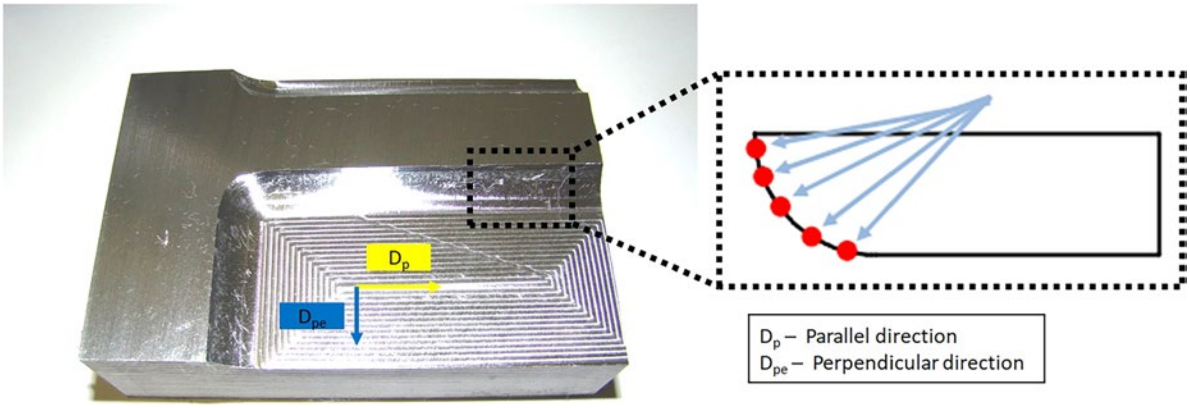

Figure 2: Areas designated for the measurement of roughness, radius of curvature and shape deviation.

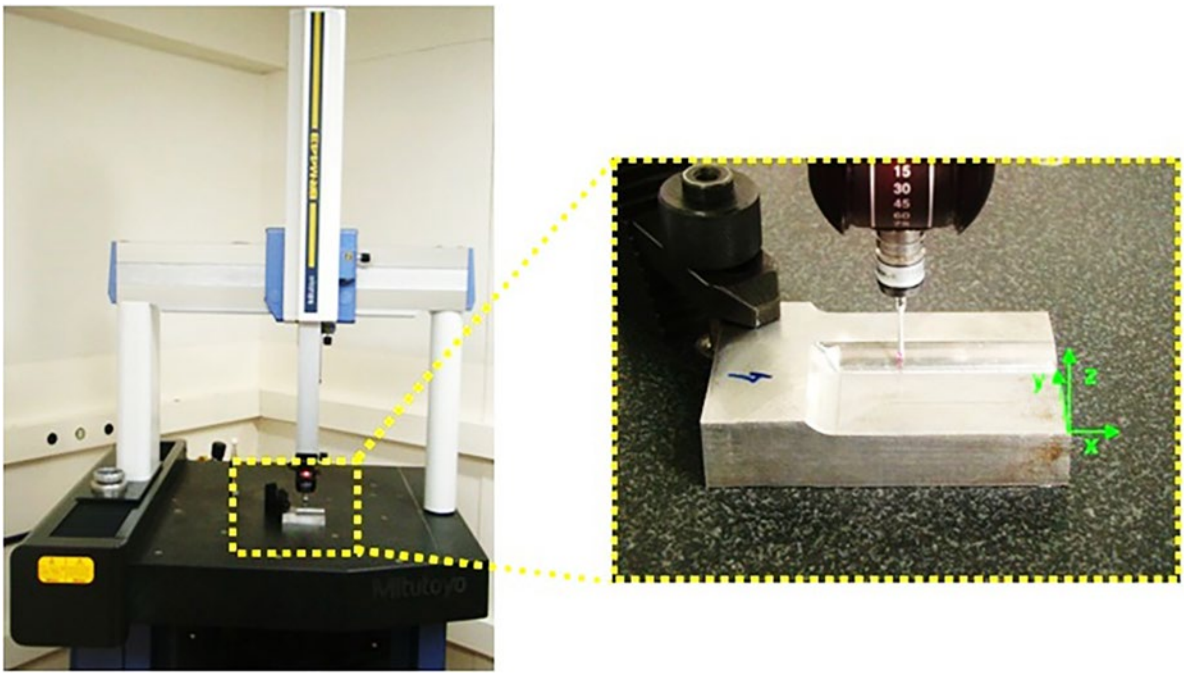

Figure 3: Measurement of the radius of curvature and shape deviation.

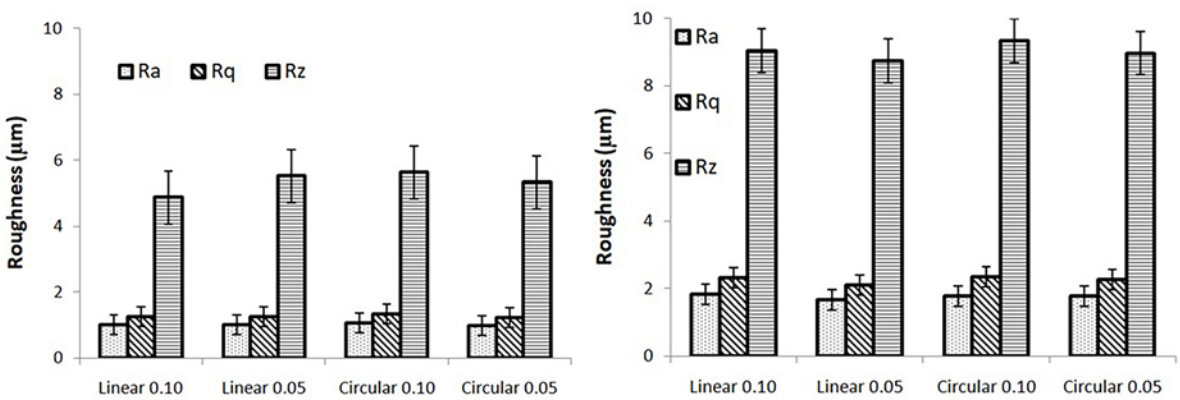

Figure 4: Surface roughness behavior: (a) Parallel direction; (b) Perpendicular direction.

values across all conditions in the parallel direction were negligible, this was not the case for the Rz parameter. In general, the Rz values were slightly lower when linear interpolation was employed, regardless of the type of tolerance applied.

In the perpendicular direction, the Ra and Rq parameters exhibited minimal variation under the evaluated conditions. However, for the Rz parameter, lower roughness values were observed when linear interpolation with a tolerance of 0.05 mm was applied. The roughness parameters measured in the direction perpendicular to the feed marks showed values ranging between 1.60 and 1.98 µm for Ra, 2.00 and 2.54 µm for Rq, and 7.70 and 10.30 µm for Rz. The bainitic/martensitic microstructure of VP50 steel significantly influences surface roughness due to its high hardness, wear resistance, and propensity to induce vibrations during machining. Nonetheless, the presence of bainite can enhance machining conformity and contribute to reducing surface roughness.

The differences in the dispersion levels among the roughness parameters Ra, Rq, and Rz can be explained by the intrinsic nature of each metric and how they respond to surface irregularities. While Ra and Rq represent average values of the surface profile and tend to smooth out local peaks and valleys, resulting in more stable and consistent measurements, Rz is highly sensitive to isolated surface anomalies, such as deep scratches or individual peaks. These can arise from minor vibrations, chip adhesion, or microstructural effects typical of VP50 steel. Therefore, even when Ra and Rq remain relatively stable, Rz values may show greater variation due to its sensitivity to extreme deviations on the surface.

For both measurement directions (parallel and perpendicular), the observed Ra values are characteristic of milling operations performed on hardened steels using carbide ball-end tools. Comparable results have been reported in the work of [26]. Additionally, it is evident that all roughness parameters (Ra, Rq and Rz) measured in the direction perpendicular to the tool feed marks are higher than those obtained when measuring in the parallel direction. This difference arises because the perpendicular direction aligns with the tool's movement path, where the feed marks left by the tool are most prominent on the surface.

It is important to note that the measurements were not simply aligned with the Cartesian axes of the part (horizontal and vertical), but rather oriented according to the feed marks left by the tool path. As the tool path involves interpolated (often circular) movements over a 3D surface, the most prominent feed marks may not be strictly horizontal. Therefore, the 'perpendicular' direction corresponds to measurements taken across the pattern of these feed marks, where surface irregularities are more pronounced.

Tables 1 and 2 illustrate the average percentage changes and statistical differences in roughness for the parallel and perpendicular directions, respectively. Positive values denote an increase in roughness, while negative values indicate a reduction. Statistically significant p-values, determined at a 95% confidence level. Notably, none of the comparisons revealed a statistically significant difference.

Table 3 presents the analysis of variance (ANOVA) for the roughness values measured across the different directions investigated in this study. The input parameters considered were the interpolation types combined with tolerance. The results indicate that none of the variables exerted a statistically significant influence.

3.2. Radius of curvature and shape deviation of anyline

Figure 5 illustrates the radius of curvature values for the part under various interpolation and tolerance conditions. The results indicate no significant variations overall; however, linear interpolation with a 0.1 mm tolerance tended to yield the most favorable outcomes. Notably, the smallest standard deviation variations were achieved with circular interpolation, corroborating its superior stability compared to linear interpolation. Consequently, the manufacturing process demonstrates higher precision when circular interpolation is employed.

Table 1: Mean percentage difference and roughness metrics in the parallel direction.

COMPARISON	R_a		R_q		R_z	
	DIFFERENCE	P-VALUE	DIFFERENCE	P-VALUE	DIFFERENCE	P-VALUE
Linear 0.10 → Linear 0.05	0.99%	0.9780	1.60%	0.9388	13.55%	0.3695
Linear 0.10 → Circular 0.10	4.95%	0.8940	6.40%	0.7603	15.61%	0.3093
Linear 0.10 → Circular 0.05	− 2.97%	0.9341	− 2.40%	0.9084	9.44%	0.5201
Linear 0.05 → Circular 0.10	3.91%	0.9111	4.72%	0.8185	1.81%	0.8857
Linear 0.05 → Circular 0.05	− 3.91%	0.9122	− 3.93%	0.8482	− 3.61%	0.7747
Circular 0.10 → Circular 0.05	− 7.54%	0.8256	− 8.27%	0.6766	− 5.32%	0.6699

Table 2: Mean percentage variation and roughness statistics along the perpendicular direction.

COMPARISON	R_a		R_q		R_z	
	DIFFERENCE	P-VALUE	DIFFERENCE	P-VALUE	DIFFERENCE	P-VALUE
Linear 0.10 → Linear 0.05	− 8.74%	0.5493	− 9.44%	0.4199	− 3.32%	0.6021
Linear 0.10 → Circular 0.10	− 3.27%	0.8185	0.42%	0.9692	3.32%	0.6015
Linear 0.10 → Circular 0.05	− 2.73%	0.8482	− 3.01%	0.7892	− 0.66%	0.9154
Linear 0.05 → Circular 0.10	5.98%	0.6761	10.91%	0.4009	6.87%	0.6746
Linear 0.05 → Circular 0.05	6.58%	0.6766	7.11%	0.5734	2.74%	0.6777
Circular 0.10 → Circular 0.05	0.56%	0.9394	− 3.41%	0.7603	− 3.85%	0.5348

Table 3: Variance analysis for surface roughness.

COMPARISON	PARAMETER	SS	D_OF	MS	F	P-VALUE
Paralleldirection	Ra	0.01000	3	0.00333	0.01	0.99
	Rq	0.02107		0.00702	0.02	0.99
	Rz	1.04258		0.34751	0.11	0.94
Perpendicular direction	Ra	0.04387		0.01462	1.10	0.40
	Rq	0.09983		0.03328	1.35	0.32
	Rz	0.55001		0.18332	0.18	0.90

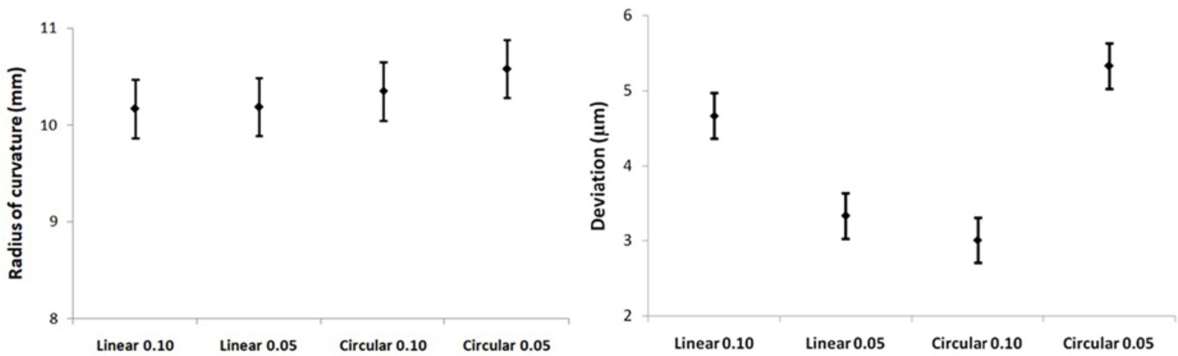

Figure 5: (a) Radius of curvature behavior; (b) Shape deviation behavior.

Table 4 summarizes the average percentage differences and statistical variations in the radius of curvature and shape deviation. The analysis indicates no statistical differences in the comparisons of curvature radius values. For the shape deviation results, only the comparisons 'Linear 0.10 → Circular 0.05' and 'Linear 0.05 → Circular 0.10' showed no statistical differences. The largest percentage difference was observed in the comparison 'Circular 0.10 → Circular 0.05' (77.07%). Notably, if a 90% confidence level were applied, the comparison 'Linear 0.10 → Circular 0.05' would also exhibit a statistically significant difference (p-value < 0.1).

Table 5 presents an analysis of variance (ANOVA) conducted on the results for shape deviations across the investigated test conditions. Statistically, it was observed that none of the input variables exerted a significant influence, as evidenced by p-values exceeding 0.05, consistent with the hypothesis at a 95% confidence level.

In general, when smaller tolerance values are applied in machining operations, the TopSolid CAM program generates shorter straight segments or arcs compared to those produced with larger tolerances. As a result, a greater number of smaller segments is created to more accurately approximate the actual tool trajectory during part machining. Figure 6 illustrates the correlation between shape deviation and the radius of curvature.

Table 4: Mean and statistical percentage differences in the radius of curvature and shape deviation.

COMPARISON	CURVATURE RADIUS		SHAPE DEVIATION	
	DIFFERENCE	P-VALUE	DIFFERENCE	P-VALUE
Linear 0.10 → Linear 0.05	0.19%	0.9481	−28.69%	0.0097
Linear 0.10 → Circular 0.10	1.76%	0.5667	−35.54%	0.0045
Linear 0.10 → Circular 0.05	4.03%	0.2286	14.13%	0.0842
Linear 0.05 → Circular 0.10	1.57%	0.6089	−9.61%	0.3298
Linear 0.05 → Circular 0.05	3.82%	0.2489	60.01%	0.0023
Circular 0.10 → Circular 0.05	2.22%	0.4702	77.07%	0.0013

Table 5: Variance analysis of shape deviations along any given line.

COMPARISON	SS	D_oF	MS	F	P-VALUE
Shape deviations along any given line	10.916	3	3.638	1.212	0.365

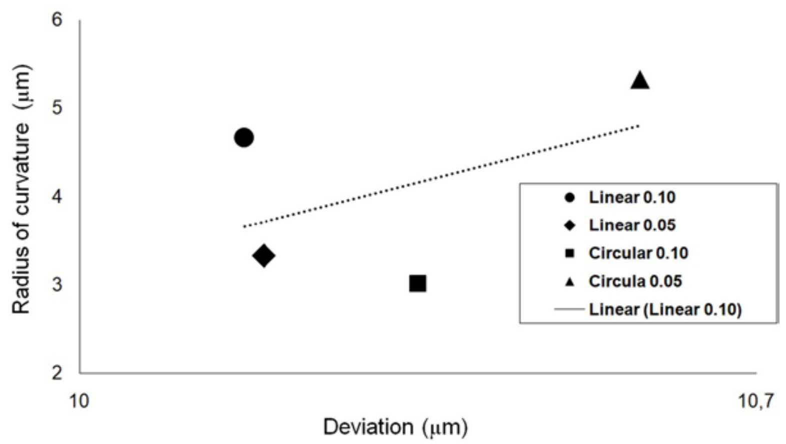

Figure 6: Linear regression analysis of shape deviation as a function of radius of curvature.

4. CONCLUSIONS

From the adopted methodology and the obtained results, the following conclusions can be drawn:

The roughness values measured in the direction perpendicular to the tool feed marks were higher than those measured in the parallel direction;

None of the input variables, including interpolation type and tolerance, exhibited a significant influence on the roughness results;

For roughness parameters measured in the perpendicular direction, the observed values ranged from 1.60 to 1.98 µm for Ra, 2.00 to 2.54 µm for Rq, and 7.70 to 10.30 µm for Rz. In general, these values were consistently higher than those measured in the parallel direction for all parameters;

Linear interpolation with a tolerance of 0.1 mm yielded the lowest average value for the evaluated curvature radius, closely approximating the design specifications. However, the reduced variations in deviation observed under circular interpolation indicated greater process slility and higher precision;

Circular interpolation with a tolerance of 0.1 mm resulted in the smallest line shape deviations. Based on the standard deviation values, it was concluded that smaller tolerances applied to the tool path led to reduced variations in the evaluated conditions.

These findings indicate that the choice of interpolation type and tolerance is critical for achieving optimal surface quality in milling VP50 steel cavities. Circular interpolation with a tolerance of 0.1 mm demonstrated superior performance in minimizing shape deviations and enhancing process precision.

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