ANALYSIS OF THE TOOL PATH INTERPOLATION RESULTS ON THE HIGH FEED MILLING OF FREE FORM SURFACES WITH SHARP EDGES

Jacson Machado Nunes, jacson@ita.br
Jefferson de Oliveira Gomes, gomes@ita.br
ITA, Pça. Marechal Eduardo Gomes, 50, Campus do CTA, CEP: 12228-615, São José dos Campos-SP

Guilherme Oliveira de Souza, guilhermeos@cimatec.fieb.org.br
SENAI CIMATEC, Av. Orlando Gomes, 1845, Piatã, CEP: 41650-010, Salvador-BA

Ricardo Sutério, suterio@lit.inpe.br
INPE - Instituto Nacional de Pesquisas Espaciais, Av. dos Astronautas, 1758, Jardim da Granja, CEP: 12227-010, São José dos Campos-SP

Abstract. *In this work, the influence of the tool interpolation method on the HSC of free form surfaces with sharp edges is analyzed. The traditional linear interpolation was compared to polynomial interpolation by application of three different values of CAM tolerance. The results were analyzed in terms of machined surface roughness, contour dimensional form error measurements and dynamic behavior of the tool machine, through the real time acquisition of feed rate in x and z axes. It was shown that polynomial interpolation offers accuracy and surface quality gains if compared to linear interpolation, in the same cutting conditions. However the decision for applying both interpolation methods has to consider the CAM tolerance value in terms of lead-time reduction. By using of linear interpolations the programmer has to decide for opener CAM tolerances due to the NC program size and consequently the time to process the program. When the CAM programmer decides for applying polynomial interpolations the CAM tolerance must be closed as soon as possible due to more surface profile adjust to polynomial curve equation.*

Keywords: *Sharp Edge, Interpolation Method, High Feed Milling, Die and Mould, Dimensional Accuracy*

1. INTRODUCTION

The industry of die and mould machining has a crescent role in the manufacturing area while global industry moves toward the reduction of lots, products customization and diversification, reduction of its life-cycle and mainly reduction of new products launch time. However, the lead-time of dies and molds manufacturing still remains extremely long, what raises the interest of this industry in High Speed Cutting (HSC) technology. Nevertheless the HSC application may be restricted by the fact that it is not only applied by high rotational speeds, but also by high feed rates, forging a peculiar machining process (Gomes, 2001 and Helleno, 2004).

The die and moulds manufacturing lead-time depends directly on the finishing milling and on the manual polishing. They represent about two thirds of all manufacturing costs due to poor quality of machined surfaces, what demands hours in plenty of polishers (Gomes, 2001). Figure 1 shows the lead-time distribution for die and mould making in three different countries, according to Fallböhmer *et. al* (2000).

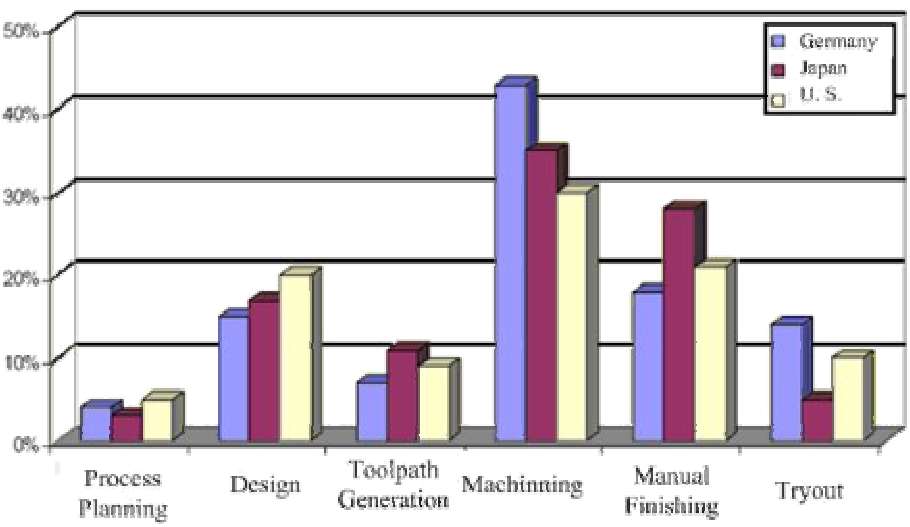

Figure 1. Typical lead-time in the die and mould manufacturing (Fallböhmer *et. al*, 2000).

The hand polishing stage is especially critical since the amount of time spent is very high. Furthermore, this operation badly influences the die and mould dimensional accuracy (Sandvik Coromant, 1999).

Tool path generation optimization is an option to minimize the amount of time wasted on secondary processes, such as hand polishing (Choi and Banerjee, 2006). To guide the tool along a surface, CAM systems generate a set of tool paths that closely reproduce that surface within a tolerance. Some mathematical interpolation methods can be used to follow these contours, amongst them one can name the linear interpolation and the polynomial interpolation, which are illustrated in Fig. 2.

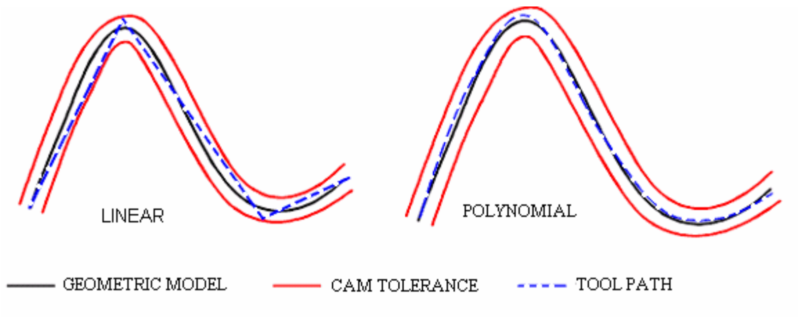

Figure 2. Linear and polynomial interpolation methods.

Through linear interpolation method, the tool paths are sequenced by a set of straight lines defined in accordance to the surface contour and the adjusted CAM tolerance. Since this method employs only straight lines, it is considered to be mathematically simpler than other methods.

Notwithstanding, with the inherent increasing of feed rates in HSC, this method has become a technology constraint, since it isn't capable of driving the tool along complex surfaces with smoothness and accuracy (Helleno, 2004). Tool paths based on Straight lines have non-continuous transitions that often lead to drastic feed speed reductions on all axes, especially on corners, due to abrupt change on feed direction. This feed rate variation along the tool path implies fluctuating cut loads and deflections, what causes negative impacts over cutting conditions, surface quality, dimensional accuracy and machining time (Sandvik Coromant, 1999).

Alternatives for dealing with these limitations and disturbances on the dynamic behavior of the machine tool are the complex interpolation methods, such as polynomial interpolation. Through polynomial interpolation method, the tool paths are sequenced by a set of equal degree polynomial curves, making them smooth and consequently improving the machined surface quality.

In the face of the exposed, the die and mould manufacturing industry needs to restructure its productive process through the use of HSM technology, with the purpose of maintaining its present productivity and competitiveness, and the knowledge of new tool path interpolation methods plays an essential role in this context.

The main objective of this work is to verify the influence of changing from linear to polynomial interpolation on surface quality and dimensional accuracy, when high feed milling free form surfaces with sharp edges.

2. EXPERIMENTAL METHOD

A finishing milling test was carried out in which the test-piece exposed on Fig. 3 was machined. This piece is characterized by a complex surface with abrupt direction change in its two cusps. In one of these there's a 4 mm blend radius joining the ascendant and descendent surfaces, while in the other these surfaces meet each other in a sharp edge, that is, no blend radius. The test-piece main dimensions are 125 mm length, 56.5 mm width and about 42.5 mm maximum high. Its material is the 7050 aluminium alloy, which was determined to maintain tool wear in a low level eliminating its influence in the tests results.

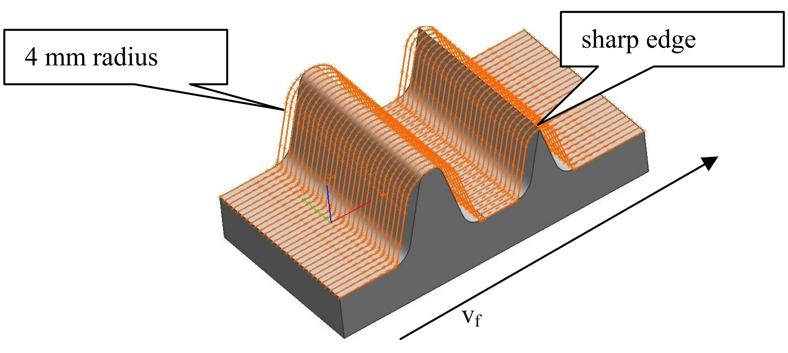

Figure 3. Test-piece geometry and feed direction.

The surface was divided in 2.1 mm width sections parallel to the feed direction indicated on Fig. 4. Distinct conditions were tested in each section varying the interpolation method among linear and polynomial and the CAM tolerance between 2 levels, 0.025 and 0.001. Remaining parameters were set in accordance with Tab. 1.

Table 1. Set of fixed cutting parameters.

D (mm)	a_p (mm)	a_e (mm)	n (rpm)	z	f_z (mm)
10.018	0.3	0.1	15915	2	0.1

Aiming to reflect typical die and mold HSM conditions, the above parameters were defined. Thus both cutting speed and feed rate values were chosen to fit these requirements for a generic tool steel (Fallböhmer *et. al*, 2000). As already said, an aluminium alloy was employed exclusively to eliminate the impact of the tool wear in experimental results.

A 5-axes machining center, Hermle C600U, with Siemens Sinumerik 840D CNC was used. CAD Modeling and CAM programming were carried out in UGS NX 4.0 software. The employed cutting tool was a 10 mm diameter carbide ball-nose mill, with cylindrical shaft and two teeth, of which manufacturer code is R216.42-10030-AK19G, produced by Sandvik Coromant.

Real-time axes position and effective feed rate data acquisition was performed through a Siemens CP 5611 card in a PC and a Labview data acquisition routine.

With the purpose of evaluate the dimensional quality of the test-piece surface, the machined test-piece was scanned with scan direction agreeing with the feed direction, and making use of a Mitutoyo Crysta-Apex C7106 coordinate measure machine, with (1.7 + 3L/1000) µm of maximum error, what is equivalent to a accuracy of about 3 µm for all performed measures. The diameter of the ruby sphere used was 1 mm. The surface scanned was compared to the profile of the CAD model, extracted with the 3D Tol software, through Mitutoyo Geopak Win a computer aided measuring software. In order to assure the exactness of the comparison, a function called bestfit was utilized, which makes translational and rotational adjusts between the profiles. The adopted comparison method was the projection of the points acquired over nominal profile, under a permissible accuracy interval of ± 0.025 mm, which is equal to the programmed CAM tolerance.

Machined surface roughness measures were also performed, and the equipment was a Mitutoyo SJ-201P surface roughness tester. The parameters considered were arithmetic average roughness R_a and mean roughness depth R_z. To meet what NBR 6405/1988 standard (ABNT, 1988) recommends, a sample length of 0.8 mm was used. Three measures were realized in each section and arithmetic averages of R_a and R_z calculated.

3. EXPERIMENTAL RESULTS

Evaluating the behavior of the effective feed rate (v_f) along the part contour, exposed in Fig. 4 and Fig. 5, one can note that for a CAM tolerance of 0.025 mm both linear and polynomial interpolation were similar, marked by abrupt reduction of the feed speed on the profile peaks, regions where feed direction roughly varies. However, when CAM tolerance was reduced to 0.001 mm the graphs clearly shown that the feed rate behavior for the polynomial interpolation becomes much more uniform, reaching almost ever the programmed feed rate (v_p), what still doesn't happens with linear interpolation, for which, as already expected, the feed speed reductions became even higher.

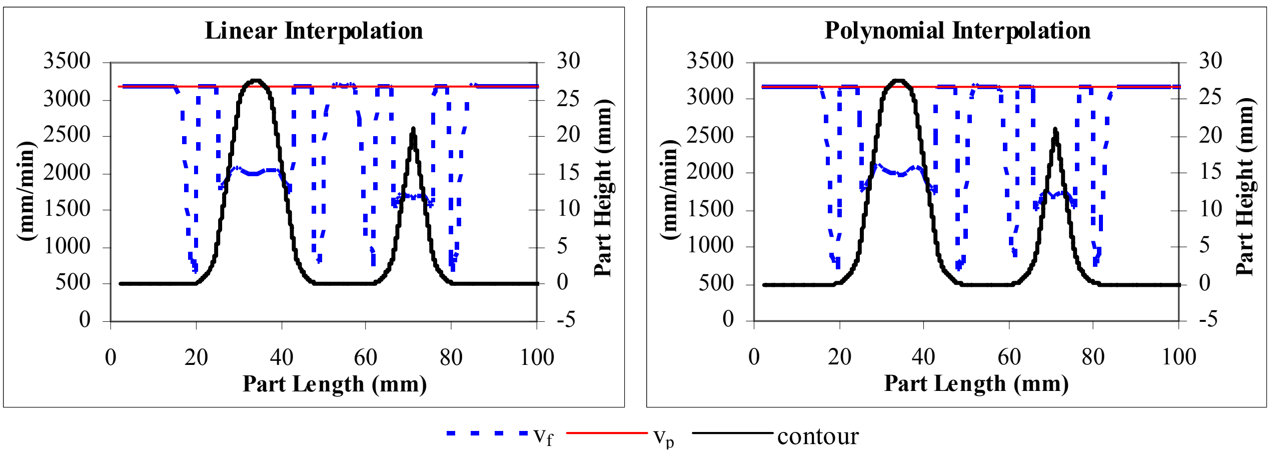

Figure 4. Feed speed behavior along test-piece contour for a 0.025mm CAM tolerance.

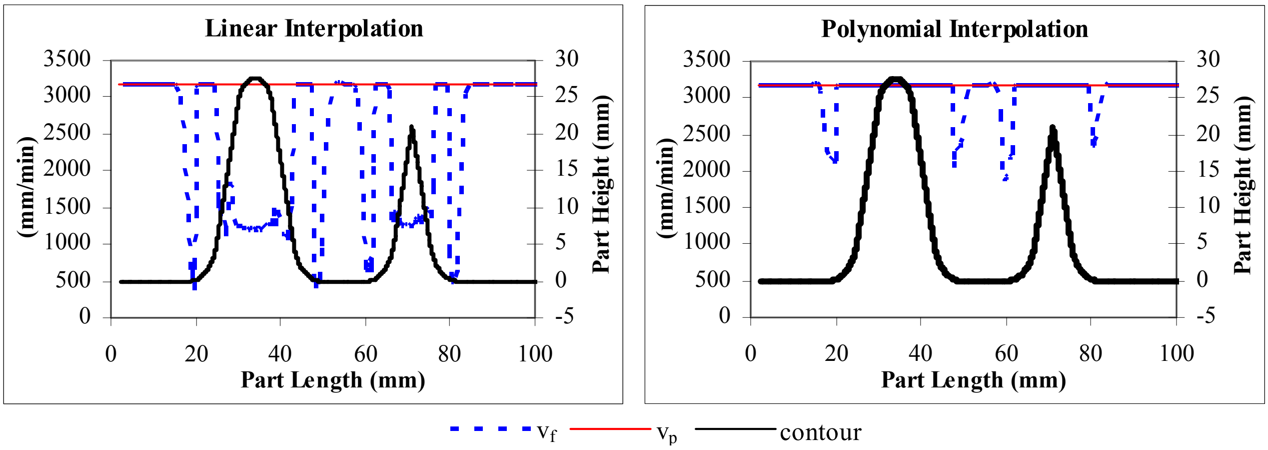

Figure 5. Feed speed behavior along test-piece contour for a 0.001mm CAM tolerance.

The reason for this unexpected improvement on the dynamic performance of the machine when the tolerance was tightened was found in the NC program. With the smaller value more polynomial interpolation blocks and less linear interpolation blocks were generated.

This bigger uniformity resulted in time save. There was a reduction of about 36% on the machining time for polynomial interpolation in comparison with linear interpolation. This can be seen on Fig. 6 which shows machining times for the different conditions tested.

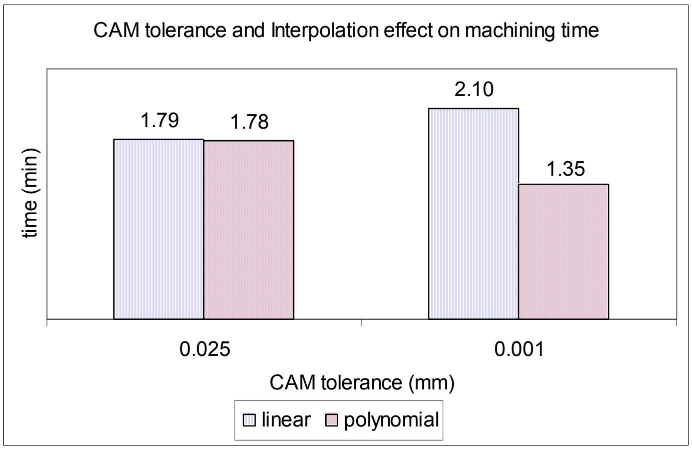

Figure 6. Influence of CAM tolerance and interpolation method on machining time

Figure 7 exposes the results of the surface scanning. It can be seen that for the highest CAM tolerance (0.025 mm), interpolation method didn't affect the dimensional accuracy. However, when tolerance is tightened on, maximum and minimum deviations for polynomial interpolation become higher than those for liner interpolation, unlike expected. The biggest difference was between the values of maximum deviation, which was 0.008 mm. A hypothesis for this surprising result is the fact that for polynomial interpolation, combined with 0.001 CAM tolerance, the tool spindle moved more freely, as shown in Fig. 5, and the machine was not able to deal with the higher feed speeds involved.

Regarding to the influence of the CAM tolerance on the dimensional accuracy, maximum and minimum deviations for 0.025 mm were larger than those for 0.001mm. But for the last one, measured values stood very far of the set value (0.001 mm). The medium deviation for this case was 0.012 mm, that is, twelve times higher than what it should be. This suggests that the accuracy threshold of the machine system (spindle/tool and part fixturing/cutting tool length-diameter) was achieved, and 0.001 mm is beyond of what it is capable with these cutting parameters.

The results of the roughness measurement are shown on Fig. 8, for the region of the peaks where the tool machined the surface going up, and on Fig. 9, for the regions of the peaks with downward cut. Both of them show that roughness parameters R_a and R_z were higher for a CAM tolerance of 0.001 mm than for 0.025mm.

Based on these graphs it cannot be said that the interpolation method affects surface roughness. The only clear discrepancy is between the roughness of the different regions analyzed. With 0.001 mm CAM tolerance, for downward cut, Rz is bigger, and Ra is slightly bigger, than for upward cut. That's because when a ball-nose mill machines downward chips are formed close to its center, where the cutting speed tends towards zero.

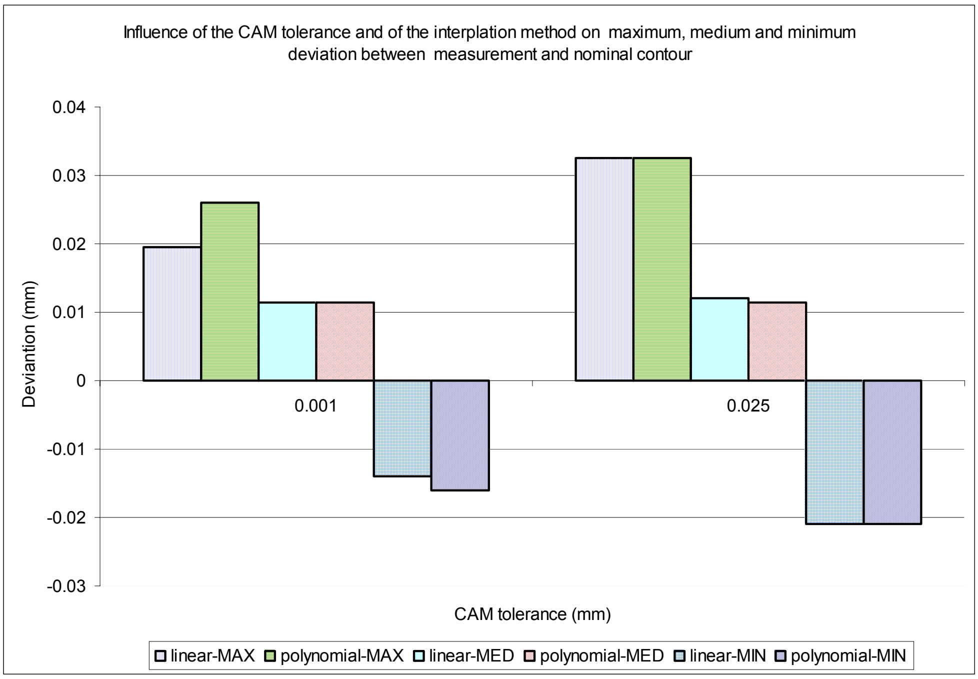

Figure 7. Influence of the CAM tolerance and of the interpolation method on maximum, medium and minimum deviation between measured and nominal contour

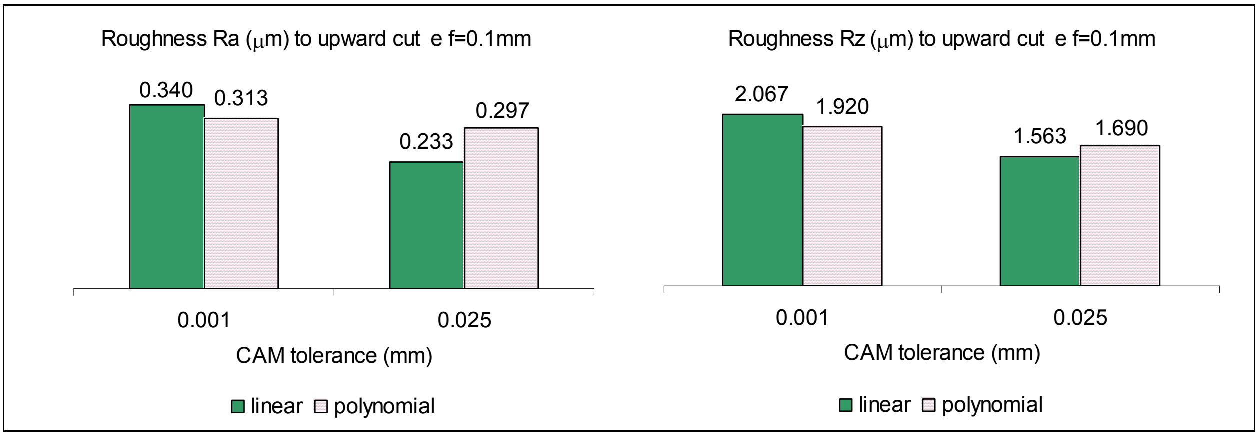

Figure 8. R_a and R_z roughness for upward cut.

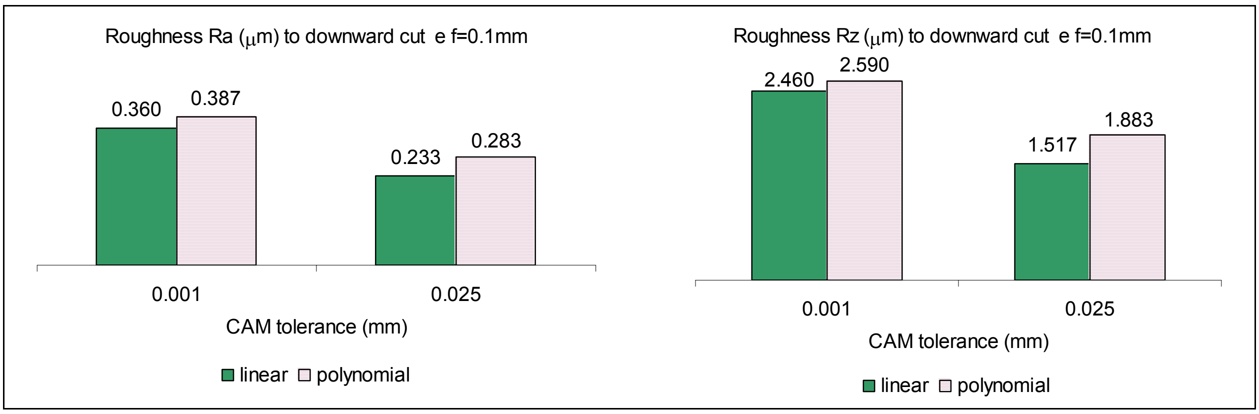

Figure 9. R_a and R_z roughness for downward cut.

4. Conclusions

The present work verified the influence of changing from linear to polynomial interpolation on surface quality and dimensional accuracy, when high feed milling free form surfaces with sharp edges. Taking these aspects into account, it can be concluded what is mentioned next.

For a CAM tolerance of 0.025 mm both linear and polynomial interpolation were similar, marked by abrupt reduction of the feed speed on the profile peaks, regions where feed direction roughly varies. However, when CAM tolerance was reduced to 0.001 mm the graphs clearly shown that the feed rate behavior for the polynomial interpolation becomes much more uniform, reaching almost ever the programmed feed rate (v_p), due to with the smaller value more polynomial interpolation blocks and less linear interpolation blocks were generated. There was a reduction of about 36% on the machining time for polynomial interpolation in comparison with linear interpolation.

It can be seen that for the highest CAM tolerance (0.025 mm), interpolation method didn't affect the dimensional accuracy. However, when tolerance is tightened on, maximum and minimum deviations for polynomial interpolation become higher than those for liner interpolation, unlike expected. A hypothesis for this surprising result is the fact that for polynomial interpolation, combined with 0.001 CAM tolerance, the tool spindle moved more freely and the machine was not able to deal with the higher feed speeds involved.

It cannot be said that the interpolation method affects machined surface roughness. The only clear discrepancy is between the roughnesses of the different regions analyzed. The machined surface roughness increases when chips are formed close to ball-nose mill center, where the cutting speed tends towards zero.

It is relevant to point out that, due to the comparative character of the experiment, the transfer of presented conclusions to tool steels, mainly those referring to dynamic behavior and machining times, is valid. With respect to the surface roughness and the dimensional accuracy must be observed that can exist some discrepancy in absolute values, but the relative conclusions remain truthful.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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7. RESPONSIBILITY NOTICE