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ORIGINAL ARTICLE

Adriano Fagali de Souza · Reginaldo Teixeira Coelho

Experimental investigation of feed rate limitations on high speed milling aimed at industrial applications

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Abstract This paper presents an experimental investigation on feed rate [mm/min] limitations when milling free form surfaces, commonly found in dies and moulds, applying the high speed cutting technology-HSC. The results appoint feed rate as the bottleneck to achieve the real benefits of HSC in terms of machining time, surface quality and process stability. That is due to unwanted large variations on the initially programmed feed rate, mainly when milling free form surfaces. These "ups" and "downs" on feed rate result in several setbacks for the machining process itself and it can be found even when using a suitable HSC milling machine available in the market. This paper addresses some of the causes for feed rate variations and evaluates an alternative approach to describe a tool path using spline polynomial technique. In order to focus industrial applications, all equipment, materials and software used are accessible in the market. The milling experiments were accomplished on a high-speed milling machine controlled by an open architecture CNC and a high-end CAD/CAM software was used. A 3D free form workpiece was designed and a real-time monitoring system was developed to investigate the feed rate variations during milling operation. The surface quality after milling and the machine tool/CNC performance were also assessed.

Keywords Free form shapes · Feed rate · High-speed milling · Spline function · Tool paths

A. F. de Souza (✉)
Sociedade Educacional de Santa Catarina – SOCIESC/IST,
Rua Albano Schmidt,
3333 Joinville-SC, Brazil, CEP 89.201-972.2
e-mail: adriano.fagali@sociesc.com.br
Tel.: +55-47-4334299
Fax: +55-47-4610134

R. T. Coelho
Universidade de São Paulo – EESC - USP,
São Paulo, Brazil
e-mail: rtcoelho@sc.usp.br

1 Introduction

Initially, due to the difficulty in manufacturing, 3D free-form surfaces were only applied in parts that definitely required such kind of geometry, such as blades of propellers and airplane parts. The evolution of the CAD/CAM systems and CNC machines has allowed products containing free form shapes to be easily manufactured. Today, 3D forms can be realistically modelled in a 3D-CAD system, the NC programs for these complex shapes can be generated in a commercial CAM system; and the part can be machined on a CNC machining centre. Consequently, a wide range of different products containing free form shapes can be designed today. Usually, dies and moulds are required for these sorts of products to be manufactured. Dies and moulds represent a key position on the whole production chain, affecting the costs, quality and lead-time of a product [1]. Lately, several limitations and drawbacks in die and mould manufacturing have been discussed. The application of the HSC technology in this manufacturing area is being taken as a driving force for this industry [2–4]. It is believed that the manual rework can be reduced quite substantially applying the HSC at the finishing milling operation. Timesaving on hand finishing can reach 80% and the costs savings concerning to this process can reach 30% [5].

According to GEIST [6], what is more important than increasing the cutting speed is increasing the feed rate (mm/min). High frequency spindles in combination with high feed rate are a more precise characterization for HSC [7], especially in die and mould manufacturing. Articles show many authors referencing feed rate to HSC as high as 20000 mm/min. However, this paper shows that high feed rate values are not realistic for milling free form geometries, even when using appropriate high-speed machines with resources such as look-ahead function and CNC with a very low block processing time. Reductions and oscillations on the programmed feed rate can be observed during milling such kinds of geometry. Normally, the real feed rate cannot even reach the value set in the NC program and varies widely along the machining path.

These oscillations increase cutting time, the process time estimated by the CAM becomes quite inaccurate and the feed per tooth varies, as well as the load on the cutting tool. Variations on feed per tooth affect the surface roughness and the load on the tool affects dimensions and surface texture on the workpiece.

Feed rate variations, during 3D free form machining can occur mainly due to:

- Machine dynamical limitation: When the machine is running at high speeds in a non-linear path, it is subjected to inertia effects and axis control system dynamics. The CNC limits the feed rate due to the machine physical structure and an internal algorithm controls its characteristics according to a set of parameters. The feed rate is then reduced in order to precisely follow a non-linear tool path.
- The CNC block processing time: If the time required for the CNC software to process a single block (line of program) and close the respective control loop is longer than that required for the tool reference point to reach such position, the moving system will reduce the feed rate up to a manageable value to process the next command block [8, 9]. Therefore, the machine should move in a feed rate lower than the programmed one.
- Tool path strategy: When the ordinary methodology of linear interpolation using small line segments (G01 NC code) is applied for milling a non planar surface, the feed rate has to be reduced due to the lack of continuity in the tool path direction, when the tool moves from one segment to another (continuity C^0) [10, 11].

Bearing these problems in mind, the present paper experimentally investigates some limitations of feed rate, which are found in most applications of milling complex free form geometries. Tool paths using the traditional method, interpolation of straight lines segments, were evaluated in different aspects against their spline counterparts. Both strategies were generated by a commercial CAM system. The surface's visual aspects, roughness, dimensional accuracy, cutting time and feed rate variation during machining were assessed. In order to be more realistically close to industrial applications, the milling experiments were made on a commercial high-speed milling machine, using P20 steel, and also a commercial high-end CAD/CAM system was used. A 3D free form workpiece was properly designed for these experiments and a real-time monitoring system was developed to efficiently investigate the feed rate variation according to machine position during the milling operation.

2 CAD/CAM/CNC process chain

In die and mould manufacturing, the integration between CAD/CAM system and CNC milling machines is conventionally used. The main steps of this process chain are schematically demonstrated in Fig. 1.

In the first step, the product geometry has to be constructed by a 3D CAD system. Usually, for die and mould manufacturing, surface modeller CAD software is most suitable for these applications. By using complex mathematical functions known as splines, the designer can model free form geometrical surfaces. The spline functions came about in the late XVII century, with the mathematician Charles Hermite, who used a polynomial equation to define a curve with two points, one at the start and the other at the end of the curve and also two tangent vectors associated with these points (Fig. 2) [12].

For example, using a third degree polynomial for two points, such as:

$$p = p(u) = k_3u^3 + k_2u^2 + k_1u + k_0. \quad (1)$$

The derivative of Eq. 1 is:

$$p' = p'(u) = 3k_3u^2 + 2k_2u + k_1. \quad (2)$$

Taking the values of ***u=[0–1]*** as a continuous interval and assuming the polynomial begins and ends within this dominium, let us calculate the values of ***p*** and ***p′*** at the extremes:

$$p(u = 0) = p_0 = k_0 \quad (3)$$

$$p(u = 1) = p_1 = k_3 + k_2 + k_1 + k_0 \quad (4)$$

$$p'(u = 0) = p'_0 = k_1 \quad (5)$$

$$p'(u = 1) = p'_1 = 3k_3 + 2k_2 + k_1. \quad (6)$$

Now there are four equations as a function of four parameters, k_i (i=1…4). Parameters k_0 and k_1 were directly found by Eqs. 3 and 5, respectively, and if these results are substituted into Eq. 4:

$$p_1 = k_3 + k_2 + p'_0 + p_0 \quad (7)$$

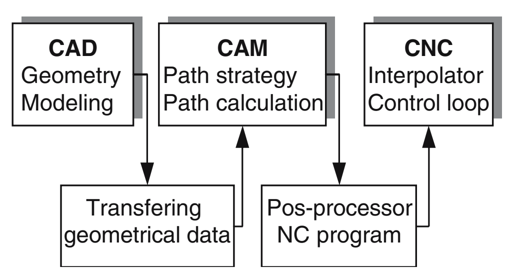


Fig. 1 Steps of manufacturing chain involving CAD/CAM-CNC systems

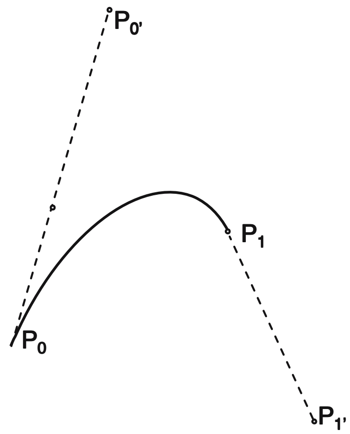


Fig. 2 Typical curve defined by Hermite

Appling now Eq. 5 into Eq. 6:

$$p_1' = 3k_3 + 2k_2 + p_0' \tag{8}$$

Then solving Eqs. 7 and 8 into the values of $\boldsymbol{k_2}$ and $\boldsymbol{k_3}$, the results are:

$$k_2 = 3(p_1 - p_0) - 2p_0' - p_1' \tag{9}$$

$$k_3 = 2(p_0 - p_1) + p_0' + p_1' \tag{10}$$

Now, substituting the obtained values for k_i (i=1…4) into the Eq. 1, the parametrical polynomial resultant is:

$$p(u) = p_0\left(1 - 3u^2 + 2u^3\right) + p_1\left(3u^2 - 2u^3\right) + p_0'\left(u - 2u^2 + u^3\right) + p_1'\left(-u^2 + u^3\right) \tag{11}$$

The tangential vector and the extreme points of the curve are helpful for modelling free-form geometries. However, the approach developed by Hermite does not represent a friendly interface to the ordinary CAD user, as it depends on the derivative of the equation. In order to overcome such inconvenience, one of the first computer representations of free form curves and surfaces was developed by Pierre Bézier, in 1972. Since then it has become the most popular method for curve design used in graphic packages and CAD system [13]. He developed a methodology to represent these kinds of entities on a computer, in order to implement the software UNISURF at the Renault industry [14]. Bézier used a polygon for controlling the curve in order to substitute the initial contour condition presented by Hermite. The degree of the Bézier polynomial equation is 1, less the number of the polygon control points. Figure 3 shows a Bézier curve and its control points.

The curve is plotted by a cubic polynomial. The points $\boldsymbol{p_0}$ and $\boldsymbol{p_3}$ of the Bézier curve are equivalents to the Hermite $\boldsymbol{p_0}$ and $\boldsymbol{p_1}$. Taking the Hermite parametrical polynomial, Bézier defined the derivative at the initial and final points as 1/3 of the difference between the consecutive points, of the new polygon, i.e.:

$$p_0' = 3(p_1 - p_0) \tag{12}$$

and

$$p_1' = 3(p_3 - p_2). \tag{13}$$

Substituting $\boldsymbol{p'_0}$ and $\boldsymbol{p'_1}$ into Eq. 11, it results into Bézier formulation:

$$p(u) = p_0\left(1 - 3u + 3u^2 - u^3\right) + p_1\left(3u - 3u^2 + u^3\right) + p_2\left(3u^2 - 3u^3\right) + p_3\left(-3u^2 + 3u^3\right). \tag{14}$$

The polynomial is now a function only of the values at the controlling polygon excluding its derivatives. Therefore, any desired free form curve or surface is driven by a polygon formed by control points. The Bézier method has two main inconveniences: the polynomial degree depends on the number of control points, which can compromise the computation task and secondly, only global curve alterations can be done. Any modification can affect the complete curve. Other spline polynomials have been developed to supply the limitation from Bézier curve. The spline state of art is known as NURBS – non-uniform rational B-spline, which has many advantages, compared to the Bézier ones, including the computational simplicity and more flexibility to geometrical representation [15]. The idea to use a parametric polynomial to represent curves remains very useful for computing applications. For many years, spline has been used in computer graphic packages, especially for CAD application. Much effort is now being spent on using spline polynomial to describe free form tool path.

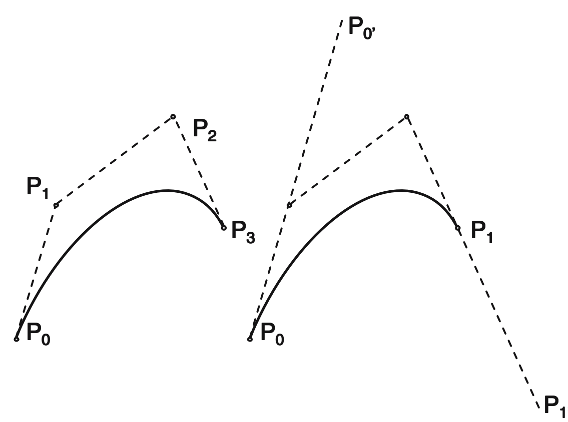


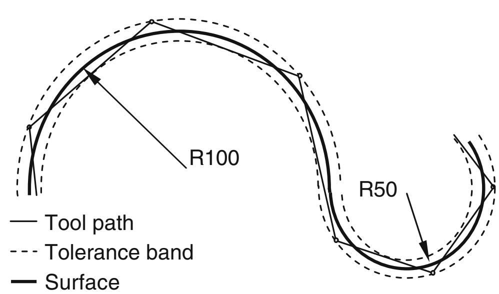
Fig. 3 Example of a Bézier Curve controlled by 4 points and the Hermite controlled by vectors

To generate the tool path, the CAM program first calculates the cutter contact path (CC) over the 3D CAD geometry. Then, the cutter location path (CL), which represents the tool path is calculated by offsetting the CC [10]. The most traditional method to describe a free-form tool path is the interpolation of straight-line segments, with continuity C^0. This is easily transformed into the ordinary G01 code, according to DIN 66025 [16]. The CAM adjusts the tool path segments inside a tolerance band defined by the user, known as "chord error". The smaller the tolerance band, the closer the tool path will be to the CAD model. Thus, linear segments are generated by such procedure and, for highly curved paths, the number of segments increases drastically, as well as the NC program size [17]. Figure 4 shows an example of segment length, considering a constant tolerance band for two different surface curvatures.

Several inconveniences can be identified when applying this method for milling free form geometries, especially when high feed rates are required [18].

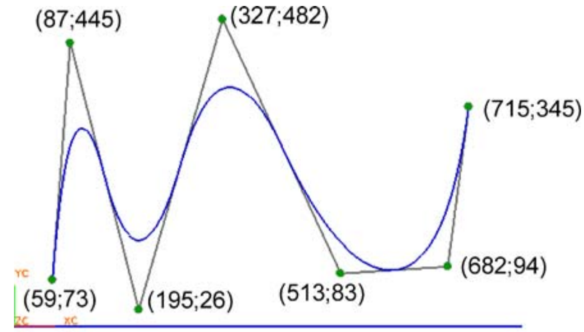
Alternatively, circular, associated with linear interpolation, can be used to describe a free form path. This combination can keep curve continuity C^1 and has shown many advantages over the line segments alone [9, 19]. This method, however, can only be applied for two dimensional simultaneous movements, since the vast majority of CAD/CAM and CNC are not capable of making free form circular interpolation in three dimensions. Another approach to describe free form tool paths is investigated in this paper: the use of a polynomial spline (Fig. 5a).

Rather then CAD modelling, at this step spline is applied to represent a tool path. Therefore, the CAM system has to generate NC programs containing the polynomial data and only the information about the curve goes to the CNC. The machine then transforms the polynomial data into speed for the axis movements. For NC programs based on spline codes generated by the CAM, it requires a new syntax to NC program, which involves descriptions of the polynomial equation. Therefore, the CAM system has to be able to generate such NC codes and the CNC has to be able to execute them. On the current market there is no standard syntax for the spline's NC code. Each CNC brand has its own syntax to understand this alternative approach of



Surface radius	Segment Length
100 mm	9.0 mm
50 mm	6.3 mm

Fig. 4 Surface curvature influencing the tool path segment length



a The Spline curve and its control points

```
POLY
PO[X]=(59,0,0) PO[Y]=(73,0,0) PO[Z]=(0,0,0)
PO[X]=(87,0,0) PO[Y]=(445,0,0) PO[Z]=(0,0,0)
PO[X]=(195,0,0)  PO[Y]=(26 ,0,0)
PO[Z]=(0,0,0)
PO[X]=(327,0,0) PO[Y]=(482,0,0) PO[Z]=(0,0,0)
PO[X]=(513,0,0) PO[Y]=(83,0,0) PO[Z]=(0,0,0)
PO[X]=(682,0,0) PO[Y]=(94,0,0) PO[Z]=(0,0,0)
PO[X]=(715,0,0) PO[Y]=(345,0,0) PO[Z]=(0,0,0)
```

b The respective NC program according to Siemens syntax for Spline codes

Fig. 5 Example of a polynomial Spline applied for free form tool paths and the corresponding NC codes

programming, among those able to run spline programs. Therefore, the CAM has to post-process the spline NC codes according to a specific CNC. Fig. 5b shows the NC spline program developed according to the Siemens 840D CNC syntax.

Several algorithms for spline calculation were developed. Koninckx and Brussel [20] present a real-time interpolator, using a third-order keeping C^2 continuous NURBS. Farouki et al. [21] suggest a CNC interpolator using Pythagorean-hodograph curves. Tikhon et al. [22] propose a NURBS algorithm for varying the feed rates in order to keep the cutting tool load constant. Lartiguel et al. [23] present a method to generate a tool path in terms of planar cubic B-spline curves, for a smooth free-form surface. Yau and Kuo [17] developed an algorithm to convert an ordinary NC program containing G01 codes into a polynomial NC code. The last method has been implemented in some up-to-date CNCs. The controller is able to make this conversion on line, during machining. This function creates possibilities of higher feed rate values when milling free form geometries, even when an NC program containing the linear interpolation is in use. However, this approach requires another tolerance band to generate the polynomial program, inside the CNC, losing the accuracy to the original CAD surface, and additionally, it represents one more task to the CNC process, compromising the CNC processing time. It is suggested that the best approach would be if the CNC receives the spline program already calculated by the CAM system. In this manner, the tolerances are well known and the CNC saves the computational task of converting the G01 codes into spline codes. The previously mentioned spline algorithms are still not available on the market.

Today, a high performance CNC can have a block processing time (BPT) less then 1 ms. Despite that a bottleneck can still occur when high speed processing is required. Trying to support this technological limitation, new CNC functions are being developed by the CNC suppliers. It is called look-ahead algorithms, and it has the function to pre-process a number of blocks ahead of time, trying to leave processed blocks ready for use. This function was also taken into account on this paper.

3 Experimental work

In order to investigate the sources of the feed rate reductions and oscillation when milling free form geometries and also to evaluate the spline NC code generated by a commercial CAD/CAM software, three experiments were carried out:

- Experiment 1: **Limitations on a circular path**. It analyzes the limitations on feed rate considering the machine tool dynamical limit.
- Experiment 2: **Limitation of feed rate on straight lines**. It analyzes the limitations on machine/CNC processing capability.
- Experiment 3: **Limitations of feed rate on complex paths**. It investigates the limitations when using spline polynomial NC codes to describe free form tool paths.

3.1 Materials, equipment and software

The Unigraphics NX 2 CAD/CAM system was used to model the workpieces and to generate the linear and splines NC programs. The milling operations were accomplished in a high speed machining centre Hermle C800, controlled by the CNC Siemens 840D. This CNC is one of the few capable of interpolating spline polynomials. The roughness was assessed by a Taylor-Hobson surftest model Surtronic 3P and an optical microscope Zeiss Axiotech, equipped with a digital camera AxioCam MRc.

3.2 System for the real-time feed rate recording

To obtain feed rate values on-line during milling operation a real-time data acquisition was developed by using the open architecture advantages of the 840D CNC. A PC containing a CP 5611 communication board was connected to the CNC, by a RS 485, using ProfiBus/MPI protocol [24]. Figure 6 shows a schematic of the communication system.

The result of the feed rate (mm/min) was obtained by the Eq. 15.

$$v_f = \sqrt{Vx^2 + Vy^2 + Vz^2} \qquad (15)$$

Where Vx, Vy and Vz are the real-time feed rate at the machine axis X,Y and Z directions, respectively. This system allowed a frequency of acquisition of up to 80 points per second.

3.3 Experiment 1: Limitations on a circular path

In order to evaluate the machine limitations when moving in a circular path, a semicircular trajectory was proposed, with a 180° extension, 40 mm radius, executing a finishing operation, by climb milling (Fig. 7). Two different strategies were used to create the tool path: a NC program containing linear segments, generated by the CAM; and the circular interpolation created by hand, using the G02 NC code. For the first strategy a tolerance band of 0.005 mm was set on the CAM, which corresponds to an ordinary value used for finishing (semicircle A). This NC program resulted in about 150 lines. The second NC program contains just a few lines, using circular interpolation, created directly on CNC machine editor (semicircle B). In both cases the feed rate programmed was 3500 mm/min.

Since the first strategy resulted in machine "vibration", it was repeated at a lower feed rate, in order to verify the influence of the feed rate oscillation on the surface roughness. This time, the feed rate was set at 1000 mm/min, which was the highest possible rate without any noticeable "vibration" (empirically observed). The spindle frequency was also reduced to keep the feed per tooth constant.

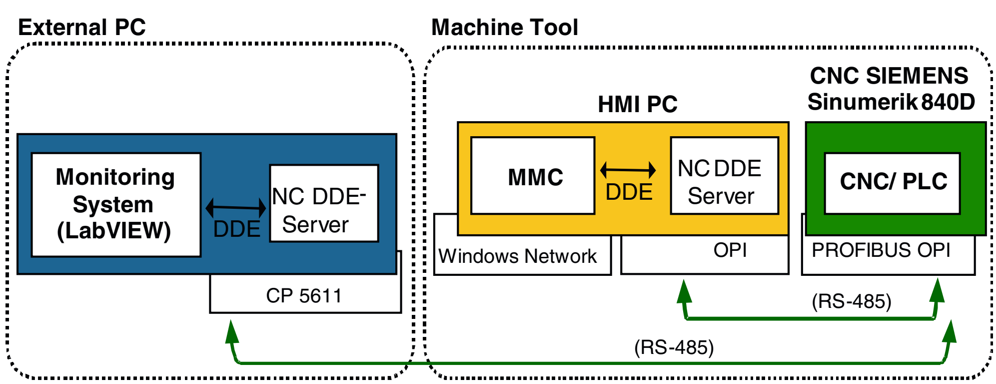


Fig. 6 Schematic of hardware and software architecture used for feed rate real-time recording [25]

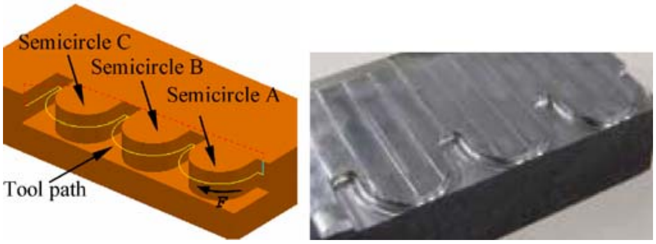


Fig. 7 Workpiece and tool path for the experiment 1

Tool and cutting conditions used are in Table 1. To compare the NC program length, two other NC programs were generated by the CAM using linear code and tolerance band of 0.05 mm and 0.5 mm. In order to verify only the feed rate behaviour, both programs were carried out without cutting material.

3.4 Experiment 2: Limitation of feed rate on straight lines

In this experiment a program for a linear movement along the X axis (600 mm long) was developed by dividing it in to small segments. Each segment corresponds to a program line (block), and the programmed feed rate was 5000 mm/min. Three different segment lengths were used, 0.05, 0.1 and 0.2 mm. Just the machine moved and no material was cut at this time. As the previous experiment, the look-ahead function was set in all of the NC programs. The maximum feed rate during the machine linear movement was registered.

3.5 Experiment 3: Limitations of feed rate on complex paths

In this experiment a finishing milling operation was performed with two different NC programs: first using the traditional interpolation of straight-line segments, and the second a NC program using a polynomial spline method; both generated by the commercial CAD/CAM system. A 3D workpiece, containing complex and specific geometries was designed for this purpose. It has flat areas with ascendant and descendent cutting conditions; semi-circular areas with convex and concave cutting conditions; and also free form geometries areas which involve different cutting conditions.

The workpiece was first cut leaving a uniform layer of 0.2 mm for the finishing cut. Half was milled by the linear interpolation method, named part A, and the other half, named part B, was milled by using a program containing the spline NC codes. Both parts were milled by climb cutting. The geometry description, the surface areas analyzed and the finishing tool path are all shown in Fig. 8. Table 2 shows the tool and cutting conditions used.

The surface quality and accuracy of both paths were also checked after milling. The look-ahead code was also set.

4 Results and discussions

4.1 The feed rate analyze

Figure 9 shows the results of feed rate when cutting the three circular tool paths (experimental 1).

During this experiment, a high level of oscillation on the feed rate could be observed when milling the semicircle A (Fig. 9a). Only at a few points on the path was the programmed feed rate reached. In semicircle B the feed rate programmed was constant during the entire path (Fig. 9b). In semicircle C, as expected, the feed rate was constant, but at a much lower value (Fig. 9c). This case was used to compare the surface roughness obtained by milling on constant feed rate against the surface obtained when the feed rate oscillates.

It was noticed that the linear segments in the NC program had an uneven length, due to the software CAM algorithm. Figure 10 shows a part of the semicircle tool path in a zoom. It demonstrates the irregular distribution of the NC program points, calculated by the CAM software, using a tolerance band of 0.05 mm.

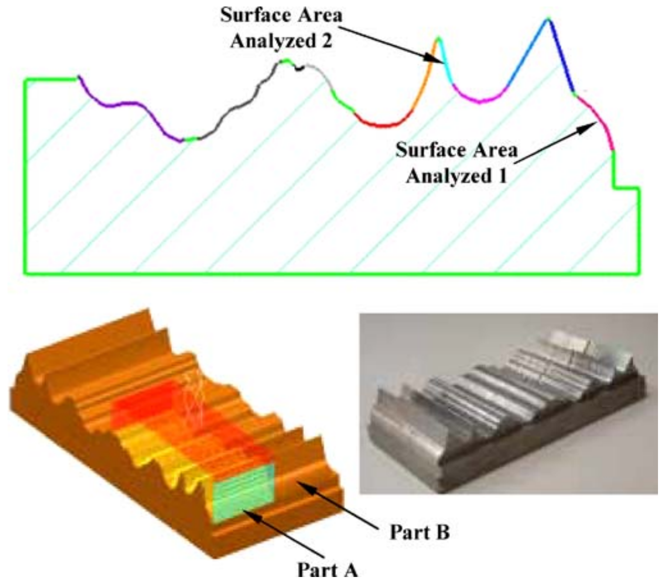


Fig. 8 The workpiece designed and the finishing tool paths

Table 1 Cutting tool and cutting conditions used on experiment 1

Tool details	*Diameter*	*Helix angle*	*Coating*	*Grade*
	20 mm–8 cutting edges	30°	TiAlN	1010 (Sandvik)
Cutting parameters	*Spindle frequency*	*Feed programmed*	a_p	a_e
	9300 RPM	3500 mm/min	3 mm	0.2 mm

Table 2 Cutting tool and cutting conditions used on experiment 3

Tool details	*Diameter*	*Helix angle*	*Coating*	*Grade*
	6 mm – 2 cutting edge	30°	TiAlN	1010 (Sandvik)
Cutting parameters	*Spindle frequency*	*Feed programmed*	a_p	a_e
	21000 RPM	4500 mm/min	0.2 mm	0.2 mm

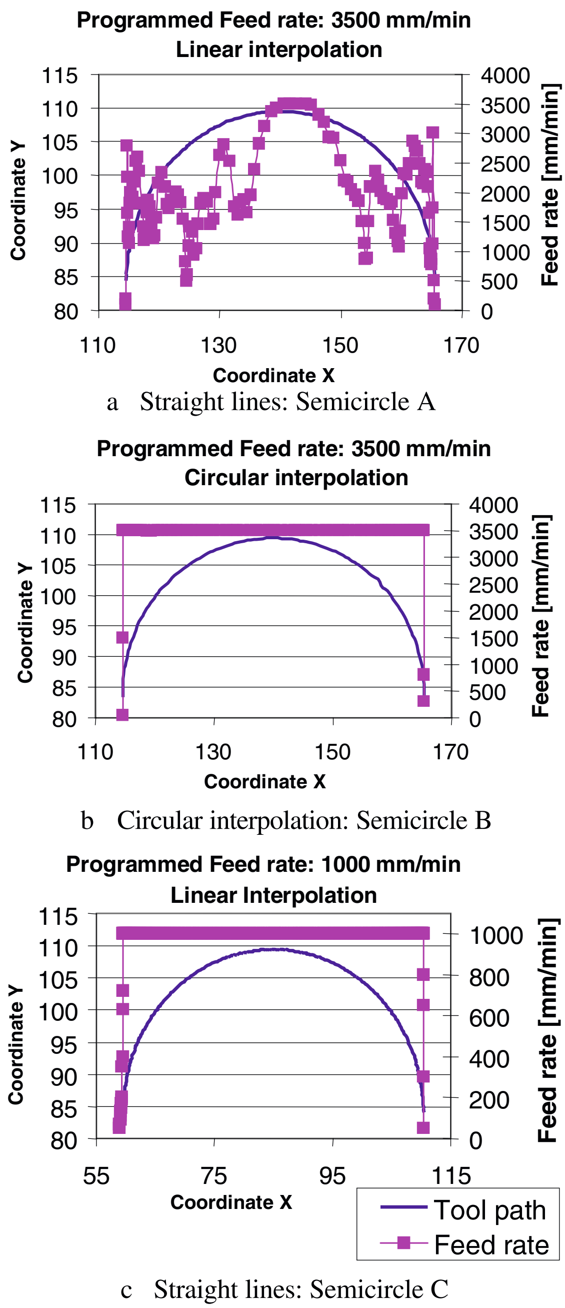


Fig. 9 Feed rate according to point location on the X-Y plan

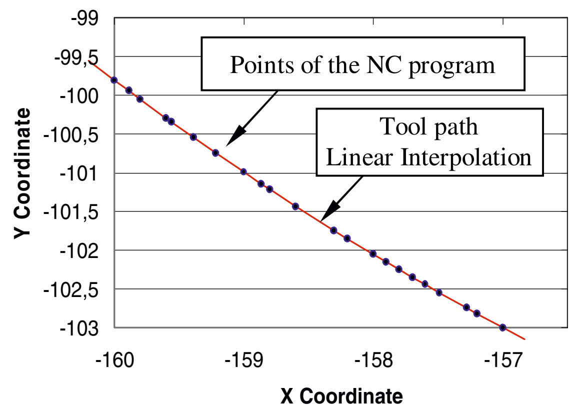


Fig. 10 Points of the NC program created by the CAM for milling the semicircle trajectory of radius 40 mm. Small part of the circular trajectory. Band tolerance of 0.05 mm

It was also observed that higher feed rate values were found where length segments were longer.

Therefore, part of the feed oscillation can be attributed to the uneven segments' length in the NC program calculated by the CAM. It disturbs the cutting tool load, increases milling time and results in poor surface quality. In this case the average feed rate was 1690 mm/min. It can be observed that as the tolerance band grows, so does the average feed rate. This can be related to the increase in segment lengths, although the "vibrations" were still present in all three cases. Table 3 shows the resulting average feed rate when the tolerance band was increased for the same tool path.

It was observed that the maximum real feed rate is related directly to the tolerance band used for path calculation. It is also important to note that the feed rate was constant, even when the machine moved in a circular path, only when the circular interpolation code G02 was applied. Therefore, in this case, the feed rate was not limited by the machine tool dynamic characteristics, but by the tool path interpolation method. However, if the inertia of the machine moving parts were very small, the "vibration" could be reduced, even at very small line segments. Additionally, the "vibration" could also come from a limitation on the block processing time, i.e. the time ranging from the interpretation of a block until the tool reference point reaches the target point.

In experiment 1 two axes were moving at the same time, while in experiment 2 a linear path, in just one axis was carried out. The path was divided in small straight-line segments in the NC program with different lengths. It was observed that a strong feed reduction occurred according to the segment length, as can be seen in Table 4. In these cases, it was noticed that the feed reached a maximum value, lower then the programmed one, and kept it constant up to the end of the trajectory. No feed oscillations and

Table 3 Feed rate according to the CAM chord tolerance

Chord tolerance [mm]	0.5	0.05	0.005
Average feed rate [mm/min]	3053	2890	1609

machine “vibration” were observed. It most likely happened due to the constant segment’s length in the NC program. These results show that the feed rate reduces even in a linear path, and it is much more influenced by the amount of information contained in the NC program than by alterations on the feed direction and dynamic machine limitation.

Considering the length of 600 mm is long enough to avoid effects of inertia on the machine, a time of block execution for linear displacement can be calculated:

$$TBE_L = \frac{\Delta l}{\overline{\nu}_F} \times 60000\ (ms). \tag{16}$$

Where Δl is the linear segment length (mm) and $\overline{\nu}_F$ is the maximum feed rate (mm/min). TBE_L is the average time the machine takes to fully execute each one of the linear segments (one program block), which, in this case, resulted in 3.33 ms for all the examples from Table 4. For estimation propose, using the TBE_L, the segment length was calculated in order to provide that programmed feed rate. In this case, the minimum segment length should be 0.28 mm, in order to keep 5000 mm/min. Appling this value of segment’s length in the experiment, the machine kept the feed rate constant (5000 mm/min).

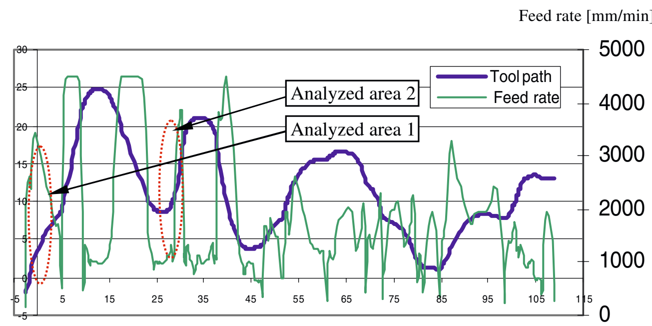
Therefore, the results up to now show the size of the segments in a NC program plays an important role on the maximum feed rate, even for a linear trajectory. Using a spline polynomial, it is intended to describe a curved path using a single NC block.

Experiment 3 compares the ordinary straight-line interpolation method for milling a free-form workpiece against the spline codes generated by the CAM. The actual feed rate at every tool position along the milling path is shown in Fig. 11, for both tool path strategies. It can be noted that average feed rate in part A is lower than that in part B, being 1644 mm/min and 2304 mm/min, respectively. The proportion, around 1.4 times higher, represents a significant gain, in terms of machining time. However, even using spline polynomial interpolation, the programmed feed rate was reached just a few times, for short periods and strong “vibrations” could still be observed during machining.

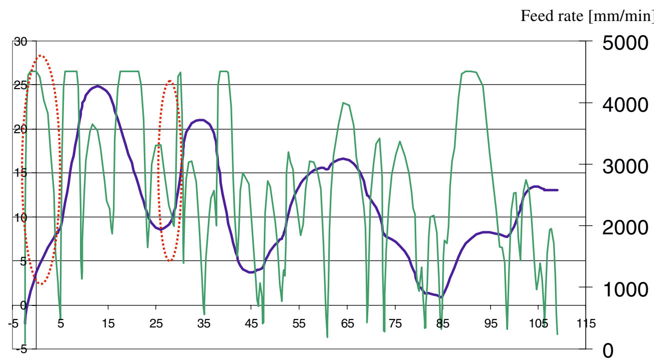
Looking at the NC program length, the program using spline method resulted shorter than that with linear segments but, it still had a relatively high number of instructions. Each line of the spline NC program still represents a relatively short tool movement. The algorithms

Table 4 Average feed rate obtained according segment length

Programmed feed rate: 5000 mm/min Segment length	*Constant feed speed along the path CNC*
0.05 mm	905 mm/min
0.1 mm	1800 mm/min
0.2 mm	3610 mm/min
0.28 mm	5000 mm/min



a Part A: Linear codes. Average feed rate: 1644 mm/min



b Part B: Polinomial codes. Average feed rate: 2304 mm/min

Fig. 11 The tool path against the feed rate plotted for the two strategies

used by the CAM system to calculate the tool paths, based on spline codes, are still not sufficient to transfer information to CNC machine controllers for segments long enough to avoid conflicts with time of block execution of the CNC machine.

In order to verify this issue, a simple tool path was generated by hand, based on a spline equation, using seven defined control points. Figure 5 shows the tool path and the spline NC program created directly at the CNC machine editor. It resulted in just seven lines. Carrying out the appropriate procedure, “the same” spline tool path was obtained by the CAM software, using 0.005 mm as a tolerance band. The respective NC program at this time resulted in 232 lines, to describe the “same path”. That means the algorithm used by the CAM to write the NC program is not fully exploiting the resources available in the CNC machine.

4.2 Surface quality

The results of surface roughness when milling the circular tool path in experiment 1 are shown in Table 5. The Ra values were measured parallel to the feed direction and are an average of five values on different points along the path.

Higher Ra values were observed in semicircle A (linear segments), and the best value was obtained in semicircle B (circular segment). In semicircle C roughness was better than A, but not as good as B. Comparing values between A and C, the same program but different feed rates, it can be stated that the surface quality was strongly affected by the

Table 5 R_a parameter on semi-circular paths from experiment 1

Semicircle	A	B	C
Ra [μm]	1.98	1.01	1.30
Standard deviation	0.01	0.01	0.01
95% confidence interval	0.03	0.03	0.05

feed rate oscillations, which generate a high variation on the cutting tool load. Therefore, using adequate feed rate, the linear interpolation can be applied with reasonably good results on surface quality and that seems to be the case of the vast majority of industries. On the other hand, for high feed rates, such as those needed in HSC, tool path strategies have to be adequate.

After milling the workpiece in experiment 3, Ra was measured and photos were also taken to show surface aspect. Figure 12 shows this data.

It can be noticed that there is some surface damage due to "vibrations" on specific areas of the workpiece according to the tool path strategy. In area 1, the feed rate oscillates strongly when the linear path was used, and remained constant when spline was used. In the spline case, surface finishing was mainly influenced by the cutting parameters, feed per tooth and steep over, unlike in the linear interpolation, which had a poor surface texture, which is likely due to the constant cutting tool load variation. Area 2 represents a region on the workpiece where both strategies produced high variations on feed rate. Therefore, a very poor surface quality was observed. Although the spline NC program was faster than the linear one, it still presents heavy oscillations.

4.3 Path accuracy

A comparison between the accuracy of both path strategies could be verified by plotting both tool paths using the X, Y and Z coordinates obtained directly from CNC, using the real-time recording system. This procedure verifies the possible distortion between the tool path interpolation method, during machine movement, and that generated by the CAM program. It does not actually verify the machine surface because some other sources of variation are not considered, such as tool deflection and temperature effects on tool and workpiece, for example. Using graphical software, the real tool path obtained directly from the CNC for both methods was plotted against the theoretical path generated by the CAM program. No deviation was observed for both methods larger than the chordal error applied for the CAM calculates the path (0.005 mm).

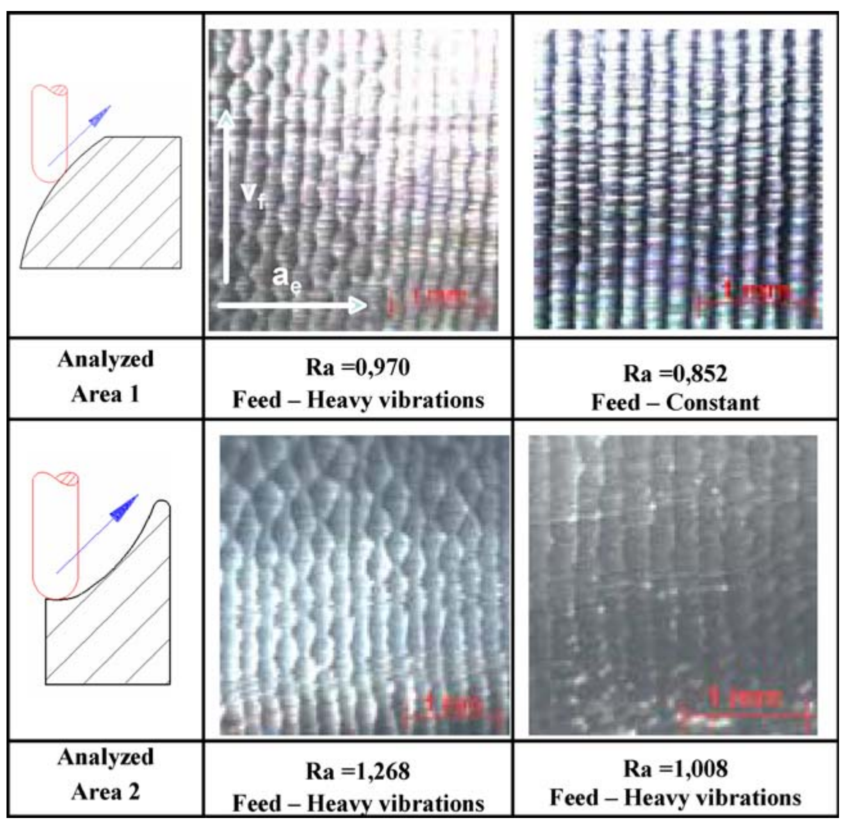


Fig. 12 Surface finishing according to the feed rate oscillation

5 Conclusions

From the experimental investigations above conducted, some conclusions could be drawn:

1. "Involuntary" feed rate reduction by the machine was noticed when using complex paths, which may generate a high volume of information. It represents the bottleneck for higher material removal and machining process stability when applying high speed milling technology on complex 3D surfaces. It happens even in modern CNCs with new function for milling in high speed. Three major reasons for feed rate reduction could be identified: machine dynamical limitation, CNC block processing time and tool path strategy. The reduction on feed rate did not occur exclusively due to the machine's dynamics, or by the constant variation on path direction, caused by the linear interpolation method (continuity C0) either. Instead, it was found to be more related to the time of block execution (TBE_L), a characteristic of the set machine-CNC. Feed rate was reduced even in a linear one-axis path. The machine TBE_L, associated with tool path strategy, was the main reason for feed rate reduction during free form surface milling. When NC programs generated by CAM were performed, it was observed that the feed reduction does not occur uniformly. It oscillates strongly, according to the segment length in the NC program used to describe a free form path. It is related to the tolerance band set at the CAM, together with the path curvature and the calculus algorithm. These oscillations negatively affect surface quality, increase milling time, vary feed per tooth, cutting tool load and also machining time estimated by the CAM becomes inaccurate.
2. In experiment 1, milling the semicircle at high speed with a NC program applying the linear interpolation, the programmed feed rate could only be reached in very short periods along the circular path. The machine presented a "vibration" related to the inertia of moving parts subjected to high accelerations, due to short traveling distances, time of block execution (TBE_L), as well as the variation on segment lengths. However, if the circular interpolation NC code is used instead, the programmed feed rate is reached and maintained for the whole circular path. In contrast, using linear interpolation constant feed rate can only be achieved at about 28% of the programmed value, in the particular tested conditions. Machine dynamical behaviour however, seemed not to be the main reason for feed rate reduction, in the experiments carried out in the present work. When G02, circular interpolation was used the programmed feed rate was reached and maintained.
3. In experiment 2, a simple procedure was used to verify the time of block execution (TBE_L) of the CNC machine. In linear interpolation, where there is no change on direction, the segment length plays the major role. The longer it is, the higher the maximum feed rate is, although it does not necessarily reach the programmed value. For the particular CNC used in combination with the machining centre, that time resulted in 3.33 ms. Although with current CAM programs there is no possibility of defining the segment length, using that time a segment length could be established to yield the feed rate desired. That value could be proved experimentally. This procedure can be very useful for benchmarking CNC high-speed machine, in terms of processing capability.
4. In experiment 3, the programmed feed rate was reached in very short periods along the path, for both tool path methodologies analyzed. Using the spline strategy for describing the tool path, obtained from the CAM, better results were observed. The spline NC program presented a reduction of about 25% on the time required for milling the designed workpiece. That can represent significant time saving, but even with shorter milling time, comparing to the linear method, the feed rate presented severe oscillations and was limited many times. The CAM algorithm employed to calculate the spline tool path divided the trajectory into a large number of spline segments. It still represented a significant amount of information to the CNC. However, if the algorithm used by the CAM was capable to fully exploit the resources present in the CNC machine, circular and spline tool path strategies could offer more advantages, keeping the feed constant and, consequently, all the benefits of such condition. In the near future two approaches will be used to further investigate the subject: improve the CNC/machine computing capability and the CAM algorithm to calculate the spline NC codes.
5. As expected, surface quality is related to machine parameters, machine performance, in terms of feed rate and some other parameters. It is also related to the tool path strategy used. In the circular path, using straight lines to approximate the profile, surface quality is poor due to "vibrations" caused by variations on the acceleration of moving parts together with variations on tool load, due to the feed rate oscillation. If circular interpolation is used, better surface quality results. It was also observed that the surface quality is much more affected by the heavy oscillations on the programmed feed rate than by the linear interpolation method in itself, as can be seen on the surfaces obtained by semicircle A and semicircle C in experiment 1. On complex geometries segment length plays a major role on surface finishing. The longer the segment length, the lower the variation on acceleration and the better the surface finish is, although long segments on strongly curved surfaces will result in large distortion from the original surface.

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