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Analysis of machining strategies for peripheral milling

H. Perez^{a,*}, E. Diez^b, J. Perez^c, A. Vizan^c

^aDepartment of Mechanical Engineering, Universidad de León, 24071 Leon, Spain

^bDepartment of Mechanical Engineering, Universidad La Frontera, Temuco

^cDepartment of Mechanical and Manufacturing Engineering, Universidad Politecnica de Madrid, Spain

Abstract

Milling is a versatile cutting process used widely in the manufacturing industry for shaping complex geometrical workpieces. Due to the flexibility of the cutting process and the different variables involved, the optimization of the milling process has become a key issue in order to achieve higher productivity and quality. To optimize the process planning, it is important to select an adequate machining strategy. A machining strategy provides a cutting mode for the tool during a particular machining operation, determining the axial and radial depth of cut and the recommended trajectories for the cutting tool. This paper presents an analysis and validation of different strategies for peripheral milling. For this purpose, a new cutting force model is used. The cutting force model used in this paper is an average-chip-thickness-based model developed by the authors in a previous publication.

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1. Introduction

Milling is a versatile cutting process used extensively in the machining of complex geometrical workpieces. It has become key technology in the manufacturing of dies and molds as well as in aerospace and automotive

* Corresponding author. *E-mail address:* hilde.perez@unileon.es

components. Due to the flexibility of the cutting process and the different variables involved, optimization of the milling process has become a fundamental aspect in order to achieve higher productivity and quality. Therefore, a precise knowledge of the cutting process is required for the efficient definition of the machining operation. For this reason, tool manufacturers propose the use of machining strategies.

A machining strategy establishes the working mode for a cutting tool in a machining operation and basically fixes the width and depth of cut, and the cutting trajectories. An in depth knowledge of the cutting tool performance is applied in each individual case. Owing to this, it is the tool manufacturers who propose the use of machining strategies for an efficient use of their cutting tools.

Figure 1 shows some of the simplest and most used machining strategies. They mainly refer to the entrance of the tool into the workpiece, contouring, slotting and pocket machining. In all these strategies the depth of cut is constant.

The machining strategies are assumed by the programmer and although it is not very common, a few commercial software packages include some of them. However, to the authors' knowledge, there is no paper in scientific or technical literature where the use of machining strategies is justified from an analytical point of view.

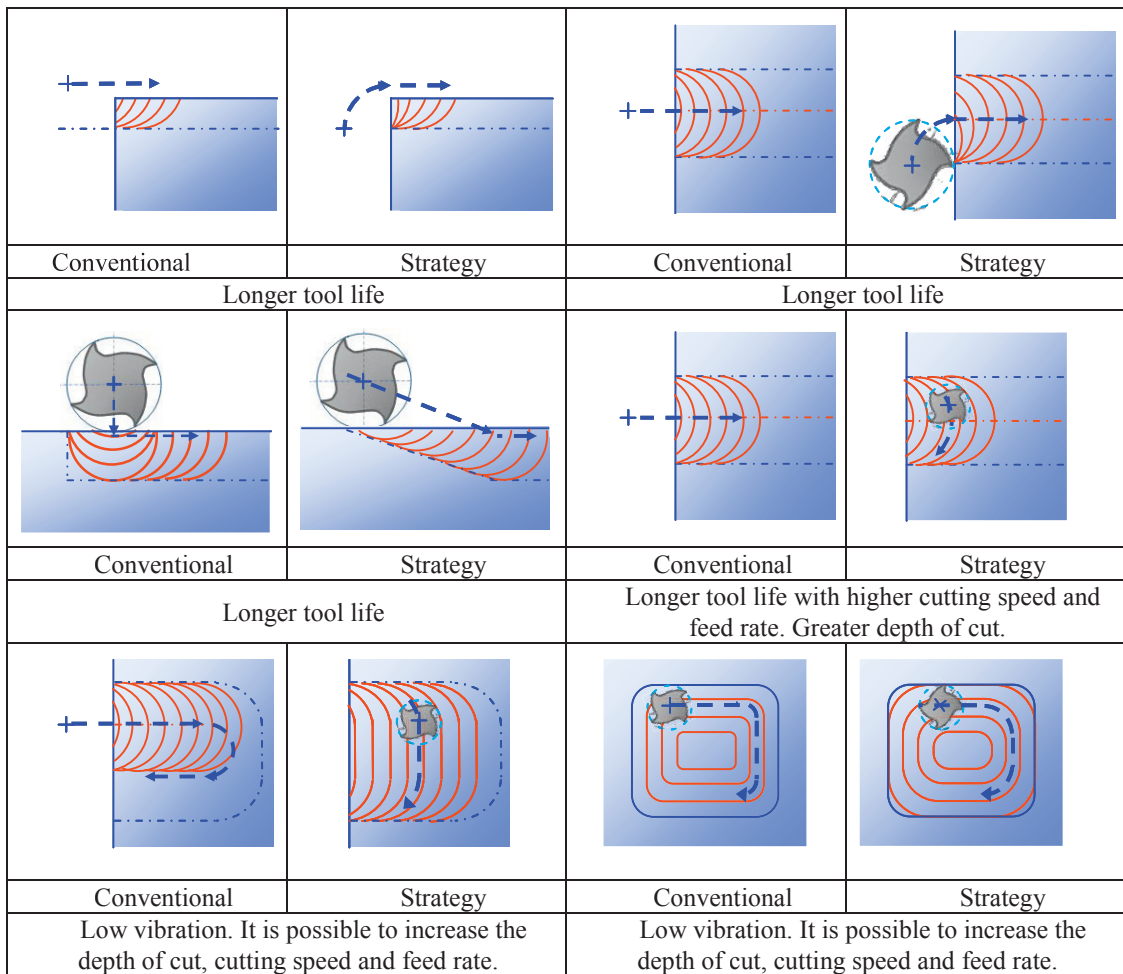


Fig 1. Machining strategies for peripheral milling

The objective of this paper is, therefore, to try to justify the adequacy of the proposed strategy for peripheral milling. For this purpose, a study of cutting tool behaviour is realized based on the resulting cutting forces as well as their effect on tool wear.

On the other hand, it has also been possible to analyse the evolution of tool wear under varying machining conditions, the proposed strategies being a clear example of this.

According to this, an adequate model for cutting force estimation is required. The way the chip is formed is crucial to optimize the cutting process because the evolution over time of the resultant cutting forces and the wear of the cutting edges depend on it.

A review of scientific literature reveals that there are many publications related to cutting force modelling for peripheral milling, as the papers presented by Wan et. al (2009) or Dang et. al (2010). However, for this research a new model has been developed, Perez et. al (2013). This model is based on chip thickness and allows us to estimate the cutting forces when machining variable geometries. It is possible to determine, at every instant, the actual position of the cutting tool, the chip thickness and the variation of the entry/exit angles of the cutting edge into the workpiece.

Some papers refer to machining strategies in milling but only from the point of view of the definition of tool path strategies in order to improve the quality of the machined surface. Zhang (2012), Ramos (2003) and Toh (2004) are some examples of research in this area.

Sikumar (2012) presents a framework for integrating different requirements in high speed milling. The best combination of cutting parameters is identified for two different objectives. In the case of rough end milling, the objective is oriented to MRV and in the case of finish end milling the objective is oriented to surface roughness.

In this paper, the objective is to explain analytically and experimentally the application of these techniques. For this purpose, a set of experiments were carried out so as to compare conventional cutting with another where these strategies are applied. This comparison takes place by means of the analysis of the cutting forces exerted on the milling tool and the progression of tool wear.

2. Machining strategies for peripheral milling

The validation of the strategy is based on different parameters such as an adequate combination of chip thickness to width of cut, the length of the arc of engagement or an adequate combination of cutting speed to width of cut. In all these cases, the way the chip is formed during the cut is a key issue to achieve longer tool life and an increase in volume of metal removal. In other words, a reduction in machining time.

The combination of chip thickness to width of cut may lead to an increase in chip thickness for small widths of cut, until the maximum value is reached for a particular cutting tool. Under these circumstances, the length of the arc of engagement is shorter. Therefore, this leads to a decrease in temperature, giving longer cutting tool life.

Chip formation is a fundamental aspect due to its effect on cutting tool wear. Tool edge entries into workpiece material with thin chip thicknesses cause high friction between the tool flank face and the material, thus increasing tool flank wear considerably. In this respect, it is preferable that the cutting flute enters the workpiece with maximum chip thickness at the beginning of the cut. When the cutting tool exits the material with thin chip thickness, this results in prolonged tool life.

Therefore, thin chip thickness on exit and small engagement arcs result in longer tool life for a particular cutting tool. Moreover, it is possible to increase the cutting speed significantly. These assumptions are the main focus of the application of machining strategies.

In addition, the resultant reduction of cutting forces and vibrations enables an increase in the depth of cut or the length of the cutting tool, which is particularly advantageous in certain circumstances.

3. Workpiece entry - Rolling into the cut

From the different cutting strategies proposed in figure 1 to improve the cutting process, the most popular techniques are those referring to entry in the workpiece.

This strategy proposes the entry of the cutter rotating on a pivot point. The cutting tool enters gradually until the nominal width of cut is reached. This technique aims to ensure the smallest chip thickness possible when exiting the cut, as is shown in figure 2.

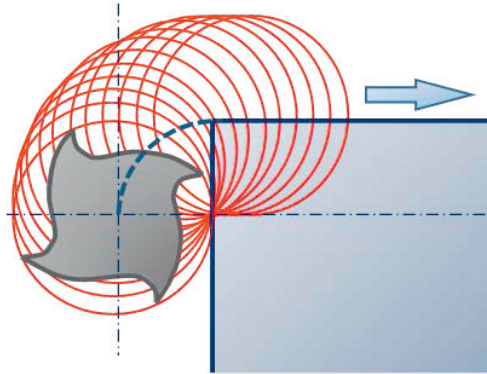


Fig 2. Workpiece entry rolling into the cut

Before the cutter is fully engaged, the arc of engagement increases gradually with the progression of the cutter in the cutting zone. This consequently leads to a gradual increase of cutting forces. The rolling-in technique also eliminates the vibration introduced when the cutter enters directly.

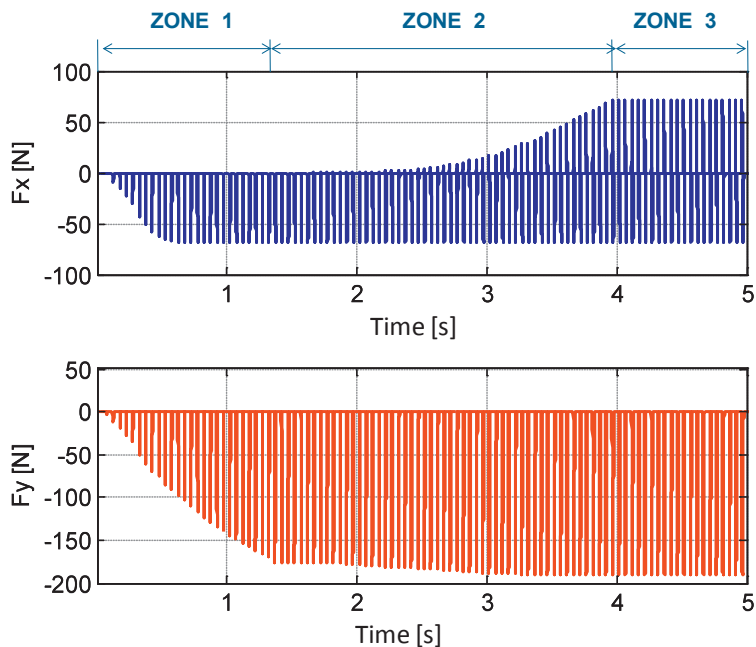
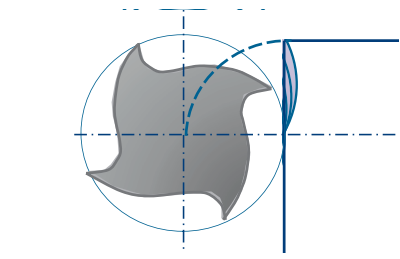
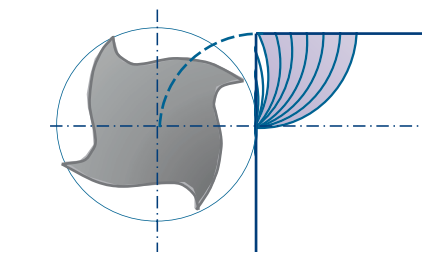


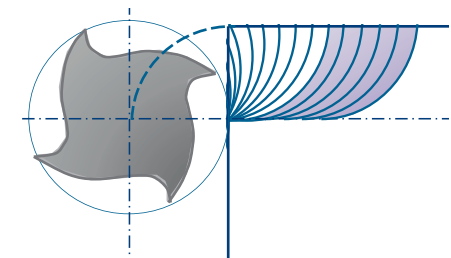
Fig 3. Cutting forces F_x and F_y for workpiece entry rolling into the cut
($D=8$ mm; $N_z=2$; $\lambda_s=30^\circ$; $f_z=0,08$ mm; $a_e=4$ mm)



Zone 1: Transient cut. The tool enters the side of the workpiece.



Zone 2: Transient cut. The tool starts to cut the top of the workpiece.



Zone 3: Uniform cut. The tool is fully engaged in the workpiece.

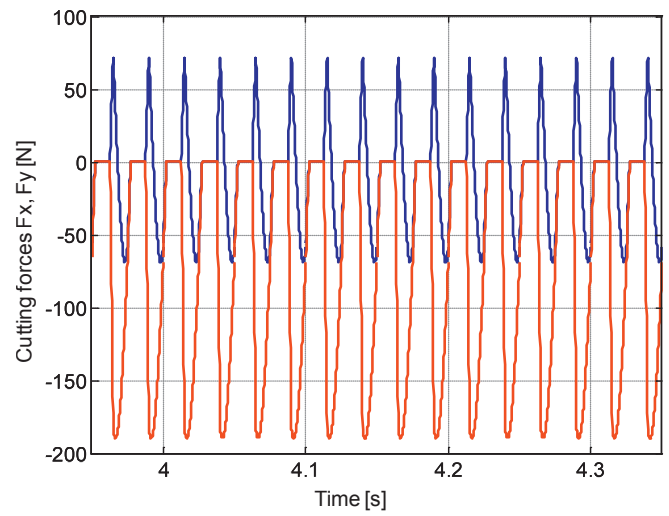
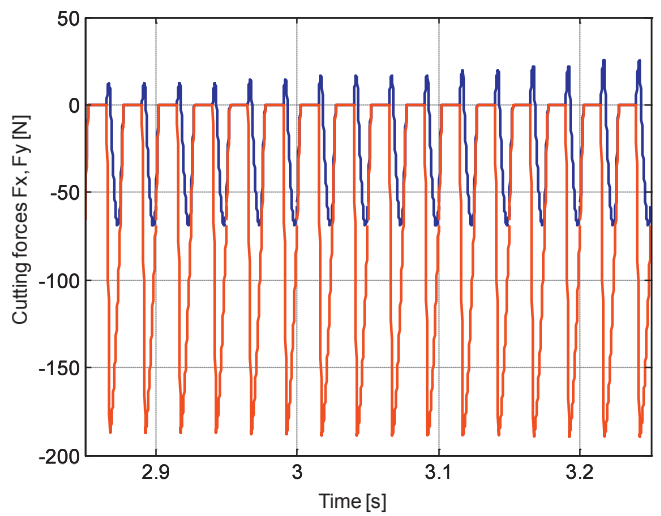
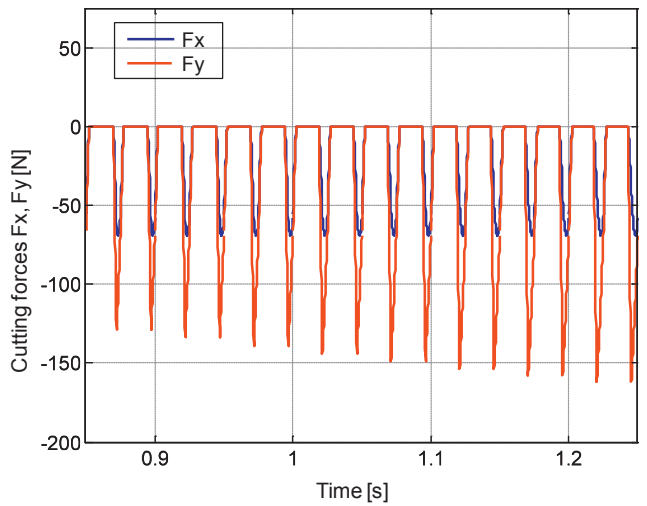


Fig 4. Cutting forces F_x and F_y for the rolling-in technique

As mentioned above, a new cutting force model is used for estimating the entry of the cutter into the workpiece until it reaches total engagement.

Cutting forces F_x and F_y , for X axis parallel to feed direction, are shown in figure 3. During the entry of the cutter in the material, three different zones can be distinguished until the milling tool is completely engaged. The first one corresponds to the start of the cut until the left corner of the workpiece is reached, figure 2. In this stage, the arcs of engagement on every revolution are small in addition to the cutting forces.

As the tool advances into the cut, it starts to cut the top surface of the workpiece. This is zone 2. Here the arc of engagement still increases in each cutter revolution and consequently the cutting forces do the same. The cutting tool still enters in the material in transient state.

Zone 3 starts when the cutter has completely rolled onto the pivot point. Once the cutter is fully engaged, the cutting conditions are kept constant as well as the force profile.

Figure 4 shows a closer view of the force diagram for each zone. In the first and second stages the cutting conditions are variable. Both entry and exit angles vary in each cutter revolution and the cutting force profile varies accordingly.

In the diagram it can be seen that, during the entry of the cutter, not only the maximum in F_x and F_y vary but also the period of the cutting forces until the tool has reached a uniform cut. The arc of engagement increases on each cutter revolution and consequently the cutting forces do the same. Once the cutter has entered completely, zone 3, the force profile is kept constant.

4. Discussion and results

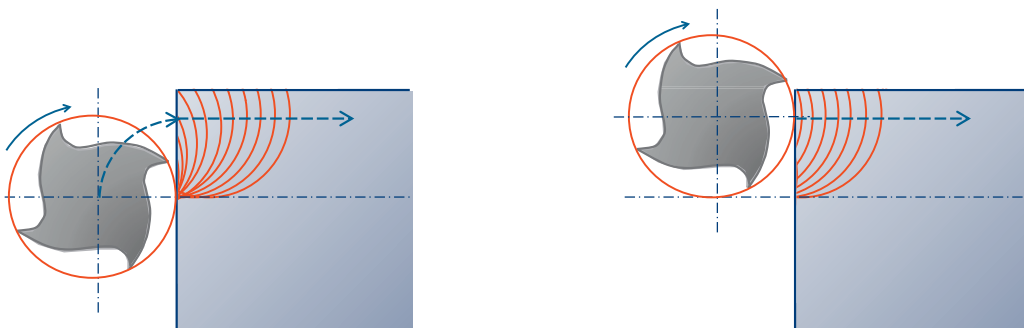
In order to show the advantages of the application of these strategies, the straight-in entry and the rolling-in entry are compared.

For this, the evolution of cutting forces, chip formation and the volume of metal removal are analysed in both cases.

Figure 5 shows a sketch of both techniques and the simulated cutting forces for an 8 mm diameter tool, $f_z=0,08$ mm, $a_e=5,6$ mm and $a_p=2$ mm.

When entering into a cut directly (figure 5 right), the cutter leaves the machining area with a thick chip thickness and consequently vibration appears in the machining process. When using the roll-in technique, however (figure 5 left), thin chips will exit the cutter from the very start of the machining process.

The evolution of the cutting forces shows that the entry of the cutter with the roll-in technique is more gradual. The cutting forces gradually increase on every cutter revolution until the cutter reaches a uniform cut, meanwhile for the straight-in case, the tool is under the highest pressure very quickly.



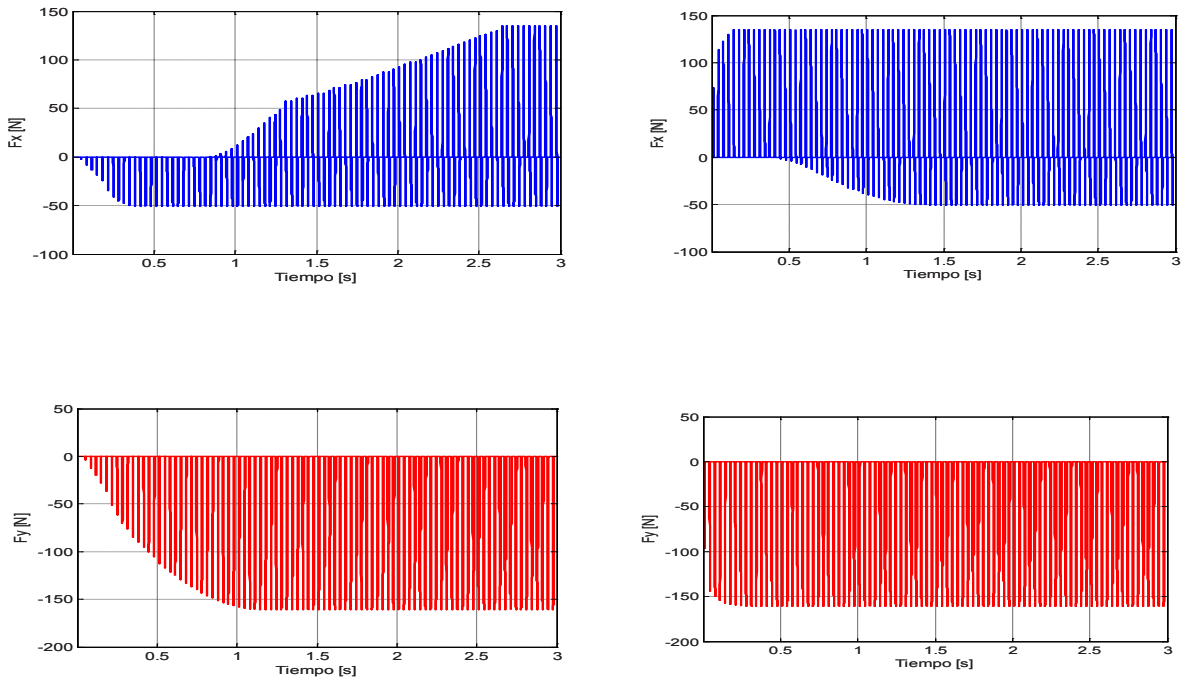


Fig 5. Comparison of workpiece entries: straight-in and roll-in

The way the chip is formed and the length of the arcs of engagement affect tool wear.

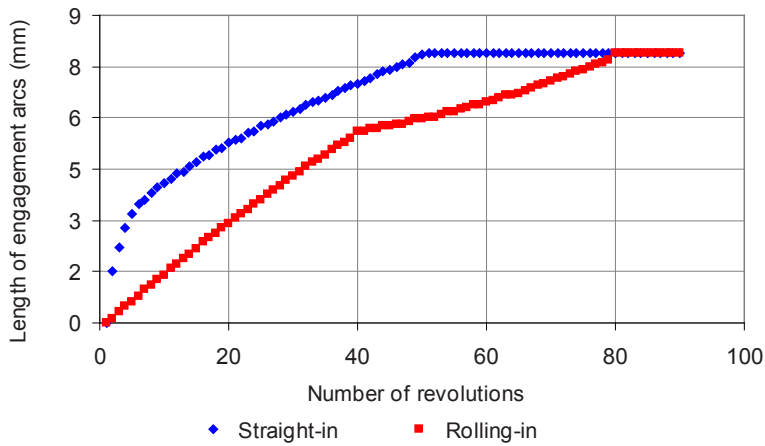


Fig 6. Evolution of engagement arcs for straight-in entry and roll-in entry.

Figure 6 shows the evolution of the engagement arcs for both entries, straight-in and roll-in. In the case of the roll-in technique, the lengths are gradually increased until the cutter is completely engaged. When applying the

roll-in technique, the length of the engagement arc is always smaller than with the straight-in technique. This leads to lower temperatures in the cutting flute and consequently less tool wear.

Furthermore, the evolution of chip thickness for both techniques, figure 7, shows that chip thickness is always smaller when applying the roll-in technique. Thinner chip thicknesses lead to lower tool pressures, resulting in longer tool life.

These results are consistent with the premises of the cutting strategies.

In order to verify that this technique leads to longer tool life than the conventional one, a set of experiments have been carried out.

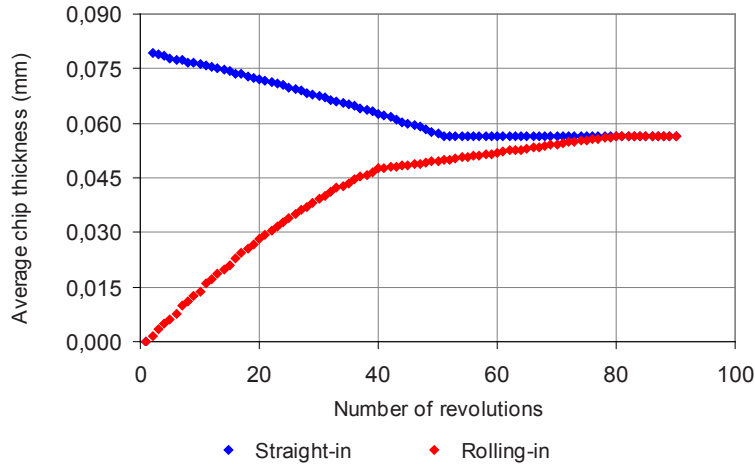


Fig 7. Evolution of chip thickness for straight-in entry and roll-in entry.

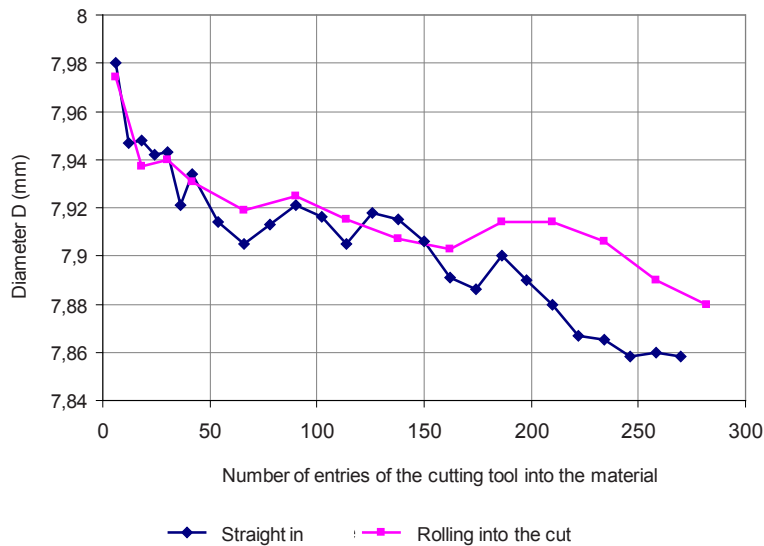


Fig 8. Indirect tool wear measuring tool diameter when machining steel alloy 1.2510

The experiment consists of using the two methods for the entry of the cutter; the conventional and the proposed strategy. The workpiece material used is steel alloy 1.2510. The cutter starts the cut until total engagement is achieved and the tool diameter is measured periodically.

In figure 8 it can be observed that from 200 entries, the tool wear is lower for the experiment using the roll-in technique. This difference increases with the number of entries.

The same experiment was carried out with softer materials such as aluminum alloy 3.4365. However, the differences between them were not clear and only a slight difference could be observed when 1000 entries were reached.

From the experiments carried out and from the data provided by tool manufacturers, it can be concluded that these cutting strategies are more suitable for harder workpiece materials.

5. Conclusions

From the experimental results, although here only a few results are shown, the following conclusions can be drawn:

- The proposed cutting strategies may provide significant improvements when machining difficult-to-cut or harder workpiece materials, such as those used for mold machining.
- The basic rule for milling, which recommends always ensuring the smallest chip thickness possible when exiting a cut, is correct, because it leads to longer tool life.
- Insignificant differences are observed when machining softer materials. In this case, the application of cutting strategies is not recommended.

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