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Research Article

A new trochoidal toolpath in milling operations

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ABSTRACT

The milling is a widely used method in the manufacturing industry, especially in the production of complex engravings such as die&molds. Rough milling often requires a large material removal rate in a short time. This purpose also requires the selection and use of the best milling tool path. Today, trochoidal milling is receiving more attention than conventional milling, especially as it significantly increases tool life. In this study, a new toolpath model for trochoidal milling is suggested and this proposed toolpath model is examined in terms of cutting temperature, cutting force, surface quality, tool wear. In this new trochoidal toolpath model proposed for the milling method, the cutting force did not change much compared to the standard trochoidal tool path, but better surface quality and less tool wear were observed.

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INTRODUCTION

As in the whole manufacturing sector, there is a need to be more efficient in machining. In this respect, in addition to the academic studies, manufacturing companies also carry out R&D in the field of machining in order to produce with shorter cycle times and less cost. Also, nowadays, workshops are encouraged to waste less energy in cutting operations. Especially in the milling of difficult-to-form materials and parts with complex shapes, an efficient use of energy is required due to the long cycle times. Meanwhile, less cutting energy, better surface finish and less tool wear are desirable. Indeed, cutting conditions and operations tend to be very conservative to avoid dramatic tool failures and idle times. Tool path strategies and cutting conditions appear as a multivariate problem that needs to be addressed with various aspects, especially in milling operations, which are widely used.

In the last few decades, the trochoidal toolpath method has been applied in milling, especially in harsh conditions, due to its various advantages.

The term called trochoidal milling (Fig. 1) is the latest milling technique in high efficiency machining technology today. In recent decades, this method has proven

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superior final product manufacturing quality and that is why many high-tech companies such as aerospace and automotive companies use this procedure with their software applications.

Compared to traditional slot milling, trochoidal milling reduces cycle time in end milling, reduces the effects of tool vibration that can be seen as surface finish in the final product, and also reduces geometric and dimensional tolerances. Trochoidal milling, which makes a significant contribution to the machining process, prolongs tool life by reducing the amount of tool wear. The use of this advantageous toolpath becomes a reasonable and attractive research topic for many researchers and also generates new ideas for designing more efficient toolpaths, especially for researchers.

Figure 1. Trochoidal milling.

In this study, a new trochoidal toolpath was suggested and its effect on tool temperature, cutting force, surface quality, tool wear was investigated.

LITERATURE REVIEW

One of the first research was revealed, called with trochoidal milling, by Otkur and Lazoglu in 2006. [1]. In the research, a tool path called "double trochoid toolpath" was applied to estimate the values of the forces and analytical and numerical models were developed. Rauch et al. [2] created a mathematical model to determine the amount of undeformed chip thickness related to trochoidal tool path parameters. The model was tested for two different interpolation models and these models were optimized for the process parameters for optimum cutting procedure. Ibaraki et al. [3] was implemented different tests to compare the processes, trochoidal and slot milling, in roughing milling. The researchers determined the processing times for trochoidal milling and slot milling. They determined that, depending on the experimental parameters, trochoidal milling had a 20% shorter cycle time compared to slot milling. Szaloki et al. [4] tested 5 different trochoidal toolpath (Fig. 2) with slot milling and compared all of them in terms of cutting forces and surface roughness. Original trochoidal milling processes has given slightly better results in comparison with modified trochoid curves.

Uhlmann et al. [5] researched on the subject about energy saving machining procedures, compared dry trochoidal machining with conventional milling with coolant addition in terms of the amount of cycle time and consumed energy. For the same amount of material removal, the power consumption of trochoidal machining was slightly higher than conventional milling (6%), while the machining time was 35% less. Szaloki et al. [6] were

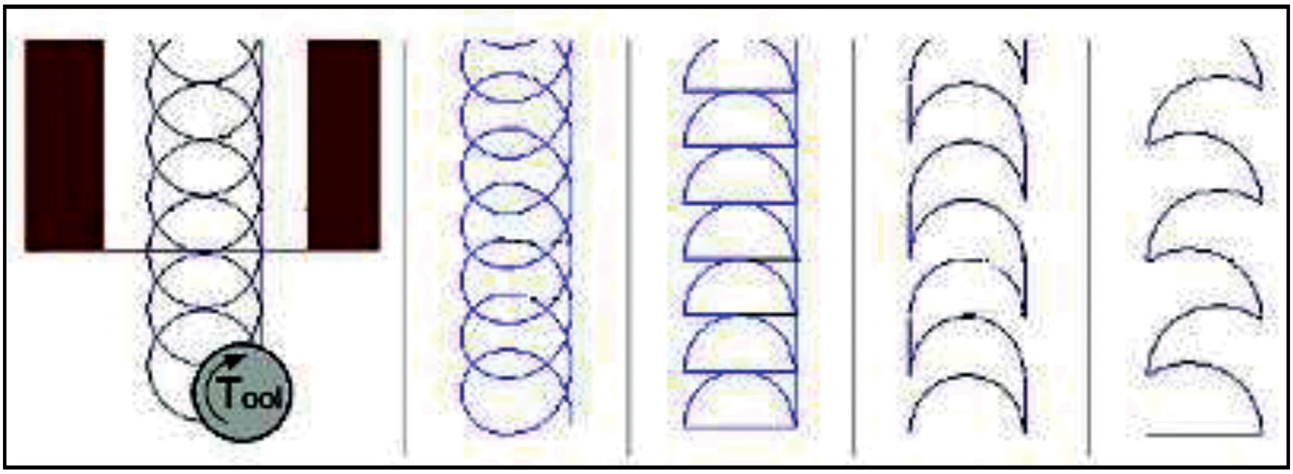

Figure 2. Different toolpaths about trochoidal milling [4].

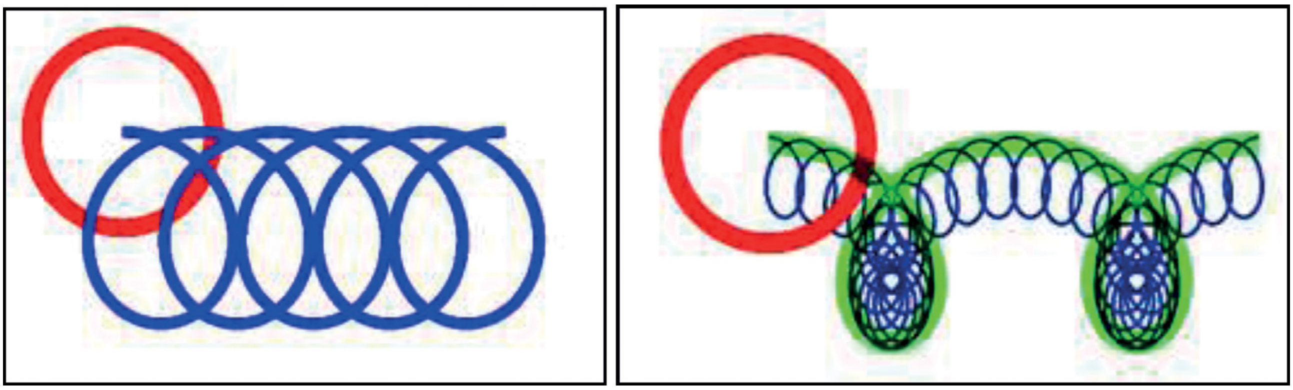

Figure 3. a) Model for trochoidal tool path; b) Model of epicycloidal tool path [10].

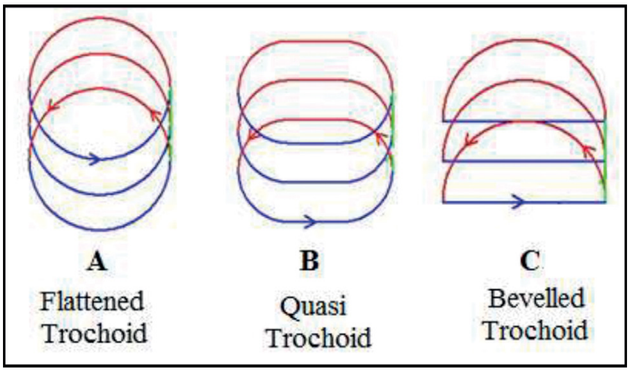

Figure 4. Paths used in research [13].

conducted a research about making correlation between process parameters of cycloid formed trochoid curves with the amount of cutting forces and effect of workpiece geometrıcal quality. In the study, empirical equations with 99% accuracy were obtained with experimental design methods. Peng et al. [7] investigated the generation of forces related to the radial depth of cut, modeled a mathematical equation and verified this equation by testing it in trochoidal milling. Polishetty et al. [8] investigated the trochoidal machining of thin-walled workpieces. They stated that cutting forces increased with feed per tooth, cutting speed and trochoid pitch. Reduced cutting forces will reduce tool wear. For this, the tool has to work with lower pitch and lower cutting speeds. For getting high surface quality of thin walled materials, tool has to be operated under small trochoidal step over. Pleta et al [9] claimed in their research that “trochoidal milling” and “circular trochoidal milling” terms were different from each other. By determining the force data on the tool in each axis, they performed studies to validate their mathematical models. Salehi et al. [10] compared the epicycloidal and trochoidal milling (Fig. 3) in terms of tool tip vibration, cutting forces and process time. In trochoidal milling, the value of amplitude was nearly 10% less than epicycloidal milling operation. However, the value of process time was 20% shorter than trochoidal milling in epicycloidal one.

Shixiong et al. [11] investigated the forces, tool wear, and machining time of contour milling and trochoidal milling in high-speed machining. They determined that the forces acting on the tool in contour milling are 100% more than in trochoidal milling, and the processing time is 30% shorter than in contour milling. Pleta and Mears [12] investigated the occurrence and origin of tool failure events due to tool wear under different machining conditions. Especially in machining superalloys, trochoidal milling showed superiority in tool wear compared to conventional milling technique. It has also been reported that the y-axis force increases by 40% after notch wear before tool failure occurs. Kowalski et al. [13] had a research about the trochoidal machining of hard metals. In the study, the effect of different types of trochoidal toolpaths (Figure 4) on the workpiece surface roughness was investigated. It was determined that the original trochoidal toolpath (A) gave better results than the modified trochoidal toolpaths. It has been defined that the forces acting on the tool are more stable and the surface roughness values are lower in the full circular tool path.

Alternative trochoidal toolpaths have been developed by Pleta et al. [14] to achieve better high-speed machining conditions. They stated that milling with a different trochoidal tool path reduces machining time and increases tool life. Kiyak and Yılmaz [15] investigated the difference between trochoidal milling and conventional milling in terms of surface roughness and tool wear. Surface roughness was 40% lower in trochoidal milling than in slot milling. In addition, mean tool wear was 40% lower in trochoidal milling than in slot milling. Deng et al. [16] researched an alternative trochoidal toolpath to discover more efficient way of shoulder milling with conventional milling techniques. They determined that the tool path length of the

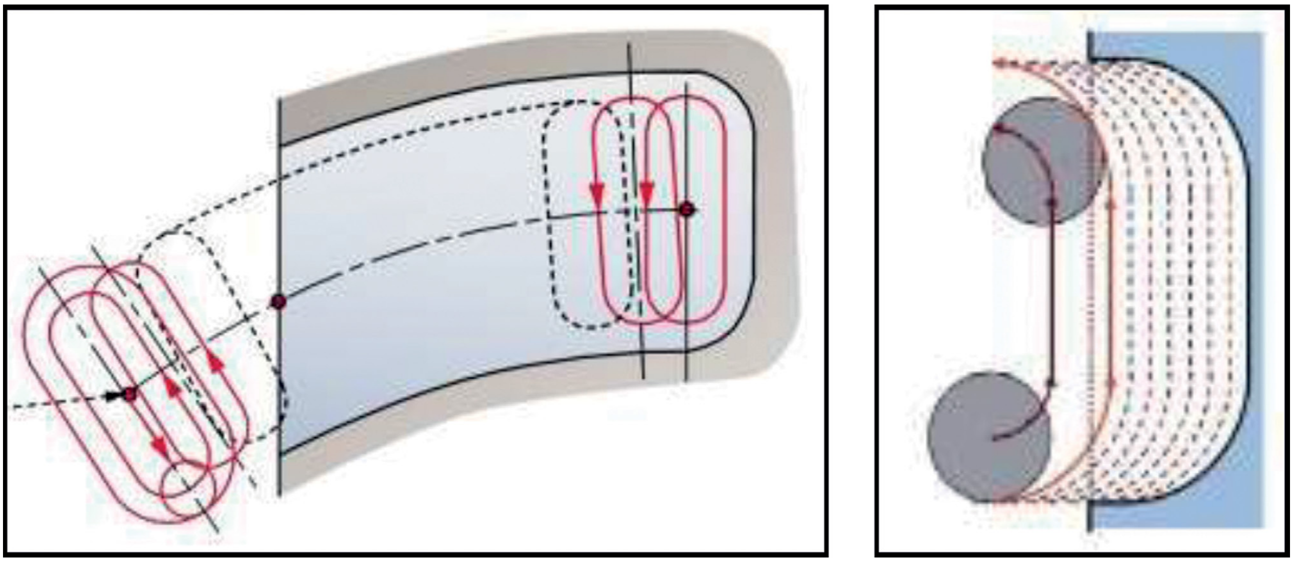

Figure 5. Wide type trochoidal tool path [17].

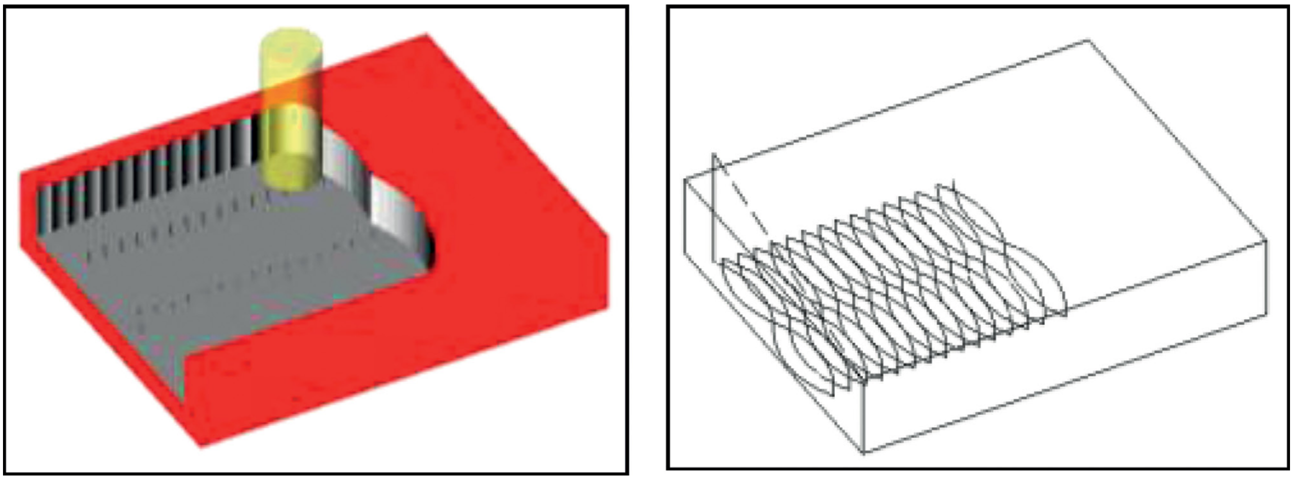

Figure 6. Suggested new trochoidal tool path ("8" type).

conventional shoulder milling process is 18% longer than the mathematically optimized alternative trochoidal path. Amaro et al. [17] investigated the effect of machining stainless steel by trochoidal milling on tool wear. They noted that in trochoidal milling, increased cutting speed increased MRR and tool life. The suggested trochoidal tool path in the study is given in Figure 5. A continuous spiral path (Fig 5), such as those programmed for the narrow groove where 50% of the time is spent with the tool out of the cut.

Pleta et al. [18] suggested different trochoidal milling toolpaths that shorten the machining time but increase the tool life. In the study, the relationship between minimum tool wear and optimization and improvement of cutting forces was investigated. Vibration occurs during the milling process. Gross et al. [19] stated in their study on this subject that trochoidal milling is not a suitable strategy to reduce vibrations and tool wear compared to linear milling. There is a need to be more productive in machining. However, processing with less energy wastage is very important. Especially in the milling of complex parts, an efficient use of energy is needed due to the long cycle times. Pelayo et al. [20] stated in their study that trochoidal milling has a very low sustainable productivity gain value.

In this study, the advantages of a proposed new trochoidal toolpath for trochoidal milling are presented. The effect of the proposed new tool path was investigated in terms of cutting force, cutting temperature, surface quality and tool wear.

Table 1. Experimental parameters

Diameter of endmill (mm)	10
Cutting speed (m/min)	40
Depth of cut (DoC-mm)	10
Radial DoC (mm)	1.5
Tool cutting edge	4
Feed (mm/rev)	0.3

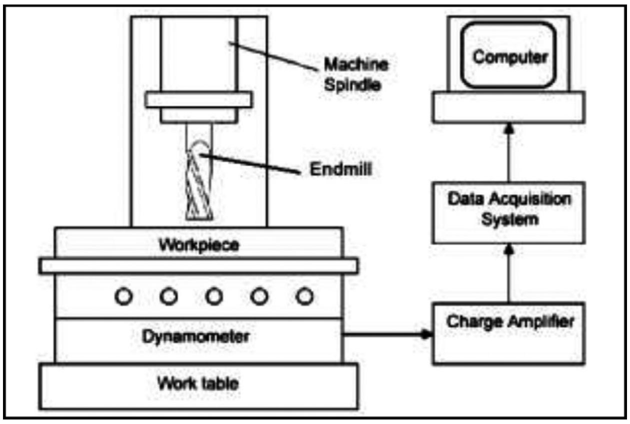

Figure 7. Experimental setup for cutting force measurement.

A NEW TOOLPATH SUGGESTION FOR TROCHOIDAL MILLING

As previously mentioned, there are various trochoidal toolpath suggested by researchers. In this study, a new trochoidal toolpath is proposed as shown in Fig. 6. The suggested new tool path is in the format "8" as shown in Fig. 6. In this respect, it is called "Trochoid Type 8". The proposed new trochoidal tool path was compared with the wide type (standard) trochoidal tool path shown in Fig. 5.

According to the results obtained, cutting temperatures increased more in the proposed new tool path. However, better workpiece surface quality was achieved. In addition, it has been observed that with the use of the proposed new tool path, less tool wear occurs, which can provide longer tool life.

EXPERIMENTAL RESULTS AND DISCUSSION

In this study, using different trochidal route; cutting temperatures, cutting forces, tool wear, surface roughness of the workpiece were tried to be revealed as process outputs. In the experiment conducted to determine the effect of the new trochoidal tool path defined within the scope of this study, AISI 1040 steel material was used as the workpiece and a 10 mm diameter HSS end mill tool was used as the cutting tool. The trochoidal milling processes were carried on FIRST brand VMC model CNC machining center. Parameters used during the tests are given in Table 1.

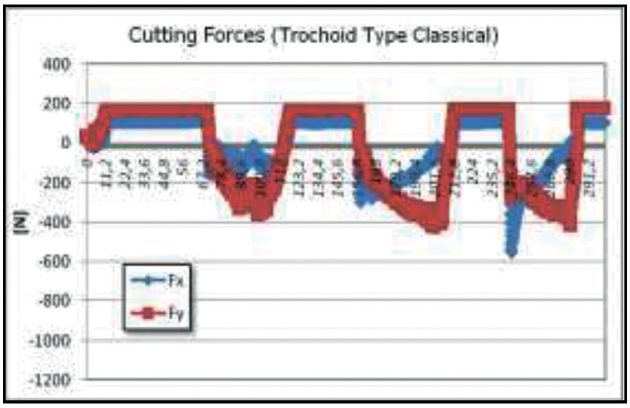

Figure 8. Cutting forces of classical type trochoidal.

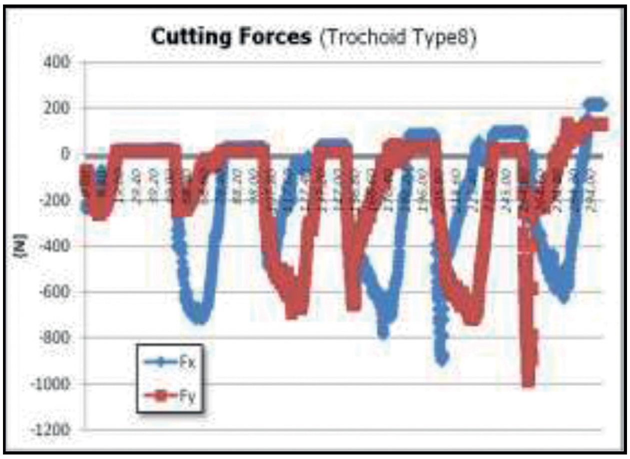

Figure 9. Cutting forces of proposed type trochoidal.

During machining, a significant part of the mechanical energy (approximately 85%) is converted into heat energy. Heat is the total energy of the motion of the molecules inside the object, where as temperature is a measure of this energy. In the study, tool temperatures were measured. In the experiments, piezoelectric type dynamometer for cutting force measurement, non-contact optical measurement system for temperature measurement, profilometer for surface roughness and toolmaker microscope for tool wear measurement were used. Experimental devices are explained in detail in the relevant sections.

Cutting Forces

During trochoidal milling processes, the cutting forces (Fx and Fy) were measured with Kistler brand 9252 B model piezoelectric type dynamometer. The experimental setup for force measurement is given schematically in Fig. 7.

The cutting force values determined in the classical trochoidal tool path and proposed trochoidal tool path application are given in Fig. 8 and Fig. 9.

Depending on the situation of down milling and up milling and depending on the angular condition of the tool, the force changes are observed. In general, down milling positive, up milling gives negative values. Although the directions were different, there was not much change in cutting forces in general. The average cutting force is around 300 N. In the application of the proposed new trochoidal milling tool path, it can be considered as an advantage that it does not create an increase in force compared to conventional methods.

Cutting Temperatures

As shown in Fig. 10, Optris brand CT laser LT model non-contact laser type temperature measurement equipment was used for measured the cutting tool temperatures. Temperature range is between −50° C to +975° C. Temperature resolution has 0.1°C. With the 1.0 ms response time, scanning is the possible for fast moving objects.

Determined cutting temperatures values are given in Fig. 11 and Fig. 12, for classical trochoidal tool path and proposed trochoidal tool path. For the purpose of determined the change in heat energy with the same cutting parameters, varying tool path profiles were used.

The mean temperature of cutting tool was determined as an 86.6 ^{0}C in classical trochidal tool path. In the proposed tool path (Trocoid Type 8), the measured average temperature value is 110.6 ^{0}C. The tool temperature has increased due to the relatively long tool path. The temperature increased due to the increased friction of the cutting tool on the workpiece. This result is in good agreement with the literature [13].

Figure 10. Laser type temperature measurement device.

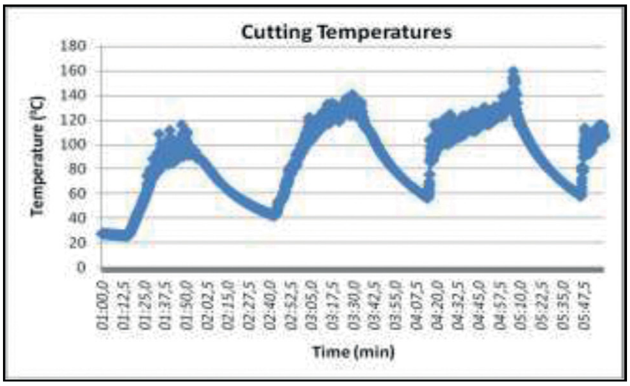

Figure 11. Tool temperature (classical trochoidal method).

Surface Roughness

After the trochoidal milling operations, the surface roughness of the machined surfaces was determined by using the Mitutoyo brand Surftest SJ-210 model portable surface roughness tester, shown in Fig.13.

Cut-off length was selected as 0.8 mm. The surface roughness was determined as an arithmetic average surface

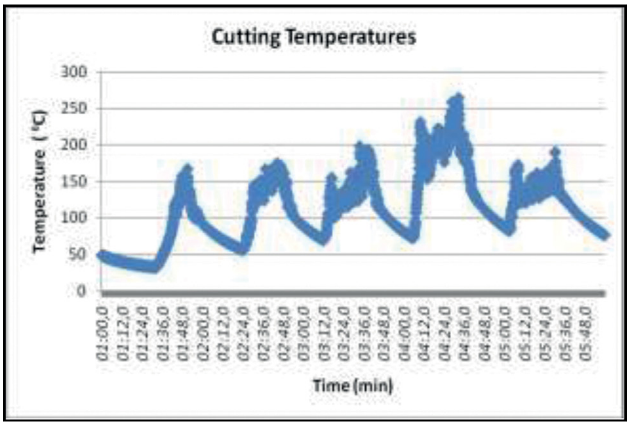

Figure 12. Tool temperature (proposed trochoidal method).

Figure 13. Profilometer used for surface roughness measurement.

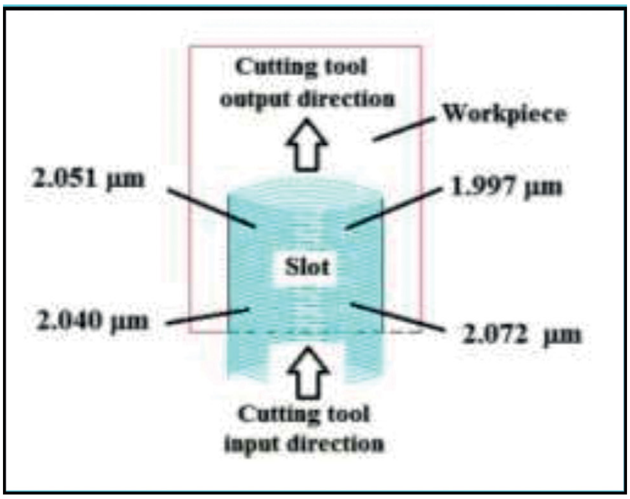

Figure 14. Surface roughness values obtained with classical trochoidal tool path.

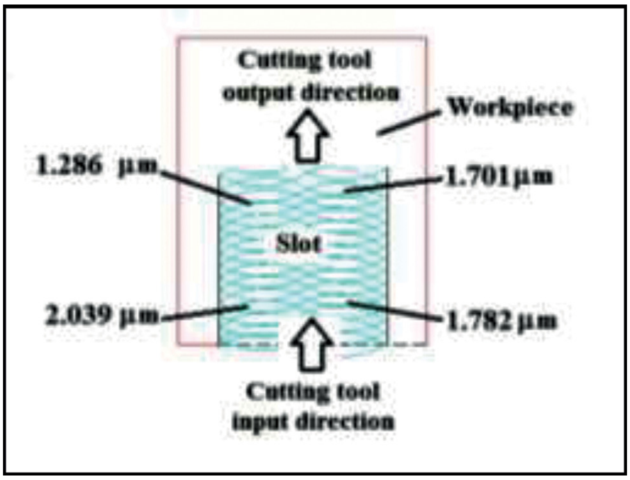

Figure 15. Surface roughness values obtained with "8" type trochoidal tool path.

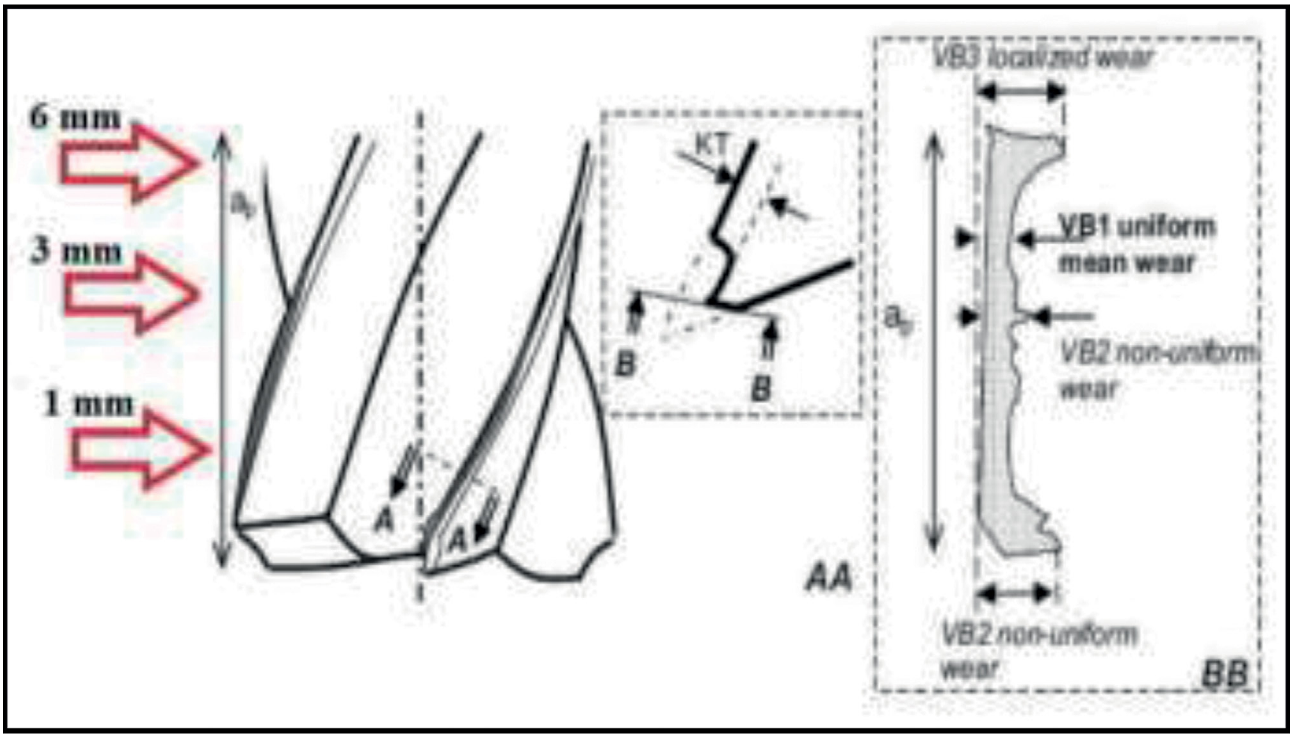

Figure 16. End mill tool wear measurement according to ISO 8688.

roughness (Ra). These measurements values are shown graphically in Fig. 14 and Fig. 15. Surface roughness was measured from four different regions and the arithmetic mean was determined. The arithmetic mean surface roughness values obtained after usage classical trochoidal tool path was 2.04 µm.

The arithmetic mean surface roughness values obtained after usage "8" type trochoidal tool path was 1.70 µm. Increasing the tool path length caused improvement of the surface quality of workpiece. As given in Fig. 6, when the tool path length (8 type trochoidal path) increased, contact surface of cutting tool increased, which in turn decreased the surface roughness of workpiece. This situation emerges as an important and remarkable issue in terms of part surface quality for the suggested new trochoidal tool path (trochoid type 8).

Tool Wear

Another consideration when developing toolpaths is tool wear.. Tool wear directly affects tool life. An improper cutting process increases the cost of manufacturing as well as rapid wear of the cutting tool and worsening of surface quality and tolerances. Therefore, today, the toolpath with the least tool wear value depending on the chip volume removed is of great importance. The wear measurements of the tools used in the experiments were measured according to ISO 8688 shown in Fig. 16 and the wear values are given in Fig. 18 depending on the cutting depth from the tool tip.

After the trochoidal milling process, the wear of the end milling tools was measured. Tool wear was measured using a SOIF Tool-Maker microscope and an Olympus OSM ocular micrometer with 1.0 µm accuracy, shown in Fig. 17.

It has been observed that the cutting tool wears less than the standard trochoidal milling method when the new "8" type trochoidal tool path recommended in this study is used.

Figure 17. Toolmakers microscope and ocular micrometer.

CONCLUSION

In this study, an approach with a new tool path modeling in trochoidal milling is proposed. For the maximization of the efficiency in the trochoidal milling operation, a different tool path strategy was examined. The proposed new

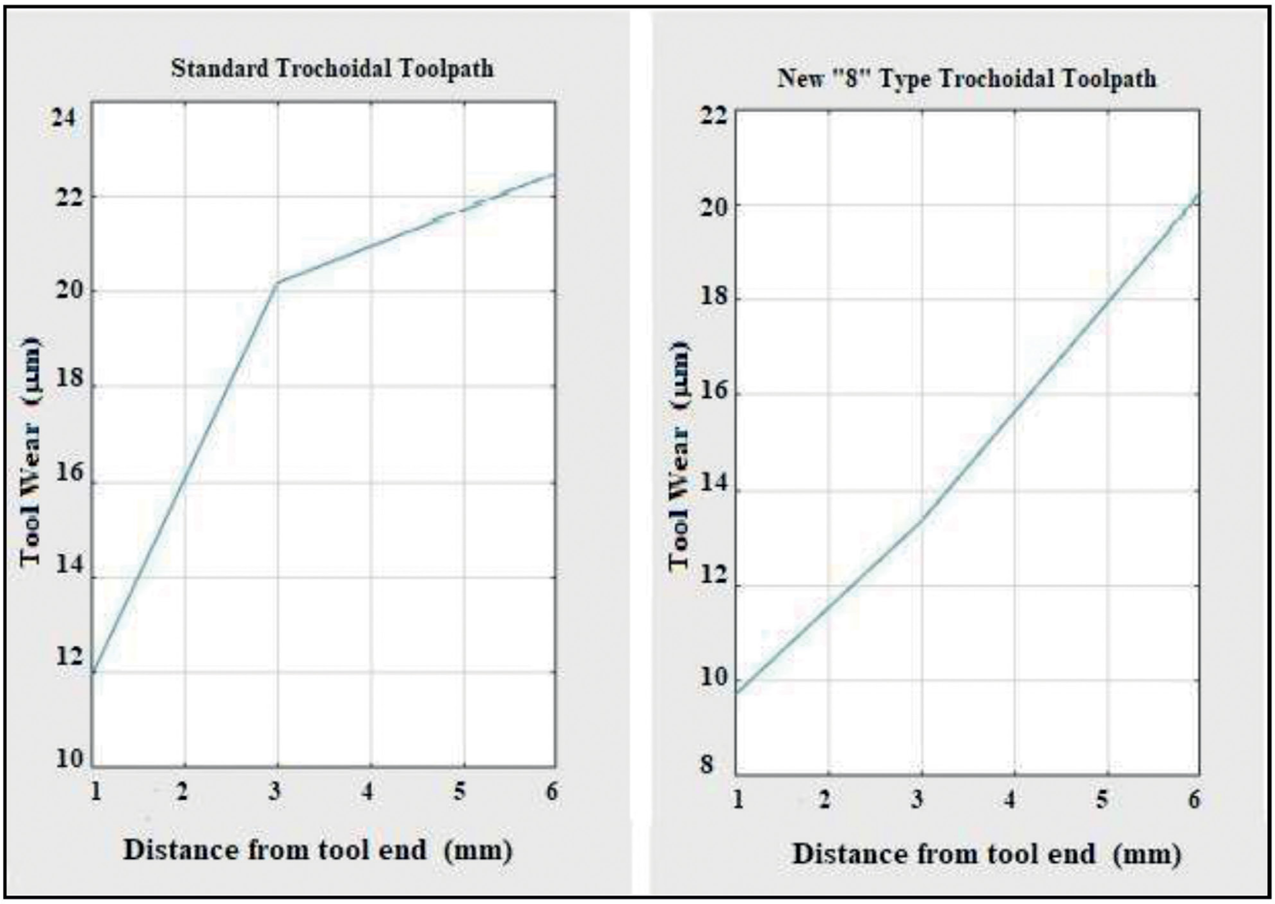

Figure 18. Comparison of standard trochoidal tool path versus recommended (8 type) trochoidal tool path in terms of tool wear.

toolpath model was investigated in terms of cutting temperature, cutting force, surface quality, tool wear.

- Although an increase of 27% was observed at the measured cutting temperature compared to the standard trochoidal toolpath application, there was no increase in the cutting force. This means that there is no difference in cutting energy between the standard trochoidal toolpath and the recommended "8 Type trochoidal toolpath". It is thought that the temperature increase is due to the increase in friction only.
- When the proposed new trochoidal toolpath is evaluated in terms of workpiece surface quality; It was determined that the surface roughness value, which was obtained as 2.04 mm with the standard (classical) trochoidal tool path, decreased to 1.70 mm with the new tool path, and the surface quality was improved by 16%.
- The proposed new trochoidal toolpath was found to provide approximately 32% less tool wear at 3 mm depth of cut and at least 10% less tool wear at 6 mm depth of cut.

In this respect, this new toolpath, which has been found to have the same cutting force, improved part surface quality and tool wear, is recommended for trochoidal milling.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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