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To cite this version:
Edouard Ducroux, David Prat, Fabien Viprey, Guillaume Fromentin, Alain d’Acunto. Analysis and modelling of trochoidal milling in Inconel 718. 17th CIRP Conference on Modelling of Machining Operations, Jun 2019, Sheffield, United Kingdom. pp.473-478. hal-02284210

HAL Id: hal-02284210
https://hal.archives-ouvertes.fr/hal-02284210
Submitted on 11 Sep 2019

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17th CIRP Conference on Modelling of Machining Operations

Analysis and modelling of trochooidal milling in Inconel 718

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Abstract

Trochooidal path increases productivity, tool life and reduces cutting forces compare to classical slot milling. Consequently, this strategy is well adapted to improve the milling performance in refractory alloy such as Inconel 718. The tool path complexity affects the tool radial engagement and axes dynamic, so it appears difficulties to perform such strategy. Therefore, this article deals with an analytical approach of trochooidal modelling to determine the theoretical radial depth of cut, cut thickness, cutting forces and machine tool behavior in function of the different methods to program the trochooidal trajectory. Finally, this methodology allows the optimization of geometrical and kinematic parameters for trochooidal milling of Inconel 718.

Keywords: Trochooidal path; Cutting Forces Modelling; Slot Milling; Inconel 718

1. Introduction

The necessity for aeronautic and aerospace industry to use more refractory material forces them to develop new machining strategies. These include development in tool geometry and grade, understanding of the cutting mechanism and improvement in machining trajectory. Research has been done to push cutting parameters such as feeds and depth of cut while producing good surface quality, improving tool life and avoiding vibrations [1].

Nomenclature

Referentials

Trochooidal parameters
\(\omega_\text{troch}\) Angular speed of the trajectory (rad.s\(^{-1}\))
\(\theta_\text{troch}\) Angle described by the tool centre along the trajectory
\(R_\text{troch}\) Radius of the tool centre trajectory
\(P_\text{troch}\) Step of the tool centre trajectory

Tool parameters

\(Z\) Number of teeth of the tool
\(z_\text{ce}\) Altitude of a cutting edge point in the \(R_\text{tool}\) referential (mm)

Cutting parameters

\(a_\text{e}\) Tool radial engagement (mm)
\(h\) Cut thickness (mm)

Geometrical objects

\(TCT[\theta_\text{troch}]\) Tool centre trajectory
\(CC_{TCT}[\theta_\text{troch}]\) Contact cutting point of trajectory
\(CE_{\text{ref}}[z_\text{ce}]\) Cutting edge reference profile
Trochoidal toolpath improves the tool life with a decreasing of the force magnitude [2]. The previous work has shown that the mechanics of trochoidal milling allows the use of the total flute length by reducing the radial depth of cut. As the cutting forces are restricted, it is possible to increase the feedrate to have a better productivity [3]. Therefore, it has been quickly used to machine slots and pockets in refractory materials such as Inconel 718 [4].

Trochoidal milling model can be separated into two different programming approaches, the circular segment trajectory model (CST) and the true trochoidal trajectory (TTT).

The CST model is the first model studied for predicting cutting forces [5]. This study focus on the computation of the radial depth of cut \( a_e \) to examine the tool load along the toolpath. It has been identified that the tool is out of cut for more than 50% of the time during the trochoidal milling. Thus, a double trochoidal path is tested where the tool goes in a direction for the first part of the arc and then in the opposite direction for the rest [6]. This toolpath increases the productivity but also the cutting forces and it affects the dynamic stability of the milling process due to the alternation in milling direction.

More recently the TTT which allows better dynamic conditions [7] has been analysed in terms of toolpath generation as it is challenging in programming and used method of interpolation to precisely represent the toolpath.

Most of the researches focuses on the prediction of the cutting forces based on the tool engagement calculation, with considering only the tool envelop. Few researches have been done to calculate the cut thickness \( h \) and tool radial engagement, i.e. the radial depth of cut \( a_e \) [8]. This allows a better forces prediction but leads to longer computation time. These researches has not analysed the CST model which is still used in some industrial process. Moreover the difference between the two trajectory models has never been investigated.

This article contains a development of trochoidal milling model for both different approaches (TTT and CST), focusing on the time determination of the radial depth of cut and the cut thickness. Then, a dynamic analysis of the machine solicitation is performed to examine which of the two trajectories is the most demanding. Finally a mechanical analysis with a force prediction model is proposed.

### 2. Study parameters

During the model construction and the experiments the tool used is a solid carbide end-mill from Mitsubishi Materials (IMX10C4HV100R10010S EP7020). It is a 10 mm diameter \( D_{tool} \) end mill with 4 teeth (Z), a nose radius of 1 mm and a 45° flute angle. The tool is modeled according to the methodology detailed in [9] to define the referential cutting edge \( CE_{ref} \) as a function of \( z_{ce} \) in the tool referential \( R_{tool} \).

The cutting parameters, presented in Table 1, are set in order to limit the engagement angle to 20°, considering a compromise between tool life and productivity.

<table>
<thead>
<tr>
<th>Cutting speed</th>
<th>Feed per tooth</th>
<th>Depth of cut</th>
<th>Trochoidal radius</th>
<th>Trochoidal step</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_c )</td>
<td>( f_t )</td>
<td>( a_0 )</td>
<td>( R_{troch} )</td>
<td>( P_{troch} )</td>
</tr>
<tr>
<td>m.min(^{-1})</td>
<td>mm.rev(^{-1}).tooth(^{-1})</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
</tr>
<tr>
<td>60</td>
<td>0.1</td>
<td>5</td>
<td>1</td>
<td>0.05</td>
</tr>
</tbody>
</table>

The machined material is an Inconel 718 with a hardness of 45 HRC and a mechanical strength of 1300 MPa.

### 3. Trochoidal milling model

#### 3.1. True trochoidal trajectory parametrisation

The tool center trajectory (TCT) for the true trochoidal trajectory towards the machine axis is defined by the equations (1) in \( R_0 \) referential with \( \omega_{troch} \) the angular speed of the TCT and \( m \) the milling mode equal to 1 in down milling and -1 in up milling.

\[
\begin{align*}
X_{troch}[t] &= \frac{P_{troch}}{2\pi} \omega_{troch} t + R_{troch} \cos[m \cdot \omega_{troch} t] \\
Y_{troch}[t] &= R_{troch} \sin[m \cdot \omega_{troch} t]
\end{align*}
\]  

(1)

A Frenet referential \( \{O_1,e_1,e_2,e_3\} \) is linked to the trajectory to follow the tool center \( O_1 \) along it. The Fig. 1 represents the TCT generated.

With this formulation, the \( \omega_{troch} \) angular speed has to be not constant in order to set the feed rate constant and equal to \( V_t \) set point. There is no analytical solution, as a consequence an approximate value of \( \omega_{troch} \) given by equation (2) is proposed with \( L_{troch} \) the length of the trochoidal curve for one revolution. The error on the real feed rate can be evaluated in function of the couple of parameters \( (R_{troch}, P_{troch}) \) as presented in Fig. 2.
According to the methodology detailed in [9] to define the pockets in refractory materials such as Inconel 718 [4]. Therefore, it has been quickly used to machine slots and increase the feed rate to have a better productivity [3]. As the cutting forces are restricted, it is possible to use the total flute length by reducing the radial depth has shown that the mechanics of trochoidal milling allows a better forces prediction but leads to longer toolpath. It has been identified that the tool is out of cut for the radial depth of cut ae to examine the tool load along the trajectory towards the machine axis is defined by the trochoidal curve for one revolution. The error on the real parameters (Rtroch, Ptroch) as presented in Fig. 2. The tool radial engagement for the position \( \theta _{troch,1} \) and the CCTCT for the previous trochoid as presented in Fig. 4. The tool radial engagement is calculated by solving equation (4) at a position near \( \theta _{troch,1} \) - 2\( \pi \).

\[
\theta _{troch,2} = \theta _{troch,1} - 2\pi
\]

Then the model need to limit the computation to the position \( \theta _{troch,1} \) where the tool is indeed engaged in the workpiece. Thus all positions where the \( a_e \) computed in equation (4) is negative indicate that the direction of \( e_2 \) is not anymore from \( \theta _{troch,1} \) to \( \theta _{troch,2} \) but the inverse. These positions correspond to the back of the trochoidal toolpath so the \( a_e \) radial engagement will be equal to 0. The tool radial engagement computed for one trochoid revolution is presented in Fig.5. It demonstrates the progressive tool engagement of trochoidal strategy.

Based on \( a_e \) engagement analysis, the main difference is located in the zone where the CST has the connection between the segment and the circle with a maximum of 0.0009 mm at \( \theta _{troch} \) equal to 2.2°. But this difference is very slight (4.9 % mean difference) and the evolution of the

\[
\alpha _{troch} = \frac{2\pi \cdot V_f}{60 \cdot L_{troch}} = \frac{2\pi \cdot V_f}{60 \int \frac{dTCT}{dt} dt}
\]
computed engagement has quite the same shape for both trajectories.

3.4. Cut thickness calculation

For the next step of the model, it needs to express all the previous variables, which depend on $\theta_{troc}$ as a function of the spindle rotation angle $\theta_{sp}$. Therefore, the equation (5) allows such transformation with considering no sliding between the spindle rotation and the trochoidal movement.

$$\frac{\theta_{troc}}{\theta_{sp}} = \frac{\theta_{sp}}{\theta_{troch}}$$

(5)

The cutting edge geometry $CE_{ref}$ parametrized by $z_{ce}$ height can be extended to all $i_z$ cutting edges with radial runout $R_{out}$ and the variable pitch of the tool $\psi$ considering equation (6).

$$CE[i_z, z_{ce}] = \text{Rot}_{Z} \left[ \frac{2\pi (i_z - 1) + \psi}{Z} \right] \cdot CE_{ref}[z_{ce}] + R_{out}[i_z]$$

(6)

Then, from the mill rotation and the TCT, the $i_{z}^{th}$ cutting edge trajectory can be described by equation (7) in the $R_0$ referential.

$$CE[i_{z}, z_{ce}, \theta_{sp}] = \text{TCT}[\theta_{sp}] + \text{Rot}_{Z} \left[ \theta_{sp} \right] \cdot CE[i_{z}, z_{ce}]$$

(7)

Considering the surface generated by $CE$ of the $i_z^{th}$ edge, the cut thickness is the normal distance between this surface and the surface generated by the (i,1)$^{th}$ edge. Thus by construction of the normal line vector $NL_{CE}$ of the surface generated by $CE$, $h$ is determined by finding the intersection between $NL_{CE}$ and $CE$ of the (i,1)$^{th}$ edge, which is the solution of equation (8) at a position $\theta_{sp,2}$ near $\theta_{sp,1} + (2\pi/Z)$.

$$\begin{cases} \text{CE}[i_z, z_{ce}, \theta_{sp,1}] = \text{CE}[i_z - 1, z_{ce}, \theta_{sp,2}] \\ + h[i_z, z_{ce}, \theta_{sp,1}] \cdot NL_{CE}[i_z, z_{ce}, \theta_{sp,1}] \end{cases}$$

(8)

In the same manner as the tool radial engagement, the cut thickness computation is limited to the positions where the cutting edges are machining. Firstly, where $NL_{CE}$ direction is opposite to $CE$ of the (i,1)$^{th}$ edge, $h$ cut thickness calculated is negative, the value has been replaced by 0. Secondly where $z_{ce}$ engagement is equal to 0, $h$ cut thickness is equal to 0, likewise where $z_{ce}$ height is higher than the axial depth of cut $a_p$. Finally, to find where the cutting edge is in materials, as presented in Fig. 6, the model needs to compute the intersection of $CE_{T}$ with $CC_{T}$ of the previous trochoid which correspond of the entry point of the $i_z^{th}$ edge.

The cut thickness $h$ determined in the case of the TTT toolpath for one trochoid loop is presented in Fig. 7. As the tool radial engagement difference between CST and TTT is slight, the cutting thickness is the same for both trajectories.

4. Mechanical analysis

4.1. Cutting forces model

From the calculation of the $h$ cut thickness, a force model has been developed via the tool discretisation method to get the cutting forces in $R_{TRA}$ presented in Fig. 8. In agreement with the norm ISO 3002-1:1993 [11], the referential $R_{TRA}$ linked to the $j^{th}$ local segment of the edge is composed by the normal at the $P_s$ plane, the normal at the $P_r$ plane, and the directional vector of the intersection between these two planes.
The k component (t, r, a) of the local cutting forces in RTRA,j is done by equation (9).

\[
\{ f_{k,j} \} \{ z_{ce} \} \{ \theta_{sp} \} = h \{ K_{kb} + K_{kh} \} \{ z_{ce} \} \{ \theta_{sp} \}
\] (9)

Then the coefficients of the cutting law (9) have been identified through inverse identification tests according to [12] in side milling configuration. Thus the set of coefficients is presented in Table 2.

Table 2. Cutting law coefficients in RTRA

<table>
<thead>
<tr>
<th>Force component</th>
<th>( f_t )</th>
<th>( f_r )</th>
<th>( f_a )</th>
</tr>
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<tbody>
<tr>
<td>( K_{tt} ) (N.mm(^{-1}))</td>
<td>62</td>
<td>60</td>
<td>45</td>
</tr>
<tr>
<td>( K_{rr} ) (N.mm(^{-2}))</td>
<td>2550</td>
<td>41</td>
<td>-8</td>
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4.2. Cutting forces experiment and comparison

The experiments have been performed on a Mikron HSM600U five-axis milling machine equipped by a iTNC530 Heidenhain CNC. The machine dynamic limitations are presented in Table 3.

Table 3. Machine dynamic limitations

<table>
<thead>
<tr>
<th>Machine axes</th>
<th>Speed</th>
<th>Acceleration</th>
<th>Jerk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(mm.min(^{-1}))</td>
<td>(m.s(^{-2}))</td>
<td>(m.s(^{-3}))</td>
</tr>
<tr>
<td>X axis</td>
<td>40 000</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>Y axis</td>
<td>40 000</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>Spindle</td>
<td>24 000 rpm</td>
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</tr>
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The experiments are performed using a Kistler 9257B piezoelectric dynamometer with a sampling frequency of 50 kHz. The cutting forces have been recorded and modeled in the R Traj referential. The equation (9) has been identified through inverse identification tests according to [12] in side milling configuration. Thus the set of coefficients is presented in Table 2.

Fig. 8. Cutting edge discretisation method, illustrated in the case of cylindrical end mill.

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\[
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The model shows good results in predicting cutting forces. Nevertheless the experiment presents non negligible forces in the positive direction of Z_Machine, which can be seen in [6] in other proportion. These forces can be due to multiple factors such as tool wear, chip flow or built-up edge formation.

5. Dynamic analysis

Firstly both trajectories are tested with the set of parameters presented in part 2, the machine axes dynamic are recorded by a CNC recorder software with the X-axis as the slot direction and the Y-axis as the orthogonal-slot direction. The results are presented in Fig. 10 where the model, the nominal and the effective curves respectively corresponded to the successive derivation of the position, the CNC command and the measure done.
It shows that the Jerk is the more likely to limit dynamically the machine as the speed and the acceleration recorded are way lower than the machine limitations. Moreover the CST seems to be more demanding than the TTT, specifically just after the curvature discontinuity, even if the machine try to compensate by decelerating and accelerating few milliseconds before and after it. Otherwise the results are close. That’s why more (R\textsubscript{troch}, V\textsubscript{f}) parameters have been tested to observe the evolution of the Jerk. The parameter P\textsubscript{troch} has been set to 0.05 mm to ensure a maximum engagement angle lower than 20°. The Fig. 11 presents the maximum jerk towards (R\textsubscript{troch}, V\textsubscript{f}) for the model, the measurements on the machine-tool of the CST and the TTT.

The analysis shows the CST induces higher axis dynamics than the TTT, then CST is more susceptible to be limited by the machine tool performances. Besides the higher the feed rate is, the more limited is the CST compared to the TTT.

6. Conclusions

The present study proposed an analytical formulation for modelling the tool radial engagement and cut thickness in trochoidal milling towards the circular approach and the true trochoidal one. This model is based on the definition of the cutting edge geometry and trajectory in order to predict cutting forces with using the discretization method.

In terms of mechanic, trochoidal milling implies a progressive variation of radial engagement helpful for reducing tool or workpiece vibrations and then is interesting for hard material milling application. The difference between the two trajectories is slight as the tool radial engagement along them is very near equal.

In terms of dynamic, the CST toolpath reach faster the machine limits and shows much more instability than the TT trajectory. This can lead to an increase of the vibration and the forces magnitude during the tool entry. Therefore a decrease of the tool life will may be observe.

Acknowledgements

The authors would like to thank the Région Bourgogne Franche-Comté for the financial support of this study.

References