Cutting Tool Geometry for Plunge Milling – Process Optimization for a Stainless Steel

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Abstract

Roughing strategies are gaining commercial relevance driven by increasing number of components in the energy sector. However, machining strategies which provide high material removal rates at large tool aspect ratios are still not available. Within this paper the stability and performance of plunge milling is investigated. The engagement condition of the tool is analyzed depending on the process parameters and micro-geometry of the tool. The process stability and performance is verified by cutting tests in X3CrNiMo13-4 attended by cutting force acquisition. The crucial geometrical features of the tool in combination with the process parameter choice are presented for plunge milling operations.

Keywords: Milling; Optimization; Tool geometry; Toolpath; Stainless steel

1. Introduction

1.1. Milling Strategies

Roughing strategies are gaining relevance driven by an increasing number of integrally designed components and, therefore, large to machine volumes. The last decades remarkable effort was put in roughing by the introduction of new strategies, e.g. the circular stagger milling [1, 2, 3]. For most machining tasks tool concepts are limited in diameter, since the geometrical accessibility to the machining area is constrained. Thus, radial cutting forces become crucial, since the tool possesses low rigidity at large tool lengths [4, 5]. Consequently, the above mentioned strategies are limited in their stability. The plunge milling is a suitable alternative for the addressed machining tasks, since the feed direction and, thus, the main cutting forces are oriented in axial direction.

1.2. Plunge Milling in the Application of Blisks

When machining blade integrated disks (blisks) by plunge milling the material is machined in a two step machining process (Fig. 1). The first step is given by the slot opening. Step 2 is the lateral positioning of the tool in order to achieve a preferably homogenous residual material distribution on the blade for further finishing processes. Due to the large engagement angle step 1 limits the process performance remarkably. Further investigations are focused on this contact condition.

Fig. 1: Plunge milling process of a blisk [1]

2. Milling Tool and Kinematics

2.1. Milling Tool

Inserted milling tools with a diameter of \(d = 12 \text{ mm}\) and an unsupported length of \(l_k = 63 \text{ mm}\) are used in the
Four different inserts with different corner radii $r_i$ are investigated. The cutting edge is characterized by two different tool approach angles $\kappa_{rs}$ and the inclination angles $\lambda_s$ (Fig. 2). The minor cutting edge $S_n$ is defined by the angle $\hat{\tau}_{sn}$.

![Milling tool geometry and angles](image)

The above mentioned geometric parameters vary among the cutting inserts. The relevant geometrical values are summarized in Table 1. Each cutting test is conducted with a single insert with two repetitions.

<table>
<thead>
<tr>
<th>Corner radius $r_i$ [mm]</th>
<th>$\lambda_{S1}$ [°]</th>
<th>$\lambda_{S2}$ [°]</th>
<th>$\kappa_{S1}$ [°]</th>
<th>$\kappa_{S2}$ [°]</th>
<th>$\hat{\tau}_{S1}$ [°]</th>
<th>$\hat{\tau}_{S2}$ [°]</th>
</tr>
</thead>
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<tr>
<td>0.2</td>
<td>0</td>
<td>17.4</td>
<td>84.7</td>
<td>97.0</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>0.4</td>
<td>0</td>
<td>18.6</td>
<td>84.9</td>
<td>97.7</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td>0</td>
<td>20.0</td>
<td>84.9</td>
<td>96.7</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>1.6</td>
<td>0</td>
<td>25.3</td>
<td>84.6</td>
<td>100.0</td>
<td>2.9</td>
<td></td>
</tr>
</tbody>
</table>

The uncut chip length $l_{cu}$ is calculated by:

$$l_{cu} = \frac{\pi \cdot d \cdot \Phi_c}{360}$$

(2)

The uncut chip width $b_{cu}$ can be calculated by [6]:

$$b_{cu}(\Phi) = \frac{d}{2} + p \cdot \sin \Phi - \sqrt{\frac{d^2}{2} - (p \cdot \cos \Phi)^2}$$

(3)

In Fig. 4, the uncut radial chip width $b_{cu}$ is plotted against the uncut chip length $l_{cu}$ for three different pitches and the constant tool diameter of $d = 12$ mm.

![Effect of the pitch on chip width and length](image)

With increasing chip length the chip width enhances constantly until the maximum value (equates the pitch $p$) is achieved. With increasing pitch the gradient $|db_{cu}/dl_{cu}|$ is steeper for both the ramp-up and the ramp-down.

The cross section of the uncut chip $A_{cu}$ can be calculated by:

$$A_{cu}(\Phi) = b_{cu}(\Phi) \cdot f_z$$

(4)

The consideration of $b_{cu}(\Phi)$ and $A_{cu}(\Phi)$ is important for the process design, since these parameters...
significantly influence the thermal- and mechanical load. Based on the cutting forces of the drilling process the forces are defined by cutting-, normal cutting-, and passive force \( (F_c, F_{cn}, \text{ and } F_p) \) (Fig. 3) \([7]\).

3. Experiments and Simulations

3.1. Setup

The cutting tests are performed on the five-axis machining centre Heller MC 25 with a maximum spindle rotation of 16000 rpm. The experiments are conducted at a constant cutting speed of 200 m/min. The work piece is fixed on a Kistler type 9255A force measuring plate. The received signal is converted by a charge amplifier into output voltages and filtered at 3kHz by a low pass filter. The digitalization is done with a sampling frequency of 15 kHz in order to avoid antialiasing. The force analysis is done with DIAdem 11.1 from National Instruments.

For the detailed investigation of the contact condition of the cutting edge analytical models are developed and simulations are done with MATLAB from MathWorks.

3.2. X3CrNiMo13-4

This stainless steel is applied in the energy sector for pumps, rotors, and compressors due to its chemical stability. The material is quenched and tempered leading to a homogenous solid solution hardened microstructure possessing a yield strength of 900 - 1100 N/mm\(^2\). For the given heat treatment the tensile strength is minimum 800 N/mm\(^2\) at RT and steadily decreasing with increasing temperature (620 N/mm\(^2\) at 300°C). The rather low content of Carbon (max. 0.03 %) leads to a rather soft nickel-martensite at a Rockwell Hardness of 28.

4. Results and Discussion

4.1. Chip formation

A dependency of the chip formation on a variation of the corner radius and the pitch was not observed. Treppmann and Tönshoff stated in their investigations the dependency of the segmentation on the material properties, deformation speed, and temperature \([8, 9]\). In Fig. 5 a cross section of a representative chip is shown.

The chips possess a saw-tooth appearance with no remarkable segments. Therefore, the given chip formation can be described by the serrated chip forming process as it is also likely to be achieved when machining other difficult to machine materials as titanium and nickel based alloys. The degree of the chip thickness variation is 35, calculated after Tönshoff \([8]\).

\[ \text{Fig. 6: Maximum forces during cutting in dependency on corner radii} \]

\[ \text{Fig. 5: Serrated chip formation: (a) overview; (b) detailed view} \]
process which can be applied to the plunge milling process in analogy [10]. The corner radius is considered as a cutting edge with constantly varying tool approach angle $\kappa$ (Fig. 7).

Thus, it is valid [10]:

$$h_{cu} = f_z \sin(\kappa)$$ (5)

$$A_{cu} = b_{cu} \cdot h_{cu} = p \cdot f_z$$ (6)

To conclude, $F_{cn}$ and $F_c$ are not dependent on the corner radius but rather on the $A_{cu}$. $F_p$ should be increased with larger corner radii due to the increased axial component of the cutting edge. However, this is only partly observed in the experiments across the pitches (Fig. 6). The arc of the corner radius is given between the points A and B (Fig. 7). The uncut chip thickness $h_{cu}$ possesses a minimal value between the positions A and S. The arc length A-S is enlarged with increasing corner radius as exemplary shown for the radii $r_\epsilon = 1.6$ mm and $r_\epsilon = 0.2$ mm. According to Albrecht’s theory the material flows for smaller uncut chip thicknesses partly under the cutting edge and causes squeezing of the material at the flank face [12]. This theory can be further strengthened when analyzing the formed chip geometry for the variation of the corner radii. The chips possess with increasing corner radius larger fringes (Fig. 8) indicating the instable material flow around the cutting edge between positions A and S (Fig. 7).

Finally, the result is a more concentrated flank wear at larger corner radii, especially for $p < r_\epsilon$ (Fig. 9). Furthermore, the thermal impact on the cutting edge and particularly on the corner radius increases with increasing pitch (Fig. 4). In Fig. 10 the inserts are shown after the tool life travel paths for $p = 0.5$ and $p = 3$ mm. For the smaller pitch and corner radii the flank wear is minor developed.

The corner radii $r_\epsilon = 0.2$ and $r_\epsilon = 0.4$ mm cutting material is cracked (markings a in Fig. 10). This occurs already after a tool life travel path of $l_1 = 1.5$ m for $r_\epsilon = 0.2$ mm and $l_1 = 1.95$ m for $r_\epsilon = 0.4$ mm (Fig. 11). The corner radius $r_\epsilon = 0.8$ mm withstands the increased thermal load as also the flank wear is at a cutting length of 6.1 m only 0.1 mm. In contrast to the flank wear development at $p = 0.5$ mm the corner radius $r_\epsilon = 0.8$ mm demonstrates a better performance.
4.3. Minor Cutting Edge

The process’s sensitivity on p and fz is further investigated. In Fig. 12 the forces are shown for a variation 0.01 mm ≤ fz ≤ 0.1 mm across the pitch range 0.5 mm ≤ p ≤ 3.5 mm.

All forces are increased with increased fz. Furthermore, Fc,in and Fc show a steady approximately linear increase through the whole investigated pitch range. The larger the feed rate per tooth the larger the gradient dFc/dp and dFcn/dp respectively. The increase of Fc,in from p = 0.5 mm to 2 mm is approximately 240%, Acu increases by 300%. For 2 mm ≤ p ≤ 3 mm the increase of Acu (75%) matches sufficiently the measured increases of Fc,in (80%) and Fc (70%). Fc presents the largest linear increase through fz and p.

In the addressed parameter frame Fp is the smallest force especially for larger fz and p. However, an increase with fz can be noticed. In Fig. 13 the minor cutting edge is shown. Dependent on its cutting edge angle κsn, f, and r, the total axial contact length is given by:

\[ l_{ax} = r_c + c \cdot \cos(\kappa_{sn}) + z \]  

(7)

The contact length c between tool and scallop of the workpiece is given by the distance between the intersections P1 and P2 at the minor cutting edge. According to Fig. 13 the cut 2 can be described by a graph y(x, β, r, ε, fz):

\[ y = -\tan(\beta) \cdot x + r_c \cdot \tan(\beta) - f_z \]  

(8)

\[ \beta = \frac{\pi}{2} - \kappa_{sn} \]  

(9)

For the investigated tool geometries the given contact lengths c are printed in Fig. 14. The contact length c increases remarkable with larger fz for all given r and κsn.

Along the contact length c and the corner radius the chip thicknesses perpendicular to the cutting edge is a varying value. In this area squeezing of the material occurs and therefore ploughing forces govern the cutting process (arc A-S in Fig. 7). Ploughing forces negligibly effect Fc, but Fp, which is in good agreement with Wyen’s and Wegener’s investigations in orthogonal turning in analogy to Albrecht’s theory [13]. The increase of Fp with increasing fz (Fig. 12) is expected to
be explainable by the increase of $l_x$. However, the complex cutting insert’s geometry possesses a large cutting edge radius of 18 - 20 $\mu$m and a varying $\kappa_r$. Therefore, the single influence of the corner radius, $r_c$, $\kappa_r$ on $F_p$ has to be furthermore investigated through a rigid experimental setup with idealised simpler cutting edge geometries.

5. Conclusion

The plunge milling process is applied for machining hard to access geometrical features limiting the process engineer in choosing rigid tool systems. Therefore, focus is set to achieve a large ratio $F_{cn}/F_p$ in order to achieve stable machining processes (Fig. 15 and Fig. 16).

Fig. 15: Ratio of $F_{cn}/F_p$ for the feed rate per tooth at $p = 2$ mm

Fig. 16: Ratio of $F_{cn}/F_p$ for the pitch at $r_c = 0.05$ mm

The milling of the martensitic X3CrNiMo13-4 forms serrated chips. Furthermore, the thermal impact on the cutting edge especially for small corner radii at large pitches could be observed by thermally induced disruptions and an increased flank wear development. Fig. 15 and Fig. 16 summarize the acquired forces which are achieved by the variation of tool geometry and process parameters. The large variation of the force ratios up to the factor seven indicate how crucial the right technological design of the plunge milling process is, in order to utilize the basic benefit of the process’s kinematical setup. Small corner radii combined with small feed rates are preferable at large tool aspect ratios.

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