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A novel tool concept for roughing and finishing operations

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Abstract

In this paper, a new tool concept suitable for simultaneous roughing and finishing operations is presented. The developed end mill has two radial recessed roughing teeth with a flank face chamfer and two sharp finishing teeth. While the chamfered cutting edges ensure a high process stability due to process damping, the sharp cutting edges generate the final surface. In order to investigate the roughing and finishing capabilities, the tool was compared with a roughing tool with chamfered teeth only and a finishing tool with sharp teeth only. With all three tool concepts milling experiments were carried out, in which forces, process stability and surface quality were analyzed. The generated surface quality for the new tool concept could be significantly improved compared to the roughing tool. However, the aimed surface quality of the finishing tool with sharp edges could not be achieved. Moreover, experimental results show that the process stability of the new tool concept is significantly higher than the process stability of the finishing tool.

Keywords: Chatter; process stability; high performance cutting; flank face chamfers; roughing, finishing;

1. Introduction

In machining of aluminum alloys, high material removal rates are of great importance for an economic production process. Besides the power limit of the machine, chatter vibrations limit the material removal rates of the production process. Common methods for the suppression of chatter are the use of serrated end mills or end mills with varying helix angle and varying tooth pitch [1, 2, 3]. The beneficial effect of those methods is the interruption of the regenerative effect due to variation of time delays. Another way to increase the process stability is the use of flank

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face chamfers [4]. The underlying effect is the generation of a velocity-dependent force due to the indentation of the flank face chamfer into the material, which can suppress chatter and increase process stability. This force can be described as indented volume V multiplied with the process damping coefficient K_{pd} [5]. Although the effect is well known, the determination of K_{pd} is time-consuming and challenging [6, 7]. Furthermore, a deterioration of the surface quality (e.g. burr formation) can be observed [8]. The reason for this are increased temperatures and frictional forces because of the flank face contact and therefore a higher deformability of the material [10].

In this work, a patented tool concept [9], which offers the advantages of both, roughing and finishing tools, is being investigated. With this ability, process steps can be reduced and the process time is improved due to higher process stability. The tool possesses chamfered roughing teeth as well as sharp finishing teeth. To prevent surface deterioration, the roughing teeth are radially recessed by ΔR. Thus, they are not in contact with the final surface. Since the radial recession leads to different uncut chip thicknesses, finishing and roughing teeth are subject to different thermomechanical tool load. Therefore, the tool is also unequally pitched to compensate the varying load conditions. A detailed view of the tool is shown in Fig 1. Although the tool concept was patented in 2013, the knowledge of the interactions between roughing and finishing teeth is still limited and no experimental investigations are published yet.

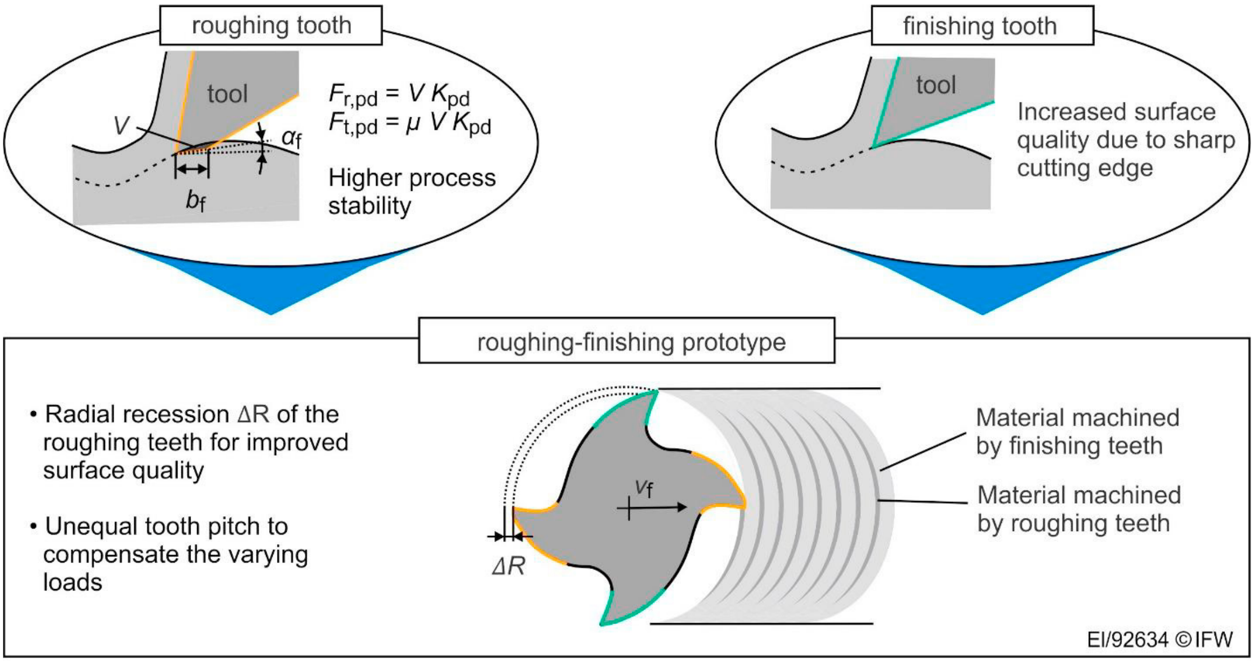


Fig. 1: Characteristics of the roughing-finishing prototype

2. Experimental Setup

To investigate the roughing and finishing ability of the new tool concept, milling experiments were carried out with the roughing-finishing prototype presented in this paper ($\Delta R = 35$ µm, $b_f = 200$ µm, $\alpha_f = 1°$) as well with a conventional roughing ($\Delta R = 0$ µm, $b_f = 200$ µm, $\alpha_f = 1°$) and a conventional finishing tool ($\Delta R = 0$ µm, $b_f = 0$ µm). All tools are cemented carbide end mills with a diameter $d = 20$ mm, number of teeth $N_t = 4$, helix angle $\delta\delta = 30°$ and tooth pitch $p = [80°\ 100°\ 80°\ 100°]$. For the experiments, Al7075 specimens were machined on a Heller MC16 machine tool. Process forces were measured for slot, down and up milling experiments with varying feed per tooth f_z and constant spindle speed $n = 4{,}000$ min^{-1}. For the force measurements, a three-component dynamometer Kistler 9257B was used. A second series of experiments included a stability analysis. In this experiments, the process stability was examined qualitatively with respect to chatter marks and noise emission for different depth of cut a_p and spindle speed n with constant f_z = 0.12 mm under full immersion conditions. Fig. 2 gives an overview of the experimental setup. Cutting tests were conducted with free corner radius of the end mill to exclude influences of the minor cutting edges. Therefore, the workpiece had to be prepared for the slot milling experiments (Fig. 2, left), to reach the depth of cut a_p = 2 mm with a free corner radius. After the cutting experiments, the machined surface topographies were analyzed using scanning electron microscope images (Zeiss EVO 60 VP) and video microscope images (Keyence VHX-600).

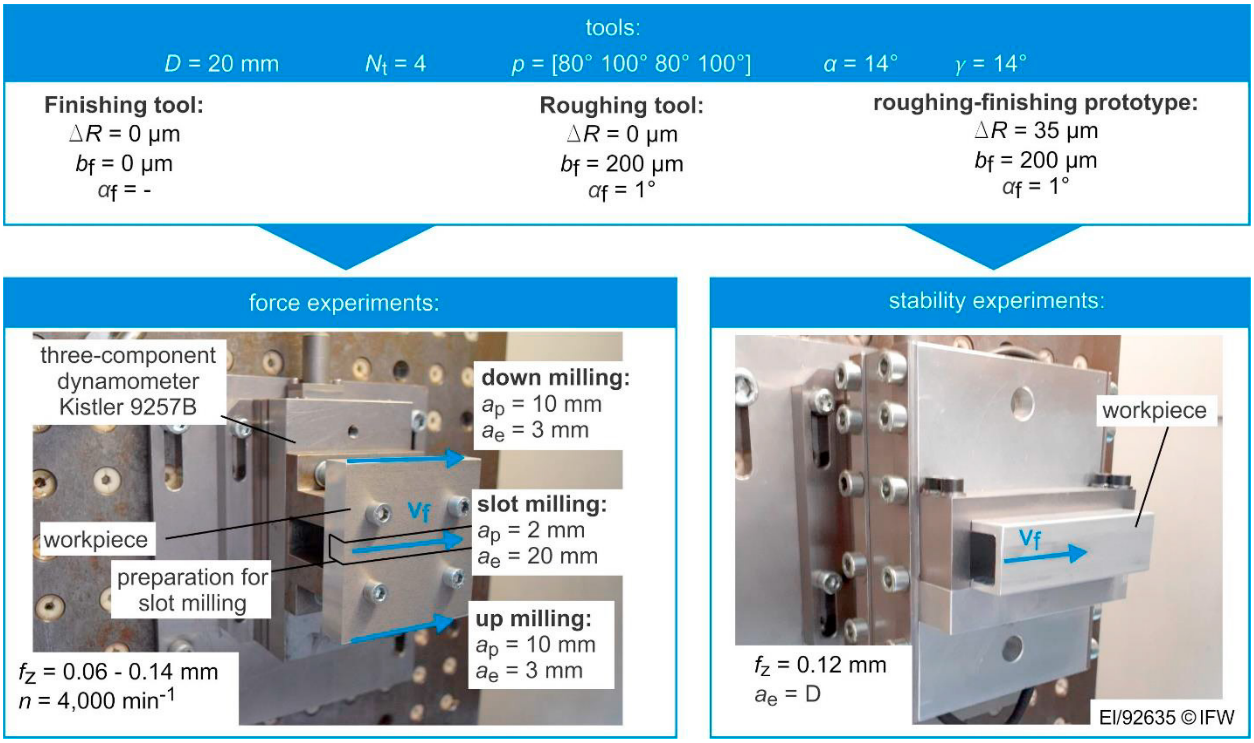


Fig. 2: Experimental setup for force and stability experiments

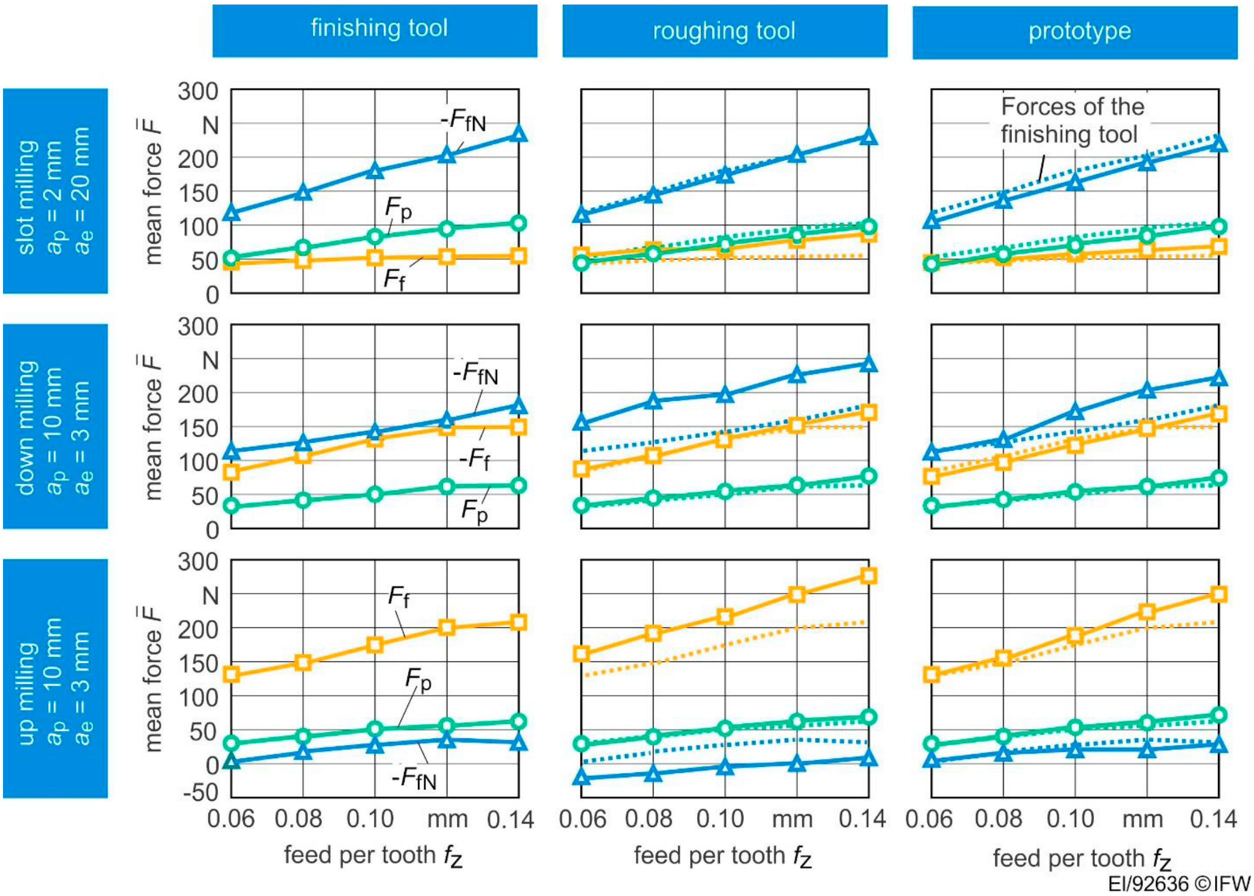
3. Results and Discussion

3.1. Investigation of the process forces

First, force measurements were conducted and analyzed. The mean forces depending on immersion condition, tool geometry and feed per tooth f_z are shown in Fig. 3. For a better comparison, the forces of the finishing tool are shown in the force diagrams of the other tools as dashed lines.

Mean process forces exhibit an approximately linear correlation with f_z in the investigated parameter range. In slot milling, only small differences occur between the three tool geometries. The mean feed normal and mean passive forces of the roughing tool and the finishing-rouging tool are slightly lower than the mean forces of the finishing tool. A possible explanation could be the reduction of the cutting forces due to higher process temperatures and thermal softening of the workpiece induced by the flank face chamfer [10]. However, a verified explanation cannot be given on the basis of the conducted experiments. More significant differences between the three tool geometries appear for down and up milling. In down milling the mean feed normal force of the roughing tool is approximately 20% higher than the mean feed normal force of the finishing tool. Similar results are obtained for the mean feed force and the mean feed normal force in up milling. These effects can be attributed to increased friction and process damping forces due to the flank face contact of the chamfer. In contrast to the slot milling process, the maximum uncut chip thickness in down and up milling is comparatively small, which leads to a higher proportion of the frictional force components on the total forces. For the roughing-finishing prototype, the differences in mean forces compared to the finishing tool are significantly lower since only two teeth are chamfered. Furthermore, the chamfered teeth are in cut for a shorter time because of the radial recession (compare Fig. 1).

Fig. 3: Mean forces depending on feed per tooth f_z, immersion conditions and tool geometry for n = 4,000 min^{-1}



To investigate the force progression in detail, Fig. 4 displays the process forces for one tool revolution using a feed per tooth f_z = 0.12 mm in up milling. As presented above, the force amplitudes for the roughing tool are increased compared to the finishing tool. This can be attributed to the increased contact between flank face and workpiece of the roughing tool. However, the force progression of both tools differs significantly from the force progression of the roughing-finishing prototype. The force progression of the roughing-finishing prototype is characterized by an increased force amplitude of the finishing teeth while the force amplitude of the roughing teeth is reduced. This observation can be explained by the different uncut chip thicknesses of these teeth. The uncut chip thickness is influenced by the radius of the teeth and the tooth pitch. With the simplification of circular tool paths, the uncut chip thickness can be calculated with eq. (1) according to [1, 2], where φ is the immersion angle, r_j and r_u are the radii of the current and the previous tooth, and p_{ju} is the angle between the current and the previous tooth, respectively.

$$h = f_z \cdot N_t \cdot \frac{p_{ju}}{2\pi} \cdot sin(\varphi) + r_j - r_u \qquad (1)$$

In case of the finishing-roughing prototype, the radial recession of the chamfered teeth leads to increased forces of the sharp teeth and decreased forces of the chamfered teeth. On the other hand, the unequal tooth pitch leads to decreased forces of the sharp teeth and increased forces of the chamfered teeth. In case of Fig. 4, the maximum uncut chip thickness, calculated by eq. (1), is h_{max} = 0.059 mm for the chamfered teeth and h_{max} = 0.110 mm for the sharp teeth. In comparison to that, the calculated uncut chip thicknesses for the roughing and finishing tool are h_{max} = 0.094 mm and h_{max} = 0.075 mm depending on the unequal pitch, which also leads to different force amplitudes. By equating the maximum uncut chip thickness of the chamfered and the sharp teeth (eq. (2)), the necessary tooth pitch for equal force amplitudes of roughing and finishing teeth can be calculated (eq. (3)):

$$f_z \cdot N_t \cdot \frac{p_{ju}}{2\pi} \cdot sin(\varphi_{max}) - \Delta R = f_z \cdot N_t \cdot \frac{\frac{4\pi}{N_t} - p_{ju}}{2\pi} \cdot sin(\varphi_{max}) + \Delta R \quad (2)$$

$$p_{ju} = \frac{2\pi}{N_t} \cdot (1 + \frac{\Delta R}{f_z \cdot sin(\varphi_{max})}) \quad (3)$$

Thereby, p_{ju} is the angle between a chamfered tooth and the previous sharp tooth and φ_{max} is the immersion angle corresponding to the maximum chip thickness. Besides the radial recession ΔR the optimized tooth pitch also depends on the feed per tooth f_z and the immersion angle φ_{max}. Therefore, the milling process has to be taken into account for the design of the tooth pitch. For f_z = 0.12 mm, N_t = 4, ΔR = 35 µm and full immersion eq. (3) results in a modified tooth pitch p = [64° 116° 64° 116°].

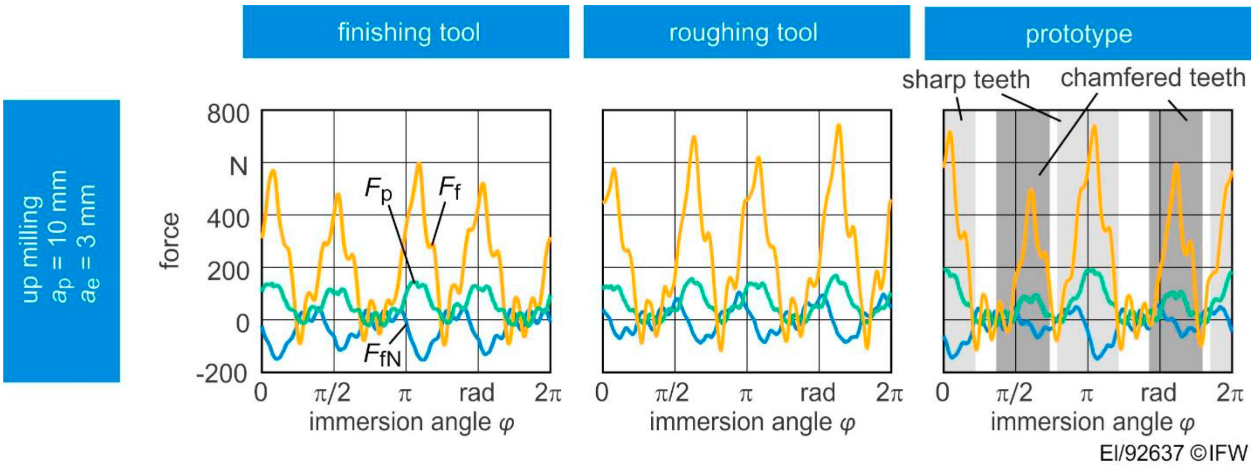


Fig. 4: Process forces for one tool revolution depending on immersion angle and tool geometry for f_z = 0.12 mm and n = 4,000 min^{-1} in up milling

3.2. Process stability

The process stability is decisive for the roughing ability of the tool. Therefore, stability experiments were conducted for all three tools. The results are shown in Fig. 5. The experiments were divided in stable, marginal stable and unstable processes. The stable processes show no signs of chatter, whereas for marginal stable processes slight chatter marks occur. The instable processes are characterized by clearly visible chatter marks and noise emission. For the finishing tool, at three out of four examined spindle speeds n, the process was unstable at a_p = 6 mm. Both other tools show noticeably larger stability limits. For the roughing tool, all stability experiments were stable, whereas for roughing-finishing prototype only experiments at spindle speed n = 8,000 min^{-1} were marginal stable. This increased stability can be attributed to the process damping due to the indentation of the flank face chamfer into the material. Another effect that possibly contributes to the increased process stability could be plastic deformations due to the indentation of the flank face chamfer, which leads to a modified outer modulation of the next tooth in cut. The outer modulation describes the waviness of the surface, which is decisive for the regenerative effect and therefore the process stability [12]. Furthermore, thermal effects can possibly influence the process stability [10].

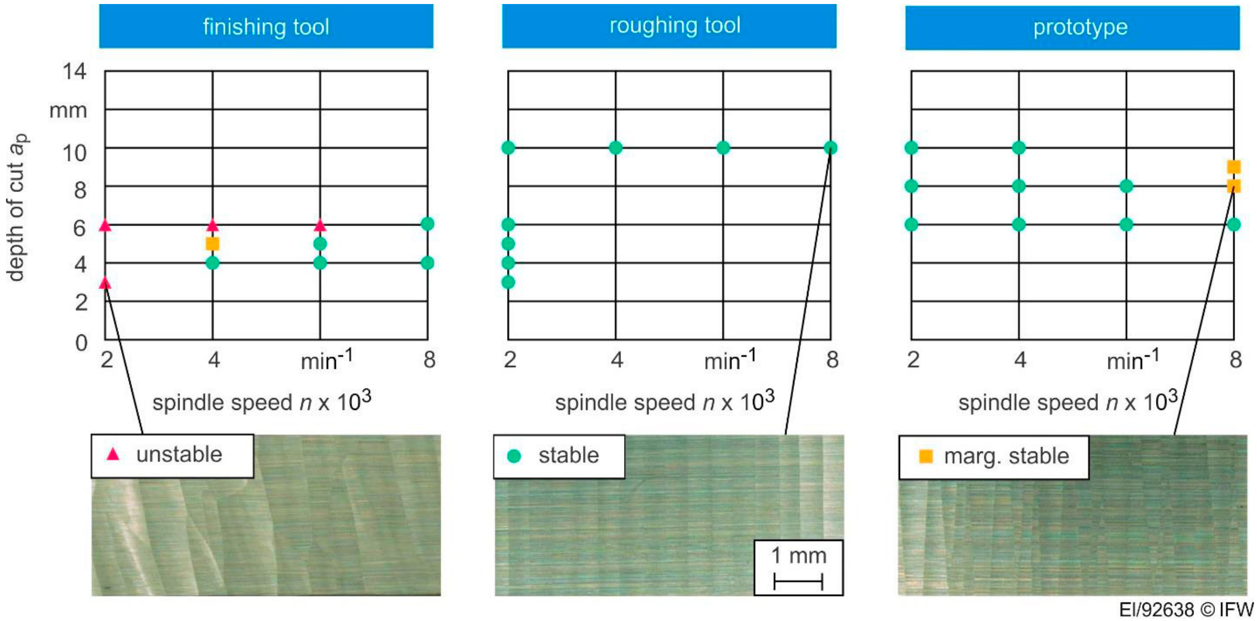


Fig. 5: Experimental stability charts for f_z = 0.12 mm and full immersion depending on tool geometry

3.3. Surface quality

The surface quality was examined for the workpieces of the cutting force experiments. Microscope images are shown in Fig. 6. The distance between the feed marks on the surface indicate that not all teeth contribute to the final surface. For the finishing tool, only one tooth generates the surface, whereas for the roughing tool and the roughing-finishing prototype two teeth machine the final surface. The shape of the feed marks of the roughing-finishing tool can be explained with the radial recessed teeth, which do not get in contact with the final surface. The effects of the roughing and finishing tools can be attributed to runout and manufacturing errors of the tool. However, for further investigation of the tool concept behavior these aspects need to be separated and optimized.

For the surface machined with the roughing tool, material adhesion occurs on the surface due to the contact of the flank face chamfer with the workpiece. For the surface machined with the roughing-finishing prototype, minor material adhesion is still visible on the surface. Since the chamfered teeth are radially recessed, they do not get in contact with the surface for an ideal process. A possible explanation for the slightly deteriorated surface quality after machining with the roughing-finishing prototype could be the heat induced into the workpiece material due to the flank face contact. In order to prove this, further experiments could be conducted, in which the workpiece is preheated before cutting, so the influence of the workpiece temperature on the surface quality can be examined.

Another important factor in the evaluation of the surface quality is the formation of burr. Fig. 7 shows scanning electron microscope images of burr formation on surfaces machined with the three applied tool concepts (view of the top burr according to [11]). The largest burr formation can be observed for the workpiece machined with the roughing tool. The reason for this is the higher deformability of the workpiece due to higher temperatures and forces because of the flank face contact. However, no burr formation can be seen on the surface machined with the finishing tool, while small deformations occur on the surface machined with the roughing-finishing prototype. This small burr formation can be attributed to the heat induction into the workpiece due to the chamfered teeth of the prototype. For further investigations, a quantification of the micro-burr deformation must be conducted with methods described by Aurich et al. [11].

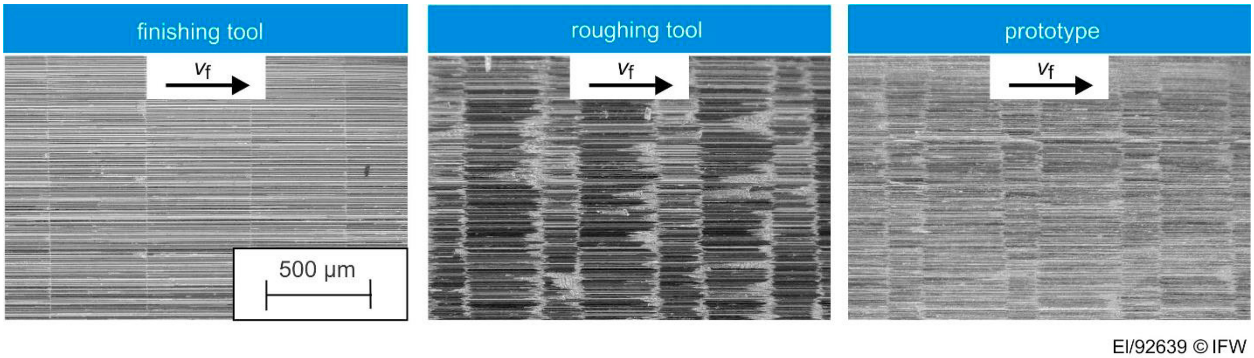


Fig. 6: Keyence microscope images of the machined surfaces in down milling with f_z = 0.12 mm, n = 4,000 min^{-1}, a_p = 10 mm and a_e = 3 mm

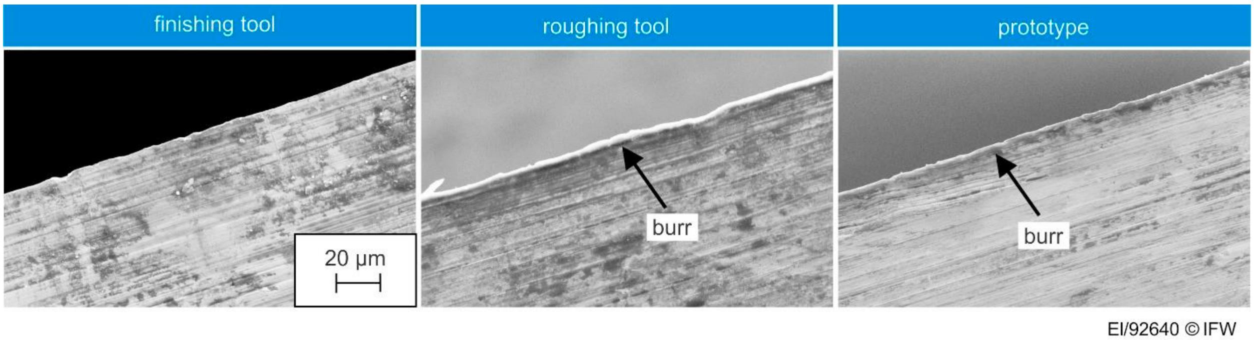


Fig. 7: SEM images of micro-burr formation of the machined surfaces in slot milling with f_z = 0.12 mm, n = 4,000 min^{-1}, a_p = 2 mm and a_e = 20 mm

4. Summary and Outlook

In this study, forces, process stability and surface quality of a novel roughing-finishing tool were examined and compared to conventional finishing and roughing tools. The finishing tool has sharp teeth only and the roughing tool has chamfered teeth only. For the force investigations, slightly higher forces can be observed in up and down milling when the chamfered teeth are in cut. This can be attributed to the contact between flank face and workpiece. Therefore, especially for the roughing tool the mean forces are increased by up to 20% compared to a sharp edged tool. For the roughing-finishing prototype, the forces of the sharp finishing teeth are higher because of the radial recession of the chamfered roughing teeth. Those differences can be reduced by a process-oriented design of the tooth pitch. Moreover, the process stability of the prototype is significantly higher compared to the finishing tool. For a spindle speed n = 2,000 min^{-1} the stability limit could be increased by at least 300%. In regards of the resulting surface quality, the highest burr formation appears on the surface machined with the roughing tool. No burr formation occurs for the surface machined with the finishing tool. The surface quality of the roughing-finishing prototype is enhanced compared to the roughing tool, but the performance must still be improved to satisfy the demands of finishing processes.

Possible next research activities are the quantification of the process damping, plastic deformations due to the flank face contact and heat related effects. Furthermore, simulations of stability charts applying the semi-discretization method [13] and the analysis of the influence of coolant on surface quality and burr formation have to be conducted. Moreover, the tool has to be applied for an industrial relevant component and compared to conventional machining tools. Possible applications are the machining of thin-walled parts, where the productivity of the finishing operations can be increased (e.g. structural components) and small parts, where a tool change significantly influences the process time (e.g. connection parts).

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