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CHATTER AVOIDANCE IN MILLING BY USING ADVANCED CUTTING TOOLS WITH STRUCTURED FUNCTIONAL SURFACES

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Abstract
The productivity of machining processes is often limited by the occurrence of dynamic effects. The presented approach intends to counteract tool deflections, and thus to damp and disrupt chatter vibrations by using milling tools with defined functional structures on the flank faces at the minor cutting edges. The potential of process stabilization is evaluated by analyzing the operational behavior of three variants of surface structures in experiments, in which an aluminum alloy was machined. An increase of the process stability and productivity of up to 60 % could be achieved.

Keywords:
Cutting tools; Chatter avoidance; Surface structures

1 INTRODUCTION

The aerospace and automobile industry as well as many other branches face an increasing demand of highly load-resistant and lightweight components. To fulfill both requirements complex geometries and aluminum or titanium alloys have to be applied [Gonzalo 2006]. Many workpieces are designed as structural components where high amounts of material removal of up to 95 % have to be realized in performant machining processes [Brecher 2007]. The economic application of cutting processes is limited by the material removal rate under the restrictions of the production accuracy and quality at minimal costs. Such goals could be archived by increasing process parameters like feed velocity and tool engagement [Denkena 2011, Tönshoff 2014, Denkena 2016]. The maximization of these parameter values is limited by the performance of the drives of machine tools or disturbing effects, which can appear during the machining process [Dietrich 2016]. Thermal effects and static deflections can be compensated when modern control systems are used, whereas dynamic effects like chatter require preventive actions and specific process strategies [Hirsch 2012]. Various chatter suppression techniques were developed, but almost all of them require significant constrictive measures or specific adaptions to the process conditions, which also constitute considerable efforts [Munoa 2016]. This motivates the development and analysis of a new universally applicable approach, which combines a cutting-edge modification and application of surface structures on the flank faces at the minor cutting edges (figure 1). While all present applications of structures on the functional surfaces aim at a reduction of cutting forces or tool wear, the presented investigation introduces a new technique to avoid disturbing dynamic effects.

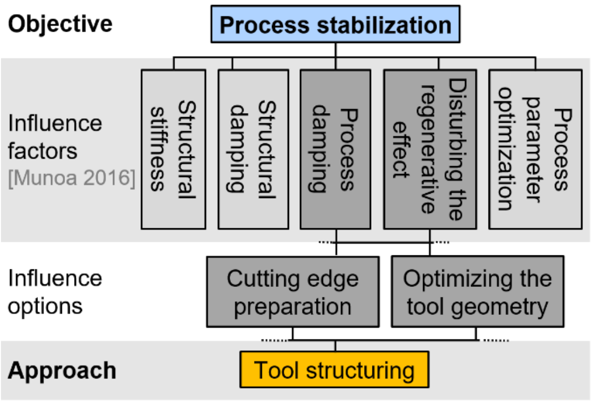

Fig. 1: Process stabilization approach.

2 STATE OF THE ART

The presented work covers scientific topics from process dynamics, tool optimization and surface structuring. The state of the art on these fields is presented in this section.

2.1 Process dynamics

Early scientific works, regarding dynamic effects in turning processes were published since 1946 [Arnold 1946, Cook 1955, Hölken 1957, Cook 1959, Tlusty 1963, Merrit 1965]. Until 1961 the mechanism that is responsible for the occurrence of dynamic effects in machining processes was not sufficiently identified [Andrew 1961], although the regenerative effect in milling processes was already described starting in 1953 [Hahn 1953, Tobias 1956, Tobias 1961, Daněk 1962, Peters 1963]. Later the regenerative effect was identified as the critical mechanism which leads to the occurrence of dynamic deflections in cutting processes [Altintas 2000, Tlusty 2000, Weck 2006]. Investigations on the impact of environmental and disturbance factors like thermal effects [Biermann 2013, Hajmodammadi 2014, Schweinoch 2015, Baumann 2016] or runout errors [Ma 2016, Baumann 2019] on the process dynamics are subject to research projects. Same applies to the dynamic behavior of workpiece and fixture systems under process conditions [Daimon 1985, Deiab 2004, Budak 2012, Siebrecht 2014, Hense 2015, Stepan 2017, Biermann 2019], or the tool-position-dependent change of modal properties of machine tools [Baumann 2017]. The avoidance of dynamic effects can be achieved by following several strategies in the design and construction of machining systems as well as the process planning and parametrization for specific operations. Five options to influence the process dynamics are defined in literature [Munoa 2016]: Enhancing the structural stiffness and damping, the process parameter value selection, the process damping maximization, and the regeneration disturbance. Increasing the stiffness or damping of machine tools constitutes a challenge in engineering, is associated with high costs and restricted in terms of scalability [Hirsch 2012, Munoa 2016, Möhring 2017, Vogel 2018]. An optimized process parameter value selection requires a detailed determination of the dynamic properties of the production system [Altintas 2014, Munoa 2016, Wiederkehr 2016]. Maximizing process damping [Sellmeier 2012, Munoa 2016] and disturbing the regenerative effect [Denkena 2010, Sellmeier 2012, Stone 2014, Hense 2015, Iglesias 2019] is largely independent of the properties of the production system and process, which is why these methods are particularly interesting in the sense of an universally applicable strategy for increasing productivity.

2.2 Tool preparation and development

The application of chamfered flank face cutting tools, which enhance the process damping [Sellmeier 2012, Munoa 2016], and serrated cutters, which disturbs the regenerative effect, constitutes a widely accepted strategy to avoid or minimize the occurrence of dynamic effects in machining processes [Denkena 2010, Sellmeier 2012, Stone 2014]. A cutting-edge rounding is also applied as a modification of the tool micro geometry, e.g., for adaption to the process-related load conditions, or as a basis for favorable adhesion properties of a tool coating, and thus appropriate to reduce tool wear and the excitation of dynamically compliant structures [Denkena 2014, Biermann 2016, Biermann 2018a, Biermann 2018b, Krebs 2018]. Another possibility to modify the cutting tool geometry and influence the process-related force conditions and tool wear progression is the application of meso and micro structures on the functional surfaces of a tool [Gajrani 2017]. Such preparation strategies are not state of the art yet, although numerous investigations for turning, drilling and milling processes are documented in literature [Enomoto 2012, Kümmel 2015, Niketh 2018]. These approaches commonly base on micro- and mesoscopic grooves on the flank face (figure 2-A), rake face (B) or structure elements such as dimples (C) [Beer 2014, Chang 2011, Fatima 2016, Xiang-yu 2017]. The structures are applied to reduce the friction and thermal effects, to decrease the process force level, and thus to reduce tool wear [Niketh 2018, Fatima 2016, Orra 2018]. In this context the orientation of the structure has a substantial effect [Enomoto 2012, Chang 2011, Orra 2018] and even adhesive wear effects could be reduced [Kümmel 2015, Fatima 2016]. When using lubrication, structure elements like dimples can act as lubricant reservoirs and reduce friction effects [Niketh 2018] as well as the use of solid lubricants [Jianxin 2011, Jianxin 2013].

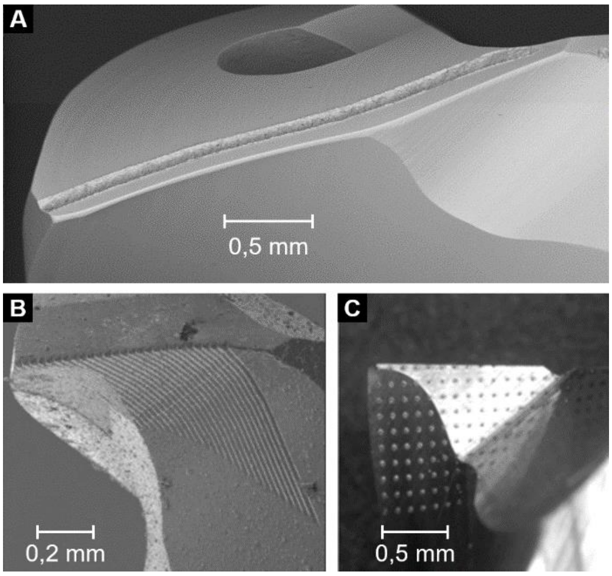

Fig. 2: Tool structuring [A: Beer 2014, B: Chang 2011, C: Xiang-yu 2017].

2.3 Surface structuring

Structured surfaces can be used to enable or support tribological, mechanical or optical functions in many applications such as chemical, medical, industrial and manufacturing technologies [De Chiffre 2003, Ramsden 2007, Wang 2009, Sieczkarek 2012, Merklein 2012]. Meso-, micro- and nanostructures are most frequently used, whereby meso- and microstructures are in focus for this application. These surface structures can be produced by a variety of technologies. The applicability of certain structuring processes is significantly restricted by the material to be structured and the geometric complexity of the surface. For the structuring of cutting tools made of high-speed steel (HSS), carbide (HM), ceramics, cermets and diamond, only processes are considered which can guarantee a reliable process and defined shaping in such materials [Hesselbach 2003]. Micro spark erosion, micro laser ablation and micromachining are promising processes [Etsion 2005, Kovalchenko 2011]. Micromilling allows to induce residual compressive stresses [Nespor 2015] and offers good surface qualities at relatively high removal rates. The high flexibility, which a five-axis milling process can offer, allows to produce a wide variety of complex structural elements. Despite the advantages of micromachining processes, only a few scientific articles have been published regarding the production of such surface structures [Matsuda 2008, Brinksmeier 2010, Quinsata 2011, Matsumura 2012, Resendiz 2015].

3 WORKING HYPOTHESIS

The following investigations are conducted to evaluate the working hypotheses for the stabilizing effect of circular structures at the flank faces of the minor cutting edges of an end mill cutter. According to the derived working hypothesis the structural elements on the tool interact with the workpiece material and counteract tool deflections by guiding the tool in the direction of the circular cutting velocity, and thus constrain radial deflections as depicted in figure 3. A vibration of the tool is inhibited by the uncut material in between the structure elements as the resulting contact forces counteract a deflection. Dynamic deflections are reduced, while side effects such as thermal loads occur and increased surface roughness values result especially within stable process sections.

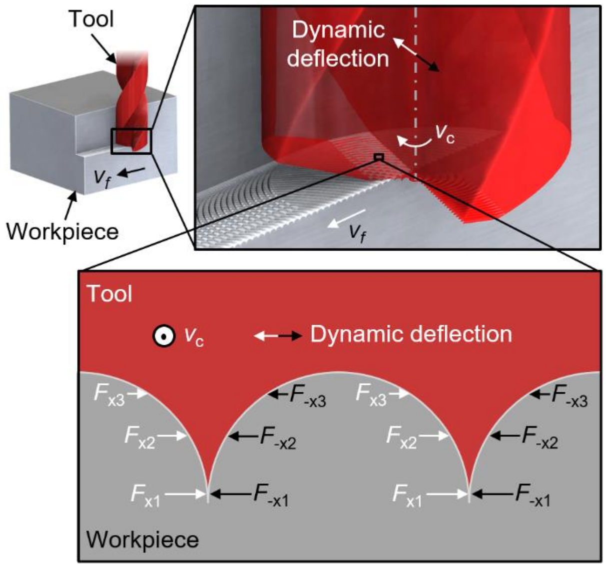

Fig. 3: Illustration of the working hypothesis.

Plastic deformation and friction effects may also absorb energy, and thus damp dynamic deflections. Side effects as thermal loads, increased surface roughness values on the machined surface and complex tool-wear distributions might appear. The influence of these effects on the process and machining results has to be investigated to evaluate the applicability and technological potential of the developed stabilization method.

4 EXPERIMENTAL SETUP

For the presented investigations, an end-mill cutter with two cutting edges and a diameter of $D = 8$ mm was used for machining of EN AW-7075 aluminum alloy. The flank face of the minor cutting edges of the used end mills were prepared with circular structural elements (structure 3 and 4 – figure 4). In addition, a non-prepared reference tool (reference) and a tool with a flat surface as a large flank face chamfer (structure 2) have been applied. The same tool holder was used for all the experiments presented in the following sections. The comparability of the tests was ensured by the use of a length adjustment screw. A length tolerance of $\Delta l \leq 0.025$ mm was defined in order to limit the influence of the tool cantilever length on the dynamic behavior of the tool and to be able to assume it as negligible, in terms of the investigated effects. In addition, a tolerance for the runout error at the cutting edge < 10 µm and a balancing quality < 1 G (DIN ISO 1940) were defined. The design of the milling process enables an evaluation of the process dynamics.

4.1 Tool preparation

The experimental test series was carried out with HSS milling tools. In contrast to carbide tools, which are established in many industrial applications, HSS can be machined reliably using micromilling. All investigated structures were machined with TiAlN-coated solid carbide tools. A cylindrical end mill cutting tool with a diameter of $D_{\mathrm{WZ\ S2}} = 1$ mm was used to machine a flat chamfer. A spherical micromilling tool with a diameter of $D_{\mathrm{WZ\ S3,4}} = 0.2$ mm was additionally applied to produce structure 3 and 4. These structures differ in the path distance of the circular NC paths with $a_{\mathrm{e\ S3}} = 120$ µm and $a_{\mathrm{e\ S4}} = 200$ µm resulting in different structure depths of $d_{\mathrm{S3}} = 20$ µm and $d_{\mathrm{S4}} = 100$ µm (figure 4).

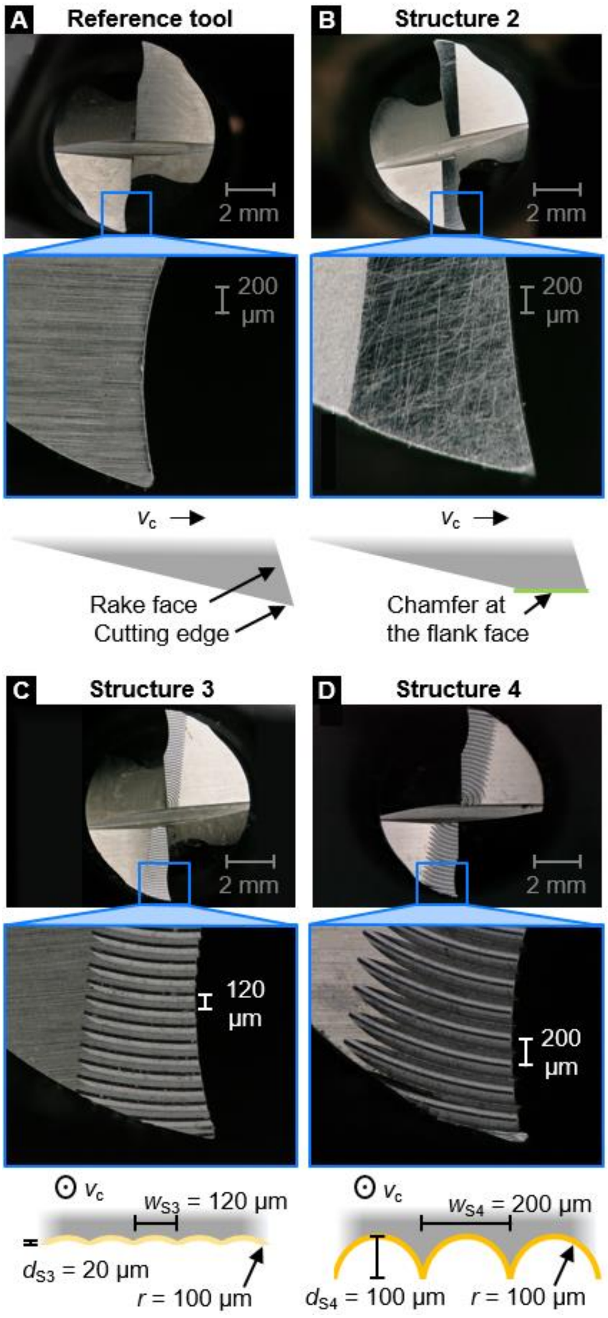

Fig. 4: Applied tools and structures.

4.2 Process design

The machining system was dynamically analyzed (figure 5-C) and a specific stability diagram was calculated (figure 5-D). The geometric-physical process simulation [Wiederkehr 2018] was applied with specifically calibrated force and dynamic models and typical process parameter values for the investigated application (figure 5-A). Based on the stability diagram, spindle speeds between $n_{\mathrm{min}} = 14085\ \mathrm{min}^{-1}$ and $n_{\mathrm{max}} = 15255\ \mathrm{min}^{-1}$ were selected, which comprise high and low process stability predictions. The selection of the operating points results in cutting speeds between $v_{\mathrm{c\ min}} \approx 350$ m/min and $v_{\mathrm{c\ max}} \approx 400$ m/min. The prepared tools were experimentally applied in dynamically critical milling processes (figure 5-B) with regard to the structure- and spindle speed-specific stability limit.

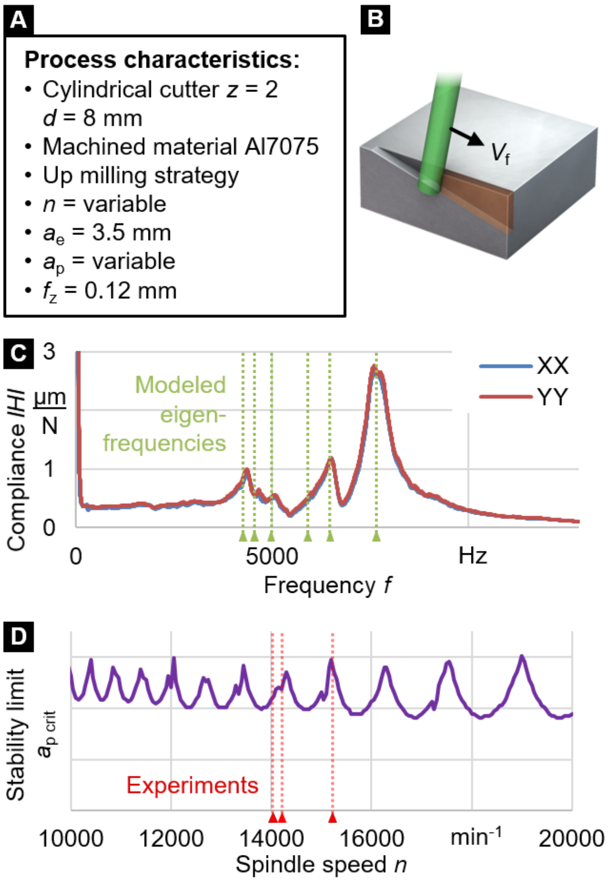

Fig. 5: Process design and parameter value selection based on simulations.

The dynamically critical process is realized by a linear increase of the depth of cut a_p, whereby the stability limit is exceeded and dynamic instabilities start to occur. A constant radial depth of cut of $a_e = 3.5$ mm and a linearly increasing axial infeed of $a_{p\,min} = 0$ mm up to $a_{p\,max} = 12$ mm, which was limited by the length of the cutting edge, were used.

5 EXPERIMENTAL RESULTS

For evaluating the process stability with regard to the occurrence of dynamic effects like chatter, face milling processes (figure 5-B) were conducted with each structured tool type and the test workpieces were analyzed due to characteristic surface properties like chatter marks and roughness values. In addition the acoustic emission during the experiment was evaluated in spectral analysis. Based on these measurements a tool- and structure-specific stability limit could be identified (figure 6). Figure 6-A depicts the surface which was machined with the main cutting edge of the reference tool, as well as the related acoustic emission level and its spectrogram. The spindle speed $f_n = 238$ Hz and tooth engagement frequency $f_t = 476$ Hz are depicted. The harmonics of these periodic, externally excited signals at f_n and f_t are indicated by increased amplitudes in the range of their integer multiples. The stability boundary was exceeded at an axial depth of cut of $a_{p\,crit} = 7.6$ mm. When chatter marks start to occur, the acoustic level increases significantly, especially in the frequency of the tools first natural frequency at $f_{0,1} = 4620$ Hz. Analogue analyzes for the experiments using the tool types with the structure variants S3 and S4 are presented in figure 6-B and C respectively. The stability limit was exceeded at a significantly higher axial depth of cut compared to the reference, when the structured milling tools were applied, which enabled an increase of the productivity and the production efficiency. The use of S4 (figure 6-C) could almost double the potential of high material removal rates at stable process conditions. Due to the reduced structural depth, the performance of a tool with S3 was lower than of the tool with S4, but still higher than the reference tool. The use of the tool with a flat chamfered flank face at the minor cutting edges (S2 – figure 4-B) did not lead to an enhanced process stability, thus, no further analyses were conducted. While figure 6 depicts the experimental results for a spindle speed of $n_1 = 14300$ min^{-1}, figure 7 presents an overview over all tested spindle speeds with certain repetitions for validation from $n_1 = 14085$ min^{-1} (A), $n_2 = 14300$ min^{-1} (B) and $n_3 = 15255$ min^{-1} (C). These experiments were carried out with one tool for each type of preparation (Reference, S3, S4).

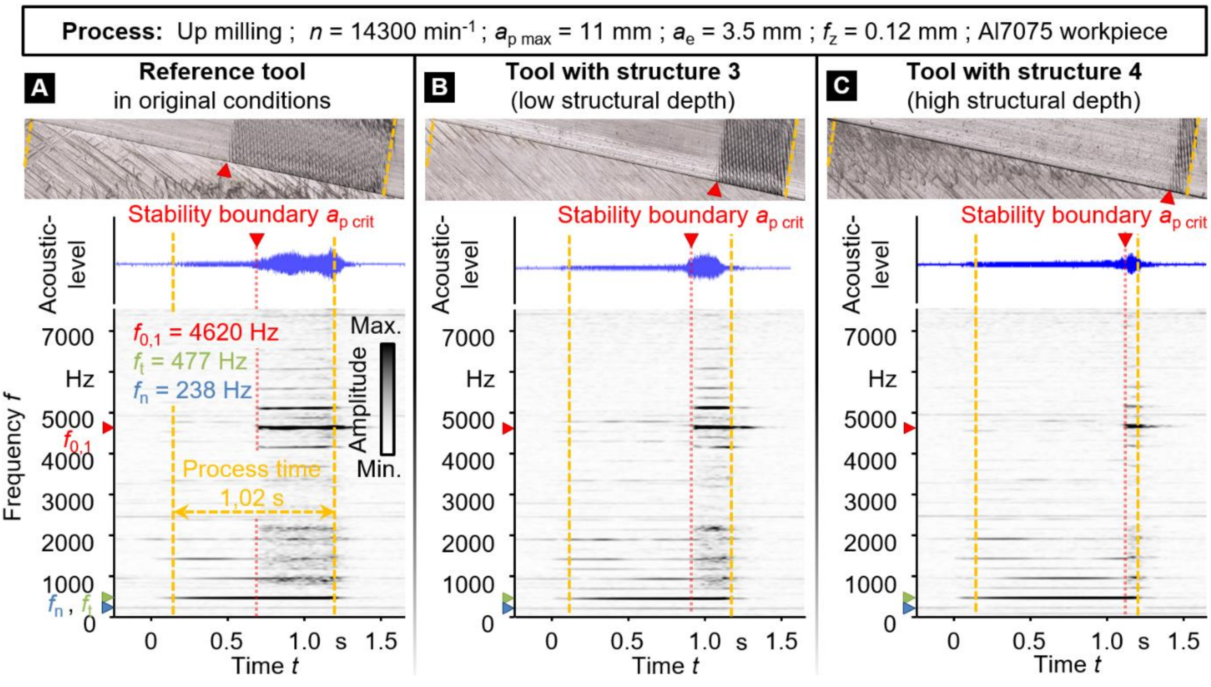

Fig. 6: Determination of the tool- and structure-specific stability boundaries.

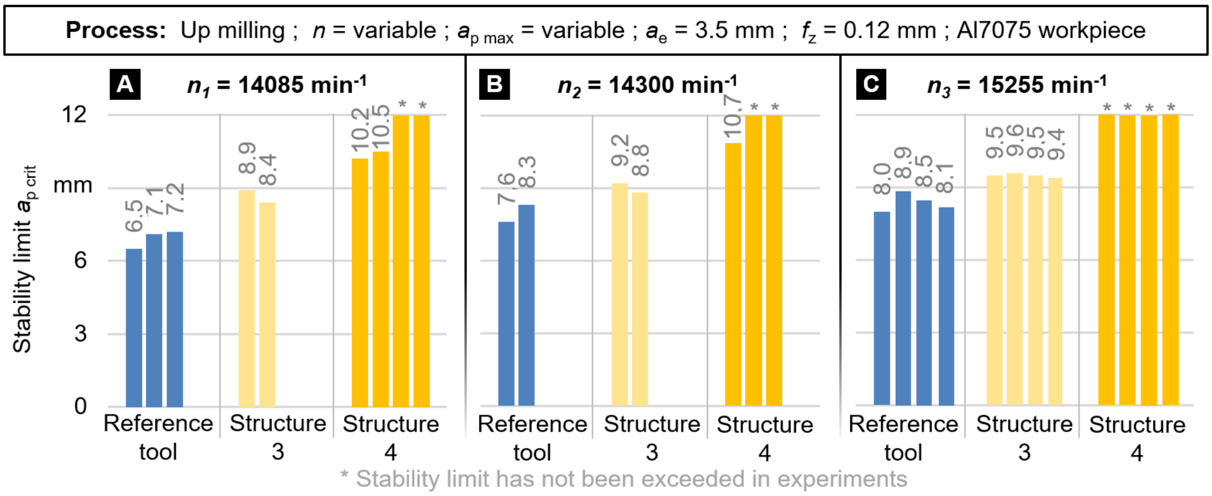

Fig. 7: Stability limit determined for each tool type and three spindle speeds.

These operating points include both, low and high stability predictions (figure 5). It could be determined that at all spindle speeds the stability limit were higher when structured milling tools were applied. In none of the conducted experiments a structured tool performed worse than the reference tool. The highest performance in terms of potential material removal rates delivered an application of structure 4, with a structural depth of d_{S4} = 100 µm (figure 4-D). At a spindle speed of n_3 = 15255 min^{-1} a stability limit could not be determined in any experiment, due to the limited length of the cutting edge of 12 mm, which defines the maximal depth of cut in the experiments.

6 ANALYSIS

The described modifications of milling tools influenced the process dynamics in a positive way, but also effects the chip formation and various aspects which are described in the following sections.

6.1 Tool wear

A critical aspect and impact factor on the potential of such a structure application is the wear contribution of the partially filigree structural elements. To evaluate the wear progression and the robustness of the stabilizing effect, wear provoking processes and additional stability tests were conducted. Figure 8-A depicts the determined stability after each tool type removed a certain material volume V_M of up to $V_{M\,max}$ = 1500 kmm^3. The wear provoking process was characterized by an axial depth of cut of a_p = 7 mm, a radial depth of cut of a_e = 3.5 mm, a spindle speed of n = 14300 min^{-1} and a feed per tooth of f_z = 0.12 mm. As typical, initial wear effects lead to a decrease, followed by an increase of the stability limit, which can even exceed the initial stability limit and then correlates to a constant value. This wear progression effect could obviously be observed when the reference tool was applied (figure 8-A – blue marks). When the tool structured with S3 was used, a significant increase of the stability boundary above the maximal depth of cut of $a_{p\,max}$ = 12 mm could be observed after a material volume of about 150 kmm³ was machined (figure 8-A – light yellow marks). During the application of a tool, which was prepared with structure 4, no stability limit was exceeded at any wear state (figure 8-A – dark yellow marks). Figure 8-B illustrates the wear state of the tool with an applied structure 4 at the flank face of the minor cutting edge after a material volume of V_M = 720 kmm³ was machined. The outer structure elements were subjected to adhesive wear. The outermost structure element was obviously loaded thermally by a significant amount. This leads to the conclusion that the outer structure elements are primary involved in the material removal process and can be seen as the mainly effective elements which caused the increased process stability. The inner structural elements interact with multiply cut surfaces, which consequently contain less uncut material. Although several wear effects appeared, a decrease of the stabilizing impact of a structure application on the flank face of a milling tool could not be observed within the test volume of $V_{M\,max}$ = 1500 kmm³.

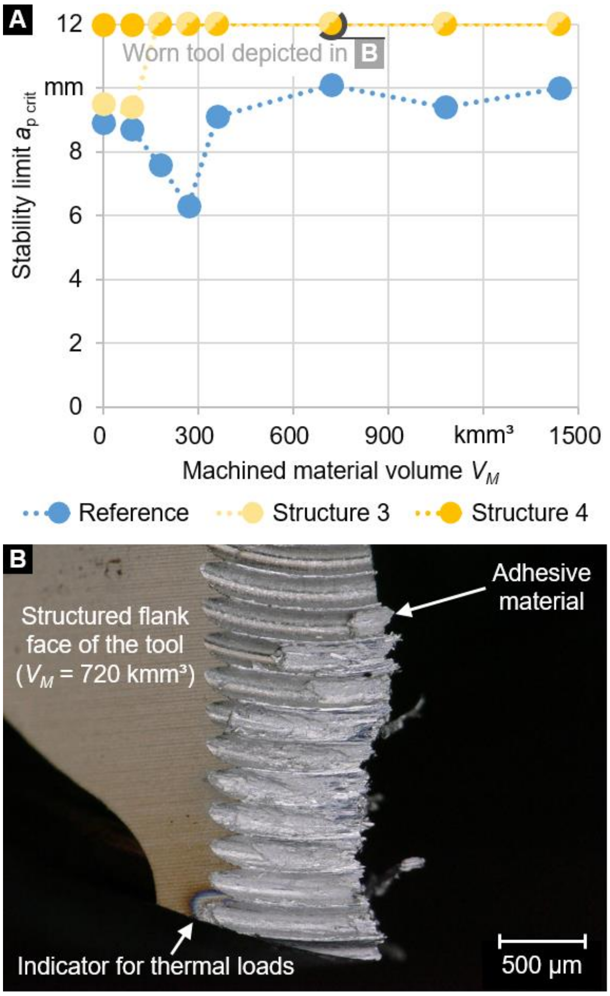

Fig. 8: Analysis of tool wear effects.

6.2 Chip formation

In experiments using tools, which were prepared with structure type 4, two different kinds of chips were produced (figure 9). Chip type A was removed by the major cutting edge – its length relates to the axial depth of cut. The significantly smaller chips (B) are produced at the minor cutting edges and their thickness relates to the width of the structural elements $w_{S4} = 200\ \mu m$. The presence of chip type B proves the involvement of the structured functional surface and modified cutting edge in the process of material removal.

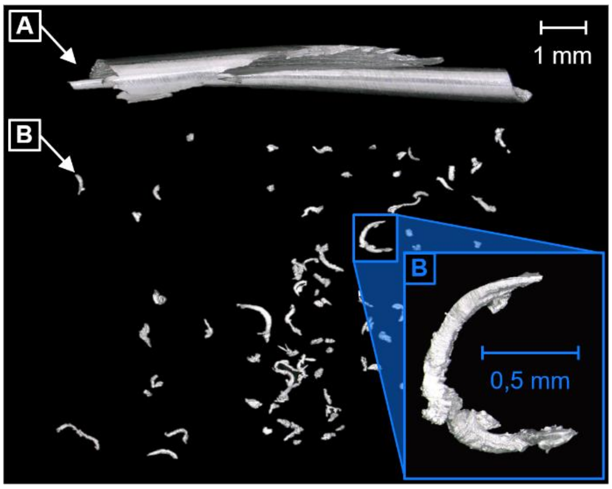

Fig. 9: Analysis of chip types (A, B) and shapes.

6.3 Surface roughness

The roughness at the surface of the machined workpiece, which is produced by the major cutting edge, was not negatively influenced by the application of structured milling tools ($R_z < 5\ \mu m$). At higher depth of cut the surface roughness values were even lower when structured tools were used, due to the enhanced process stability. Beside this, the surface roughness, machined by the minor cutting edge at low and stable infeed conditions, was slightly higher when structured tools were applied ($R_z < 22\ \mu m$) compared to the reference tool ($R_z < 16\ \mu m$). At the maximum depth of cut of $a_{p\ max} = 12$ mm the structured tools produced a lower surface roughness ($R_z < 17\ \mu m$) in contrast to the reference tool ($R_z < 25\ \mu m$) due to the stabilizing effect of the surface structures. In so far, the tool structuring approach was especially appropriate for roughening processes, where high material removal rates are desired and the relevance of surface roughness values is low.

7 CONCLUSIONS

The presented investigations support the presented working hypothesis on the stabilizing potential of an adapted surface structure on a milling tool in the context of process dynamics. A complete prove and description of all relevant cause-effect relationships cannot yet be derived, which is why further experiments and analyses are scheduled. The application of appropriate structures on the functional surfaces at the minor flank faces of a milling tool enables a significant increase of the potential in terms of process stability and productivity. The exploitation of the increased stability potential enables an increase in material removal rates and thus in productivity of up to 60%. An important advantage of the presented approach is that the stabilizing effect seems to be independent from the spindle speed and eigenfrequencies. In so far, the approach could be universally applied and does not require comprehensive measurements of specific properties of the production system and further analyses, which constitutes a relevant advantage in terms of the potential for an industrial use. The approach still allows a combination with other chatter avoidance techniques. Further investigations will concentrate on the explanation for the causal relations between the application and properties of surface structures on milling tools, and the stabilizing effect regarding the process dynamics. This will allow an optimization of the geometry of the structure and an aligned process design.

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