Advanced Materials Research *Online: 2008-04-08*
ISSN: 1662-8985, Vol. 43, pp 37-46
doi:10.4028/www.scientific.net/AMR.43.37

Machining of Lightweight Frame Components

D. Biermann[1,a], K. Weinert[1,b], A. Zabel[1,c], T. Engbert[1,d] and J. Rautenberg[1,e]

[1]Institute of Machining Technology, Technische Universität Dortmund,

Baroper Str. 301, 44227 Dortmund, Germany

[a]biermann@isf.de, [b]weinert@isf.de, [c]zabel@isf.de, [d]engbert@isf.de, [e]rautenberg@isf.de

Keywords: Cutting technology, lightweight components, drilling, milling, reinforced aluminum

Abstract. Lightweight frame components made of aluminum and load optimized connecting elements allow the reduction of weight and energy consumption as well as the increase of payload. Complex frame structures which nowadays can be designed and optimized with the help of modern simulation technologies require the use of adapted manufacturing technologies. Especially the flexible machining of single or limited products on the basis of common machining strategies is still inefficient and economically unacceptable. This article describes the development of adequate strategies for a high quality machining using simultaneous five-axis milling. Consequently, the machining of composite extruded aluminum profiles with continuously embedded steel-wire elements and the preparation of joining areas on nodes and commonly extruded profiles for innovative joining by forming processes have been analyzed.

Introduction

Modern lightweight frame components are the basis for many constructions in automotive engineering and aerospace industry. These load-optimized and highly customized products need to fulfill the particularly complex requirements of certain applications, so the costs of manufacturing can increase easily due to a great variety.

The investigations described in this article are part of a project within the "Collaborative Research Center (SFB/TR10)" which is supported by the German Research Foundation (DFG). It deals with the development of handling, machining and joining of single lightweight structures in a flexible process chain [1]. Fig. 1 shows the main aspects of the project A6.

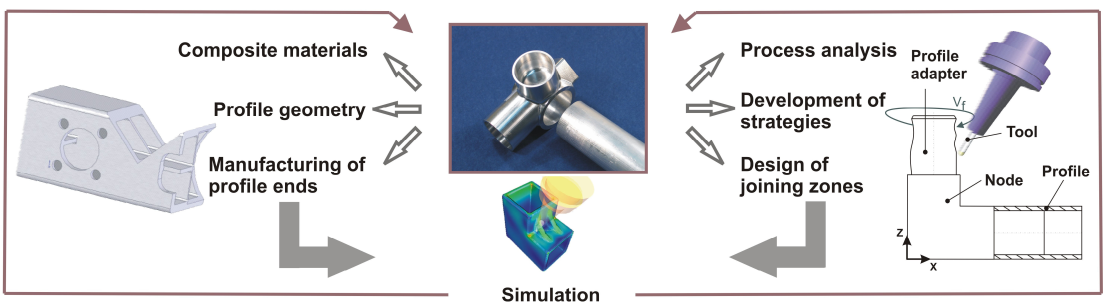

Fig. 1: Requirements for machining modern lightweight components

The machining of modern steel-wire reinforced aluminum profiles with various profile geometries is still regarded as critical in consideration of tool wear [2]. The manifold requirements of machining composites depend on the materials used and their configuration, the chosen tools and strategies on the one hand and on the specifications of the connecting elements and the joining zones on the other hand. Simulations help to support, control, evaluate and optimize the processes [3]. This article focuses on the evaluation of milling strategies for machining continuously reinforced materials, the effects of the strategies on tool wear, and the quality of the machined surfaces and the milling preparation of areas that are necessary to increase the efficiency of hydro-bulged joints.

Milling Strategies for Continuously Reinforced Materials

Milling operations always offer a number of options. After a detailed process analysis, apparently similar looking options often show large differences that affect tool wear and machining quality without changing process duration. Milling strategies must be adapted to workpiece and material, which is especially difficult, when two different materials are combined in a composite material. Continuously reinforced extruded profiles are an attempt to create new lightweight and highly resilient structures, but the combination of a light metal matrix material with endless wire-like reinforcing elements, offers new challenges for the machining technology. Referring to the machining of boreholes, circular milling has generally proved to be an adequate alternative to the conventional drilling process [4]. In addition to the right choice of tool shape, substrate and coating as well as adapted cutting parameters for macroscopic inhomogeneous composites a modulation of the milling strategy can be relevant for tool life. Measurements have shown that the mechanical load on the tool is significantly higher while cutting the reinforcing element than during the machining of aluminum matrix material [5]. Depending on the milling strategy, part of the minor cutting edge and part of the major cutting edge of a single edge milling tool, are stressed differently. The effects become clear when taking a closer look at a case differentiation.

A view from the spindle of a three-axis machining center in direction of the workpiece allows an easy explanation of two different strategies. To specify the position of the tool when machining the workpiece in 2D-drawings, depth levels are defined along the borehole axis. The gap between tool and workpiece prior to the machining operation is defined as a positive z value. When just touching the surface of the workpiece the z value is zero, going further the z value becomes negative. The whole workpiece has a thickness of $t = 5$ mm, the reinforcing fiber has a diameter of $d = 1$ mm in this example and is located in the middle of the profile. Therefore, the reinforced area lies nominal between $z = -2$ mm and $z = -3$ mm if the machining starts at $z = 0$ mm and the tool reaches the bottom of the profile at $z = -5$ mm. With an axial infeed of $a_p = 3$ mm per helix, the tool moves along an arc of $\varphi = 120°$ of its circular path projected onto the xy-plane, which is perpendicular to the borehole axis while the tool moves one millimeter further in z-direction. If the reinforcement fiber lies eccentric in a borehole, the infeed motion in the range of $z = -2$ mm to $z = -3$ mm can either be done in the area of the reinforcement or in the matrix material so that it is possible to position the load, acting on the tool, caused by the reinforcing fiber, exactly on selected parts of the major and minor cutting edges. Two different strategies have been object of experimental investigations:

Strategy 1: The cutting of the fiber is done by both, the major cutting edge and the minor cutting edge. The exclusive machining of the reinforcing element by the minor cutting edge is not possible, but to make a difference between the two strategies, the machining of the fiber by the minor cutting edge is increased to a maximum while the stress on the major cutting edge is reduced to a minimum. Therefore, the infeed motion in the range from $z = -2$ mm to $z = -3$ mm, is done in the area of the reinforcement, causing high stresses on the corner of the tool.

Strategy 2: The cutting of the fiber is exclusively done by the major cutting edge of the tool. In the range from $z = -2$ mm to $z = -3$ mm, where the reinforcement element is located, the infeed motion is done aside from the fiber in matrix material so the minor cutting edge and the corner are not getting in contact with it. Therefore, wear on the minor cutting edge and the corner must refer to the machining of aluminum only.

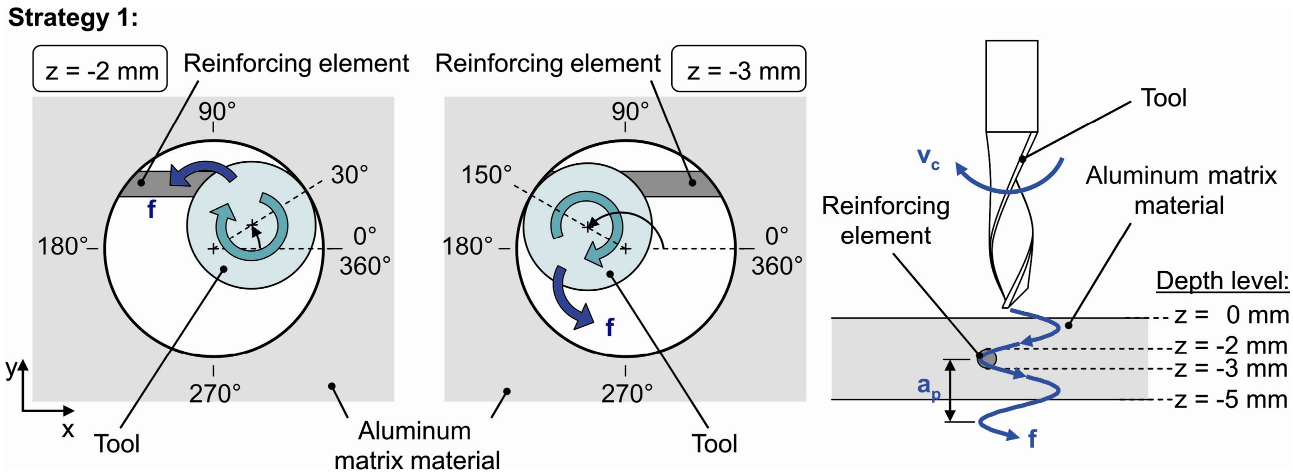

Fig. 2: Cutting the reinforcing element with major and minor cutting edge

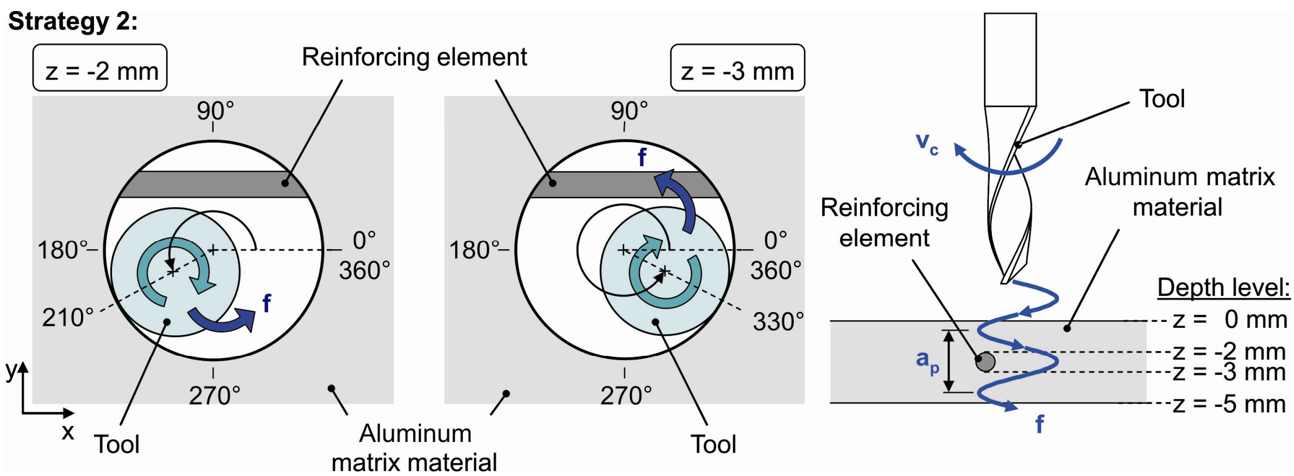

Fig. 3: Cutting the reinforcing element with major cutting edge only

The two strategies are realized by a slight variation in the starting point. The milling process is started while the tool is in front of the workpiece and the starting point describes the positive space between tool and surface. After being placed concentric above the subsequent borehole the milling cutter moves radial in the positive direction of the x-axis. The starting position is marked in Fig. 2 and Fig. 3 by the angle of $\varphi = 0°$. Afterwards the tool begins to move along the helical path until reaching the programmed depth. Therefore, the starting point determines the angle in the xy-plane that is reached when the tool starts to cut the fiber (z = -2 mm).

When using strategy 1, the depth level of z = -2 mm has to be reached at an angle of $\varphi = 30°$ so at a depth of z = -3 mm the angle is $\varphi = 150°$ (cp. Fig. 2). When using strategy 2, the tool has to reach the depth level of z = -2 mm at an angle of $\varphi = 210°$ (cp. Fig. 3). With an infeed of $a_p = 3$ mm the angle at a depth of z = -3 mm is $\varphi = 330°$ and the deepest point of the reinforcing fiber is undercut. The minor cutting edge is not involved in cutting the fiber. The experimental research was done with uncoated tools with a diameter of d = 5 mm to generate tool wear rapidly. The diameter of the boreholes produced was D = 8.5 mm. To analyze wear progression qualitatively referring to the influence of the machining strategy, major and minor cutting edge were analyzed under a light-optical microscope in regular intervals. Selected pictures are displayed in an overview in Fig. 4.

In general, the wear progress turned out differently. While the contour of the minor cutting edge and the corner including the chamfered area remained in quite a good condition during the tests when using strategy 2, the minor cutting edge showed chipping after producing a few boreholes when using strategy 1. These chippings concentrated at the corner of the tool and due to the rough surface of the damaged regions, aluminum adhesion occurred. After producing 70 boreholes the differences were obvious. Strategy 1 caused massive chipping at the corner as well as on the minor cutting edge while the corner and the minor cutting edge were less significantly damaged using strategy 2.

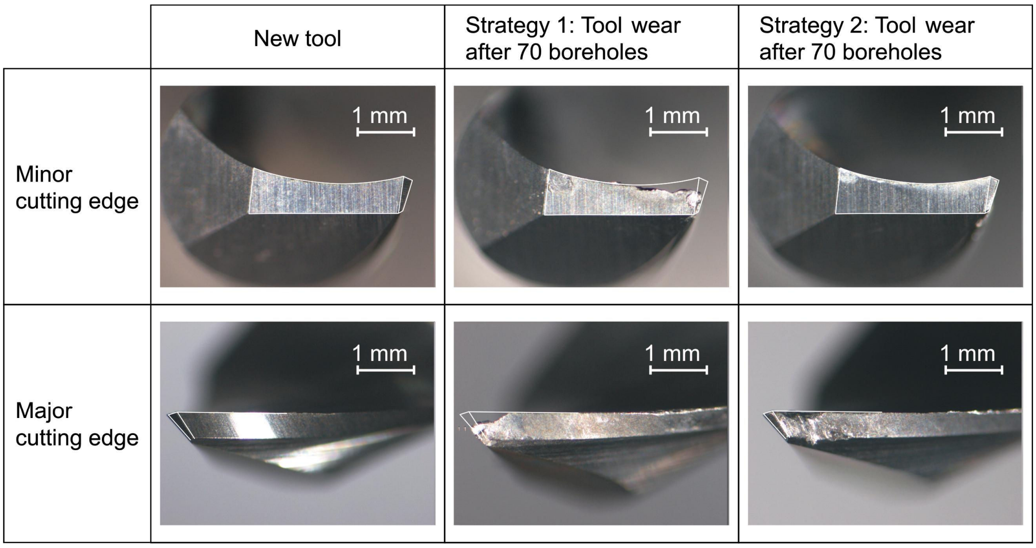

Fig. 4: Photographic images of the tool wear when using different milling strategies

Strategy 1 is an attempt to reduce the stress on the major cutting edge, but it is impossible to avoid contact with the fiber. The feed motion in the range of z = -2 mm and z = -3 mm occurs in the area of reinforcement. During the progress of feed motion, not the entire fiber material is removed, so the major cutting edge completes the cutting on the following rotation on the helical track which causes wear along the major cutting edge due to surface disruptions. Hence, not only the massive chipping at the corner of the tool but also the damage along the major cutting edge has to be considered when rating the strategy.

After producing a few boreholes with strategy 2, a damaged region was observed on the major cutting edge close to the corner. The rough surface was covered with aluminum due to adhesion. Further cutting operations led to an increased number of small bursts on the major cutting edge which took up the biggest part in machining the reinforcing element. In general, the contour of the major cutting edge remained quite well. Again, two regions were affected by wear. In addition, to the part of the edge close to the corner, which became rounded due to the small chippings mentioned above, there was a region in far distance to the corner that showed similar wear characteristics as seen in strategy 1.

The high flank wear on the minor cutting edge as well as the burst of the corner were often reasons for early tool failure during past circular milling investigations [5]. The major cutting edge of the used tools has got a bigger wedge angle and therefore, a better stability of the edge so wear resistance is better according to chippings. The investigations concerning the use of different circular milling strategies when cutting continuously reinforced aluminum profiles indicate a close connection between tool wear and milling strategy. Besides the known influencing parameters of machining like cutting velocity or feed rate, there is an additional parameter to set when machining reinforced profiles. If the implementation of different strategies is possible, the variation of strategy may influence tool wear without changing process duration. In this case, strategy 2 would be far more suitable for the machining operation described above than strategy 1 considering the wear characteristics of the tool. The mechanical impact during the machining of the reinforcing element is the main reason for the initiation of tool wear. The milling strategy needs to be adapted in a way that parts of the tool with low wear resistance, like the corner, are less involved in machining the reinforcing element and more rigid parts, like the major cutting edge, remove most of the hard material. The adaptation of the milling strategy will improve the quality of the borehole as well as the endurance of the tool.

Milling of reinforced profile ends. To connect single profiles to an entire frame, it is necessary to finish the ends of the profile after cutting them to the right length. Again, the milling strategy is of major importance when cutting continuously reinforced material. To take advantage of the flexibility of the milling process, the same tools can be used in this peripheral milling application. Thus, non-productive time is reduced when different cutting operations have to be done to complete a workpiece. Due to the different mechanical loads generated in machining aluminum matrix material and steel, surface imperfections occur at the workpiece. The analysis of the surface by use of a confocal whitelight microscope reveals the topography as shown in Fig. 5. The produced surface is uneven.

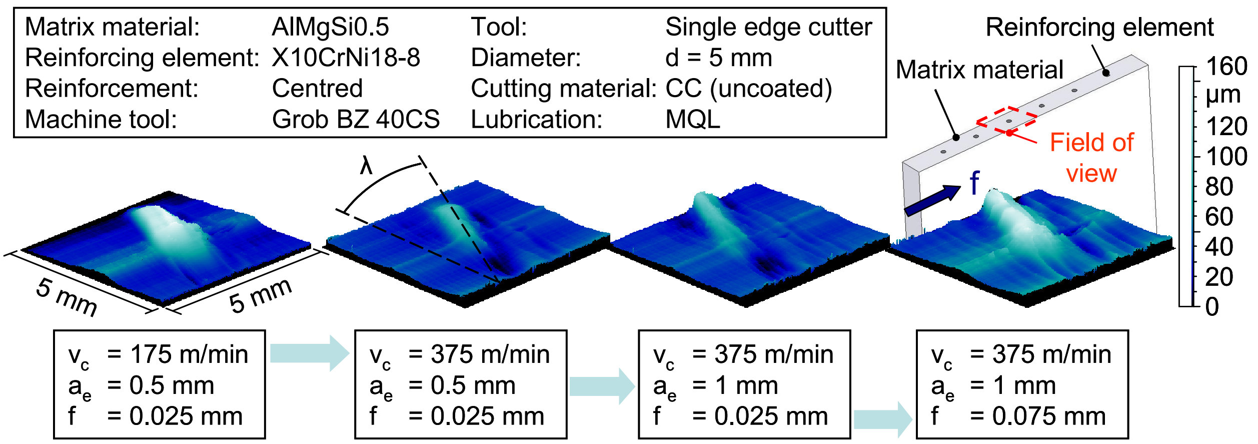

Fig. 5: Surface unevenness when milling reinforced profile ends

Single edge milling cutters with small diameter lack in bending stiffness due to their capacious chip flute. The tool is deflected radially when the reinforcement fiber is cut. A material wall builds up corresponding to the twist angle and the bending line of the tool. The height of the material wall is dependent on the cutting parameters. So if the bending stiffness of the tool used is low, surface imperfections can be reduced by choosing a combination of high cutting speed and small depth of cut as well as low feed rate.

Preparation of Joining Areas by Milling

The milling of lightweight aluminum connecting elements (nodes) and the preparation of areas for following joining methods is the second focus within this project. The difficulties in simultaneous five-axis milling and the combination with a simulation system that allows to noticeably reduce oscillations of long tools, to adapt the recent engagement conditions between cutting tool and workpiece, to harmonize the tool movement, and to provide a process-safe collision detection and avoidance, which have been described in [2].

One aspect in machining nodes is the preparation of areas that help to increase the tensile and torsional strength between the node and a joined tube. Functional surfaces with specific surface roughnesses are relevant in several mechanical parts which are moving against another part (e.g.

bearings and axis, cylinders and pistons, gears) or fixed (e.g. sealing surfaces or force-fit and form-fit connections). According to the strength of a joint, the surface quality of connected lightweight elements plays an important role for the resistance against tension, or torsion.

Aluminum tubes and nodes can be joined using additional material (e.g. welding, soldering, bonding) or without (hydroforming, EMU, rolling in, Friction Stir Welding (FSW) to obtain a force-fit, form-fit or adhesively joined connection. The main focus in this article is the preparation for surfaces that can be used for joining by dieless hydroforming.

Exemplarily, Fig. 6 shows an aluminum node with adapters for joining three different tubes. Two tubes can be joined by welding; a third profile can be joined by hydroforming. There are two different basic ways of structuring a surface of a joining zone. The macro-structure allows the profile to fit into the structured areas of the node to increase the strength of the joint. The micro-structure/surface roughness is important for a grouting between the inner and the outer part. Although the transition between both influencing factors is fluent, a measurable surface roughness (e.g. smaller than 50 µm) and a structure, which can have the form of a groove or a pocket and has a visible depth (e.g. greater than 0.1 mm), can be distinguished. Both factors have a particular influence on the strength of a hydroformed connection. Whereas the micostructure, according to the influence on the friction and the tangential stress between both joining partners, leads to a more force-fit based connection, macrostructured elements offer a high potential to increase the form-fit. To reduce the complexity of the workpieces for basic research, the necessary part of the node is substituted by a ring element (Fig. 6, right side).

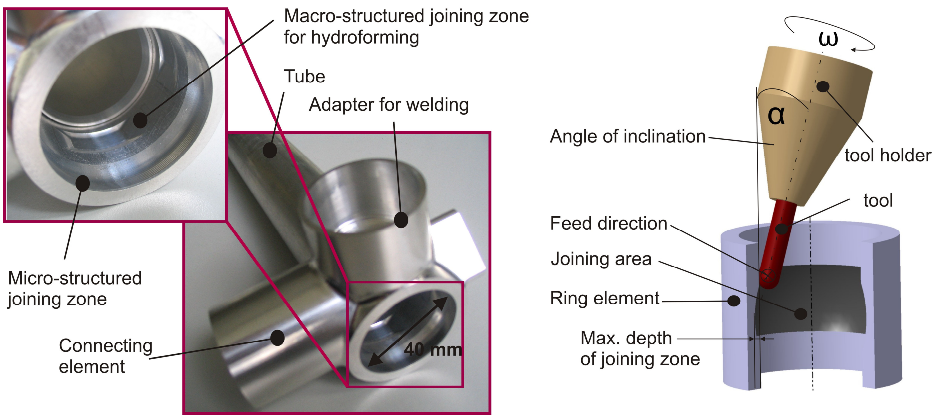

Fig. 6: Joining areas at an aluminum node (left) and substituted ring element (right)

Joining by dieless hydroforming

Joining by dieless hydroforming or hydro-bulging is one of the hydroforming processes and is a feasible process for manufacturing of tubular joints in lightweight frame structures [6]. The detailed description of the process principle for joining by dieless hydroforming (as indicated in Fig. 7), as well as more detailed experimental investigations on force-fit joints are explainend in [7] and briefly in the article "New Aspects of Joining by Forming of Tubular Workpieces" inside of this issue. This information could be summarized as follows: In a special fixture, the inner tube is inserted into the outer ring element. The hydro-probe is fed into the tube and the hydro-medium is set under pressure and directed into the gap between the hydro-probe and the inner surface of the tube. O-ring seals limit the length of the joint area and close the chamber in which the forming process takes place. After releasing the pressure, the tube-ring element recovers elastically but maintains the plastic deformation of the tube that has been produced during the bulging operation.

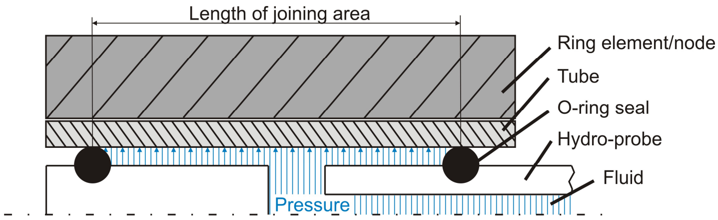

Fig. 7: Principle of hydrobulging

Manufacturing of Lightweight Connecting Elements. The manufacturing of the pockets (not described in this article) and the specific layout of the surfaces on the ring elements has been produced by five-axis CNC machining on a Deckel-Maho milling machine (DMU 50 Evolution) at the Department of Machining Technology, University of Dortmund. This multi-axis machining concept has been chosen to provide a flexible possibility for an efficient process of these lightweight components and to fulfill the requirements of geometric accuracy and surface quality. The main focus was put on a finishing process with a reproducible roughness. The NC-data was generated by a common CAM-system as used for the manufacturing of dies and moulds. High process forces as they appear in machining of hard and hardened materials [8] were not expected for the surface finishing process of the outer ring so that a deformation of the thin-walled specimen could be excluded.

To fulfill the restrictions of flexibility and efficiency, the use of standard tools is inevitable. Ball end mills with a diameter of 6 mm with a coating that reduces the adhesive behavior of the ductile aluminum alloy have been used to provide a high flexibility in covering a wide range of micro- and macro-structures with process-safe strategies. Ball end mills also allow producing small radii at the bottom of macro-structured pockets. If the radii of the tools are too small, machining time would increase and a process-safe manufacturing can not be guaranteed due to small flutes that limit the handling and transportation of the chips. The main difficulties in machining the inner areas of a ring segment are similar to the machining of cavities in die and mould industry [9, 10]. Collisions between the tool or the tool holder need to be avoided and the range of angles of inclinations, which also depend on the length of the tool and the tool holder, and the depth of the undercut of the joining area is limited (s. Fig. 6, right side).

Micro-Structured Surfaces. Several variations of milling parameters (s. Fig. 9) have been carried out in order to find process-safe, repeatable strategies that allow manufacturing selective surfaces with a ball end mill with a diameter of 6 mm. To hold up the required flexibility, a wide range of parameters has been covered (Fig. 9). The average surface roughness Rz, as it is an internationally used and standardized value, has been used as criterion to describe the surface. All experiments were used without lubrication in order to evaluate economic, process-safe manufacturing parameters, contrary to the common use of a full floating coolant. The strategy that was chosen is a helix-based finishing process. The CAM-system generates the NC-data in a way that the ball end of the tool is milling the structure of the joining zone in a continuous, helical movement. This guarantees a constant quality of the surface and avoids time-consuming, idle movements of the tool.

In a first step, visible damages of the surface were identified. Visible damages can be either blurrings (Fig. 9, right side) or tear-offs and lead to a significant detraction in categorizing the surfaces. An aggregation of blurrings can be identified as matt-shining spots in the manufactured surfaces. Measuring the average surface roughness Rz does not give a repeatable value to describe the quality surface in a reproducible way and it can be assumed that a blurred surface has an influence on the interlocking of the outer ring and the tube after the joining process that can not be clearly identified. The exposure that was made with a confocal whitelight microscope (type:

NanoFocus µsurf) demonstrates the irregular appearance of the damages which can result from temporary built-up edges [11] and chips that have not been directly forwarded through the flutes of the tool due to their adhesive behavior, which is supported by the dry milling process. A tool wear related change of the appearance of damages could not be detected during the experiments.

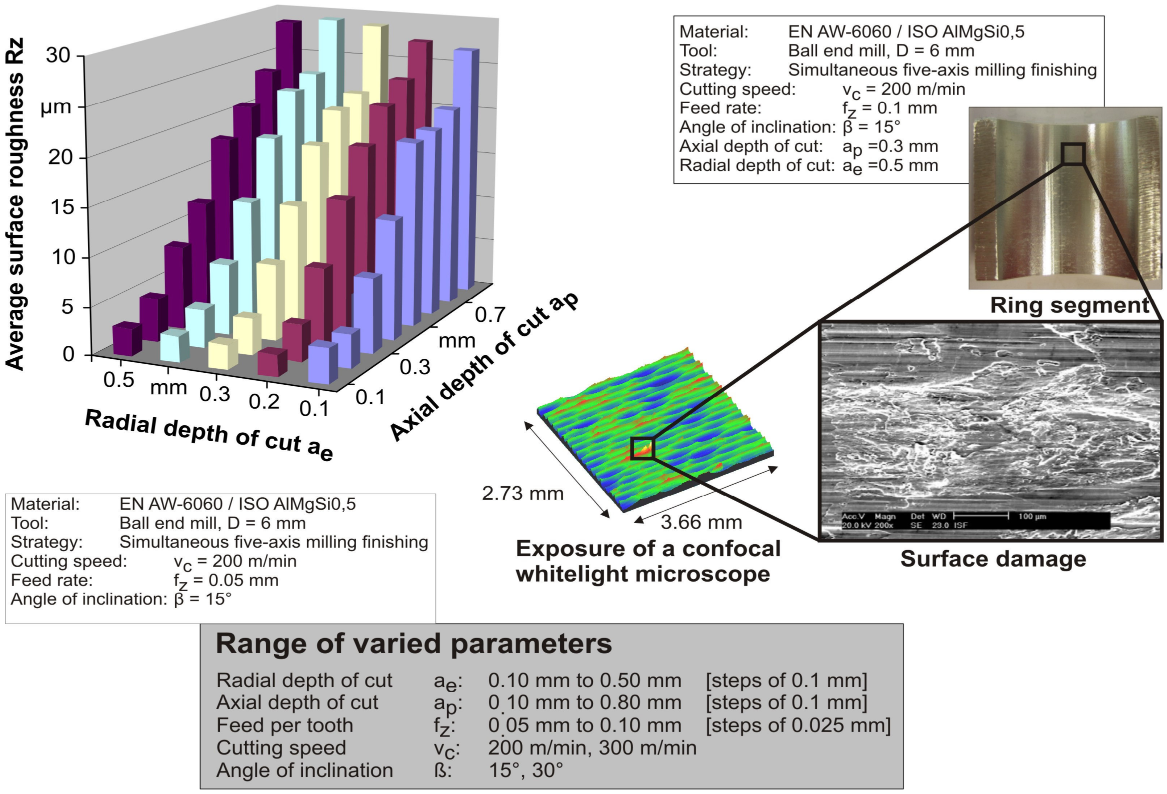

Fig. 9: Surface roughnesses on milled ring elements

It is known that aluminum alloys require high cutting speeds to achieve an adequate surface quality [12]. The specimens that were manufactured with the higher cutting speed of $v_c = 300$ m/min showed a surface quality without visible damages and were selected as a basis for further investigations. When using a ball end mill, the variation of the angle between the tool and the surface also allows varying the effective cutting speed of the cutting edge that is in contact with the material. While the effective cutting speed at the tip of the tool is zero, it reaches its maximum when the maximum diameter of the ball end is in use. Therefore, a lowering of the angle of inclination increases this effective cutting speed and supports the needs for a reproducible process.

The axial depth of cut (exemplarily shown in one set of parameters in Fig. 9, left side) is identified as the main influencing factor, whereas the radial depth of cut shows no significant influence. This corresponds with cognitions about the theoretical roughness from literature [13]. The measured values are similar to the calculated values. The real values are always a bit higher than the estimated values, but they approximate with increasing axial depth of cut. Smaller depths of cut ($a_p < 0.5$ mm) lead to an increase of the difference up to 6 µm so that, for the demands of a precise description of higher surface qualities, a control by measuring is inevitable.

In a next step the manufacturing of the inner surface of the ring elements was transferred to an exemplary preparation of tubes on the outer surface for three different surface structures. The ring elements were left unmanufactured and after the hydro-bulging process the tensile strength was tested on a ZWICK tensile testing machine (type 1475) to verify the quality of the joint. The results of the tests can be seen in Fig. 10.

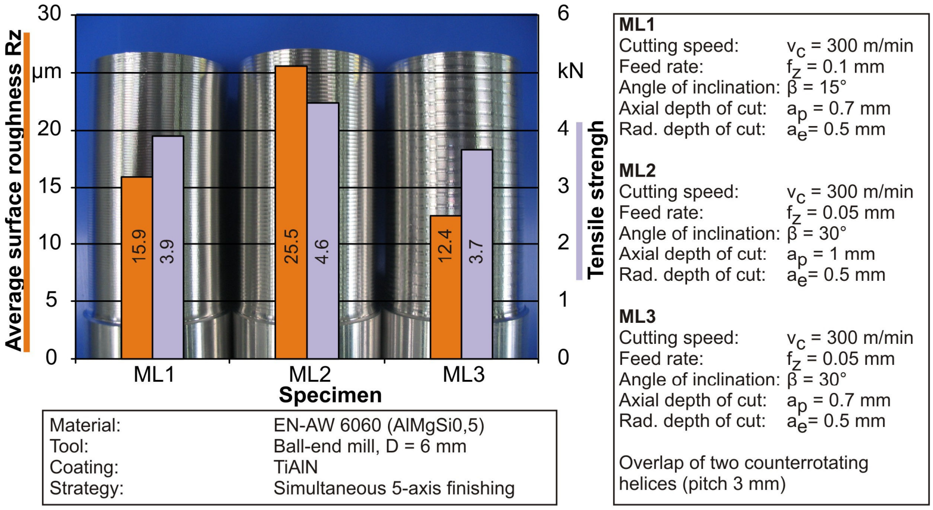

Fig. 10: Tensile strength of surface-structured tubes

It is obvious that the roughness of the surface has an influence on the tensile strength of a hydro-bulged connection between a surface structured tube and a non-structured ring element. The higher the manufactured roughness gets, the stronger becomes the joint. This results in the assumption that a rougher surface is helpful for an increase of the grouting between inner and outer part and therefore supports the resistance against a tensile load. While a non-structured cylindrical joint prepared by drilling with an average surface roughness below Rz = 5 µm has a disrupting force of 2.45 kN (not included in Fig. 10). The use of a tube that has a roughness of Rz = 15.9 µm leads to an increase in strength of 60 %. A tube with a surface roughness of Rz = 25.5 µm needs a disrupting force of 4.6 kN to destroy the joint, which equals with an increase of 100 %. For further optimization of the strength of tubular joints it will be necessary to find out the maximum in the average surface roughness that still allows a grouting. If the depths between the milled lines become too intense, the ratio of contact area to total area would change and only the peaks of the surface would carry the load and would therefore reduce the strength of a connection. But up to a surface roughness of Rz = 25.5 µm, an enhancement of the strength of a joint is verifiable.

Summary

Tool wear and surface quality are affected by the milling strategy used in machining composites. It is possible to determine which part of the tool is stressed by cutting the reinforcing element and in some cases the load can be shifted to the most rigid part of a tool to increase endurance. Surface imperfections occur during peripheral milling operations due to a radial deflection of the tool. Stiffer tools and an adapted setting of the cutting parameters can improve the result. Simultaneous five-axis milling strategies allow a reproducible structuring of the surface of lightweight connecting elements in order to control and increase the tensile strength of joints manufactured by hydrobulging. Further investigations for the preparation of joining areas will be carried out to achieve a dedicate overlay between micro-structures and free-formed macrostructures and to characterize the influence of the tool geometry. The adequate use of tools and strategies for milling lightweight frame components reduces tool costs and to increases economic efficiency of the process as well as the quality of the products.

Acknowledgement. This paper is based on investigations of the Collaborative Research Center SFB/TR10 which is kindly supported by the German Research Foundation (DFG).

References

[1] M. Kleiner, M. Schomäcker, A. Klaus: *Verbundstrangpressen.* In: Aluminium, International Journal for Industry, Research and Application, Volume 80 (2004) 12, pp. 1370-1374

[2] K. Weinert; N. Hammer; J. Rautenberg: *Analysis and Simulation of Cutting Technologies for Lightweight Frame Components.* In: Flexible Manufacture of Lightweight Frame Structures, Kleiner, M. et al. (eds.), TTP Trans Tech Publications Ltd, Switzerland, Vol. 10 of Advanced Materials Research, ISBN 0-87849-403-0, pp. 53-64, 2006

[3] J. Mehnen, J. Rautenberg, M. Hagedorn, J. Schaefer: *Fertigung von Leichtbaustrukturen.* In: Spanende Fertigung, 4. Ausgabe, Hrsg. K. Weinert, Vulkan Verlag, Essen, 2005, ISBN 3-8027-2935-8, pp. 403-410.

[4] K. Weinert, T. Engbert, S. Grünert, and N. Hammer, *Bearbeitungs- und Simulationskonzepte für die Zerspanung dünnwandiger und langfaserverstärkter Leichtmetallrahmenstrukturen*. In: Tagungsband Symposium Strangpressen, 26.- 27. Oktober in Weimar, WILEY-VCH Verlag, 2006, S. 183-196; ISBN 978-3-527-31844-5

[5] K. Weinert, T. Engbert, S. Grünert and N. Hammer: *Machining of Thin-Walled Structures and Continuously Reinforced Light-Metal-Matrix Composites.* Sixth International Conference on High Speed Machining, 21. – 22. March 2007, San Sebastian, Spain, digitally published on CD, 7 pages

[6] W. Przybylski; J. Wojciechowski; M. Marré; M. Kleiner: *Influence of Design Characteristics and Manufacturing Process Parameters on the Strength of Tubular Aluminium Joints Produced by Hydroforming.* In: Archives of Mechanical Technology and Automation, Vol.27 Nr. 1, Polish Academy of Science, 2007, ISSN 1233-9709

[7] M. Marré; W. Homberg; A. Brosius; M. Kleiner: *Umformtechnisches Fügen.* In: Fortschr. Ber. VDI Reihe 2 Nr. 661, VDI-Verlag Düsseldorf, 2007, ISBN 9783183661022

[8] C. E. Becze; P. Clayton; L. Chen; T.I. El-Wardany; M. A. Elbestawi: *High-speed five-axis milling of hardened tool steel.* International Journal of Machine Tools and Manufacture, Vol. 40, Issue 6, May 2000, pp. 869-885

[9] K. Weinert, K.; J. Rautenberg; T. Surmann; J. Mehnen: *Simulation of the Milling Process for Lightweight Aluminum Connectors.* Production Engineering – Research and Development, Annals of the German Academic Society for Production Engineering, XII (2005) 1, ISBN 3-9807670-6-x, pp. 125-128

[10] A. Zabel, M. Stautner: *Einsatzfelder der mehrachsigen Frässimulation.* wt Werkstattstechnik online, 95 (2005) 1-2, pp. 56-61

[11] P. Albrecht: *New Developments in the Theory of the Metal-Cutting Process, Part I, The Ploughing Process in Metal Cutting.* Trans. ASME 82, 1960, pp. 348-358

[12] W. König; F. Klocke: *Fertigungsverfahren 1 - Drehen, Fräsen, Bohren.* VDI Verlag Düsseldorf, 1997

[13] S. Hock: *Hochgeschwindigkeitsfräsen im Werkzeug- und Großformenbau.* Shaker Verlag, Aachen, 1996