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Internal Threads for Thin-Walled Sections

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Connecting aluminium extrusions with other structural elements via screw-coupling is often challenging due to the small wall thickness of the profile sections. The manufacturing technique of flow drilling combined with a subsequent threading operation offers a possibility to cope with this difficulty. With flow-drilled holes, more threads can be integrated into a thin-walled section due to a bushing formed from the displaced material. During the machining operation, high process-related mechanical and thermal loads act on the extrusion, and finally affect the machining results. To evaluate correlations between the process parameters, the geometric form of the machining results and the subsurface microstructure of the material, experimental investigations have been conducted using extruded aluminium wrought alloy components. To evaluate the geometric form and to examine the post-process subsurface microstructure of the material, longitudinal sections of flow-drilled holes are analyzed. To quantify the benefits of flow drilling, threads were produced by forming process, tapping, and thread milling, separately, in ordinary holes and in flow-drilled bushings for tensile tests. The ultimate tensile strength of the threads is used as a quality benchmark for the overall machining results.

Keywords: *Aluminium wrought alloy, flow drilling, thread forming, tapping, thread milling*

1. Introduction

Aluminium extrusion profiles are known as widely used versatile, semi-finished products. In order to achieve load-case adapted structures, for example for lightweight construction, the complexity of the cross-section design has increased over the past few years [1]. With the increasing complexity, the wall thickness of single struts within the profiles decreased, resulting in a higher number of thin-walled sections. To manufacture internal threads into these thin-walled sections, the wall thickness of the profile can be raised locally during the hole-making operation. Through flow drilling, the depth of threads produced subsequently is significantly higher than the original wall thickness, and therefore can be sufficient for screw-coupling. The strength of these threads is strongly depending on the hole-making operation and on the selected thread-machining method. Hence, this research has been carried out to characterize the influence of the peripheral tool-speed on the flow-drilling results and to find the most suitable combination of machining operations for aluminium wrought alloy extrusions.

Besides the changes in the geometric form of the profile, flow drilling also affects the material characteristics of the workpiece [2]. These effects can be made visible by analyzing the subsurface microstructure. The microstructure of the bushing is transformed again during the subsequent threading operation. Thread forming, tapping and thread milling lead to considerably different results due to the individual characteristics of each threading operation. To separate the process-related effects caused by the hole-making operation and the threading processes analyzed, it was necessary to integrate a hole-making operation different from flow drilling. Circular milling, a milling technique with helix-shaped feed motion [3], provides a discontinuous cut and leads to a much lower level of mechanical and thermal loads than flow drilling, hardly affecting the workpiece material. Therefore, changes of the microstructure after circular milling and thread forming, tapping or thread milling can be associated with the particular threading operation.

2. Flow drilling and threading of thin-walled aluminium extrusion

Flow-drilling is a non-chip-producing method of manufacturing bushings in thin-walled structures like sheet metals, tubes or extrusions by using a polygon-shaped pin with conical head made of cemented carbide [4]. The different steps of the flow-drilling process (1-6) as well as the characteristics of the mechanical load profiles acting on the tool and the workpiece are shown in Fig. 1. The pin can be used on drilling machines or machining centres where it is accelerated up to a defined peripheral speed and is fed into the workpiece. The tool is pressed against the workpiece material either with a defined force, or by using a defined feed rate (as applied during investigations, regarding Fig. 1). Friction between the tool and the workpiece generates heat that lowers the yield strength of the workpiece material. By pushing the pin further into the workpiece, material, which is displaced by the tool, yields in the opposite direction of the feed first, and in the direction of the feed later on. The material yielding towards the spindle can either be cut off by countersink cutting edges of the pin (as applied during investigations, regarding Fig. 1), or can be formed to a predefined flange with a shoulder of the pin. The material, displaced in the direction of the feed, is deformed to a stable collar which can be used for threading, in addition to the wall thickness of the profile.

Threading, as a subsequent machining operation after flow-drilling, can be carried out via different machining operations. Threads can either be cut by tapping or thread milling, or formed by thread forming. In contrast to the conventional method of tapping, the axial forces acting on the workpiece are usually smaller than those when using thread milling, which can be advantageous for machining thin-walled profiles. The main advantage of the forming process compared to cutting operations is the resulting grain flow within the workpiece material [5]. The workpiece material is strengthened by work-hardening. The applicability of the thread forming technique is strongly dependant on the mechanical characteristics of the workpiece material. A tensile strength of about $Rm \leq 1200$ N/mm^2 should not be exceeded, and the elongation after fracture should be more than $A \geq 5$-8 % to make cold forming feasible [6]. Since no chips are created, chip packing cannot occur and so the process reliability is increased compared to that of tapping.

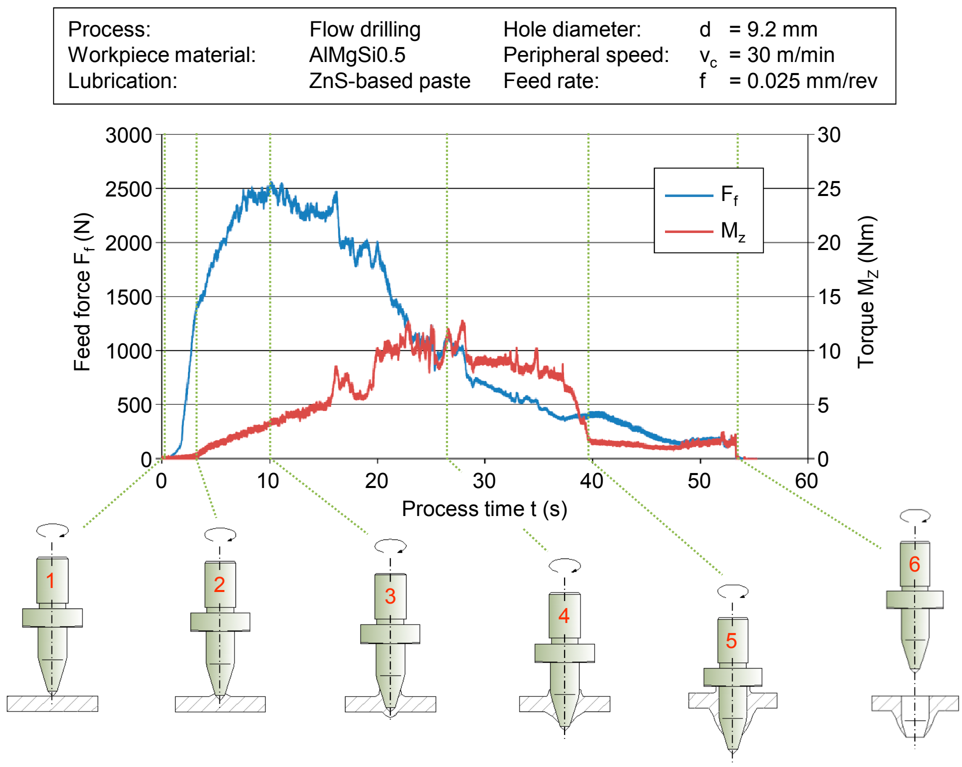

Fig. 1 Flow-drilling process-steps, feed force and torque

3. Experimental Setup

The experiments were conducted on two different three-axis machining centres. While flow-drilling experiments and subsequent threading operations were executed on GROB BZ 600 CNC machining centre, tests combining circular milling as hole-making operation with thread forming, tapping and thread milling were completed using GROB BZ 40 CS CNC machining centre, providing a higher maximum rotational speed, which is advantageous for milling operations. All samples machined are AlMgSi0.5 flat-sectioned extrusions with a wall thickness of t = 5 mm. The samples have been fixed perpendicular to the spindle axis with a special clamping device to minimize workpiece deformation.

A flow-drilling tool with a diameter of d = 9.2 mm has been used for hole making prior to thread forming, a pin with a diameter of d = 8.5 mm was used before tapping and thread milling. All threads produced are M10 regular threads. To restrain adhesion, a ZnS-based solid lubricant has been used on flow-drilling tools and some oil has been added, either applied automatically via MQL during circular milling, or manually by using a brush before threading. The peripheral speed of the flow-drilling process was varied in the experiments since this parameter has the most significant influence on mechanical and thermal loads acting on the tool and on the workpiece. The feed rate was always set to a value of f = 0.025 mm/rev during flow drilling. Tools and parameter settings for circular milling and all threading operations were chosen according to the requirements of each process. A single edge cutter made from cemented carbide, coated with a combination of TiAlN and an amorphous carbon layer was used for circular milling. The tools used for tapping and thread forming are made from high speed steel coated with TiN in case of thread forming, and TiCN in case of tapping. The thread milling tool is made from cemented carbide, coated with TiAlN.

4. Machining Results and Discussions

The machining results are evaluated by the overall geometric form of the bushing created via flow drilling and the subsurface microstructure after flow drilling, thread forming, tapping and thread milling. These evaluations lead to the understanding of what makes some threads stronger against tensile loads than others, which is demonstrated in Fig. 4. In this context, Fig. 2 shows photographs of longitudinal sections of holes and Fig. 3 shows polished and etched section surfaces of threads and differently produced bushings compared to samples with milled holes.

Workpiece material:	AlMgSi0.5	Lubrication circular milling:	MQL	C. milling feed rate:	f = 0.05 mm/rev
Lubrication flow drilling:	ZnS-based paste	Circular milling c. speed:	v_c = 375 m/min	Infeed per helix:	a_p = 3 mm

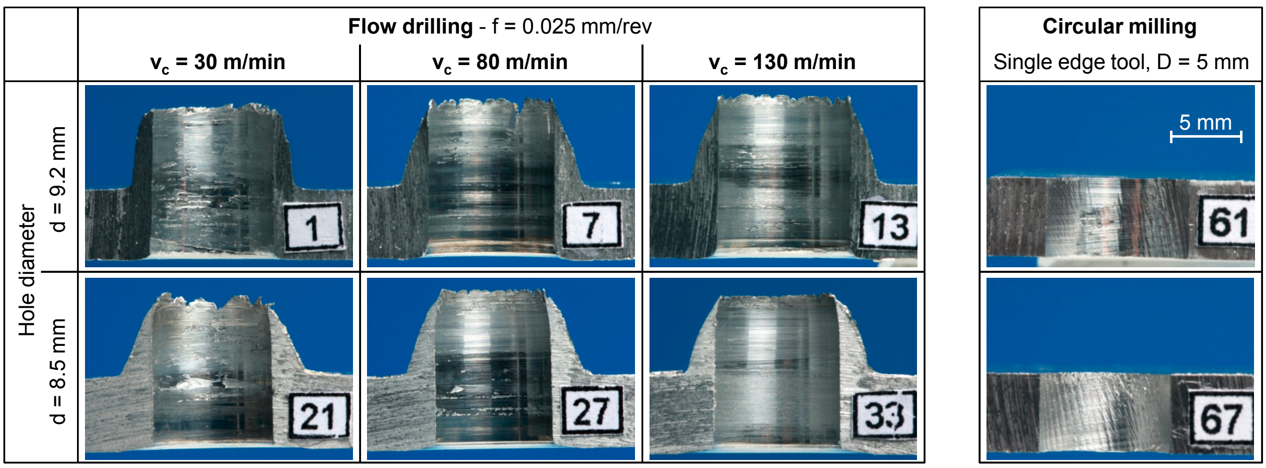

Fig. 2 Longitudinal sections of the flow-drilled holes and the holes produced via circular milling

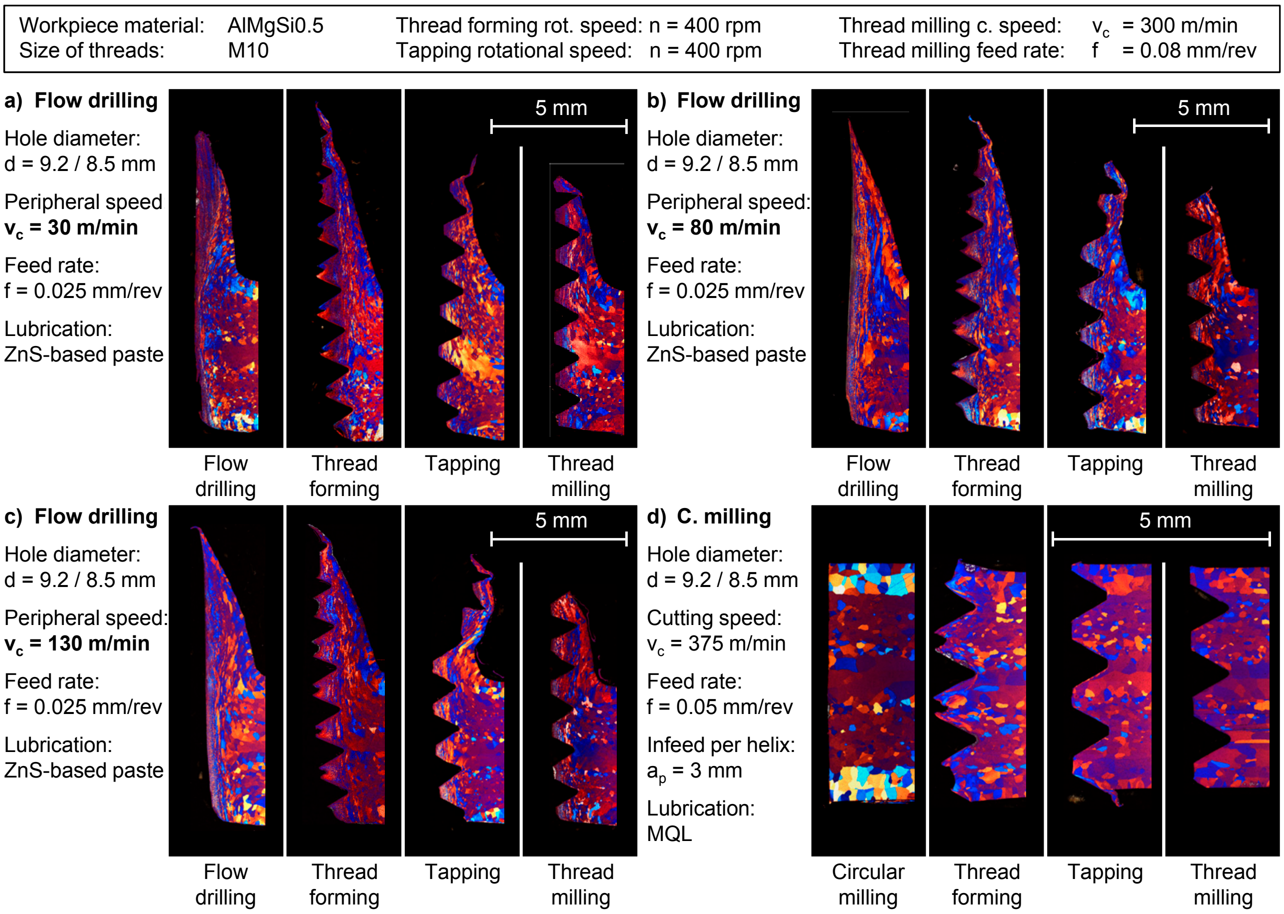

Fig. 3 Subsurface microstructure of flow-drilled and cut holes as well as formed and cut threads

The geometric form of the bushing changes with the peripheral speed of the flow-drilling process. Higher peripheral speed leads to less crack formation at the top of the bushing and more uniform results. The height of the holes lateral area that can be used for threading after hole-making is approximately double the height of the holes produced via circular milling. The surface has a certain roughness due to adhesion effects of the aluminium material at the flow-drilling tool (Fig. 2).

Due to the severe plastic deformation during flow drilling, the subsurface microstructure of the workpiece material is changed as shown in Fig. 3. Some of the presented bushings were deformed during the compression process, which is part of the metallographic preparation. However, the microstructure of the material can be analyzed on the basis of these pictures. The arrangement of grains is determined by the process-related material displacement during flow drilling. Rearrangement and elongation of grains range from the surface up to several millimetres inside the workpiece material. This effect can be seen best in the area of the bushing that protrudes from the profile surface. Directly underneath the surface of the hole, a layer of fine grains can be observed. This layer exists along the whole longitudinal section of the flow-drilled holes. Grain refinement is known as an established method of improving mechanical properties of aluminium alloys [7].

No significant changes in the grain structure and size can be observed when circular milling is used as a hole-making operation. The separate influence of the threading operation can therefore be seen from the pictures in Fig. 3 d). Here, the subsurface microstructure of the holes produced by circular milling and that of the threads produced by forming and cutting after circular milling is shown. Thread forming also leads to changes within the grain structure and size underneath the surface of the threads. Since the threads are created through material displacement, the arrangement of grains again follows the material flow. Similarly to flow drilling, this leads to an elongation of grains along the flanks of the threads. A small amount of the fine grains can also be observed along the thread surface when thread forming is used. Tapping as a cutting operation does not significantly affect the grain structure and arrangement, however some spots of fine-grained structure can also be observed along the flanks of the threads. Stress due to synchronization errors between spindle rotation and feed may be the reason for that. Thread milling after circular milling leads to no observable changes within the subsurface microstructure at all. Another interesting aspect is the analysis of combinations between flow drilling and thread forming, tapping or thread milling. The changes in the microstructure induced by the hole-making operation and the threading process are combined and lead to considerably different results. While the fine-grained layer along the surface, created by the flow-drilling operation, is retained after thread forming and the fine grains are rearranged along the whole new surface, the cutting operations remove parts of the fine-grained layer. The fine-grained flank structure is not destroyed but since the depth of cut exceeds the width of the layer, the roots of the threads mainly consist of bigger grains similar to the core material.

For a quantitative analysis of the machining results, tensile tests were conducted. A threaded stud was screwed into the workpiece at one end and was fixed to a clamping device at its other end. During the test, the workpiece was moved relative to the stud in the direction of the central axis of the hole with a defined speed until fracture while forces were recorded. The maximum tensile force is charted for a sample of five threads in each case. Fig. 4 shows the mean values of these samples as well as the margin of error. The benefit obtained through flow-drilling is obvious and is particularly high for a subsequent thread forming operation. All threads either formed or cut in flow-drilled bushings resist higher maximum tensile loads before failure than threads in holes produced via circular milling. Both, the additional threads within the bushing as well as the fine-grained microstructure affect positively the strength of the threads. Since thread-cutting operations remove the fine-grained layer partly and may also shorten the overall bushing length when the depth of cut exceeds the width of the bushing, they are not as strong as the formed threads, which relocate the fine-grained layer. The combination of flow-drilling and thread forming provides not only the highest transferrable tensile loads but also the smallest margin of error. The influence of the peripheral speed during the flow-drilling process is not clearly indicated. Fig. 4 provides no clear trend concerning the conditions of the flow-drilling operation.

Workpiece material:	AlMgSi0.5	Size of threads:	M10	Tapping rot. speed:	n = 400 rpm
Diameter of holes:	d = 9.2 / 8.5 mm	Lubrication threading:	Oil film	Thread milling c. speed:	v_c = 300 m/min
Lubrication flow drilling:	ZnS-based paste	Thread forming rot. speed:	n = 400 rpm	Thread milling feed rate:	f = 0.08 mm/rev

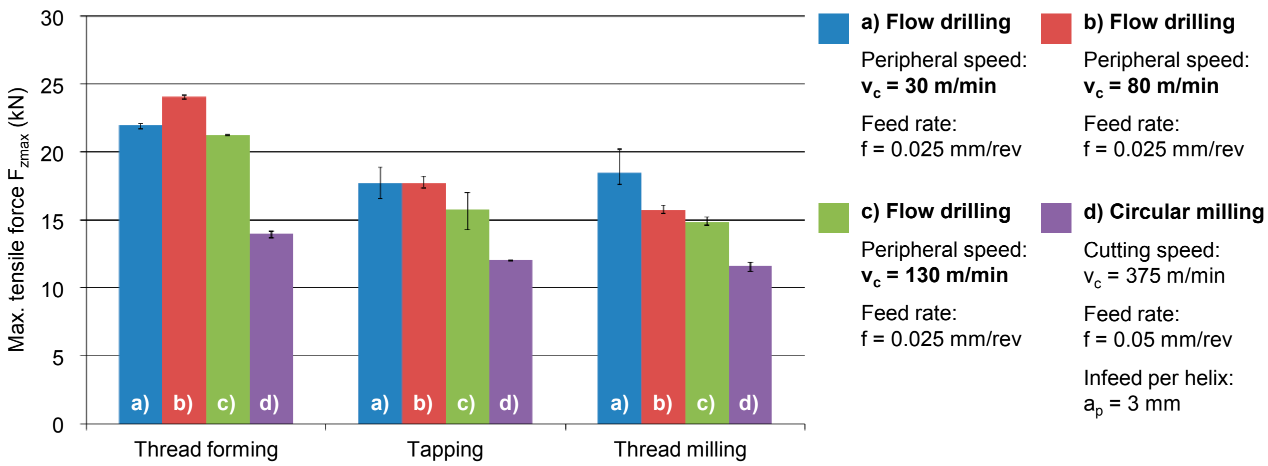

Fig. 4 Maximum tensile forces transferred by threads in aluminium extrusions

5. Conclusions and Outlook

Different ways of producing internal threads, including the hole-making operation, lead to significant differences in the performance of the machining result. When it comes to threading of thin-walled structures, the wall-thickness can be increased locally via flow drilling to provide a sufficient depth of threads without using additional parts. Flow drilling does not only affect the height of the holes lateral area but also the subsurface microstructure. Due to intensive shearing and plastic deformation, grains are rearranged within the workpiece material and grain refinement close to the surface can be observed. Threads formed in the lateral area of flow-drilled bushings have the fine grains all along their surface since the grains resulting from flow drilling are only displaced and not removed. Tapping and thread milling operations partly remove the fine-grained layer. The consequence is a lower ultimate tensile strength of the cut threads in comparison to the formed threads.

Further investigations according to flow drilling and internal thread machining deal with the processing of continuously reinforced aluminium-matrix composites. Aluminium profiles with steel-wire reinforcement and steel-tape reinforcement are the main topics here. Continuously reinforced extrusions provide improved mechanical properties, like increased tensile strength compared to homogeneous profiles, but since the reinforcement can seriously affect the machining operations as well as the machining results, adapted processing strategies are necessary.

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