Deep Hole Drilling of Thermoplastics

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Abstract:

The properties of polymers can be adapted to nearly every functional need, so they are getting more and more attention as construction material. Individual and complex shaped parts demand machining operations to achieve the required workpiece quality. A challenge in machining polymers is their very low melting point, especially when drilling holes with a large length-to-diameter ratio. In the presented investigations, the comprehensive knowledge acquired from the single-lip deep-hole drilling process of metals is transferred to the machining of polymers. The results confirm the expected advantage of the single-lip deep-hole drilling tools concerning the hole quality with respect to the workpiece material.

Keywords:

Deep hole drilling; thermoplastic resin; hole quality

1 INTRODUCTION

Polymers come across everywhere in the everyday life. Well known are consumer goods like bottles, films or toys, for example. But the use is not limited to consumer goods only. During the manufacturing of polymers it is possible to adapt their properties as per the functional requirement. Adding additives or reinforcements like fibers influence the mechanical properties. This makes the material interesting for mechanical elements like gears or conveyor screws.

Polymers are materials of high molar mass because of the large number of macromolecules. These molecules are like fibers and consist of shorter chemical bonded monomers. The polymers are divided into three groups depending on the connection of the macromolecules. Densely meshed polymers are called thermosets; whereas low meshed polymers are called elastomers, better known as rubber. The third group concerns polymers whose fibers are not connected. Theses fibers are mostly looped like cotton wool. Under special conditions they form local crystal-like structures. These types of polymers are called thermoplastics. Typical examples are polyethylene (PE) or polyamide (PA) [2].

The fiber structure of the polymers leads to a different mechanical and physical behavior in comparison to the crystal structure of metals. Depending on the connection of the macromolecules, four different areas or phases and their corresponding temperatures can be identified. They are namely hard and brittle, thermoelastic, thermoplastic and the decomposing or pyrolysis phase. The transition between these phases is fluent [2].

Of utmost importance for machining polymers are the temperature range of the thermoplastic phase and the decomposing temperature. At the decomposing temperature, ranging from 100°C to 400°C depending on the polymer, the macromolecules decompose to their monomers. The thermoplastic temperature is critical for the machining process, because the polymer soften plastically and adheres to the cutting tool or to the machined surface. Both lead to insufficient workpiece quality [1, 3, 6]. But to manufacture mechanical elements of high precision or complex shapes machining is essential.

1.1 Single-lip deep hole drilling

Deep hole drilling is a machining process for holes with a large length-to-diameter ratio ($l/D \geq 5$). Holes that are machined by deep hole drilling processes are characterized by low deviations of the diameter and the roundness, as well as by the high surface quality. Most deep hole drilling tools have an asymmetric tool design, in contrast to twist drills. The radial components of the cutting force and the passive force are non-zero. These forces are carried by the guide pads and applied to the hole wall. This imbalance of forces generates the so-called "inner force flow". Thus, a self guiding effect of the tool within the hole is achieved. The second function of the guide pads is to smooth the hole wall by a forming process and improve the surface quality [4, 5].

The single-lip deep hole drilling can be applied in the range of hole diameters between D = 0.5 mm and D = 40 mm. Characteristics for the operating principle of the single-lip deep hole drilling is the internal cooling lubricant supply through the coolant channel in the core of the tool. The removal of the mixture of chips and cooling lubricant takes place along the external chip flute of the tool (Figure 1). Because of the guide pads the tool needs guidance from the beginning of the process. This can be achieved by two methods. One method is the use of a boring bush as shown in Figure 1. The second method is the use of a pilot hole. This hole is manufactured by a conventional twist drill and the deep hole drilling tool is fed slowly into the hole until the selfguidance of the tool begins [5]. In this investigations the pilot hole was used.

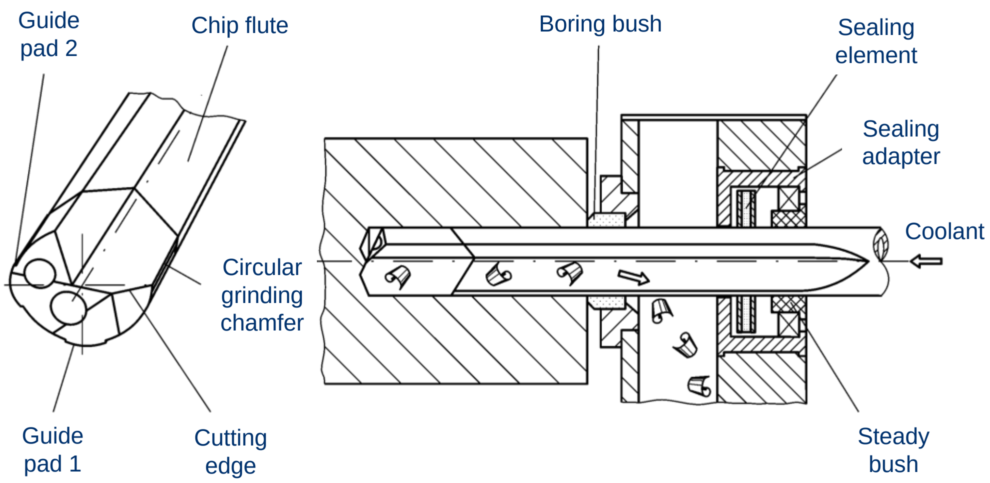

Figure 1: Schematic illustration of the single-lip deep hole drilling [5]

2 EXPERIMENTAL SETUP

All investigations were carried out by using a combined deep hole drilling and machining center, type IXION TLF 1004. With this machine boring depth up to 1,000 mm are possible. It supports both methods for the tool guidance at the beginning of the process. For longer tools a support is also integrated.

Three different types of single-lip drills and a special twist drill for deep hole drilling were analyzed to determine possible influences of the tool shape on the process. A common single-lip drill (SLD 1) with a nose grind of 30° / 20°, a supported tool (SLD 3) with the same nose grind as SLD 1 but with a different guide form and a single-lip drill (SLD 2) with a special nose grind of 85° / 0° were chosen as per the recommendation of the tool manufacturer to drill thermoplastics. All single-lip drills were made of cemented carbide (grade K15) and have a steel (C60) shank. Beside the classic single-lip drills, a specially ground twist drill was also used for deep hole drilling. In case of the twist drill higher feed rates are possible which increase the productivity. The investigated twist drill for deep hole drilling was made of cemented carbide (grade K30). A detailed description of the tools is given in Table 1.

	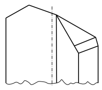	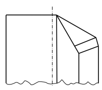	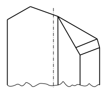	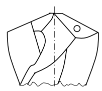
Marking	SLD 1	SLD 2	SLD 3	TD
Diameter	12.4 mm	12.4 mm	12.4 mm	12.4 mm
Clearance angle	14°	14°	14°	9°
Wedge angle	76°	76°	76°	55°
Rake angle	0°	0°	0°	26°
Nose grind / Point angle	30° / 20 °	85° / 0°	30° / 20°	140°
Guide form	C 	G 	G 	-
Carbide grade	K15	K15	K15	K30

Table 1: Details of the investigated deep hole drilling tools

The investigated specimens are made of three different thermoplastics with the dimension 80x80x350 mm. The thermoplastic in detail are polyoximethylen (POM) as representative of polymers with great strength and hardness as well as a high density and amount of crystal-like structures. Polyamid (PA) with nearly the same mechanical properties as POM but with a lower amount of crystal-like structures. It is used for various mechanical elements because of its good frictional properties. The third one is polyethylen (PE) as a polymer which is used in a wide range of applications with outstanding properties concerning elongation at break and Charpy impact strength by low density. An overview about the mechanical properties is shown in Table 2.

	POM-C	**PA 6-G / Oil**	**PE-UHM**
Density ρ in kg/dm³	0.93	1.14	1.41
Yield strength σ_y in MPa	17	80	68
Elongation at break σ_b in %	300	50	35
Tensile modulus E_t in MPa	700	3,000	3,100
Melting temperature T_s in °C	165	220	130 - 135

Table 2: Mechanical and physical properties of the investigated specimen material

3 EXPERIMENTAL RESULTS

3.1 Comparison with a common drilling process

Because of the close cooperation between the industry and the university in this project and the fact that literature about deep hole drilling of thermoplastic is quite hard to find, first of all the feasibility of the deep hole drilling process for thermoplastics was to be analyzed. For this the described deep hole drilling tools were compared with a common drilling process. As expected from the comprehensive knowledge acquired from the single-lip deep-hole drilling process of metals, the hole quality is improved in comparison to the common drilling process (Figure 2).

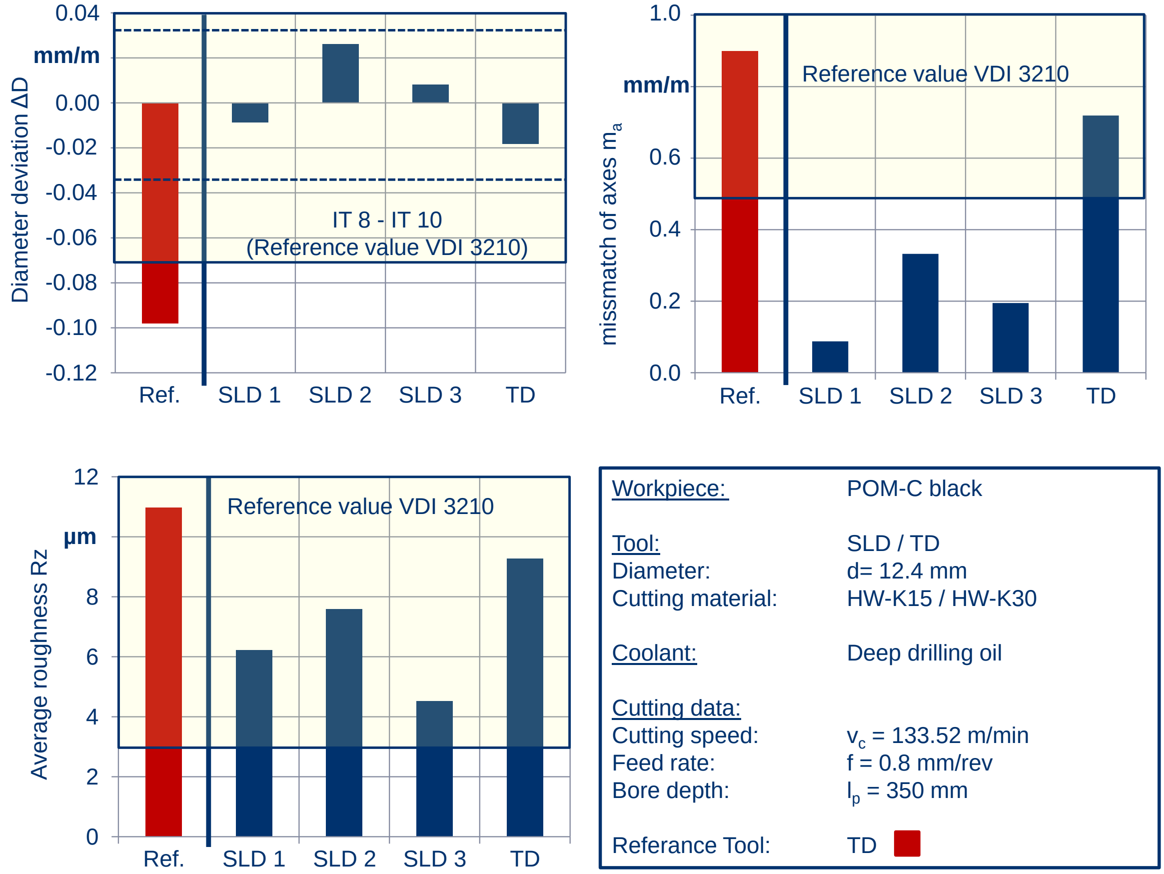

Figure 2: Results of the comparison investigations

Especially the mismatch of axes and the surface quality is improved by the single-lip drills due to the function of the guide pads. Remarkable is the special twist drill. Despite the adaption to the deep hole drilling process the mismatch of axes and the surface roughness reaches nearly the results of the common twist drill. Because of the small cross section of the chip flutes of the twist drill the cross-section of undeformed chip which can pass the flutes is limited. This maximum is reached with a feed rate of f = 0.8 mm/rev. The chip is squeezed out by the pressure of the coolant and rubs on the surface of the chip flute and the bore wall. This friction induces heat into the chip which leads to a temporary adhesion between the chip and the bore wall [1]. Due to the continuous chip transport the adhesion breaks up and the surface becomes rougher.

3.2 Deep hole drilling of POM, PA and PE

After showing that the single-lip deep hole drilling of the thermoplastics has potential advantages, in this section the influence of the workpiece material is analyzed. The results show that the mechanical properties of a polymer cannot be used to predict the workpiece quality. Although the materials POM and PA have nearly the same mechanical and physical properties, their chip formation shows a differing behavior. The PE is exactly the opposite, due to the high elongation at break always a single, long continuous chip is formed, independent of the cutting conditions and the tool shape.

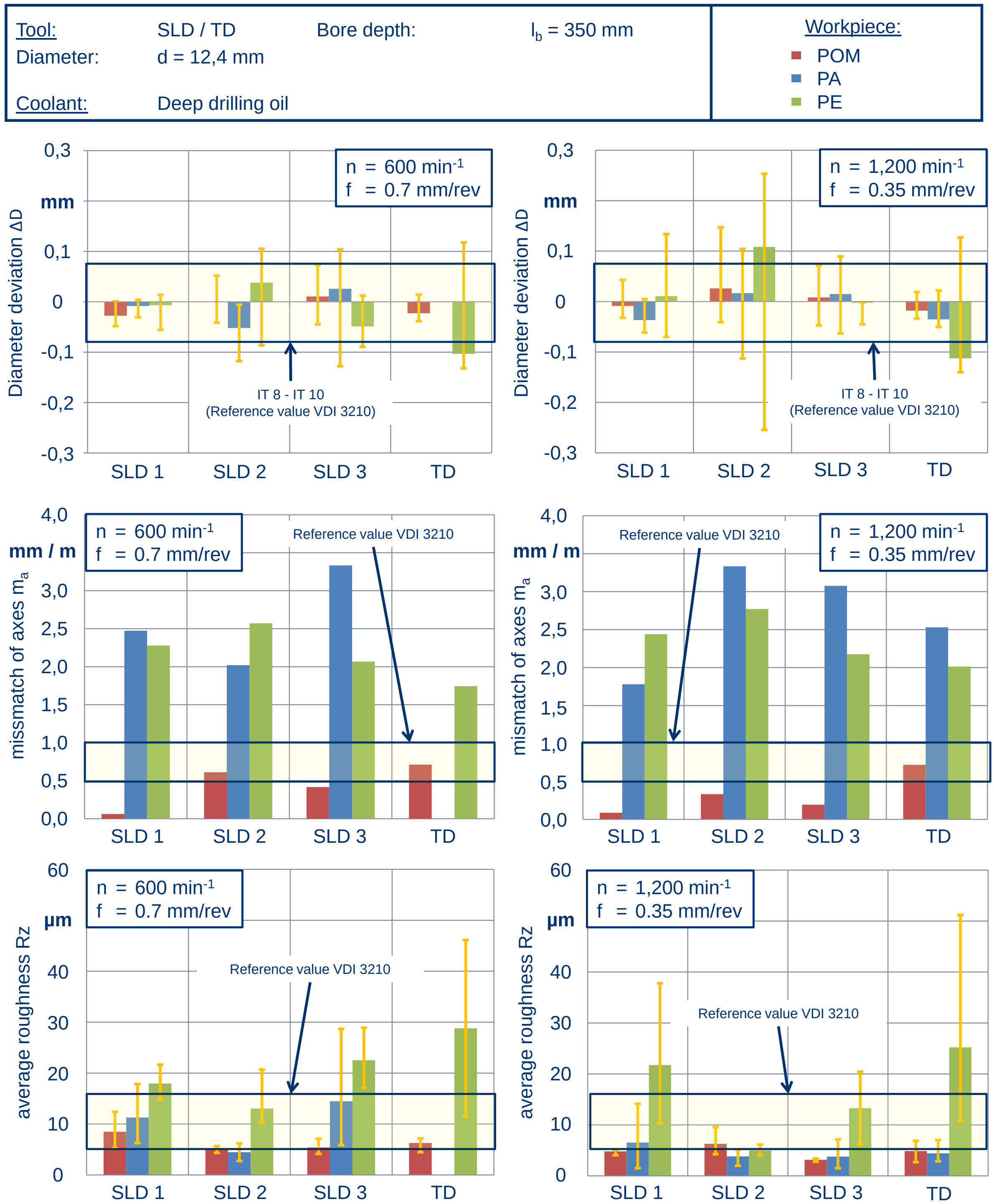

Figure 3: Results of the deep hole drilling of POM, PA and PE

This different behavior can be observed in the measured hole quality shown in Figure 3. The error bars represent the variance in values which were measured and can be used as an indicator for the process stability. Over all with increased spindle speed and reduced feed rate, the process became more instable. The reason is the low softening temperature of the material. With increased spindle speed more heat is generated [1, 6] and with the lower feed rate the contact time between the guide pads and the hole wall inclines. Both generate more heat which softens the material. The effect can be observed in particular with the PE, which has a melting temperature of only 130 °C. Another influence on the material softening has the nose grind of the single-lip drilling tools. This becomes clear with SLD 2 whose nearly right-angled nose grind generate more friction along the cutting edge which increases the heat. Both effects lead to a widened hole diameter.

Referring to the mismatch of axes an influence of the generated heat because of the cutting parameter can only be observed for the PE with its low melting temperature. Rather the chip formation of the polymer got into the point of view. The POM generated small needle like chips during the process, independent of the cutting parameter or the tool shape. These chips can easily be transported along the chip flute out of the hole. The reason is the low value for the elongation at break.

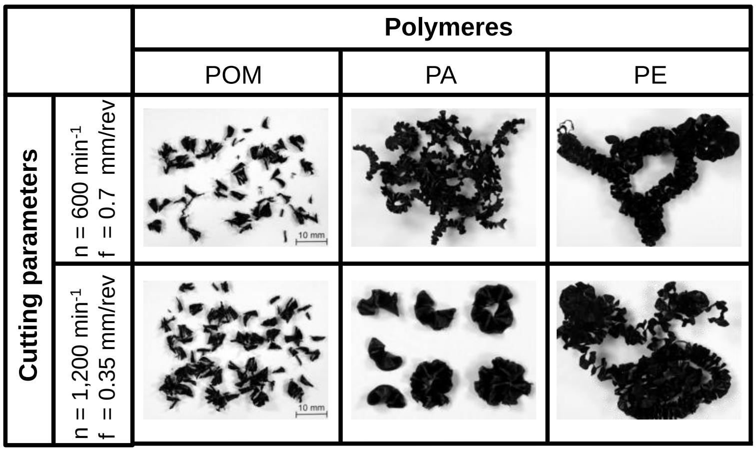

Figure 4: Chip formation at different cutting parameters

In contrast, the PE has a very high value for the elongation at break (> 300 %). Due to this, the long continuous chip is formed, independent of the cutting data. On the one hand this single chip can wrap around the tool shank which leads to a continuous deviation of the tool. While on the other hand, the single chip accumulates at the bearing point of the tool and forms long loops. These loops cause an imbalance of the tool during the rotation which influences the mismatch of axes negatively. An example of these loops is given in Figure 5. Together with the low melting temperature of the PE the high values in mismatch of axes can be explained.

Figure 5: Looped chips at the tool shank

For the PA the influence of the chip formation was also observed for both combinations of cutting parameters. Although at the higher spindle speeds and the lower feed rates smaller chips were generated, but those chips could fill the space between the tool shank and the drilled hole. This caused a deviation of the tool and increases the mismatch of axes.

The depiction of the determined surface roughness shows again a significant influence of the cutting data and the shape of the tool. The main reason for the reduced surface roughness at a spindle speed of n = 1,200 min^{-1} in comparison to the other combinations of cutting parameter is the halved feed rate value. But especially the roughness values of the PE show a significant influence of the tool shape. The tools with the closed guide form G generated more heat due to the higher friction between the guide pad and the hole wall, which occurred from the higher spindle speed, and smoothed the surface. With the open guide form C, in contrast, the coolant were able to flow between the two guide pads, so the surface was cooled down and the surface roughness increased.

The special twist drill for deep hole drilling applications showed no influence of the hole quality due to the cutting data. But some differences between the specimen material can be observed. During the drilling of POM the same small needle like chips were formed just like that by the single-lip tools, and it resulted in a comparable hole quality. But during the drilling of PA and PE two long, single continuous chips were formed, independent of the feed rate or the spindle speed (Figure 5). These chips have to move along the twisted chip flute and cause friction. This friction leads to nearly equal conditions between the two single chips and the bore wall with both cutting parameters sets. That is the reason for why no differences in the acquired values for the hole quality can be observed.

4 SUMMARY AND CONCLUSIONS

This paper presents the results of the investigation of deep hole drilling of thermoplastics with deep hole drilling tools. These investigations were carried out to analyze, if the comprehensive knowledge acquired from the single-lip deep-hole drilling process of metals can be transferred to the machining of polymers. The investigations show that the advantages of the single-lip deep hole drilling of polymers include low surface roughness and low mismatch of axes. The main influencing factor is the low melting temperature of the thermoplastics. This temperature limits the range of the applicable cutting data because of the produced heat during the process. An influence concerning the mechanical properties was not observed because the two thermoplastics with nearly the same mechanical properties behave completely different when machining. Here the chemical structure is the reason.

Examples are the analyzed polyoxymethylen (POM) and the polyamid (PA) thermoplastics. Both have nearly the same mechanical and physical properties. The differences are the amount of crystal-like structures and the resulting fiber orientation. This leads to the observed different behavior with regard to the chip formation and the results of the hole quality, especially the mismatch of axes. When deep hole drilling polyethythlen (PE) the low melting temperature and the low elongation at break are the reasons for the insufficient hole quality depending on the cutting data. By selecting the optimal cutting data and also the tool shape, the hole quality can be improved.

These investigations represent the first analysis of the deep hole drilling of thermoplastics. Further investigations are necessary to improve the hole quality and the process stability. As the results showed, the tool shape and the cutting parameters itself are the starting point for an improvement.

5 ACKNOWLEDGEMENT

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