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Precision machining of glassy carbon

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Abstract
Glassy carbon is a modification of carbon that features a high hardness, corrosion-resistance and is highly stable at elevated temperatures (up to 3000°C). Thus, glassy carbon is ideally suited as a mould material for the replication of high temperature (High-Tg) glasses. In contrast to its excellent mechanical and thermal properties, this material is extremely challenging to machine.
Thus, different mechanical machining methods for machining glassy carbon are evaluated according to their performance and economic viability for making optical moulds. Traditional grinding with fine-grained grinding wheels is taken as reference in a comparison with coarse-grained engineered grinding wheels and micro-laser assisted turning of glassy carbon. Furthermore, subsequent polishing is analysed to assess the ultimately achievable surface quality. As for the micro-lased assisted machined samples, the achievable surface finish is still higher than expected and desired, i.e. beyond the range of an optical surface. The analysis of the engineered grinding wheels, however, show that a better surface form is achieved than for fine-grained wheels, although at a higher surface roughness. Nevertheless, the samples can be machined to an optical surface finish by a subsequent polishing.

Glassy carbon, engineered grinding wheels, micro laser-assisted turning, optical moulds

1 Introduction

Glassy carbon (also called vitreous carbon or glass-like carbon) is a non-graphitising form of carbon that combines properties of glasses and ceramics [1]. It features a high hardness, corrosion-resistance and is highly stable at elevated temperatures (up to 3000°C) [2]. Thus, glassy carbon is ideally suited as a mould material for the replication of high temperature (High-Tg) glasses [3]. In contrast to its excellent mechanical and thermal properties, this material is extremely challenging to machine. Typically, focused ion-beam machining (FIB), dry and wet etching or laser machining are applied [3,4], which is time-consuming and thus not economically viable. Hence, lenses and moulds with optical surface finish are usually manufactured by grinding and polishing [5].
Different methods for machining glassy carbon are evaluated according to their performance and economic viability for making optical moulds. Traditional grinding with fine-grained grinding wheels is taken as reference in a comparison with coarse-grained engineered grinding wheels [6] and micro-laser assisted turning [7] of glassy carbon. The former was chosen to obtain a more deterministic grinding process due to the coarse-grained, single layer, metal bonded wheels, while the idea of the latter is to soften the material in the cutting zone thermally to facilitate the ductile material removal of the glassy carbon and reduce the need for subsequent polishing steps.
The analysis conducted here focuses on the achievable surface roughness, waviness and form as well as on the subsurface damage generated by each process. Thereafter, selected samples are polished in order to assess the ultimate surface quality for the potential use in precision moulding of glass lenses.

2 Precision grinding of glassy carbon

2.1 Setup and design of experiments

In a first experimental analysis, ultra-precision grinding of glassy carbon (Type Sigradur G by HTW GmbH, Ø60 mm, h = 3 mm) was analysed. While it is well known from literature, that mechanical machining of glassy carbon is possible, this experiment aimed to evaluate whether the use of engineered grinding wheels offered a significant benefit in terms of tool wear, surface finish and requirement for post-processing by polishing in comparison to typical fine-grained diamond wheels.

All experiments were carried out as plunge-cut grinding on a Twin Turret Generator (TTG350) by Cranfield Precision (Figure 1).

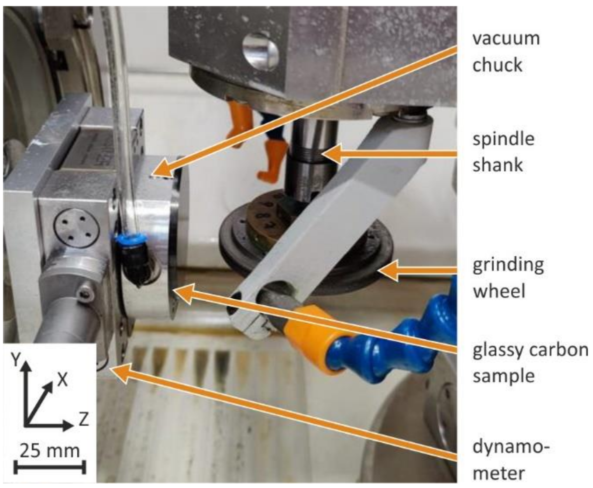

Figure 1. Experimental setup for grinding glassy carbon

A fine-grained diamond wheel (D3, resin bond, Riegger Diamandwerkzeuge GmbH) with a diameter of 100 mm and a width of 3 mm and an engineered diamond wheel (D301, galvanic bond, Stroh Diamantwerkzeuge GmbH) with a diameter of 75 mm and a width of 6 mm, both, were applied.

During the experiments, rectangular slots of 10 mm length and 5 mm width were generated for each grinding wheel and set of process parameters. As for the latter, two cutting speeds were selected for the comparison (v_c = 60 m/s and v_c =120 m/s) while the applied feedrate remained constant (v_f = 10 mm/min). Several rough cutting passes at a_p = 10 µm were performed, until a continuous cut was achieved and then a finish cutting pass at a_p = 5 µm was performed in all cases. The complete set of parameter variations is comprised in Table 1.

Table 1: Process parameters for grinding

	run 1.1	run 1.2	run 2.1	run 2.2
workpiece	Sigradur G, Ø60 mm, h = 3 mm			
diamond wheel	D3, resin-bonded, Ø100 mm, w = 3 mm		D301, galvanic, Ø75 mm, w = 6 mm	
cutting speed v_c	30 m/s	60 m/s	30 m/s	60 m/s
feedrate v_f	120 mm/min			
infeed a_p (rough)	10 µm			
infeed a_p (finish)	5 µm			
ground area	10 x 5 mm²			

After machining, all surfaces were measured using a coherence scanning interferometer (Talysurf CCI HD by Taylor Hobson). Five measurements at 10x magnification, using Filter I (broadband light), were taken from each ground patch for a basic statistical evaluation of the surface finish. All following results are given as mean and standard deviation (±1 σ).

2.2 *Measurement results for grinding*

The achieved RMS surface heights Sq of the grinding experiments are shown in Figure 2.

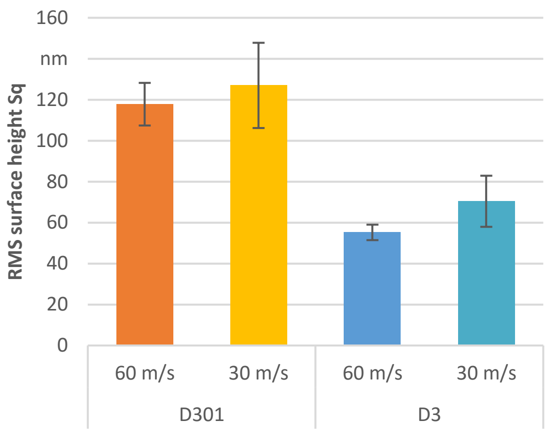

Figure 2. RMS surface height Sq for grinding glassy carbon with coarse- (D301) and fine-grained (D3) grinding wheels at low (30 m/s) and high (60 m/s) cutting speeds

It can be observed that the surface roughness obtained by the fine-grained diamond wheels is about half that of the engineered grinding wheels for similar cutting speeds. Moreover, a higher cutting speed seems to yield a slightly lower surface roughness in general. The lowest surface roughness of Sq = (55±4) nm is obtained by the D3 diamond wheel at vc = 60 m/s while the D301 engineered wheel at 30 m/s cutting speed yields the highest surface roughness with Sq = (127±21) nm.

In contrast to the results for the surface roughness, the engineered grinding wheels achieve a significantly lower waviness than their fine-grained counterparts (Figure 3). The lowest surface waviness is generated by the D301 and measures at Wq = (58±13) nm. In addition, the cutting speed has a significant impact on the waviness, as shown by the tripled mean values and the increased uncertainties. The highest measured waviness was generated by the D3 grinding wheel at 60 m/s cutting speed with a total value of (318±96) nm.

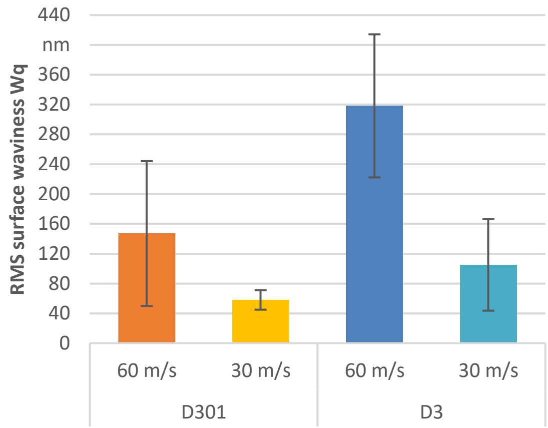

Figure 3. RMS surface waviness Wq for grinding glassy carbon with coarse- (D301) and fine-grained (D3) grinding wheels at low (30 m/s) and high (60 m/s) cutting speeds

3 Laser-assisted machining of glassy carbon

3.1 *Setup and design of experiments*

A second set of experiments was designed for evaluating micro laser-assisted machining (µLAM, see Figure 4) for its capability to generate glassy carbon optics. In contrast to grinding, µLAM offers significantly reduced processing times, as it is based on a typical diamond turning process. It has been previously shown to work for a number of difficult-to-cut material, such as silicon, germanium, tungsten carbide and glass. Typically, spindle speeds of 1000 – 4000 min^{-1} and feed rates of 1 – 3 µm/rev can be applied successfully, making the generation of 50 mm diameter optics a matter of only minutes instead of hours. Moreover, µLAM causes only minimal subsurface damage, thus reducing the need for additional polishing of the optics.

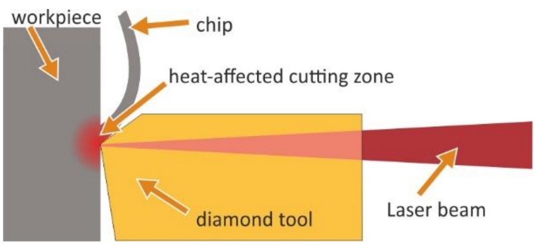

Figure 4. Micro-LAM cutting process

The cutting experiments for glassy carbon were performed on a Moore Nanotech 350 FG using the Optimus T2 toolpost and laser system by Micro-LAM, Inc. The same sample types as for the grinding experiments were selected, but cut across the whole diameter for each set of parameters. As there are no known settings for cutting glassy carbon with µLAM, the laser power, spindle speed and feed were selected based on recommendations for BK7 glass by the manufacturer. On this basis, the tool geometry (rake angle γ and nose radius r_ε), spindle speed n and feed f were varied according to a Plackett-Burman design for 4 runs and 3 two-level factors (Table 2). However, the initial run with the -35°-tool immediately resulted a catastrophic tool wear (Figure 5). Hence, the second run with this tool was abandoned and additional runs using the -65°-tool while varying feed and laser power were added instead.

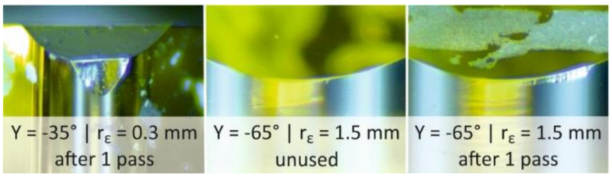

Figure 5. Diamond tool wear for µLAM of glassy carbon

Table 2: Design of experiments for micro laser-assisted machining

	tool geometry γ|rε	spindle speed n	feed f	laser powe r P
run 1	-35°|0.3 mm	1000 min^{-1}	2 µm	8 W
run 2	-65°|1.5 mm	1000 min^{-1}	1 µm	8 W
run 3a*	-35°|0.3 mm	2000 min^{-1}	2 µm	8 W
run 3b	-65°|1.5 mm	2000 min^{-1}	2 µm	8 W
run 4	-65°|1.5 mm	2000 min^{-1}	0.5 µm	8 W
run 5	-65°|1.5 mm	2000 min^{-1}	1 µm	4 W
run 6	-65°|1.5 mm	2000 min^{-1}	1 µm	16 W

**run 3a abandoned due to catastrophic tool wear in run 1*

3.2 Measurement results for µLAM

The results for the achieved surface roughness for micro laser-assisted turning of glassy carbon are shown in Figure 6.

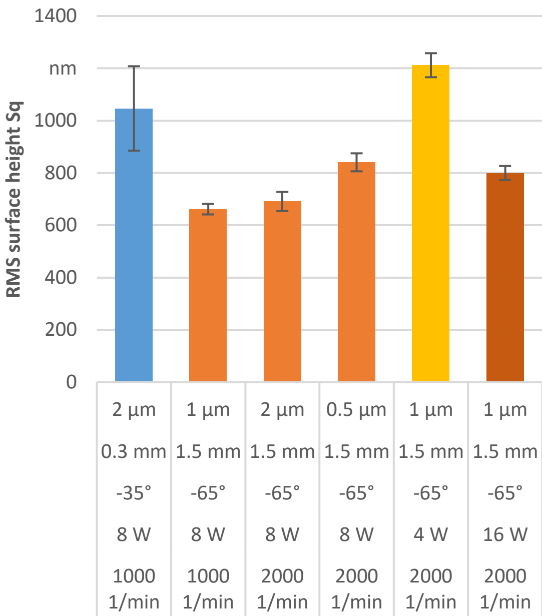

Figure 6. RMS surface height Sq for µLAM of glassy carbon with varied infeed, tool radius/rake angle, laser power and spindle speed

In general, all measurements yield a significantly higher surface roughness than obtained by grinding. The lowest RMS surface height was achieved using the -65°|1.5 mm tool with a medium laser power of 8 W, a slow spindle speed of 1000 min^{-1} and a feed of 1 µm per revolution. However, even this result is at (661±20) nm. Increasing the spindle speed to 2000 min^{-1} also increases the surface height, even if the feed is reduced as a compensation (run 4, Sq = (840±34) nm). Surprisingly, the measured surface height in this case even exceeds the one that is achieved after doubling the feed (run 3, Sq = (840±34) nm). However, the largest impact on surface roughness seems to result from the applied laser power. This can be seen in runs 5 and 6 in which the laser power is first halved, resulting in a ≈400 nm increase in Sq compared to run 4, and then doubled, reducing the surface height to (800±27) nm, i.e. slightly below the level of run 4.

The progression of the surface waviness is similar to that of the surface roughness (Figure 7). However, it is noteworthy that the waviness obtained by µLAM (approx. 20-40 nm) is significantly smaller than that previously achieved by grinding (approx. 60-320 nm).

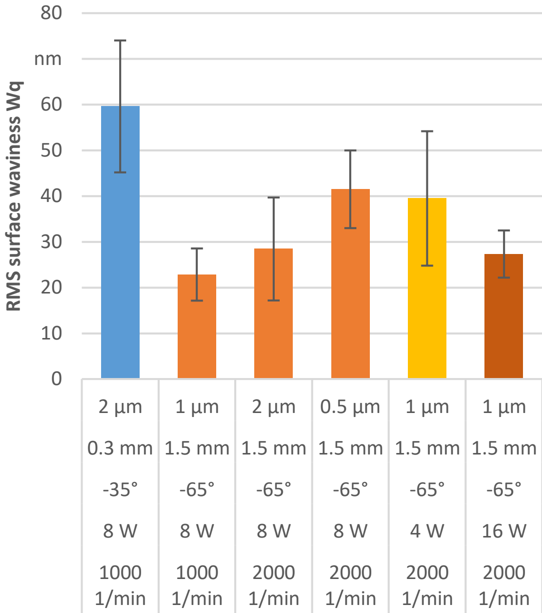

Figure 7. RMS surface waviness Wq for µLAM of glassy carbon with varied infeed, tool radius/rake angle, laser power and spindle speed

4 Polishing of selected glassy carbon specimen

4.1 Experimental setup

Polishing of selected samples was performed on a Precitech Microfinish M300 using a polyurethane polishing pad and a polishing suspension with 1 µm grain size. The setup is depicted in Figure 8.

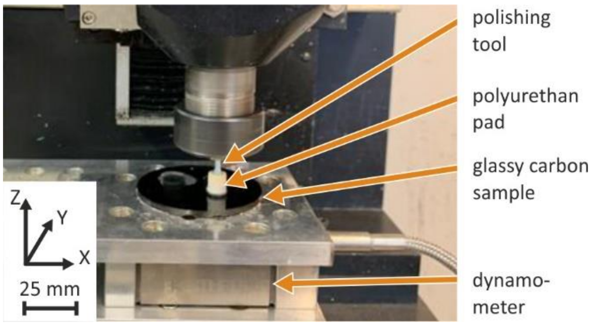

Figure 8. Experimental setup for polishing of glassy carbon

The polishing tool was rotated at 200 min^{-1} and engaged to the sample at a constant polishing pressure of 2 N. Then, three passes along the previously ground patches at a feed velocity of 10 m/min were performed.

After polishing, the samples were measured by the CSI using the same parameters as before at roughly the same positions as for the grinding experiments.

4.2 Measurement results for polishing

The RMS surface height of the polished samples is shown in Figure 9. As expected, the subsequent polishing step reduces the surface roughness into the optical regime, i.e. Sq below 10 nm, in all considered cases. Differences that may be attributed to the previous grinding operation are marginal at best. The surface roughness achieved by the D301 engineered grinding wheel is slightly higher than that of the D3 grinding wheel, regardless of the applied cutting speed. Moreover, the results indicate that the lower cutting speed results in a more stable process, because the standard deviation is significantly smaller in this case ($\sigma_{30m/s}$ = 0.2 nm) than for the higher cutting speed ($\sigma_{60m/s}$ = 2.3 nm).

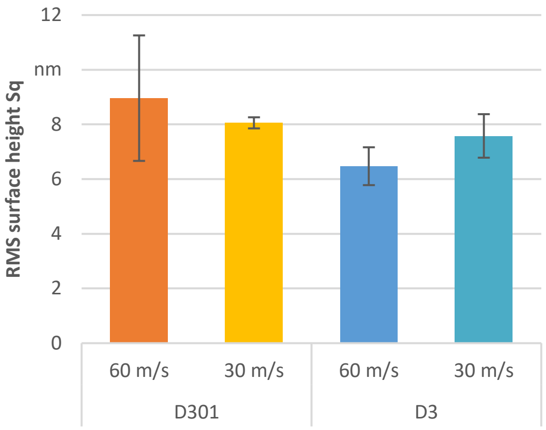

Figure 9. RMS surface height Sq for polishing glassy carbon with samples pre-ground by coarse- (D301) and fine-grained (D3) grinding wheels at low (30 m/s) and high (60 m/s) cutting speeds

This is not the case for polishing the patches pre-ground by the D3 grinding wheel. Here, the mean value for the 30 m/s cutting speed is slightly higher than that for 60 m/s, while the standard deviations are similar.

The measured waviness (Figure 10) is not significantly affected by the subsequent polishing, with the exception of the patches ground at 60 m/s cutting speed. Here, the waviness is increased from (147±97) nm to (220±84) nm for the engineered grinding wheel and is reduced from (318±96) nm to (134±26) nm for the fine-grained grinding wheel. The lowest waviness is achieved for the surface ground by the D301 wheel at 30 m/s, which yields (38±3) nm.

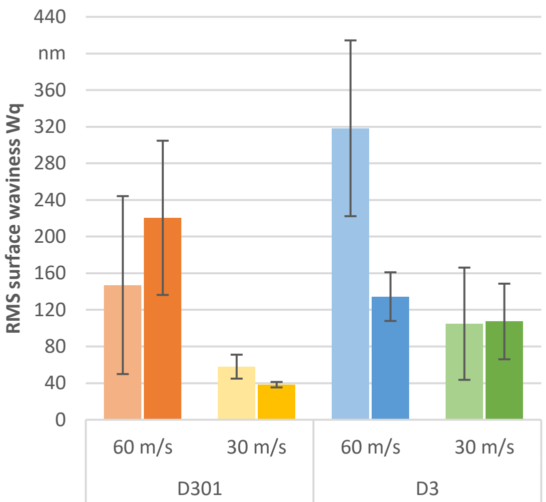

Figure 10. RMS surface waviness Wq for polishing glassy carbon with samples pre-ground by coarse- (D301) and fine-grained (D3) grinding wheels at low (30 m/s) and high (60 m/s) cutting speeds (right bars); left bars show value of pre-ground surface for reference

5 Summary and conclusion

In this study, machining of glassy carbon by different mechanical machining processes has been evaluated. First, grinding with engineered and fine-grained diamond wheels was analysed, which showed that fine-grained diamond wheels yield a lower surface roughness, but a higher waviness in comparison to the engineered grinding wheels. An initial explanation for this could be the use of engineered grinding wheels introduces more variation to the cutting conditions, as these grinding wheels cannot be trued and dressed as good as the conventional grinding wheels, i.e. the higher surface roughness. On the other hand, the more rigid structure of the engineered wheel seems to be favourable in terms of waviness.

As a second set of processes, micro laser-assisted machining was evaluated as a potentially economic machining variant. However, the experiments showed that the achievable surface roughness and waviness is significantly inferior (i.e. higher) to that achieved by the grinding procedure. There is, however, much potential for further analysis, as this was only the first attempt in machining glassy carbon by this process. Moreover, subsequent polishing as well as the impact of the µLAM process on the subsurface damage has yet to be analysed.

Lastly, the ground surfaces were subjected to a subsequent polishing. This reduced the surface roughness well into the optical regime in all cases. The most promising results are obtained with the surfaces pre-ground by D301 engineered grinding wheels at low cutting speed (30 m/s). In this case, the achieved surface roughness and waviness already meet the requirements for optical moulds with Sq = (8±0.2) nm and Wq = (38±3) nm, respectively.

Overall, further analysis, especially of the µLAM process will be conducted to facilitate the use of glassy carbon as a durable and high-quality mould material for glass pressing.

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