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Impact of Cutting Process Parameters on the Mechanical Quality of Processed Glass Edges

Paulina Bukieda, Bernhard Weller

Technische Universität Dresden, Germany, paulina.bukieda@tu-dresden.de

Abstract

The inspection of glass edges is gaining in importance in research, as the strength of a glass edge has been found to be highly dependent on its processing. Glass edges are produced by cutting. Depending on their type, they may be additionally seamed, ground or polished in the grinding process. Cutting and grinding processes create mechanical interference in the brittle material, leaving flaws and cracks in the edge surfaces. The current state of the art presents cutting process parameters which correlate with minor flaws and a high glass edge strength. Research at the Technische Universität Dresden aims to understand the impact of grinding processes and to develop parameters for processing glass edges with a defined and reproducible optical and mechanical quality. To isolate observations of the grinding process from the cutting process, this paper examines the impact of cutting process parameters on further processed glass edges. Several different cutting parameter-sets formed the basis of various test series that were performed on specimens whose glass edges were processed by the same manufacturer. This paper presents an optical and mechanical examination of the specimens. The results show that higher optical and mechanical qualities of the cut edge and arrised edge can be obtained by adjusting the cutting process parameters. It had no major impacts on smooth ground and polished edges.

Keywords

Glass edges, Cutting Parameters, Grinding Process, Edge Strength

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1. Introduction

1.1. Edge strength of glass

Glass is a brittle material. Its strength is highly dependent on the quality of the surface (i.e., its geometry and the number of existing defects) and the tensile stress applied that opens the defects until the glass breaks. Consequently, the structural strength of glass is not a material parameter but is determined by experiment. DIN EN 1288-3 defines the strength determination of flat glass, based on the commonly used characteristic bending strength value of 45 N/mm² for annealed glass. In general, this strength represents the glass pane's resistance to perpendicular loading.

To dimension glass in structural applications or in applications with high thermal stress on the glass edges, the edge strength of the glass has to be determined in a separate procedure. To design glass edges that are subject to tensile stress, current regulations propose reducing the characteristic bending strength generally to 80 % (DIN 18008-2 2019) or by differentiating according to edge type (draft of CEN TS 250/SC11 Structural Glass). Thus, although the need to consider glass edge strength is known, it has not yet been fully investigated. The Kantenfestigkeit *('Edge strength')* working group of the Fachverband Konstruktiver Ingenieurbau e.V. has been investigating the strengths of different edge types since 2009. An extensive study of different edge types from six manufacturers reveals that edge strength is not only dependent on the edge type but, more significantly, on the manufacturing process (Kleuderlein 2014). Strength reduction can be understood as the use of a lower strength level for the sake of safety, but there is also a great potential for producing glass edges with a higher glass strength. To date, the influence of the cutting process on glass edges has been well studied and has resulted in the proposed cutting process parameters and strength estimations (Ensslen 2017; Schneider 2020).

1.2. Objective

This article examines the proposed cutting parameters and the feasibility of their implementation in a cutting process performed by one external manufacturer and machine. First, the influence of cutting wheels was examined, followed by a further examination of their influence on further processing. The variously cut specimens were further seamed ground and polished. The examinations incorporated optical and mechanical testing to determine whether cutting had an impact on the quality of further processed glass edges.

2. Influence of cutting parameters – State of the art

2.1. Cutting Process

Industrial cutting generally consists of two steps. First, the glass is scored with a hard cutting wheel, consisting out of tungsten carbide or diamond. This introduces a stress distribution within the glass which leads to a crack system. Subsequent local bending along the resulting fissure opens up the cracks, causing the glass to break along the score line. The seperating process and the typical remaining system oof cracks depend on the stress distribution created during scoring, which is mainly associated with the characteristics of the cutting wheel (material, size and cutting angle) and the applied cutting force. In addition, the cutting velocity, cutting fluid, and time between scoring and breaking need to be taken into account for a good-quality cut.

The resulting crack system can be described by two measurable parameters: the lateral crack on the surface of the glass pane and the median crack on the surface of the glass edge (cf. Fig. 2, cut edge). The cutting process and crack system are described fully in Müller-Braun et al. (2020) and Müller-Braun (2021).

2.2. Research overview and recommendations

In recent years, the strength of cut glass edges has been frequently investigated by both optical and mechanical means in several research projects (Ensslen 2017; Schneider 2020, Müller-Braun 2021), in which various cutting process parameters were examined along with the crack system. All specimens were cut on the same type of cutting machine (ProLam46 from HEGLA GmbH & Co. KG). The strength was determined by four-point bending tests around the strong axis, with a load introduced at the pane level. Reproducible process parameters were developed for 8 mm glass to obtain a high edge strength (Ensslen 2017). The crack system was analyzed by digital photomicroscopy, confocal microscopy and indentation testing (Müller-Braun et al. 2020). Microscopic analysis and crack measurement revealed important correlations between strength and the visible crack system. Two strength plateaus were found to correspond with the length of the cracks encountered and the cutting force (Schneider 2020). The smaller the lateral and median crack lengths, the higher the resulting edge strength. Fig. 1 shows the general qualitative relationship for 8 mm thick annealed glass.

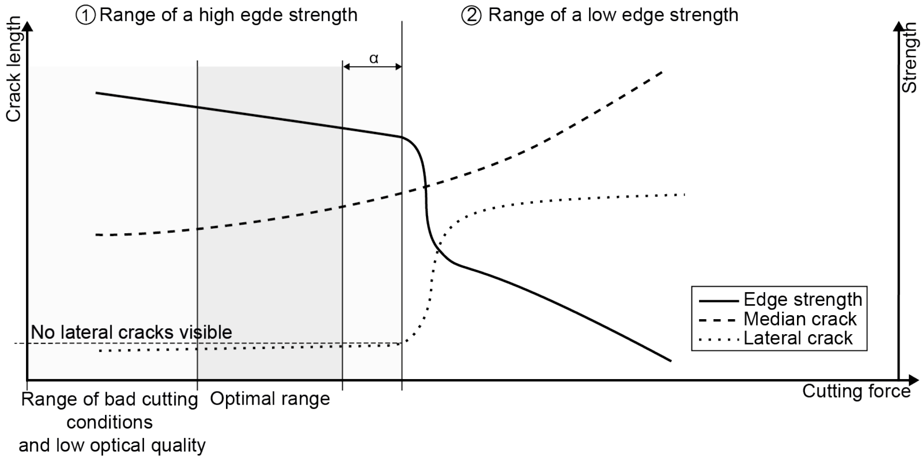

Fig. 1: Qualitative correlation between cutting force, edge strength and crack lengths according to Schneider (2020)

The lengths of the median and lateral cracks increase with higher cutting forces. While the median crack length behaves proportionally to the cutting force, the lateral crack shows a gradual offset at a certain cutting force. The edge strength also displays this offset with this cutting force. Consequently, the size of the lateral crack can be further used to make a non-destructive estimation of the edge strength.

Two ranges are described in which to the process parameters can be set for high cut edge strength. The first is not practicable because both the cutting force and the cracks are too small to ensure good cutting conditions. In addition, the occurrence of unclear fractures and in turn a low optical quality is likely. The second range represents an optimal crack length with a cutting force corresponding to a high edge strength. A further range describes a safety distance α that ensures a high edge strength. Note that the strength tests were performed with 8 mm thick glass and the results are therefore currently only valid for this glass thickness. Since the absolute length of the cracks and the cutting force depend on the glass thickness, cutting wheel, and individual process parameters, they must be determined iteratively for each cutting process (Schneider 2020). The deeper the median crack, the easier the glass can be separated. However, the deeper the cracks, the lower the edge strength. Thus it is important, that the median cracks are as low as possible. Müller-Braun (2021) suggests guideline values of a required median crack length depending on the glass thickness. To open up glasses easily and clean, median crack lengths of 100 µm are needed to open glass of 4 mm, 200 µm for glasses of 6 to 8 mm and 400 µm for glass of 12 mm thickness.

3. Further processing of glass edges

Following the cutting process, the glass edges can be subjected to further processing. Common types of glass edge are classified in the standards DIN 1249-11 (2017) and EN ISO 12543-5 (2011). An overview of the different finishes is presented in Fig. 2. In grinding and polishing processes, multi-grain tools rotate over the glass surface and the brittle material is removed by undefined microscopic fragments.

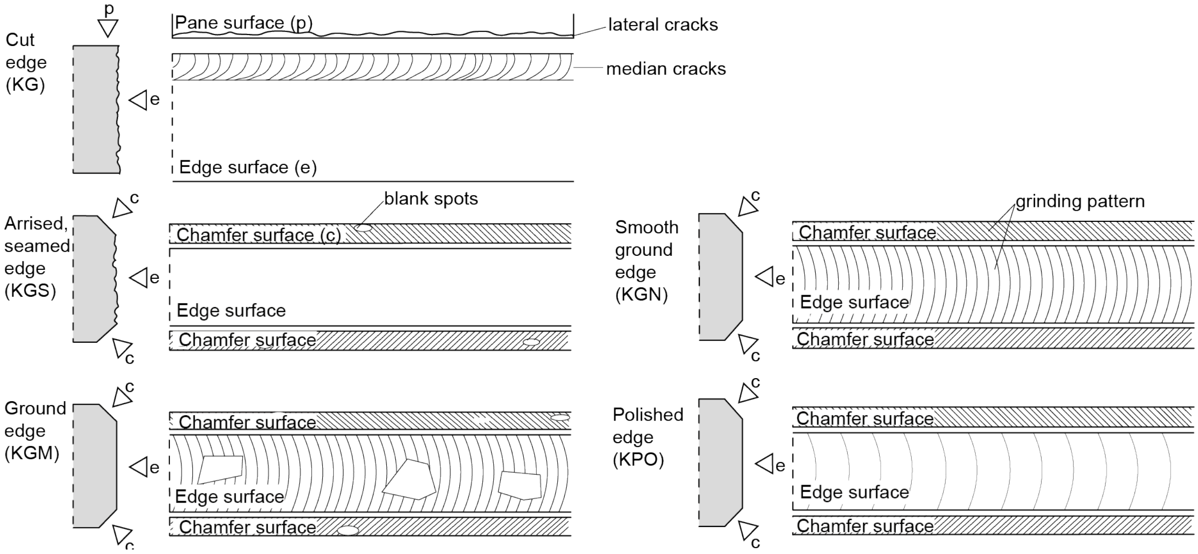

Fig. 2: Glass edge finishing types according to DIN 1249-11 (2017) and EN ISO 12543-5 (2011)

In practice, several grinding machines are suitable for processing glass edges. A cross-belt machine consists of a movable belt coated in an abrasive material. For chamfering or grinding, the glass edge or sharp corners , they are pressed manually against the belt. Horizontal double-sided or vertical single-sided edge grinding machines are also commonly used. With these, the glass edge passes through several fixed stations bearing grinding cup wheels. Straight wheels process the edge surface and inclined wheels create the chamfer. The number of stations varies depending on the grinding machine and the desired edge finish. The size and hardness of the tool grains decrease with each step. To produce uniform and smooth ground surfaces, the material is removed by diamond grinding cup wheels. The subsequent use of smooth polishing cup wheels can produce a high polished edge. A more detailed description of the grinding process using a typical vertical edge-grinding machine is given in Bukieda et al. (2020) and Lohr (2019).

The grinding processes introduce new flaws and cracks into the edge surface. As they influence the bending strength, they need to be taken into consideration when determining the edge strength. Several studies have been conducted to determine the strength of processed glass edges (Lindqvist 2013; Kleuderlein et al. 2014; Vandebroek 2014; Bukieda et al. 2020). An essential finding was that the quality and strength of a processed glass edge is highly dependent on the individual processes performed by the manufacturer. A general statement regarding edge type was not yet possible. The current study therefore examines the process, as conducted by one manufacturer.

4. Examinations

4.1. Specimen

All specimens in this study were made of 8 mm thick annealed glass with dimensions of 1100 mm x 125 mm. The dimensions are based on the test setup for four-point bending and correspond to previous studies. An Optimax 6133 Est Twin Plus cutting machine made by HEGLA GmbH & Co. KG was used. The manufacturer uses a carbide cutting wheel (4.1 mm x 1.42 mm x 1.08 mm) as standard with an angle of 158° for cutting 8 mm glass. Scoring is applied at a cutting pressure of 2.2 bar and a velocity of 100 m/min and the cutting fluid MKU Dionol®GT 644-1. Reference samples were produced with standard cutting process parameters. To improve the cutting process, a different type of cutting wheel with a surface microstructure was recommended by the industry (Bohle AG). Fig. 3 shows the standard cutting wheel used (Fig. 3, left) and the microstructured Cutmaster®Platinum wheel (Fig.3, right) in detail along with the fissures they produced on the glass surface.

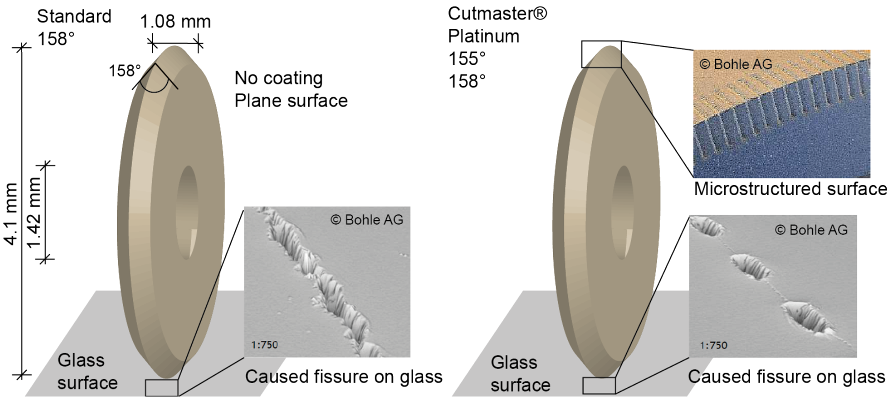

Fig. 3: The standard and microstructured cutting wheels used and the microscopic fissures produced on the glass surface

Due to the microstructure, the cutting wheel results in partial but very sharp intervention in the glass, which changes the stress distribution on its surface. This results in a smaller indentation and causes a smaller crack system. In the first part, the effect of the Cutmaster®Platinum cutting wheel was examined at angles of both 155° and 158°. Rather than adjusting the cutting force, most cutting machines are controlled by the cutting pressure. The relation between cutting pressure and cutting force varies for each cutting machine. Although cutting force would be preferable in the interest of comparability within individual machines, the equivalent cutting force could not be determined in this study. To determine the cutting pressure, the manufacturer gradually increased the cutting pressure (starting from 1.6 bar) until a good break was achieved. The resulting cutting pressure was 2.2 bar for all specimens. Table 1 presents the parameters of the cutting test series. The test series 1 and 2 were subsequently repeated to ascertain their reproducibility. The time of production is marked with I and II.

Table 1: Test series - cut edge

Test series	Time	Edge type	Cutting parameters			Quantity
			Cutting wheel type	Cutting pressure [bar]	Velocity [m/min]	
1	I	KG	158° Standard	2.2	100	10
2	I	KG	158° Platinum	2.2	100	5
3	I	KG	155° Platinum	2.2	100	10
4	II	KG	158° Standard	2.2	100	11
5	II	KG	158° Platinum	2.2	100	9

The next part of the investigation examined whether the cutting process influenced the optical and mechanical quality of the further processed edges. For this purpose, the cutting parameters from test series 1 and 3 were used to cut the specimens prior to further processing into arrised, smooth ground and polished edges at the second time of production. The processed specimens were produced with a vertical, single-sided, edge grinding machine. As depictured in Fig. 4, the glass is guided through the process by a robotic arm. This reduces manual turning of the glass, and any applied coatings are not damaged. The edge grinding machine consists of a total of nine stations.

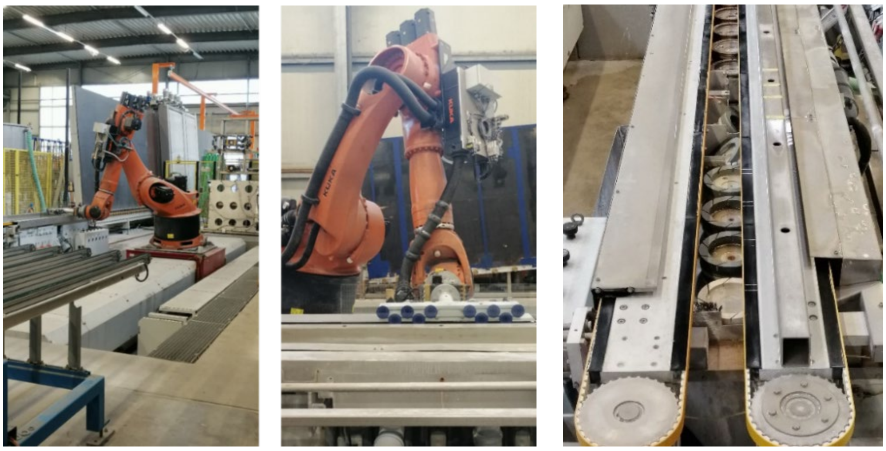

Fig. 4: Single-sided edge grinding machine process with robotic arm

Table 2 presents the processed edge test series. Test series 6 and 7 were only chamfered with the inclined grinding cup wheels, i.e., the surface of the edge was not processed. The smooth ground series (test series 8 and 9) were produced by moving four grinding cup wheels over the edge and performing further chamfering. The incremental grit size is shown in Table 3. The polished edge (test series 10 and 11) was additionally machined with a polishing cup wheel.

Table 2: Test series - processed edge

Test series	Cutting wheel type	Edge type	Grinding parameters			Quantity
			Cup wheel data grind size	Grinding depth [mm]	Velocity [m/min]	
6	158°S	KGS	180 (only chamfered)	hor. (45°): 1	1.8	10
7	158° P	KGS	180 (only chamfered)	hor. (45°): 1	1.8	10
8	158°S	KGN	213/ 181/ 126/ 107	vert. (90°): 2	1.5	10
9	158° P	KGN	213/ 181/ 126/ 107	vert. (90°): 2	1.5	10
10	158°S	KPO	213/ 181/ 126/ 107/ *	vert. (90°): 2	1.5	10
11	158° P	KPO	213/ 181/ 126/ 107/ *	vert. (90°): 2	1.5	10

* no data available on the grind size of the polishing cup wheel

4.2. Testing procedure

The testing procedure and setup used at the Technische Universität Dresden are presented in Bukieda et al. (2020). Each specimen was subjected to a four-point bending test including localization of the fracture origin. These tests were performed about the strong axis as referred to in DIN EN 1288-3 (2000). The tested edge is oriented downwards, where the tensile bending stresses occur. The measured breaking load was used to determine the breaking stresses. Before the bending test, the edge, chamfer and transition surfaces were imaged microscopically using a Zeiss Smartzoom 5 digital light microscope at a magnification of 70x for the edge surface and 100x for the chamfer and the pane surfaces. Three specimens from each test series were imaged over a length of about 200 mm, which corresponds to the subsequent loading area in the four-point bending test. In addition, images of approximately 20 mm in length were taken of the surfaces of every specimen to compare the optical characteristics of each test series. For the cut edge specimens, the maximum length of the lateral and median cracks was measured using the associated software. The measurement was taken at a random location. Fig. 5 shows a pictogram with definitions of the typical surfaces and the microscope used for recording the chamfer surfaces of the specimens.

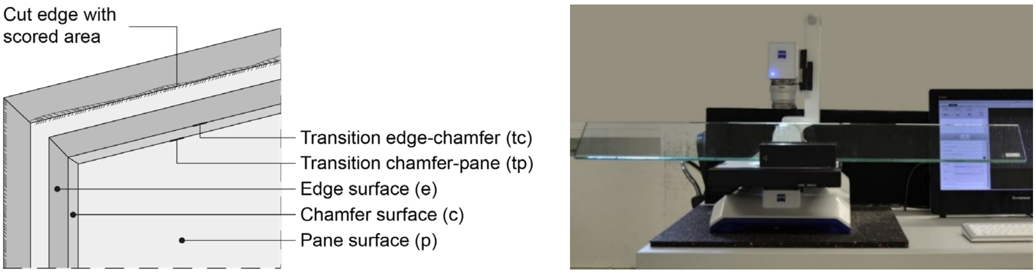

Fig. 5: Definitions of surfaces of cut and processed edges (left) and Zeiss Smartzoom 5 digital light microscope (right)

5. Results and discussion

5.1. Optical results of the test series – cut edge

Fig. 6 shows typical images of the edges and the two pane surfaces from the cut edge test series 1, 2 and 3. The lateral cracks appearing on the upper pane surface and the median cracks on the edge surface show the effect of the different cutting wheels. The mean values of the measured crack lengths are given beneath the pictures. Test series 1 (KG 158 S I) shows the largest cracks, with clearly visible median cracks (mean 740 µm) and lateral cracks (mean 700 µm). The Cutmaster®Platinum cutting wheel resulted in smaller cracks. In particular, the lateral cracks occurring with this type of cutting wheel were smaller. The KG 155 P test series 2 showed median cracks with a mean length of about 575 µm and lateral cracks with a length of about 300 µm. With the Cutmaster®Platinum cutting wheel with 158° (test series 3), the crack size was even smaller, with 454 µm for the median cracks and 260 µm for the lateral cracks. The microstructured cutting wheels thus show the expected reduction of the crack system. The median cracks of the test series could be reduced to about 61 % and the lateral cracks to about 37 %. Thus, with constant cutting process parameters the predicted lower stress distribution was reached.

The manufacturer reported that the breaking force applied to open the cut was significantly higher with the microstructured wheels. The KG 158 P I test series 2 showed many unclean breaks with uneven cuts, which is why the number of specimens is low. Cutting pliers were used to open test series 5 (KG 158 P II) which enabled a clear separation of the specimens. The more complex manufacturing process must be taken into account to produce higher optical and mechanical edge qualities.

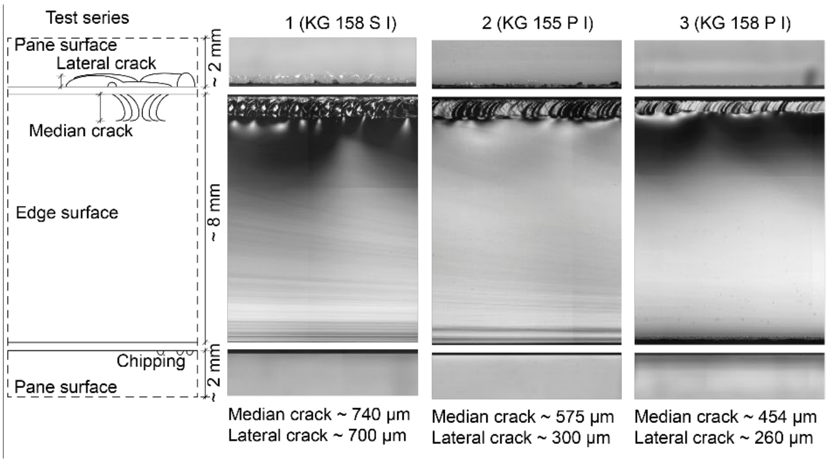

Fig. 6: Microscopic images of the cut edge test series with different cutting wheels

5.2. Optical results of the test series – processed edge

Fig.7 shows the microscopic images of the cut edges and the further processed edge surfaces. For an arrised edge, the inclined grinding cups remove the sharp edges and the crack system from the cutting process. The images of the chamfer surface are inserted between the pane and the edge surface.

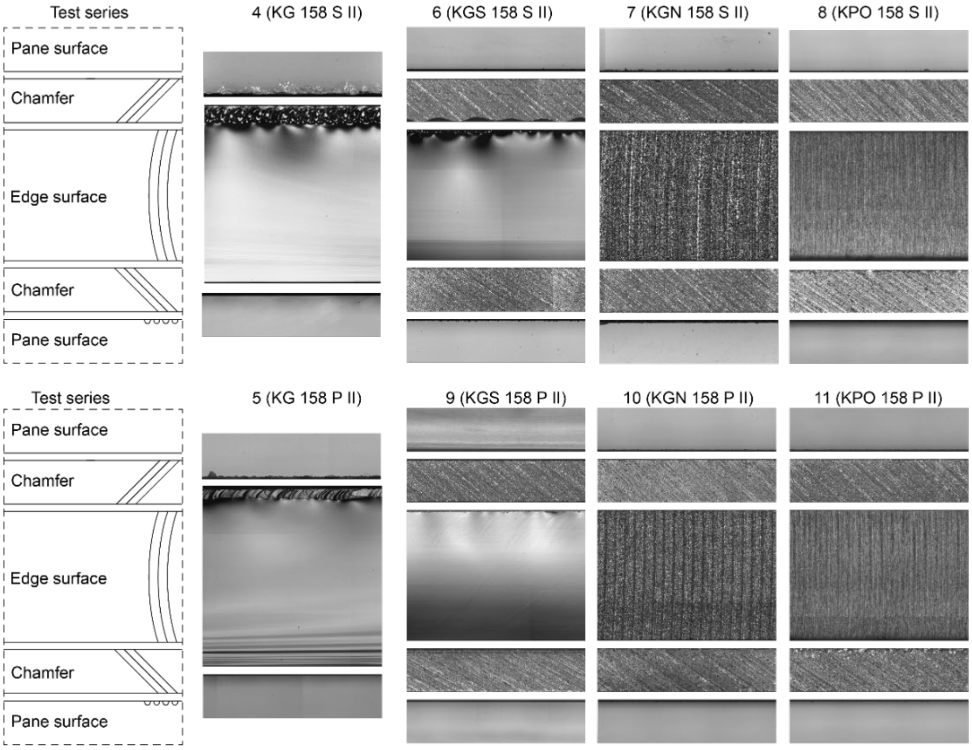

Fig. 7: Microscopic images of the cut edge and further processed test series, cut by different cutting wheels

Grinding and polishing of the edge constitutes a material interference that creates a roughness on the surface. A grinding pattern is visible at the microscopic level. The processes remove unevenness and result in homogenous and uniform glass surfaces. Comparison of the smooth ground and polished surfaces reveal no visible differences on a microscopic level. Macroscopically, a distinct difference is visible between the smooth ground edge and the polished edge surfaces.

Comparing the arrised edges, the influence of the different cutting wheels becomes visible. While the median cracks are clearly visible in the transition area between the edge chamfer and the upper surface on KGS 158 S II, they are almost absent on the KGS 158 P II series. Since the microstructured cutting wheel causes smaller median cracks, these can be removed by seaming the sharp edge.

With smooth ground and polished edges, no differences between the different cutting wheels can be seen. This leads to the assumption, that a grinding depth of 2 mm is optically fully removing the system of cracks from the cutting process. Bit unclear and uneven cut specimen are complicating the grinding process whenever the amount of material removal is differing a lot.

5.3. Mechanical results

The breaking stresses determined for each test series are shown in Fig. 8 in the form of boxplots. The thick lines in the box indicate the median, while the median value and specimen number (n) are given next to the boxes. For the evaluation, only fractures with a break from the edge (including chamfer surfaces) in the loaded area were considered. Generally, the bending tensile stresses of each test series show a large scatter, which is typical for glass material. It was not possible to perform a more detailed statistical evaluation including determination of characteristic strength because the number of valid specimens in each series was less than ten. The results should be regarded as depicting a tendency only and need to be confirmed in further examinations.

Fig. 8: Boxplots of the breaking stresses of the examined test series showing the number of evaluated specimens

The test series are sorted by edge finish. The cut edge test series 1 (KGS 158 S I) and 2 (KG 158 S II) show very similar ranges with median breaking stresses of 39.08 N/mm² and 39.65 N/mm², respectively. The similar test series 1 and 4 (KG 158 P) as well as 2 and 5 (KG 158P II) show similar values, signaling good reproducibility of the cutting process. Furthermore, an increase in median breaking stress to 65.96 N/mm² can be observed when using a microstructured cutting wheel instead of a standard wheel (test series 1 and 4). Comparing the optical results and breaking stresses according to Fig. 1, it can be expected that the determined breaking stresses in this study are in the lower range for the standard cutting wheel (test series 1 and 4) and in the upper range for the microstructured wheel (test series 2, 3 and 5), even though the cutting pressure was the same.

When chamfering the edge, the median breaking stress value increases to 96.02 N/mm². The KGS 158S II test series (6) shows lower values than the KGS 158P II series (7). A look at the optical results shows that this could be due to the quality of the edge surface, since the optical results show that the cutting crack system could not be completely removed in the KGS 158 S II series (cf. Fig.7). Analysis of the fracture shows that the origin is mainly at the scored edge or in the transition area between edge surface and chamfer (cf. Fig.5). The removing of the crack system from the cutting process is increasing the bending stresses significantly.

Regarding the breaking stresses of the smooth ground (KGN) and polished (KPO) test series, the median value is lower, with the values ranging between 45.41 N/mm² and 51.6 N/mm². Since the variation in values is quite small, it is suspected that a grinding depth of 2 mm is sufficient to remove the crack system of cu edges. Moreover, the cause of fracture was found mainly at the edge surface, which also means that the fracture defect was caused by processing the edge. Thus for further examinations, the grinding process can be observed isolated from the cutting process when a defined grinding depth is assured.

6. Conclusions and outlook

6.1. Resulting crack system

To increase the strength of cut edges, the crack system after cutting must be as small as possible. In this study, microstructured cutting wheels were used to create a different stress distribution with minimal lateral cracks. The maximum length of the lateral cracks was measured. Although a more accurate measurement of the shape as well as averaging were performed in the literature (Müller-Braun et al. 2020), the method used in our study enabled sufficient first evaluation of the crack as a pre-evaluation of the individual cutting process. It is possible for the manufacturer to improve the edge strength by making process adjustments to modify the interaction between the cutting wheel and cutting force or pressure. The goal of producing a small crack system can be achieved by modifying the appropriate parameter.

6.2. Impact on arrised edges

The practical purpose of edge chamfering is both to reduce the risk of injury and to prepare a component for further thermal processing by removing the cracks before conducting the cutting process. The removal of median and lateral cracks also tends to increase breaking stresses. The arrised edges examined in this study had the highest breaking stresses, making them very interesting for structured applications. The cutting process was also found to have an impact. Median cracks in the range around 700 µm caused by the standard cutting wheel used in this study could not be removed by edge seaming. The effect is visible in the microscopic and fracture analyses, as the mean breaking stresses are slightly below the arrised edges produced with the microstructured wheel. Here, the smaller crack system was almost completely removed by seaming, resulting in the highest values.

6.3. Impact on smooth ground and polished edges

No influence of the cutting process could be determined for the smooth ground and polished edges. It is assumed that the material interference from the grinding process and the grinding depth of 2 mm can be considered separately. In this study, the standard parameters tend to produce lower breaking stress values. Other studies show that a well-adjusted grinding and polishing process can lead to higher breaking stresses (Bukieda 2020; Kleuderlein 2014). To get a better understanding of the grinding and polishing process and define essential parameters for a higher optical and mechanical edge quality, smooth ground and polished edges are further examined at the Technische Universität Dresden.

6.4. Outlook

A test series of ‘arrised edges’ (not presented in this study) was produced with unintentional processing of the edge surface equivalent to ground edge finishing. The evaluation of the breaking tests performed showed that the breaking stresses were lower than arrised edges with no processing of the edge surface. The fracture origins occurred mainly in the edge areas at the ground spots. In practice, compared to the arrised edge, the ground edge is treated as higher edge quality because a better size accuracy. In order to ensure the high strength potential of arrised edges, further examinations need to be performed along with a clear definition of their production.

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