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The Effect of Edge Processing in Thin Glass for Cold Bending Applications

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Cold bent glass is nowadays of primary importance both for industrial and civil applications. In fact, thin glass with a maximum thickness of 1.5 mm is often part of a wide range of technological devices and architectural surfaces (e.g. touchscreens, displays, mirrors, optical instruments, claddings and building interiors). The manufacturing process of cold bent glass is generally considered faster and less demanding in terms of necessary equipment with respect to hot bending or casting techniques. On the contrary, both the design of the manufacturing procedure and of the products are still a challenge and they are mainly based on a trial and error approach. Generalized defects and imperfections are always present on the surface of the raw glass product, while another significant source of flaws is usually localized at the edges and it is associated with the specific cutting technique and edges processing. The aim of this work is to experimental investigate the influence of the edge processing on the failure strength of 1.5 mm glass plates by means of four point bending tests. Two edge conditions are taken into account: manual diamond cut and ground by hand-operated tool which introduces randomly diffused small-size flaws. Test results are then statistically assessed and compared with the stresses that arise during the cold bending process due to the imposed curvature. In the end, grinding somehow increases the level of damage as it increases the number of flaws. On the contrary, the improved uniformity of the damage leads to less scattered resistance values. These allows to achieve smaller curvature radii or, for a given design radius, it reduces accidental failures during the cold bending process.

Keywords: Thin glass, Edge processing, Cold bending, Strength

1. Introduction

The aim of this study is to investigate the effect of the edge processing in thin glass subjected to cold bending. The use of thin glass with a maximum thickness of 1.5 mm is constantly increasing in a wide range of fields spreading from civil applications (e.g. cladding surfaces and furniture) up to consumer electronics (e.g. touchscreens and displays) and advanced optics (e.g. mirror of big array telescopes). Using basic soda-lime silicate glass for such applications is very attractive because it allows a significant reduction of the costs with respect to special purpose glass. Nevertheless, the manufacturing process of cold bent glass is generally considered faster and less demanding in terms of necessary equipment with respect to hot bending or casting techniques. However, both the design of the manufacturing procedure and of the products are still a challenge and they are mainly based on a trial and error approach.

In this context, the bending strength of glass and its associated probability of failure, as well as the bending stresses that arise because of the cold bending play an important role. For the typical range of sizes of the above-mentioned products, the strength of glass depends on flaws and the well-known fracture mechanics theory applies (Griffith 1920). Basic assumptions are that a random population of defects is always present at raw glass surface and only the critical one is involved in the failure initiation (weakest link theory). In addition, considering the glass failure criterion of the maximum tensile stress, only Mode I crack opening are taken into account (Haldimann 2006). From a quantitative point of view the relationship between the flaw size and the failure stress is expressed in Eq. 1 by means of the critical stress intensity factor, K_{Ic} as follows (Irwin 1957):

$$K_{Ic} = Y\sigma_f\sqrt{\pi a} \tag{1}$$

where, σ_f is the failure stress, a is the depth of the critical flaw and Y is a geometry factor. Values of K_{Ic} (also known as fracture toughness) are available in literature. For soda-lime glass it is generally assumed 0.75 MPa $m^{1/2}$.

Another significant source of flaws is usually localized at the edges and it is associated with the edge conditions (Vandebroek et al. 2011). The characterization of machining-induced flaws has already been the subject of several researches (Vandebroek et al. 2012; Lindqvist and Louter 2014). It is well known that the edge flaw population, both in terms of size and form, have a strong influence on the failure strength and so on the bending capacity of the considered glass element (Mecholsky et al. 1977; Agnetti 2013).

The present research focuses the attention on the edge strength of two sample groups characterized by different edge conditions: diamond cut and ground by hand-operated tool, and it addresses the results in the context of the manufacturing of cold bent glass. Though, those edge conditions are based on handcrafted methods and may not be representative of the current state of the art, they are conceived to show the role of the number and size of the flaws.

To achieve the above-mentioned goal, the bending strength of 1.5 mm glass plates is experimentally investigated by means of four-point bending tests. Test results are then statistically assessed and compared with the stresses that arise due to the imposed curvature during the cold bending process.

2. Materials and Methods

2.1. Specimens

The samples are made by 1.5 mm thin annealed soda-lime silicate glass manufactured by float process. The tin side was preliminary detected and for consistency of results it was always tested in tension. Annealed glass presents ideally near zero or negligible level of residual stresses therefore no surface stress measurement has been carried out.

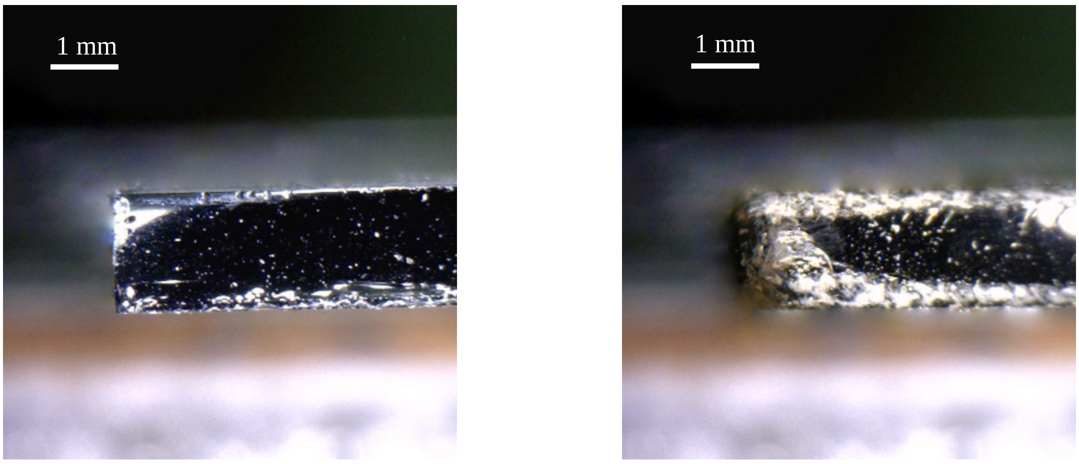
To the scope of the present research the following two edge conditions are considered and they apply to all samples' edges.

- Cut edge, (CE): manual cut by means of a traditional diamond wheel tool. The cutter makes a few microns score on one glass surface marking the cutting line. A small action applied next to the score drives the fracture along the damaged surface. This breaks the glass following the desired path. The resulting cut surface is sharp, but its edges are not the same and it is possible to recognize a scoring edge and a non-scoring edge (see Fig. 1a).
- Ground edge, (GE): the cut surface is ground by means of a hand-operated tool. The work of an appropriate rotating abrasive stone on the cut surface increases the edge roughness. The side of the glass becomes filleted and a significant number of randomly diffused small-size flaws can be recognized (see Fig. 1b).

Ten specimens for each edge condition (CE, GE) are accounted. Both the above-mentioned processing techniques are based on handcrafted methods and therefore they are not directly linked to current industrial or commercial applications. However, the considered edge conditions have the advantage of clearly highlighting the role of the number and size of the flaws. After the edge working the specimens were stored for 24 hours in the laboratory room before being tested.

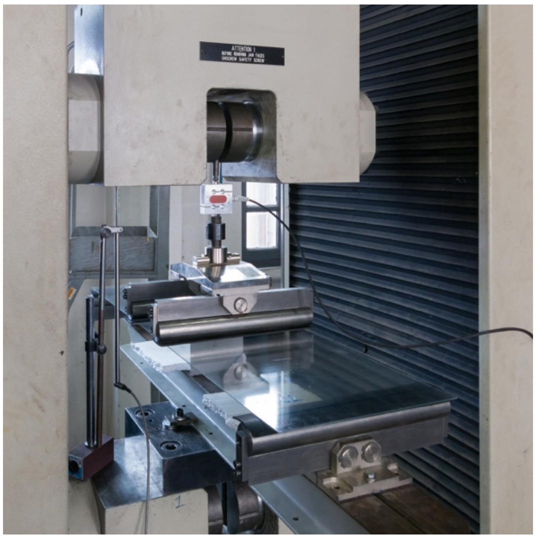
The specimens' geometry and dimensions are in accordance with EN 1288-3. This allows to determine the bending strength of the glass including the effect of the edges processing. The specimens have a rectangular shape with a nominal length, L of 1100 mm ± 5 mm and a nominal width, B of 360 mm ± 5 mm. The mean value of the actual width and thickness of each specimen has been determined by means of appropriate measuring instruments. The mean value of the thickness was determined with an accuracy of 0.01 mm and it is expressed as the average of several measurements took in the failure origin's area. All the tested specimens result within the specified tolerances.

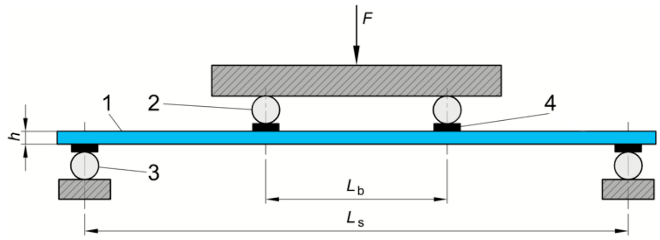
Finally, a plastic adhesive film has been fixed to the side of the specimens facing the bending rollers. The film bonded to the compressed side does not influence the results, while it holds together the fragments after the failure and so it helps locating the fracture origin.



a) b)

Fig. 1 Microscope pictures of specimen's edge: cut edge a) and ground edge b).





a) b)

Fig. 2 a) Picture of the test setup, b) schematic representation of the four point bending test: 1. specimen, 2. bending roller, 3. supporting roller, 4. rubber strip, L_b = 200 mm, L_s = 1000 mm.

2.2. Test Apparatus and experimental procedure

The bending strength of the samples, including the effects of the edges, is determined by four point bending tests in accordance with EN 1288-3. The test apparatus and a schematic representation of the test setup are depicted in Fig. 2, respectively a) and b). The tests have been carried out by means of an electromechanical universal testing machine equipped with an appropriate flexural bench. The distance between the bending roller, L_b is 200 mm and the distance between the supporting roller, L_s is 1000 mm. All the rollers are free to rotate and have a diameter of 50 mm. Rubber strips are placed between the rollers and the glass surface to avoid point contact.

The applied load, F is measured by a load cell with a measuring range of 600 N appropriately calibrated for the expected load range. This is necessary because the capacity of the load cell embedded into the testing machine is too big with respect to the small estimated failure load. The specimen's mid-span deflection, y is indirectly measured by means of a linear variable displacement transducer (LVDT) with a measuring range of 100 mm, which monitors the crosshead displacement of the testing machine. The accuracy of this measure is considered satisfactory because specimens undergo very large deflections with respect to any possible settlements of the loading device.

The specimen is first loaded by its self-weight and then by increasing the mid-span displacement at a constant speed that corresponds in loading to a stress rate of 0.4 MPa ± 0.1 MPa up to failure. The low stress rate adopted is to minimizes the possible shock during loading. On the contrary, subcritical crack growth may not be negligible (Wiederhorn and Bolz 1970).

The tests have been carried out at ambient temperature of 20 °C ± 2 °C with relative humidity of about 50 % ± 5 %. This condition was kept constant and monitored during the tests execution.

Before the tests all the specimens were inspected using a digital microscope. The flaw population in terms of number and sizes was qualitatively studied and recorded by taking images of the edge surfaces (see Fig. 1a-b). After the failure, samples are visually inspected and the type of failure recorded.

3. Test Results

Table 1 and Table 2 reports the test results for specimens with cut edges (CE) and ground edges (GE), respectively. For each specimen both the failure load, F_{max} and the mid-span displacement at failure, y_{max} are provided. In addition, the bending strength (failure stress, σ_f) is computed by means of the Eq. 2 derived from calculation expression presented in EN 1288-3 and adapted as follows:

$$\sigma_f = F_{max}\frac{3(L_s-L_b)}{2Bh^2} + \frac{3\rho g L_s^2}{4\mathrm{h}} \tag{2}$$

assuming a density, ρ of 2500 kg/m^3 for the glass.

Studies on the determination of the bending strength of thin glass (Maniatis et al. 2016) showed that linear equations for the inverse analysis and identification of the bending strength are not able to detect the additional bending moment due to the large deformations experienced by specimens tested in accordance with conventional EN 1288-3 four point bending test. However, both the two specimen groups will be affected by this secondary effected depending on their deflections so the discussion of the results presented hereinafter in this paper will not be significantly affected.

The observed type of failure was always related to the bending resistance of the sample. Indeed, the failure origin was located within the loading rollers area. Single crack propagates from the side of the specimen's edge subjected to tension and suddenly splits into several branches (see Fig. 3). Non-compliant breakages (e.g. not starting from the edge) were disregarded.

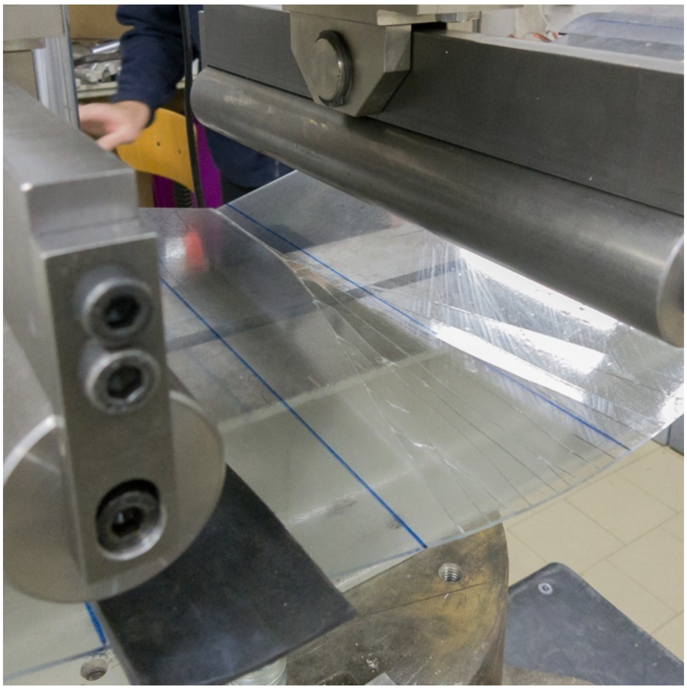


Fig. 3 Typical type of failure.

Table 1: Test results for specimens with cut edges, (CE).

Specimen code	Failure load, F_{max} (N)	Displacement at failure, y_{max} (mm)	Failure stress, σ_f (MPa)
CE-01	16.8	62.9	37.2
CE-02	27.1	84.3	52.5
CE-03	17.7	64.4	38.5
CE-04	21.2	73.6	43.6
CE-05	25.2	80.7	49.5
CE-06	27.8	88.7	53.5
CE-07	28.9	88.4	55.0
CE-08	16.6	60.9	36.7
CE-09	31.4	92.8	58.8
CE-10	30.6	90.7	57.6

Table 2: Test results for specimens with ground edges, (GE).

Specimen code	Failure load, F_{max} (N)	Displacement at failure, y_{max} (mm)	Failure stress, σ_f (MPa)
GE-01	18.3	64.9	39.3
GE-02	18.3	65.1	39.3
GE-03	15.5	56.8	35.2
GE-04	14.7	57.8	34.0
GE-05	13.0	55.5	31.5
GE-06	13.5	55.5	32.3
GE-07	15.0	56.7	56.7
GE-08	16.0	60.8	36.0
GE-09	18.0	62.4	38.9
GE-10	16.8	59.4	37.2

4. Discussion and Conclusions

Test results can be statistically assessed accounting for a Gaussian standard distribution. The mean value, $\sigma_{f,m}$, the standard deviation, SD, the coefficient of variation, COV and the 5% characteristic value of the failure stress, $\sigma_{f,k}$, are reported in Table 3.

Table 3: Statistical assessment of the test results.

Specimen code	Mean value, $\sigma_{f,m}$ (MPa)	Standard deviation, SD (MPa)	Coefficient of variation, COV (%)	Characteristic value, $\sigma_{f,k}$ (MPa)
CE	48.3	8.6	17.8	25.2
GE	35.8	2.8	7.9	28.2

The mean value of the bending strength of ground edge samples (non-industrial technique) is lower than the one of cut edge samples (traditional technique). However, ground edge results show a smaller standard deviation compared to simply cut edge and therefore this leads to a higher characteristic value of the bending strength.

This finding can be interpreted in terms of fracture mechanics. In fact, according to the classic theory of linear elastic fracture mechanics (LEFM) applied to brittle material, the strength is proportional to the crack size. The bigger is the flaw the lower is the strength. On the contrary, a bigger number of flaws increases the probability to find a defect, that is the basis of the so called size effect. Taking into consideration the flaw population of the two sample groups, which has been qualitatively analyzed in the previous section (see Fig. 1), it is possible to recognize that ground edge specimens have approximately the same flaw size with respect to cut edge specimens, but the number of defect is significantly increased and more randomly diffused.

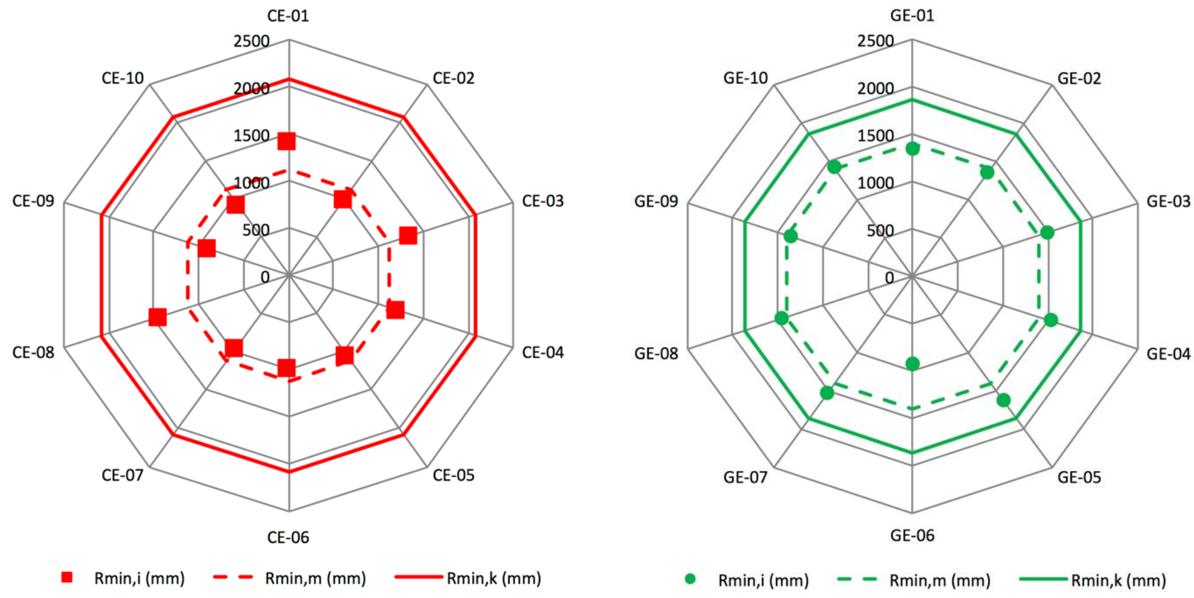
In the context of cold bending manufacturing, the minimum radius, R_{min} feasible for curved glass is derived by the correlation between bending moment, M_u and curvature, K_u at failure, as it is shown in Eq. 3 and 4 hereinafter (adapted from Fildhuth and Knippers 2011):

$$K_u = \frac{1}{R_{min}} = \frac{M_u}{\mathrm{E}\cdot\mathrm{I}} = \frac{\sigma_f}{\mathrm{E}\cdot h/2} \tag{3}$$

$$R_{min} = \frac{E\cdot h/2}{\sigma_f} \tag{4}$$

where, E is the Young's modulus assumed 70 GPa (validated assessing the experimental results), I is the moment of inertia of the considered cross-section, σ_f is the glass bending strength and h/2 is the distance of the outer fiber from the neutral axis (0.75 mm for the considered case).

Hence, the possibility to achieve a certain design radius for a given glass thickness depends explicitly on the glass strength only. The effect of edges processing is generally implicitly considered by reducing the glass strength. However, introducing in Eq. 4 the value of the bending strengths determined both by testing (Table 1 and 2) and from the statistical assessment (Table 3) it is possible to explicitly show the effect of the considered edge processing on cold bending applications (see Fig. 4).



a) b)

Fig. 4 Summary of the evaluation results: cut edge a) and ground edge b).

The plots summarize the results of the above-mentioned evaluation and show the possibility to achieve smaller design radius for ground edge samples with respect to the one with cut edges, that is to say the possibility to manufacture glass panels with higher curvature. More in detail, dashed lines show the possibility to achieve, in terms of average values, a smaller curvature radius for cut edge specimens ($R_{min,m}$ = 1120 mm) compared to ground edge specimens ($R_{min,m}$ = 1400 mm). However, the positions of the markers, which is related to the individual resistance of the specimen, give a clear visual representation of the scattering in the results for each sample group. As a consequence, continuous lines show that, in terms of characteristic values, ground edges allows for smaller curvature radius ($R_{min,k}$ = 1860 mm) with respect to cut edges ($R_{min,k}$ = 2080 mm).

In the end, the present study shows that grinding has a positive influence in terms of glass characteristic bending strength, which results in a broad range of applications in the context of cold bent glass (e.g. more complex panel shape itself and/or lower number of panels to match a given complex geometry, etc.). Moreover, for a given design radius, the low scattering of the results is associated with a good reliability of the manufacturing process. For those reasons the use of ground edges glass in cold bent applications should be the preferred choice.

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