Analysis of Tensile Fracture in Brittle Materials

Using Three-Point Bend Test

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Abstract

Three-point bend tests were performed to analyze the average modulus of rupture (MOR) and standard deviation values for the as received and ground standard soda lime glass rods samples using RSL machine. Ground glass rod samples were prepared by grinding with abrasive papers that had different grit sizes, 60, 150 and 320. Results for the ground glass rod samples based on fracture mechanics predictions were reported, where the scaling factor was estimated to be 8.4055. The values of the average modulus of rupture were calculated to be 128.0, 60.53, 70.76, and 77.22 MPa for as-received, 260, 97.0 and 46.2 µm ground samples, respectively. The value of MOR increases with the decrease of the grinding grit diameter. The standard deviations were determined to be 27.7, 7.02, 6.5 and 5.1 MPa for as-received, 260, 97 and 46.2 µm ground samples, respectively. This experiment suggested that the magnitude of the modules of rupture for a specific ceramic material is greater than its fracture strength measured from a tensile test.

Introduction

A fracture is defined as the parting of material into two or more fragments under the action of stress. Prior to fracture, metals show significant plastic deformation while ceramics and inorganic glasses show little or no plastic deformation. Therefore, ceramics and inorganic glasses are considered brittle materials, in which fracture is caused by the propagation of cracks under tensile stresses acting perpendicular to the surface of the crack.[1] Fracture stresses and the effect of the crack distribution on them in brittle materials can be determined by preforming tensile tests. However, tensile tests involve costly sample preparation, and the testing procedure is impractical. Instead, three-point bend tests can be used because of the ease of the specimen preparation and the convenience of the testing process. The crack distribution is a consequence of the processing of the material and following shaping operations such as grinding and polishing. [1,3] It is worthwhile to note that even though the stress distribution is not uniform in bending, the extreme tensile stresses occur at the sample surface. Bend testing is a suitable test technique to measure fracture stresses and its correlation to the distribution of cracks at the sample surface. [1,2]

Figure 1 shows the geometry of the three-point bend test. The point of fracture happens at the maximum tensile stress, on the bottom of the beam under the loading pin F at the beam center. The tensile stress acts along the axis of the beam. As a result, the crack plane normal to the stress will be across and into the beam. The distance L is measured between the F/2 support pins. [1]

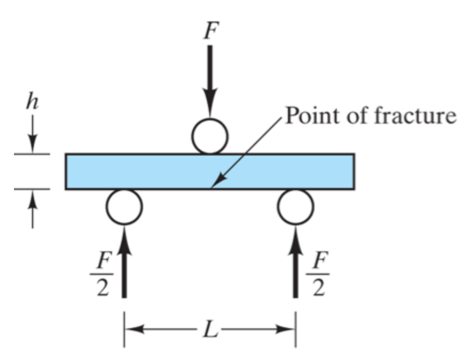

Figure 1. The geometry of the three-point bend test. [1]

The relation between all these variables and the modulus of rupture is given in the following equation:

$$\sigma_{max} \equiv MOR = \frac{8F_{max}L}{\pi D^3} \tag{1}$$

where σ_{max} is the fracture stress, MOR is modulus of rupture, L is the distance between the two support pins, D is rod diameter, and F_{max} is the load at fracture.[1,2]

In order to vary the crack sizes on the glass rod samples prior to bend testing, a distribution of cracks can be introduced by grinding with abrasive papers having different abrasive grit sizes. Fracture mechanics predicts the following relation:

$$MOR = \sigma_{max} = \frac{K_c}{\sqrt{\pi a_{max}}}$$

$$MOR = \frac{K_c}{\sqrt{\pi\alpha}} \frac{1}{\sqrt{D}} = AD^{-\frac{1}{2}} \tag{2}$$

where K_c is fracture toughness, a is the crack length, D is grit diameter, and α is a scaling factor. [1]

The objectives of this experiment were to analyze the average modulus of rupture (MOR) and standard deviation values for the as-received and ground glass rod samples using three-point bend tests. Ground glass rod samples were prepared by grinding with abrasive papers that had different grit sizes, 60, 150 and 320. Results for the ground glass rod samples based on fracture mechanics predictions were reported (MOR vs. $D^{-1/2}$ where D is the diameter of the abrasive particle for a specified grit size).

Experimental procedure

In this experiment, a total of forty standard soda lime glass rods were examined. Ten rods were mounted as received, and the other rods were ground with the abrasive paper (grit sizes 60, 150, and 320). The equipment used for gritting was Grizzly Industrial (G8688 Variable Speed

Metal Lathe). The equipment used to preform three-point bend tests was RSL (Digital Displacement Loading Frame). The RSL software uses a graphical interface combining a unique control of all testing parameters and ease of operation. The experiment was performed at room temperature and an absolute pressure of 1 atm.

The glass rod samples and abrasive paper were obtained. One-inch wide circumferential grinding patterns were made at the center of specified glass rods using an electric drill to rotate the rod and one-inch wide abrasive paper strips. The abrasive paper strips were changed periodically to assure a constant conformation of crack disruptions created on the surface. The samples were grinded for one minute. The diameter d (mm) of each glass rod was measured and recorded using the digital calipers. Three-point bend tests were performed using the fixture in the RSL machine. The breaking loads for the glass rod for the specified test conditions were recorded.

Results and Discussion

For the as-received glass rod samples and each abrasive grit size used for the grinding the remaining thirty samples, multiple tests were performed to get statistically significant data. The results for each sample are summarized in Table 1. The values of modulus of rupture were calculated using Equation 1. The breaking load findings for the as-received samples fluctuated from 1723.24 to 2839.32 N, whereas the breaking load results for each set of the ground samples were in much smaller ranges.

Table 1. Measured dimeters, test conditions, the breaking load and MOR values.

Sample #	d (mm)	Test condition	F_{max} (N)	MOR (MPa)
1	12.68	as received	1723.24	109.343369
2	12.65	as received	2188.08	139.828537
3	12.71	as received	1124.06	70.8205595
4	12.68	as received	1891.38	120.012406
5	12.67	as received	1769.05	112.516553
6	12.69	as received	2452.30	155.236489
7	12.69	as received	2180.07	138.003583
8	12.70	as received	2029.72	128.182878
9	12.67	as received	2839.32	180.586646
10	12.70	as received	1987.46	125.514101
11	12.70	260 µm	945.691	59.7231492
12	12.70	260 µm	791.338	49.9752967
13	12.66	260 µm	933.681	59.5253453
14	12.70	260 µm	893.647	56.436409
15	12.70	260 µm	1148.08	72.5049157
16	12.64	260 µm	923.895	59.1814866
17	12.66	260 µm	1148.08	73.1943397
18	12.61	260 µm	985.725	63.5938476
19	12.69	260 µm	873.630	55.3028119
20	12.65	260 µm	875.410	55.9427898
21	12.63	97.0 µm	1149.86	73.8313818
22	12.68	97.0 µm	1092.03	69.2921734
23	12.68	97.0 µm	1130.29	71.7195359
24	12.71	97.0 µm	1288.20	81.1619592
25	12.69	97.0 µm	985.725	62.3986933
26	12.70	97.0 µm	1093.81	69.0777362
27	12.72	97.0 µm	966.153	60.7280143
28	12.68	97.0 µm	1221.92	77.533848
29	12.68	97.0 µm	1009.74	64.070568
30	12.68	97.0 µm	1226.37	77.8161467
31	12.70	46.2 µm	1070.68	67.6169474
32	12.65	46.2 µm	1157.87	73.9934315
33	12.70	46.2 µm	1205.91	76.1568561
34	12.68	46.2 µm	1364.27	86.5658827
35	12.65	46.2 µm	1266.40	80.929453
36	12.72	46.2 µm	1252.17	78.7059457
37	12.69	46.2 µm	1196.12	75.7175618
38	12.70	46.2 µm	1304.21	82.3651613
39	12.69	46.2 µm	1232.15	77.9983428
40	12.69	46.2 µm	1140.07	72.1695959

As indicated in Table 2, the values of the average modulus of rupture were calculated to be 128.0, 60.53, 70.76, and 77.22 MPa for as-received, 260, 97 and 46.2 μm ground samples, respectively. As-received samples have the largest average value of MOR, while the samples grounded with the largest the grinding grit diameter of 260 μm have the smallest MOR average. The average modulus of rupture increases as grinding grit diameter decreases. The standard deviations are determined to be 27.7, 7.02, 6.5 and 5.1 MPa for as-received, 260, 97 and 46.2 μm ground samples, respectively. The standard deviation is larger for as-received samples. Furthermore, the standard deviations for the ground samples tend to decrease as the grit diameter decreases.

Table 2. The average MOR and the standard deviations of MOR for each test condition.

Test condition	MOR_{avg} (MPa)	$MOR_{std\ dev}$ (MPa)
As received	128.0045	27.70285
260 μm	60.53804	7.02264
97.0 μm	70.76301	6.591769
46.2 μm	77.22192	5.117769

Given the fact that the maximum tensile stresses occur at the sample surface, fracture in the ground samples require less tensile stresses than the as-received samples because damage patterns and constant crack size distributions are introduced to their surfaces by grinding. [1] Additionally, the results obtained for the average modulus of rupture show the MOR value is inversely proportional to the grinding grit diameter.[2] This relation can be explained with Equation 2. The size of the cracks is directly proportional to the grinding grit diameter. [1,3] The largest cracks with crack planes normal to the tensile stress direction causes fracture, and thus it yields smaller value for the modules of rupture. [2] These findings agree with the reported values found in literature. [2,3]

The standard deviation of the as-received samples was significantly higher than the values reported for the samples going through the process of grinding because the crack distribution is not uniform. [2,3] In other words, the as-received samples did not have a concentration and a pattern of the crack sizes while the ground samples experienced less variations in the results because damage patterns and constant crack size distributions were introduced to their surfaces before testing. [1] Figure 2 shows a graph of MOR_{avg} vs. $D^{-1/2}$ where D is the grinding grit diameter. The slop was found to be 0.1946 and the r-coefficient was found to be 0.9711.

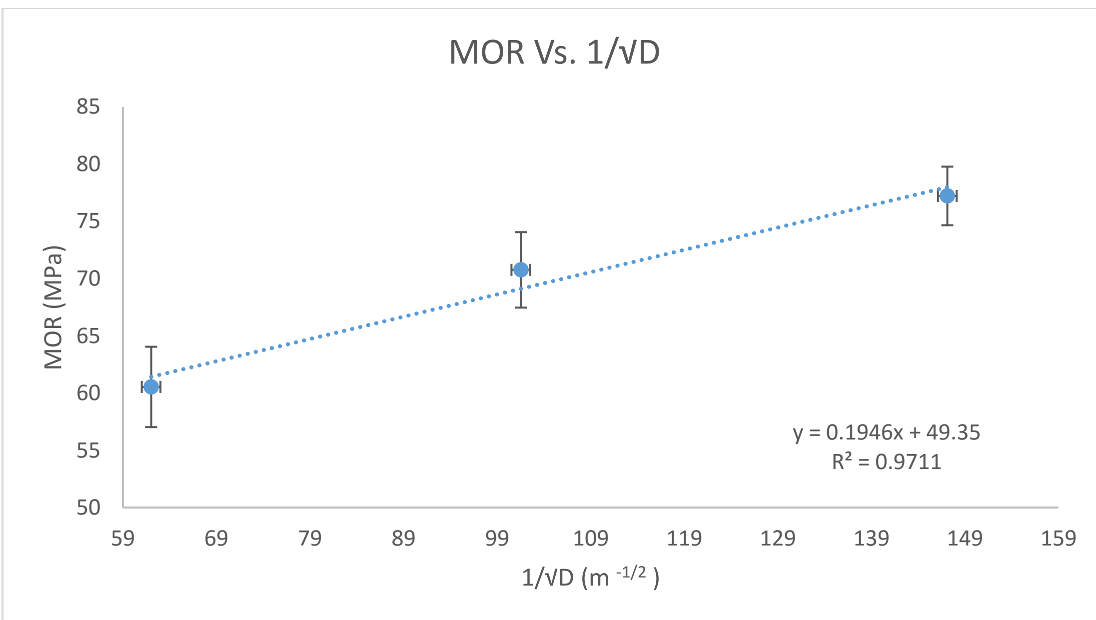

Figure 2. Modules of rupture verses $D^{-1/2}$ where D is the diameter of the abrasive particle for a specified grit size.

Based on the slope obtained for the graph and Equation 2, the scaling factor k between the crack length a and grinding grit diameter D, a = kD was estimated to be 8.4055. The glass fracture toughness K_c was equal to 1 MPa-$m^{1/2}$. The value of k depends on many factors, some of which are the sample hardness, the shape of the grit particles and the pressure applied to the abrasive paper.[1] Because the surface cracks are the factors that cause failure in brittle materials, the resulting average MOR value for each set of samples is a consequence of the distribution of the cracks.[1,2]

Conclusion

The objective of this experiment were to analyze the average modulus of rupture (MOR) and standard deviation values for the as received and ground glass rod samples using three-point bend tests. Ground glass rod samples were prepared by grinding with abrasive papers that had different grit sizes, 60, 150 and 320.

Overall, the experiment was successful in showing the relationship between the modules of rapture and the grinding grit diameter. The values of the average modulus of rupture are calculated to be 128.0, 60.53, 70.76, and 77.22 MPa for as-received, 260, 97.0 and 46.2 μm ground samples, respectively. The value of MOR increases with the decrease of the grinding grit diameter. The standard deviations are determined to be 27.7, 7.02, 6.5 and 5.1 MPa for as-received, 260, 97 and 46.2 μm ground samples, respectively. The scaling factor k between the crack length a and grinding grit diameter was estimated to be 8.4055. Further experiments are needed to examine how the sample hardness, the shape of the grit particles and the pressure applied to the abrasive paper affect the scaling factor k.

This experiment implies that when preforming three-point bend tests instead of tensile tests, the magnitude of the modules of rupture for a specific ceramic material is greater than its fracture strength measured from a tensile test. This phenomenon is due to variances in specimen volume that are exposed to tensile stresses. The entire specimen is under tensile stresses in tensile tests, whereas only some volume portion of a flexural specimen is imperiled to tensile stresses in three-point bend tests.[2,3]

References

[1] L. Reynolds, Three Point Bending Test, MSE 355 experiment description, 2016.

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