



Influence of the normal load of scratching on cracking and mechanical strength of soda-lime-silica glass

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ABSTRACT

The response of glass to a scratch experiment is first reviewed. Then the influence of the applied load on the microcracking pattern, the apparent friction coefficient, and the strength (post scratch test) are studied and discussed for a soda-lime-silica glass (standard window glass composition). As the normal load increases, the depth of the radial crack seems to stabilize at about 100 μm length. Correlatively it is observed that the residual strength of the scratched glass remains at about 40 MPa whatever the scratch load above 0.5 N. Generally, this work contributes theoretically in the understanding of the existing factor controlling scratch in glasses.

1. Introduction

Contact between a solid particle and a surface of a brittle material is fundamentally interesting to understand the formation and the propagation of cracks as well as the deterioration in general on the ceramics and glasses surface exposed to the different exterior attacks either by erosion, abrasion corrosion or by scratching. It also constitutes a basic method to estimate the hardness of an indentation or scratching and the resistance to rupture of brittle materials.

Glass is a material particularly sensitive to surface damage which can occur when objects are formed, handled or used. Among all the surface damage features, the radial/median cracks have a direct influence on the mechanical strength while the lateral cracks are detrimental to the optical properties (transmission or reflection). Scratching is then of paramount interest because it affects the strength [1]. Knowing the scratch shape permits correlating the response of the material, under controlled contact solicitations, to the physical mechanisms that govern the nature of the damage [2–9].

When performing the scratch test, controlling the contact loading history is necessary because scratches are not only plastic deformation but also cracking, a phenomenon sensitive to the environment [10] and the stiffness of the scratching device [11].

Along a scratch performed under a monotonous increasing load on the glass, three different damage regimes are typically observed [3–5] (Fig. 1):

- 1) Micro ductile regime I (permanent track without visible damage).
- 2) Micro-cracking regime II, presence of lateral cracks reaching the surface – chips or flakes, and curved radial cracks – chevron.
- 3) Micro abrasive regime III (presence of much debris and eventually of small emerging lateral cracks).

2. Experimental procedure

The glass used in this study was a soda-lime-silica float glass manufactured by ENAVA (Entreprise Nationale du Verre et Abrasifs, Algeria). Samples were square-shaped, $30 \times 30 \times 4 \text{ mm}^3$, cut from the same plate.

The chemical composition given by ENAVA is in Table 1.

Young's modulus (E): 72 GPa, Poisson's ratio (ν): 0.22 and hardness (Hv): 6.55 GPa were measured respectively by ultrasonic pulse echo technique and macro indentation [12].

Samples were scratched with a laboratory homemade linear sclerometer, designed to permit loading and scratch velocity to be controlled during the test. The tangential and the normal forces were recorded during the test [3]. The indenter was a Vickers diamond type, leading edge oriented.

The scratches were made under different normal loads (W): 0.1; 0.3; 0.5; 0.7; 1.0; 1.5; 2.0 N (± 0.01 N), with a constant scratching velocity of $(10 \pm 1) \mu\text{m/s}$.

The loading path was composed of a ramp followed by a plateau (Fig. 2).

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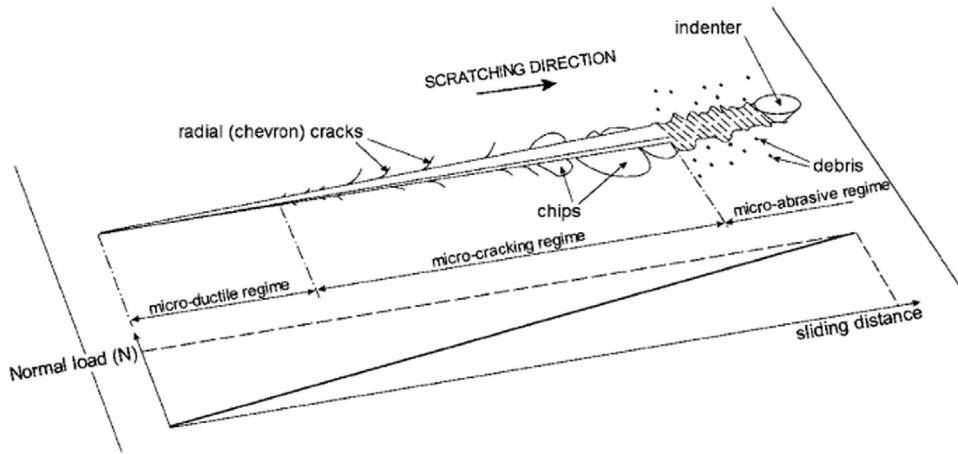


Fig. 1. Typical scratch obtained on a soda-lime-silica glass [3].

Table 1
Chemical composition of the glass.

Oxides	SiO ₂	Na ₂ O	CaO	MgO	Al ₂ O ₃	K ₂ O	SO ₃	Balance
Wt (%)	71.5	1.77	8.33	3.97	13.2	0.83	0.69	0.20

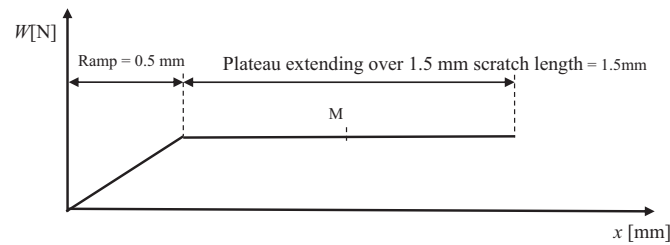


Fig. 2. Loading path consisting of a ramp and a constant-load plateau.

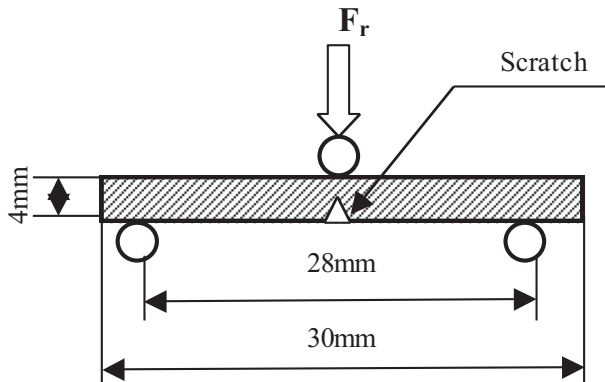


Fig. 3. Three-points bending test.

Just after scratching, top view microscopic observations have been done using a microscope 2D and bending tests were performed on specimens to determine strength, with a three points bending device mounted on a LLOYD LR 50 K compression testing machine (Fig. 3). The scratch was positioned under the upper loading point so as to have the maximum opening tensile stress perpendicular to the scratch [1]. The median crack length was measured at the origin of the rupture, on the fractured surface after the strength test.

The monotonous loading rate three-points bending test is carried out according to the instructions of the NFT57-105 standard, then the mechanical strength σ_r has been calculated using [7,13].

$$\sigma_r = \frac{3F_r l}{2ba^2} \quad (1)$$

with F_r is the fracture load, l the distance between the two lower supports (28 mm), b the width of the sample (measured for each sample) and a the thickness of the sample (4 mm).

3. Results and discussion

The top view optical observations of scratches obtained for each condition are gathered in Table 2. A schematic representation of the subsurface crack pattern has been drawn for each scratch.

We can observe that for 0.1 N, there is only the birth of the median crack, and from 0.3 N until 0.7 N, lateral cracks initiate and propagate inside the material without intersecting the surface. Beyond 1 N until 2 N lateral cracks are intersecting the surface and result in chips growing while increasing the load. The micro abrasive phenomena is occurring at the end of the scratch due to the plowing of the indenter with glass debris (chips and fragments) when scratching.

Increasing the load (W) modifies the cracking system and develops the elasto-plastic deformation, which causes an increase in the tangential force (F_t). The apparent friction coefficient μ_0 , ratio between F_t and W , allows for a better understanding of the influence of all these effects when plotting versus the normal load W (Fig. 4).

The apparent friction coefficient increases almost linearly until W reaches 0.7 N and then stabilizes for W around 2 N. In the case of scratching of glass, we consider that the tangential effort, (F_t) should be divided as follows: a ductile deformation effort (F_{def}), a coulombian friction effort (F_f) and a cracking effort (F_{cr}): $F_t = F_{def} + F_f + F_{cr}$.

Thus

$$\mu_0 = \frac{F_t}{W} = \frac{F_{def} + F_f + F_{cr}}{W} = \mu_{def} + \mu_f + \mu_{cr}$$

with $\mu_{def} = \tan(\beta) = \text{constant}$ (considering a pure plastic deformation, where β : is the rake angle), $\mu_f = \frac{F_f}{W} = \text{constant}$ (considering a Coulombian friction).

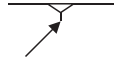

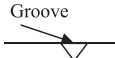

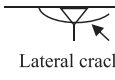


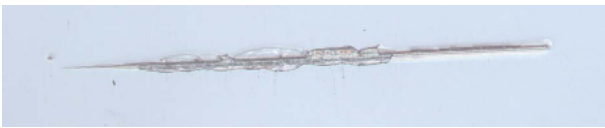






Extrapolating μ_0 to $W = 0$ allows measuring the Coulombian friction coefficient $\mu_f = 0.16$, a key parameter when trying to model and simulate scratching experiment by means of numerical methods.

When $W > 0$, assuming that μ_{def} and μ_f are constant, the increase of the apparent friction coefficient μ_0 in the range [0.1–0.7 N] is due to the cracking effort F_{cr} which rises as the median crack. Above 1 N the cracking effort F_{cr} becomes more stable due to the occurrence of the lateral cracking acting as a lever on rear side of the indenter.

Focusing on the cracking phenomena, the depth of the median crack p_{crack} increases rapidly for loads ranging from 0.1 to 0.7 N, the upper bound to represent the median to lateral crack transition (Fig. 5).

To model the increase of the median crack depth p_{crack} as a function

Table 2
Optical top-view of scratches for the different loads (0.1; 0.3; 0.5; 0.7; 1.0; 1.5; 2.0 N) at a constant velocity $V = 10 \mu\text{m/s}$.

W [N]	Crack scheme	Optical top-view of the scratch
0.1	 Median crack	
0.3	 Groove	
0.5	 Lateral crack	
0.7	 Lateral crack	
1.0	 Lateral crack	
1.5	 Lateral crack	
2.0	 Lateral crack	

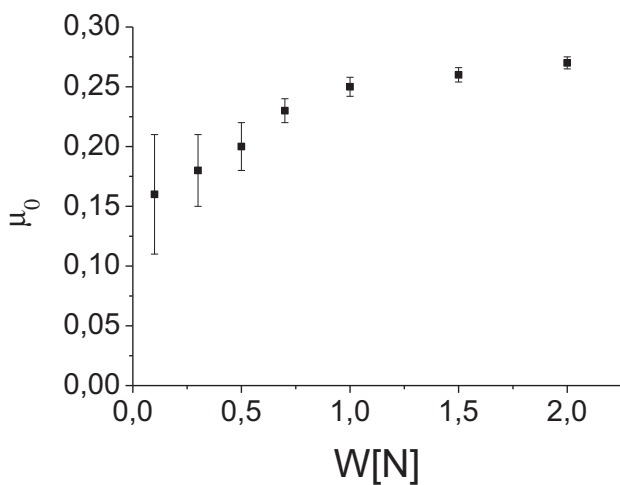


Fig. 4. Effect of normal load on the friction coefficient (μ_0).

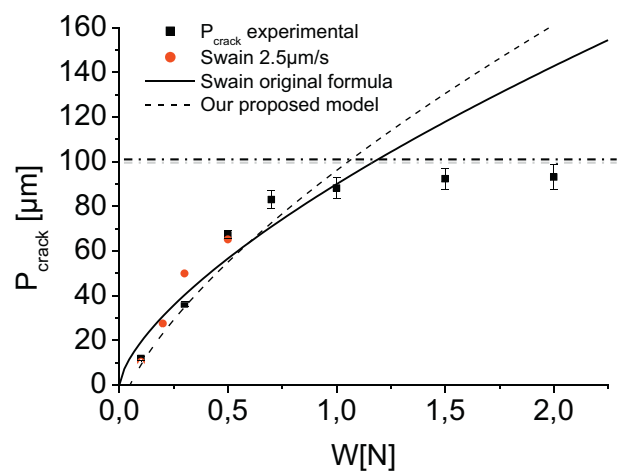


Fig. 5. Effect of the normal load on the median crack depth.

of applied normal load W , one can use the model proposed by Swain [14–15]:

$$P_{crack} = \frac{1}{\pi} \left(\frac{m_e \sqrt{1 + \mu^2}}{K_c \tan \psi} \right)^{2/3} W^{2/3} \quad (2)$$

where μ is the Coulombian friction coefficient, K_c the toughness, ψ the half-angle at the vertex of the indenter and m_e a modifying factor that

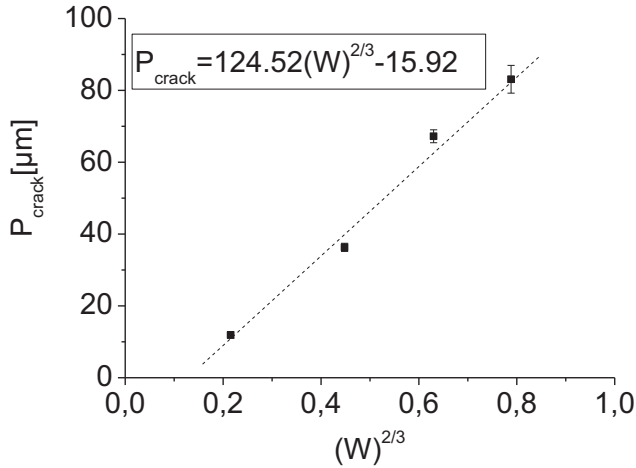


Fig. 6. Effect of normal load for [0.1–0.7 N] on the median crack depth.

takes into account slight differences in crack shape from that considered by Lawn and Fuller [15] and also allows for the increased indentation pressure.

The comparisons of Swain's experimental results obtained for a scratching velocity of 2.5 $\mu\text{m/s}$ with ours show a good agreement even if the scratching speed is a little bit different. When fitting all the data with Swain original formula, one found that the value of the constant m_e is equal to 8 instead of 4 as proposed in Swain's original publication.

Swain's model is not taking into account a cracking threshold. Reporting the crack depth as a function of the normal load on a graph $p_{crack} = f(W^{2/3})$, allows for an estimation of this threshold (Fig. 6).

The 2/3 power law is in good agreement with the median crack length evolution. A $W_0 = 0.046$ N load, below which there is no cracks $p_{crack} = 0$, confirms the existence a threshold.

So, the model in accordance with the experimental results in the range [0.1–0.7 N] that we proposed is:

$$p_{crack} = \frac{1}{\pi} \left(\frac{m_e}{K_c \tan \psi} \right)^{2/3} \sqrt[3]{(1 + \mu_r^2)} (W - W_0)^{2/3} \quad (3)$$

where W_0 is the threshold load.

Reporting the mechanical strength σ_r , versus the applied load W below or equal to 1 N (Fig. 7), allows saying that one have a good agreement with the theory of the fracture mechanics, meaning that the mechanical strength decreases with the increase of the flaw size created on the surface.

The mechanical strength tends to stabilize near 40 MPa for a load

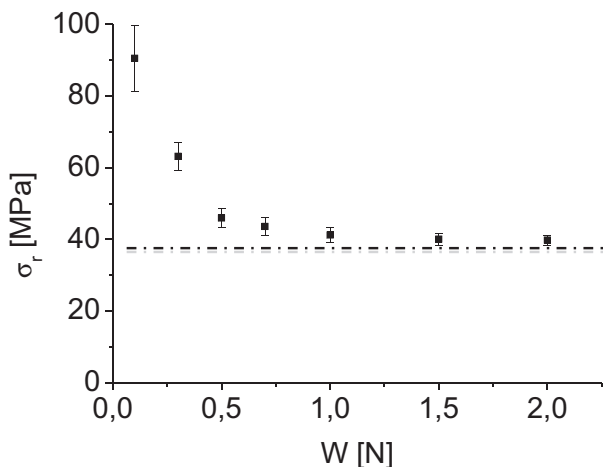


Fig. 7. Effect of normal load on the mechanical strength (σ_r).

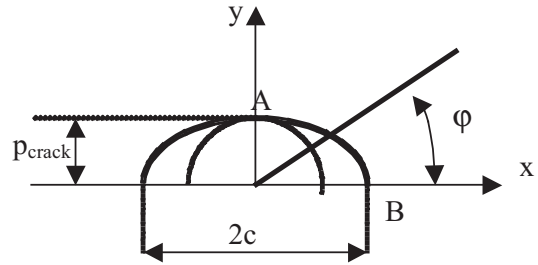


Fig. 8. Semielliptical crack geometry.

larger than 1 N. This confirms the saturation of the median crack length (p_{crack}) (see Fig. 5). σ_r is clearly controlled by the deepest crack that is the median crack for the case of scratching.

As a consequence, the optimal load to ensure the good cut of a piece of glass, without any lateral cracks, i.e. with clear edges, is $W = 1$ N. However, in Swain [14] or Cheng [16] papers, one can deduce that to have a good cut of the glass it's necessary to increase the load to a certain level (see Fig. 5).

The determination of the mechanical strength by three points bending allows characterizing the crack responsible for this rupture that is the median crack. One can consider this surface crack as a semi elliptical one submitted to a tensile stress (see Fig. 8).

The stress intensity factor K_c can be expressed as [17–19]:

$$K = \sigma \frac{M}{\varnothing} \sqrt{\pi p_{crack}} \quad (4)$$

where σ is the fracture stress, p_{crack} is the crack length, M is a correction factor depending on the position of the crack initiation site (in our case the point A), and M takes the value of 1,14 [17–19]. ϕ is an elliptic integral that depends on the ratio p_{crack}/c (where $2c$ is the scratch length in our case):

$$\varnothing = \int_0^{\pi/2} \sqrt{\sin^2 \varphi + \frac{p_{crack}^2}{c^2} \cos^2 \varphi} d\varphi \quad (5)$$

Measuring the crack length allows to estimate the toughness of the glass from Eqs. 4 and 5. A value of 0.73 $\text{MPa}\cdot\text{m}^{1/2}$ is, in good accordance with the value determined experimentally by a 2.492 N indentation (Fig. 9). One can notice that the toughness is almost constant, considering the measuring uncertainties, for loads ranging from 0.3 to 2 N. Considering the value of the toughness obtained for 0.1 N, one have a value 15% below the mean ones. This should be due to the fact that one has some low residual stresses on the surface which should

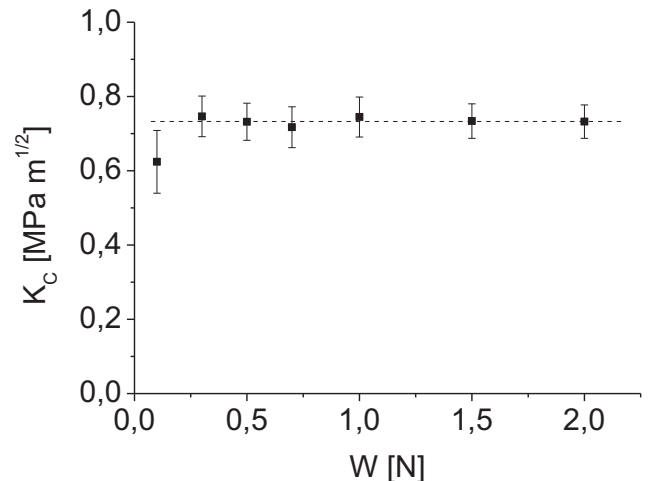


Fig. 9. Fracture toughness as a function of the normal load for scratching.

influence the propagation of very short cracks.

4. Conclusion

In this study we tried to simulate two phenomena: one is the machining (carving) of the glass by scratching and the other conditions of aggressions caused by the bad manipulations. These lead to scratches on the soda-lime glass surface (under controlled conditions of the laboratory) in order to understand the nature of the damage, the system of cracking and the role of one of the scratching parameters which is the load on the evolution of the deterioration.

Our work is essentially based on the influence of the applied load on geometric parameters of the scratch, the median crack, friction coefficient and their consequences on the mechanical strength as well as the toughness of soda-lime glass.

On the basis of the obtained experimental results, we can conclude that:

- The deformation level becomes more and more important while increasing the load (W).
- The friction coefficient increases with the increase of the load until 1 N then beyond this load it stabilizes.
- The coefficient corresponding to a pure friction $\mu_{ad} = 0.156$.
- The growth of the friction coefficient (μ_0) for the interval of load [0.1–1 N] is caused by the increase of the cracking effort. Beyond the load of 1 N until 2 N, this effort (F_{fis}) becomes stable.
- While increasing the load from 0.1 N until 0.7 N, the depth of median crack (p_{crack}) increase, which generates the reduction of the mechanical strength (σ_r).
- Load 0.7 N represents the radial/lateral transition load.
- For loads from 0.1 until 0.7 N, the evolution of the median crack has tendency curve $p_{crack} = 124,52 W^{2/3} - 15,92$.
- The load line of cracking where we don't have a median crack ($p_{crack} = 0$) is $W_0 = 0.046$ N.
- From the load of 1 N until 2 N we have a mutual stabilization of the mechanical strength (σ_r) and of a median crack.
- The optimal load to insure a good cut (machining) of a glass is $W = 1$ N.
- For loads from 0.3 until 2 N the toughness is almost constant $K_c \approx 0.73$, but it is weaker $K_c \approx 0.62$ for the load of 0.1 N.
- For the weak load 0.1 N we have an elastic-plastic deformation. But for the other loads ($W > 0.1$ N) the deformation is purely plastic.

This study offers an additional contribution to understanding and prediction of the soda-lime glass cracking, from the process of

scratching, if it is submitted to very definite aggression conditions and their influences on one of the most important mechanical properties which is the mechanical strength. Finally, we consider that this work is complementary to the works of Swain [14] and Weili Cheng [16].

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