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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, $30 \times 30 \times 4\ mm^3$, 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 ± 1) μm/s.

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

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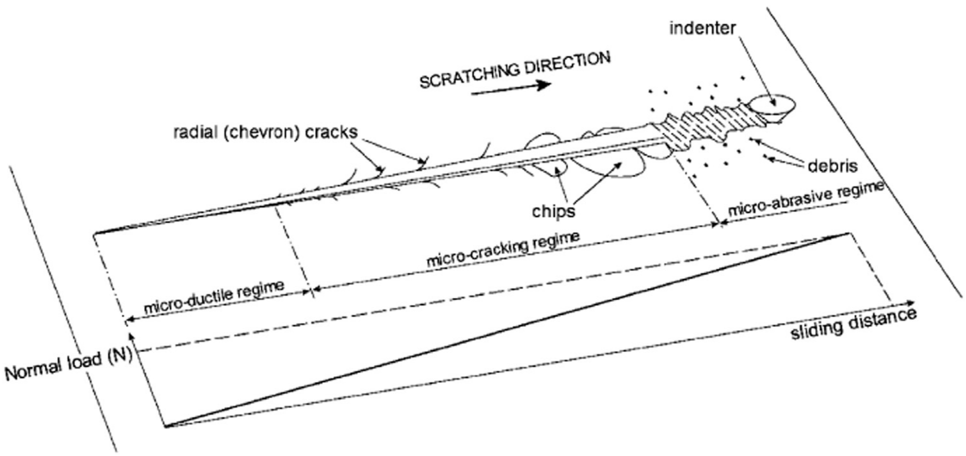

Fig. 1. Typical scratch obtained on a soda-lime-silica glass [3].

Table 1
Chemical composition of the glass.

Oxides	SiO_2	Na_2O	CaO	MgO	Al_2O_3	K_2O	SO_3	Balance
Wt (%)	71.5	1.77	8.33	3.97	13.2	0.83	0.69	0.20

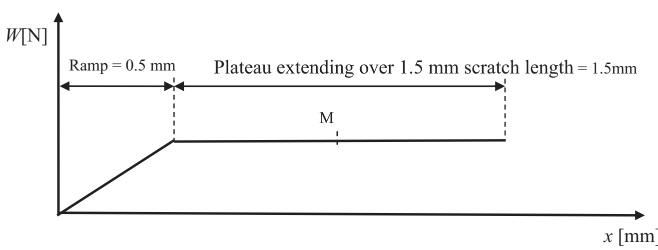

Fig. 2. Loading path consisting of a ramp and a constant-load plateau.

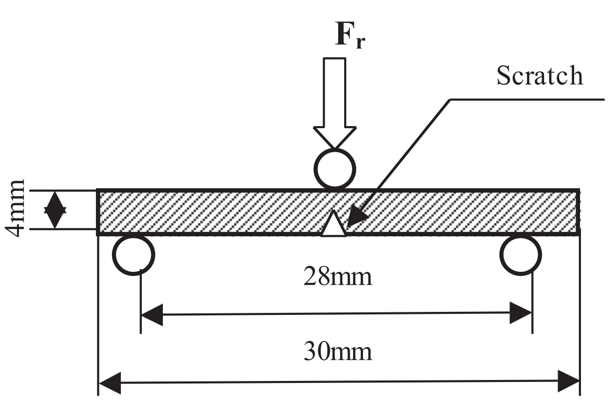

Fig. 3. Three-points bending test.

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].

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

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