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Study of light scattering on a soda lime glass eroded by sandblasting

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Abstract

In Saharan areas of Algeria, sandstorms can damage vehicles windshields inducing incidental light diffusion that affects the driver's visibility. Vehicles technical controllers find some difficulties with damaged windshields. The control being made visually with the naked eye, it is therefore difficult to judge when a damaged windshield is no more valid to use. In this context, we studied the influence of the surface state of a soda lime glass on the scattering of a white light. The varying parameters considered are the projected sand mass, the opening of the light beam and the distance sample-receptor. By increasing the projected sand mass up to 200 g, the optical transmission falls from 91.6 to 13% and the roughness increases from 0.035 up to 2.27 μm and then tends toward a constant level. For the as-received state, the image obtained using a CCD camera presents a net boundary and the transmission profile shows a saturation plateau. By damaging the surface, the image boundary deforms and becomes diffuse. For the highly damaged states, the image become completely blurred and the transmission profile disappears. The variation of the transmission according to roughness shows an inflection point at $T = 73\%$ and $R_a = 1.5$ μm. This point seems to separate two domains: a transparent field ($R_a < 1.5$ μm) and a blur field ($R_a > 1.5$ μm). The visibility limit obtained in our tests conditions is estimated at about 73%.

Keywords: Glass; Erosion; Diffusion

1. Introduction

In the Sahara, sand winds have a great influence on the environment. In general, this influence leads to a surface damage of a great number of objects, particularly those processed of brittle materials such as glasses and ceramics. In the case of glass made products for example, sandstorms can damage vehicles windshields surface, headlights optics, protecting glasses of infra-red plane sensors, solar panels and various glazings.

In general, the surface damage of brittle materials eroded by sandblasting occurs primarily by the formation and the propagation of radial and lateral cracks.[1,2] The material removal is characterized by a chipping mechanism. It was often observed on materials such glass that the sand particles impacts generate defects similar to those obtained by Vickers indentation. Damage caused by sharp particles is always more severe than the damage caused by rounded particles. When the number of impacts in a given area increases, there is an interconnection of cracks. The number of scales as well as their depth will increase and the distance between individual scales will decrease. This leads to the formation of damaged zones.[1] The kind and the extension of the damage (defects size) on the glass surface are dependent on the kinetic energy of the incidental particles, their shape and the mechanical properties of the erodent and the target. The size of the surface defects increases by increasing the kinetic energy of the incidental particles.[3]

When a light beam arrives on a glass surface, several phenomena can occur: reflection, transmission, absorption and diffusion. The last of these is commonly termed scattering. The decomposition of the incidental beam in different percentages of these light transformations is done according to the glass constitution, homogeneity and surface quality. Under real conditions, the

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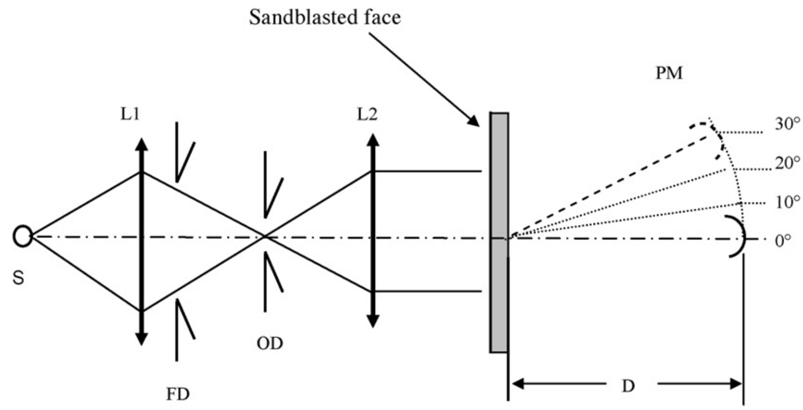

Fig. 1. Illustration of the optical assembling used for the light diffusion measurements.

visibility through a windshield damaged by sandblasting is enormously reduced at night, or during sunrise and sunset because of incidental light diffusion. Holtmann et al.[4] report that the stray light on automotive vehicles windshields caused by the impact of small particles imposes severe safety hazards during night driving. Because of the reduced contrast caused by stray light, non-illuminated objects are perceived much later than through pristine windshields.

The objects seen through eroded windshields become partially or completely fuzzy according to the mileage increase and the vehicle locality. There is a transmission loss primarily caused by the incidental light beam diffusion due to scattering at small surface defects such as scratches and impact sites. The diffusion is simply related to the surface characteristics of the enlightened glass. It takes place without any wavelength change. It is what an observer perceives during the reflection of a light beam on a dioptre plane. If there are no suspended particles in the air, one clearly perceives the mark of the beam on the enlightened surface. This, because a part of energy is lost out of the specular direction and is collected by the eye. This diffusion is due to the presence of irregularities on the sample surface.[5]

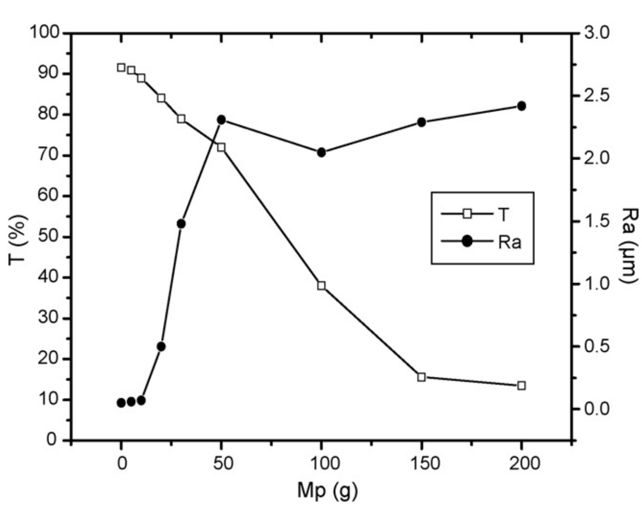

Fig. 2. Variations of the optical transmission and arithmetic roughness according to the projected sand mass.

In preceding works,[6,7] sandblasting tests were carried out in laboratory on a soda lime glass in order to simulate sandstorm effects. Influence of the main parameters such as the projected sand mass, the flow speed and the impact angle were studied. In general, an increase in the mass loss and the roughness were observed when the projected sand mass increases. At the same time, the optical transmission and the bending mechanical strength fall notably. These tendencies are in good concordance with those reported in literature on various types of brittle materials and under various tests conditions.[8,9]

The windshields degradation by sand or dust particles can lead to serious problems for drivers. In operational use, the windshield glass may encounter multiple high velocity impacts with solid particles, usually silica. Simulating reality in laboratory is rather complex if one refers to the different conditions of a windshield of vehicle circulating in Saharan regions. Indeed, the diffused light depends on several parameters such as:

- The state of the damaged surface or the vehicle mileage.
- The shape of the windshields (variable bulging form according to the type of vehicle).
- The windshield inclination which varies according to the type of vehicle (cars, buses, . . .).
- The various directions (variable angles) and intensities (variable distances) of the incidental light.
- The visual capacity of the driver which, generally, depends on his age.

Vehicle drivers should see the real world as if there was no windshield which should provide the driver a high visibility and an undistorted view of a traffic scene ahead. It is reported that visual orientation is essential for safe driving and 90% of the necessary information for safe driving is noticed visually.[10,11]

In this work, some preliminary results concerning the influence of a soda lime glass surface state on the diffusion of a white light are presented in order to study the effect of sandstorms on vehicles windshields in the Saharan regions. We considered the case of samples in a normal position and the following variables parameters: the damaged surface state, the distance sample-receptor and the diameter of the incident light beam.

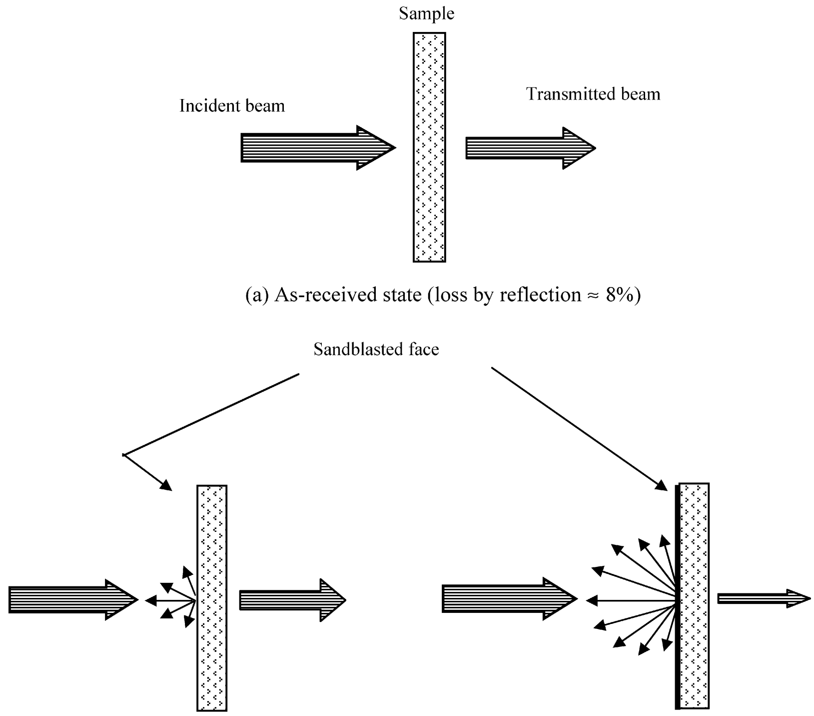

Fig. 3. Schematic illustration of the transmitted light through glass samples having various surface states.

2. Experimental procedure

The target used in all tests is a soda lime glass with 3 mm thickness. A batch of samples of dimensions 40 mm × 40 mm is prepared. A sample in its as-received state is taken as a reference sample (undamaged). The others were subjected to sandblasting tests on one side by varying the projected masses M_p: 5, 10, 20, 30, 50, 100, 150 and 200 g. The angle of selected impact corresponds to the most unfavourable case, i.e. a normal orientation of the sample to the sand flow (90°). The speed of the sand flow is taken equal to approximately 16.5 m/s which is an average speed usually encountered in the Algerian Sahara. Under real conditions, the sand winds usually starts from a speed of about 12 m/s. The maximum speeds recorded up to now are variable between 25 and 30 m/s.[12]

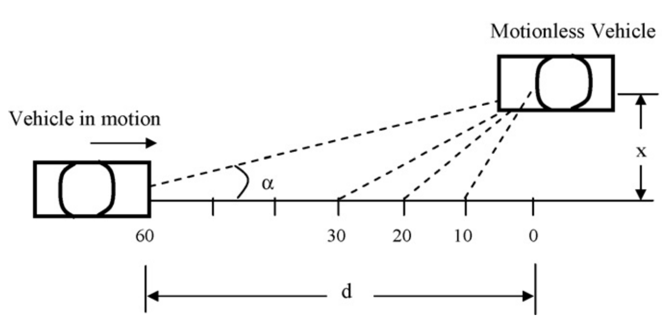

Fig. 4. Diagram illustrating some scattering angles defined at a maximum distance of 60 m between a fixed vehicle and a second vehicle moving in the opposite direction (x = 2.40 m).

The erodent (sand) used in this study originated from the area of Ouargla (Algeria). It has a rather homogeneous average granulometry ranging between 200 and 250 μm. The composition is mainly silica. The general shape of individual particles is variable: angular for the majority of small particles and rounded for larger particles. Their elongation index varies from 1 to 1.8.[13]

In order to determine the variation of the optical transmission according to the scattering angles, we used a photomultiplier connected to a nano-amperemeter. For the diffusion measurements, we used a 350 W power source of white light and a goniometer with a turning table provided with an arm

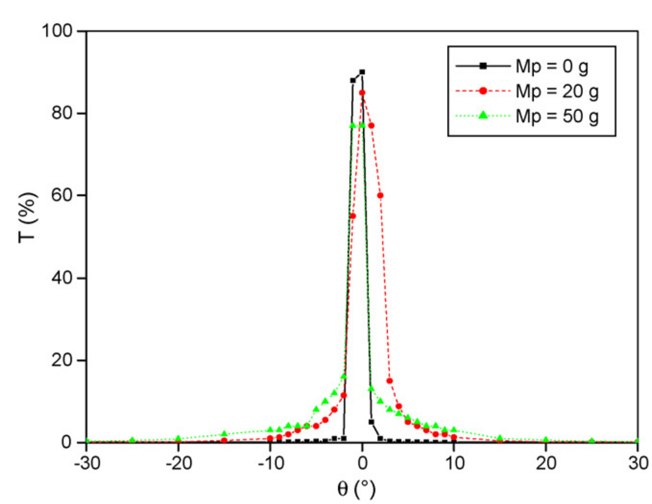

Fig. 5. Variation of the optical transmission according to the scattering angles for three samples having various surface states (Φ = 2.26 mm and D = 100 mm).

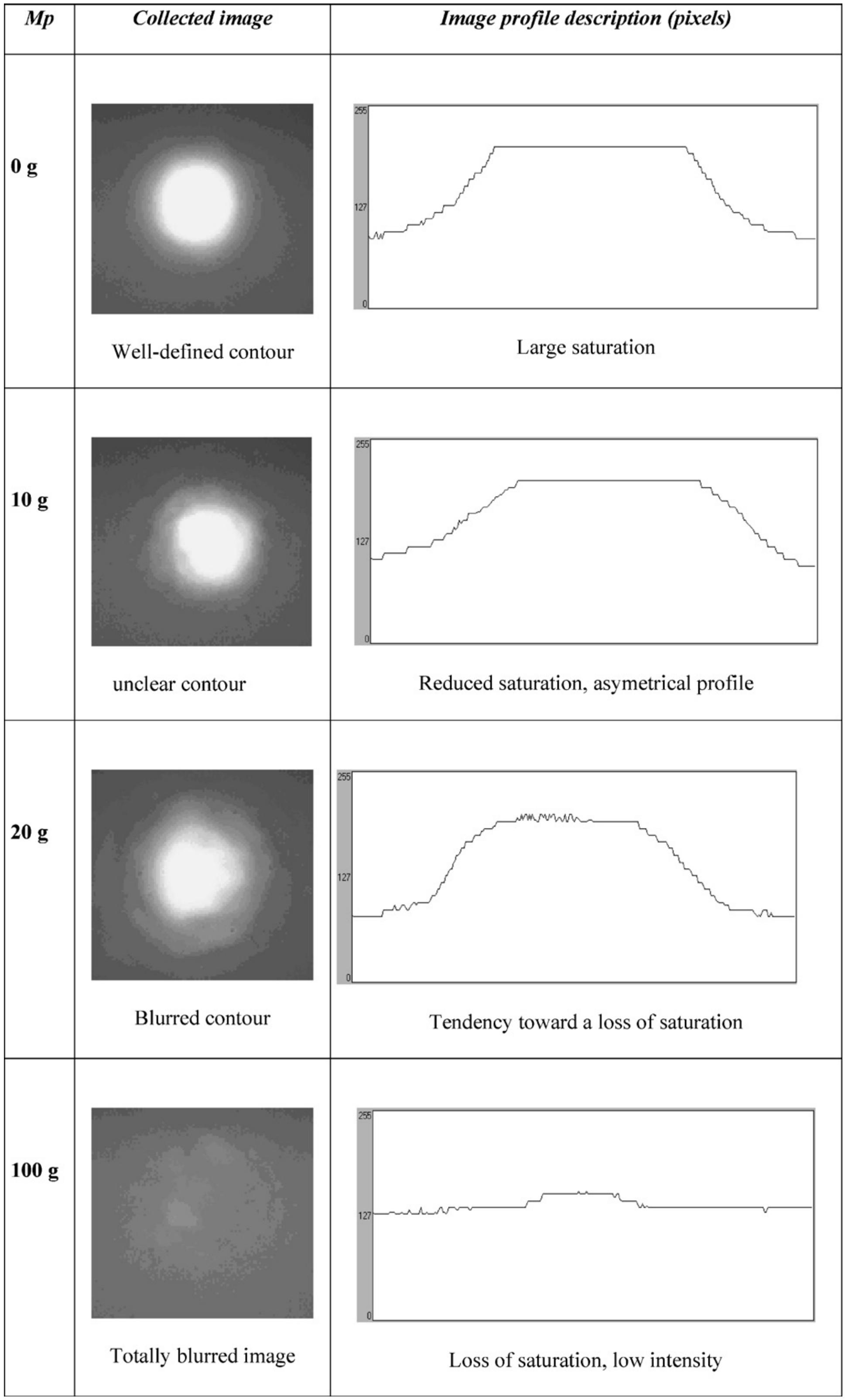

Fig. 6. Influence of the samples damage state on the clearness of the collected image and the transmission profile.

length of 315 mm. The used optical assembling is presented in Fig. 1.

The (S) source emits a beam of white light which is focused by the lens (L1). The field diaphragm (FD) enables to fix the diameter of the exit beam. The opening diaphragm (OD) allows controlling the incidental light intensity on the sample surface. A parallel beam (with constant energy and diameter) is obtained using the lens (L2). The outgoing rays are oriented in their turn

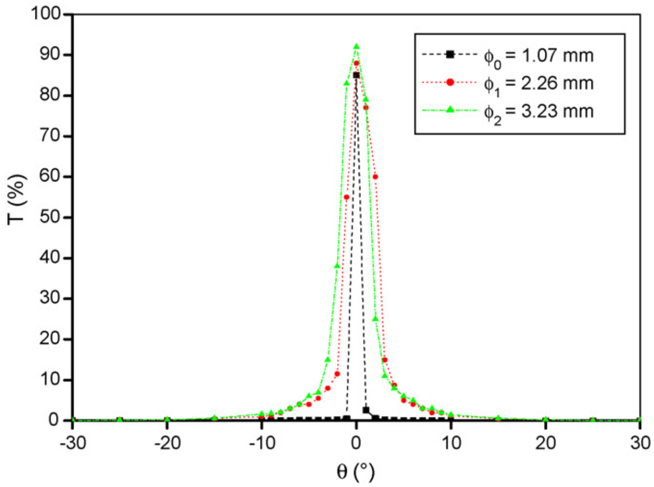

Fig. 7. Variation of the optical transmission according to the scattering angles for various incidental beam diameters ($D = 100$ mm, $M_p = 20$ g).

on the sample (S) which diffuses the light. The photomultiplier (PM), placed at a distance D, collects the radiation transmitted from which the variations $T = f(\theta)$ are determined. The scattering angle varies from −30 to +30° with a step of 2°. The images obtained are collected by a CCD camera. The variable parameters are: the distance D (50, 100 and 150 mm) and the diameter of the incidental beam ($\Phi = 1.07$, 2.26 and 3.23 mm). For each scattering angle θ and for each distance D, the transmitted intensities are measured and the transmission factor T is evaluated.

3. Results and discussion

The evolution of the optical transmission T and the arithmetic roughness R_a obtained according to the projected sand masses M_p is presented in Fig. 2. It is observed that the transmission and the roughness evolve in opposite directions.

The roughness strongly increases up to 2.27 μm ($M_p = 50$ g) and tends towards a saturation level beyond that. Earlier studies[1] show that the roughness behaviour presents the following steps: a sharp increase up to a maximum value followed by a nearly constant level "plateau" with a low amplitude wavy form around this plateau. This wavy form is explained by elimination of the peaks (equalization of the facies) and then creation of differences between hollows and peaks.

The optical transmission falls regularly until approximately 16% (150 g of projected sand mass) and tends to be stabilized beyond that. The total transmission fall is about 76%. The transmission loss is done by reflection for the low projected masses because the eroded surface is not sufficiently damaged. For larger projected sand masses, the loss is mainly done by diffusion because of the great number of scaling and damage which diffuse the incidental light. It is well known that the first stage of glass erosion that is crucial for the formation of stray light is the creation of scales and scratches. Damage sites resulting from sand particles (ranging into the interval 200–250 μm) are often microscopic, but the microcracks and flaws that are created act as efficient scattering centres for incoming light. As a result, the optical transmission suffers.

Fig. 3 illustrates the light crossing glass samples having three different surface states: an undamaged surface (a), a lightly damaged state (b) and a severely damaged state (c). With a good surface quality, almost 92% of the light is transmitted and approximately 8% of loss is attributed to the reflection on the two sample surfaces.[14] If the surface is lightly damaged, a part of the light is lost by reflection and diffusion. Finally, if the surface is severely damaged, the transmission loss is primarily attributed to the surface diffusion. It falls sharply until approximately 13–16%.

To choose the diffusion angles, an example of a motionless vehicle located at a distance $d = 0$ m and a second vehicle moving in opposite direction starting from $d = 60$ m, is considered. The distance ($x = 2.40$ m) separating the azimuth axis of the mobile vehicle and the position of the driver on the fixed vehicle is supposed sufficient and constant (Fig. 4). The different obtained angles are indicated in Table 1.

When the distance separating the vehicles decreases, the scattering angles tend towards 25.6°. The diffusion curves (Figs. 5 and 7) are therefore plotted using scattering angles varying from 0° to 30°.

The variation of the light transmission according to the scattering angles for an undamaged sample and for two samples sanded with 20 and 50 g is presented in Fig. 5. The conditions used for the tests are: the diameter of the incidental beam is 2.26 mm and the distance sample-detector $D = 100$ mm. It is noted for the undamaged state that the transmission loss is very weak and occurs essentially by reflection. The loss by diffusion is negligible. For 20 g of projected sand, the specular transmission falls from 91.6 to 87%, whereas the diffuse transmission remains low enough (≈13%). This represents a haziness of about 15%. The haziness H is defined as the rate of the diffused intensity I_{dif} on the transmitted intensity I_{tr} ($H (\%) = (I_{dif}/I_{tr}) \times 100$). The diffusion starts to appear and spreads out until a scattering angle of approximately 25°. For a more damaged sample ($M_p = 50$ g), the specular transmission becomes weaker and the haziness increases further and reaches 28%. It is noticed that beyond 20°, the transmission becomes almost null.

The evolution of the curves presented in Fig. 5 is in good agreement with the images taken by a CCD camera and with the transmission profiles (Fig. 6). This last is obtained following the median line of the collected image. It translates the variation of the light intensity according to the sample width.

In Fig. 6, the enlightened mark evolution is clearly shown. When the surface is damaged, the transmitted light decreases and tends to disappear. The enlightened mark obtained on the initial undamaged state is clearly represented and the contour is well defined. The two sides of the transmission profile are symmetri-

Table 1
Some diffusion angles defined by a distance between 0 and 60 m ($x = 2.4$ m)

d (m)	Angle α
60	2°29
30	4°57
20	6°84
10	13°49
5	25°64

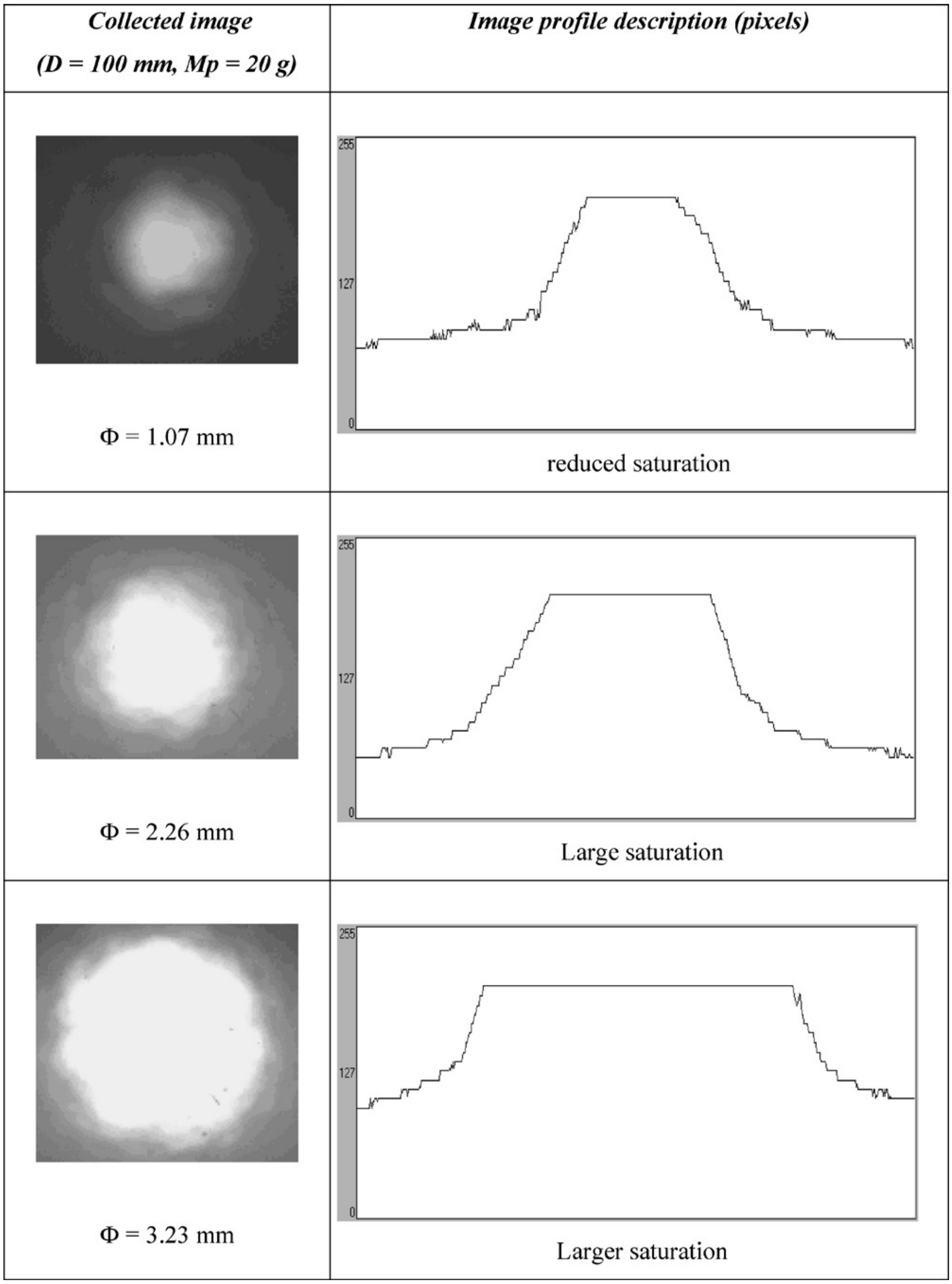

Fig. 8. Images and corresponding profiles obtained through sanded samples using various light beam openings ($D = 100$ mm and $M_p = 20$ g). The saturation level increases with the diameter opening.

cal. The transmission profile presents a saturation state "plateau" because of the large transmitted light intensity. For the damaged states, the transmitted light intensity decreases gradually and the contour becomes increasingly indefinite. The recorded profile becomes asymmetrical. The sample eroded with 100 g of sand gives a fuzzy image and the transmission profile disappears completely. It can be noticed that the profile amplitude is strongly reduced.

Fig. 7 shows the diffusion curves when the diameter of the incidental light beam is varied from 1.07 to 3.23 mm ($D = 100$ mm and Mp = 20 g). It can be observed that the optical transmission maximum decreases as the beam diameter is reduced. The following values are reported: 91.4% for $\Phi = 3.23$ mm, 89% for $\Phi = 2.26$ mm and 86% for $\Phi = 1.07$ mm. It is well known that the diffusion evolves in the opposite way. It can be concluded that the light diffusion is proportional to the intercepted defects number. This means that for good driving conditions, it is necessary to have a good quality of the headlight optics. In real conditions, this quality is strongly dependent on the car locality, the mileage and the individual driver.[15]

The images collected by camera and the corresponding profiles obtained from a sample eroded with 20 g of sand are shown in Fig. 8. As the beam diameter increases, the enlightened mark becomes progressively intense and the saturation plateau becomes larger. It is evident that for a given light power, energy increases with the diameter increase.

4. Determination of the visibility limit

In order to estimate a visibility limit as a validity test of eroded samples with different sand masses, a *H* character with dimensions 1 cm × 1.2 cm is used as an observed object. This character is placed at 1 cm below the sample[16] and photographs for various surface damage states are taken (Fig. 9).It can be noticed that for the initial state (without sandblasting), the *H* character appears very clear and as the glass surface is increasingly damaged, it becomes increasingly blurred.

We know that the technical controllers of vehicles find some difficulties with quality control of damaged windshields in Saharan regions. The exposed problem is that this control is only made visually with the naked eye making it difficult to judge if a windshield damaged by sand particles is still valid for use or not. To answer this question by defining a visibility limit, the variation of the optical transmission according to the roughness is established (Fig. 10). A linear decrease with an inflection point is shown.

It is also noticed that the standard deviations of R_a increase as increases the projected sand mass. They tend to be stabilized beyond approximately 2 μm. Evolution of these standard deviations is probably related to the increase of the created defects number and to the interconnection of the lateral cracks generated by the repeated sand impacts.

Only the standard deviations of the roughness values are showed because the roughness measurement error is relatively more important than that of the transmission. The average val-

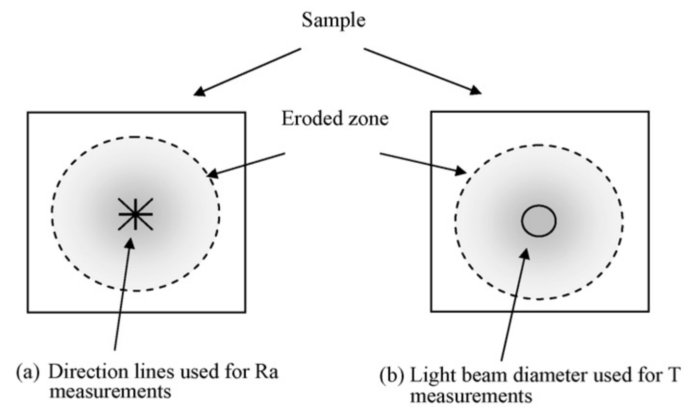

Fig. 10. Variation of optical transmission versus the roughness, showing the inflexion point.

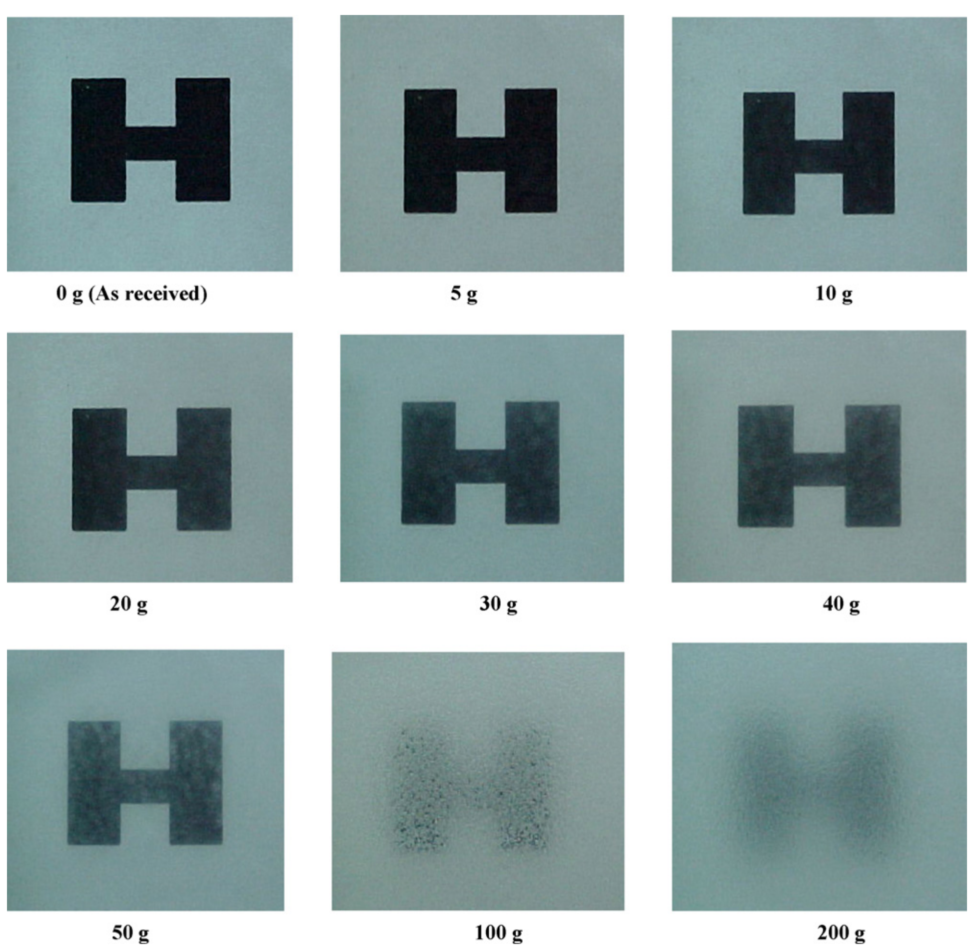

Fig. 9. Aspect of an *H* character seen through samples sanded with various sand masses.

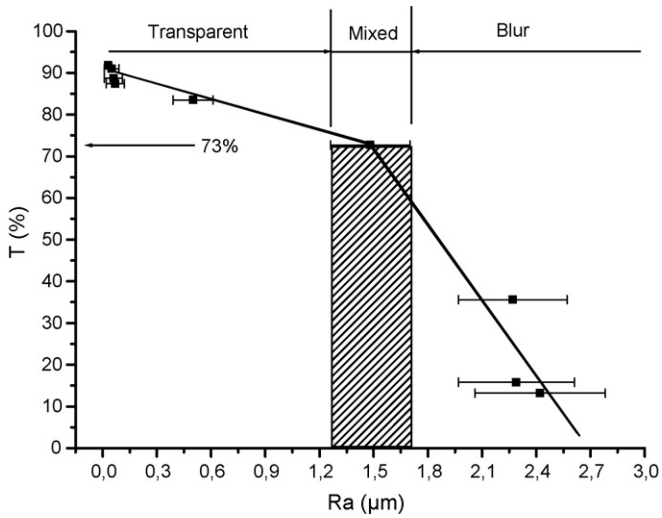

Fig. 11. Schematic diagrams showing the central zone of a sample eroded by sandblasting: (a) direction lines used for measuring the roughness; (b) light beam diameter used for optical transmission measurement.

ues of roughness are given according to four direction lines in the damaged central zone. Those of the transmission are given according to a surface corresponding to the incident light beam diameter (2.2 mm in the central zone). This beam intercepts a higher defects number. In Fig. 11, two schematic diagrams explain the roughness and the transmission measurements.

According to Fig. 10, an inflection point is located at about $T = 73\%$ and $R_a = 1.5\ \mu m$. This point separates two distinct domains: a field corresponding to a slow decrease of T for roughness values lower than 1.5 µm, and a second field corresponding to a sharp decrease of T for roughness values greater than 1.5 µm. Two optical domains can be therefore defined:

- A transparency field (1st branch) where the optical transmission is rather high and the roughness is rather low.
- A second blurry field (2nd branch) where the optical transmission is weak enough and the roughness is high.

Nevertheless, the definition of a visibility limit between these two optical fields is not clearly apparent. It can be admitted that there is a mixed field. The limits of this mixed domain can be defined by the roughness standard deviation values corresponding to the inflection point ($R_a = 1.5 \pm 0.22\ \mu m$). In order to allow technical services to securely control the damaged windshields, the lower roughness value ($R_a = 1.5–0.22 = 1.28\ \mu m$) can be proposed as a "limit value". In our test conditions, this value corresponds to an optical transmission limit of about 73%. The inflection point located at $T = 73\%$ is concordant with literature data. Indeed, Savaete[17] reported recently that in USA and Japan, the minimum light transmission allowed for windshields is 70%, whereas in Europe it is 75%.

In reality however, the vehicle windshields are generally made of a double glazing separated by a PVB transparent sheet and are placed in oblique position. These differences will probably affect the obtained results. Their influence will be treated in an ulterior work.

5. Conclusion

In this work, some light diffusion aspects of a soda lime glass eroded by sandblasting using different sand masses are studied. The aim is to define an optical transmission limit that separates the acceptable transparency domain from the harmful fuzziness. This problem arises during the quality control of the vehicle windshields eroded by sand winds in the Saharan areas of Algeria. Variation of the optical transmission versus the samples roughness was determined. The results show that the roughness increases with the increase in the projected mass whereas the optical transmission decreases and tends towards a constant level located towards 13%. For the low projected masses, the optical transmission is maximal in the specular direction (normal light incidence). As the projected mass increases, a spreading out of the curves is observed.

In the optical characterization part, the light diffusion made for various surface states is studied in particular. The varying parameters are: the distance between the samples and the detector, the incidental light beam diameter and the scattering angles.

- For weak scattering angles, there is a strong diffusion. When moving away from the specular direction (when the angle becomes large), the diffusion tends to become undetectable.
- The increase in the incidental beam diameter involves the increase in light energy. This leads to an increase of the diffused intensity.
- For the initial undamaged state of glass (not sandblasted), the contour of the enlightened mark collected by a CCD camera is well defined. As the projected mass increases, the contour becomes blurred. This is related to the light diffused through space.
- The variation of the optical transmission according to the arithmetic roughness allows to define a visibility limit which is localised at about $T = 73\%$ and $R_a = 1.5\ \mu m$.

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