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1 Estimation of laser-induced damage depth from 2 surface image features

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10 **Abstract:** In laser damage experiments, damage initiation and growth are typically monitored
11 by imaging the surface of the tested fused silica sample, ignoring their bulk morphology. The
12 depth of a damage site in fused silica optics is considered to be proportional to its equivalent
13 diameter. However, some damage sites experience phases with no diameter changes but growth
14 in the bulk independently from their surface. A proportionality relationship with the damage
15 diameter does not accurately describe the growth of such sites. In the following, an accurate
16 estimator for damage depth is proposed, which is based on the hypothesis that the light intensity
17 scattered by a damage site is proportional to its volume. Such an estimator, using the pixel
18 intensity, describes the change of damage depth through successive laser irradiations, including
19 phases where depth and diameter variations are uncorrelated.

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21 1. Introduction

22 Fused silica optics are prone to damage when exposed to high-fluence laser beams at UV
23 wavelength and ns pulse duration [1]. Once a damage site has initiated, it grows after each
24 laser shot with an energy greater than a growth threshold [2]. Damage initiation and growth
25 are phenomena that limit the operation of high-power laser installations such as those designed
26 to achieve fusion by inertial confinement [3, 4]. Damage experiments were thus conducted
27 to show that the damage growth probability was dependent on laser fluence, pulse duration,
28 laser wavelength and damage size among other properties [5–8]. To quantify damage growth,
29 images of damage sites are acquired through the face of the tested sample and sizes are estimated
30 through pixel-counting on binarized images [6, 9]. Damage sites take the form of highly fractured
31 craters [10, 11]. The knowledge of the morphology of the crater in terms of lateral dimension
32 and depth is useful for the development of mitigation techniques [12, 13] or when the optical
33 component is a vacuum window that may break [14, 15]. The depth of a damage site is considered
34 to be a proportion of its equivalent diameter on the face of the sample, namely, a 3rd for fracture
35 depth, a 5th for the crater depth [10]. However, experimental results have underlined the existence
36 of phases with constant apparent damage size on sample surfaces while damage grew in depth
37 (*i.e.*, so-called Veinhard plateaus [16]). The relationship between damage depth and equivalent
38 diameter is thus not always linear, thereby underlying that fused silica crack growth is a stochastic
39 phenomenon [17].

40 Imaging the volume of a damage site to get a better knowledge of its growth is not straight
41 forward as it needs dedicated sample preparation [10, 16], or complex equipment such as confocal
42 microscopes [18, 19]. Further, measuring the depth of damage sites in brittle materials such as
43 fused silica by top view defocused images is inaccurate due to multiple reflections induced by
44 complex damage patterns. Therefore, an accurate damage depth estimator using only surface
45 images is desirable to quantify damage growth. The analysis of gray levels in non-binarized

46 surface images has proven to be more accurate than pixel-counting as a means of determining
47 equivalent damage diameters [20]. It was also shown that, during Veinhard plateaus, the gray
48 levels in surface images increased [21]. Besides, gray-level analyses have also been shown to
49 enable for the detection of damage growth earlier than pixel-counting methods on binarized
50 images [22].

51 In the following, it is proposed to provide gray level analyses in conjunction with pixel-counting
52 to obtain a robust damage depth estimator only based on non-binarized images of surfaces.
53 A laser damage growth experiment was conducted on four different damage sites on a highly
54 instrumented optical setup (Section 2.1). A traditional surface imaging, as well as from the
55 side of the sample, make it possible to measure both damage diameter and depth between each
56 laser shot. Two of these four sites experienced the aforementioned Veinhard plateau phases. A
57 series of corrections was applied to ensure that all the images in a sequence were comparable
58 (Section 2.2). Relevant features were extracted from images, namely, surface diameters and sum
59 of pixel intensities (Section 2.3). An estimator for damage depth was then inferred from these
60 two surface features. Such estimator is based on the hypothesis that the light intensity scattered
61 by a damage site is proportional to its volume. The proposed depth estimator was tested for four
62 different damage sites (Section 3).

63 **2. Materials and methods**

64 Damage growth sequences were conducted on the laser damage setup MELBA [23]. Both surface
65 and bulk images were acquired during growth experiments with tunable laser parameters. A
66 dedicated sample with polished edges without beveled corners was needed to acquire bulk images.
67 The acquired images were processed to correct for camera motions between acquisitions, gray
68 level variations and focus changes. Damage features were extracted from corrected images such
69 as damage diameter, sum of pixel intensities from images of the surface and damage depth from
70 bulk images. Such features were analyzed in order to estimate damage depth only from surface
71 data.

72 *2.1. Laser damage set-up*

73 MELBA is a laser damage test setup designed for the metrology of laser damage initiation and
74 growth. It delivers a 351 nm laser beam with up to 9 mm in diameter and customizable temporal
75 and spatial profiles [24]. For previous laser damage experiments, a fused silica sample was
76 polished on one of its lateral sides [16, 25]. As a complement to standard surface imaging, a
77 camera was added on the side of the sample to provide pseudo-volume images describing damage
78 sites in the sample bulk (Figure 1).

79 The imaging system used to acquire images of the surface was a Leica M420 microscope,
80 set up to have a pixel size of 6.45 μm in the object plane. Volume imaging was based on a
81 Navitar Zoom 6000 lens system coupled with a CCD camera, with a pixel size of 2.28 μm in the
82 object plane. The sample was lit by a white LED bar on one of its edges during damage growth
83 sequences. The lighting system was the same for both imaging systems.

84 Four damage sites were initiated on the silica sample by setting a phase ring in the laser beam
85 to provide a high fluence spot on the sample. For image correction purposes, three surface
86 fiducials were initiated on the surface of the sample near each damage site using the laser beam
87 of the MELBA setup. Such surface fiducials were visible on surface images but not in volume
88 images. Bulk fiducials, were initiated in the bulk of the sample using a laser beam with a pulse
89 duration of 0.8 ps at a wavelength of 1054 nm [26]. The bulk engraving method was similar to
90 the process described in Ref. [27]. The laser beam was focused at several depths varying between
91 0 and 1 mm below the surface of the sample (Figure 5 in Appendix).

92 The four damage sites were then subjected to a growth sequence consisting of 250 to 450 laser
93 shots at an incidence of a few degrees with mean fluence ranging between 1 and 8 J/cm^2 . Both

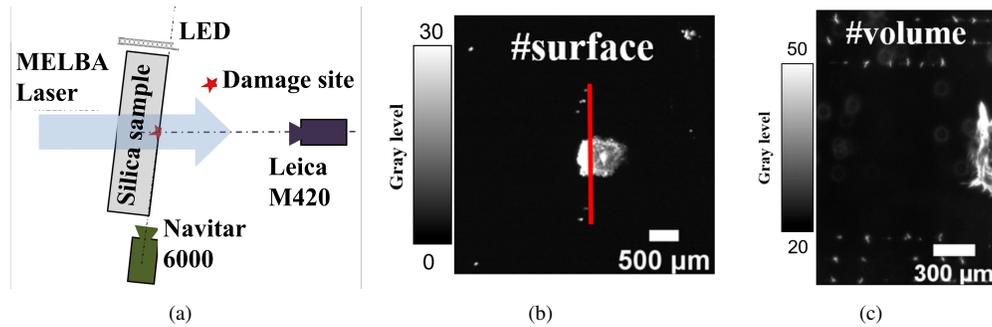


Fig. 1. (a) Imaging system used on the MELBA experimental setup to perform damage growth sequences and acquire images of surface and bulk of damage sites. The surface camera was moved in front of the sample after each laser shot and removed before the next one. Images of the surface with Leica M420 macroscope (b) and bulk with Navitar 6000 and CCD camera (c) of a damage site were acquired after each laser shot. The image plane of the bulk image is represented by the red line in the surface image. Example of images taken on site 1 after shot # 218/413

94 surface and volume images were captured between each laser shot. The MELBA beam diameter
 95 was approximately 6 mm on the sample surface. To avoid growth on surface and bulk fiducials,
 96 the spatial shape of the beam was locally shadowed in order not to irradiate them during the
 97 growth sequence. The damage sites were subjected to temporally square laser pulses, with a
 98 pulse duration of 5 ns flat in time for sites 1 and 2, and 10 ns flat in time for sites 3 and 4 (thereby
 99 ensuring a variety of lighting conditions). The fluence was regularly modified between every
 100 laser shot in order to ensure slow and gradual damage growth.

101 2.2. Image corrections

102 Throughout the growth sequence, images were affected by disturbances such as displacements,
 103 spurious light and focus changes. In order to ensure that the images are comparable during the
 104 whole sequence, with differences between them only caused by damage growth, all of those
 105 changes had to be corrected [28]. Displacements between images were corrected using Digital
 106 Image Correlation [29]. Brightness and contrast corrections were applied to reduce the effect
 107 of lighting variations [30]. Then, the images were convolved by a Gaussian kernel whose
 108 standard deviation was adjusted to equalize sharpness levels throughout the image sequence.
 109 Such corrections, fully described in the Appendix, were needed to exploit gray levels and to
 110 ensure that the damage segmentation process was consistent throughout the sequence.

111 2.3. Feature extraction

112 To extract relevant features from both surface and volume images, the first step was to determine
 113 the outline of the main damage site in every image. In both types of images, the segmentation
 114 method was the same. An example of the proposed segmentation process of a volume image is
 115 shown in Figure 2.

116 First, the outline of the damage site and its fractures were intensified through the use of a Sato
 117 filter [31] (Figure 2(b)). Originating from medical image analysis, the Sato filter was designed to
 118 identify curvilinear structures, and it is thus adapted to heavily-fractured laser damage sites. The
 119 output of the filter was then subjected to a global thresholding, which, after contour selection,
 120 resulted in a mask containing the main damage site (Figure 2(c)). The specific parameters of the
 121 Sato filter and thresholding were determined empirically, and were the same for every damage

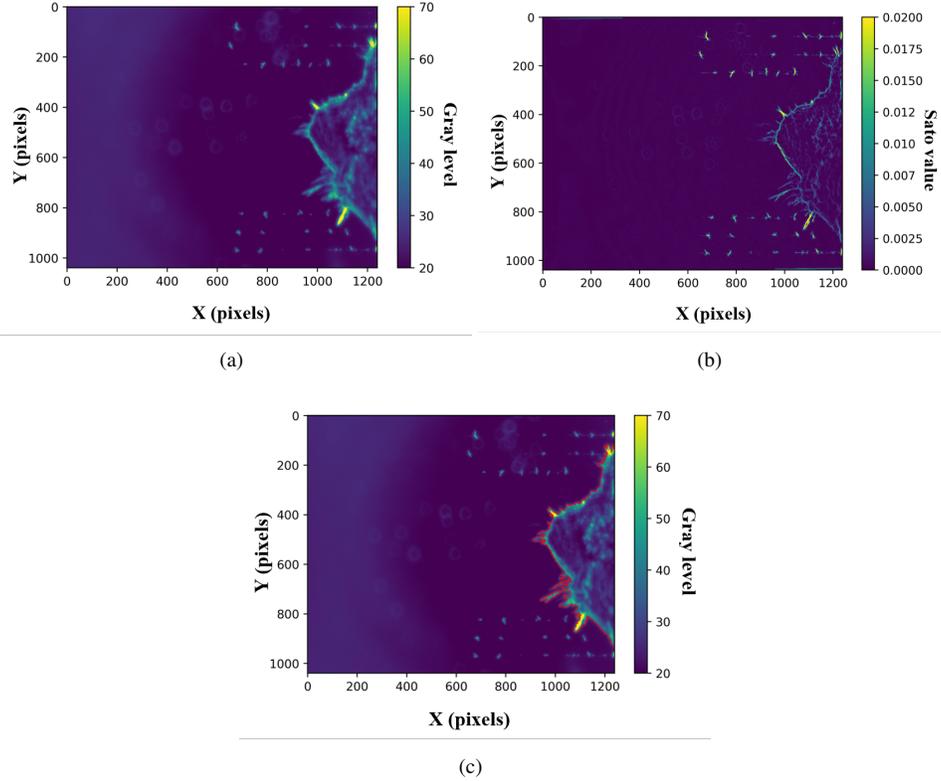


Fig. 2. Steps of the segmentation process for a volume image: (a) original image of site 2 acquired after shot # 394/412, (b) output of Sato filter and (c) resulting contour in red. Filtering allows laser damage features to be isolated from the background and bulk fiducials

122 site (although they differed between surface and volume images, as their dynamic ranges were
 123 different).

124 The obtained mask was used for pixel-counting in surface images, which yielded the apparent
 125 damage area A , as well as its equivalent diameter d

$$d = 2\sqrt{\frac{A}{\pi}}. \quad (1)$$

126 For each surface image, the RMS residual and the sum of pixel intensities were extracted from
 127 the damage mask. In volume images, the depth of the damage site was estimated with the farthest
 128 point to the surface of the sample in the damage mask. The values for damage depth, surface and
 129 equivalent diameter were converted into micrometers to be expressed on the same scale.

130 In order to estimate the depth of a damage site from surface features (*i.e.*, damage diameter
 131 and sum of pixel intensities), it was assumed that the light intensity scattered by a damage site
 132 was proportional to its volume

$$TIS = \alpha V_d, \quad (2)$$

133 where TIS (Total Integrated Signal) is the sum of pixel intensities (*i.e.*, a part of the scattered
 134 light by the damage site), V_d the volume of the damage site, and α a proportionality coefficient.
 135 Assuming that the shape of the crater of a damage site was similar to that of a spherical dome,

136 the volume of a damage site is written as

$$V_d \approx \frac{\pi}{6} \left(\frac{3}{4} d^2 \delta + \delta^3 \right), \quad (3)$$

137 where δ is the maximum depth of the damage site.

138 From Equations (2) and (3), a cubic equation is obtained

$$\delta^3 + \frac{3}{4} d^2 \delta - \frac{6}{\alpha \pi} TIS = 0 \quad (4)$$

139 The unique real damage depth solution, δ_s , to Equation (4) reads

$$\delta_s = \sqrt[3]{\frac{3TIS}{\alpha\pi} + \sqrt{\frac{3d^4}{1024} - 8\frac{TIS^3}{(\alpha\pi)^3}}} + \sqrt[3]{\frac{3TIS}{\alpha\pi} - \sqrt{\frac{3d^4}{1024} - 8\frac{TIS^3}{(\alpha\pi)^3}}} \quad (5)$$

140 The proportionality factor α was estimated using a linear fit for damage site 1, and was equal
141 to $6 \times 10^{-3} \text{ GL}/\mu\text{m}^3$.

142 3. Results and discussion

143 The estimators of damage depth based on the fraction of damage diameter or on the proposed
144 model (Equation (5)) were evaluated according to the R^2 scores reported in Table 1. The R^2 score,
145 or Pearson correlation coefficient, quantifies the quality of a linear regression [32]. A perfect
146 regression involves an R^2 score equal to 1. The best fraction of damage diameter was evaluated
147 to be $\frac{1}{2.32}$ for these four damage sites. Such fraction is close to $\frac{1}{3}$ reported in Ref. [10]. Thus,
148 the damage sites studied in this paper were representative of those evaluated in the afore-cited
reference.

Table 1. R^2 score on each site for both depth estimators (best fraction of diameter and Equation (5)).

Depth estimator	R ² score			
	Site 1	Site 2	Site 3	Site 4
Equation (5)	0.96	0.95	0.96	0.96
Best fraction of diameter	0.81	0.98	0.98	0.99

149
150 The R^2 scores were calculated between the true depth measured on the images (in green in
151 Figures 3 and 4) and that given by the different estimators, namely, best fraction of diameter, $\frac{1}{2.32}$
152 (in red) or the proposed equation (in blue). Sites 2, 3 and 4 were well described by the depth
153 estimator based on a fraction of diameter, with R^2 scores ranging between 0.98 and 0.99. The
154 depth of site 1 on the other hand could not be described solely with a constant fraction of damage
155 diameter, as shown by an R^2 score of only 0.81, mainly because of a large Veinhard plateau
156 during the growth sequence. Such phase is observed in **Visualization 1** between images 240 and
157 295.

158 As demonstrated in Ref. [10], the variation of the aspect ratio of a damage site during growth
159 sequence confirmed that it is not possible to monitor damage depth using only the fraction
160 of damage diameter. The depth estimator based on the damage diameter fraction provided a
161 rough depth estimation, but did not allow uncorrelated changes in diameter and depth to be
162 described (as for site 1).

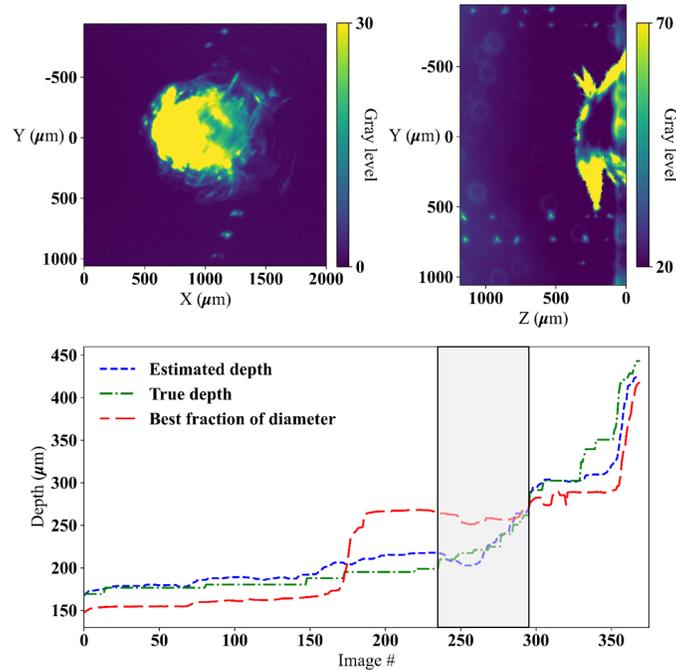


Fig. 3. Damage depth as a function of laser shot number for damage site 1; true depth in green, best fraction of diameter in red and estimated depth using the proposed estimator of Equation (5). A Veinhard plateau is observed between images 240 and 295 corresponding to damage growth in the bulk and not on the surface. The best fit is obtained with a spherical dome modeling (Equation (5)) despite the uncommon growth behavior. Bulk and surface images were acquired on site 1 after shot # 413/413 (i.e. the last laser shot of the sequence of **Visualization 1**).

163 The depth estimator based on the assumption that the scattered light intensity of a damage
 164 site is proportional to its volume (Equation (4)) yielded good results throughout the shooting
 165 sequences for all 4 damage sites. The R^2 scores were nearly identical for the 4 sites (i.e., varying
 166 between 0.95 and 0.96). Such R^2 scores were slightly lower than those obtained by the best
 167 fraction of diameters for sites 2, 3 and 4 but higher for site 1. These results demonstrate the
 168 efficiency of the proposed depth estimator, even when the studied damage site follows so-called
 169 Veinhard plateau phases. The estimated depths using the proposed method were similar to that
 170 measured by imaging the edge of the sample. The proposed method may avoid bulk observations
 171 of a damage site by the edge, which is time consuming because of the need to polish one edge. It
 172 is worth noting that the proposed method allows for measurements of the depth for all damage
 173 sites, not just sites on the edge of the sample, as opposed to edge observation.

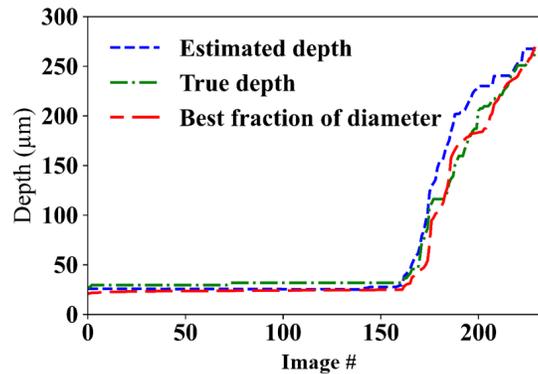


Fig. 4. Damage depth as a function of laser shot number for damage site 4; true depth in green, best fraction of diameter in red and estimated depth using the proposed estimator of Equation (5). In the present case, both estimators yielded similar results

174 **4. Conclusion**

175 The laser damage growth experiments described in the present work showed that the conventional
 176 proportionality between damage diameter and depth was not accurate for every growing site.
 177 Such relationship was modified using the hypothesis that the scattered light of a damage site was
 178 proportional to its volume. From this hypothesis, the damage depth was written as a function of
 179 damage diameter *and* intensity of scattered light.

180 Gray levels in surface images were an efficient indicator of damage growth on the surface and
 181 in the bulk even in cases when damage areas appeared constant through counting the number of
 182 lit pixels. By only using the damage size on surface images as a damage growth indicator,
 183 laser damage sequence experimenters may take the risk of considering a damage site as still,
 184 even though it grows predominantly in its bulk (*i.e.*, Veinhard plateau phases). The damage
 185 growth probabilities may therefore be underestimated. The analysis of gray levels in surface
 186 images allowed this pitfall to be avoided. It was demonstrated that increasing damage depth with
 187 constant diameter was observable only with surface images by taking into account gray level
 188 variations. The damage depth was quantitatively estimated for four damage sites using only the
 189 sum of pixel intensities and damage diameter.

190 In this paper, damage depth was estimated from TIS and damage diameter for a specific
 191 observation system but the method could be extended to different spatial resolutions, dynamic
 192 range or even other lighting systems. These parameters of the imaging and illumination system
 193 may have a significant impact on the measurement performance. These points may be the subject
 194 of further investigation knowing that damage observation systems differ from one laser damage
 195 testing setup to another. The description of the shape of a laser damage site by a spherical dome
 196 could also be refined to improve the accuracy of the proposed method for estimating damage
 197 depth. It would also be interesting to take into account cracks in the damage site, using for
 198 example fractal dimensions [16].

199 The results presented in this article pave the way for fast and accurate damage depth estimation
 200 with no need for complex instruments or time-consuming preparation of the sample. This easy
 201 access to the depth of damage sites may, among other things, bring an additional dimension
 202 to laser damage studies. The proof of concept focused on laser damage testing setup, but the
 203 application field could be extended to other domains where accurate and fast monitoring of
 204 transparent media is necessary (*e.g.*, glass and windshield industries).

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209 **Data availability.** Data underlying the results presented in this paper are not publicly available at this time
210 but may be obtained from the authors upon reasonable request.

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309 **Appendix: Registration procedure**

310 The metric used to evaluate the efficiency of image corrections was the Root Mean Square (RMS)
311 residual [29]. The RMS residual is the normalized quadratic norm of the difference between the
312 reference and the corrected image over zones of interest, expressed as a percentage of the dynamic
313 range of the reference image. For each sequence, the first image was used as the reference.

314 The first step of image corrections was to define the fiducial zones that were used as references.
315 Two different fiducial masks were created, both shown for site 1 in Figure 5. The first one, type
316 A, was composed of large rectangles containing the bulk fiducials. The second one, type B, was
317 defined through Otsu thresholding to tightly segment bulk fiducials [33]. Type A was used for
318 spatial registration in the same way as in Ref. [34]. Type B was dedicated to brightness and
319 contrast corrections [28]. It was assumed that lighting variations affected the fiducial pixels
320 (type B) the same way as the pixels of damaged sites while it may not be the same for the pixels
321 corresponding to bulk silica (background). Some fiducials were not included in these masks
322 as they ended up being absorbed by the main damage site during the growth sequence. Such
323 fiducials were not suitable as reference markers. For consistency and comparison purposes, all

324 displayed RMS residuals were calculated on type B fiducial zones, even if the correction itself
 was based on type A zones.

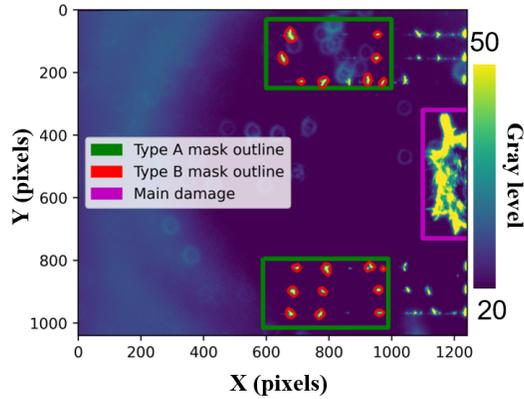


Fig. 5. Outline of type A (resp. B) fiducial masks in green rectangles (resp. red contours) and main growing damage site in the magenta rectangle. Example from volume image # 250/412 of site 2.

325 First, the volume images of one damage site were used to exemplify the proposed corrections,
 326 before moving to less complex surface images. Camera motions between images may arise due
 327 to vibrations, or hysteresis in the motorized systems of the cameras. Digital Image Correction
 328 was used to estimate the displacement field \mathbf{u} between reference image I_0 and subsequent image
 329 I_n . By decomposing the displacement field on a selected basis consisting of 4 fields (*i.e.*, rigid
 330 body translations and rotation, as well as scale changes) [28], the cost function
 331

$$\Phi_A^2 = \sum_{\mu_A} [(I_n(\mathbf{x} + \mathbf{u}(\mathbf{x})) - I_0(\mathbf{x}))^2] \quad (6)$$

332 was minimized over the type A fiducial mask μ_A (Figure 5) with respect to the unknown
 333 amplitudes associated with the kinematic basis with a Gauss-Newton method [29].

334 As shown in Figure 6(a), the image registration procedure decreased the RMS residual on
 335 fiducial zones, making it less than 3% of dynamic range. However, several jumps in the residuals
 336 remained, corresponding to discontinuities in the estimated kinematic parameters (Figure 6(b)).
 337 It is worth noting that such discontinuities occurred only when the system had to be reset,
 338 moving the cameras back into place and turning off the LED bar. They were also associated with
 339 significant time gaps, during which spurious lighting variations may have arisen, explaining why
 340 the residual variations were still visible after correction for camera motions. Changes in the
 341 way the sample was illuminated led to differences in gray levels of the images. To correct such
 342 variations, brightness and contrast fields b and c were introduced in the cost function [30]. In
 343 order to minimize the cost function $\Phi_B^2 = \sum_{\mu_B} [(1 + c(\mathbf{x}))I_n(\mathbf{x} + \mathbf{u}(\mathbf{x})) + b(\mathbf{x}) - I_0(\mathbf{x})]^2$, b and
 344 c were decomposed on a polynomial basis of low degree (2 in the present case). The amplitudes
 345 of brightness and contrast fields were estimated by solving a linear system [28]. Here, the
 346 summation was performed on the type B fiducial mask μ_B (Figure 5), as the camera acquired
 347 images of the light scattered by damage sites. Therefore, it was assumed that fiducials provided a
 348 similar response to illumination changes as the main damage sites, while that of bulk silica was
 349 different. Such differences required to use tightly segmented fiducials for an accurate estimation
 350 of the brightness and contrast fields on the damage site.

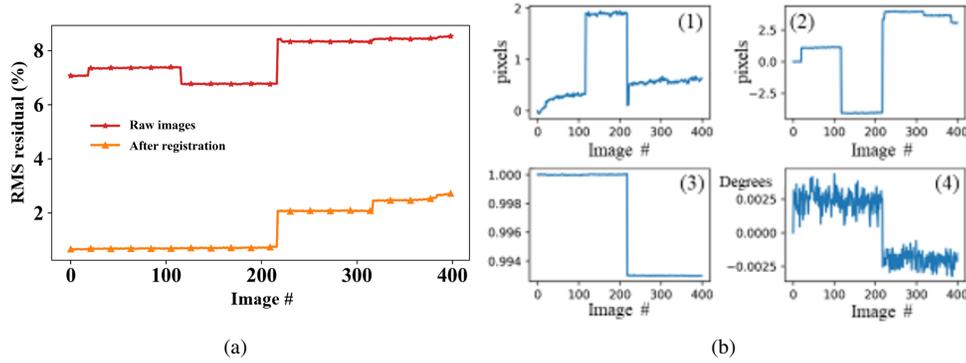


Fig. 6. (a) Normalized RMS residual on type B zones before (red) and after displacement correction (orange). Kinematic parameters estimated during the displacement correction process via Digital Image Correlation: (b-1) vertical translation in pixels, (b-2) horizontal translation in pixels, (b-3) scaling and (b-4) rotation in degrees.

351 The last correction was related to camera focus and consequently to image sharpness. The
 352 Tenengrad function on the segmented fiducials was used to estimate image sharpness [35]. Then
 353 images were convolved by a Gaussian kernel whose standard deviation was adjusted to equalize
 354 sharpness levels throughout the image sequence. Another effect of such correction was an overall
 355 decrease in RMS residual values since the convolution smoothed out acquisition noise. After
 356 displacement, brightness, contrast and sharpness corrections, variations in the RMS residual
 357 levels remained, as observed in Figure 7, but their amplitude decreased more than five-fold thanks
 358 to the efficient image processing pipeline.

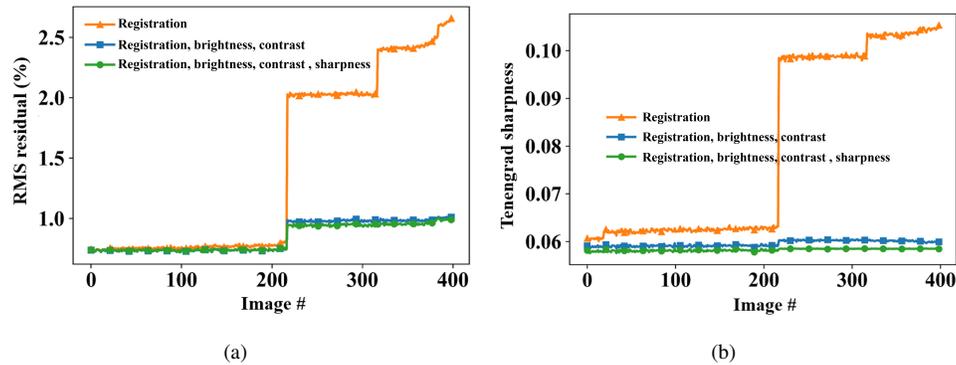


Fig. 7. (a) Normalized RMS residual on type B zones after displacement (orange), brightness and contrast (blue) and sharpness (green) correction for volume images. (b) Tenengrad sharpness on type B zones after displacement (orange), brightness and contrast (blue) and sharpness (green) corrections.

359 The surface images required less complex corrections than the set of volume images. As
 360 shown in Figure 8, after displacement and gray level corrections, no significant residual variations
 361 remained. Therefore, no further corrections were applied to surface images.

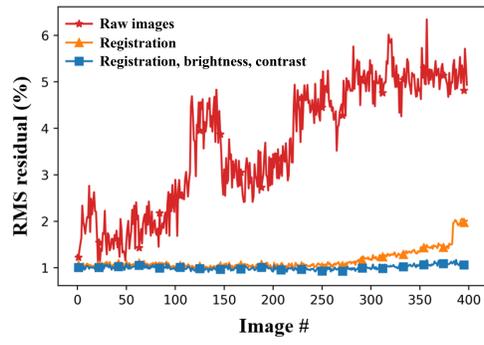


Fig. 8. Normalized RMS residual on type B zones for surface images before (red), after displacement (orange) and after brightness and contrast correction (blue) for surface images.