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Influence of the Paint Coating Thickness in Digital Image Correlation Experiments

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***Abstract*—**In the past decade, the use of digital image correlation (DIC) techniques has increased significantly in the area of experimental mechanics, especially for materials behavior characterization. This non-contact tool enables full field displacement and strain measurements over a complete region of interest. The DIC algorithm requires a random contrast pattern on the surface of the specimen in order to perform properly. To create this pattern, the specimen is usually first coated using a white matt paint. Next, a black random speckle pattern is applied using any suitable method. If the applied paint coating is too thick, its top surface may not be able to exactly follow the deformation of the specimen, and consequently, the strain measurement might be underestimated. In the present article, a study of the influence of the paint thickness on the strain underestimation is performed for different strain levels. The results are then compared to typical paint coating thicknesses applied by experienced DIC users. A slight strain underestimation was observed for paint coatings thicker than about 30µm. On the other hand, this value was found to be uncommonly high compared to coating thicknesses applied by DIC users.

***Keywords*—**Digital Image Correlation, paint coating thickness, strain.

I. Introduction

DIGITAL Image Correlation technique is a non-contacting measuring tool based on the acquisition, storage and processing of images taken from a specimen, with the purpose of extracting full-field shape, displacements or strains of this specimen [1]. The use of DIC tools in experimental mechanics has increased notably in the last years, utilizing its capacities for a wide range of purposes: from measuring deformations at a microscopic level [2], [3], to full-field characterization of large structures [4], [5]. On the other hand, capabilities of DIC have been extended to characterize the behavior of a wide variety of materials such as rubber [6], concrete [7] or even composite structures [8].

Regardless of the material nature, specimen size, or type of experiment, all objects to be measured have in common that a random contrast pattern needs to be present over the surface of interest. The DIC algorithm requires this random contrast pattern in order to compare unique discrete grayscale functions between the reference and deformed image [9]. The most common technique for creating the abovementioned pattern is using ordinary spray paint. Usually, the surface of the specimen is first coated with white matt paint. This layer should have enough coverage, and the thickness required usually depends on the color and properties of the surface of the object under investigation. After that, a black random speckle is applied to create the contrast pattern. Using this methodology to create the random contrast pattern, the DIC user actually measures the deformation of the top face of paint coating attached to the object under investigation. As such, the strain should be transmitted to the coating without amplification or attenuation. This implies that the strain should be uniformly distributed through the thickness of the paint layer. If the applied coat is too thick, however, it might not be able to deform in conjunction with the specimen surface, therefore, leading to strain underestimation.

The present work aims to characterize this strain underestimation in relation to the paint coating thickness and the strain level. To this purpose, a steel dog-bone tensile specimen was painted with 8 increasing coating thickness, and then subjected to tensile loads up to a uniform strain level of about 12%.

After image processing, a tendency to underestimate the strain measurements was noticed from coating thickness of about 30µm, for strain levels over 2%. On the contrary, no significant influence of the coating thickness was observed for elastic range deformations with this test configuration.

It was then decided to perform a new test with a smaller pixel size in order to increase the sensitivity of the measurements. Only two different coating thicknesses where used in this configuration since the field of view decreased significantly. Four strain levels ranging from 0.05% to 0.12% were applied in this study. No significant influence of the coating thickness was observed up to strains of 0.1%.

Finally, the results obtained from the tests were later compared to coating thickness of real specimens painted by 5 different experienced users of DIC with the aim of discerning whether the critical coat thickness values obtained in the study were usually reached or not.

It was found that experienced DIC users apply a layer thickness close to 12µm on average, with a standard deviation of 5.6µm. Consequently, it is concluded that critical coating thickness values are rarely reached by DIC users.

Nevertheless, this study establishes limits on the thickness of paint layers used in DIC experiments to prevent strain underestimation.

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II. Test Description: Plastic Strain Test

As previously stated, a dog-bone type tensile specimen was used for the present experiment. It was painted with 8 increasing coat thicknesses along its uniform deformation zone. Next, the specimen was subjected to a uniaxial tensile load up to 12% uniform strain, well below the onset of diffuse necking of the test material.

In the following subsections the test procedure and results obtained will be presented.

A. Specimen Preparation

The test specimen is prepared from a SS304 steel sheet using laser cutting and the dimensions are in accordance with ASTM E8M-96.

The original gauge length (L0=80 mm) was divided in 8 different zones with increasing paint layer thickness. A matt white stray paint was utilized for the application of these layers. The gauge length was then subjected to increasing strain levels up to 12% uniform deformation. The maximum uniform strain (i.e. the onset of diffuse necking) of the test material was about 40%. As such, uniform deformation is guaranteed in the experiment. In order to ensure increasing coating thickness from one region to the next one, the spray paint was applied by layers, covering one region at each layer application. That is, the thinnest region would have only one paint layer, meanwhile over the thickest region there would have been applied 8 layers. A maximum time period of 30 minutes between layer applications was established to ensure good overlapping between paint layers. The painted specimen is shown in Fig. 1. It clearly shows different levels of coverage. A black speckle pattern was later sprayed over all 8 regions.

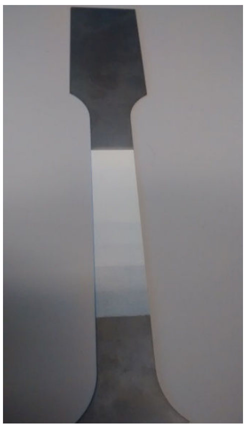

Fig. 1 Painted specimen

An ultrasonic thickness gauge was utilized to perform the coating thickness measurements. The results obtained for each region are presented in the following graph (Fig. 2). The paint layer thickness ranges from about 10μm to 110μm.

B. Test Procedure

Uniaxial loading was applied to the specimen using a Zwick Z010 testing tensile machine. The setup of the specimen and the cameras used to acquire the images can be seen in Fig. 3. Stereo DIC was utilized to perform the analysis and the achieved pixel size was 0.092 mm.

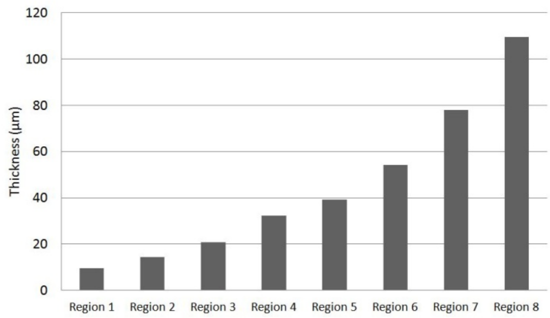

Fig. 2 Coating thickness of each region

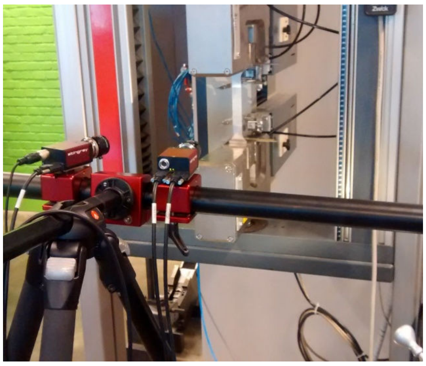

Fig. 3 Test setup

An ordinary displacement controlled tensile test was carried out on the specimen with a cross head speed of 0.1 mm/s. Images were taken with a frame rate of 1 Hz. The influence of the layer thickness on the accuracy of the strain measurement was evaluated at 6 different strain levels from 2.4% to 12.1%. The reference was measured using the extensometer of the tensile machine. The initial position of the sensor arms of the extensometer exactly spanned the painted area.

All the images captured during the test were processed utilizing the image correlation software Match ID 3D [10], and the proceedings settings are summarized in the Table I. The obtained axial strain fields were utilized in the present study.

TABLE I
Image Correlation Parameters for Plastic Test

Parameter	Value
Subset size	21 pix.
Step Size	5 pix.
Transformation order	Affine
Strain window	21 pix.
Strain interpolation	Q4
Strain convention	Euler-Almansi

C. Test Results

After processing all images captured during the test, results were extracted at 6 selected load steps. As an example, the strain field corresponding to a deformation close to 8% is shown in Fig. 4. This figure clearly reveals a decreasing tendency of the strain as the paint thickness increases. The same behavior was observed for the rest of the strain states.

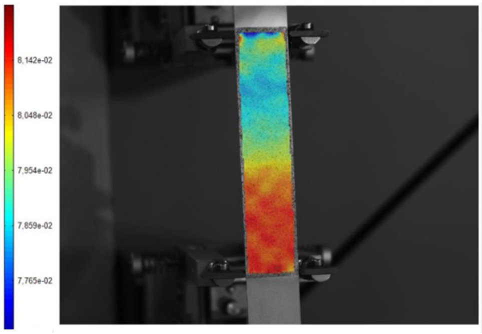

Fig. 4 Strain field distribution at actual strain of 8.12%

In order to quantify the strain error when increasing the paint thickness, the mean strain value in each of the 8 paint layers was calculated. For the sake of clarity, these values were then normalized by the reference strain. The results are shown in Fig. 6 that it can be inferred that the strain error increases from a coating thickness of 30µm. It can be also noticed that the evolution of the strain decrease in relation to the coating thickness is independent of the strain level. Finally, it is important to point out that the strain decrease is notable, close to 5 % in all load steps.

During the analysis of all the images processed in this experiment, no strain differences were observed when increasing the coating thickness for small strains, i.e. within the elastic limits of the material. In order to investigate whether increasing the image precision (decreasing the pixel size), a strain underestimation effect could be discerned; a new test configuration was carried out as described in the following section.

III. Test description: Elastic Strain Test

As mentioned in the previous section, the purpose of this study was to assess whether at a higher precision, the paint thickness would have a more significant influence on the strain measurements in the elastic range of the material. Since, the field of view needed to be notably decreased in order to increase the image resolution, only two coating thickness steps were produced on this specimen. These thicknesses correspond approximately to the thinnest and thickest coating areas of the previous experiment (8.11µm and 113.12µm respectively). A pixel size of 24µm was achieved in this configuration. The specimen's region of interest for both coating thicknesses are shown in Fig. 5.

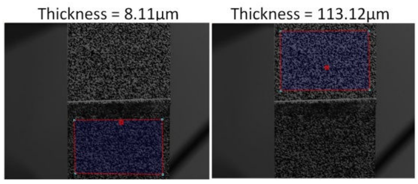

Fig. 5 Area of interest of both coating thickness steps

The specimen and experiment setup was the same as the one described in the previous section. A total of 4 increasing load steps were applied ensuring elastic behavior of the specimen. The main DIC settings used for the image correlation are summarized in Table II.

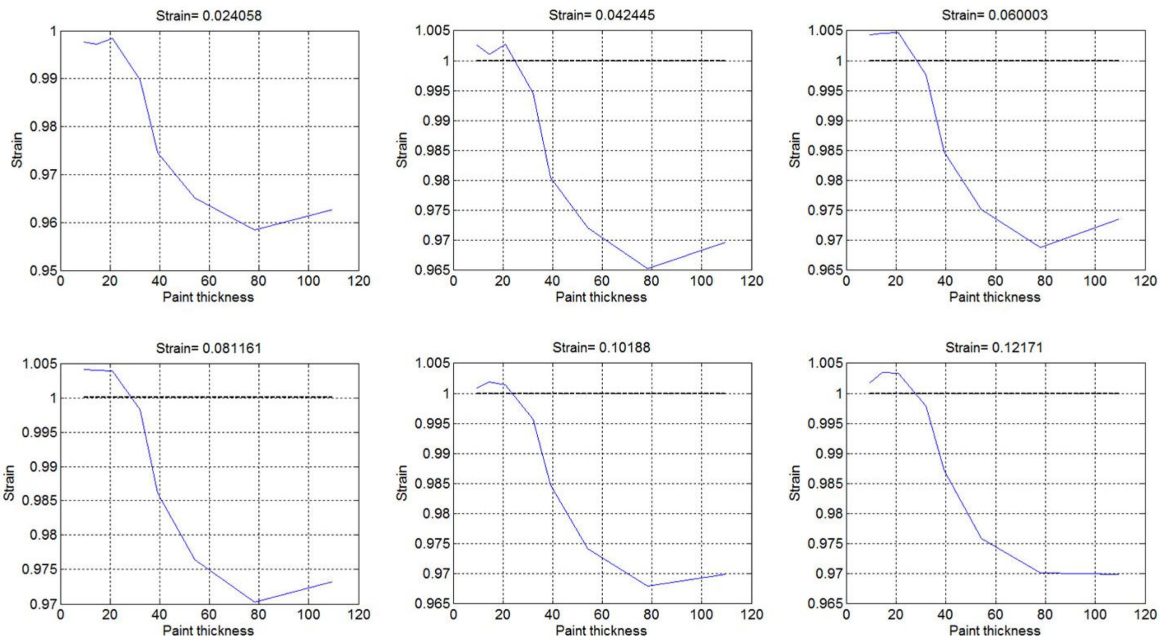

Fig. 6 Normalized strain evolution with increasing paint thickness for different strain levels

TABLE II
IMAGE CORRELATION PARAMETERS FOR ELASTIC TEST

Parameter	Value
Subset size	21 pix.
Step Size	9 pix.
Transformation order	Affine
Strain window	19 pix.
Strain interpolation	Q4
Strain convention	Euler-Almansi

The strain versus force graph is shown in Fig. 6, where a linear behavior can be observed for the first 3 load steps imposed. A slight non-linearity might be observed at the 2200N load step, likely because the proportionality limit of the material was reached. It was then decided not to apply larger loads that might increase any non-linearities.

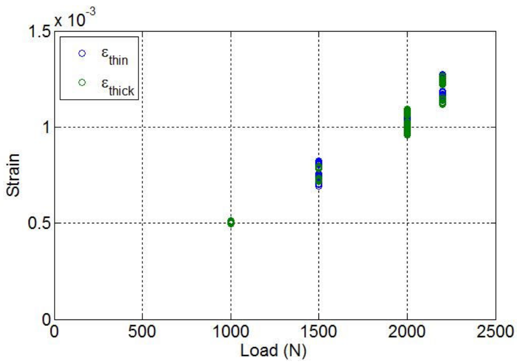

Fig. 6 Strain versus load for both thin and thick paint coatings

Although it can be observed from Fig. 6 that both thin and thick coatings exhibit similar behavior, a more profound analysis is presented in the next section.

A. Test Results

Fig. 7 shows the ratio between mean strain values obtained at thin and thick regions for each image captured. No tendency is noticed for the first three load steps. A slight decreasing tendency of the strain ratio is observed for the 2200N load steps, meaning that the strains obtained for the thinner area are slightly higher than for the thicker one.

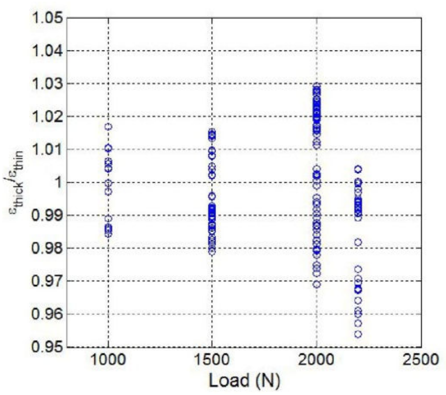

Fig. 7 Strain ratio between thin and thick coatings for every load step

As stated before, the goal of this test was to increase the resolution and precision of the strain measurements: first, the pixels size was decreased to 24µm; secondly, the processing settings were aimed to minimize noise for both coatings applied. The standard deviation and the relative standard deviation achieved for each of these coatings and for every load step can be seen in Figs. 8 and 9 respectively.

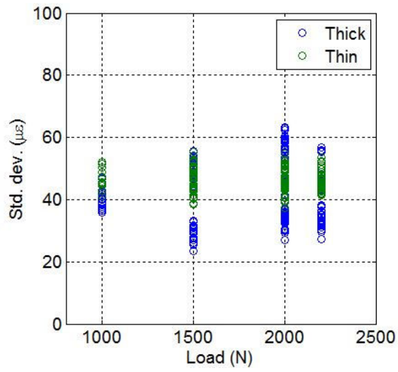

Fig. 8 Strain standard deviation at thin and thick coatings for every load step

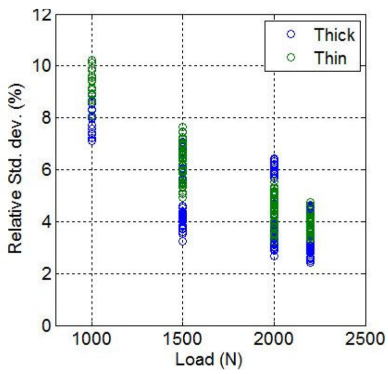

Fig. 9 Strain relative standard deviation at thin and thick coatings for every load step

Observing the results obtained in Section II regarding material plastic deformation, it was seen that the strain underestimation at the thickest coatings rarely exceeds 4%. It also was found to be independent on the strain level. Based on these results, also a relative maximum error of 4% should be expected at the strain levels of this experiment.

On the other hand, since the expected underestimation value is smaller than the relative standard deviation of most of the results obtained in the present study (Fig. 9), it is likely that the precision achieved with this test configuration would not be sensitive enough to discern the strain underestimation due to the coating thickness in the elastic range of the material.

For the 2200N load case, the relative standard deviation takes values close to 4%, and, as stated before, a slight strain decrease can be discerned at the thick coating in relation to the thin coating. That could point out that the strain sub-estimation is visible from strains values of around 0.12% with the present test configuration.

IV. DIC Users Coating Thickness Characterization

From the obtained results in the tests performed, it can be concluded that a strain underestimation is incurred when the paint thickness increases, observed to be significant when the coating thickness exceeds 30µm. From a practical point of view, it might be of significant interest for regular DIC users to know whether this critical thickness value is easy to reach or not. To this purpose, the coating thickness of 9 different specimens painted by 5 different DIC experienced users was measured. For each specimen, 20 measurements were acquired at different locations of the painted surface. The mean thickness and standard deviation for each specimen are shown in Fig. 10.

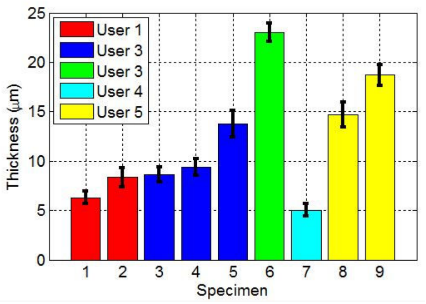

Fig. 10 Strain relative standard deviation at thin and thick coatings for every load step

The overall mean thickness obtained is 11.98 µm with a standard deviation of 5.66 µm. Only user 3 applied paint coating over 20µm (22.8 µm), which is below the critical paint layer thickness found in the previous sections.

V. Conclusion

This article investigates the influence of coating thickness on the accuracy of strain measurements using DIC. Separate tests have been carried out to evaluate this influence for larger strains over the yield limit of the material ($\varepsilon > 2\%$) and for smaller strains within the elastic range ($\varepsilon < 0.15\%$).

For plastic strains, a clear influence of the paint thickness on the results was observed. Strains in this case are underestimated if the coating thickness exceeds 30um. The influence proved to be independent on the strain level and can be divided into 3 separate regions in relation to the paint thickness:

- Thickness under 30 µm: No influence on the strain calculations.
- Thickness from 30 µm to 80 µm: increasing strain underestimation tendency up to a relative error to the reference of 3-4%.
- Thickness over 80µm: Strain underestimation stabilizes.

Regarding the linear elastic strains study, no significant influence of the paint thickness on the results was noticed with the test configuration described in Section III. Consequently, there would be no need for the DIC user to concern excessively about paint thickness when measuring elastic deformations in steels, inasmuch as the test precision is equal to or less than the one described in Section III. Nevertheless, for test configurations with a smaller pixel size, an equivalent study should be performed to assess the paint thickness influence.

Additionally, from the study of the coating thickness on real specimens, it was found that that critic thickness values are far from the usual ones applied by regular DIC users.

Finally, it is worth to point out that the strain underestimation due to too thick paint coatings occurs at unusual high paint thickness values. On the other hand, this error becomes significant at very thick coatings, getting close to relative 5% deviations in some cases.

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