



EFFECTS OF STRAIN RATE ON THERMOPLASTICS MATERIALS: AN EXPERIMENTAL ANALYSIS APPLYING DIGITAL IMAGE CORRELATION

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Abstract. *With the great need of study of the materials mechanical properties, fundamentally in engineering, the extensometric technics already exists in several ways, nevertheless new technics arise, always with the intention of perform measurements ever more accurate and punctual, with simple installation and simple methodology. In this setting, the optical extensometry emerge with image correlation technique, which has as principle to use a software, Correli Q4^{LMT}, to analyze a tensile testing recorded in pictures captured by a high-speed camera with high resolution. The singularity of this procedure is a texture layer that must be applied to the specimen before the test. The aforementioned software, basically, divides the first picture – with no deformation called reference image – in several little parts – called zones of interest, ZOI –, and then compares the second image with the first, searching for the same zones of interest and calculating their displacement and deformation, after this compares the third picture with the second and so on until to compare all the pictures selected. At the end, the software provides a file with all the testing data, then is used the gauge function that allows the placement of virtual gauges, that will get all the displacement and strain data in both directions of the plan – the same way that strains gauges, but without their complicated fixation procedure - from each picture compared with the previous. This study aimed to apply the digital image correlation technique to tensile testings with PVC – polyvinyl chloride – and HDPE – high density polyethylene.*

Keywords: *tensile testings, extensometry, digital image correlation (DIC), polymeric mechanical behavior.*

1. INTRODUCTION

Extensometry is a set of techniques for determining the deformation state around a point in a body, from the knowledge of the extensions that point in different directions (Portela and Silva, 1996). Among all the techniques, the use of electric extensometers, called strain gages, is the most used, due to your accuracy and capacity to measure deformations in both directions of plan. Still new techniques with different principles appears and developed, in this direction, the digital image correlation (DIC) is one of most the most promising extensometric techniques.

The DIC principle is based on the fact that the distribution of grey scale values of a rectangular area in the initial image corresponds to the distribution of grey scale values of the same area in the destination image. A cumulative strain map can be obtained by comparing each current deformation image with the initial image, while an incremental strain map can be computed by comparing the image at the current load step with the image recorded just before the current load increment. These maps are computed from the recorded data by the software Correli Q4^{LMT} developed by Hild and Roux (Benallal, et al., 2008). To apply this technique the effect of strain rate on polymeric materials were analysed.

Polymers are materials highly susceptible to creep (Sperling, 2005), that is the permanent and time-dependent deformation, when the material is submitted to constant stress (Callister, 2000). The intensity of this phenomenon is affected by three factors: stress, time e temperature (Gerry and Ron, 1994). This highly susceptibility of the polymers to creep deformation is due to the molecular structure of these materials that when subjected to a load presents as response two types of deformation, one permanent, similar to the fluids deformation, and other resilient, characteristic of an elastic behavior such as Hookean solids. The phenomenon by which a polymer has characteristics of a fluid and an elastic solid at the same time is called viscoelasticity (Canevarolo Jr, 2006). The elastic portion of this deformation is due to angles and distance variations between the polymeric chain atoms, while the plastic portion appears due to the friction and flow between the polymeric molecules (Canevarolo Jr, 2006).

On this basis, this study aimed to analyze, through tensile tests and using DIC technique, the effect of strain rate on the mechanical behavior of the thermoplastic materials PVC (Polyvinyl chloride) and HDPE (High density polyethylene). Altogether, ten tensile tests were performed, with the strain rate varying in a range between 10^{-1} s^{-1} and $10^{-3.5} \text{ s}^{-1}$, four of them were carried notched specimens and six of them using smooth specimens. Those notches are applied to create stress concentration on specimens and one can observe their effects on the necking zone formation. From the data curves were plotted, from which the mechanical properties were obtained. It is worth noting that the mechanical behavior of polymers is still controversial, the existence of a limit of elasticity or Young's modulus is rather questionable and the characterization of these materials depends strongly on factors such as the load application rate,

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temperature at the testing, the specimen historic, etc. (ASTM International, 2010). Still, during the analysis of the tests, we tried to follow the ASTM D638-10 standard for determining the polymers mechanical properties.

2. THE DIGITAL IMAGE CORRELATION

This technique consists in use a high-definition and high-speed camera to record a test, in view of there is necessary a lot of pictures that follows a chronological sequence orderly of the test.

So that the images can be analyzed, a texture pattern, as shown on Fig. 1, must be applied on the specimen surface, so that the image is recognized by the software in gray levels. This painting consists in apply a homogeneous black paint, throughout the specimen surface that will be photographed, followed by the random deposition of minuscule white ink droplets. It is noteworthy that the first painting can be with white ink and the droplets can be black, the important thing is create a texture that can be recognized in gray levels. Despite the heterogeneity of texture, the deposition of droplets should be as homogeneous as possible, given that the program, during its analysis, discretizes the region of interest of the first picture (without any strain), called reference image, in a lot of small rectangles called Zones of Interest (ZOI).

The DIC principle is to read the gray level of each ZOI on the reference image, and search for the same pattern in the following picture, recognizing the ZOI and calculating its displacement in comparison with the previous picture and the extent of its dimensions variation (Hild and Houx, 2006).

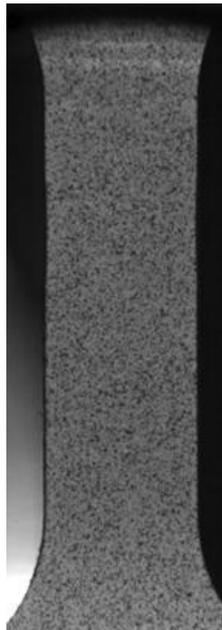


Figure 1. Example of a pattern texture necessary to apply this technique.

3. EXPERIMENTAL PROGRAMME

Before performing the test, the specimen is subjected to a texturing process quite simple as explained in the previous section.

The high-speed camera must be positioned to focus on the specimen, already positioned in the testing machine, and its mounting or support must be sufficiently rigid so that no flickering occurs because the smaller displacement of the camera during the test will result in errors, since the program compares an image with the precious one, this unwanted movement is usually calculated by the program as an normal displacement of each ZOI. The mounting apparatus is shown in Fig. 2.



Figure 2. The mounting apparatus of DIC technique

Still before start the testing, to guarantee that the testing will be analyzed appropriately, a picture must be taken and pre-analyzed on Correli Q4^{LMT}, where it will have its gray levels plotted on a histogram, in which must be observed a normal distribution if the texture applied to the test body has a good quality, and the lightning conditions are good.

As there was no device that activates the camera at the same time the machine started the test, the camera was turned about to activate the testing machine, this way the first pictures do not show any difference in relation to each other, and therefore, after obtaining the results it is always possible to identify clearly the moment the test began, since the strain values for the first images are always near-zero (on the order of 10^{-6}), which would be the margin of error of the program, these values remain near-zero until a peak is observed which is then interpreted as the test start.

The step after test completion is to use software Correli Q4^{LMT} and select some parameters:

1. Select reference image (image of the specimen without deformation)
2. Select the Region of Interest (ROI): Since there is only interest on specimen, it is not necessary analyze the entire image, so the ROI selection consists in set up the area of the image that will be analyzed.
3. Set up calculation parameters: number of iterations, number of scales and size of ZOI. All associated with the analysis's refinement degree, the more scales and iterations plus accurate is the calculation, but more time consuming. Further analysis will be more punctual the smaller the size of ZOI.
4. Select the images to be analyzed. If there are many pictures you can use a parameter called increment, which works by selecting a few images from a sequence as a reason in an arithmetic progression.
5. Selected images and parameters, the program performs, independently, an extensive sequence of calculations and in the end provides the option to save a file MAT format that contain all the analysis data and allows, through own Correli viewing test results as displacement and strain fields in both directions of the plane, as will be shown in the results discussion.

Finally, since the file MAT saved. We can use the *gauge* function of Correli that allows you to place a rectangle of any size, called virtual gage, anywhere in the ROI, such rectangle performs the same function of a strain gage by calculating deformations locally, the evident difference is that the strain gage need to be attached directly to the specimen in a complicated and expensive procedure, while the virtual gage is disposed on an image of the specimen, and so it can be placed in any place of specimen, in any quantity. Another vantage is the selection where the gage is placed, unless the specimen has a notch, it is very difficult to predict where will happen the necking. As the virtual gage is placed after analyzing the images you can view exactly where the necking was and put a virtual gage there to obtain the material data until rupture.

In the Tab.1, it is described all the tests performed and some parameters:

| Test | Cross head speed (mms ⁻¹) | Nominal strain rate (s ⁻¹) | Camera acquisition shutter (frames/s) | Type of specimen |
|---------|--|---|---|------------------|
| PVC_01 | 0,3300 | 10 ⁻² | 50 | Notched |
| PVC_02 | 3,3000 | 10 ⁻¹ | 50 | Notched |
| PVC_S01 | 0,3300 | 10 ⁻² | 50 | Smooth |
| PVC_S02 | 3,3000 | 10 ⁻¹ | 50 | Smooth |
| PVC_S04 | 0,0104 | 10 ^{-3,5} | 0,033 | Smooth |

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| | | | | |
|-----------------|--------|-------------|-----|---------|
| PVC_S05 | 0,104 | $10^{-2,5}$ | 0,5 | Smooth |
| HDPE_01 | 0,3300 | 10^{-2} | 50 | Notched |
| HDPE_02 | 3,3000 | 10^{-1} | 50 | Notched |
| HDPE_S01 | 0,3300 | 10^{-2} | 50 | Smooth |
| HDPE_S02 | 3,3000 | 10^{-1} | 50 | Smooth |

Table 1. Some parameters that differentiates the tests performed

4. EXPERIMENTAL RESULTS

4.1 Difficulties encountered and observations

Due to the innovation of this technique some observations have to be made about the difficulties encountered to do this work, so that in future works some mistakes can be avoided. It is noteworthy that these difficulties are unrelated with the technique, but with the choices made about some parameters, and considering the innovative character of this technique, some mistakes, eventually, have to be committed to learn how to do it right.

The first mistake was the use, in some tests, of a camera that did not have high-speed image capture and did not save the pictures in TIFF format but CR2 (not recognized by the available version of Correli Q4), so was necessary to use a program to convert the images to TIFF, probably this conversion altered the image integrity, what impaired the analysis of the tests with very slow speed, from a total of 14 tests only the 8 tests recorded with the high-speed camera presented acceptable results, in other words much more data could be obtained.

Other point that could be improved the analysis of some tests, was consider that the analyzed materials exhibit a very large ductility, so the vertical size of the images captured from some tests should be higher, given that in two tests (HDPE_01 and HDPE_S01) the specimen deformed in such a way that the necking zone fled from the camera range, and then the maximum strain cannot be observed, that maximum strain would reinforce the conclusions about the results. Through Fig. 3 we can see how many data were lost because this lack of resolution, the exhibited test (PEHD_01) was recorded in 10049 pictures. The necking zone starts to fled from the camera range approximately in the middle of the test, and the Correli had no way to calculating what is out of resolution.

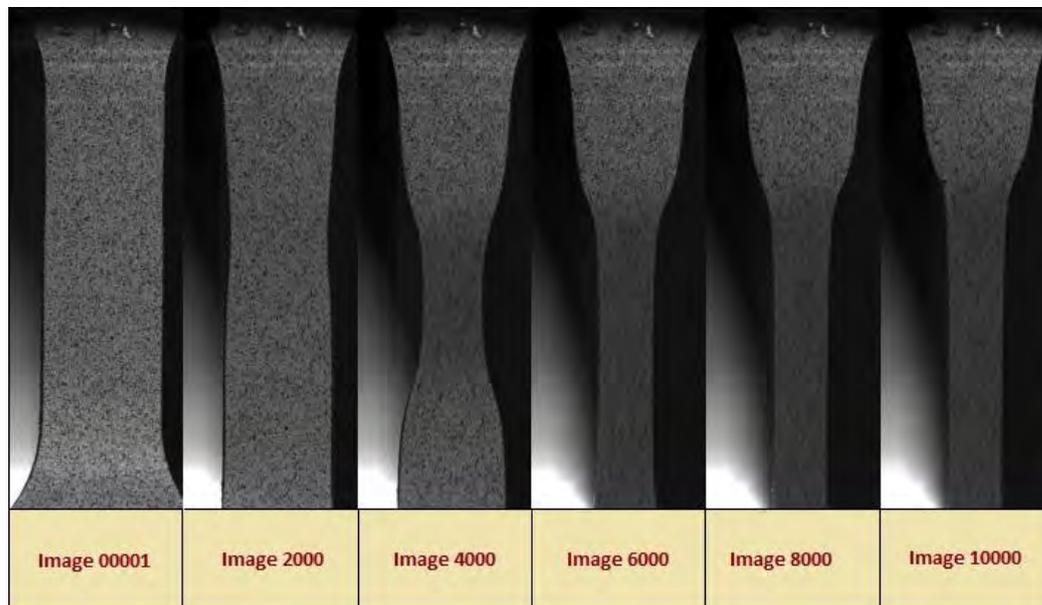


Figure 3. Pictures from the test PEHD_01 showing that part of the necking zone from specimen, fled from camera range.

4.2 Effects of strain rate on analyzed thermoplastics

4.2.1 Effects on stress-strain curves

In Fig. 4 can be visualized a comparison between the stress-strain curves obtained from the tests with PVC_01 and PVC_02, and in the Fig. 5 are displaced the same curves from the tests PVC_S01 and PVC_S02. The parameters of each test are displaced in Tab.1.

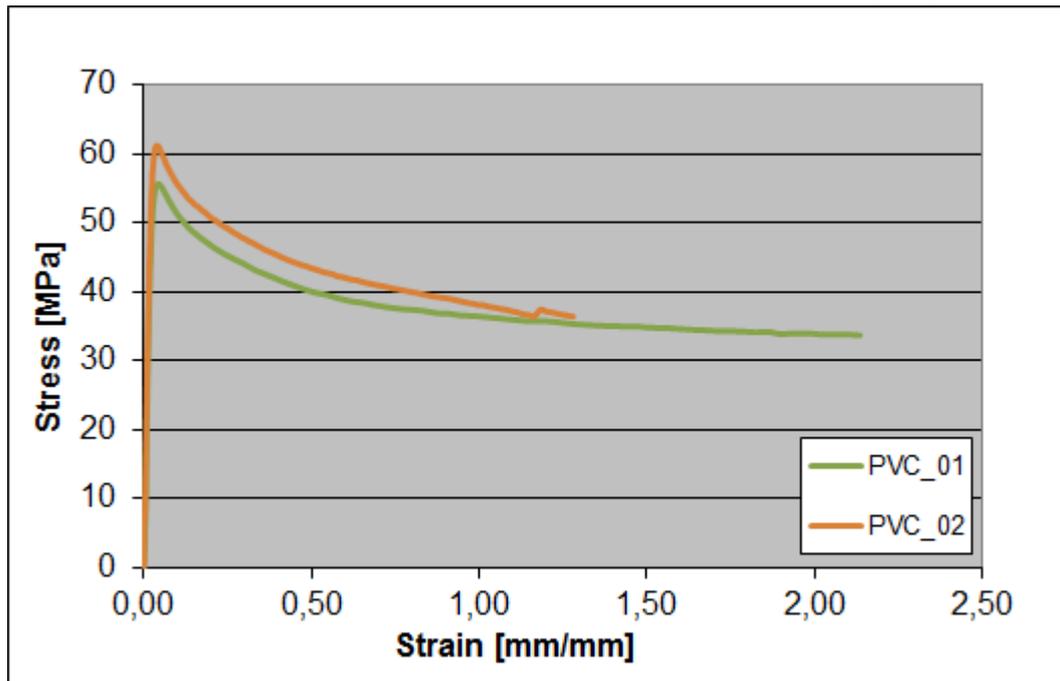


Figure 4. Comparison between the stress-strain curves of two tests with different strain rates.

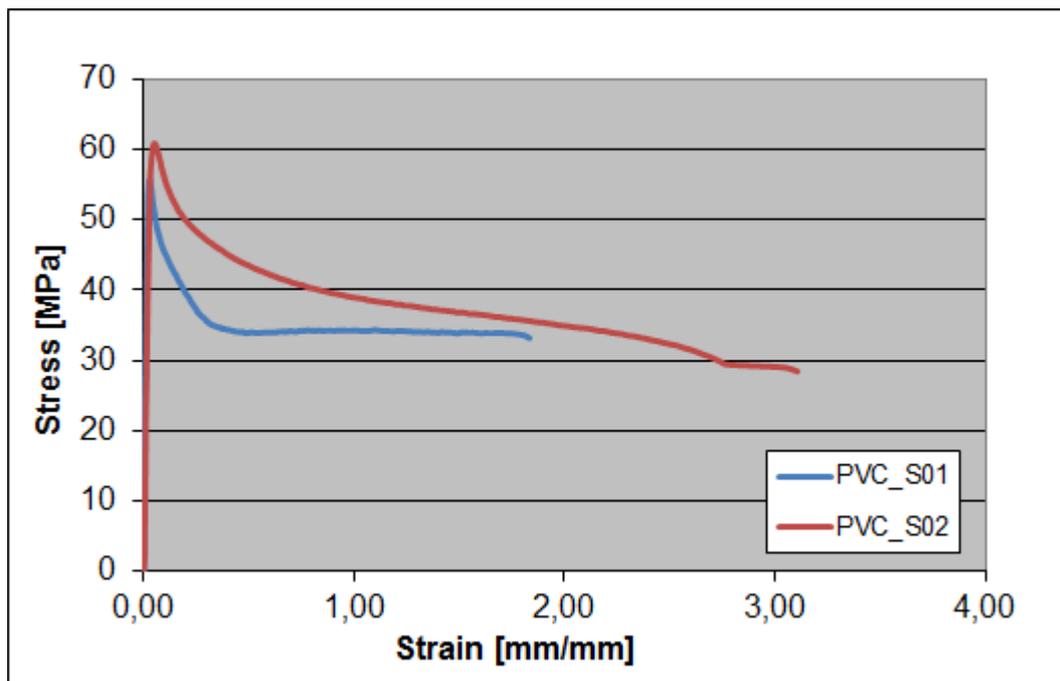


Figure 5. Comparison between the stress-strain curves of the PVC_S01 and PVC_S02 tests.

As we see, it is clear that the test PVC_01 (strain rate of 10^{-2} s^{-1}) presents a maximum stress lower than PVC_02 (strain rate of 10^{-1} s^{-1}), on the other hand PVC_01 had a much higher maximum strain than PVC_02.

Analyzing at Fig. 5 we can make an observation that, initially, left confused the authors of this work. The point is, theoretically, the specimen of test PVC_S01 should have presented a greater strain than the specimen of test PVC_S01, but this not happened, and the reason was found when the strain fields were seen, which will be shown on next section.

4.3 Effects on necking zone formation

The necking zone is a small part of the specimen that concentrates almost all the strain that occurs due to the displacement caused by the test machine. The DIC propitiated, not only, to watch the formation of these zone (as shown in Fig. 6), but also, visualize the displacement and strain fields that helps to see where was the necking zone and the extension of this deformation by a field in map color that allows to view punctually strain and displacement.

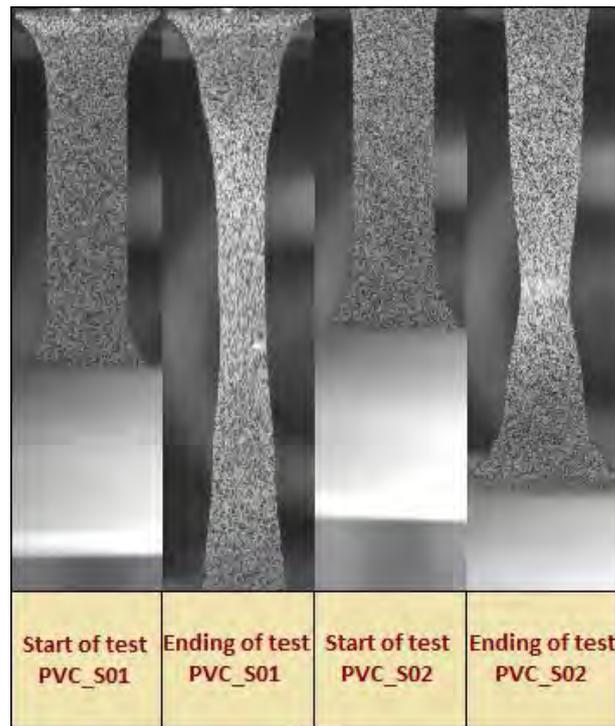


Figure 6. View of simple pictures showing the effects of strain rate on necking zone formation.

As we can see, at a relative high strain rate (PVC_S02) favors the elastic behavior of polymers, and the necking zone is very concentrated with the plastic strain occurring only in a small area. On the other hand, a lowest strain rate (PVC_S01) favors the viscous behavior in these materials and then a large flow occurs exhibiting a strain more dispersed and homogeneous along the specimen.

This phenomenon can be more accurately visualized in a displacement field as shown in Fig. 7, which was withdrawn from the Correli visualization option of displacement fields.

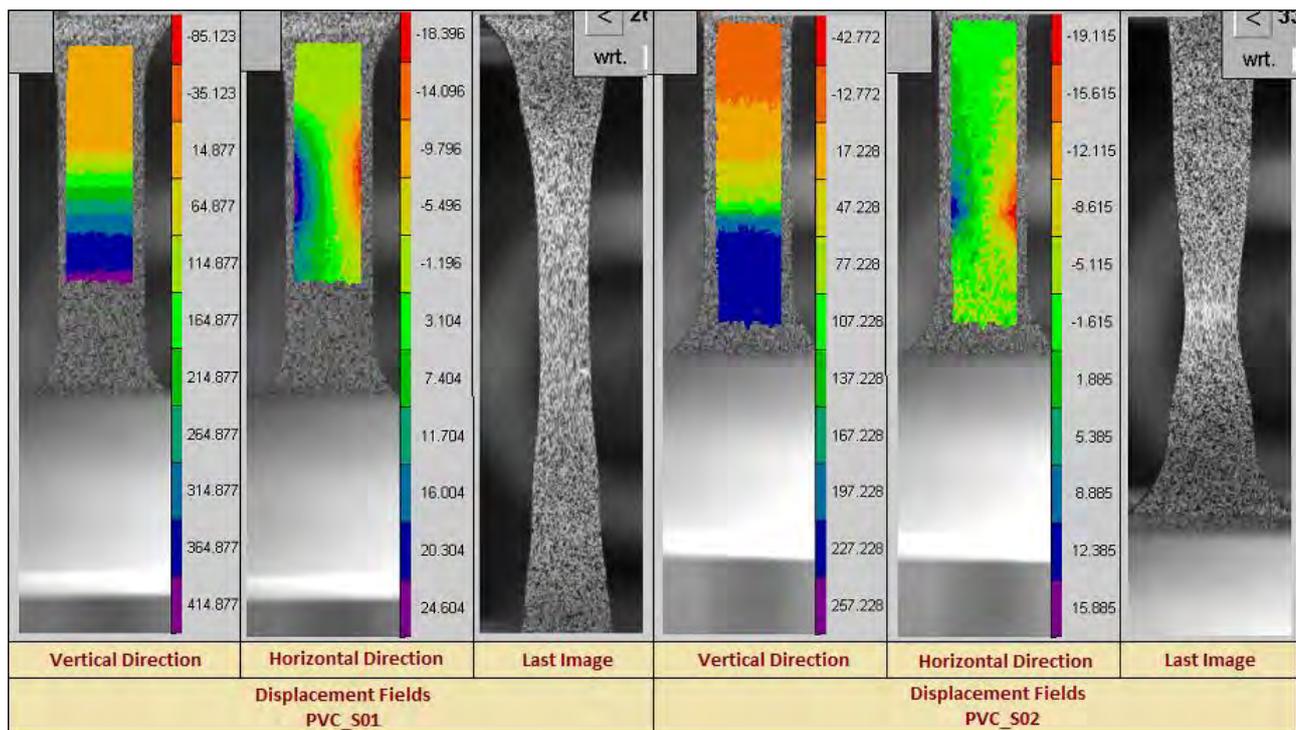


Figure 7. Displacement fields of two tests with different strain rates using PVC specimen.

In Figure 7, we see for each test, three pictures, for each one, the two left pictures are the reference image (specimen in initial state without any strain), and the right picture is the last picture before the rupture. The map color seen on the reference image represent the punctual displacement (in pixels accordingly with the graduation on the image side) in comparison with the last picture.

In that case, we can observe in the vertical direction displacement field of the test PVC_S01 that the areas immediately above the necking zone, in orange color, presented showed near-zero displacement, on the necking zone we can observe clearly a transition with many bands, until come at the blue and purple color that represents the zones that presented maximum displacement. On the horizontal direction we see two great bands, in color blue and orange, that mark accurately the necking zone, which extended a lot over the specimen.

In turn, on the test PVC_S02, the vertical direction displacement fields exhibit a transition on the necking zone which was not gradual, but abrupt. We can see in the horizontal direction displacement fields that the necking zone was not distributed along the specimen, but concentrated in one small area.

In these pictures it's clear that the test PVC_S01, which has, comparatively with PVC_S02, a low strain rate, presented an extensive necking zone, while the PVC_S02 exhibit a great displacement concentration.

Other great visualization provided by Correli is from the strain fields that exhibit the punctual strain along the specimen, as shown in Figure 8.

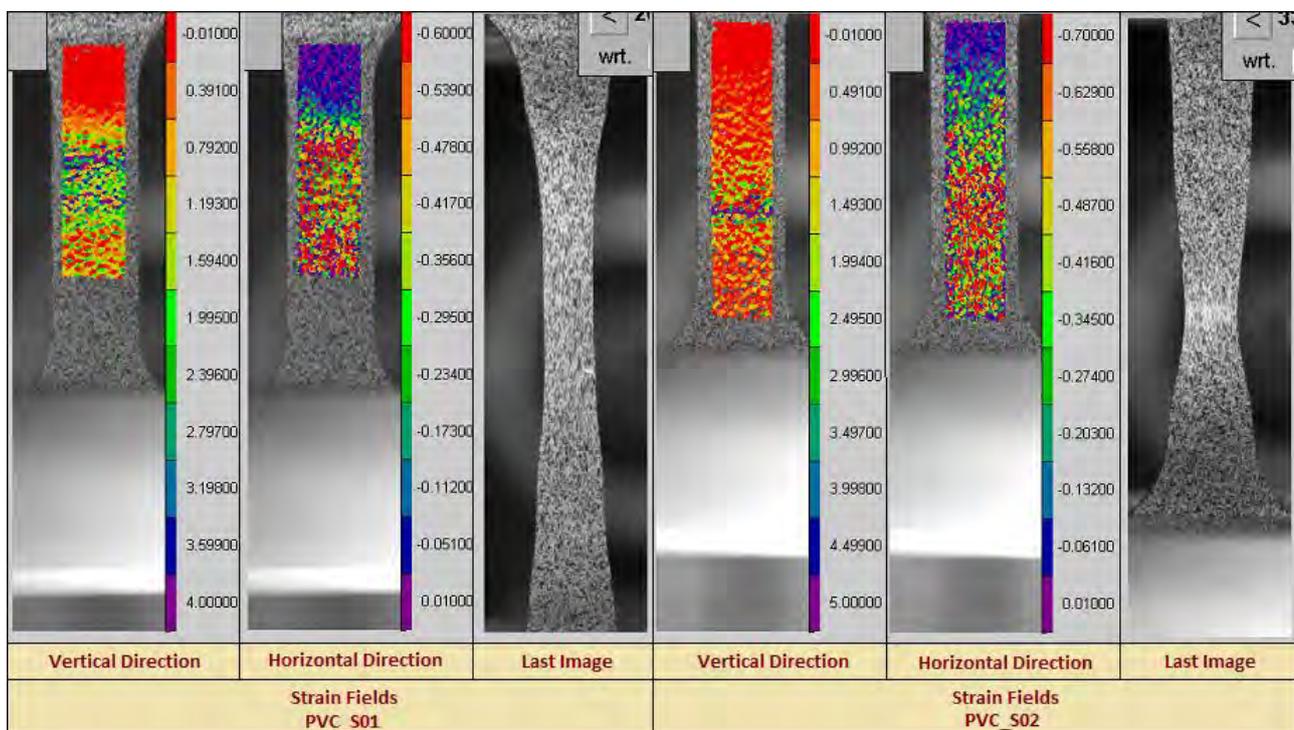


Figure 8. Strain fields of two tests with different strain rates using PVC specimen.

After look at these pictures, the observations made about the displacement fields are confirmed, looking at the vertical direction strain field of PVC_S01 we can see a necking zone as a great band who extends from the end of the red area to beginning of the other area with many red points. The strain values reach 400% (purple color points). On the other hand the vertical direction strain field of PVC_S02, shows an extremely concentrated deformation (purple color) that reach 500%, while the rest of specimen showed almost no deformation (red zone).

Finally, we can observe as mentioned on previous section, the specimen of test PVC_S02 exhibited a greater strain than in the test PVC_S01, even with a greater strain rate, which, theoretically, would confer to the material an elastic behavior, meaning a more rigid response and less deformations. But how we can see on strain fields, the explanation comes from the necking zone, which extends along a large track in the PVC_S01, while is extremely concentrated on PVC_S02. That way even with a larger displacement of the PVC_S01 (which is evident when comparing the last pictures of each test), the PVC_S02 presented a greater strain due to the large strain concentration in its necking zone.

5. CONCLUSIONS

The results showed that DIC technique is a great tool for tests analysis, considering that in addition to providing all resources for materials characterization, offer a whole range of views that assist to understand the mechanical behavior of the material in analysis.

And using this technique it was possible to visualize the effect of strain rate on these polymeric materials in a complete analysis that did not include only stress-strain curves but also the displacement and strain fields visualization, which

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only this technique can offer. Other advantage is the fact that, with DIC technique, it is possible to determinate the elastic properties, as the failure properties. This is an important thing in tests with polymers, since techniques like the use of strain gages do not offer that possibility in some cases, as is mentioned in the standard ASTM D638-10, Note 12: "If it is desired to measure both modulus and failure properties (yield or break point, or both), it may be necessary, in the case highly extensible materials, to run two independent tests. The high magnification extensometer normally used to determine properties up to yield point may not be suitable for tests involving high extensibility. If allowed to remain attached to the specimen, the extensometer could be permanently damaged. A broad range incremental extensometer or hand-rule technique may be needed when such materials are taken to rupture." (ASTM International, 2010).

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