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Mechanical Behavior of D-Shaped Hiperco Specimens under Tension Measured by Digital Image Correlation

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Abstract

Hiperco, manufactured by Carpenter Technology Corporation, is the trademark name for an alloy of equal composition iron and cobalt, with 2 percent vanadium added for enhanced mechanical properties (49Fe-49Co-2V). The alloy is interesting due to its very high magnetic saturation and flux density, yet undesirable mechanical properties such as brittleness and low strength. Several Hiperco specimens cut to a "D"-shaped geometry were placed under tension in a load frame, with a constant strain rate at room temperature, until failure occurred. Digital image correlation was used to obtain strain field data throughout the experiment. The data is to be used to compare with a finite element model, to investigate if Hiperco's unusual behavior can be modeled accurately with chosen model parameters. Between the five specimens tested, high-level results were consistent. Maximum strain and ultimate tensile strength all fell within acceptable bounds. However, several qualitative results differed from specimen to specimen. These differing results include the point of failure, the start point of Lüders band formation, as well as the presence or absence of Lüders bands on the curved section of the "D" specimens.

Nomenclature

UTS	= ultimate tensile strength
ε_{yy}	= normal Lagrangian finite strain in the direction of tension
σ_y	= yield strength
σ_0	= intrinsic (friction) stress
k	= Hall-Petch coefficient
d	= grain size

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I. Experimental Setup

The experimental setup consisted of a load frame, the “Ruppen 1A” frame, with a load cell to measure force, grips holding the specimen, LED arrays for lighting, and a high-resolution camera. The camera was a FLIR camera with a 12.3 megapixel resolution, that had a maximum frame rate of 30 frames per second. Its serial number was SN 18166664. The lens used was an Edmunds 50 mm lens. The load cell had a 5000 lbf capacity, serial number SN 10541. Finally, the grips holding the specimens were manufactured by Test Resources and had a 20 kN capacity (4496 lbf). A bull’s eye level was used to level the camera.

The Hiperco specimens were prepared by first wire electro-discharge machining (EDM) stock material into the D geometry [5]. Then, the residue brass coating was sanded off with a combination of hand tools and grinder wheels, due to the sensitivity of Hiperco to chemical etching and to minimize surface roughness stress concentrators. The purpose of the brass removal was to prevent contamination of the furnace. Next, the specimens were subjected to a heat treatment, run profile given below. The alloy is heat treated to optimize its magnetic properties, as well as slightly change its mechanical properties depending on the heat treatment specifications [4]. Finally, the specimens were speckled for digital image correlation using a coat of white spray paint, and a speckle pattern of black spray paint.

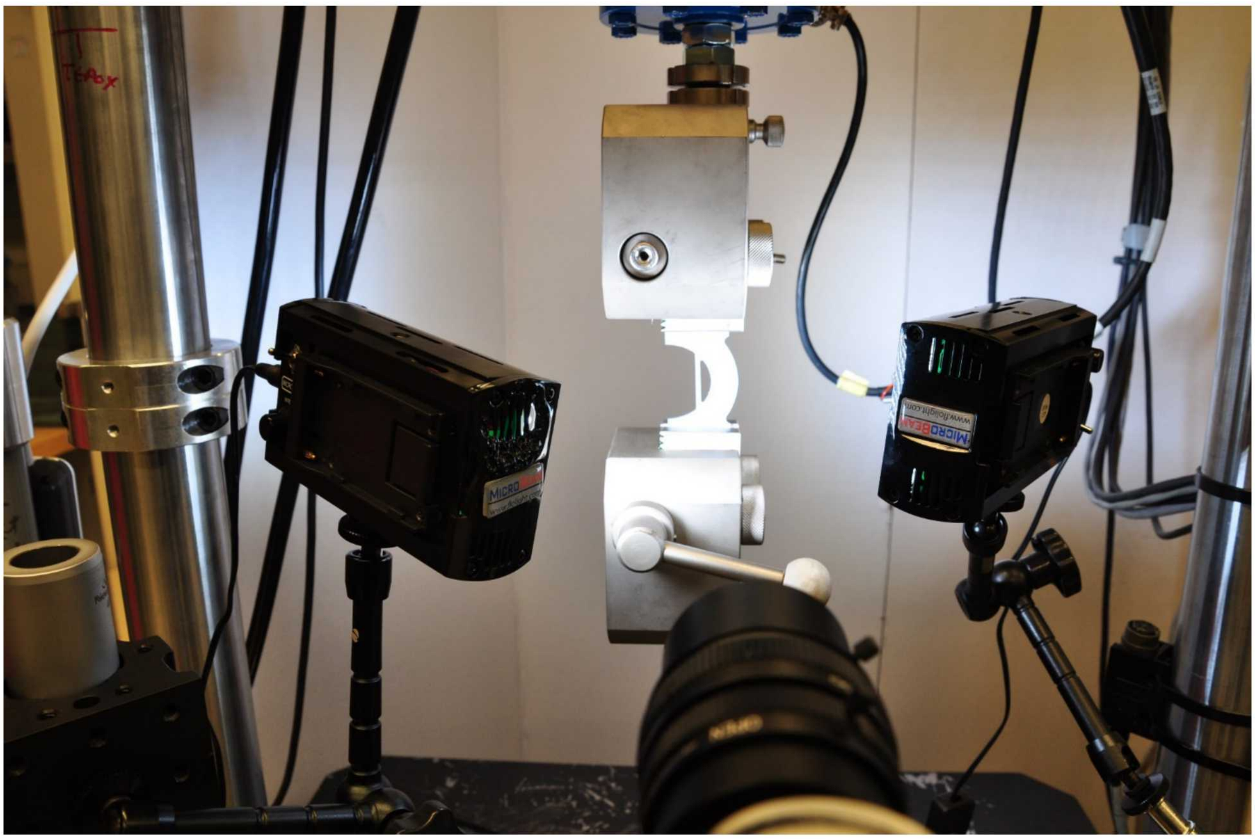


Figure 1. Photo of test setup. A D specimen in the test setup. Two LED arrays are used for lighting the specimen, which is held between two Test Resources grips. The load cell, partially out of frame, was connected to the top grip.

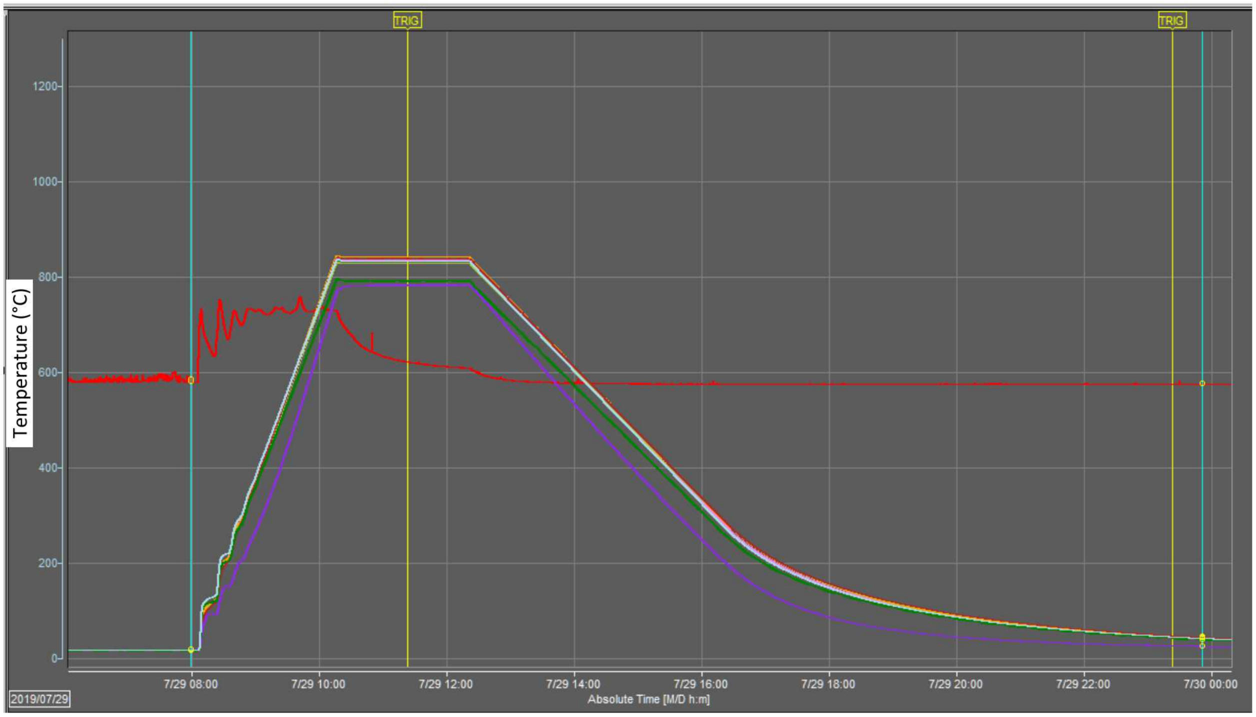


Figure 2. Heat treatment run profile. The heat treatment run profile used for the five test specimens. Different colors represent thermocouples at different locations within the furnace. Temperature is in degrees Celsius.

The specific D geometry was chosen for finite element model calibration, through the so-called virtual fields method. The variety of stress states present in the geometry, which covers a substantial portion of two-dimensional stress space, is invaluable for model calibration [3].

II. Test Procedure

A block of scrap metal was used to align the specimen vertically in the grips. Only the rectangular sections on the top and bottom rectangular portions of the D specimens were subjected to gripping. The test, data collection, and camera were all started simultaneously through the MTS software. Several strain gages were digitally affixed to the specimen during tests to monitor the strains at several selected points. There were some problems with specimen slippage in the grips, which sometimes led to rotation of the specimen in the grips. The slippage is apparent through the pictures taken, as well as scoring on the gripped sections of tested specimens. It is possible the rotation caused non-ideal behavior.

Images were processed in Correlated Solutions' Vic-2D software, version 6.2.0, build 1321. Subset size was chosen to be on the order of 30 pixels, and step size was chosen to be 3 for DIC on each specimen.

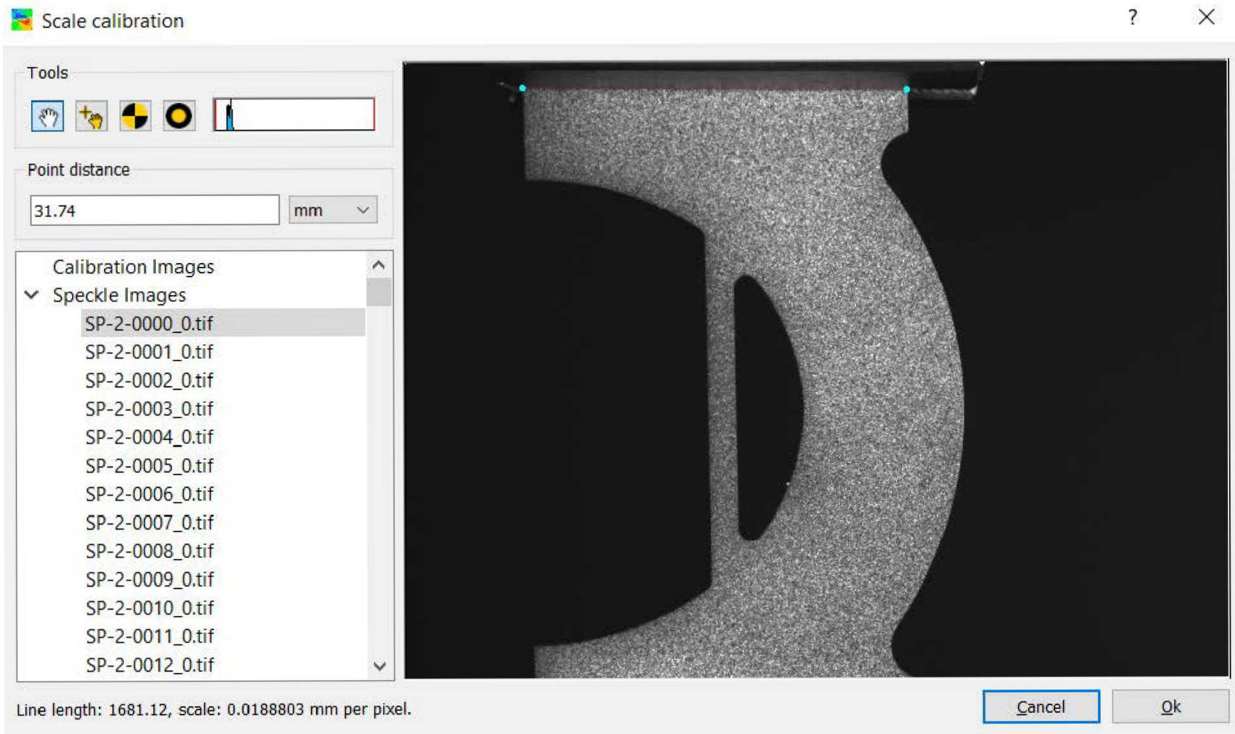


Figure 4. Scale calibration in the VIC-2D. The scale in VIC-2D, expressed as mm per pixel, was calibrated in each test using the test's first image, the undeformed "reference" image. A known length, in this case the length along the top rectangular part of the specimen, is indicated above with cyan points, and the measurement is entered into the software.

III. Results

Results are summarized in the table below. A detailed explanation for each specimen follows. For scale calibration as in Fig. 4, the length was measured using calipers after the test was completed. Although it would have been best to measure beforehand, the length change should be negligible due to the proximity of this section to the grips and its distance from the theoretical areas of high strain.

SP-#	UTS, lbf	Max ε_{yy} at any Point	Max ε_{yy} in Straight Section	Displacement Rate, in/s	Lüders Band Start Point	Straight Section Failure Point	Curved Section Failure Point	Diagonal Lüders Banding? Y/N
SP-1	1907	4.9%	4.5%	4 x 10^{-4}	Middle	Very high	Low	Y
SP-2	1731	4.7%	3.5%	0.0024	High	N/A	Very high	Y
SP-3	1483	5.2%	4.6%	0.0024	High, Low	Very low	High	N
SP-4	1344	5.4%	5.4%	0.0024	High	Very low	Middle	N
SP-5	1476	4.7%	4.1%	0.0024	Low	Low	Middle	N
Mean	1588	5.0%	4.4%					

Table 1. Summary of Results. The table lists several experimental results for each specimen. Maximum strains are consistent, as is ultimate tensile strength with the exception of SP-1. However, there is high variability in qualitative results such as failure point. Maximum strain always occurred at the inside edge at the mid-height of the curved portion of the sample (as shown in Figure 4).

3.A. Specimen 1 (SP-1)

Notably, this specimen was the only one tested at a different strain rate, which was one-sixth of the strain rate used in subsequent tests. The test parameters were: a displacement rate of 4×10^{-4} in/s, a data sample rate of 102.40 Hz, and a picture rate of 2 Hz. The parameters used for the correlation process was a subset size of 39, and a step size of 3. The length of the specimen along the top gripped section was measured to be 31.76 mm, resulting in a scale of 0.02897 mm/pixel.

As expected, the failure point on the straight section corresponds with the point of maximum strain on that section, evident when comparing Fig. 4a and 4b.

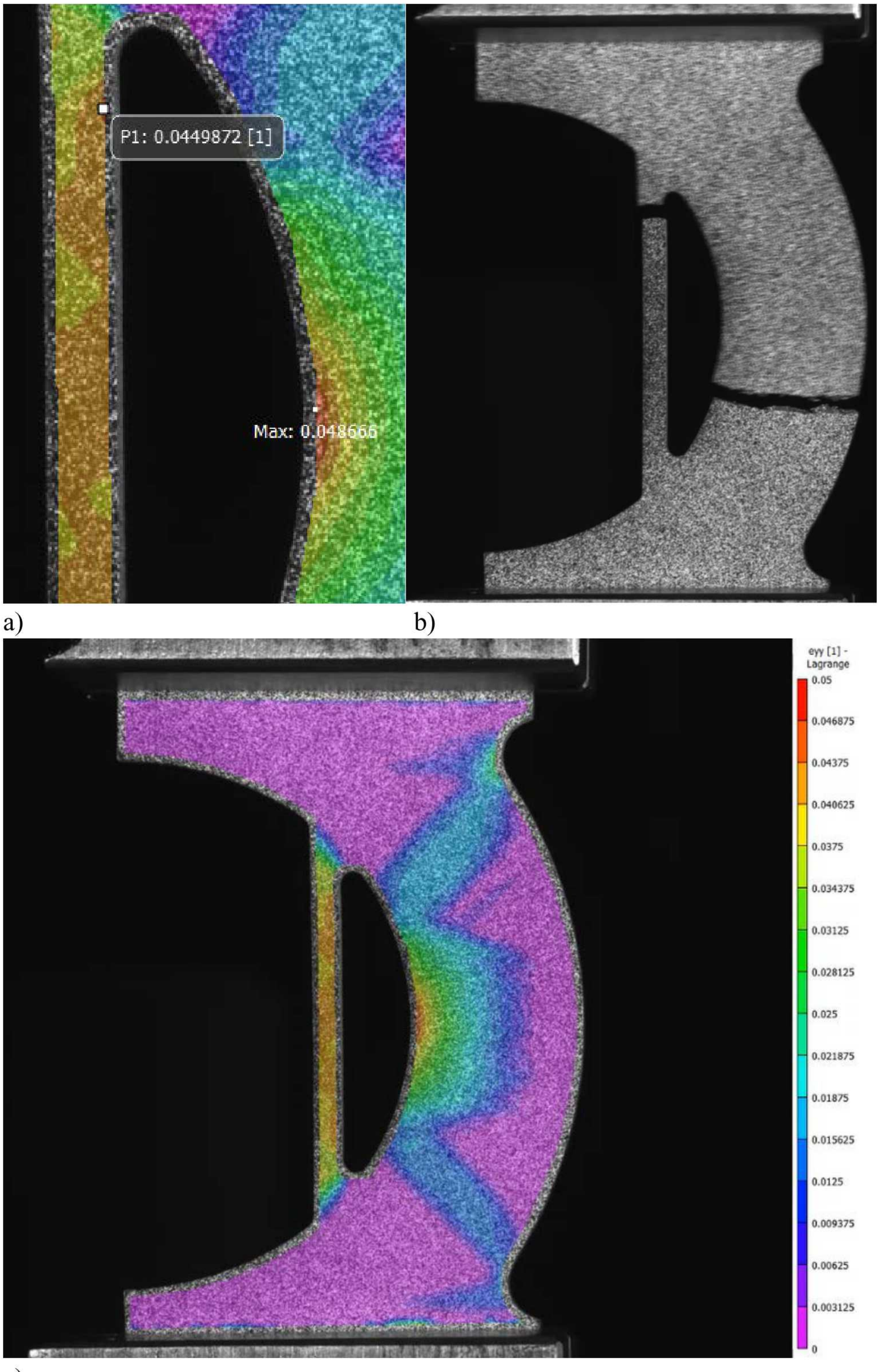
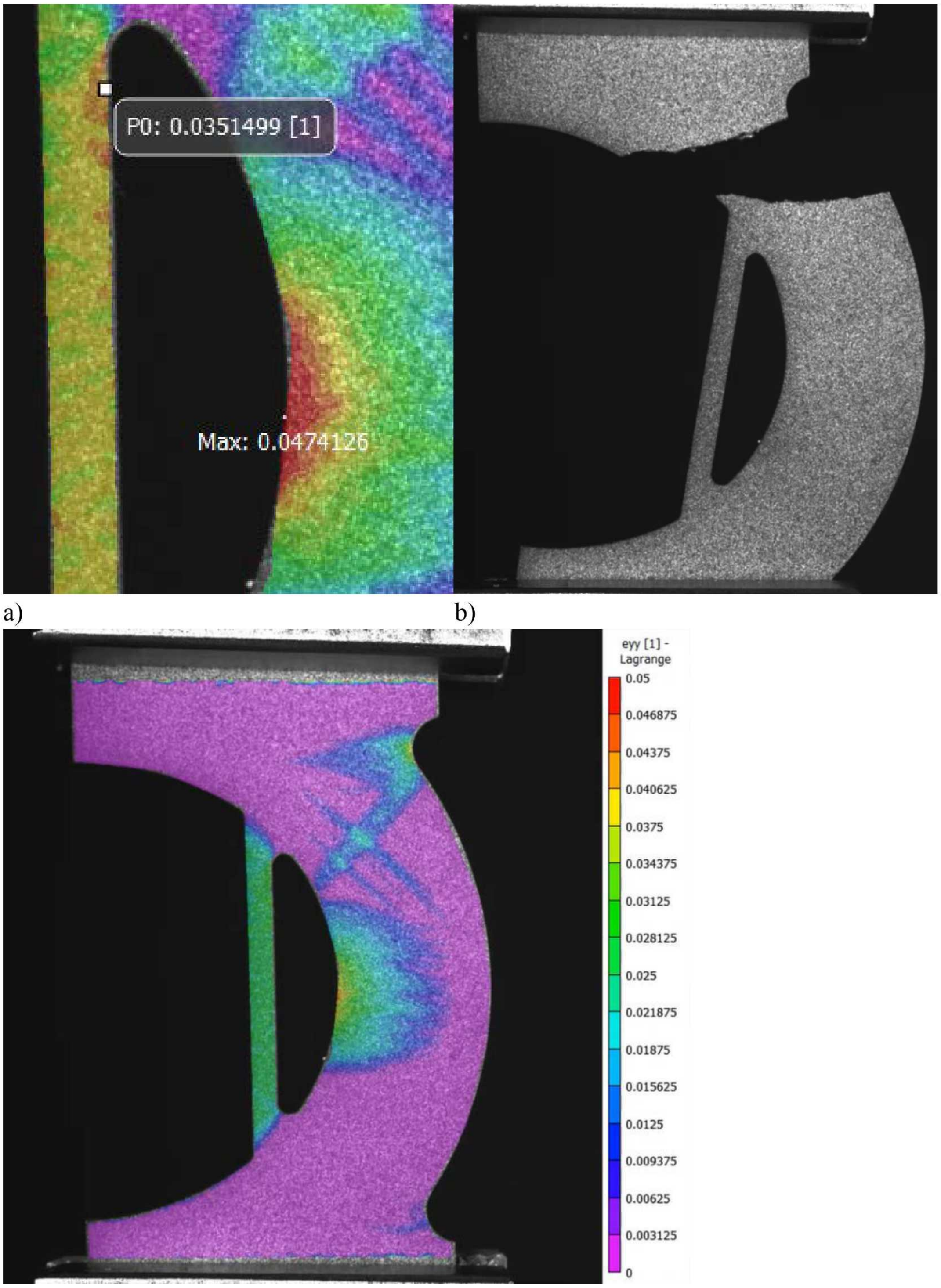


Figure 4. SP-1 Pictures. a) A partial strain map of the specimen, with two labels showing the absolute maximum strain, and another showing the maximum strain localized to the straight section, just before failure. b) A photo showing the failure points. c) A full-field strain map prior to failure. Note the diagonal Lüders bands emanating from the inner curve; the top band appeared several seconds before the bottom band.

3.B. Specimen 2 (SP-2)

The test parameters for this specimen and all following specimens are identical: a displacement rate of 0.0024 in/s, a data sample rate of 49.951 Hz, and a picture rate of 5 Hz. The correlation parameters were: a subset size of 31 and step size of 3. The length along the top was measured to be 31.74 mm, resulting in a scale of 0.01888 mm/pixel.

This test has a very unique failure point, which did not occur in the straight section at all. Compared to other tests, the strain in the straight section is very low. This could be due to a stress concentrator on the curved portion of the specimen that led to premature failure before the straight ligament accumulated significant amounts of strain.



c)

Figure 5. SP-2 Pictures. a) A partial strain map of the specimen, with two labels showing the absolute maximum strain, and another showing the maximum strain localized to the straight section, just before failure. Even higher strains were detected just adjacent to the grips, but were discarded. b) A photo showing the failure point. This is the only specimen that failed entirely outside of the straight section, possibly due to grip slippage and rotation. c) A full-field strain map prior to failure. Note the singular diagonal Lüders band emanating from the inner curve.

3.C. Specimen 3 (SP-3)

The test parameters for this specimen were identical to those used for SP-2. The correlation parameters were: a subset size of 31 and step size of 3. The length along the top was measured to be 31.75 mm, resulting in a scale of 0.02046 mm/pixel. As expected, the failure point on the straight section corresponds with the point of maximum strain on that section, evident when comparing Fig. 6a and 6b.

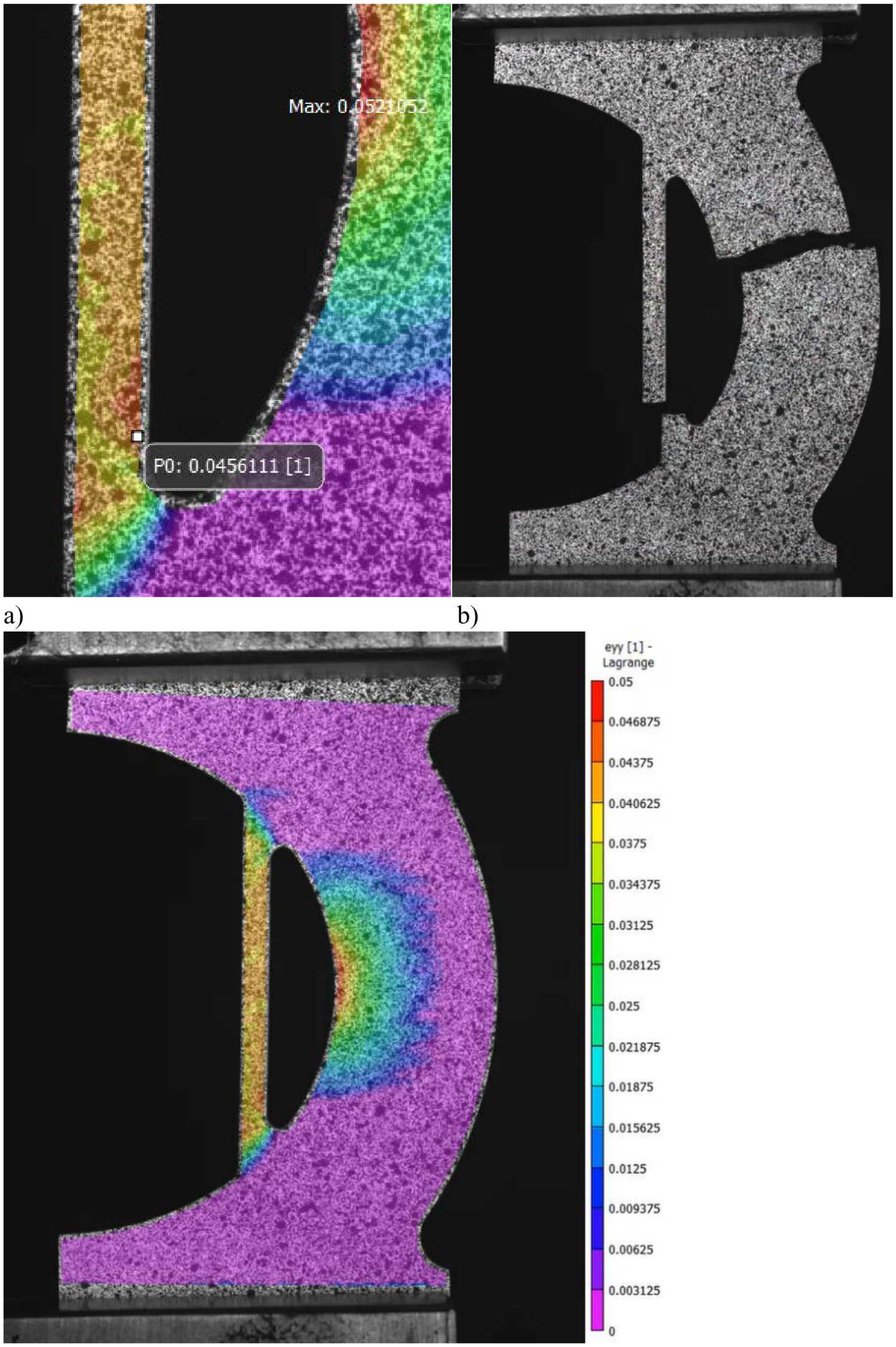


Figure 6. SP-3 Pictures. a) A partial strain map of the specimen, with two labels showing the absolute maximum strain, and another showing the maximum strain localized to the straight section, just before failure. b) A photo showing the failure points. c) A full-field strain map prior to failure. No Lüders bands appear in the curved section.

3.D. Specimen 4 (SP-4)

The test parameters for this specimen were identical to those used for SP-2. The correlation parameters were: a subset size of 31 and step size of 3. The length along the top was measured to be 31.76 mm, resulting in a scale of 0.02009mm/pixel.

During this test, the specimen slipped out of the grips twice, first at 306 lbf then again at 100 lbf. These mishaps shouldn't have influenced the results since these loads are well below the ultimate tensile strength, and behavior is still elastic. To rectify the slipping, the speckle paint was manually sanded off the grip sections, and the grip handles were torqued with a wrench and hammered to maximize grip pressure. In Fig. 7b, the scoring of the specimen by the grip is clearly visible, especially on the top grip section.

As expected, the failure point on the straight section corresponds with the point of maximum strain on that section, evident when comparing Fig. 7a and 7b. Uniquely, in this test, the curved section failed before the straight section did, with a time gap of several seconds.

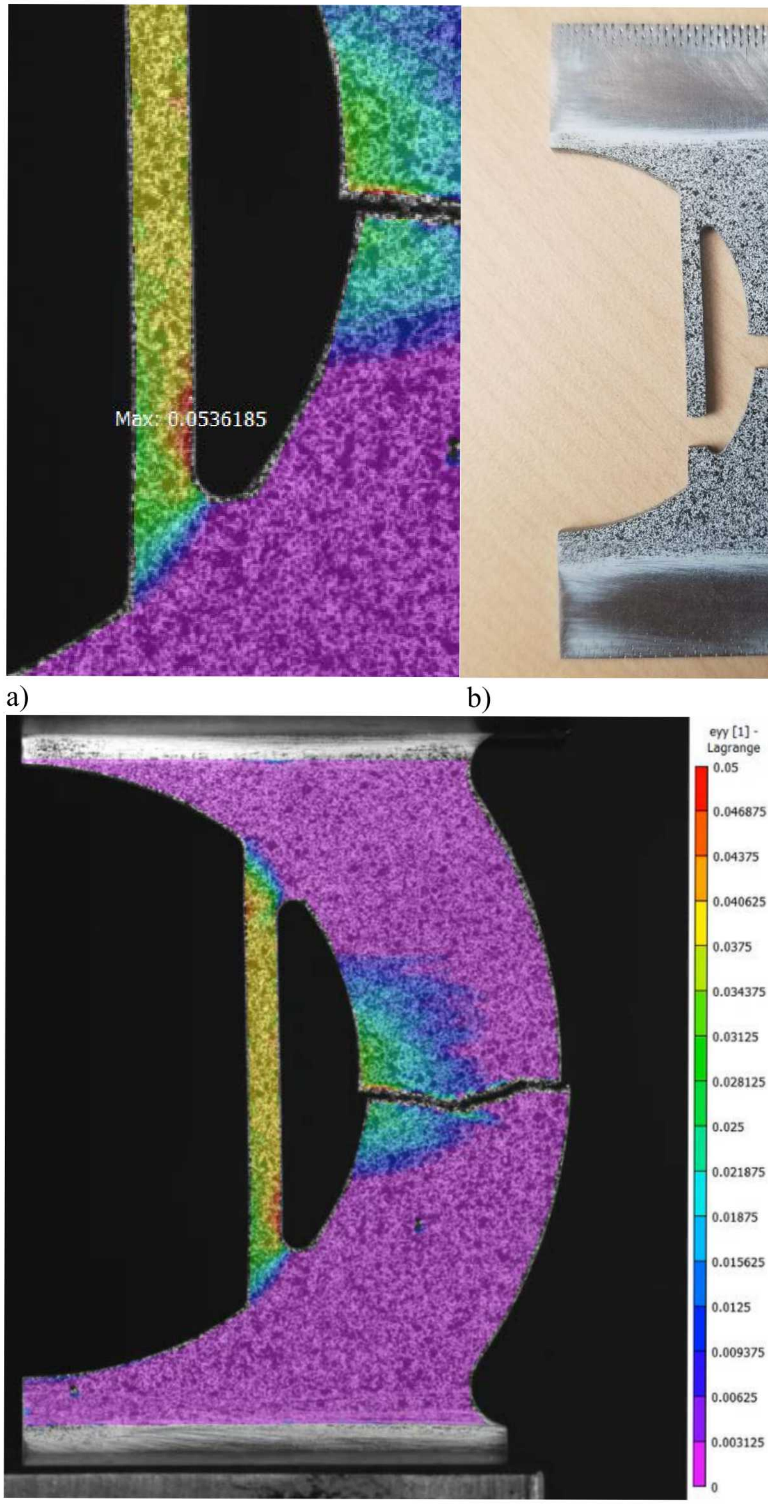


Figure 7. SP-4 Pictures. a) A partial strain map of the specimen, with one label showing the absolute maximum strain, which uniquely occurred in the straight section and not in the curved section. b) A photo showing the failure points. The curved section failed several seconds before the straight section did, so a final photo had to be taken post-test. c) A full-field strain map prior to failure. No Lüders bands appear in the curved section.

3.E. Specimen 5 (SP-5)

The test parameters for this specimen were identical to those used for SP-2. The correlation parameters were: a subset size of 31 and step size of 3. The length along the top was measured to be 31.77 mm, resulting in a scale of 0.02000 mm/pixel.

This specimen is somewhat unique due to the poor speckle pattern, due to unforeseen issues with spray paint supply. This may be the reason why the fracture point on the straight segment did not correspond with the strain maximum point in the segment. In three of four previous tests, the failure point did correspond with the strain maximum, at least in the straight region.

Like with SP-4, the gripped sections in this test were also sanded prior to the test, and the grip handles were hammered and torqued with a wrench.

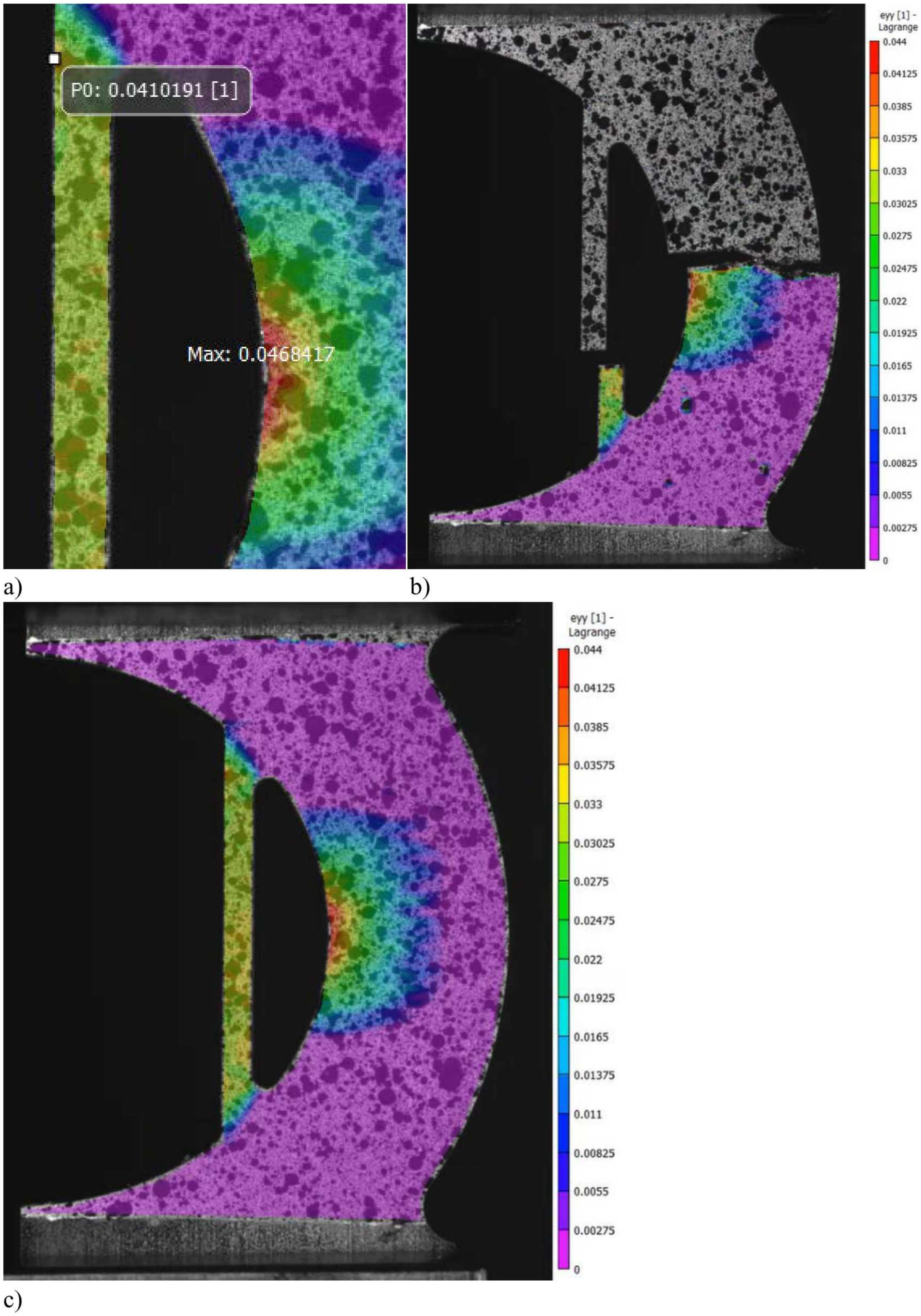
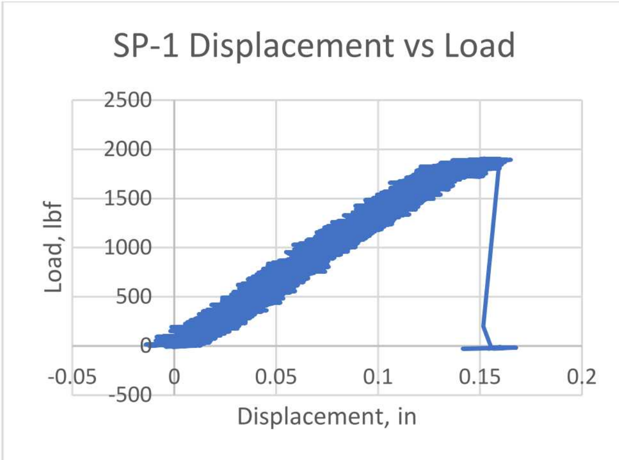


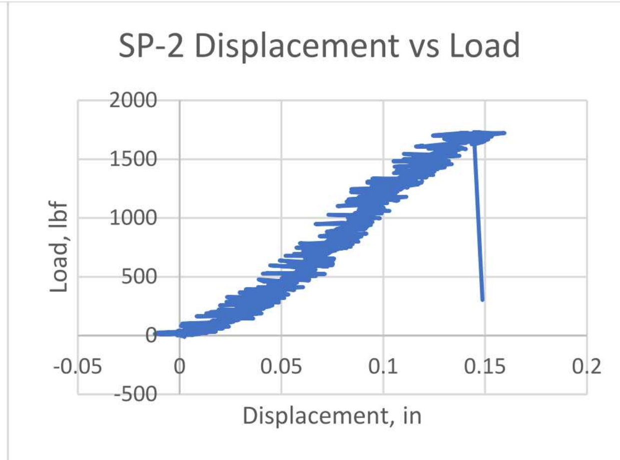
Figure 8. SP-5 Pictures. a) A partial strain map of the specimen, with two labels showing the absolute maximum strain, and another showing the maximum strain localized to the straight section, just before failure. b) A photo showing the failure points. c) A full-field strain map prior to failure. No Lüders bands appear in the curved section.

F. Displacement vs. Load Curves

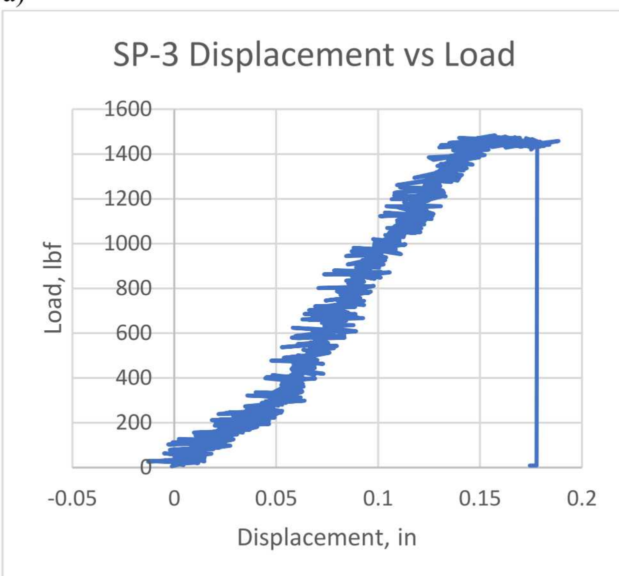
Because stress and strain are not easily quantifiable in these experiments, machine displacement vs. load curves taken directly from load cell data are given below as analogs.



a)



b)



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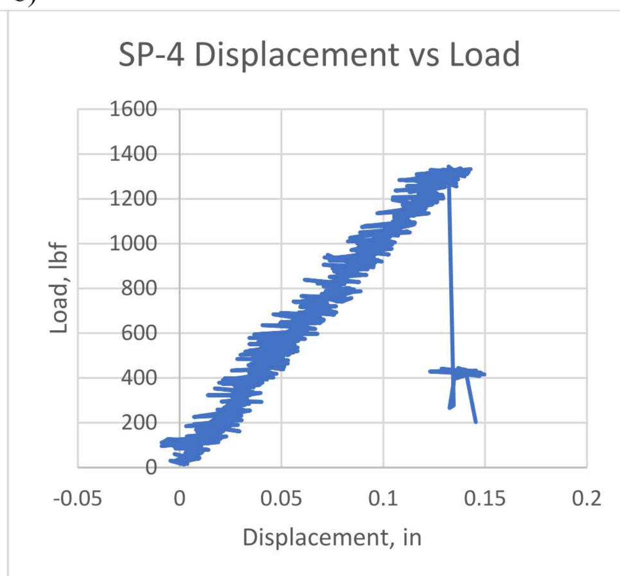
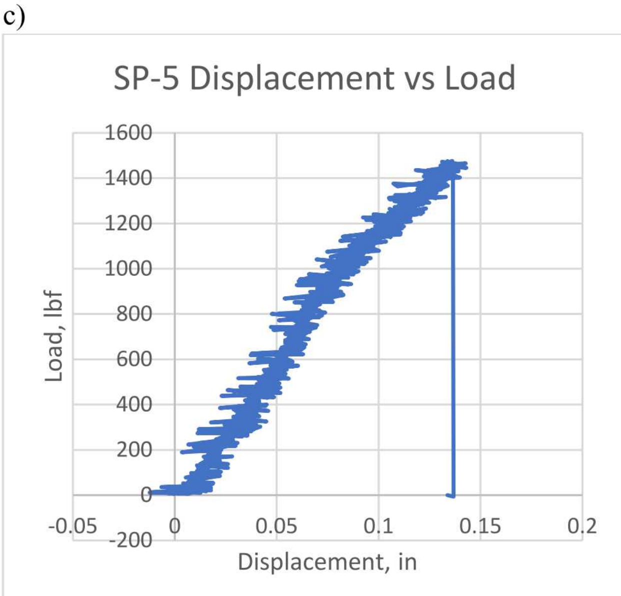


d)



e)

Figure 9. Displacement-load curves.

IV. Discussion

From the literature, Hiperco's strength is highly dependent on grain size; this is known as the Hall-Petch effect [1].

$$\sigma_y = \sigma_0 + k \cdot d^{-\frac{1}{2}} \tag{1}$$

It appears that the formation of Lüders bands is due to the dislocation structure in the ordered state [2]. Heat treatment can also affect grain size, along with the machining method. Our specimens were directly cut from bar stock using EDM; it is unclear what these machining techniques might have had on grain size. However, the high temperatures associated with EDM quite possibly have an impact on grain size.

Imperfections can have a significant effect also on the behavior of any Hiperco specimen. Surface defects, either not completely grinded away, or even produced by imperfect grinding, can influence the behavior of Hiperco significantly. Even knife-edge extensometers are impractical for use on Hiperco due to its sensitivity to surface defects.

Finally, the low strain rate used in the first trial corresponded with a high UTS and the most prominent Lüders bands of all the tests. Of course, nothing can be conclusively drawn from one test, but the possibility of correlation between strain rate and these observations cannot be ignored and should be further investigated in the future.

V. Conclusions

There are several key observations that can be made, even with data limited to only five tests. First, Hiperco's behavior is not uniform across specimens. This is clear from the qualitative behaviors such as the presence or absence of diagonal Lüders bands, the differing locations of Lüders band emanation, and the differing points of failure. The causes of this are not clear, but there are several probable reasons. One possible reason is the variation of grain phases, grain size between samples, and grain size between regions in the same samples. Smaller grain size is correlated with higher strength according to the Hall-Petch relationship and is likely conducive to Lüders band formation. Another reason may simply be imperfections in the material. The manual grinding and sanding of the specimens make this a non-negligible factor. Finally, the first test which used a low strain rate and produced slightly different results

Further tests, preferably with a more ideal setup, are needed to ascertain the properties of Hiperco. Analyses of the microstructure of the tested specimens, such as for grain sizes and boundary data, would also be immensely valuable in this endeavor.

References

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