STRAIN MEASUREMENT CONSIDERATIONS FOR DISCONTINUOUS CARBON FIBRE REINFORCED COMPOSITE PARTS

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Keywords: *Discontinuous, Composite, Digital Image Correlation*

ABSTRACT

High volume-fraction carbon fibre polymer composite cut into "chips" is a material form that can be easily moulded into complex shapes, providing inexpensive parts with high stiffness, high damage tolerance, and reasonable strength. The structural behaviour of these discontinuous materials is similar in many ways to quasi-isotropic continuous fibre composite laminates, but the discrete form of the chips creates an inhomogeneous material with a complex strain and stress state when under load, resulting in a very challenging strain measurement problem during part performance testing. To support the development of an aero-engine part manufactured from this material form, this work used digital image correlation (DIC) to provide optical strain measurement over the surface of the part. As a further challenge to strain measurement, part testing was performed under hot conditions (approx. 180°C / 350°F) meaning that thermal effects posed an additional challenge to the collection of accurate optical measurements. This paper describes the strain measurement challenge created by the inhomogeneity of this material form, the additional problems caused by the compression moulding process used to create complex-shaped parts from it, and the DIC technique developed to provide surface strain measurements under the hot operating conditions typical for an aero-engine part.

1. INTRODUCTION

Polymer composite materials cut into "chips" from high volume-fraction, continuous fibre prepreg have been researched for a number of years [Ref. 1] and used in a limited number of aircraft applications [Ref. 2]. This material form can be created from either thermoset or thermoplastic prepreg, and from either unidirectional (UD) or fabric reinforced material. Chip sizes that have been commonly researched range from 3.0 to 12.5 mm (0.125 to 0.5 inches) in minimum dimension (e.g. width), by 12.5 to 51 mm (0.5 to 2.0 inches) in maximum dimension (e.g. length). Because of the discontinuous nature of the fibres, they can be moulded into complex shapes using matched metal tools and a compression moulding process.

To mould a part, a premeasured amount of the chip material is deposited in the mould cavity and the mould closed. Heat and high pressure are applied to soften the material and cause it to flow and fill the entire mould cavity. Peak temperatures must be above the melting point for thermoplastic materials or follow a prescribed time-temperature cycle for thermoset polymers. Once material flow and compaction / cure are complete, the mould can be cooled, opened, and the part removed. This process can produce net shape parts with very complex geometries and can incorporate moulded-in metallic inserts where required.

For flat, constant thickness parts / areas of parts, as-moulded material properties are generally similar to quasi-isotropic lay ups of the same material in continuous fibre form, except that tensile strength is reduced. For areas of parts where significant material flow occurs during moulding, for example flow into the farthest areas of a mould cavity or flow around tight corners, the chip form of the material can become distorted (e.g. spread out or broken up for UD material), and the fibres can exhibit a degree of preferential alignment in the flow direction. In these areas, the as-moulded material properties will deviate to some extent from the quasi-isotropic ideal.

2. COMPOSITE PART TO BE MEASURED

The work described in this paper focussed on a part manufactured from 12.5 x 12.5 mm (0.5 x 0.5 inch) chopped UD Carbon / PEEK thermoplastic material with the part manufactured using a well-controlled, repeatable moulding process. The mould design ensured a moderate level of material flow through most regions of the part, with high flow in a few localized regions (e.g. around tight corners and inserts). The part has moderately complex geometry and two moulded-in metallic inserts, with a maximum dimension of approximately 7 cm (2.8 inches). It is shown in Figure 1.

Figure 1 - Part compression moulded from discontinuous UD Carbon / PEEK

This is an aero-engine part and is an ideal candidate for manufacture from discontinuous composite material due to its geometry, size, and the fact that the application involves modest loads. However, the part is required to operate in a hot environment, with peak temperatures of approximately 180°C (350°F). The principal structural concerns for this part relate to stresses caused by thermal expansion due to the high operating temperature and its assembly to a part made from a dissimilar material. NOTE: This paper only considers thermal expansion effects on the part in the unrestrained (i.e. unassembled) condition, in order to focus on the challenges related to strain measurement for materials and parts of this type.

3. STRUCTURAL BEHAVIOUR CONSIDERATIONS

Mechanical properties tests of coupons made from these discontinuous materials have shown their overall structural behaviour to be similar in many ways to quasi-isotropic continuous fibre composite laminates [Ref. 3]. This is a natural result of the random placement and orientation of the chips : if there is a well randomized orientation of chips across the surface and through the thickness of the part, overall properties will be quite similar to a quasi-isotropic continuous fibre laminate made from the same material. However, unlike the continuous fibre laminate, the discrete form of the chips results in an inhomogeneous material with a complex strain and stress state when under load, with complex, localized stress interactions and stress concentrations as load is transferred from chip-to-chip across the part. This effect is shown in Figure 2.

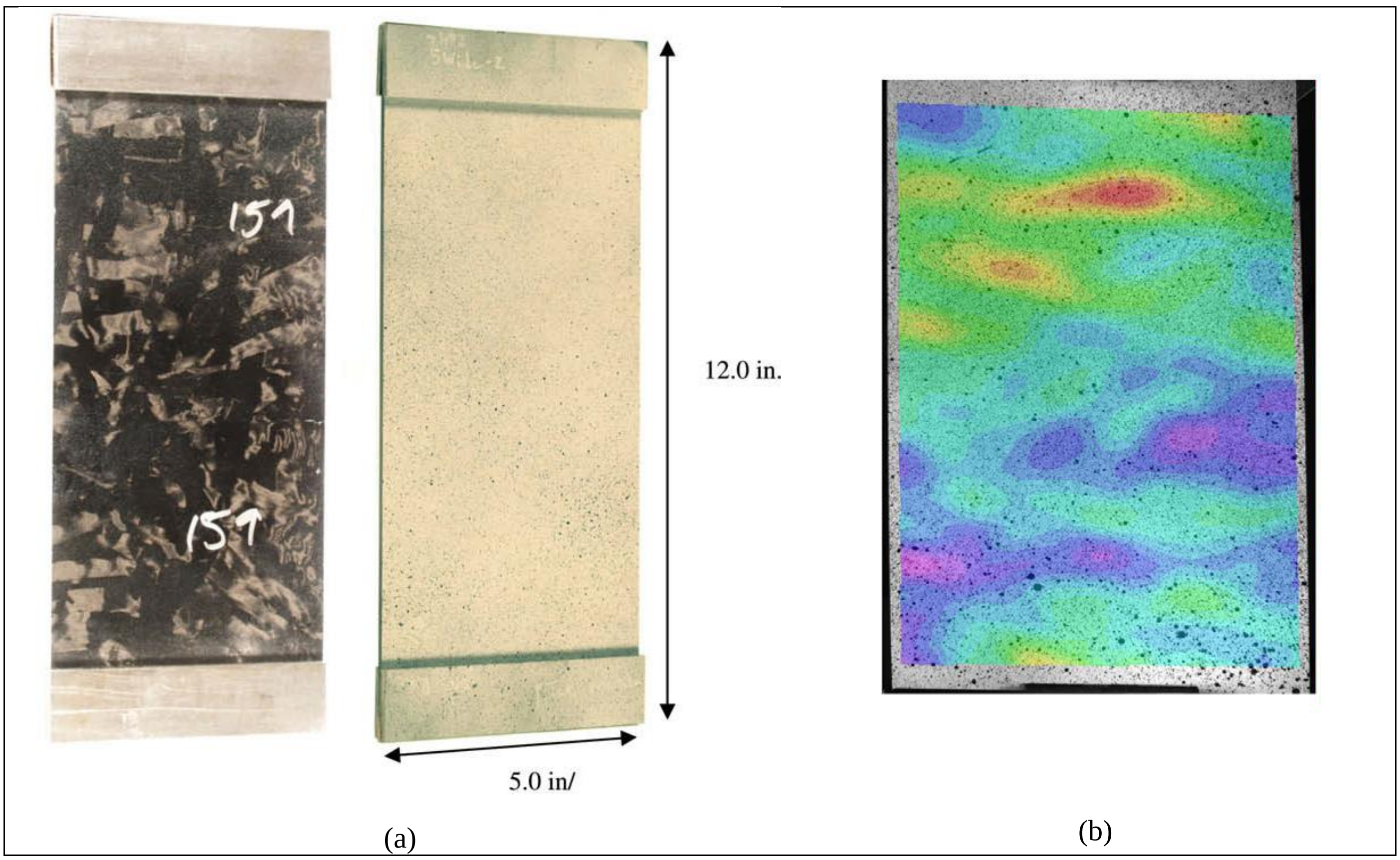

Figure 2 - (a) Large format tensile coupon with and without speckle paint for DIC. (b) Large format tensile coupon under load with DIC results showing level of variability across the surface. [Ref. 4 ; used with permission]

Figure 2 shows the level of strain variability across a flat panel manufactured with well randomized chip placement and limited flow during moulding (i.e. flat panel pressing). For the part being measured in the present work, there was the additional concern about the possibility of localized areas of preferential fibre alignment caused by high flow during moulding. This was expected to add to the level of strain variability across the surfaces of interest.

4. STRAIN MEASUREMENT CONSIDERATIONS

4.1. Challenges in Strain Measurement

As indicated by Figure 2, the inhomogeneous nature of the material causes an inhomogeneous strain and stress state across the surface of the part and results in a very challenging strain measurement problem during performance testing. Traditional methods of strain measurement, e.g. strain gauges, are not suitable for this material since the scale of variability across the surface is determined by the scale of the chips which is similar to or larger than typical strain gauges.

In this work, part-to-part variability was also of concern as related to strain measurement since it was expected that the exact orientation of a chip prior to moulding would affect the extent to which it was distorted during moulding in areas of higher flow, and this distortion would in turn affect the localized strain and stress concentrations around the chip when under load.

It must also be noted that at any point in the part there is a random stack-up of chip orientations through the thickness, meaning that for thinner walled parts, such as this one, there is a limited number of chips through the thickness and this will result in localized areas of the part having an under-representation or over-representation of certain orientations. This will cause these areas to be softer (less stiff) or harder (more stiff) than the average, and this will result in areas of higher strain and lower strain than the average. Therefore, any method used to measure strain during performance testing of parts made from these materials must take a "global approach" and measure part performance based on average behaviour across broad areas of the part, while still looking for "hot spots" of strain/stress concentration that might indicate potential failure locations.

4.2. Optical Strain Measurement Approach

Full field strain measurements were captured during testing using a three dimensional (3D) digital image correlation (DIC) system. Image acquisition was performed using VicSnap software (Correlated Solutions Inc.) and two AVT Dolphin F-145B camera (Allied Vision Technologies, Stradtroda, Germany) with a resolution of 1392 x 1040 pixels and Schneider wide angle lenses. The specimen was illuminated using a high intensity LED light array mounted behind the camera system. Image processing was performed using Vic-3D software (Correlated Solutions Inc., Columbia, SC, USA) to calculate the strain fields.

Two issues made this testing more challenging than usual. The first was the complex geometry of the part and the second was the need to reduce strain field noise that resulted from making measurements at higher temperature. The first challenge was addressed by determining which specific locations on the parts were of interest and then using a flexible arm to hold the part in a precise position that optimized the data in the region of the interest. The second challenge was how to reduce the effect of the large temperature gradient between the camera and the test piece. The index of refraction of air changes with temperature and high temperature air currents moving stochastically around a test piece can distort the image enough to result in large parasitic strain gradients. Two strategies were employed to reduce this effect, the first was to employ an aperture on the backside radiant heater (Figure 3) that focused radiant heat on the test object and blocked it from the camera. The second technique was to take a large number of images and time average them as a means to reduce stochastic noise.

5. APPLICATION TO PART

5.1. Test Set Up

The load case of interest for this work was heating of the part from room temperature to 180°C (350°F) under a condition of free thermal expansion. Reference images were taken at room ambient conditions and strain analysis was performed by correlating these to images taken at the test temperature. To provide maximum contrast for image correlation, the part was painted white with black speckles. The test set up is shown in Figure 3.

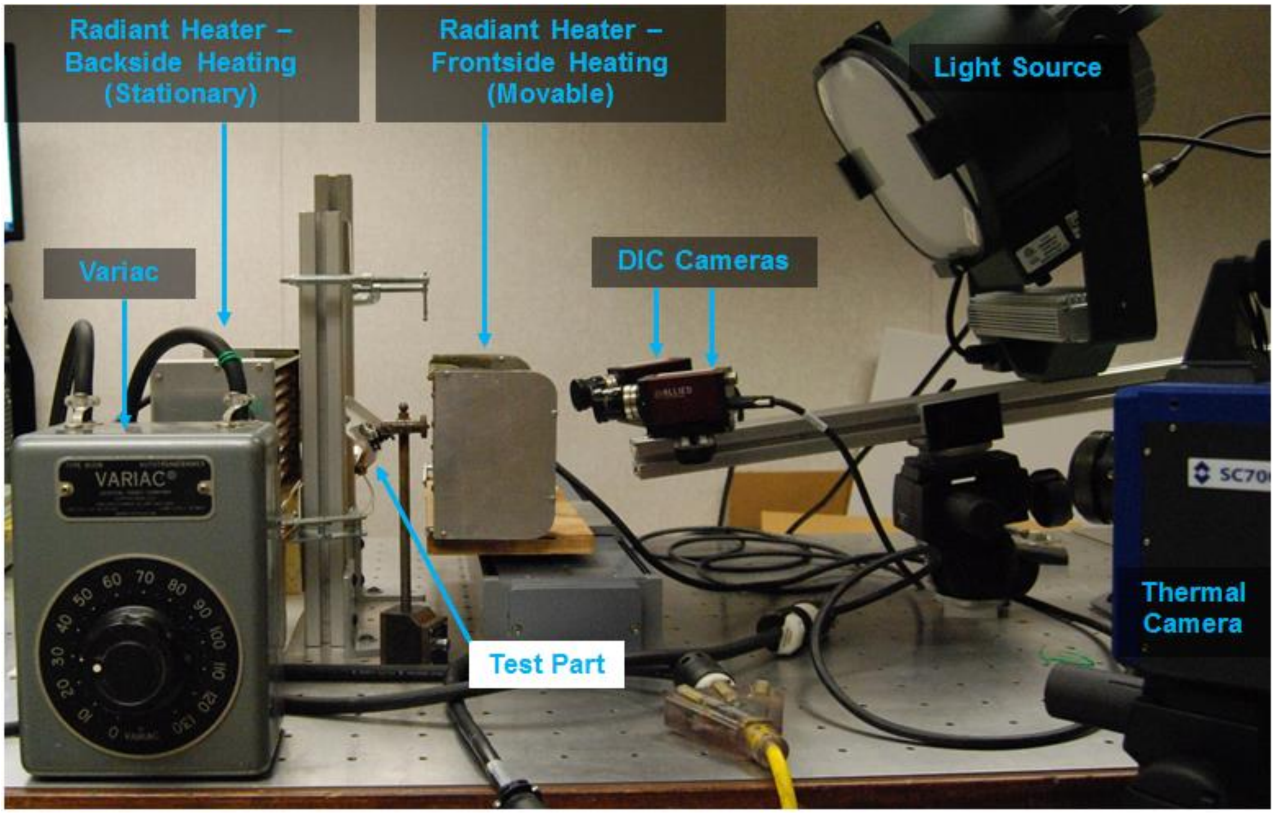

Figure 3 - Test set up for thermal loading and image collection

The part was held rigidly in space by a support fixture with a bolt through one of the two mounting points moulded into the part. Radiant heaters were used to heat the part, with power to the heaters controlled by Variacs which were manually controlled to achieve the test temperature. While the backside heater was stationary, the frontside heater was mounted on a linear slide. Once the test temperature was reached, after a short soak period, the frontside heater was quickly slid aside and images captured within 5 seconds. Thermocouples mounted on the backside of the part were used to monitor part temperature. As an initial check on temperature uniformity, the first few trials included a thermal camera viewing the part frontside.

Figure 4 is one of the thermal images of the part at temperature, showing the level of temperature uniformity achieved with this test set up.

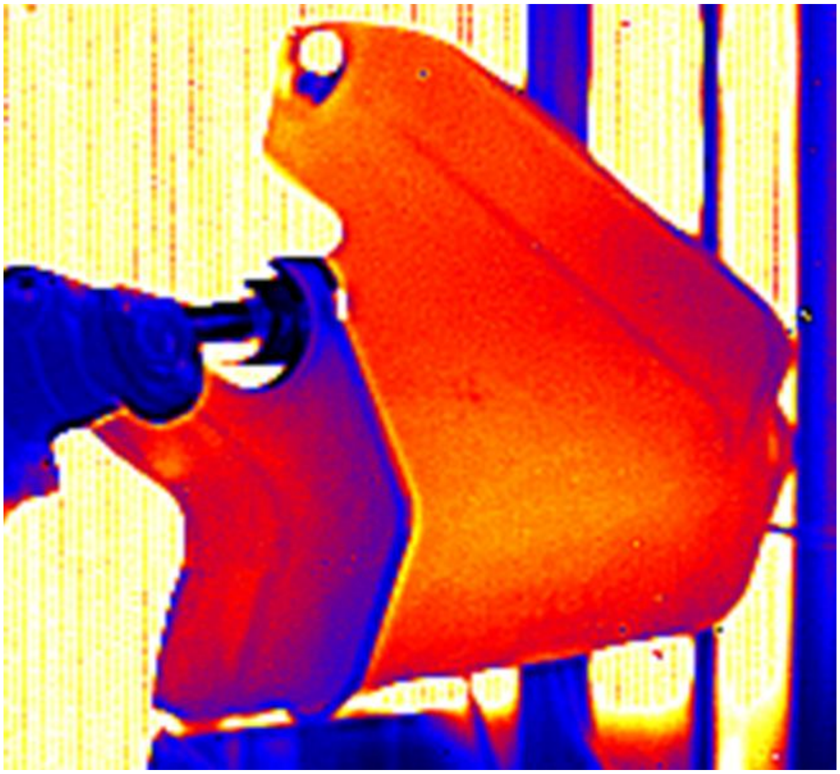

Figure 4 - Thermal image of the part at temperature

5.2. Test Results

Two parts from the same moulding batch were tested in a variety of views (i.e. part orientations and camera angles) in order to gather images that were correlated to their room temperature images in order to assess strain for all regions of interest across the part. Only one view is shown here in order to focus on the issue of strain variability caused by the discontinuous material form and to assess the level of part-to-part variability. The maximum principal strains caused by heating to 180°C (350°F) in the unrestrained state (i.e. free in space) for the same view on the two parts are shown in Figure 5. The direction vectors indicate the orientation of the strains over the surface of the parts.

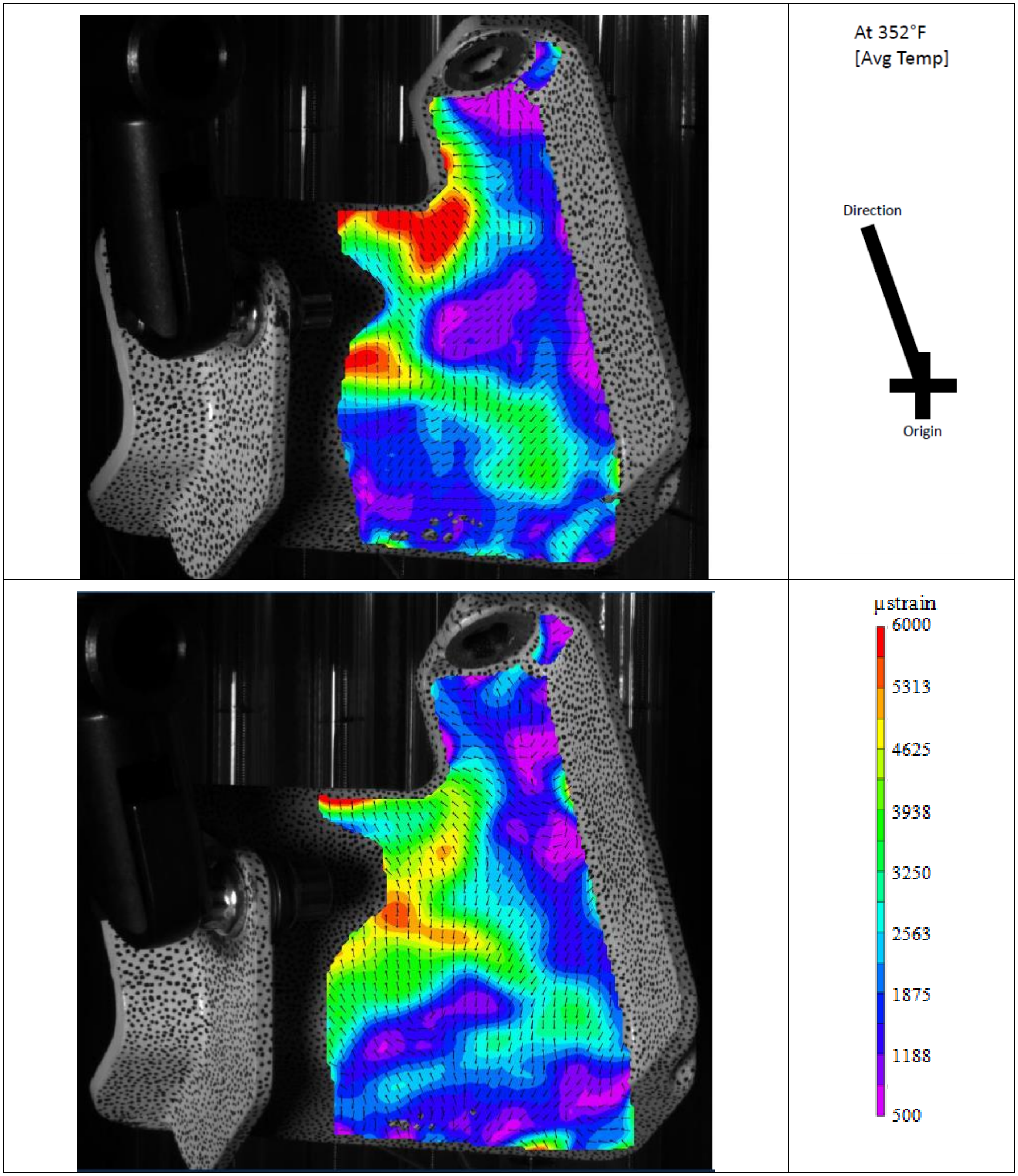

Figure 5 - Maximum principal strains caused by heating for two parts from the same moulding batch

As can be seen in Figure 5, free thermal expansion causes large variations in strain (500 – 6000 µstrain) over the surface of the parts. Comparing the two parts, there is a moderate level of part-to-part variation in strain magnitudes, although in general, the regions of high and low strain are consistent. It should also be noted that the strain direction vectors are reasonably consistent between the two parts. Considering how these parts are moulded, it is possible that the strain direction vectors are related to material flow effects during moulding, but further investigation would be required to determine the extent of correlation.

6. CONCLUSIONS

High fibre volume fraction prepreg cut into chips provides an interesting material form for production of complex shaped composite parts. The discrete form of the chips produces an inhomogeneous material which results in an inhomogeneous strain and stress distribution in the parts when they are placed under load. This complex strain and stress state presents significant problems when trying to measure part behaviour during performance testing. Traditional measurement approaches such as strain gauges are not suitable for this material since the scale of variability across the surface is usually similar to or larger than typical strain gauges. Instead, a more 'global approach' is needed in which overall part behaviour is determined by measuring average response over large areas of the part. In this work, an optical strain measurement method using digital image correlation was successfully employed to measure the response of a discontinuous Carbon / PEEK part to free thermal expansion from room temperature to 180°C (350°F). The results showed large variations in strain across the surface of the part and also showed a moderate level of variation when comparing the strains between parts taken from the same moulding batch.

7. REFERENCES

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