# Evaluation of Inhomogeneous Deformation and Stress Concentration in Polymer Composites Injection Weld by means of Thermoelastic Techniques

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Fiber composite materials are widely used in aerospace industries due to their high specific strength and stiffness. Especially, the increasing use of polymer composite materials for injection of automobile components has led to a considerable interest in the application of stress pattern analysis by thermal emission to these composite materials. Therefore, in this study the microstructure of glass fiber orientation at the parent and weld line of polycarbonate is observed by a light transmission microscope. And we also investigate a stress concentration model of a notch including short glass fibers. Especially the polymer injection weld reorients the fiber to suggest a new method for the evaluation of inhomogeneous deformation.

**Key Words :** Polymer Composite, Inhomogeneous Deformation, Injection Weld, Thermoelastic Techniques, Stress Pattern Analysis, Thermal Emission

## 1. Introduction

Fiber composite materials are widely used in the aerospace industry where their high specific strength and stiffness may be exploited to great advantage. Among fiber composite materials thermosetting matrices reinforced by glass, aramid or carbon fibers are commonly used. On a macroscopic scale, a unidirectional fiber composite may be treated as a homogeneous orthotropic material of which the properties are symmetric about orthogonal axes. This orthotropy is undesirable in structural components because the fiber plies by these components will generally be oriented in two or more directions to give the required balance of properties. Therefore, the dependence of strength on fiber orientation in the matrix, especially for polymer composite materials is important. There are a number of experimental methods for the stress analysis in the anisotropic materials, including strain gages, photoelastic modeling, finite element analysis and the infrared technology.

The increasing use of non-homogeneous anisotropic materials, such as woven carbon epoxy composites in aerospace structures and polymer composite materials for injection in automobile components, showing the difficulties to apply traditional stress analysis methods, have led to a considerable interest in the application of stress pattern analysis by thermal emission (SPATE) to these composite materials.

Following the work of Lord Kelvin (Thomson, 1858) a number of interesting experimental studies were carried out using contacting thermal instrumentation. There is a review of these studies done by Rocca and Bevar (Rocca and Bevar, 1950). Recent studies using sensitive contacting

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devices include those done by Jordan and Sandor (Jordan and Sandor, 1978) and Beghi (Beghi et al, 1986). The majority of applications of SPATE system have been concerned with homogenous and isotropic materials.

This study represented a review of critical aspects of non-contact measurement and identified the wide range of application for inhomogeneous and anisotropic composite materials. For this study, the microstructure of glass fiber orientation at parent and the weld line was observed by the light transmission microscope (LM). We also investigated a stress concentration model of a notch in polymer composite materials including the short glass fiber.

## 2. Experimental Procedure

### 2.1 Principles of SPATE

SPATE is a recent technological development based on thermoelastic effect which is a relationship between temperature change and the adiabatic elastic deformation of a solid body. This effect was first researched by Lord Kelvin (Thomson, 1858) and applied to homogeneous isotropic materials under an adiabatic loading condition.

The SPATE system has clearly identified and mapped stress concentration in test samples. These tests under dynamic load conditions illustrate the potential of the method for identifying stress features due to structural geometry and defects like cracks. Stress-induced temperature changes as small as $10^{-3}$K may therefore be detected. The equipment can be programmed to measure the strain-induced temperature change for a matrix of points over the test surface and to reproduce the data as a color-coded display on a monitor.

This system is illustrated in Fig. 1. The operating frequency range of the instrument is 0.5Hz to 20kHz and hence a wide range of components can be tested under conditions appropriate to service conditions.

Data acquisition is automatic, which is controlled by a microprocessor. The stress data are stored on a non-volatile memory as the scan progresses. They may be calibrated to read directly in any selected stress units by an operator. The stress map is displayed on a monitor screen with stress levels represented by up to 16 colors. Scanning, storage and display options are selected from the keyboard.

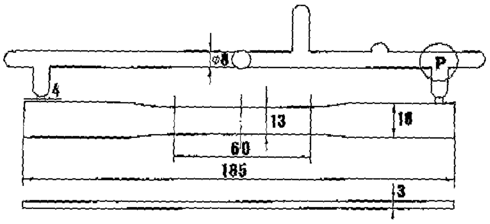
**Fig. 1** General view of the test apparatus

### 2.2 Test material

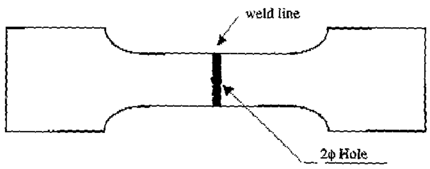
The polymer composite materials used in this experiment are polycarbonate (PC) with amorphous structure as general engineering plastics including 30% short glass fiber. The dimension of glass fiber is 13$\mu$m in diametes and 200~400$\mu$m long.

A double-gated mold used in this study is shown Fig. 2(a). It is for a dumbbell type tensile specimen with a weld line at the center, and we also could mold a specimen without a weld line by turning valve P to close the right side gate.

The specimen has been microtomed and polished with a sand paper at first and then alumina powder on the glass plate by hand. Then, the section about 10~15microns thick is prepared for microscopic observation.




(a) Injection mold




(b) Dog bone type specimen

**Fig. 2** Layout and dimensions of injection mold and specimen

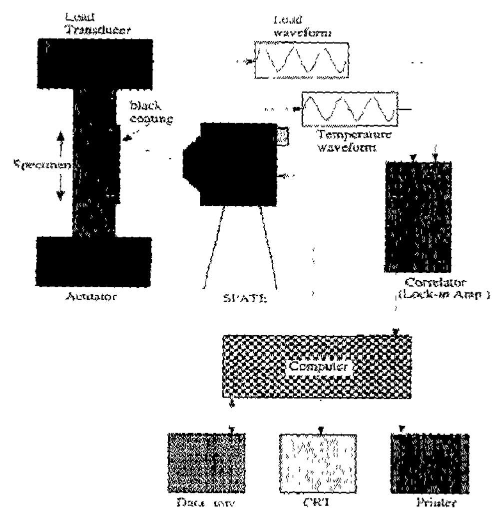



**Fig. 3** Schematic diagram of SPATE 9000

### 2.3 Test method

Dog bone type specimens of PC parent and weld were cyclically loaded at 10Hz in 50 kN capacity. MTS servo-hydraulic fatigue testing machine was used to investigate the linearity with load and repeatability of stress measurement.

Prior to loading both specimen were degreased and sprayed with the black paint matted and heat radiating. Special precautions were taken to ensure that the loading conditions were repeatable and that the variable levels of lock-in amp were correct. Figure 3 illustrates a schematic diagram of the main elements used in the system. This system is composed of fatigue testing machine, SPATE, Lock-in Amp and computer. Two cyclic signals which are the load waveform of fatigue testing machine and the temperature waveform detected with SPATE enter to lock-in amplifier and analyze the stress level of the specimen coated black.

Figure 2(b) shows the test specimen for SPATE. The SPATE 9000 system detects the infrared radiation emitted from a point on an observable surface, as a result of the minute cyclic temperature changes caused by the thermoelastic effect under cyclic loading conditions.

This high resolution produce a measurement spot of 0.5mm diameter and enabled the local stress variations from the geometry of the injection weld in polymer composite materials with short glass fiber to be measured.

## 3. Results and Discussion

### 3.1 Microstructure of parent and weld

The fiber orientation pattern is highly influenced by mold geometry, processing conditions and rheological properties of the material. The rheological properties are affected by the viscosity of the polymer matrix, fiber/matrix adhesion and other factors such as fiber aspect ratio, injection temperature and pressure, etc.

Figure 4 shows photomicrographs taken on three-dimensional fiber orientation of the PC parent by LM. The z-axis is the mold filled direction(MFD). Fiber orientation in the x-z plane can be explained by shearing and that in the y-z plane by elongational flow. In the x-y plane, one can observe the fiber section only.

On the y-z plane, however, the fiber orientation makes the fountain or volcano-like pattern (Hagerman, 1973) at weld line as shown in Fig. 5. For the mold size, thickness is 3mm in the y-z plane contrast to 13mm width in the x-z plane. Volcano-like pattern creates orientation at 90° to main polymer flow direction, namely, in the thin plate, but flower-like pattern is creating in the wide plate due to shear force in the surface in the

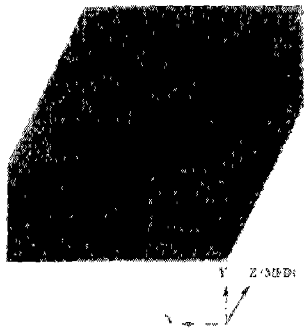


**Fig. 4** Photomicrograph taken on three dimensional fiber orientation of PC parent

**Fig. 7** Stress distribution of PC weld ($P_{min}$=50kg, $P_{max}$=100kg)

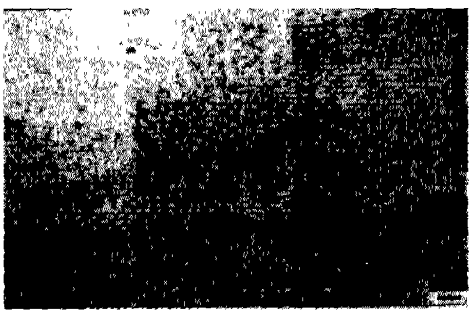
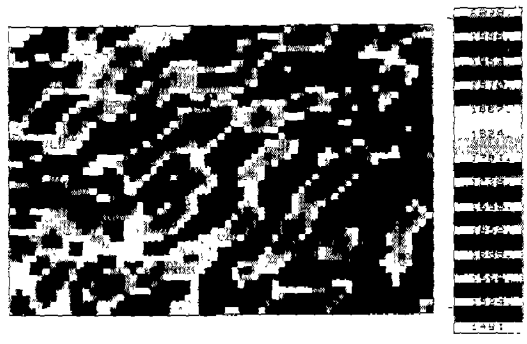


**Fig. 5** Photomicrograph of volcano-like pattern of PC weld

(a) The cyclic load range from 50kg to 250kg



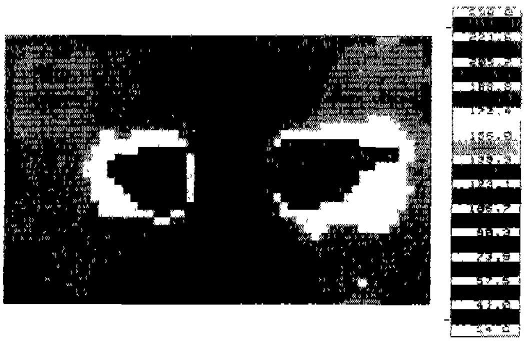
(b) The cyclic load range from 50kg to 400kg

**Fig. 8** The shape of stress distribution increasing with load in PC parent

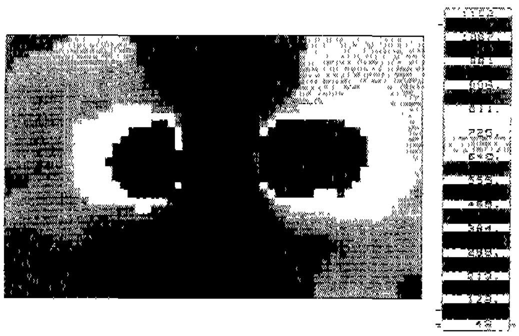
**Fig. 6** Stress distribution of PC parent ($P_{min}$=50kg, $P_{max}$=250kg)

side of mold. Mold walls cool the melt and increase its viscosity at the edge of the channel, retarding like flow. Flow at the center of channel continues at a higher rate, creating melt spill from center to edge of channel. So flow front makes change to perpendicular direction only.

Another important feature which correlates to the flow is that of weld or knit lines. This is a region where two flow fronts come together. The glass fibers are randomly oriented and therefore result in a weak spot. And then, formation of a weld line in injection molded products is practically unavoidable. Multiple gating or splitting of the melt flow in any way must rise to points within the structure where the flowing fronts will recombine and weld. The strength of

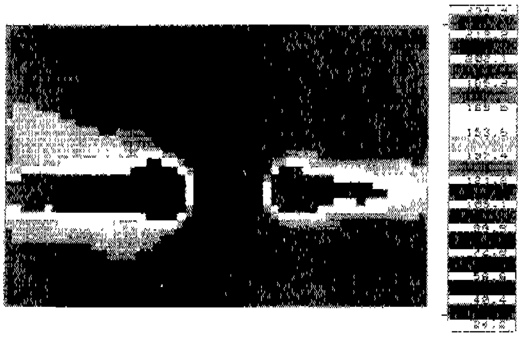


(a) The cyclic load range from 10kg to 100kg

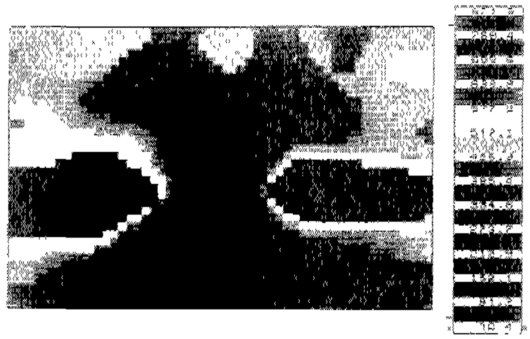


(b) The cyclic load range from 10kg to 250kg

**Fig. 9** The shape of stress concentration increasing with load in PC parent with hole



(a) The cyclic load range from 10kg to 70kg



(b) The cyclic load range from 10kg to 130kg

**Fig. 10** The shape of stress concentration increasing with load in PC weld with holes

the weld line tends to be markedly weaker than the bulk without weld.

### 3.2 Thermoelastic stress distribution at inhomogenous deformation

Figure 6 illustrates the shape of stress distribution PC parent. This polymer composite material is inhomogenous material compounding the polymer matrix and short glass fibers. The stress level is different along the boundary of the matrix and fiber. Figure 7 shows the stress concentration map at the PC weld. This stress concentration in the same dimension depends on the difference of elastic moduli at PC parent and weld, and affects the fiber orientation at the polymer injection weld. The stress distribution clearly shows a weldment caused by the fiber density and orientation surrounding the weld.

Figure 8 illustrates a change in thermoelastic stress distribution as a result of damage accumulation in the plane plate and PC weld with hole under vertical fatigue loading at 10Hz. Figure 8(a) shows the stress distribution at 10Hz producing a nominal mean load of 150kg and a peak to peak cyclic load of 250kg. The level of stress concentration is gradually increasing with load to maximum load, 400kg, as shown in Fig. 8 (b). The bright and red region in the scan area shows higher stress at the same dimension. Figure 9 shows the shape of stress concentration increasing with load in the PC parent with holes. The shape of stress distribution is the elliptic in the central line. The stress level of peak load is increasing with load from 238s to 1152s and then the shape of stress concentration in the leading edge of hole is nearly same.

Figure 10 shows the shape of stress concentration increasing with load in PS weld with holes. The stress level in the loading edge of the hole increases from 234s to 821s, depending on the maximum load. The peak load is increased from 70kg to 130kg. And then, the shape of stress

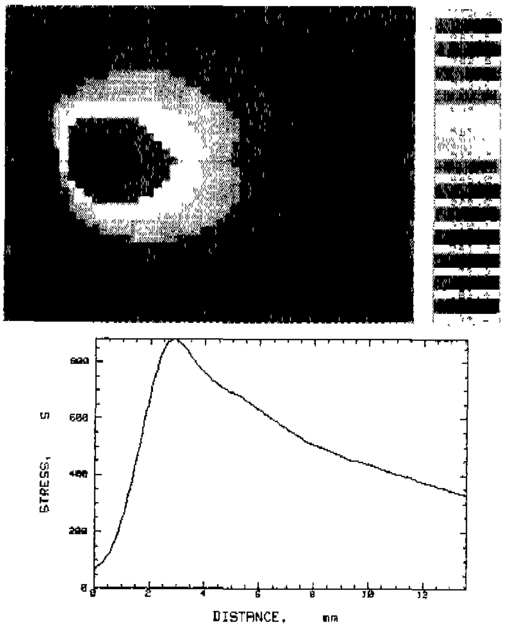
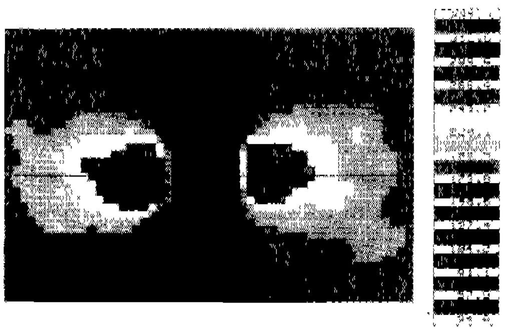
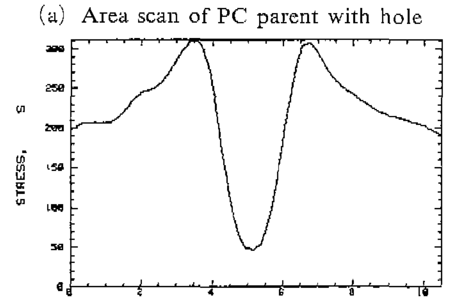



**Fig. 11** Stress concentration map around the notch tip of PC

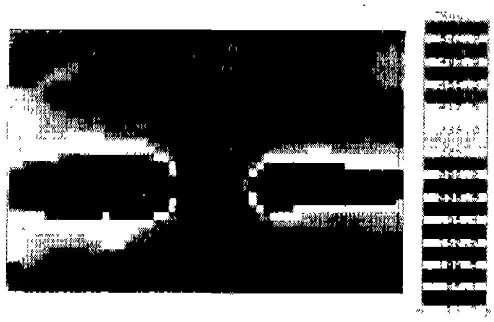


(a) Area scan of PC parent with hole

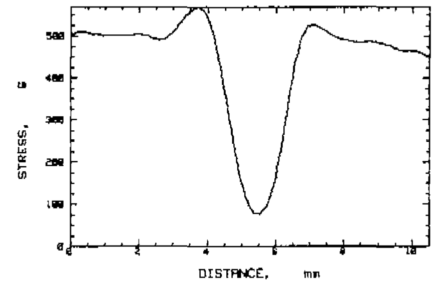



(b) Line stress plot across cental region

**Fig. 12** High resolution in the phase scan showing around the hole of PC parent



(a) Area scan of PC weld with hole




(b) Line stress plot across central region

**Fig. 13** High resolution in the phase scan showing around the hole of PC weld

concentration is different from the parent as shown in Fig. 9. The area of stress concentrated is increasing along with the weld line. This shape of stress concentration is one of reasons of reducing the strength in polymer injection weld. The stress concentration induced by a notch and the submicroscopic stress distribution due to a fabric structure are clearly observed. It is confirmed that higher temperature change is detected in the weld region of short glass fiber reinforced polymer composite.

### 3.3 Stress concentration at notch of polymer injection weld

A reproduction of the SPATE 9000 color monitor screen, the stress concentration map aruond the notch tip of PC, is shown in Fig. 11. This stress map contains over 1400s stress measurement points and represents an area of 20 mm × 13mm on the specimen. The cyclic load is 10kg to 150kg at the loading point. The scale on the right of the monitor screen shows the linear stress scale, with zero stress at the bottom and increasing values through to the full scale values. The stress map clearly shows small areas of higher stress on the specimen. These higher stress areas of notch tip appear as the oval type stress map.

On examination of the specimen with the SPATE 9000 projected light spot, the geometry of these higher stress positions correlated very well with the geometry of the specimen, suggesting that the localized stress concentrations were caused by the geometry of the glass fiber filled polymer composite material. The stress level of center line to the direction of crack growth shows the peak at the position of 3mm far from the notch tip and slowly decreases.

Figure 12 and 13 illustrate selection of the frame scan work applied around the hole of PC parent and weld. Figure 12(a) shows a stress distribution map and stress level around the hole of PC higher stress on the specimen. with cyclic load of 10kg to 100kg. These higher stress areas of notch tip appear as the oval type stress map. Figure 12(b) is the line stress plot across central region of the hole. The line plot in Fig. 12(a) is taken across section +——+ of the frame scan. This stress level is typically decreased to the distance of the hole edge.

Figure 13 represents the stress concentration around the hole of PC weld. Figure 13(a) shows the stress distribution map. The stress concentration area around the hole is enlarged to the weldment.

The shape of stress concentration is a long type and transverse to the tension direction. Figure 13 (b) is taken across section +——+ of the area scan in Fig. 13(a). The stress level around the hole is gradually decreased to the distance from the modulus for these two materials, parent and weld reinforced with short glass fiber. This can also be a reason that the strength in polymer injection weld is reduced.

## 4. Conclusions

In this paper, we investigated the microstructure and fiber orientation and the shape of stress concentration and distribution in the polymer composite materials including short glass fiber by SPATE. Results obtained in this study can be summarized as follows :

(1) Microstructure and fiber orientation of PC injection flow depend on the position of mold, especially injection welds are the place where two flow fronts come together and shows the fiber orientation of a volcano-like pattern.

(2) The stress concentration of a plane plate of PC weld without any geometrical stress concentration showed microstructural stress concentration at the weld because preferential fiber concentration was confirmed by SPATE using the difference of thermoelastic stress.

(3) The stress concentration according to fiber orientation effect of polymer injection weld contained various orientation of fiber is growing to the weld line and this valuation has strong effect on stress concentration with respect to tensile axis and also plays a dominant role in deformation and fracture behavior.

(4) The shape of stress concentration in polymer composites is the oval due to the effect of fiber orientation, so the stress distribution map and stress level around the hole of PC parent and weld are greatly different. That is, the geometrical stress concentration of parent with holes is the oval type and the weld having the fiber orientation transversely to the loading axis is the long hole growing to the transverse direction.

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