# MEASUREMENT OF RESIDUAL STRESSES
# IN CLEARWELDS USING PHOTOELASTICITY

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## Abstract

Residual stresses are detrimental to a plastic joint for a number of reasons. They lead to reduced strength and fatigue life in joints, act as stress concentrators and cause crazing, cracking when exposed to solvents. In this paper, the residual stresses in Clearweld[®1] joints were measured using photoelasticity. This interference based technique was used in conjunction with a stress separation algorithm to quantify the maximum residual stress level and the stress distribution in the weld region. Also, the effects of process parameters like welding speed, power and ink solvents on residual stresses were evaluated. The GE solvent test was also employed for comparison with the photoelasticity results. A comparison of the residual stresses between various joining processes was also made.

## Introduction

The use of lasers to join plastics and composites is gaining momentum in the automotive, medical, packaging and a number of other industries, especially for through transmission infrared welding (TTIR) processes. The inherent advantages of this technique being that it is a non-contact process that does not require relative motion between the components joined. Also, through multi-axis CNC machines it is possible to weld complicated contours at high welding speeds. However, one of the primary drawbacks of TTLW is that one of the components has to be transparent to the wavelength of the laser beam used and the other opaque.

Clearweld [1] is an innovative laser joining technique, which has all the advantages of conventional TTIR coupled with the fact that it can be used to weld two infrared transparent parts to each other. Welding of two infrared transparent materials is possible by applying a laser absorbing layer at the interface. Upon absorption, the energy of the laser beam is converted to heat causing melting and fusion to take place due to conduction. The absorber becomes colorless after the welding process thereby creating a seamless weld between the two components. The presence of the absorbing layer yields greater flexibility in process parameters for achieving the desired strength and toughness.

The primary parameters involved in the Clearweld process are: power, welding speed, applied pressure, and quantity of the absorber. This work investigated the effect of variations in the above-mentioned process parameters on residual stresses formed. The residual stresses in Clearweld joints were quantified using photoelasticity and solvent testing. A comparison of residual stresses was made between Clearweld and other plastic joining techniques. The effect of ink solvents on the strength of the joint was also studied. Polycarbonate was chosen as the material for analysis because of its excellent engineering and optical properties [2].

## Background

### Photoelasticity theory

Photoelasticity has emerged as a powerful tool in the quantification of residual stresses in plastic welds. Although the use of the technique is limited to birefringent plastics like polycarbonate and PETG, it provides powerful insights into residual stresses in viscoelastic materials. Photoelasticity in itself is only an indicator of the principal stress difference at any point on the sample. In order to calculate the normal stress distribution along and perpendicular to the weld a stress separation algorithm is employed. The algorithm is derived from a finite difference approximation involving the shear difference technique [3]. A grid system was employed and the following basic equations were used to determine shear stresses and normal stress differences at each station in the grid [4].

$$(\tau_{xy})_{i,j} = \frac{1}{2}\left(\frac{f}{t}\right)(N)_{i,j}\sin 2(\theta)_{i,j}$$
$$(\sigma_x)_{i,j} - (\sigma_y)_{i,j} = \left(\frac{f}{t}\right)(N)_{i,j}\cos 2(\theta)_{i,j} \tag{1}$$

Where $f$ is the stress optic coefficient [2] for polycarbonate, $t$ is the thickness of the sample $N_{i,j}$ and $\theta_{i,j}$ are the fringe order and the isoclinic angles at each station. The isoclinic angles were measured positive counterclockwise from the x-axis to the direction of the greatest principal stress. It was determined from previous analysis that the stresses perpendicular to the weld were of the highest magnitude and therefore the most important for analysis. The

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maximum stress was determined by using the following equation:

$$\left(\sigma_x\right)_{i,j+1} - \left(\sigma_x\right)_{i,j} + \frac{1}{2}\left(\frac{x_{i,j+1} - x_{i,j}}{y_{i+1,j} - y_{i-1,j}}\right)\left[\left(\tau_{xy}\right)_{i+1,j} - \left(\tau_{xy}\right)_{i-1,j}\right] +$$
$$\frac{1}{2}\left(\frac{x_{i,j+1} - x_{i,j}}{y_{i+1,j+1} - y_{i-1,j+1}}\right)\left[\left(\tau_{xy}\right)_{i+1,j+1} - \left(\tau_{xy}\right)_{i-1,j+1}\right] = 0 \quad (2)$$

To simplify the calculations, the boundary and the symmetry conditions were used in determining the shear stresses and the normal stress difference. Starting from the boundary where the stress normal to the boundary is zero, the normal stress values were sequentially calculated and plotted along the grid lines.

## Experimental Procedures

### Welding

Prior to welding, samples were prepared by applying methoxy-propanol (MOP), methyl ethyl ketone (MEK), or ethanol-based inks containing the absorber to the end of a precut sheet 7.2cm by 2.5 cm. The samples were then pressed end to end in a butt joint configuration. A 940 nm diode laser was used to transmit the laser beam through one part to scan the interface. The effect of scan speed and power was evaluated by varying the scan speed from 0.12 m/min to 1.5 m/min and the power from 90 to 300 Watt. The pressure was removed immediately after welding.

### Tensile Testing

The welded samples were tensile tested to determine joint strength and energy to fracture. The testing was done on a computer controlled Instron (Model No. 4468) tensile testing machine. The cross-sectional dimensions of the samples were 25.4mm x 2.5 mm. The crosshead speed was set at 5 mm/min.

### Photoelasticity

The residual stresses developed due to the welding process were measured using photoelasticity. The challenge presented by the very small heat affected zone (HAZ) in Clearweld joints was overcome by the use of polarized microscopy. Magnifications of 5X and 10X were employed in order to determine isochromatic (lines indicating regions having the same principal stress difference) fringe order. The setup was initially calibrated in order to ensure accurate calculations [2]. A dark field polariscope (see Figure 1) was used to map the isoclinic fringes (lines indicating principal stress orientation). With the help of the fringe maps and the equations mentioned above, normal residual stresses perpendicular to the orientation of the weld were calculated.

### Solvent testing

The solvent testing technique [5] was used in order to serve as a comparison to the results of photoelasticity. The welded parts were exposed to varying concentrations of acetone in methanol for a period of three minutes. The samples were then observed for cracking and crazing along the weld. The lowest concentration of the solution that caused cracking was noted down and the corresponding residual stress values were obtained from the critical stress versus concentration chart for polycarbonate [5].

### Residual stress effects

The effects of residual stresses on joint strength and energy to fracture of Clearweld was investigated by exposing the sample to a low concentration of solvent, followed by tensile testing. The sample was exposed to a 10% acetone in methanol solution for 3-4 minutes. The samples were then dried in a vacuum oven and tensile tested. The strength of the samples was compared to that of welded samples that were not exposed to the solvent.

## Results and Discussion

As shown in Figure 2, Clearweld joints have a very small HAZ compared to that of hotplate welds. As shown in Figure 3, despite the very high heating and cooling rates, the residual stresses in Clearwelded joints are slightly lower than in conventional TTIR welds and substantially lower than in ultrasonic welds [6]. No direct relationship was identified between the size of the heat-affected zone and the residual stresses in the plastic joints. It was also found that the residual stress distribution in plastic joints are similar to those modeled using the multi-bar analogy, where regions close to the weld are under high tensile stress while the regions away from the weld are under compressive stress [4].

Figure 4 shows that for MEK-based inks with a constant welding speed 0.89 m/min, the residual stresses increased with an increase in laser power. Notice the good agreement between the GE solvent test estimates and the photoelasticity measurements. This can be explained by the fact that an increase in power allows greater absorption of energy by the absorbers and thereby results in higher temperatures and temperature rise rates. Therefore, temperature gradients during cooling should increase with increasing power resulting in higher residual stress levels.

Figure 5 shows the effect of laser scan speed on residual stress levels for ethanol, MOP, and MEK based inks. Here too, the GE solvent test estimates are in good agreement with the photoelasticity measurements. Figure 5 shows that increasing the scan speed results in a small

increase in maximum residual stress levels. It is also observed that the nature of the solvents in the ink plays a considerable role in affecting the residual stresses in the joints. The ethanol-based ink was found to cause more residual stresses in polycarbonate welds than the MEK and MOP-based inks.

Figure 6 shows that a maximum of 77% of the bulk material strength was achieved in the welded samples used for the analysis. The greatest strengths were achieved in the MOP-based inks and MEK-based inks (77% and 78% bulk material strength respectively). It was also observed that higher concentrations of absorbers resulted in considerable improvement in joint strength without causing high residual stresses.

Figure 6 also shows that a reduction of about 35-40% in tensile strength was observed in samples exposed to solvents of very low concentrations (10-20% acetone in methanol). Exposure to solvents causes crazing and cracking at the joint [5]. Therefore, these regions act as stress concentrators leading to poor performance of the welds under load. In some cases the drop in tensile strength was as high as 60-70% of the original strength. This reduction could be attributed to the cracking and crazing caused by the solvents.

## Summary

Residual stresses present in Clearweld joints are higher than hotplate welding but lower than other high speed joining processes. High residual stresses cause crazing and cracking in joints that are exposed to solvents or corrosive environments, which can adversely affect the performance of the joint under load.

Therefore, measurement of the residual stress levels in welded structures and understanding the influence of process parameters on residual stress formation is important to improving welding methods and weld performance.

## Acknowledgement

## References

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## Keywords

Photoelasticity, Laser Welding, Residual stress, Shear difference technique, Solvent testing, Clearweld, and Absorbers.
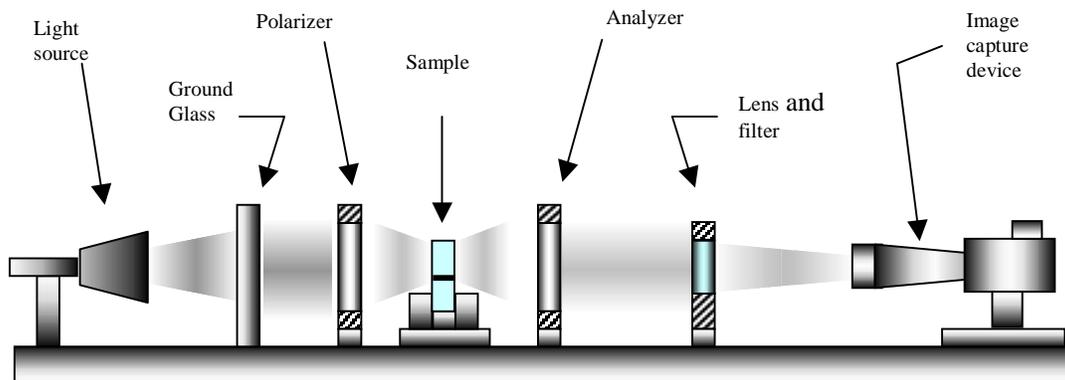


Figure 1. Photoelasticity setup for residual stress measurement.
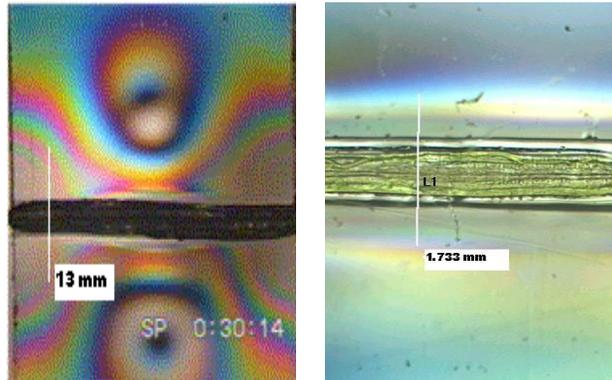
Figure 2.  HAZ (Heat affected zone)  map for hotplate
and laser welds at different magnification (polarized
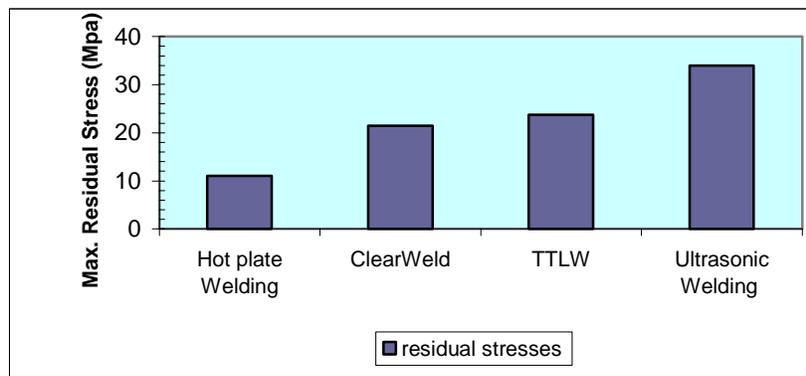light microscopy).



Figure 3.  Comparison of residual stresses for Hotplate, Clearweld, TTLW and Ultrasonic welding techniques.
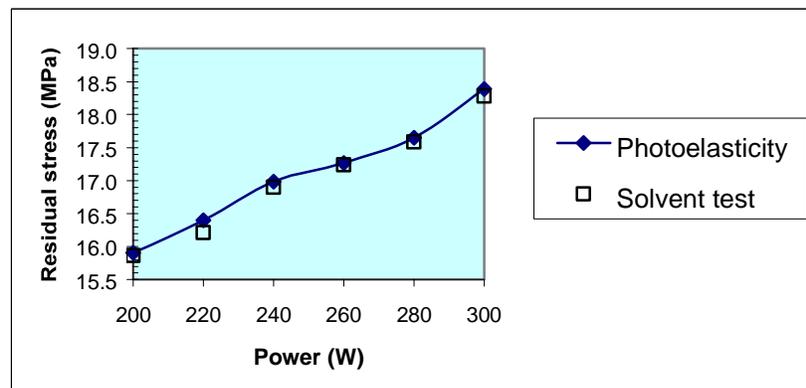


Figure 4.  Variation of residual stresses with increase in power for MEK based inks.
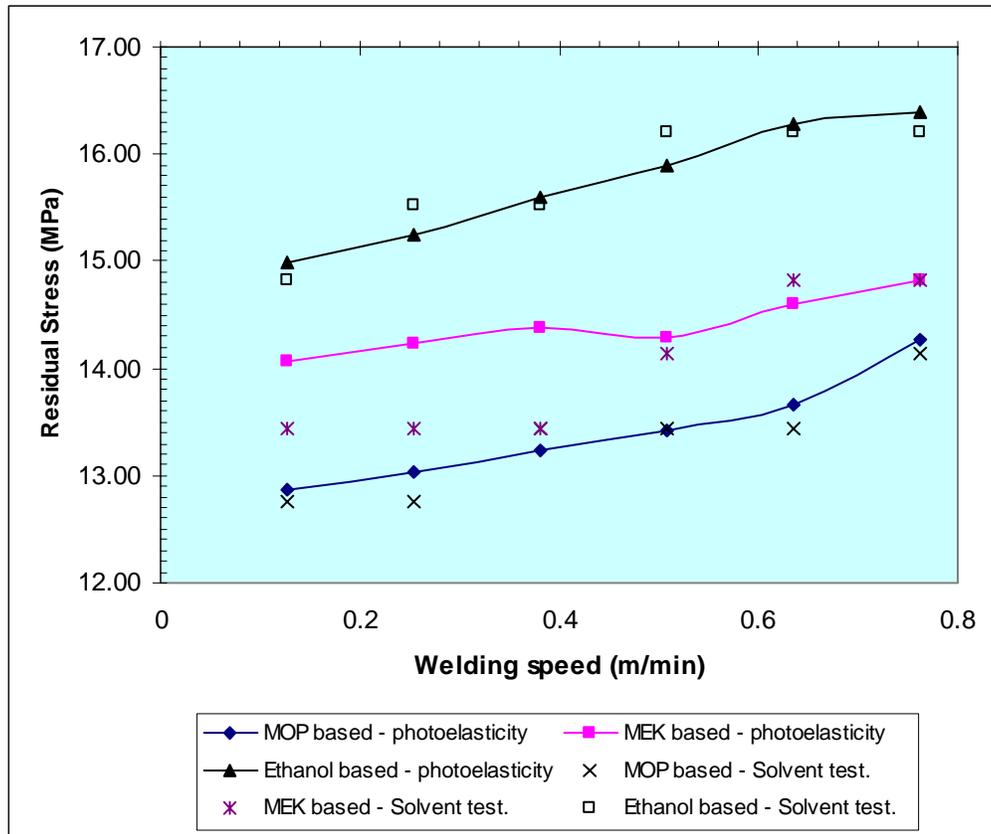
Figure 5.  Variation in residual stresses with increase in welding speeds for MEK,
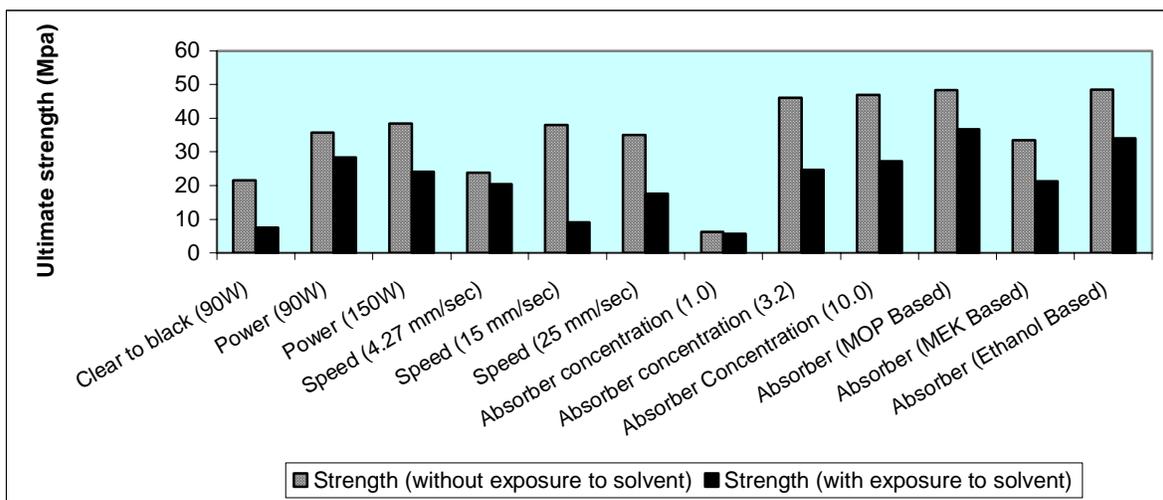Ethanol and MOP-based inks. (P=300W)



Figure 6.  Effects of residual stresses on tensile strength of the samples.