DESIGN OF EXPERIMENT TO OPTIMIZE ABSORBER IN RESIN WELDING PARAMETERS

Michelle M. Burrell, William H. Cawley and Joseph P. Verespy
GENTEX Corporation
Carbondale, PA 18407-0315, USA

Abstract

Through Transmission Laser Welding can be accomplished using either a coating or a weldable resin. As part of the weldable resin work, it was necessary to conduct a series of experiments to define optimum welding parameters. In one study, a DOE was conducted to determine the optimum welding parameters for polycarbonate and to develop a prediction equation which could be used in other tests. This DOE studied the effects of absorber concentration, energy density, thickness and pressure. The ability to weld the PC was achieved by blending a Clearweld® infrared absorber with PC resin and molding the parts into a weldable form. This paper summarizes the test procedures and results of the DOE.

Introduction

Laser welding of plastics, using various types of diode and Nd:YAG lasers, is an established process for joining thermoplastic components [1,2]. Recent work has also shown that fiber lasers can play a key role in field of plastic welding [3]. All of these lasers use a through transmission laser welding process. That is, the laser radiation passes through a laser transparent upper layer and is absorbed by the lower layer. The absorbed radiation is converted into heat near the interface of the lower layer. The heat is conducted from the interface to the upper and lower levels causing the materials to melt and flow together to form a weld joint.

Traditionally, the transmission welding process requires the use of an additive to increase the absorption of plastics [4]. Carbon black is used in laser welding in a wide array of industrial applications that require the laser welding of plastic components [5]. This system works well, but it introduces a dark coloration to the parts which is objectionable in applications that require transparent or lightly colored components.

An alternative system that enables the welding of transparent or opaque plastic materials has been developed by TWI Ltd in conjunction with GENTEX Corporation [6]. The Clearweld® process utilizes organic-based near infrared absorbers as coatings on polymers or as additives to resins.

In the case of the coating, a thin film of absorber is applied to the surface of one of the parts at the weld interface only. The coating, which has a slight coloration prior to exposure to the laser energy, absorbs the laser energy and converts it to heat energy which allows the plastic on either side of the surface to flow together to form a weld joint. The coloration of the coating is dissipated in the reaction, thereby permitting the formation of a transparent weld joint. As this occurs, the ability of the absorber to convert infrared light to heat is lost and any additional infrared energy is transmitted through the lower layer. This results in a relatively small heat affected zone adjacent to the weld.

Alternatively, absorbers can be directly incorporated as additives into the plastic material. This welding process is similar to that used with carbon black welding; but with much more color flexibility. Clearweld® additives have high absorptance in the near infrared range and low absorptance in visible range of the electromagnetic spectrum. The additives are formulated to match an absorber’s maximum absorption wavelength with the wavelength of the laser used in a specific application.

Much of the early work on Clearweld® additives dealt with coatings systems. The mechanism for their use is straightforward. But the welding process changes when infrared absorbers are blended into resins, which are then used in the production of molded parts. As in the case of carbon black, the entire lower part will now act as a heat sink for the laser energy. This changed the dynamics of the welding process and required some laboratory studies to determine how this system works [7]. It was necessary to conduct a series of experiments to evaluate the welding parameters of the absorber-in-resin systems. A design of experiment approach was adopted for these experiments.

A Design of Experiment (DOE) is a structured, organized method for determining the relationship between factors affecting a process (variables) and the output of that process (results). The objective of a DOE is to identify important factors affecting the process. The type of design selected can vary. However, all rely on the use of basic statistical analysis in dealing with the results of the experimentation [8].

Traditional experimental methods collect large quantities of data by holding each variable constant in
turn until all possibilities have been tested [9]. This approach can give misleading conclusions in experiments that have interactions between the variables. The statistical method is characterized by experimental designs employing factorial structures. It allows one to depict the function in terms of contour plots and to think in terms of the geometry of the experimental region. An ultimate goal of the experiment should be the generation of a prediction model for the system being studied.

As mentioned earlier, there are several DOE formats that can be used to successfully. The Clearweld experiments utilized a Two Level Factorial Design for the experiment format. It can be used to screen many factors to determine which are significant. It will also allow one to predict interactions between the variables that are studied. And it will generate a prediction equation that can be used to optimize the results.

In this experimental method, each factor selected is examined at two levels – a low and a high level. For two levels of three factors we would need to conduct $2^3$ or 8 test runs. If we added a fourth factor (say reaction time) we would need to conduct $2^4$ or 16 test runs. The Two Level Factorial Design permits the estimation of the effects of several factors simultaneously.

A DOE uses a design pattern or matrix in which each of the variables is at either a low or a high value. The low and high values for each variable are staggered so that each trial run contains a unique set of low and high values. When the tests have been run and the results data collected, the response data is entered into the test matrix. Several software programs have been developed to manipulate and analyze the experimental data.

Experimental

A Design of Experiment study was conducted in order to define the effects of various parameters used to weld infrared absorbers which were blended into thermoplastic resins. In particular, the welding results of a polycarbonate substrate that was impregnated with an infrared absorbing material were analyzed. Our objective was to determine how the welding results would be affected by varying the infrared absorber concentration, laser power, welding speed, clamping pressure and the thickness of the part. In order to do this, we developed a 2-level design of experiment (DOE) format with five variables.

A series of screening tests were run in order to establish the limits for absorber concentration and welding parameters. The limits were defined by our ability to achieve a weld at the lower welding parameters and to avoid overheating of the resin at the higher welding parameters. Our intent was to use a wide range of both laser powers and welding speeds. However, overheating of the resin and entrapment of bubbles at high laser powers and slow welding speeds limited the range of the welding parameters. As a result, we opted to combine laser power, welding speed and beam size into a single factor, laser energy density. We held the laser power and beam size constant and varied the welding speeds. This changed our study to a 2-level, 4-factor format. The factors that were studied and the ranges that were used are shown in Table 1.

The test samples that were used in the experiment were prepared by blending Clearweld® infrared absorber LWA267 (targeted for 940nm wavelength absorption) with Makrolon FCR 2407 polycarbonate resin (Bayer Corporation) and molding the blend into test plates that could be welded. A master-batch, or high concentration mixture of absorber and resin, was first made. The master-batch was then blended with additional resin to create various concentrations of absorber-in-resin test plates that were 38.1mm wide and 114.3mm long. The flat plates were welded by overlapping a top plate, which did not contain the infrared absorber, and the test plate. The test plates were divided into three cells. Lower absorber concentration, higher absorber concentration, and mid-range absorber concentration (control samples). A total of 57 samples were tested in random order.

The sample plates were placed into a clamping fixture that consisted of an aluminum base plate that was pushed against a top plate by an air cylinder, Figure 1. The upper plate was a clear PMMA plate with minimal absorption of infrared light (90.3% transmission of incident light). The lower plate contained the various concentrations of infrared absorber. A clear sample plate of polycarbonate without an infrared absorber was placed on top of the first plate. The two plates were overlapped by 10mm. The two pieces were held together so that a weld could be formed by applying pressure with the clamp. The air pressure on the cylinder was varied in order to create differing levels of clamping pressure. The welding was achieved by means of a Rofin, 150 watt, contour, 940nm diode laser with a 3mm beam. The laser power was held at 50 watts for all of the test runs. The laser was mounted onto a Techno-Isel CNC table so that the speed of the welding operation could be varied. The results of the tests were measured by using a Model 4466 Instron Tensile Test.

A software package that was developed by Stat-Ease, Design Expert Version 6.0, was used to design the test array and to manipulate the data analysis. We replicated each point with three samples and we also ran three mid-point sets in this study.
Results

During the tensile tests, the fractures occurred at three locations. At low concentration, energy density and pressure, the samples tended to separate in the weld joint. At higher concentration and energy density and low thickness, the parent material broke. At high concentration and energy density and high thickness the samples broke at the edge of the weld. The contribution of bending and peel shear to the tensile result may be reflected in this behavior.

The analysis of the test data verified that the results were statistically significant. They indicated that absorber concentration, sample thickness and energy density had significant effects on the weld strength results. In addition, there were interactions between the absorber concentration and clamping pressure as well as sample thickness and clamping pressure. The final equation for the effects is shown in Table 2. The equation that was generated by the Stat Ease software was tested and verified in subsequent welding trials.

Figure 2 shows the tensile results of changes in the absorber concentration, the thickness and the energy density. The variable of pressure was held constant at the mid-point value. The graph demonstrates anticipated weld strength results. At the lower energy density, the result doubled as the absorber concentration was increased from the low to the high value and was essentially independent of the sample thickness. Similarly, at the lower absorber concentration, the result doubled when the energy density was increased from a low to a high value. However, at high absorber concentration, increasing the energy density will not improve the weld strength. Similarly at high energy density, a high absorber concentration will not improve the weld strength. The thickness had little effect on the results. This relationship is shown in a slightly difference manner in Figure 3. The individual faces of the cube are laid out side-by-side to illustrate the trends.

This interaction of the absorber concentration and the energy density is shown clearly in the contour graph in Figure 4. At low concentration and energy density levels, a weak weld is formed. If either or both of the variables are increased a uniform increase in weld strength can be anticipated. At some set of values, the weld results will tend to plateau and not change significantly with changes in either variable. And at high absorber concentration and/or energy density there will be a slight drop in weld strength as the substrate "overheats".

Table 1 shows the relationship between the sample thickness and the absorber concentration. Since the infrared absorber is blended into the lower substrate, the entire lower substrate will act as a heat sink and will absorb and dissipate the laser energy as heat. The depth of penetration of the laser energy makes this relationship interesting. At low absorber concentration there is a very slight increase in weld strength as sample thickness is increased. At high absorber concentration there is also a slight increase in weld strength as the thickness is increased. However, the effect of the absorber concentration is greater than that of the increased mass of the substrate.

Figure 6 shows the relationship between the sample thickness and the energy density of the laser. We anticipated that the graph would be very similar to that for absorber concentration and thickness. However, the plane of the graph is very flat. If the scale for the results (z-axis) is reduced a slope can be introduced to show the effects of thickness and energy density. Figure 7 illustrates that thicker samples gave stronger welds than thinner samples at the energy densities studied.

Summary

1. Absorber concentration and energy density have the greatest impact on weld strength. They are somewhat linear in their effect on the welding result. A quantified change in either one will have a similar effect on the weld strength that is achieved.
2. The absorber concentration and energy density should be balanced to prevent overheating of the samples and a reduction in weld strength.
3. Sample thickness has a lesser effect on strength. The sample thickness appears to be more significant when varying absorber concentration than when varying energy density.
4. Clamping pressure had little effect on the results of the weld test. As long as the pressure is sufficient to insure close contact between the two substrates, an adequate weld result should be possible.

Acknowledgements

The authors wish to thank Mike Lubianetsky and Gentex Optics for providing molded parts and Harry Tomasofsky of Gentex Corporation for his efforts in providing tensile test results for our work.

Key Words

Clearweld, Design of Experiment, laser welding, weldable resin
References


<table>
<thead>
<tr>
<th>Factor</th>
<th>Units</th>
<th>Low Value</th>
<th>High Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber Conc.</td>
<td>Relative</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Sample Thickness</td>
<td>Mm</td>
<td>1.57</td>
<td>3.18</td>
</tr>
<tr>
<td>Energy Density</td>
<td>J/mm²</td>
<td>1.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Clamping Pressure</td>
<td>MPa</td>
<td>4.48</td>
<td>5.86</td>
</tr>
</tbody>
</table>

Table 1
Values for Factors Studied in the Experiment


Table 2
Final Equation for Experiment

Figure 1
Pneumatic Clamping System

Figure 2
Weld Strength Results Cube Graph
(Pressure = 5.17 MPa)
Figure 3
Concentration and Energy Density Effects

Figure 4
Concentration and Energy Density
(Thickness = 2.38 mm; Pressure = 5.17 MPa)

Figure 5
Concentration and Thickness
(Energy Density = 2.75 J/mm²; Pressure = 5.17 MPa)

Figure 6
Energy Density and Thickness
(Concentration = 2; Pressure = 5.17 MPa)

Figure 7
Energy Density and Thickness
(Concentration = 2; Pressure = 5.71 MPa)