Hot Pin Welding of Thin Poly(vinyl chloride) Sheet

James D. Van de Ven, Arthur G. Erdman
Mechanical Engineering Department, University of Minnesota, Minneapolis, Minnesota 55455

This paper develops a method of welding two thin sheets of poly(vinyl chloride) (PVC) with a heated pin, thus allowing construction of a relationship between the weld temperature and weld strength. Constructing a relationship between weld strength and temperature is necessary for modeling many welding processes, including laser transmission welding. An experimental approach to establishing this relationship is required because of the complex melting behavior of PVC. The designed experimental device uses a single heated pin to weld samples by using varying pressure and temperature for one second dwell time. An electro-mechanical loadframe pulled the welded samples until joint failure occurred, thereby allowing determination of the weld strength. An experiment varying welding pin temperature and joining pressure found the temperature to be a highly significant determiner of weld strength, while the pressure was found to be not significant. A transient numerical heat transfer model was used to calculate the weld interface temperature for each pin temperature. The relationship established in this paper can be used to predict the weld strength from the temperature output from models of alternative welding methods. J. VINYL ADDIT. TECHNOL., 13:110–115, 2007. © 2007 Society of Plastics Engineers

BACKGROUND

Laser transmission welding (LTW) is a promising plastic-joining alternative that creates a subsurface weld. Much work has focused on creating numerical models of the LTW in order to predict the material temperature and pressure for a specific set of input parameters [1–6]. Relating the weld pressure and temperature predicted in these models with the actual weld quality is critical to evaluating the model output.

During previous modeling of LTW, different approaches have been taken in quantifying the properties necessary for a satisfactory joint. Some researchers report the temperature distribution from the model and do not address the interpretation of these values [4]. A more common approach is to assume a satisfactory weld is created when a designated temperature, typically the melt temperature, is exceeded [2, 5]. The author is unaware of any previous work experimentally relating LTW model output parameters with weld quality.

The melting temperature of polyvinyl chloride (PVC) is not well-defined, owing to the large distribution in crystalline particle size. This variation in particle size results in a very broad melting range, which is characterized by particulate flow [7]. While the flow of material, as required for welding, could be modeled with molecular diffusion kinetic equations for many thermoplastics, particulate flow in PVC requires an experimental model. As a rough estimate, the onset of flow in PVC is at approximately 175°C [8].

Relating PVC weld temperature and weld strength has received attention in hotplate welding research. The heating time during hot plate welding is typically between 10 and 20 s [9], approximately one or two orders of magnitude greater than in LTW. In hot plate welding, the temperature of the material can be carefully controlled, thus making the results valuable for knowledge in the LTW field, where the material temperature is difficult to verify. Results from experiments by V. Stokes show that PVC welds created above 218°C achieve strength in excess of 90% of the parent material tensile strength. This same work finds a slight decrease in weld strength at temperatures above 288°C [9]. This decline quite likely is due to material decomposition during the long heating time. Work by Grewell and Benatar in the field of impulse welding found the weld strength to be a strong function of the temperature history of the two faying surfaces, not a single temperature [10].

Relatively little work in the LTW field has studied the influence of pressure in the weld zone, beyond assuring material contact. Further work by Grewell found that optimal weld strength was achieved with a clamp pressure near 2.2 MPa [11]. Work by Potente et al. found that the maximum weld strength is achieved at a clamping pressure near 1.5 MPa, yet the overall influence of weld pressure around this value was found to be insignificant because of the large amount of variation in the data [12]. It is interesting to note that both of these works found a

Correspondence to: James D. Van de Ven; e-mail: vandeven@me.umn.edu
Contract grant sponsor: Andersen Corporation.
DOI 10.1002/vnl.20111
Published online in Wiley InterScience (www.interscience.wiley.com).

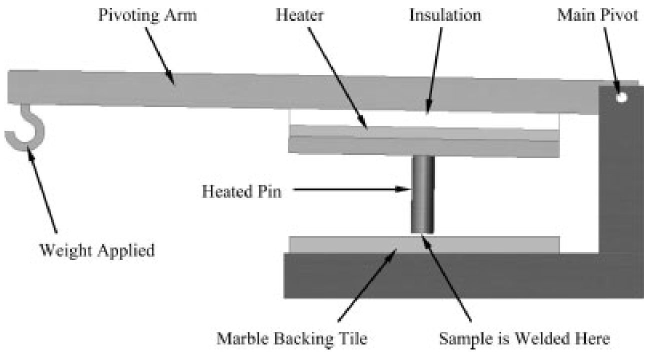

FIG. 1. This drawing of the pivoting beam hot pin welder identifies all major components.

decrease in weld strength when increasing the clamping pressure above a certain level.

A definitive investigation of the influence of pressure and temperature on a laser welded joint would ideally be accomplished through laser welding experiments. Unfortunately, this option is challenging, owing to the difficulty in accurately measuring the temperature in the weld zone during laser transmission welding. First, thermocouples cannot be used in the weld zone, as they will be heated by the laser radiation to a temperature not representative of the surrounding thermoplastic [5]. A contact-less temperature measurement method such as radiation pyrometry requires making a subsurface temperature measurement through the transmissive material. This subsurface measurement requires knowing the emissivity of the transmissive material at the operating wavelength of the pyrometer. Determining the emissivity has been found to be highly imprecise [1]. Because of the difficulty of precisely measuring the weld temperature, other methods must be utilized to study the influence of pressure and temperature on the weld properties.

EXPERIMENTAL SETUP

As an alternative to LTW experiments, a hot pin welding method was designed that closely simulates laser welding, while allowing careful control of the temperature and pressure. From LTW models, the maximum temperature occurs at a depth of 0.1–0.2 mm below the part interface into the absorptive part [3]. Heating of the transmissive material occurs primarily through conduction. The devised testing method simulates these conditions by welding two 0.102-mm (0.004″) thick PVC sheets with a heated pin. Contacting only one of the two thermoplastic sheets with the heated pin creates a temperature distribution similar to that of LTW in a controlled method.

The primary design concerns for the heated pin are providing a large thermal mass and a flat contact surface. The large thermal mass requirement is accomplished by using a 9.5 mm × 51 mm × 152 mm steel mounting plate. Adequate weld size is achieved with a machined steel pin of 12.7 mm diameter. A pin of this diameter was chosen in order to minimize the effects of the transition between the welded and nonwelded regions, while being small enough to achieve the desired welding pressure with force application. External threads cut at the end of the pin allow it to be connected directly to the mounting plate. To minimize an abrupt edge on the pin that might cause stress concentrations in the welded samples, the sharp edge of the contacting surface was filed slightly, thus causing insignificant reduction in surface area of the pin face. The temperature of the pin is monitored with a thermocouple that is mounted along its circumference.

The heated pin, mounting plate, and a marble backing are mounted in a custom pivoting-beam load applicator. This device consists of a base mounted to a bench and a pivoting bar where the pin and mounting plate are

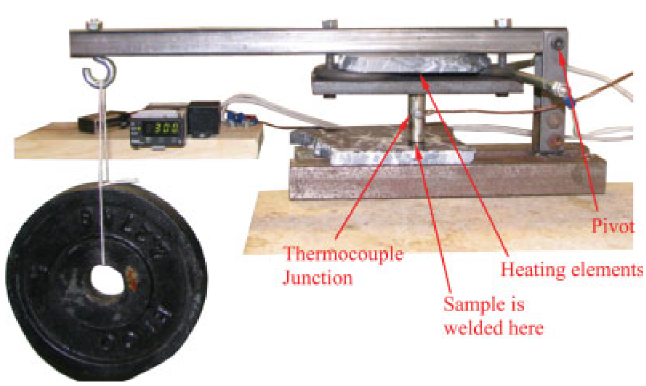

FIG. 2. This photograph shows the pivoting beam hot pin welding device. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

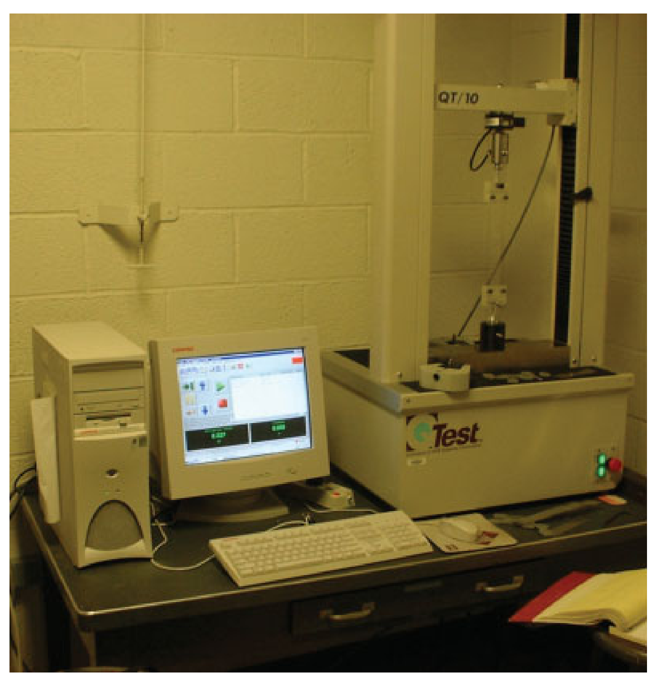

FIG. 3. The MTS electro-mechanical loadframe and control PC with the *T*-peel sample in place. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

FIG. 4. A sample mounted in a *T*-peel arrangement in the custom grips. This test is designed to measure the force required to peel apart the spot welded samples. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

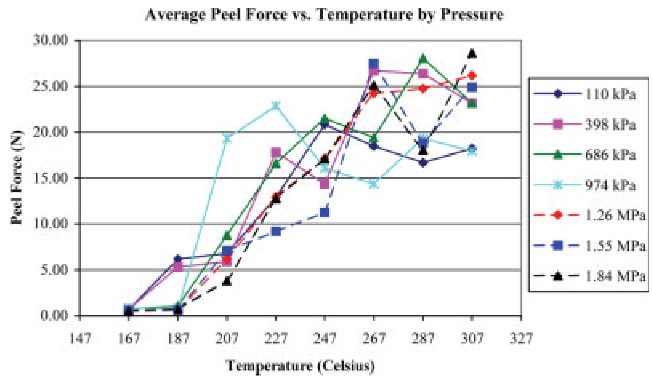

FIG. 5. This interaction plot shows the heated pin temperature on the *x*-axis, the welding pressure in the different lines, and the *T*-peel test maximum force on the *y*-axis. Each node represents the average of the three experimental samples at each distinct factor level combination. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

attached. The pin can be heated to temperatures in excess of 350°C by using two 250-W heating elements and a Fuji fuzzy logic controller. Temperature feedback for the controller comes from the thermocouple mounted to the pin. The device can apply pressure to the pin up to 1.8 MPa (267 psi) in increments of 288 kPa (42 psi) by placing weights to the end of the pivoting arm. To run an experiment, the pivoting bar with the heated pin is raised, and a sample is placed on the marble backing plate. The arm is then lowered, thus allowing the pin to contact the sample directly. A drawing of the device is presented in Fig. 1, and a picture of the device can be seen in Fig. 2.

The primary measure used to assess the weld quality is the force required to peel apart the weld. This characteristic was selected over visual appearance, as it is easier to quantify. The samples were tested for peel force in an MTS QTest QT/10 electro-mechanical loadframe with a 1000 N load cell (Fig. 3). Samples were secured in a pair of custom mechanical grips in a *T*-peel test arrangement. In the *T*-peel setup, the ends of the two sheets making up the sample are held in opposing grips [13]. The samples were pulled at a strain rate of 25.4 mm per minute in order to peel apart the weld (Fig. 4).

EXPERIMENT DESIGN

To understand the influence of process parameters on the peel strength of a welded joint, an experiment was designed with two crossed factors, clamping pressure and heated pin temperature. The temperature range of interest extends from below the onset of flow into the melt phase. A range between 167 and 307°C was selected. The temperature factor was divided into eight levels, with 20°C dividing each level. The applied clamping pressure of interest ranged from 110 kPa, to explore weakly clamped joints, through 1.84 MPa, which is near the values found optimal through other works described in the Background section. The pressure factor was divided into seven levels, with 290 kPa dividing each level. A balance between adequate replication and time constraints dictated that each subgroup contain three samples. In summary, the experiment contains two fully crossed factors, temperature with eight levels and pressure with seven levels, with a replication of three for a total sample number of 168.

A consistent spot welding procedure was utilized for each sample. The prepared sample, consisting of two 3-cm by 15-cm by 0.102-mm thick sheets, was placed on the marble backing plate directly below the heated pin.

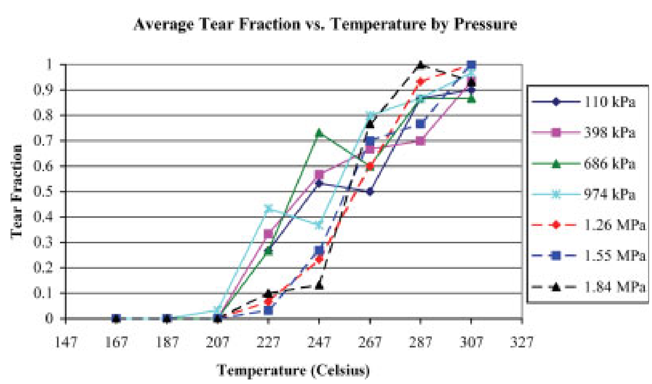

FIG. 6. This interaction plot shows the heated pin temperature on the *x*-axis, the welding pressure in the different lines, and the fraction of the weld zone where a tear began on the *y*-axis. Each node represents the average of the three experimental samples at each distinct factor level combination. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

DOI 10.1002/vnl

TABLE 1. This ANOVA table[a] uses the *T*-peel test force data.

	Degrees of freedom	Sum of squares	Mean square	*F*-statistic	*p*-value
Constant	1	1609.7	1609.7	1021.88403	<1 E–08
Temperature	7	606.56	86.651	55.00989	<1 E–08
Pressure	6	7.5773	1.2629	0.80173	0.56999
Error	154	242.58	1.5752		

The table demonstrates that the temperature of the heated pin is highly significant, whereas the welding pressure main effect is not significant.

[a] ANOVA table for using the model: pull force = temperature + pressure.

The heated pin was brought into contact with the sample at the desired pressure. Following a 1 s dwell time, the heated pin was removed from the sample, thereby forming a weld. After cooling, the force required to peel apart the welded samples was tested in the loadframe by using the *T*-peel test.

RESULTS

The results of the *T*-peel tests realized two distinct modes of failure. For samples welded at lower temperatures, weld failure was characterized as interfacial failure, meaning that the weld peeled apart, thus separating the two sheets of PVC. The second mode of failure, which occurred more often in samples welded at higher temperatures, was tearing of the parent material in the weld zone – not allowing the joint to be peeled apart. In these cases, the tear fraction, defined as the distance into the weld where a tear began, became a second test measurement in addition to force at failure.

The peel force data show a clear correlation between weld temperature and joint strength. An interaction plot of the peel force versus temperature by pressure can be found in Fig. 5. At 207°C and below, the peel force is quite negligible. It also appears that a plateau is reached in the peel force above 267°C. One notable item from Fig. 5 is that the welding pressure appears to have little effect on the weld peel force within this pressure range. The influence of pressure will be further discussed below.

The tear fraction through the 12.7-mm diameter weld zone was a second important output from this experiment. All samples welded at temperatures below 207°C resulted in interfacial failure, with no tearing occurring. As the welding temperature was increased, sample tearing became more frequent, and the tear fraction increased. In other words, tearing occurred in the weld zone earlier with increased temperature. This behavior continued to the maximum temperature tested, 307°C, where nearly all of the samples tore at the beginning of the weld zone,

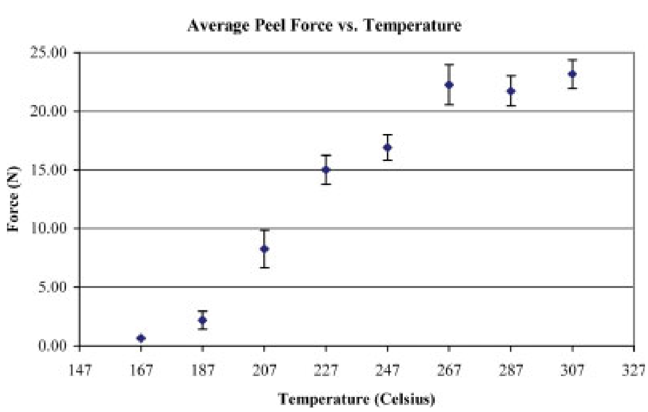

FIG. 7. This is a plot of the average peel force for each temperature level. The heated pin temperature is on the *x*-axis, and the *T*-peel force is on the *y*-axis. Each node represents the average of 21 samples. The error bars are the standard error for each temperature level. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

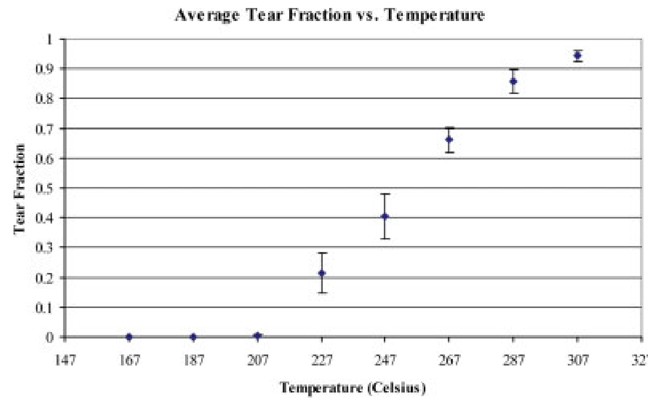

FIG. 8. This is a plot of the average tear fraction for each temperature level. The heated pin temperature is on the *x*-axis, and the tear fraction is on the *y*-axis. Each node represents the average of 21 samples. The error bars are the standard error for each temperature level. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

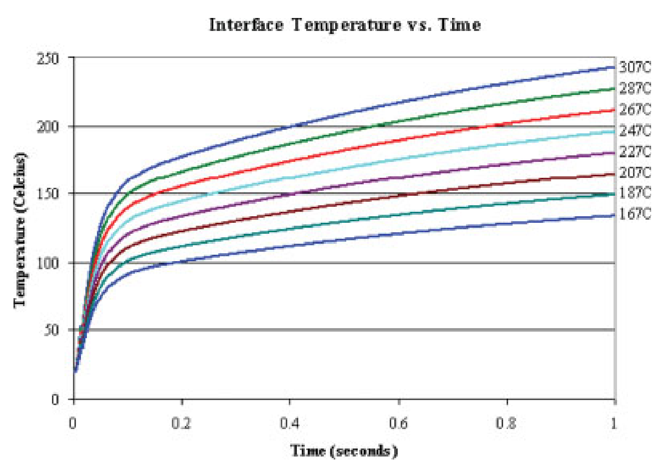

FIG. 9. This plot shows the weld interface temperature predicted by the one-dimensional transient numerical heat transfer model. The time in contact with the heated pin is displayed on the *x*-axis, the interface temperature on the *y*-axis. The different lines represent heating with different heated pin-temperatures. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

TABLE 2. Peel force and tear fraction results as a function of the pin temperature.

Heated pin temperature (°C)	167	187	207	227	247	267	287	307
Weld interface temperature after 1 s dwell (°C)	134	149	165	180	196	211	227	242
Average peel force (Newton)	0.65	2.19	8.26	15.01	16.91	22.25	21.72	23.16
Average tear fraction	0.00	0.00	0.00	0.21	0.40	0.66	0.86	0.94

This table uses the results from the numerical heat transfer simulation to relate the heated pin temperatures used in the experiment to the weld interface temperature after the one-second dwell time. The average peel force and tear fraction are also provided.

equating to a tear fraction of 1. As with the *T*-peel force data, the tear fraction data indicate very little influence of welding pressure. These data can be found in Fig. 6, which is an interaction plot of the average tear fraction of the three samples in each factor level combination.

Statistical analysis of the *T*-peel force and tear fraction data resulted in similar findings. An analysis of variance (ANOVA) found that the temperature of the heated pin is highly significant, with a *p*-value of $<1 \times 10^{-8}$, while the welding pressure is not significant, with a *p*-value of 0.56999. Traditionally, *p*-values less than 0.05 are considered statistically significant, and *p*-values less than 0.01 are considered highly statistically significant [14]. This ANOVA can be found in Table 1.

Because the influence of the pressure is not statistically significant, the data can be analyzed as purely a function of the welding temperature. Averaging the data across the levels of pressure made the influence of temperature on the *T*-peel force and tear fraction readily apparent. The *T*-peel force begins to increase rapidly near 207°C and reaches a plateau at 267°C that extends through the maximum temperature tested. The tear fraction begins to increase at 227°C and approaches a tear fraction of 1 at the maximum temperature. Plots of the peel force and the tear fraction averaged across each temperature level can be found in Figs. 7 and 8, respectively. In these plots, the standard error is used to define the error bars. The standard error is calculated by dividing the standard deviation by the square root of the number of samples in the subgroup.

MODELING WELD INTERFACE TEMPERATURE

One point that does need to be emphasized is that the temperature measured in these experiments is the heated-pin temperature, not the weld interface temperature. The heated pin contacts the surface of the 0.102-mm thick PVC sheet for the 1-s dwell time. This experimental method was chosen because it closely simulates the temperature distribution and conductive heating of LTW. As previously described, models of LTW have shown that the maximum temperature is reached ~0.1–0.2 mm away from the part interface. With both heated pin welding and LTW, a decreasing temperature gradient is created from the heated source to the weld interface.

To calculate the temperature at the weld interface based on the heated pin temperature, a one-dimensional transient numerical heat transfer simulation was created. Because the sheets of PVC are quite thin compared to the contact area of the heated pin, they can be modeled as infinite plates, thus allowing a one-dimensional simulation to be valid. By using an explicit finite difference approach [15], a model was constructed with 10 nodes spaced 0.02 mm apart through the two sheets of PVC and 26 nodes spaced 0.5 mm apart through the marble tile. To start the model, one side of the PVC sheets is set to the pin temperature at time = 0. The boundary of the noncontacting side of the marble backing plate is set to a convection condition with ambient air, as the marble tile is not supported directly along the axis of the pin.

All interfaces are assumed to be in perfect contact, and the thermal conductivity is assumed constant throughout the temperature range. Starting from an initial condition with all nodes at 20°C, the simulation was run for a period of 1 s with time-steps of 0.2 ms.

The numerical simulation allows the interface temperature to be estimated as a function of time during the spot welding procedure, as can be seen in Fig. 9. This figure demonstrates that the difference between the pin temperature and the weld interface temperature is quite significant. For convenience, Table 2 presents the predicted interface temperature after the 1 s dwell time, average *T*-peel failure force, and average peel fraction for each pin temperature.

DISCUSSION

Important knowledge was gained from this experiment for predicting the properties of a PVC weld based on operating parameters. Weld strength is clearly shown to be highly dependent on the welding temperature, where an increase in temperature leads to an increase in joint strength, within the region explored. The influence of joining pressure is not a significant factor within the range of exploration.

Utilizing the results from the heat transfer model allows discussion of the *T*-peel force and tear fraction as functions of the calculated interface welding temperature. Analyzing the *T*-peel force data from Fig. 7 and converting the heated-pin temperature to the calculated interface temperature (Table 2) realizes two conclusions. First, the *T*-peel strength begins to increase at a calculated interface temperature of 165°C. Second, a plateau in the maximum *T*-peel strength occurs above a calculated interface tem-

DOI 10.1002/vnl

perature of 211°C. Performing a similar evaluation of the tear fraction data from Fig. 8 recognizes that the tear fraction begins to increase above a calculated interface temperature of 180°C and reaches nearly full weld tearing at a calculated interface temperature of 242°C. Evaluating the force and tear fraction results in terms of the interface temperature is important, because it allows translation of this work to other welding methods.

CONCLUSION

A model of welding processes, including LTW, typically provides information about the pressure and temperature distribution throughout the materials being joined. This paper provides a method to use the temperature and pressure information in order to predict the weld quality. Previous work made assumptions that joining occurred when the material was heated above the melting point. Because of the large variation in particle size within PVC, the melting point is not well-defined, but characterized by a range of "particulate flow". To provide a more concrete method of predicting the weld properties, hot pin welding experiments were designed and conducted.

The designed experiment spot-welded samples, consisting of two thin sheets of clear PVC, by using a 12.7-mm diameter heated pin. The two sheets of plastic were clamped between a marble backing plate and the heated pin at a desired temperature and pressure for a 1 s dwell time. The experiment contained eight levels of temperature and seven levels of pressure, all fully crossed, with three replications of each factor level combination. The quality of the weld was evaluated with a destructive *T*-peel test in an electro-mechanical loadframe. A statistical analysis found that the temperature is a highly significant factor influencing both the weld strength and the tear fraction, while the pressure is not significant within the pressure range of exploration. To allow direct comparison to other welding methods, a one-dimensional numerical heat transfer model simulated the temperature at the weld interface as a function of the heated pin temperature.

One critical area that was not explored in this paper was polymer decomposition in the weld zone. Thermal decomposition is strongly dependent on the time of exposure to elevated temperatures. A main focus of this paper was developing a relationship between temperature and strength for laser transmission welding. Because the heating times are drastically different for LTW and hot pin welding, exploring decomposition through hot pin welding is not beneficial to advances in LTW. Not only is the heating much more rapid in laser welding, the highest-temperature areas are within the core of the material and not exposed to oxygen, thus slowing the material decomposition rate.

REFERENCES

1. F. Becker and H. Potente, *Polym. Eng. Sci.*, **42**, 365 (2002).
2. H. Potente and G. Fiegler, *Kunstst. Plast. Eur.*, 53 (2004).
3. H. Potente and G. Fiegler, in ANTEC 2004, Chicago, IL, 1193 (2004).
4. K. Sato, Y. Kurosaki, T. Saito, and I. Satoh, *Photon Process. Microelectron. Photonics*, **4637**, 528 (2002).
5. Y. Kennigh, H.R. Shercliff, and G.C. McGrath, in ANTEC 2002, San Francisco, CA, 1132 (2002).
6. Y.P. Huang, A. Yu, D. Watt, and B. Baylis, in ANTEC 2006, Charlotte, NC, 2310 (2006).
7. G. Matthews, *PVC: Production, Properties and Uses*, Institute of Materials, London (1996).
8. F.G. Bachmann and U.A. Russek, *Proc. SPIE-Int. Soc. Opt. Eng.*, **4637**, 505 (2002).
9. V.K. Stokes, *J. Vinyl Addit. Technol.*, **6**, 158 (2000).
10. D. Grewell and A. Benatar, in ANTEC 2006, Charlotte, NC, 2205 (2006).
11. D. Grewell, in ANTEC 1999, New York, 1411 (1999).
12. H. Potente, F. Becker, G. Fiegler, and J. Korte, *Welding World*, **45**, 5,2 (2001).
13. K. Oba and F. Bjork, *J. Adhes. Sci. Technol.* **7**, 987 (1993).
14. G.W. Oehlert, *A First Course in Design and Analysis of Experiments*, W.H. Freeman and Company, New York (2000).
15. Y.A. Cengel, *Heat Transfer: A Practical Approach*, McGraw-Hill Companies, Boston (1998).