Heat Sealing of Semicrystalline Polymer Films. I. Calculation and Measurement of Interfacial Temperatures: Effect of Process Variables on Seal Properties

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SYNOPSIS

A finite element analysis (FEA) modeling technique was used to predict the interfacial temperature as a function of time during the sealing of semicrystalline polymer films. An experimental technique using micro-thermocouples to measure rapidly changing interfacial temperatures during sealing was also developed. Agreement between predicted interfacial temperature profiles and measured values for polyethylene films was good except at temperatures substantially above the final melting point of the polymer. This deviation is caused by film-thickness changes occurring during sealing that are not taken into account in the calculations. The effect of heat-sealing process variables (seal bar temperature, dwell time, and pressure) on seal properties (seal strength, seal elongation, and seal energy) of polyethylene films has also been quantitatively determined. Seal properties are determined primarily by the maximum temperature achieved at the interface during heat sealing. Dwell time must be sufficiently long to bring the interfacial temperature to a desired level, but longer times at a given interfacial temperature do not improve seal properties at the conditions of our experiments. A slight pressure is helpful in bringing two microscopically uneven film surfaces into intimate contact, but higher pressure has no beneficial influence on seal properties. However, increased pressures and dwell times at temperatures above the final melting point of the polymer are detrimental to seal appearance due to material deformation in the sealing area. © 1994 John Wiley & Sons, Inc.

INTRODUCTION

Heat-sealing is widely used in the packaging industry to join polymer films. There are many different types of heat-sealing techniques, including jaw-type bar sealers, rotary sealers, band rotary sealers, impulse-type sealers, bead sealers, hot knife or side-weld sealers, etc. In these techniques, two films are pressed together between heated platens or dies to achieve fusion at the interface between the films. To achieve high production rates in commercial practice, the time of contact between the platens and films, i.e., the dwell time, is short, of the order of a second or less. The seal strength, toughness, failure mode, and appearance of such seals after

cooling to room temperature are important seal properties.

The literature concerning heat-sealing process variables, seal testing, and seal properties have been reviewed by Dodin[1,2] and by Theller[3]. More recently, Stokes[4] gave an overview on Joining Methods for Plastics and Plastic Composites, including the heat-sealing technique. The temperature of the interface between the films being sealed is recognized as an important process variable. In an early computation, the interfacial temperature was calculated by solving the unsteady-state heat-conduction equation, assuming negligible heat-transfer resistance between the heated platens and polymer films.[5] Subsequently, interfacial temperatures based on finite element analysis (FEA) calculations have been presented. However, the accuracy of temperatures calculated by such methods has not been experimentally verified because of the difficulty of measuring rapidly

changing temperatures at the interface between thin (ca. 25–50 μm) films. The dependence of interfacial temperatures on seal bar temperature and dwell time has therefore not been quantitatively assessed.[3] The effect of sealing pressure on seal properties was briefly reported by Theller,[3] who concluded that slight pressure was required to bring two film surfaces into close contact, but that higher pressures had little further effect on seal strength.

Testing of heat seals between thin films has generally been done using T-peel tests.[1,6] As illustrated in Figure 1(A), the two legs of a test piece are pulled at a constant rate and a force vs. extension curve is obtained. The maximum force/width value obtained in such a test [Fig. 1(B)] is commonly defined to be the seal strength. At sufficiently high extension, failure of the test piece occurs. The elongation of the test piece at failure (seal elongation) and the area under the curve (seal energy) are commonly taken as indicative of the toughness of the seal. Figure 1(C–E) schematically illustrates three types of failure that can occur, i.e., peeling failure along the initial contact surface, tearing failure, and a combination of peeling–tearing failure. When peeling

mode failure occurs, suitably conducted peel tests can be used to measure the intrinsic work of adhesion of the films.[7] However, under typical circumstances, the seal strength measured in a peel test includes large contributions from bulk deformation of the test piece. Additionally, when tearing mode failure occurs, the interface formed between the films is not separated, and the seal strength defined above, indeed, measures the bulk properties of the film rather than an interfacial property. We therefore refer to such values as apparent values. Figure 2 is a schematic plot of the apparent seal strength vs. seal bar temperature for a crystalline polymer such as polyethylene. Apparent seal strength is low and peeling failure is observed when the seal bar temperature is substantially lower than the melting point of the polymer. At high temperatures, apparent seal strength reaches a plateau level and there is a tendency for tearing mode failures.

In this first in a series of papers, we present an FEA model to calculate the transient interfacial temperatures of films as a function of seal bar temperature and dwell time. An experimental method to measure interfacial temperatures between the
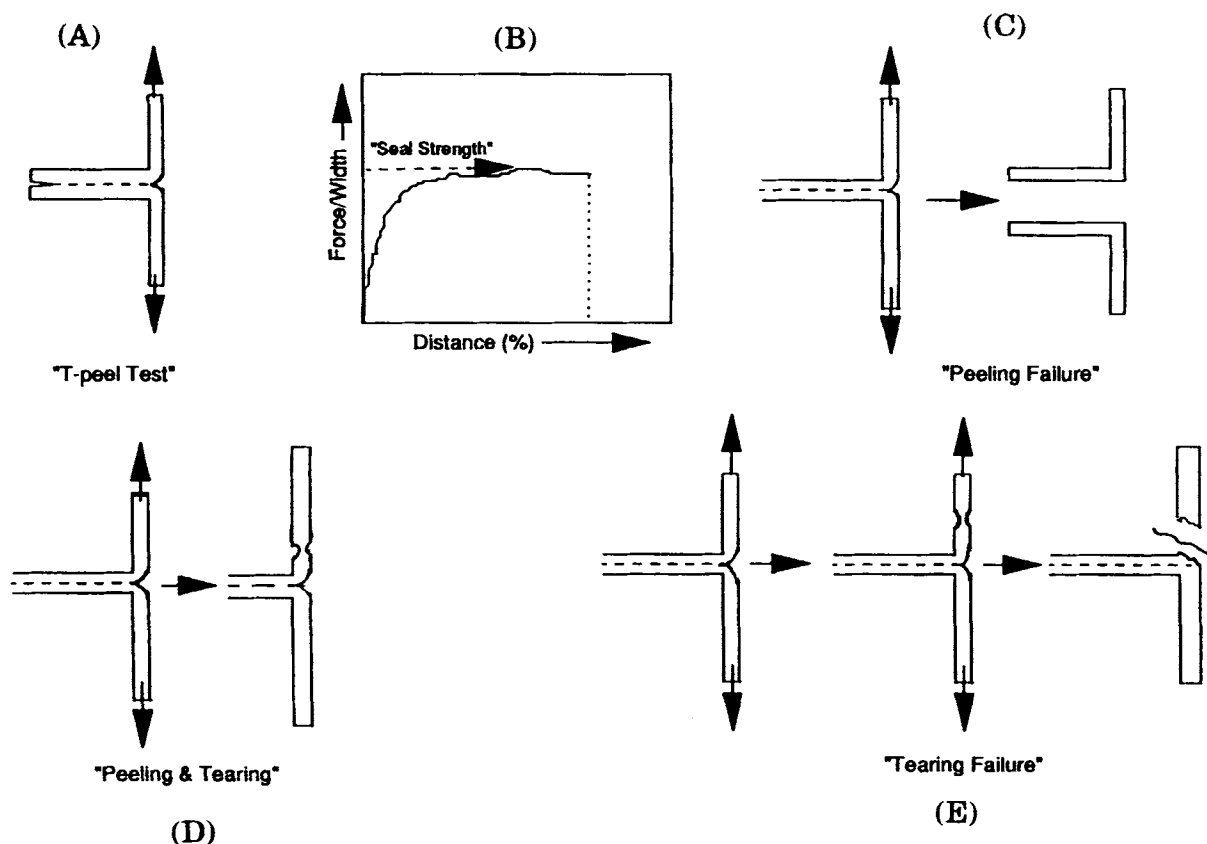
Figure 1 Schematic illustrating the T-peel test and the type of seal failures that can be observed.
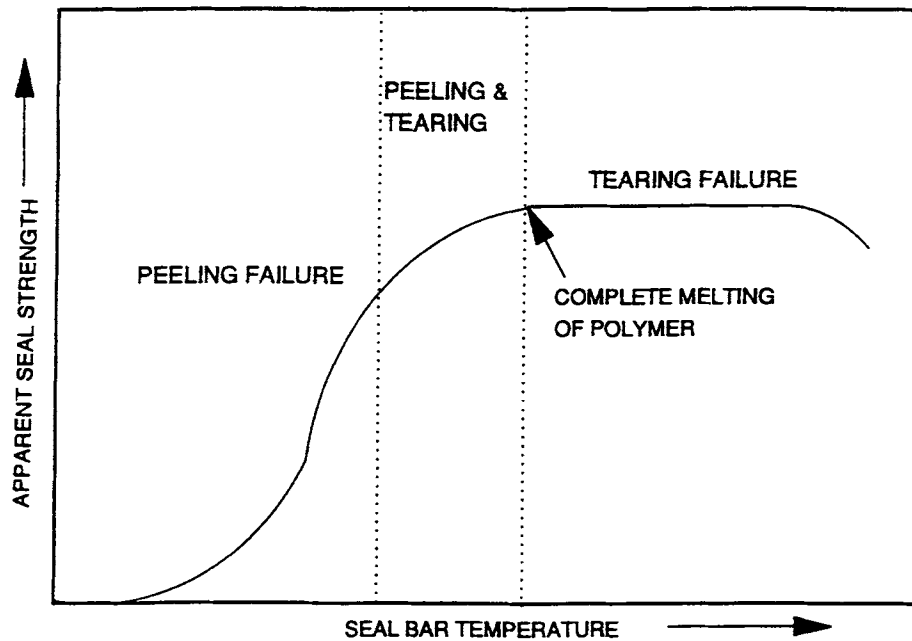
Figure 2   Schematic plot of apparent seal strength vs. seal bar or platen temperature for semicrystalline polymer.

thin films is also described, and the calculated and measured interfacial temperatures are compared. Additionally, the role of seal bar temperature, contact time, and pressure on seal properties of polyethylene films is quantitatively established. Subsequent papers will address the influence of melting distribution on heat-sealing characteristics and the influence of interfacial diffusion on seal failure modes.

Finite Element Analysis (FEA) Calculation

The FEA model for the heat-seal sandwich structure involving two films of identical thicknesses between two heated platens of identical temperature was modeled. Since the film sandwich structure and the platens configuration is symmetrical, only half of the total configuration, i.e., a single layer of film thickness and a platen, is modeled in two dimensions, and the configuration is shown in Figure 3. The two dimensional model of the film structure is done using the Patran® software package on a Tekronix-4129 terminal. The heat-transfer elements DC2D4 (four-node linear interpolation) are used with a length/width ratio of 1. The heat-transfer problem was solved using ABAQUS software on a mini VAX computer.

Heat conduction is assumed to be governed by Fourier's Law:

$$f = -k(\delta T/\delta X) \tag{1}$$

where k is the thermal conductivity matrix, $k = k(T)$, f is the heat flux, and x is the position. The thermal conductivity is assumed to be isotropic, as the orientation in the films under investigation is minimum. The boundary conditions were specified for temperature, $T = T(x,t)$ and, for surface convection, $q = h(T - T°)$, where $h = h(x,t)$ is the heat-transfer coefficient.

The physical properties used in the model for the polyethylene are as follows:

$$\text{Density} = 0.92 \text{ g/cm}^3$$
$$\text{Thermal conductivity} = 4.63 \times 10^{-03} \text{ W/cm K}$$
Linear expansion coefficient
$$= 2.37 \times 10^{-04} \text{ (cm/cm K)}$$
$$\text{Specific heat} = 1.9 \text{ W/g K}$$
$$\text{Elastic modulus} = 3.88 \times 10^{-06} \text{ g/cm}^2$$
$$\text{Heat-transfer coefficient} = 0.391 \text{ W/cm}^2 \text{ K}$$

Although there is some discrepancy in the literature concerning values for thermal conductivity and on its dependency on temperature[8–11] for polyethylenes, a constant value of 4.63×10^{-03} W/cm K was used for the entire temperature range investigated. The specific heat also used one value for the entire temperature. The linear expansion coefficient, specific heat, and elastic modulus values were obtained from the literature.[12]. The heat-transfer coefficient is an adjustable parameter in our model, as we were not able to measure it experimentally or find an appro-
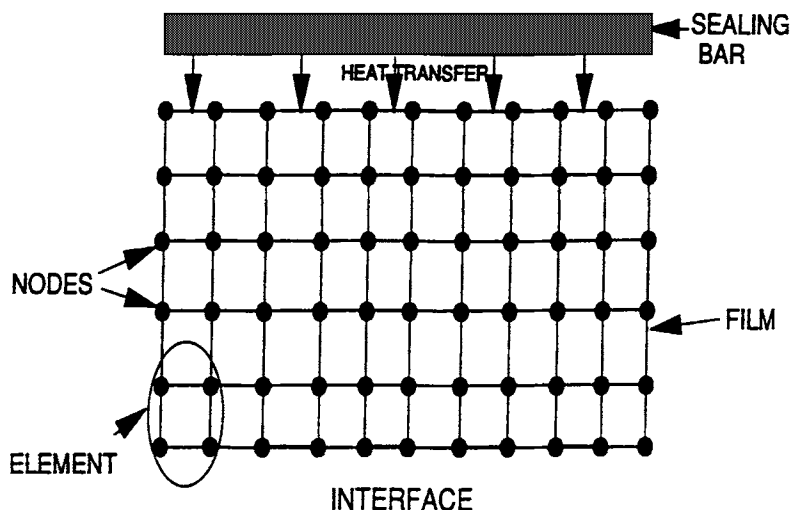
Figure 3   Configuration of the film and heat-seal platen modeled by FEA.

priate value from the literature. As one might expect, the heat-transfer rate depends strongly on the heat-transfer coefficient, and after extensive initial model evaluations, a heat-transfer coefficient of 0.391 W/cm K was used for all the calculations. As discussed below, this value was selected to obtain the best fit between calculated and measured temperatures when polyethyene was heat-sealed at temperatures substantially below the peak melting point of the polymer. Some calculations were made assuming no latent heat of fusion, whereas other calculations assumed a heat-transfer equal to 34 cal/g, a value that is representative of polyethylenes having 0.92 g/cm^3 density (approximately 49% crystallinity).

EXPERIMENTAL

Polymers and Films

Polymer films used in this study were made from Escorene® 158BW, a low density polyethylene (LDPE) with 0.923 g/cm^3 density as determined by ASTM D1505 and a melt index (MI) of 2.0 g/10 min as determined by ASTM D1238, and Escorene 1001, an LLDPE with 0.918 g/cm^3 density and a MI of 1.0 g/10 min. The differential scanning calorimetry (DSC) peak and final melting temperatures for Escorene 158BW were 110 and 118°C, and the corresponding values for Escorene 1001 were 119 and 126°C. Films of 50 μm thickness made on a 38.1 mm Egan Blown Film line at a 4:1 blowup ratio. Films of 150 μm thickness made on a 25.4 mm Killion Mini-cast Film Line were used for interfacial temperature measurements.

Method for Making and Testing Heat Seals

All heat seals were made using a Theller Model EB laboratory heat sealer made by H. W. Theller, Inc., of Precision Instruments West, Petaluma, CA. The heat platens used for heat-seal studies were flat and 9.5 mm in width, whereas 25.4 mm-wide platens were used for interfacial temperature measurement. The temperature resolution on the heat platens was ±1°C, and the dwell time was controlled accurately to ±15 ms in the dwell time range of 0.15–10 s. Except where otherwise indicated, the two platens were set at the same temperature. The pressure on the heat platens was controlled to within ±2 N/cm^2, in the range of 15–1000 N/cm^2. The polyethylene film structure was sandwiched between two layers of 25.4 μm thick Mylar® film to prevent the polyethylene from sticking to the heated platens. After the sealing at appropriate conditions, the sandwich structure was allowed to cool to room temperature at ambient conditions.

The heat-sealed samples were allowed to condition at room temperature for at least 24 h. The samples were cut into 25.4 mm wide and tested for seal properties including seal strength, elongation at break, and energy at break on an Instron testing machine using 508 mm/min strain rate and 50.8 mm initial jaw separation. Reported values are the average of six or more measurements. For calculating deformation around the seal area, the thickness of the sealed samples was measured running across the two seal edges with a Vernier calipers. The thicknesses were an average of six or more measurements on each sample.

Experimental Design for Process Variable Effects

For the investigation of the effect of heat-sealing process variables, temperature, pressure, and dwell time, 50 μm-thick Escorene 1001 blown films were used. An experimental design technique (RS1/Explore by BBN Software Products Corp.) was used to select the number of experiments and the conditions for sealing. A central composite-faced design, three-level quadratic model was used with 15 runs plus five replicates of the center point. The ranges of temperature, pressure, and dwell time are 100–170°C, 15–100 N/cm^2, and 0.15–1.5 s, respectively.
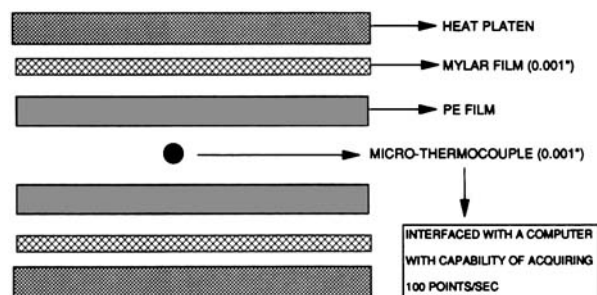
Measurement of Interfacial Temperature

The experimental setup for measurement of interfacial temperatures is shown in Figure 4. Temperatures were measured using small-diameter copper/constantin microthermocouples from Omega Engineering Inc. A small number of measurements made using 13 μm thermocouples yielded values that were virtually identical to those obtained using 25 μm-diameter thermocouples. All data reported herein were therefore obtained using 25-μm diameter thermocouples because these were less fragile than the smaller-diameter thermocouples. For high-speed temperature data acquisition, a WB-FAIB high-speed interface card from Omega Engineering Inc. was used with a Compaq 286 computer. Each thermocouple was used only once when measurements were made above the melting point of the polymer because of the difficulty of removing adhering polymer from the fragile thermocouples after use.

RESULTS AND DISCUSSION

Calculated and Experimental Interfacial Temperature During Sealing

The FEA model predictions for interfacial temperature on a 50 μm-thick polyethylene (Escorene


Figure 4   Experimental setup for laboratory measurement of interfacial temperature during heat sealing.

158BW) as a function of time for three values of heat-transfer coefficients (0.15, 0.391, 0.856 W/cm^2 K) between the platen and the film surface is shown in Figure 5, for the condition of platen temperatures at 423 K (150°C). The heat of fusion was assumed to be zero in this calculation. As expected, the interfacial temperature as a function of time is a strong function of the heat-transfer coefficient between the platen and the polymer film surface.
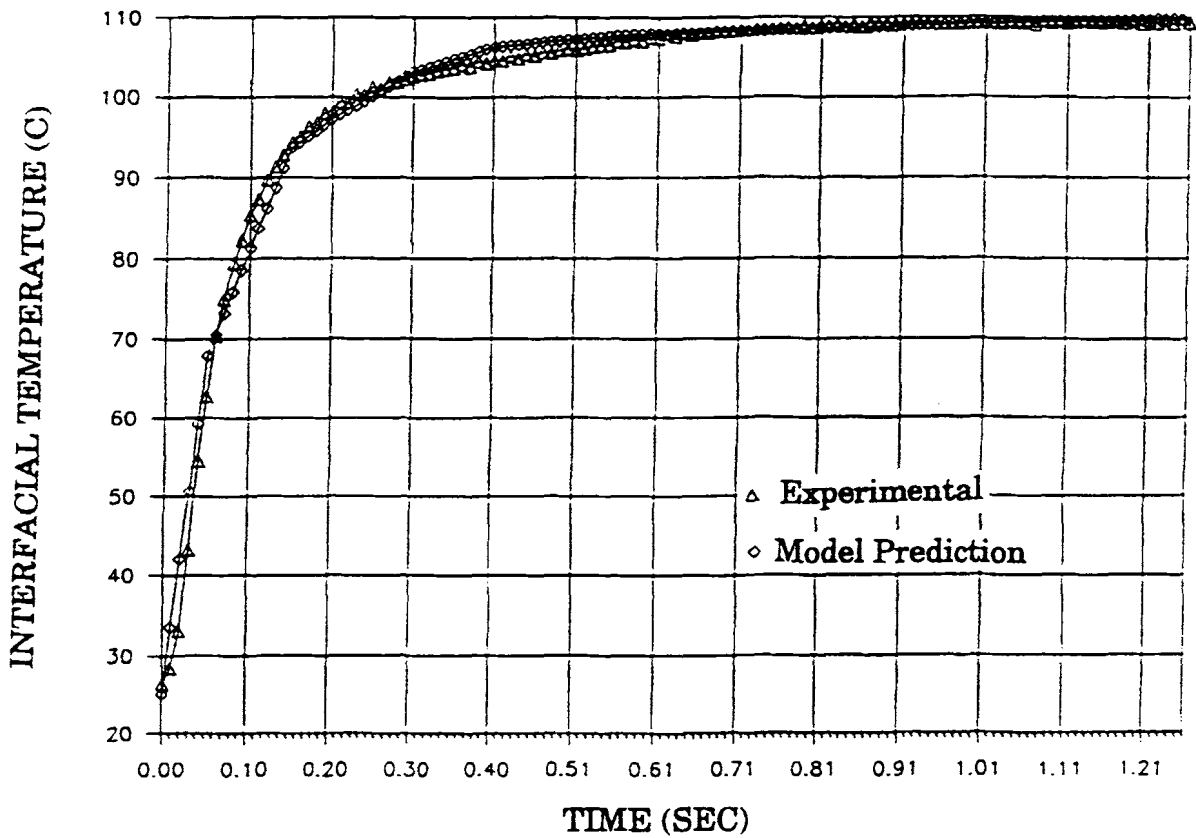
The interfacial temperature calculation by the FEA model and laboratory-measured profiles as a function of time for the condition of heat platens at a temperature of 110°C, 0.391 W/cm^2 K heat-transfer coefficient and zero heat of fusion is shown in Figure 6. The platen temperature of 110°C is below the final melting temperature of the polymer film, which melts completely by 118°C. The agreement between the model predictions and laboratory-measured profiles is satisfactory over the entire time scale, and a heat-transfer coefficient of 0.391 W/cm^2 K was therefore used for all the model calculations. It is evident from this figure that the interfacial temperature achieves a value within 5°C of the set platen temperature in approximately 0.5 s and that about 1 s is required to approach the set platen temperature to within 1–2°C.

Calculated interfacial temperatures assuming zero heat of fusion for a platen temperature of 150°C are compared to experimental values in Figure 7. Agreement between calculated and experimental values is good at temperatures less than ca. 90°C, i.e., at temperatures below the melting range of the polymer. In the 90–125°C region, calculated temperatures are higher than experimental values. This deviation is attributed to neglect of the endothermic heat of fusion of the polymer in this calculation. Neglect of the heat of fusion causes calculated interfacial temperatures to rise more rapidly than experimental temperatures after melting begins. At temperatures greater than about 125°C, calculated interfacial temperatures are higher than experimental values.

As shown in Figure 8, agreement between calculated and experimental interfacial temperatures is excellent at low and intermediate temperatures, i.e. up to about 110°C, when the heat of fusion is taken into account in the calculation. However, beyond 110°C, measured interfacial temperatures are significantly greater than the calculated values. This deviation is attributed to thinning of the polymer films during the sealing operation, which is not taken into account in the calculations, and, consequently, more rapid heat-transfer to the interface. Material flow and consequent thickness changes during seal-
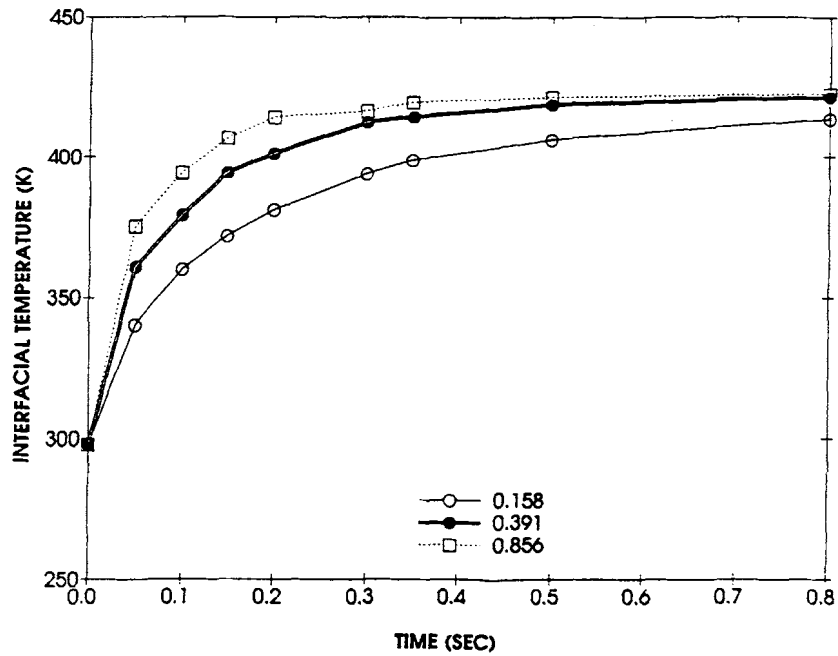
Figure 5 Interfacial temperature vs. dwell time calculations based on the FEA model for three different values of the heat-transfer coefficient at a platen temperature of 150°C, on 50 μm-thick Escorene 158BW films.

Figure 6 Interfacial temperature vs. dwell time as calculated by the FEA model in comparison with experimentally measured values for the condition of platen temperatures of 110°C on 50 μm-thick films and using a heat-transfer coefficient value of 0.391 W cm² K.
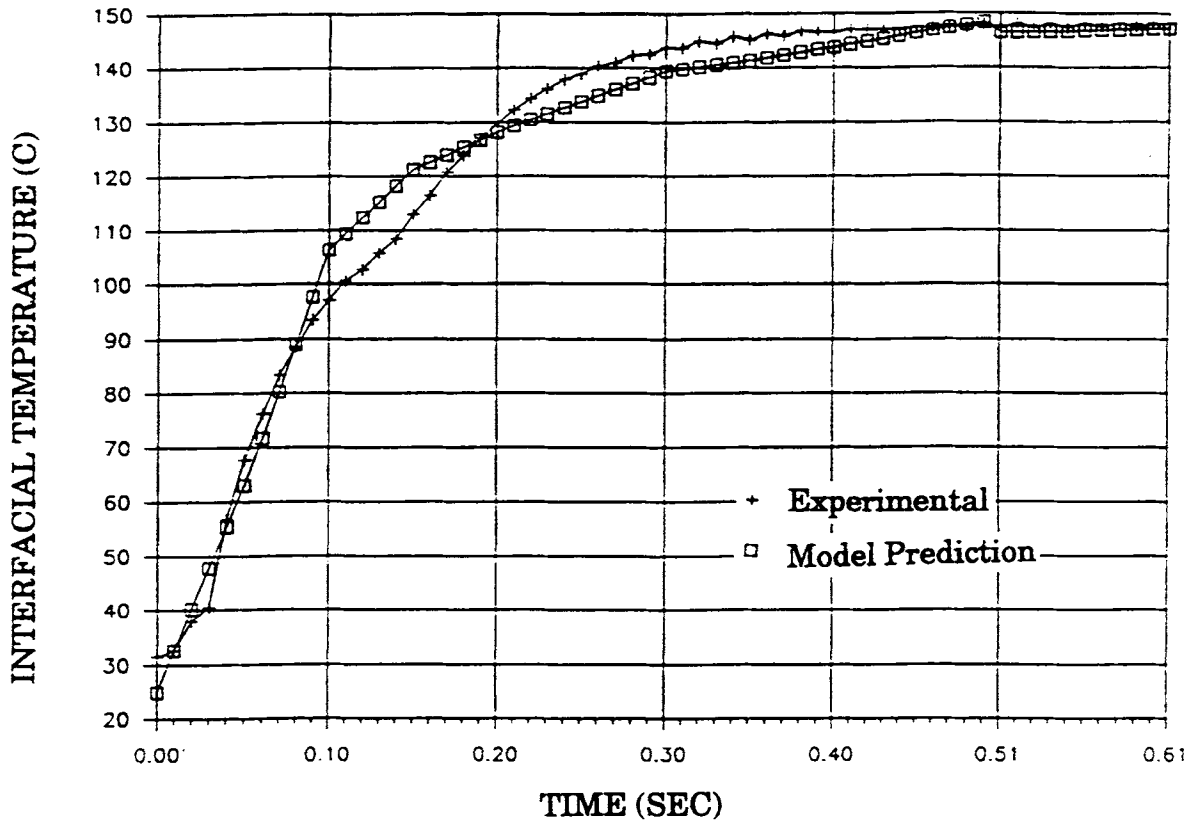
Figure 7   Interfacial temperature vs. dwell time as calculated by the FEA model in comparison with experimentally measured values for the condition of platen temperatures of 150°C on 50 μm-thick Escorene 158BW films.

ing could be included in the model and better agreement between calculated and experimental interfacial temperatures would then be expected. However, such calculations would require data on viscosity and density characteristics of the polymer being sealed, and they have not been made.

Calculated interfacial temperatures are useful for estimating platen temperatures and dwell times required to seal films of different thicknesses. Calculated interfacial temperatures for films of different thicknesses, i.e., 50 and 150 μm, and different platen temperatures, i.e., 110 and 170°C are given in Figure 9. In these calculations, the heat of fusion and the change in thickness during sealing was assumed to be zero. Consequently, the time required to achieve a given interfacial temperature will be overestimated when the platen temperature is above the final melting point of the polymer. As expected, significantly longer times are needed to achieve a given interfacial temperature for thicker films.
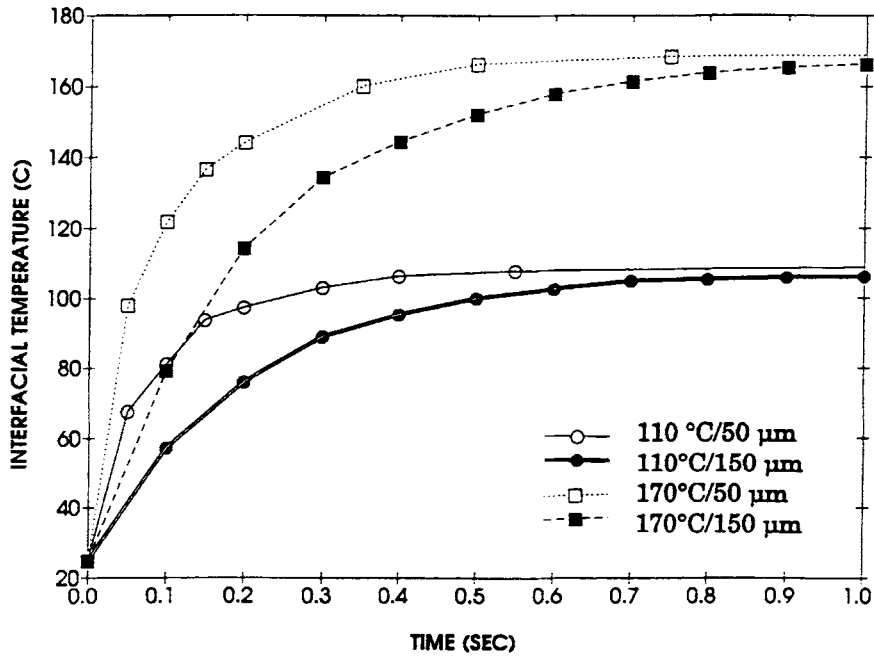
Calculated interfacial temperatures are also useful for estimating platen temperatures and dwell times required for heat-sealing various semicrystal-

line polymers. Calculated interfacial temperatures for various dwell times and platen temperatures between 90 and 250°C for 50 μm films, assuming zero heat of fusion and zero thickness changes, are given in Figure 10. We emphasize that these calculations were made using an effective heat-transfer coefficient appropriate for the platens used in this work (0.391 W/cm^2 K). In commercial practice, platens are often covered with a non-uniform Teflon cloth to prevent adhesion to the polymer film, and the effective heat-transfer coefficient using such platens will be different from our value. Consequently, caution should be exercised in applying the calculated interfacial temperatures shown in the figure to other platen conditions.

As an example of the use of Figure 10, assume that 50 μm-thick high-density polyethylene (HDPE) film were to be heat-sealed at a production rate of 200 seals/min, corresponding to a maximum dwell time of 0.3 s. To obtain the highest possible seal strength for a given semicrystalline polymer, the interfacial temperature should be raised to a temperature equal or slightly higher than the final
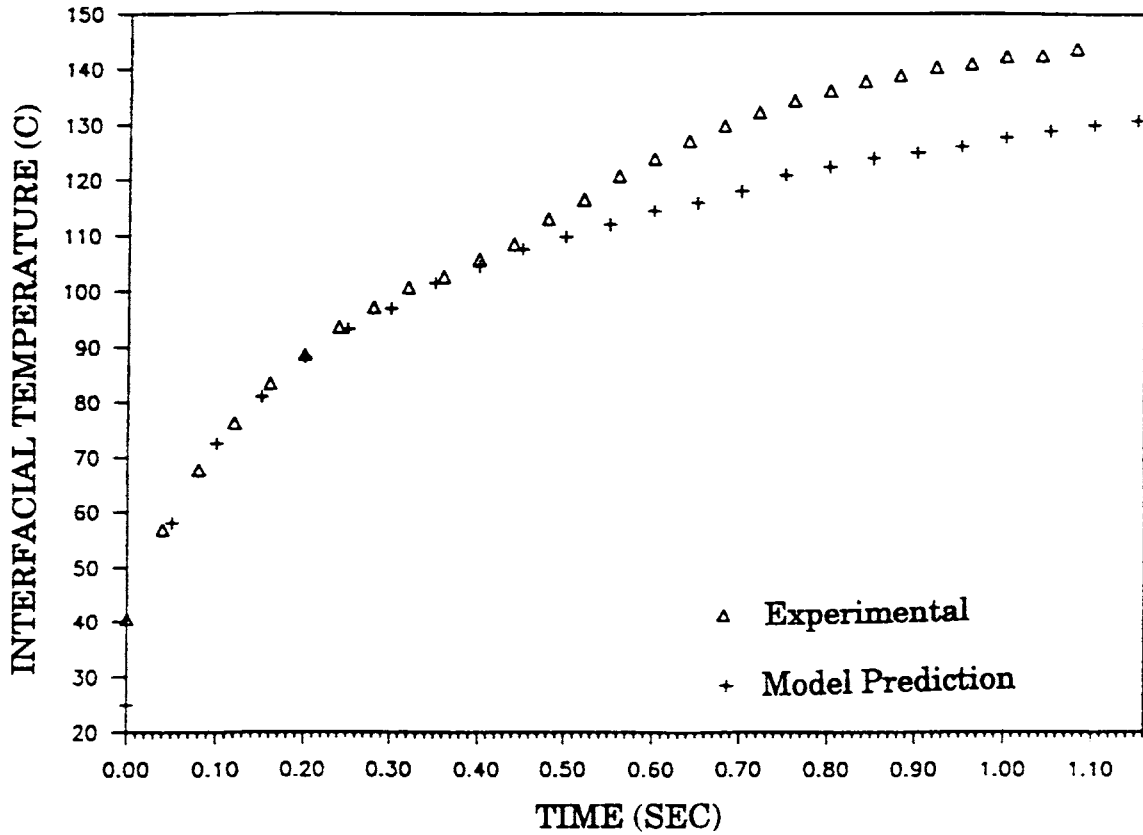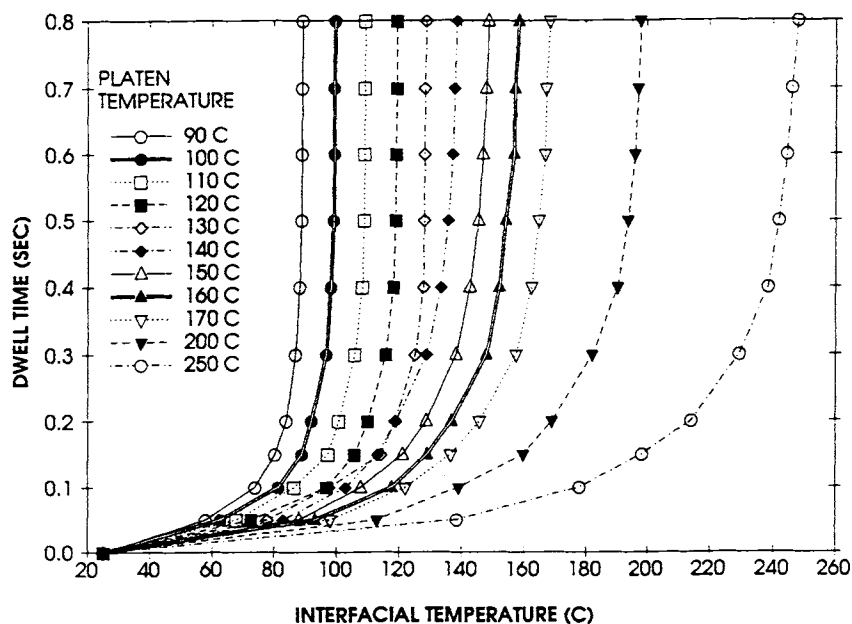
Figure 8   Interfacial temperature vs. dwell time as calculated by the FEA model including the heat of fusion of the polymer in comparison to the experimentally measured values at a platen temperatures of 150°C on 50 μm-thick films.

Figure 9   FEA model calculations of interfacial temperature vs. dwell time for two different thickness films and for two platen temperatures.

Figure 10   Interfacial temperature vs. dwell time profiles as calculated by the FEA model under different platen temperatures ranging from 90 to 250°C.

melting point of the polymer, e.g., 135–140°C for HDPE.[13] According to these calculations, an interfacial temperature of 140°C can be achieved in 0.3 s at a platen temperature of 150°C. Figure 10 can also be used to estimate the maximum rate of heat-sealing. For example, the desired 135–140°C interfacial temperature to seal HDPE could be achieved in about 50 ms if the platen temperature were set at 250°C, translating into a production rate of 1200 heat-seals/min.

Interfacial Temperature Measurements with Different Platen Temperatures

Heat-sealing is often practiced industrially with different platen temperatures, either to achieve selective melting of surface components or to influence failure modes of the ultimate seal. Interfacial temperature profiles with different platen temperatures were therefore measured on 50 μm-thick polyethylene films. The interfacial temperature profiles as a function of time are shown in Figure 11, for two cases of platen temperature combinations, i.e., top/bottom values of 120/25°C and 170/25°C. The interesting observation in these temperature profiles is that steady-state interfacial temperatures of approximately 92 and 112°C are obtained at ca. 0.35 s with 120/25°C and 170/25°C platen temperatures, respectively. The 0.35 s dwell time is short enough for achieving high production rates on commercial

heat-sealing lines, provided that the interfacial temperatures obtained are sufficient for sealing the polymer films of interest. The observation of relatively constant interfacial temperatures by this approach implies that, by proper choice of the platen temperatures, dwell times can be optimized easily to give a stable interfacial temperature.

EFFECT OF PROCESSING VARIABLES ON SEAL PROPERTIES

Data pertaining to the effect of process variables on apparent seal strength, elongation, energy, and seal distortion are tabulated in Table I. The coefficient of variation of these property measurements is about 5%. The effect of process variables on apparent seal strength, elongation, and energy was very similar, so only apparent seal strength and seal distortion are discussed in detail below. An important seal characteristic, i.e., the mode of failure, is not discussed here but will be treated in a future publication.

Effect of Platen Temperature, Dwell Time, and Pressure on Seal Strength

From the earlier discussion of calculated and experimental interfacial temperature profiles, one would expect seal properties to depend primarily on
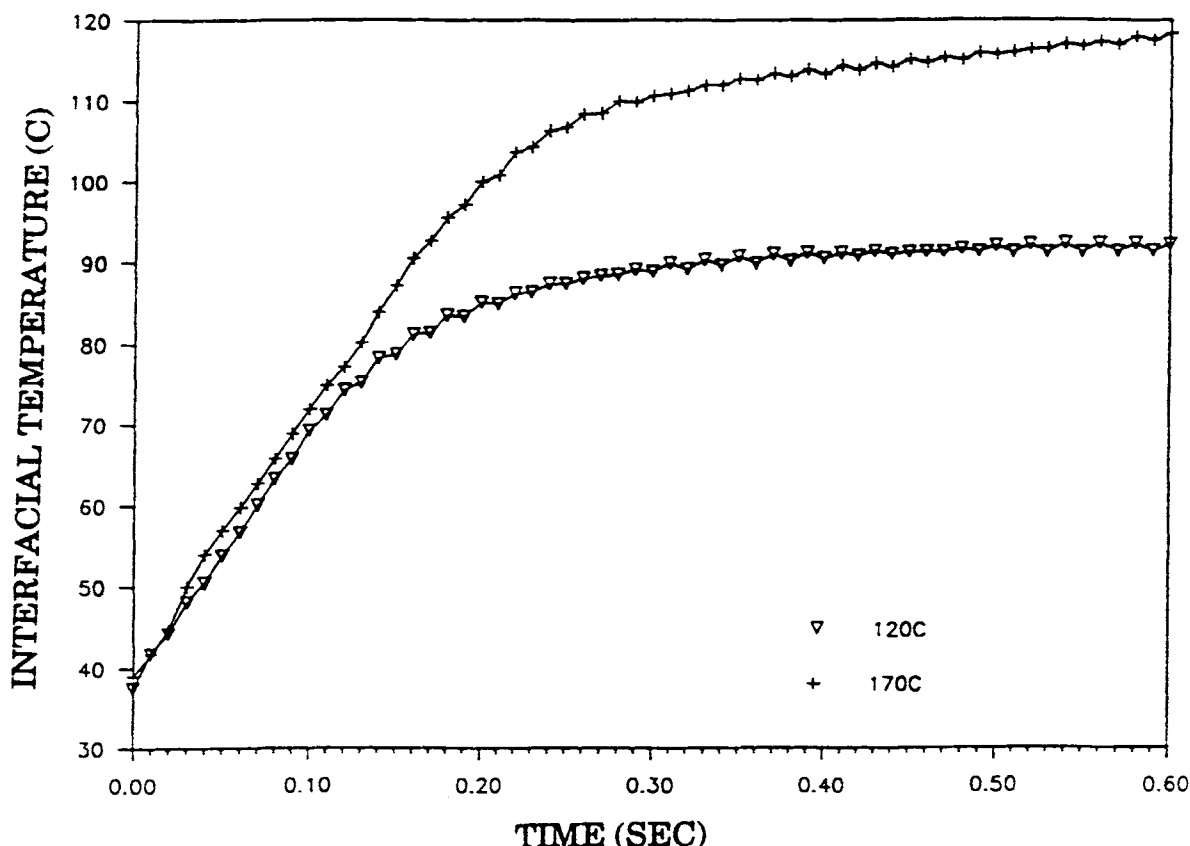
Figure 11   Experimentally measured interfacial temperature vs. dwell time profiles for condition of 125°C/25°C and 170°/25° (top/bottom) platen temperatures on 50 μm-thick Escorene 158BW films.

platen temperatures and secondarily on dwell time. This expectation is consistent with the regression equation obtained from the analysis of the experimental data given in Table I, for sample Escorene 1001, i.e.:

Seal strength (N/cm) = 5.83 + 7.45

$$\times\ 10^{-2}(T - 137.5) + 0.3(D - 0.825)$$

$$-\ 2.03 \times 10^{-2}(T - 137.5)^2 - 8.66$$

$$\times\ 10^{-3}(T - 137.5)(D - 0.825)\quad (2)$$

where T is the temperature in °C and D is the dwell time in seconds.

The absence of a pressure term in this equation reflects the fact that pressure has no measurable affect on seal strength in the range of pressure used in these experiments. The effect of platen temperature and dwell time on seal strength is graphically illustrated in the contour plot given in Figure 12. The strong influence of platen temperature on seal strength is readily apparent from this figure. Dwell time has a relatively small influence under our sealing conditions. For example, according to this plot, increasing the dwell time from 0.4 to 1.4 s at a 130°C platen temperature increases seal strength only by 10%. At higher platen temperatures, the effect of dwell time is even smaller. Figure 13, a contour plot of seal strength vs. platen temperature and pressure at a dwell time of 0.6 s, shows the strong effect of platen temperature and the ineffectiveness of pressure on seal strength.

The absence of pressure term in eq. (2) does not mean that heat-sealing can be done at zero pressure. When two microscopically uneven, heated surfaces are brought together, a small, undetermined level of pressure should be required to bring the surfaces into intimate contact across a significant fraction of the film surface.

The results of Theller,[3] who looked at the effect of dwell time at constant platen temperatures, indicates that the seal strength is a strong function of platen temperature and is not dependent on dwell

**Table I Experimental Design Conditions and Heat-sealing Properties for Escorene 1001/50 μm Blown Film**

Platen Temperature (°C)	Dwell Time (s)	Pressure (N/cm²)	Seal Strength (N/cm)	Elongation at Break (%)	Energy at Break (N-cm)	Seal Distortion (%)
170	0.83	57.5	6.11 ± 0.35	435.2 ± 34.67	164.94 ± 21.91	114.9 ± 1.82
137.5	0.83	57.5	5.9 ± 0.59	419.0 ± 36.42	153.2 ± 23.83	109.2 ± 0.6
137.5	0.83	57.5	5.69 ± 0.29	444.6 ± 46.2	158.38 ± 14.91	109.4 ± 2.6
105	1.5	15	1.72 ± 0.71	47.82 ± 4.36	1.58 ± 1.24	103.52 ± 1.64
170	1.5	100	6.35 ± 0.86	533.8 ± 23.59	207.86 ± 31.74	122.65 ± 6.1
105	0.15	100	0.84 ± 0.1	17.79 ± 19.61	0.23 ± 0.11	102.8 ± 1.9
137.5	0.15	57.5	5.44 ± 0.23	395.4 ± 42.48	141.89 ± 23.38	103.84 ± 0.9
170	1.5	15	5.99 ± 0.45	474.4 ± 43.07	180.07 ± 34.79	119.98 ± 4.3
137.5	0.83	57.5	6.04 ± 0.23	428.8 ± 22.95	167.87 ± 20.68	107.28 ± 0.85
137.5	1.5	57.5	6.06 ± 0.35	431.6 ± 44.37	163.12 ± 25.53	114.98 ± 3.9
105	0.15	15	0.6 ± 0.12	17.9 ± 12.5	0.11	101.6 ± 0.34
137.5	0.83	57.5	6.07 ± 0.82	450.4 ± 38.82	176.0 ± 31.63	108.32 ± 1.25
137.5	0.83	15	5.37 ± 0.88	383.2 ± 92.82	141.1 ± 55.58	105.64 ± 2.6
105	1.5	100	1.52 ± 0.61	49.92 ± 7.52	1.36 ± 0.45	101.35 ± 1.95
105	0.83	57.5	1.65 ± 0.36	45.2 ± 3.77	1.36 ± 0.45	101.35 ± 0.92
137.5	0.83	100	6.09 ± 0.29	438.4 ± 26.33	173.84 ± 11.74	116.6 ± 1.3
137.5	0.83	57.5	5.92 ± 0.63	405.8 ± 39.56	159.06 ± 26.99	110.2 ± 2.35
170	0.15	15	6.06 ± 0.49	406.4 ± 20.82	153.87 ± 16.04	106.2 ± 2.05
137.5	0.83	57.5	5.78 ± 0.49	424.2 ± 25.44	160.2 ± 26.54	104.9 ± 2.23
170	0.15	100	6.04 ± 0.44	417.2 ± 34.05	161.1 ± 25.6	109.6 ± 3.9

time beyond 0.4 s for an LDPE film sealed at 106 and 110°C, confirming the results that we have observed. Theller[3] also found that, at short dwell times of less than 0.4 s, the seal strength is continuously changing with dwell time due to the transient change in the interfacial temperature with time, which we have shown clearly by the finite element analysis model calculations and laboratory measurements.
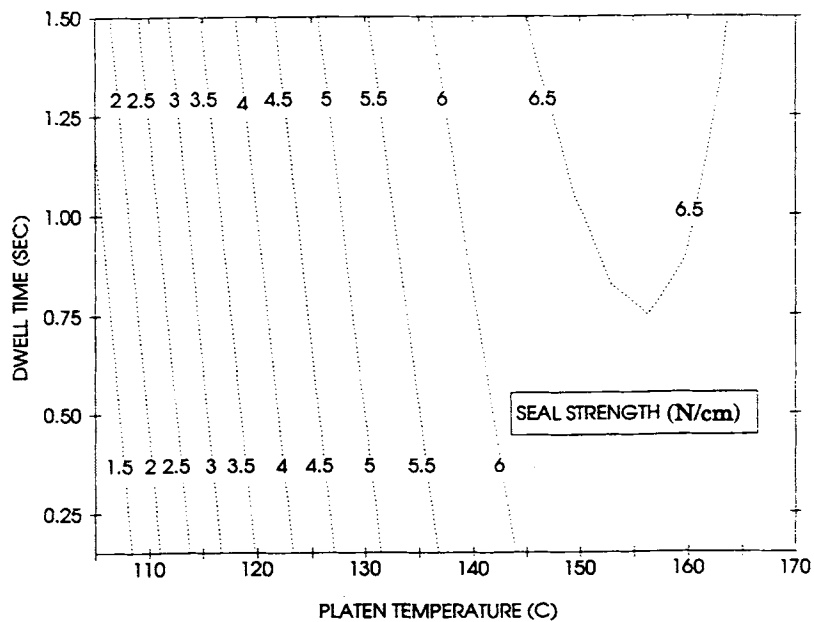
Figure 12 Contour plot of apparent seal strength as a function of dwell time and platen temperature at a pressure of 25 N/cm² on 50 μm-thick Escorene 1001 films.
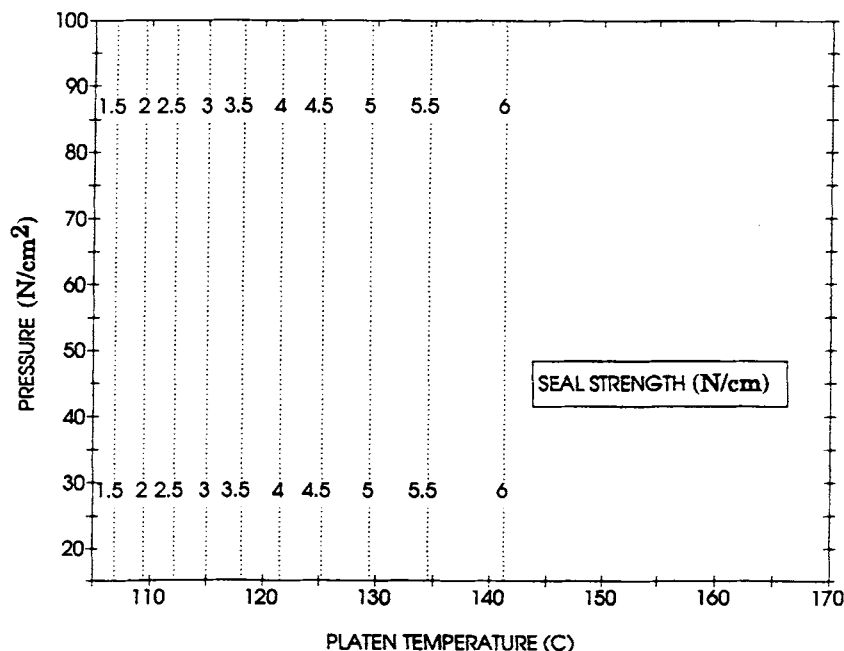
Figure 13 Contour plot of apparent seal strength as a function of pressure and platen temperature at a dwell time of 0.6 s on 50 μm-thick Escorene 1001 films.

Similarly, the effect of pressure was found to be minimum by Theller for HDPE films at pressures of 27.56 and 275.56 N/cm² in the temperature range of 80–127°C and virtually no pressure-dependence was found on an LDPE film from 0.69 to 413.4 N/cm² at a temperature of 106°C

Effect of Temperature, Pressure, and Dwell Time on Seal Deformation

At severe sealing conditions, molten polymer is squeezed out between the platens and thickening at the edges of the seal occurs. Such a distorted seal may be aesthetically unacceptable, and sealing conditions should be selected to avoid such thickening. The thickness at the edge of the seal after sealing divided by the initial film thickness structure, termed seal distortion , for sample Escorene 1001 was affected by platen temperature, dwell time, and pressure according to the regression equation

Seal distortion (%) = 108.7 + 0.187(T − 137.5)

+ 6.085(D − 0.825) + 4.18 × 10⁻²(P − 57.5)

+ 9.46 × 10⁻²(T − 137.5)(D − 0.825)   (3)

where P is the pressure in N/cm².

Representative results are graphically shown in Figures 14 and 15. Figure 14 is a contour plot of seal distortion against platen temperature and pressure at constant dwell time of 0.6 s, and Figure 15 is a plot of the seal distortion against platen temperature and dwell time at constant pressure of 25 N/cm². As expected, higher seal distortion occurs at high platen temperatures, dwell time, and pressures. Similar results were observed by Berger.[14]

Selection of Sealing Conditions

The preceding results show that interfacial temperature is the dominant variable controlling seal strength, elongation, and energy. Interfacial temperature, in turn, is affected by platen temperature, dwell time, and film thickness, and it can be calculated by the described FEA model. Alternatively, interfacial temperature can be accurately measured using the described experimental procedure. In a future publication we will show that the preferred interfacial temperature for heat-sealing a crystalline polymer is a few degrees above final melting point of the polymer film, a value that is easily obtained by a differential scanning calorimetry (DSC) measurement. For example, Escorene 1001 has a final melting point equal to 126°C, and ca. 128°C is an appropriate target interfacial temperature.

A given interfacial temperature can, in principle, be achieved by a wide range of platen temperature–dwell time combinations. However, the combination
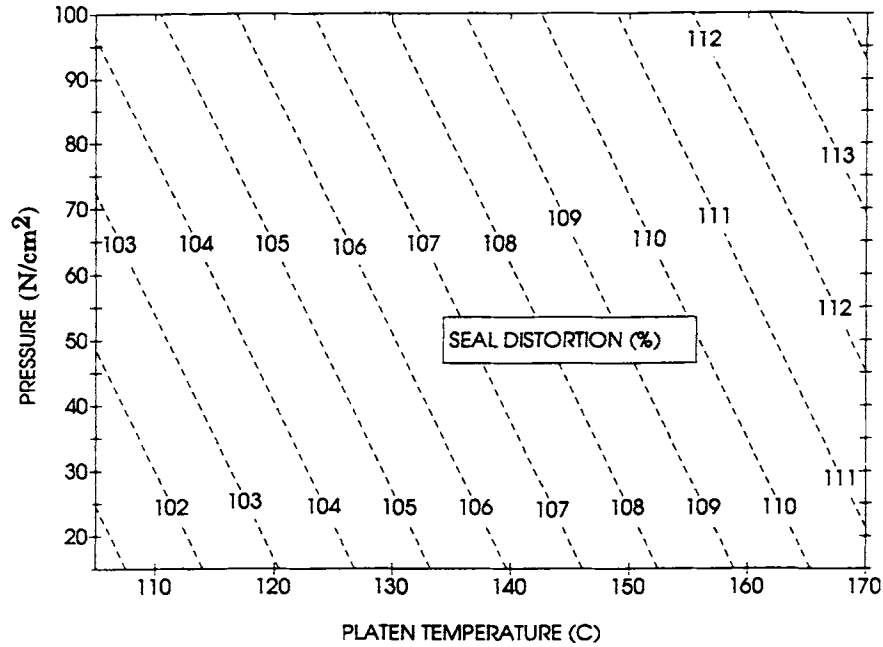
Figure 14   Contour plot of seal distortion as a function of pressure and platen temperature at a dwell time of 0.6 s on 50 μm-thick Escorene 1001 films.

of high platen temperature and short dwell time will lead to less precise control of interfacial temperature because temperatures will be rising rapidly with time when the target temperature is achieved. Time permitting, it is therefore desirable to use longer dwell times and platen temperatures slightly higher than

the target temperature, i.e., to operate closer to a steady-state temperature condition. The interfacial temperature at the end of a dwell time period can be estimated using FEA calculations for a given platen temperature, dwell time, and thickness. The dwell time should then be chosen so that the inter-
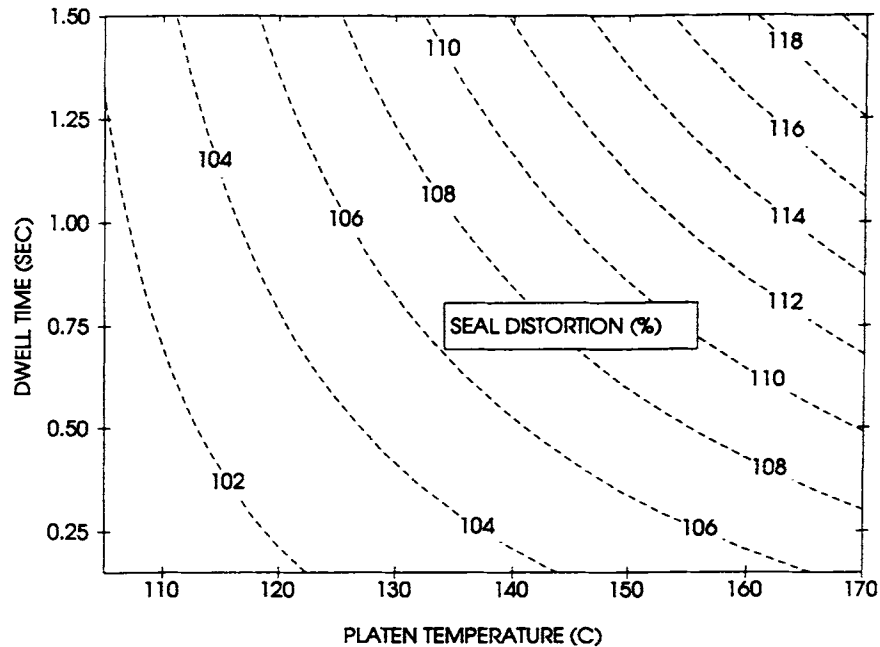
Figure 15   Contour plot of seal distortion as a function of dwell time and platen temperature at a pressure of 25 N/cm² on 50 μm-thick Escorene 1001 films.

facial temperature is within a few degrees of the platen temperature at the end of the dwell time. Very long dwell times should be avoided, however, because they contribute to seal distortion. For example, a dwell time of 1 s at a 135°C platen temperature is an appropriate choice for 50 μm-thick Escorene 1001 films.

What pressure should be used in heat-sealing? Pressure had no beneficial effect on seal properties in the range of pressures used in our experiments. However, some level of pressure is necessary to bring two heated films into intimate contact. The minimum pressure required under ideal sealing conditions (i.e., minimal surface roughness, uniform film thickness, perfect alignment of flat sealing platens, temperatures above the final melting point of the polymer) is probably substantially smaller than the smallest pressure used in our experiments: 15 N/cm^2. Under practical operating conditions, pressures of about 5 N/cm^2 or more are probably desirable to bring the opposing film surfaces into contact. If the precision of pressure levels on the heat-sealing line is insufficient for control at such a low pressure, then the smallest pressure that can be consistently maintained should be used. Higher pressures may also be needed to compensate for nonuniform film thicknesses and misalignment of platens. Some sealing techniques using serrated dies may require slightly higher pressure to help force flow of the polymer into the gap areas. Gusset seals, where polymer films are folded in such a way that there are four layers in the seal area, may also require slightly higher pressures to obtain good seal properties on a consistent basis.

To recapitulate, sealing pressures should be kept at a low level. Use of high pressure in heat-sealing has no beneficial influence on seal strength, elongation, and energy. On the other hand, the use of high pressure at high sealing temperatures causes material flow and deformation around the sealing area, which gives rise to distorted, aesthetically displeasing seals.

The above procedure for selecting sealing conditions is sufficient if the mode of seal failure is not a concern. The described procedure will yield a tearing failure mode for most but not all semicrystalline polyolefin films that are sealed using equal platen temperatures.

CONCLUSIONS

1. A FEA model of heat-transfer during the heat-sealing of semicrystalline polymer films

provides estimates of interfacial temperature profiles at the boundary between the films as a function of platen temperature and dwell time. An experimental technique to measure interfacial temperatures has also been developed. Calculated interfacial temperature profiles and measured values are in good agreement except at temperatures above the final melting point of the polymer. This deviation is caused by film-thickness changes occurring during heat-sealing that are not taken into account in the calculations.

2. The effect of sealing process variables on seal properties of polyethylenes has been quantitatively determined. Seal strength, elongation, and energy are determined by the maximum interfacial temperature achieved during sealing, and they are not affected by pressure. Seal distortion increases as dwell time and pressure increases, especially at platen temperatures above the final melting point of the films.

3. A procedure for selecting platen temperature, dwell time, and pressure for a heat-sealing operation has been proposed. Time permitting, platen temperatures should be set slightly above the final melting point of the polymer film, and the dwell time should be sufficiently long to permit the interfacial temperature to approach the platen temperature to within a few degrees. Pressure should be kept low, roughly 5–15 N/cm^2, in order to minimize seal distortion. Higher pressures may be required if the pressure control is imprecise, if the film thickness is non-uniform, or if the platens are poorly aligned.

4. Platen temperatures far greater than the melting point of a crystalline polymer are required for very fast sealing procedures, where dwell time must be very short. The platen temperature needed to achieve a target interfacial temperature at a specified short dwell time can be estimated from the FEA calculations.

5. Fairly stable interfacial temperatures can be obtained even when operating with different platen temperatures. Importantly, dwell times of the order of 0.3–0.5 s required for commercial productions rates can be obtained by proper selection of the individual platen temperatures.

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