The ultrasonic welding process is modeled using a five part model that includes mechanics and vibration of the parts, viscoelastic heating, heat transfer, flow and wetting, and intermolecular diffusion. The model predicts that melting and flow occur in steps, which has been confirmed by experiments. The model also indicates the possibility of monitoring joint quality by measuring the dynamic mechanical impedance of the parts during welding, which has also been verified experimentally by indirectly monitoring the magnitude of the impedance via measurements of both the power and the acceleration of the base. When the melt fronts of the energy directors meet, at the end of welding, the dynamic impedance of the composites’ interface is shown to rise rapidly. This raises the possibility of developing closed loop control procedures for the ultrasonic welding of thermoplastic composites. Ultrasonic welding of polyetheretherketone (PEEK) graphite APC-2 composites produced joints with excellent strengths.

INTRODUCTION

Advanced thermoplastic composites offer many advantages over thermosetting composites—including the potential for lower manufacturing costs. However, thermoplastic composites generally require higher forming pressures and temperatures, and they do not enjoy as high a level of integration as do thermosetting composites. Therefore, joining of thermoplastic composite parts is a critical manufacturing step. A variety of methods were evaluated for the joining of advanced thermoplastic composites (1). Three techniques—resistance welding, induction welding, and ultrasonic welding—were found to work best (1). Of the three successful methods, ultrasonic welding produced the strongest joints and offered the greatest flexibility. Ultrasonic welding of polyetheretherketone (PEEK) graphite APC-2 composites with resin rich triangular energy directors produced parts with a short-beam shear strength equal to the strength of compression molded parts (1, 2). It was also possible to weld large composites in scan or sequential welding with joint strengths of about 80 percent of the short beam shear strength of compression molded parts (1, 2).

In the ultrasonic welding joining process high frequency (20 to 40 KHz) low amplitude (2.5 μm to 0.25 mm) vibrations are applied to the parts. The vibrations result in heating and melting of surface asperities and welding of the parts. Ultrasonic welding is often used for joining thermoplastics in mass production because it is fast, economical, and easily automated. With proper design of fixtures, ultrasonic welding can be very flexible and it can be used in small lot production of even large parts. In some cases, dissimilar materials can also be welded together (3). For example, J Polymer graphite composites and PEEK graphite composites were successfully welded together (2).

Although ultrasonic welding is often used for fusion bonding of thermoplastics, it is not a technique that is well understood. Current use of ultrasonic welding is based on qualitative knowledge, extensive experience, and trial-and-error. This is probably due to the complexity of the process. Land (4) used a high speed camera to make the process visible and to gain some understanding of the melting and flow that occurs. He filmed the ultrasonic welding of polycarbonate, glass reinforced polycarbonate (30 percent by weight), ABS, nylon 6, and glass reinforced nylon 6 (30 percent by weight). He noticed that the welding process occurs in stages, rather than continuously,
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for all of the materials tested. The gap between the parts alternately decreases for a short time duration and then becomes stationary. The number and durations of these gap decrease-stationary cycles varied for the different materials.

Aliosio, et al. (5) investigated the ultrasonic welding of polycarbonate, ABS and Noryl—using rectangular energy directors. They modeled the viscoelastic heating of the energy directors assuming adiabatic heating, and using elastic analysis to estimate the strain amplitude within the parts. Even with these simplifications, their predicted temperature rise rates agreed fairly well with their experiments. Bekmurazaeu and Volkov (6) looked into concentrating the ultrasonic energy in the weld zone by using small rectangular spacers (energy directors). Like Aliosio, et al., Bekmurazaeu and Volkov found that the spacer concentrates the energy and heats up faster than the bulk; this was confirmed both theoretically (using an Aliosio-like mechanics model) and experimentally.

Tolunay, et al. (7) studied the ultrasonic welding of polystyrene parts without energy directors. They found that increasing the static pressure resulted in higher power levels, although bond strengths did not differ substantially. They developed models for bulk heating and interface heating, including one-dimensional heat conduction. Based on their experimental results and models, they concluded that the total heating during ultrasonic welding is a combination of volumetric heating and localized heating at the interface.

There are few published works on the ultrasonic welding of advanced thermoplastic composites. General Dynamics/Convair (8) studied the use of ultrasonic spot welding of graphite thermoplastic trusses in a vacuum and/or zero gravity environment. They found that welding in a vacuum did not affect the weld strength or the welding parameters. They also found a good correlation between weld energy and weld strength and showed that valuable information was gained by monitoring the power profile. Shepard and Lukeman (9) studied the fabrication and joining of polyphenylenesulfide composites. They successfully used ultrasonic welding to spot weld stiffeners to skins. In order to minimize deconsolidation around the horn, pressure was applied by a shoe that surrounded the horn.

**THEORY**

Ultrasonic welding is a complex process that is actually made up of five distinct yet highly coupled subprocesses, namely:

1. Mechanics and vibrations of the parts.
2. Viscoelastic heating of the thermoplastic.
3. Heat transfer.
4. Flow and wetting, and
5. Intermolecular diffusion.

In order to develop a process model, one must first model each subprocess—itself a complex task. Then, all the subprocess models are combined to develop one overall process model.

### Mechanics and Vibrations

A mechanics and vibrations model of the parts, fixture and welder is necessary for evaluating the strain distribution within the composites. From the strain distribution, one can determine the heating that results in the materials. In order to form a good weld rapidly, it is necessary to concentrate the ultrasonic energy at the weld zone. This is accomplished by forming triangular or rectangular protrusions, or energy directors, on the part surface (see Fig. 1). Rectangular energy directors are rarely used, but they are much easier to analyze. Therefore, we initially studied the heating rates in PEEK APC-2 composites with rectangular energy directors (2, 10). Since the parts were thin (at most 2 cm) compared to the wavelength at 20 KHz (about 13 cm), we were able to use a lumped parameter model for the parts (see Fig. 2). The lumped masses accounted for inertial effects, and Voigt-Kelvin models described the viscoelastic materials. The heat flow was modeled using one-dimensional heat conduction. The model agreed very well with experimentally measured temperature rise rates (2, 10) (see Fig. 3) showing that a lumped parameter model is very effective in describing the heating during ultrasonic welding.

To analyze triangular energy directors, one must first consider the flattening of the tip due to static loading (see Fig. 4). When a force \( F \) is applied to the...
Ultrasonic Welding of PEEK Graphite APC-2 Composites

energy director, the area of contact at the tip \( A_2 \) increases, with the material yielding and plastically deforming until (11)

\[
A_2 = \frac{F}{H} \approx \frac{F}{3\sigma_y}
\]

where \( H \) is the hardness and \( \sigma_y \) is the yield strength. From conservation of mass, the height at which deformation due to static loading will cease is

\[
h_1 = \frac{A_1h_1}{A_1 + A_2} \quad (2)
\]

One may use either a nonlinear or a linear viscoelastic model for a triangular energy director. A linear model may be used if the energy director is divided into many equivalent rectangular masses, each with a spring constant and damping coefficient, (see Fig. 5). The advantage of the linear model is that the solution of the equations is simpler. Therefore, the linear model was chosen. Now, one can develop an overall model for the welder—including the composites, the fixture, and the base. Figure 6 shows a schematic of the system and the lumped parameter model. The state equations for the lumped parameter model are:

\[
\begin{align*}
\frac{dv_{m2}}{dt} &= \frac{1}{m_2 + m_1} \left( F_0 + m_1 \frac{dv_0}{dt} - f_{k2} - b_2v_{m2} + b_3v_{m3} \right) \\
\frac{dv_{m3}}{dt} &= \frac{1}{m_3} \left( f_{k3} + b_3v_{m3} - b_3v_{m3} - f_{k3} - b_3v_{m3} + b_3v_{m4} \right) \\
\frac{dv_{m4}}{dt} &= \frac{1}{m_4} (f_{k4} + b_4v_{m4} - b_4v_{m4} - f_{k4}) \\
\frac{dv_{m5}}{dt} &= \frac{1}{m_5} (f_{k5} - f_{k5}) \\
\frac{dv_{m6}}{dt} &= \frac{1}{m_6} (f_{k6} - f_{k6} - b_6v_{m6}) \\
\frac{dv_{m5}}{dt} &= \frac{1}{m_6} (f_{k6} - f_{k6} - b_6v_{m6})
\end{align*}
\]
For the energy director the state equations are,

\[
\frac{dv_{m7}}{dt} = \frac{1}{m_7}
\]

\[
\cdot (f_{k_2} + b_2 v_{m2} - b_2 v_{m7} - f_{k_7} - b_7 v_{m7} + b_7 v_{m8})
\]

\[
\frac{df_{k_7}}{dt} = k_7(v_{m7} - v_{m8})
\]

\[
\frac{dv_{mi}}{dt} = \frac{1}{m_i}
\]

\[
\cdot (f_{k_{i-1}} + b_{i-1} v_{mi-1} - b_{i-1} v_{mi} - f_{ki} - b_i v_{mi} + b_i v_{mi+1}) \quad (4)
\]

\[
\frac{df_{ki}}{dt} = k_i(v_{mi} - v_{mi+1})
\]

\[\text{for } i = 8, 9, \ldots, n - 1\]

\[
\frac{dv_{mn}}{dt} = \frac{1}{m_n}
\]

\[
\cdot (f_{k_{n-1}} + b_{n-1} v_{mn-1} - b_{n-1} v_{mn} - f_{kn} - b_n v_{mn} + b_n v_{mn+1})
\]

\[
\frac{df_{kn}}{dt} = k_n(v_{mn} - v_{mn+1})
\]

The remaining requirement is that if the horn comes off of the composites on the upstroke, then the sum of the spring force and damper force for all masses is non-negative. This is required because the masses are just resting on top of each other and they cannot support a force which tries to separate them. This requirement results in:

\[
\begin{align*}
    f_{k2} &= f_{k2} = 0 \quad \text{if } f_{k2} + f_{b2} < 0 \\
    f_{k3} &= f_{k3} = 0 \quad \text{if } f_{k3} + f_{b3} < 0 \\
    f_{k4} &= 0 \quad \text{if } f_{k4} < 0 \\
    f_{k5} &= 0 \quad \text{if } f_{k5} < 0 \\
    f_{k6} &= f_{b6} = 0 \quad \text{if } f_{k6} + f_{b6} < 0 \\
    f_{k7} &= f_{b7} = 0 \quad \text{if } f_{k7} + f_{b7} < 0 \\
    \vdots \\n    f_{kn} &= f_{bn} = 0 \quad \text{if } f_{kn} + f_{bn} < 0
\end{align*}
\] (5)
Viscoelastic Heating

A viscoelastic material that is subjected to a sinusoidal strain dissipates some energy into heat through intermolecular friction. The storage modulus for a viscoelastic material is the in-phase modulus, and it is a measure of the ability to store energy. The loss modulus is the out-of-phase modulus, and it is a measure of the energy dissipated. If the material is subjected to a sinusoidal strain $\epsilon = \epsilon_0 \sin \omega t$, then the total work ($W$) done per cycle is:

$$W = \int \sigma \epsilon dt = \int \sigma_{\text{id}} dt$$  \hspace{2cm} (6)

But the stress is related to the strain through the elastic and loss moduli

$$\sigma = E'\epsilon_0 \sin \omega t + E''\epsilon_0 \cos \omega t$$ \hspace{1cm} (7)

where $E'$ is the storage modulus and $E''$ is the loss modulus. Therefore,

$$W = \int_0^{2\pi/\omega} E'\epsilon_0 \sin \omega t \epsilon_0 \cos \omega t dt + \int_0^{2\pi/\omega} E''\epsilon_0 \cos \omega t \epsilon_0 \cos \omega t dt$$ \hspace{1cm} (8)

which reduces to

$$W = 0 + \pi E''\epsilon_0^2$$ \hspace{1cm} (9)

So the elastic in-phase components produce no net-work, while the out-of-phase components dissipate energy every cycle. The average energy dissipated per unit time ($Q_{\text{avg}}$) is then

$$Q_{\text{avg}} = \frac{W}{2\pi} = \frac{\omega \epsilon_0^2 E''}{2}$$ \hspace{2cm} (10)

This is in agreement with the results of other researchers (5–7).

The storage and loss moduli, required for the viscoelastic heating model, vary with both temperature and frequency. Therefore, in order to model the mechanics, vibration, and heating, one must know these moduli as a function of temperature for the frequency of operation (in this case, 20 KHz).

A variety of techniques may be used for measuring the dynamic properties of polymers (12, 13). Low frequency measurement is usually favored because of commercially available equipment, and because inertial effects are negligible. In addition, the commercial equipment incorporates environmentally controlled chambers and computer interfacing. One can then use time-temperature superposition to estimate the dynamic properties at higher frequencies.

The Rheovibron is a low frequency forced vibration instrument which can be used to measure the dynamic mechanical properties of polymeric films or fibers. The sample is placed under a static tensile load, and then a sinusoidally varying strain is applied to one end, with the stress being measured at the other end. The amplitude of strain is kept small in order to minimize nonlinear effects. The temperature of the sample is varied while the frequency is kept constant (so that isochrones are produced) (13).

The dynamic mechanical properties of PEEK films were measured using the Autovibron. The Autovibron uses a Rheovibron DDV-II (Toyo Baldwin Co.) with a computer automation package (Imass Inc., Accord, MA). The computer controls the tensioning of the sample and the temperature of the environmental chamber. The computer also acquires the data and performs the initial data reduction. The Rheovibron DDV-II can operate over the temperature range of approximately −120 to 180°C. It can make measurements at four discrete frequencies—3.5, 11, 35, and 110 Hz. However, measurements at 35 Hz are not recommended because that is the resonant frequency for lateral vibration of the instrument. Therefore, the dynamic mechanical moduli of PEEK were measured for the frequencies of 3.5, 11, and 110 Hz over the temperature range of −100 to 180°C. The experimental data was corrected for machine compliance and for slippage in the grips (2). Figure 7 shows the corrected storage and loss moduli for PEEK. As can be seen in Fig. 7 the scatter in the storage modulus data is much less than the scatter in the loss modulus. This occurs because for small phase angles, the Rheovibron measurement of the loss tangent is less accurate and has poor repeatability.

Using data collected at lower frequencies, time-temperature superposition can be used to estimate the dynamic moduli for polymers at 20 KHz. Originally, time-temperature superposition—also known as the method of reduced variables—was developed empirically. Theories have been developed which support it. The basis of these theories is to consider the effect of temperature on relaxation time and, therefore, on material properties. Ferry (13) discusses the theoretical basis and the application of time-temperature superposition. Although the basic theory applies to amorphous polymers only, time-

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Equations 3 and 4 were integrated numerically using Euler and Runge-Kutta integration schemes (2).

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**Fig. 7. Elastic ($E'$) and loss ($E''$) moduli for PEEK at 3.5, 11, and 110 Hz.**
temperature superposition has been empirically applied to semicrystalline polymers with good results. The time-temperature shift factor ($a_T$) relates the relaxation time at a given temperature to the relaxation time at a reference temperature through

$$a_T = \frac{\tau(T)}{\tau(T_0)}$$

where $\tau(T)$ is the relaxation time at temperature $T$, and $\tau(T_0)$ is the relaxation time at the reference temperature $T_0$. For the majority of polymers, the time-temperature shift factor ($a_T$) can be described by the Arrhenius equation

$$\ln a_T = \frac{H}{R} \left( \frac{1}{T} - \frac{1}{T_0} \right)$$

or by the Williams, Landel, and Ferry (WLF) equation

$$\ln a_T = -\frac{C_1(T - T_0)}{C_2 + (T - T_0)}$$

where $H$ is the activation energy of the relaxation, $R$ is the universal gas constant, and $C_1$ and $C_2$ are constants. The WLF equation is usually applicable to glass-rubber relaxation of amorphous polymers. The Arrhenius equation is applicable to relaxation in amorphous polymers below the glass transition temperature and for relaxation in semicrystalline polymers.

Experimentally, the time-temperature shift factor is generally determined from horizontal shifting of isotherms (curves of reduced modulus vs. frequency for a constant temperature) so that the curves superpose (13). However, in some cases (as when using the Rheovibron), it is easier to measure isochrones (reduced modulus vs. temperature for a constant frequency). Isochrones are not superposable by horizontal shifting because of the nonlinear dependence of $a_T$ on temperature. The time-temperature shift factor can be determined by relating the slopes of the isochrones in accordance with the following equation (13):

$$\left( \frac{\partial \log E'}{\partial T} \right)_\omega = \left( \frac{\partial \log E'}{\partial \log \omega} \right)_T \left( \frac{\partial \log a_T}{\partial T} \right)_\omega$$

One can simplify Eq 14 by recalling that, for a constant temperature, $E'$ is a function of $\omega$ but not of $a_T$. Also, for a constant frequency, only $a_T$ is a function of $T$; $\omega$ is independent of $T$. Therefore, Eq 14 reduces to

$$\left( \frac{\partial \log E'}{\partial T} \right)_\omega = \left( \frac{\partial \log E'}{\partial \log \omega} \right)_T \left( \frac{\partial \log a_T}{\partial T} \right)_\omega$$

The derivative of $\log E'$ with respect to $\log \omega$ can be estimated by assuming that chords connect the isochrones. The resulting equation for estimating $\log a_T$ is

$$\log a_T(T + \Delta T) = \frac{\Delta \log E'/\Delta T}{\Delta \log E'/\Delta \log \omega} \Delta T + \log a_T(T)$$

For the three isochrones, one can calculate multiple values for $a_T$ from Eq 16 and thereby increase the accuracy. One may start the evaluation of $a_T$ at the reference temperature, $T_0$, where $\log a_T(T_0) = 0$. This procedure was implemented in a computer program. Unfortunately, when calculating derivatives from experimental data, a lot of noise is introduced (and the errors are magnified). Therefore, for temperatures below the glass transition temperature, $a_T$ was determined by trial-and-error using Eq 12. An activation energy for $a_T$ was chosen and the data was shifted; this process was continued until the best superposition of the data was found. For PEEK, the Arrhenius equation for $a_T$ which provided the best superposition of the data was

$$\log a_T = \begin{cases} 1100 \left( \frac{1}{T} - \frac{1}{T_0} \right) & 173^\circ K < T < T_g \\ 4.9 \times 10^4 \left( \frac{1}{T} - \frac{1}{T_0} \right) & T_g < T < 453^\circ K \end{cases}$$

where $T_g$ is the glass transition temperature and for PEEK it is 416°K. The moduli for PEEK at 20 KHz, shown in Fig. 8, were estimated using Eq 17 and Fig. 7 (2).

The limited temperature range that can be used on the Rheovibron enabled measurement of the moduli for temperatures only slightly above $T_g$. However, for the lumped parameter model, the moduli should be known up to the melting temperature. Therefore, the moduli at temperatures near the melting temperature were estimated from nondimensional plots of the known moduli of other semicrystalline polymers (2). Figure 9 shows the final estimated moduli for PEEK from room temperature to nearly the melting temperature.

Heat Transfer

As the energy directors get hotter from the dissipation of vibrational energy, heat is conducted from the energy directors into the (relatively) cooler com-
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Fig. 9. Elastic ($E'$) and loss ($E''$) moduli for PEEK at 20 KHz for temperatures up to $T_m$.

Flow and Wetting

Once any portion of an energy director exceeds the melting temperature, it will start to flow—primarily as a result of the forces applied by the welder. Figure 11 shows the typical geometry which results from the melting of the whole energy director. It looks very much like a squeezing flow of a polymeric liquid. Due to the high viscosity of the polymers, wetting of the composite surfaces also depends on the squeeze flow—as long as mold releases do not contaminate the surfaces.

Squeezing flows are encountered in many situations involving the processing of plastics. Grimm (15) presents an excellent review of the work done on the squeezing flows of polymeric liquids. Although many models have been developed, none can adequately predict the elastic effects for a power law fluid (15). Lee, et al. (16) and Phan-Thien, et al. (17) have developed theories which account for elastic effects in the squeezing flows of constant viscosity liquids. Bird and Armstrong (18) developed a squeeze flow model which includes elastic effects for a power law fluid, however they neglect inertial effects and assume a quasi-steady-state approximation.

The importance of inertia, compressibility, and elasticity can be estimated by calculating the nondimensional Reynolds, Mach, Deborah, and Weissenberg numbers for ultrasonic welding. During the process, a static force is applied—and superimposed on top of it is a dynamic displacement. Assuming that the two act independently simplifies the evaluation of these numbers.

In order to estimate the Deborah and Weissenberg numbers, it is necessary to estimate the relaxation time for the material. Here, like in Grimm’s work (15), the relaxation time ($\lambda$) for a power law fluid is defined to be

$$\lambda = \left(\frac{m}{\eta_0}\right)^{1/(n-1)}$$

where $\eta_0$ is the zero shear rate viscosity. The constitutive law for the fluid is $\tau_{\mu} = m\dot{\gamma}_{\mu}^{n}$, where $\tau_{\mu}$ is the shear stress, $\dot{\gamma}_{\mu}$ is the strain rate, and $m$ and $n$ are constants. The advantage in using such a definition...
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is that $\lambda$ can be obtained from viscosity measurements alone.

Although the squeeze flow is not isothermal (because of viscous heating and heat transfer to the composites), isothermal flow is assumed, to make this problem manageable. Also, since the squeeze flow is accompanied by viscous heating, it is assumed that the majority of flow occurs at a temperature of about 380°C for PEEK. PEEK at 380°C can be described as a power law fluid (see Fig. 12) with the following relation:

$$\tau = 38000(\text{Pa} \cdot \text{s}^{0.31})^{0.31}$$

(19)

and the zero shear rate viscosity is $\eta_0 \approx 2 \times 10^3 \text{ Pa}\cdot\text{s}$. Therefore, the relaxation times for PEEK is $\lambda_0 = 0.014 \text{ s}$.

Here, the residence time for the Deborah number is also defined here as it appears in Grimm’s work (15). It is the time required for the gap height ($h$) to decrease to one-half the original gap height. For the static loading ($F$), this time can be estimated from the quasi-steady-state squeeze flow equation for a power law liquid of width $2b$ and depth $w$

$$\frac{h_0}{h(t)} = \left(1 + \frac{t}{\tau}\right)^{n/(2n+3)}$$

(20)

$$\tau = \frac{4n + 2}{2n + 3} \left(\frac{b_0}{b_i}^{2n+3} \frac{w \cdot F}{m} \right)^{1/n}$$

(21)

For the dynamic loading, the residence time is approximately the period for one cycle of vibration. Similarly, estimates of the Reynolds, Mach, Deborah, and Weissenberg numbers were calculated at different times in the welding process for both static and dynamic loadings. These estimates are presented in Table 1 for a typical static force of 400 N and dynamic amplitude of vibration of 2.286 × 10^{-3} m. It is assumed that the whole amplitude of vibration is taken up by the molten interface.

From Table 1, it is seen that, early in the welding process, both the inertial effects and the elastic effects are important—while compressibility is negligible. At this stage, under static loading the molten energy director behaves like a soft spring in parallel with a soft damper. Dynamically, it behaves like a moderately hard spring. (Note the higher Deborah and Weissenberg numbers.) As the ultrasonic welding progresses, and more flow occurs, under static loading the spring disappears while the impedance of the damper keeps rising. Dynamically, the molten polymer behaves like a stiffer spring. Close to the end of the process, the static behavior is that of a quasi-steady-state flow. Dynamically, the molten polymer behaves like an even stiffer spring and compressibility still remains negligible. Finally, when all the melt fronts meet, the static behavior is that of a quasi-steady-state squeeze flow. Dynamically, compressibility becomes important and elastic effects dominate ($We \gg 1$). At this stage, the impedance of the molten layer suddenly becomes very large. Therefore, realistically, some of the vibration amplitude is taken up by other parts in the system (like the composites and the base). By measuring the power, the end state can be detected by the rapid rise of power dissipated into the composites and the base. The acceleration of the base also increases suddenly, as more vibration is transmitted to it.

Modeling of the flow can be divided into two uncoupled parts—the static and the dynamic models. The large difference in the Deborah and the Weissenberg numbers—between the static and dynamic loading—indicates that the two can be modeled independently. The flow under the static loading can be regarded as a squeeze flow with inertial and elastic effects being important only in the beginning, but becoming less important as the flow progresses. Under dynamic loading, little (if any) flow takes place; the higher Weissenberg number indicates that the

### Table 1. Estimates of the Nondimensional Numbers for PEEK.

<table>
<thead>
<tr>
<th></th>
<th>Static</th>
<th>Dynamic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early in the Welding Process</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Re$</td>
<td>$&lt;&lt; 1$</td>
<td>$\approx 1$</td>
</tr>
<tr>
<td>$M$</td>
<td>$&lt;&lt; 1$</td>
<td>$= 0.2$</td>
</tr>
<tr>
<td>$De$</td>
<td>$&lt;&lt; 1$</td>
<td>$= 280$</td>
</tr>
<tr>
<td>$We$</td>
<td>$&lt;&lt; 1$</td>
<td>$&gt;&gt; 1$</td>
</tr>
<tr>
<td>Close to the End</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Re$</td>
<td>$&lt;&lt; 1$</td>
<td>$= 1$</td>
</tr>
<tr>
<td>$M$</td>
<td>$&lt;&lt; 1$</td>
<td>$= 0.04$</td>
</tr>
<tr>
<td>$De$</td>
<td>$&lt;&lt; 1$</td>
<td>$= 280$</td>
</tr>
<tr>
<td>$We$</td>
<td>$&lt;&lt; 1$</td>
<td>$&gt;&gt; 1$</td>
</tr>
<tr>
<td>At the End</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Re$</td>
<td>$&lt;&lt; 1$</td>
<td>$&gt;&gt; 1$</td>
</tr>
<tr>
<td>$M$</td>
<td>$= 0.2$</td>
<td></td>
</tr>
<tr>
<td>$De$</td>
<td>$= 280$</td>
<td></td>
</tr>
<tr>
<td>$We$</td>
<td>$&gt;&gt; 1$</td>
<td></td>
</tr>
</tbody>
</table>

![Fig. 12. Power law fit to the viscosity of PEEK at 380°C.](image-url)
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recoverable shear strain is much greater than the nonrecoverable shear strain. Therefore, the dynamic model can be a purely elastic one or, if enough information is available, it can be a viscoelastic one with a relatively low loss tangent.

As discussed earlier, no available models adequately describe the squeeze flow under static loading when both inertial and elastic effects are important. Therefore, one must rely on experimentally determined results. Grimm (15) provides plots of the dimensionless gap as a function of dimensionless time for different Deborah numbers. From these plots, one can determine the changes in the gap over time for a constant load and thus describe the flow during ultrasonic welding under static loading.

The high De and We numbers for the squeeze flow under dynamic loadings show that the molten polymer behaves as a viscoelastic solid. The moduli for this solid can be approximated in two ways. First, one may extrapolate the data for the moduli beyond $T_m$. Second, one may use the relaxation time constant for a Maxwell liquid and estimate the shear modulus. The latter method assumes that, for power law fluids, the Maxwell viscosity can be assumed to be $\eta_0$ and that the time constant calculated from Eq 18 is still applicable. These provide a very rough estimate of the moduli. For a better estimate, the first normal stresses as well as the viscosity must be measured.

**Intermolecular Diffusion**

The diffusion of long polymer chains across the bond interface and entanglement of these chains is what gives the ultrasonic bond its strength. The motions of individual linear polymer chains is modeled using the reptation theory developed by DeGennes (19, 20). In the reptation model, a chain is confined into an imaginary tube which represents the constraints of adjacent chains. The chain is free to move in snake-like fashion within the tube but, except for end segments, it cannot leave the tube. Over a period of time, the end segments (and those adjacent) move outside the tube. This motion propagates to the center of mass of the tube until, finally, the whole chain moves out of the original tube and a new tube is generated. Segmental diffusion and entanglement is sufficient to establish a good bond. For amorphous polymers, the diffusion time is related to the temperature of the polymer relative to the glass transition temperature; the higher the temperature above glass transition, the faster diffusion occurs (21). For semicrystalline polymers, the diffusion time is difficult to measure because it occurs very quickly once the melting temperature is exceeded. A molten semicrystalline polymer behaves like an amorphous polymer at a temperature much above glass transition. Estimates of the healing time for semicrystalline polymers are on the order of $10^{-2}$ s, which is at least 6 orders of magnitude less than the weld time for ultrasonic bonding (2). As this means that intermolecular diffusion presents no time limitation to the welding process, it need not be modeled. For all practical purposes, it can be assumed that intermolecular diffusion occurs almost immediately after melting and achieving of intimate contact at the interface.

**Construction of the Process Model**

Now that all four subprocess models have been developed (as one was not required for intermolecular diffusion), they can be combined into a single iterative process model. A block diagram of the calculation procedures is presented in Fig. 13. Starting with the original geometry, the lumped parameter model is used to calculate the mechanics and dynamics of the parts. From the estimated strains, the viscoelastic heating is calculated or the lumped parameter model can be used to calculate the energy dissipated by the dampers. Next, the finite element heat transfer program is activated to determine the temperature rise and if melting has occurred. If melting occurs, the flow model is used to determine the effective impedance of the molten layer, as well as the amount of flow. Then, the material properties and the geometry

![Fig. 13. Procedures for combining the submodels to form an overall process model.](image-url)
are updated, and control is returned to the lumped parameter model. (If no melting occurs, then the material properties are updated and control is returned to the lumped parameter model.) The sequence is repeated until the welding process is completed: completion is defined by the meeting of the melt fronts of the different energy directors.

EXPERIMENTAL PROCEDURES

Ultrasonic welding of thermoplastics and thermoplastic composites requires the application of static pressure plus superimposed high frequency vibration. For this work, a Branson Sonic Model 8800 welder was used. During welding one can control the cylinder air pressure, the rate of horn descent, the weld time, the hold time, and the pressure level that triggers the ultrasonic vibration. For these experiments, the static pressure was applied (for one or two seconds) before the ultrasonic vibration was triggered; therefore the trigger pressure control was not utilized. The horn descent rate was kept constant at the maximum rate.

Figure 14 shows a close-up of the aluminum fixture used to hold the parts during welding. The fixture was bolted to the base plate of the welder. Four bars were used to hold the composites from moving sideways. The composites were supported by an aluminum plate which rested on top of the force transducer. The fixture also included mounting holes for an accelerometer and for a displacement sensor.

PEEK/AS4 APC-2 composites were compression molded for 30 min under a pressure of 4.3 MPa and temperatures of 360 to 375°C. They were machined down to a size of 2.3 by 2.3 by 0.13 cm. To create a resin rich surface, a 0.025 mm thick layer of PEEK film was placed as the last ply in the layup. All composites were unidirectional, with the energy directors molded perpendicular to the fiber direction. Energy directors with bases of 1 mm and heights of 0.5 mm were molded by cutting grooves in a steel bar. The bar was placed in the mold, then two PEEK films and the prepregs (in that order) were placed on top. During molding, the PEEK melted and filled the grooves, thereby producing both the energy directors and the resin rich surface. Each composite had a total of 5 energy directors; the energy directors were molded 4 mm apart. (See Fig. 15.)

Measurement of Critical Parameters

It is useful to be able to monitor the impedance of the parts during the ultrasonic welding process and, therefore, to ascertain the states and the geometries of the energy directors. Measuring the impedance at high frequencies (e.g. 20 KHz) and high dynamic loadings, is difficult, however. Inertial effects—and the compliance of the fixture and the base plate—are important, yet the dynamic forces and displacement cannot be easily measured. Force transducers with wide enough dynamic ranges are unable to survive the high loadings and vibrations, while fixtures holding the displacement sensors are compliant at high frequencies. These difficulties can be overcome by using a fixture and a base with known impedances to support the composites. Then, the acceleration of the fixture gives a measure of the magnitude of the dynamic impedance of the composites.

Figure 16 shows a simplified model of the system. (A more elaborate lumped parameter model was discussed earlier.) For a constant input acceleration, if the impedance of the composites increases, then more of the acceleration (displacement) drop occurs across the fixture and base; therefore, acceleration of the fixture increases.

The impedance of the fixture and base must be determined in order to relate the acceleration of the fixture to the impedance of the composites. This was done by mounting an accelerometer (Bruel and Kjaer Model no. 8309) on the fixture. The ultrasonic welder with a booster horn with a gain of unity was used to excite the fixture and base. Then, the resulting force and acceleration were measured using a high speed 7D20 Tektronix digital oscilloscope. The ultrasonic welder has a tuning adjustment which matches the
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Fig. 16. Simplified model of the welder and parts using mechanical impedances.

excitation frequency to the resonant frequency of the converter-booster-horn system. The tuning adjustment was used to vary the frequency of excitation for the base; the range of frequency was limited by the amount of power available to drive the converter.

With the impedance of the fixture and base known, ultrasonic welding experiments were performed on the PEEK composites. During welding, the power supplied to the piezoelectric transducer was measured with a Branson Wattmeter Model A410A. The static displacement and the dynamic displacement drops across the composites were measured using a fotonic sensor (Mechanical Technology Inc. Model KD-45A, with a 2.7 mm random probe). The acceleration of the fixture was also measured.

Data Acquisition Systems

In order to measure the impedance of the fixture and the base, it was necessary to store the force and acceleration traces. These were stored on a digitizing scope and then transferred, via an IEEE-488 interface, to an IBM PC for analysis.

Acceleration, power, and displacements were measured throughout the welding process. Since welding times are on the order of seconds, it was not possible to store the actual oscillations in acceleration or dynamic displacement; that would have required too much memory. An alternative was to store the root mean squared values. Although the phase information was lost, the magnitudes were known—and those magnitudes were then used to monitor the magnitude of the dynamic impedance of the parts. An Analog Devices' AD636 RMS-TO-DC converter was used to get the root mean square values for both the acceleration and the dynamic displacement measurements. The static displacement was measured by passing the fotonic sensor output through a two-pole low pass RC filter with \( f_{3dB} = 160 \) Hz. The power trace from the wattmeter had oscillations with a frequency of 120 Hz. These were filtered out using a two-pole low pass RC filter with \( f_{3dB} = 53 \) Hz. All four signals were then fed into a Metrabyte DASH-16 analog-to-digital conversion board. The digitized signal was stored and analyzed on an IBM PC.

Machine Parameter Variations

The ultrasonic welder provides controls for cylinder air pressure, weld time, hold time, horn descent rate, and trigger pressure. As mentioned earlier, the rate of descent was set and left at the maximum speed. The trigger pressure was not used because the static pressure was applied prior to activating the ultrasonic vibration. The cylinder air pressure is directly related to the static pressure or force that is applied to the parts; the cylinder air pressure varied from 140 to 690 KPa, which resulted in the variation of the static force from 690 to 3450 N. The weld time and hold time were manually controlled. The hold time was held constant at about 3 s, and the weld time was varied up to a maximum of 8 s.

One can vary the vibration amplitude by changing the booster horn and/or horn. In all experiments, a unity gain horn was used; the vibration amplitude was varied by changing the booster horn only. The booster horns had gains of 1, 1.5, 2, and 2.5. This resulted in equal gains in vibration amplitude.

RESULTS AND DISCUSSION

Ultrasonic welding of PEEK APC-2 composites produced joints with excellent strengths. The model which was developed for ultrasonic welding provides much insight into the process. The model predicts that melting and flow occur in steps, as was observed by high speed video (2). The model also predicts a rapid rise in the impedance of the interface at the end of welding; this was verified through measurements of power and base vibrations. Predictions of the time required for complete welding were also quite good considering the assumptions which were incorporated into the model.

Modeling the dynamics and vibrations of the parts during welding requires knowledge of the dynamic impedance of the fixture and base. Therefore, the impedance of the support fixture and the base was determined from measurements of the excitation force and the resulting acceleration of the fixture. Figure 17 shows the lumped parameter model of the fixture and base. For a sinusoidal input force, the ratio of the complex force \( (F^*) \) to the complex accel-
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Fig. 17. Lumped parameter model for the fixture and base.

The transfer function (\( a^* \)) is

\[
\frac{F}{a^*} = m - \frac{k}{\omega} - j\frac{b}{\omega}
\]

or, the magnitude and phase shift are

\[
|\frac{F^*}{a^*}| = \left( m - \frac{k}{\omega^2} \right)^2 + \left( \frac{b}{\omega} \right)^2^{1/2}
\]

\[
\phi = \tan^{-1} \frac{-b/\omega}{m - k/\omega^2}
\]

Therefore, by measuring the magnitude and the phase over a range of frequencies, the mass, spring constant, and damping coefficient can be determined.

**Figure 18** shows a typical trace of the dynamic force; it is sinusoidal at a frequency of about 20 KHz. **Figure 19** shows the corresponding acceleration trace. Fourier transform analysis shows that the acceleration trace is made up of two superimposed sinusoids. One sinusoid has a frequency of about 20 KHz and the other has a frequency of about 70 KHz; the first is due to the applied force and the second corresponds to the natural frequency of longitudinal vibration for the 1.5 in long bar which makes up the fixture (68 KHz). In order to eliminate the high frequency from both the force and acceleration traces, a digital 5-pole Butterworth filter was used. **Figures 20 and 21** show the filtered data. From the plots, the excitation frequency and the magnitude and the phase shift were calculated. The magnitude was found to be 0.105 ± 0.014 kg and the phase shift angle was 31.9 ± 14.9°.

Knowing the magnitude and phase shift of the transfer function for the base and fixture does not provide enough information to determine \( m, k, \) and \( b. \) However, since the phase angle is positive, the spring term dominates over the mass term. Therefore, the fixture and base impedance is modeled as a spring and damper in parallel, with the spring constant being \( 1.41 \times 10^9 \) N/m and the damping coefficient being 6970 Ns/m. It is assumed that the fixture and base act linearly with increasing amplitude. In other words, the values calculated for \( k \) and \( b \) are assumed to remain constant for all amplitudes. This is a reasonable assumption, given that the fixture and the base are made of aluminum — a material which behaves elastically.

During the ultrasonic welding of PEEK APC-2 composites, the power, fixture acceleration, dynamic displacement drop across the parts, and static displacements were measured. The data was then digitized and analyzed on the microcomputer. A variety of booster horns were available to us, so that the amplitude of vibration could be varied by a factor of 2.5. The vibration amplitude was measured using the fotonic sensor. It was found to be 0.011 mm for the...
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1:1 booster horn, and it could be increased to 0.028 mm with a 1:2.5 booster horn. The static load could be varied from very close to 0 up to 3450 N. Generally, increasing the amplitude of vibration and/or the static force increases the dissipated power.

For PEEK composites, as with other semicrystalline polymers, high power inputs are necessary in order for the temperature to exceed the melting temperature. (For amorphous polymers, the temperature only needs to exceed the glass transition temperature.) Therefore, attempts to weld using 1:1, 1:1.5, and 1:2 booster horns were generally unsuccessful, even for long weld times (over 7 s). The only exception we encountered was when we used a 1:2 booster, a 690 KPa cylinder pressure, and a weld time of about 8 s. Using a 1:2.5 booster increased the power level, and parts were successfully welded at cylinder pressures over 410 KPa.

The weld time for a composite is not only a function of the vibration amplitude and static pressure, but also of the uniformity in the thickness of the parts. Parts with large thickness variations require longer weld times—to allow for heating and flow at the thinner sections. In general, the composites used in this research had thickness variations on the order of 0.08 mm or less. Although the number of data points is scarce, Fig. 22 shows a decrease in weld time with increasing pressure. The results of some very rough simulations are also shown in Fig. 22. Although indicating the same trend, the simulations predict shorter welding times and higher power levels; this is probably due to the assumptions made within the model. For example, it was assumed that the composites and energy directors were completely uniform in size, and that equal contact was achieved throughout the sample. Also, it was assumed that the molten energy directors would behave as linear viscoelastic materials in response to the high frequency vibrations. Still, the actual weld times are close to the theoretically determined ones.

The simulations were done using the lumped parameter model, finite element heat transfer, and empirical curves for flow predictions. Although the simulations give some unexpected results, they can all be explained. One might expect the model to begin, for example, by predicting melting at the tip of the energy director. Instead, however, due to the heat transfer from the tip to the bottom composite, melting occurs first above the tip. Figure 23 shows that, in simulation of the case using a 1:2.5 booster and a cylinder pressure of 690 KPa, melting first occurs after about 0.01 s and the melted region is about 1/8 of the way up from the energy director's tip. Also, since the composites are anisotropic, heat is conducted along the fibers faster than transverse to them; thermal contours predicted by the finite element program are, therefore, elongated in the fiber direction. (See Fig. 24.)

Land (4) was likely the first researcher to notice that ultrasonic welding occurs in stages rather than in one continuous operation. A high speed video (manufactured by Eastman Kodak) was used to videotape the ultrasonic welding of PEEK APC-2 composites; the video was recorded at the maximum speed of 1000 frames/s. Although the flow of the

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**Fig. 20.** Filtered force trace.

**Fig. 21.** Filtered acceleration trace.

**Fig. 22.** Relation between cylinder air pressure and weld time for complete welding.
molten polymer towards the camera obstructed the view, one can still use the video to measure the gap between the composites. Figure 25 shows that the gap does not decrease continuously, but rather in stages, as previously observed by Land (4). The simulation of the welding process also predicts this behavior. As the molten polymer flows in between the composites, it decreases in thickness and it encounters composite surfaces which are cool. The cool composite surfaces are sometimes sufficient to freeze the melt fronts and to halt flows until additional heating remelts the fronts. The freezing and melting of the flow fronts were found to depend greatly upon the loss modulus of the molten layer. In the simulation, the gap could be made to decrease continuously by assuming a relatively high loss modulus and a very slow flow. This allowed for the generation of enough heating to warm the cool composite surfaces and to keep the flow fronts molten. Further work needs to be done to determine the material properties of the molten layer and to further explain how the gap decreases.

In the Theory Section, the impedance of the molten layer and its relation to the flow was discussed. As noted there, the sample impedance is expected to rise rapidly at the end of the bonding process—when all the melt fronts have met. This is due to elasticity and compressibility dominating the behavior of the molten layer when all melt fronts meet and are subjected to ultrasonic vibration. As shown in Table 1, after the melt fronts meet, the Mach number jumps to 0.3.

The increased impedance of the molten layer results in more vibration amplitude being absorbed by the composites, the fixture, and the base. Therefore, the acceleration of the fixture and the power level should increase as the lossy composites and base dissipate energy. For all samples which bonded well, the experimental results confirmed these simulation predictions.

Figures 26–31, show the rms acceleration of the fixture and the power traces for selected samples. For all three examples, a rapid rise in the rms acceleration trace and the power trace are clearly visible.

Sample 13 was welded using a 1:2.5 booster and a cylinder pressure of 690 KPa. As shown in Figs. 26 and 27, for sample 13 a rapid rise occurs after a weld time of about 3 s, followed by a rapid decline after 5 s. This indicates that sample 13 was well bonded after 3 to 4 s; the decline after 5 s indicated a melting of the composites. Examination of the sample showed that the composites did indeed melt, and that fibers and polymer flowed out sideways. Therefore, for sample 13, the weld time was too long.

Sample 9 was welded using a 1:2 booster and a cylinder pressure of 690 KPa. In Figs. 28 and 29,
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Fig. 26. RMS acceleration of the fixture during ultrasonic welding of PEEK composites with cylinder air pressure of 690 KPa and 1:2.5 booster (Sample 13).

Fig. 27. Power dissipated during ultrasonic welding of PEEK composites with cylinder air pressure of 690 KPa and 1:2.5 booster (Sample 13).

Fig. 29. Power dissipated during ultrasonic welding with cylinder air pressure of 690 KPa and 1:2.5 booster (Sample 9).

Fig. 30. RMS acceleration of the fixture during ultrasonic welding with cylinder air pressure of 550 KPa and 1:2.5 booster (Sample 16).

Fig. 28. RMS acceleration of the fixture during ultrasonic welding with cylinder air pressure of 690 KPa and 1:2 booster (Sample 9).

Fig. 31. Power dissipated during ultrasonic welding with cylinder air pressure of 550 KPa and 1:2.5 booster (Sample 16).
one can see that the weld time for this sample was also too long. Just before the ultrasonic vibration was stopped, the traces for sample 9 started to decline. One would expect, then, some fiber/polymer flow. A flow was indeed observed, but not half as much as in sample 13.

Sample 16 was welded using a 1:2.5 booster and cylinder pressure of only 550 kPa. From Figs. 30 and 31, one can see that the ultrasonic vibration was stopped just as the power and acceleration traces started rising. Therefore, in this case, no composite melting—or fiber/polymer flow—occurred. Cross-sectional examination of sample 16 showed complete flow and meeting of the energy directors. Mechanical testing showed that an excellent ultrasonic bond was indeed produced.

The impedance of ultrasonically welded composites is related to the flow of the molten energy directors and, therefore, to the bond quality. At the end of the weld cycle, when the melt fronts meet, the magnitude of the composites’ dynamic impedance was shown to rise quickly. So, by measuring composites’ dynamic impedance during processing, one could theoretically control the quality of bonding. Unfortunately, however, dynamic impedance measurements at high frequencies—and high forces and powers—are difficult to perform.

An alternative approach for controlling process quality would be to measure related variables, such as power and acceleration of the base. As can be seen in Figs. 26 to 31, power traces and rms acceleration traces behave very similarly. Theoretically, then, one could measure only one of these variables, but that is not recommended. By measuring both parameters, one might be provided with warnings of unwanted effects. For example, drifting of frequency in the power supply might result in an increase in power; the increase, however, might be read as proof of a good bond. Similarly, improper joining of the fixture to the base (or loosening or fracture of that element) might result in an increase in base acceleration; again, an observer might be misled and assume that a good bond has been achieved. If both power and acceleration are measured, such unwanted effects can be detected and corrected in a timely fashion.

CONCLUSIONS

Fusion bonding of advanced thermoplastic composites is critical to the manufacture of a variety of aerospace structures. Ultrasonic welding of advanced composites provides excellent joint strengths and is very flexible. Therefore, ultrasonic welding of advanced thermoplastic composites was studied theoretically and experimentally. Theoretically, the process was subdivided into five highly coupled subprocesses—1) mechanics and vibration, 2) viscoelastic heating, 3) heat transfer, 4) flow, and 5) intermolecular diffusion. These subprocesses were individually modeled, and then they were coupled together in order to enable simulation of the complete process. From the model, it was determined that the impedance of the composites’ interface is related to the flow of the molten polymer. It was predicted—qualitatively—that when the melt fronts meet, the impedance will quickly rise. A lumped parameter model was developed as part of the mechanics and vibration subprocess; its purpose was to relate interface impedance to the more-easily-measured power and fixture/base acceleration. The experimental work verified that the power and fixture/base acceleration can be used to measure the magnitude of the interface impedance. It was also verified—experimentally—that the interface impedance, or the power and acceleration traces, rise quickly when the melt fronts meet and a good bond is produced. This behavior allows for the development of closed loop control for ultrasonic welding of advanced composites.

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