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Welding of Plastics: Fundamentals and New Developments

This paper provides a general introduction to welding fundamentals (section 2) followed by sections on a few selected welding processes that have had significant developments or improvements over the last few years. The processes that are discussed are friction welding (section 3), hot plate welding (section 4), ultrasonic welding (section 5), laser/IR welding (section 6), RF welding (section 7) and hot gas/extrusion welding (section 8).

1 Introduction to Joining

Despite designers' goals of molding single component products, there are many products too complex to mold as a single part. Thus, assembly of sub-components is critical for manufacturing of many products. The methods for joining plastics components can be divided into three major categories: mechanical joining, adhesive bonding, and welding (see Fig. 1). Mechanical joining involves the use of separate fasteners, such as metallic or polymeric screws, or it relies on integrated design elements that are molded into the parts, such as snap-fit or press-fit joints. In adhesive bonding, a consumable (adhesive) is placed between the parts (adherents) where it serves as the material that joins the parts and transmits the load through the joint. In welding or fusion bonding, heat is used to melt or soften the polymer at the interface to enable polymer intermolecular diffusion across the interface and chain entanglements to give the joint strength. Each of these categories is comprised of a variety of joining methods that can be used in a wide range of applications. This paper is devoted to welding processes only. Accordingly, only thermoplastics are considered, because thermosets cannot be welded without the addition of tie-layers such as thermoplastics layers. Greater details on welding processes can be found in several monographs [1 to 4].

Welding processes are often categorized and identified by the heating method that is used. All processes can be divided into two general categories: internal heating and external heating, see Fig. 2. Internal heating methods are further divided into two categories: internal mechanical heating and internal electromagnetic heating.

External heating methods rely on convection and/or conduction to heat the weld surface. These processes include hot tool, hot gas, extrusion, implant induction, and implant resistance welding. Internal mechanical heating methods rely on the conversion of mechanical energy into heat through surface friction and intermolecular friction. These processes include ultrasonic, vibration, and spin welding. Internal electromagnetic heating methods rely on the absorption and conversion of electromagnetic radiation into heat. These processes include infrared, laser, radio frequency, and microwave welding.

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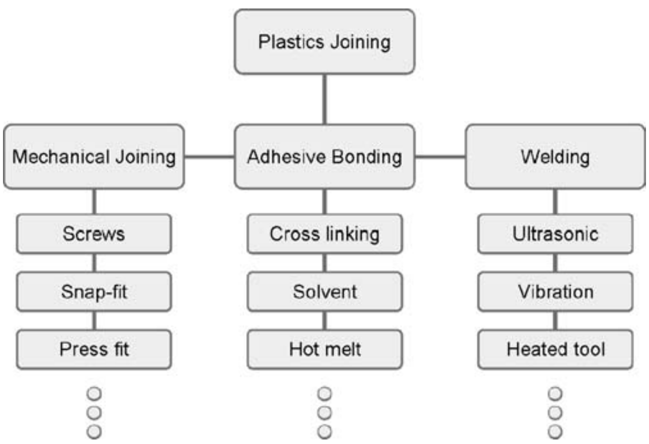


Fig. 1. Possible plastic joining techniques

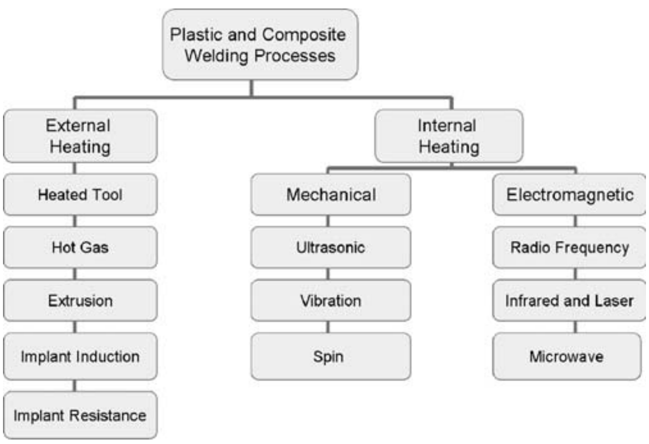


Fig. 2. Classification of welding techniques

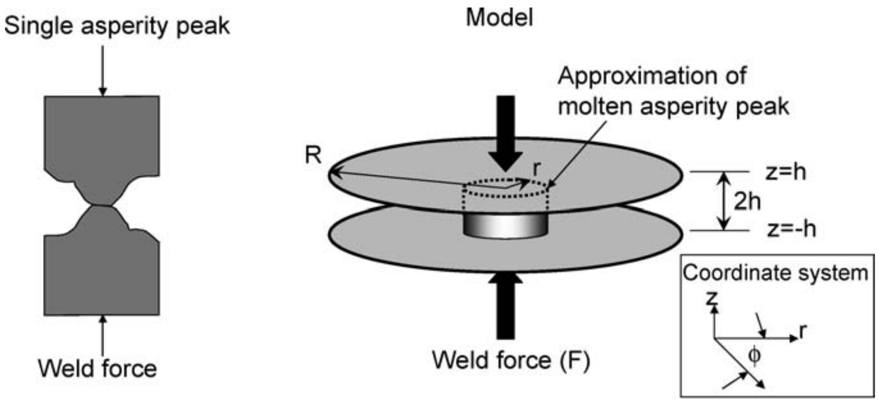


Fig. 3. Details of model for asperity peek squeeze flow

2 Introduction to Welding

When two interfaces of the same polymer are brought together in a molten state, the interfaces will conform to each other over time to achieve intimate contact followed by intermolecular diffusion and chain entanglement and weld to each other. The degree of welding (DW) is based on many parameters, including material properties, temperature, interfacial pressure and time. Investigators such as *DeGennes* [5] and *Wool* [6], have demonstrated that polymer molecular motion can be approximated by reptilian motion. In these models, there are several fundamental assumptions, such that the interfaces are in full intimate contact and at a relatively constant temperature. In most applications, these assumptions are not valid. For example, even with relatively smooth surfaces, asperity peaks prevent full intimate contact. Intimate contact can only be achieved after squeeze flow of the asperity peaks. In addition, only well controlled experiments have constant temperature conditions.

During welding, these asperity peaks are softened and they flow so as to fill the interstitial spaces. In order to better understand this flow, the surface can be modeled as many small [7], identical cylinders of material placed between two rigid plates separated by some arbitrary distance 2 h. In order to simplify the model, only a single asperity can be considered as seen in Fig. 3. In this model, the original height and radius are defined as $2h_0$ and r_0, respectively.

It has been shown that it is possible to define the non-dimensional relationship of h_0/h where h is half the gap distance at some arbitrary time (t);

$$\frac{h_0}{h(t)} = \left(\frac{16\pi F h_0^2}{3\mu r_0^4} t - 1\right)^{1/4}. \tag{1}$$

Eq. 1 can then be used to predict the gap height as a function of time, or more importantly, the closing of two faying surfaces as a function of time. In this model, F is the applied force and μ is the Newtonian viscosity.

Once the interfaces conform to each other, they heal together by diffusion and entanglement of molecules. Healing of the interfaces is basically diffusion of polymer chains across the interface from one side to the other. This mechanism is depicted in Fig. 4 at various times and degrees of healing. Under ideal conditions at complete healing, polymer chains from each side of the interface migrate across the interface so that it essentially becomes indistinguishable from the bulk material.

By using Einstein's diffusion equation, *Jud* [8] proposed that the diffusion coefficient is an Arrhenius function of temperature (T) and it can be expressed as shown in Eq. 2.

$$D(T) = D_0 e^{\left[\frac{-E_a}{kT}\right]}, \tag{2}$$

where D_0 is the diffusion constant, E_a is the activation energy and k is the Boltzmann constant (1.3807×10^{-23} J/K). While many investigators have assumed that activation energy is temperature-independent, such as *Loos* and *Dara* [9] who studied the healing of polysulphone, there is data in the open literature that suggest differently. While this estimate is reasonable, it has been proposed that a better fit to experimental data can be achieved with a model in which the activation energy is temperature-dependent [10]; this is especially true and useful when squeeze flow and intermolecular diffusion are combined into one model. In this case, it is proposed that the relationship between the activation energy and temperature follows an exponential form, see Eq. 3:

$$E_a(T) = A_0 e^{-k_a T}, \tag{3}$$

where A_0 is a material constant (units of J) and k_a is the temperature parameter (1/K). It is important to note that this approach is non-classical and more classical approaches proposed by *Bastien* [11] can also be applied.

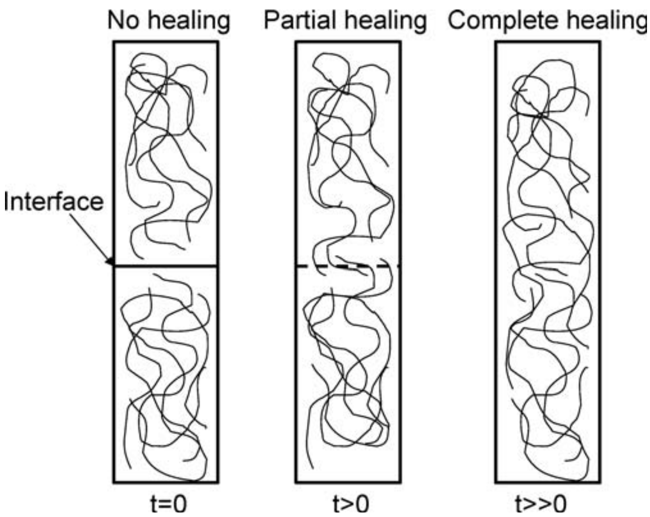


Fig. 4. Details of molecular healing of the interface over time

Because both processes (squeeze flow and healing) occur during welding and both have similar time dependence (proportional to $t^{1/4}$), it has been proposed that both processes can be lumped into a single expression [10]. Because most industrial welding processes produce temperature histories that are time-dependent, it is possible to simplify the temperature histories by dividing a given temperature history into finite time intervals (Δt). In this case, assuming no healing prior to welding, and assuming welding occurs between time = 0 and t', it is proposed that the degree of healing and squeeze flow can be defined as seen in Eq. 4.

$$DW(T,t)_h = \sum_{t=0}^{t=t'} K_0 \cdot e^{-\frac{A_0 e^{[-k_a T]}}{kT}} \cdot \Delta t^{1/4}, \tag{4}$$

where A_0, k_a and K_0 can be determined experimentally and represent both squeeze flow and healing processes. In this case, k is the Boltzmann constant (1.3807×10^{-23} J/K). Thus, these equations can be used to accurately predict interfacial healing as a function of time and temperature.

In order to predict the temperature fields as a function of time a number of possible relationships can be used. One equation often used to predict temperature fields in many plastic welding processes is based on a heat flux in 1-dimension as detailed in Eq. 5 [12].

$$\theta(x,t) = \theta_i + \frac{2 \cdot \dot{q}_0}{\lambda}\left[\sqrt{\frac{\kappa \cdot t}{\pi}} \cdot \exp\left(-\frac{x^2}{4 \cdot \kappa \cdot t}\right) - \frac{x}{2} \cdot \mathrm{erfc}\left(\frac{x}{2\sqrt{\kappa \cdot t}}\right)\right], \tag{5}$$

where θ is the temperature, x is the position, t is time, θ_i is the initial temperature of the solid, $\dot{q}_0$ is the heat flux at the surface, λ is the thermal conductivity, κ is the thermal diffusivity, and $\mathrm{erfc}(z)$ is the complementary error function.

Another boundary condition that can be relevant to plastic welding is a constant surface temperature (θ_s) where temperature fields in 1-dimension can be predicted using Eq. 6 [13].

$$\theta(x,t) = \theta_i + (\theta_s - \theta_i) \cdot \mathrm{erfc}\left(\frac{x}{2\sqrt{\kappa \cdot t}}\right). \tag{6}$$

Once the healing process is completed, the heat source promoting welding is removed and the interface solidifies. Once the parts are cooled, residual stresses resulting from nonlinear thermal expansion and contraction and squeeze flow remain in the parts. If the squeeze flow rate is high, molecular alignment [14] will result parallel with the flow direction (shear thinning) and this molecular orientation can be “frozen” during solidification depending on the cooling rate. This molecular orientation may result in weak welds as well as in flow-induced residual stress in the weld because the molecules are forced to remain in a stretched state. The analysis of residual stresses is important for a number of reasons [15 to 18]:

- Residual Stresses can considerably reduce the strength and quality of the joint under static as well as dynamic loading conditions.
- It can decrease the fatigue life of a joint.
- It can reduce the fracture toughness of the weld.
- Residual stress can increase the corrosive effects of solvents resulting in micro-cracks.

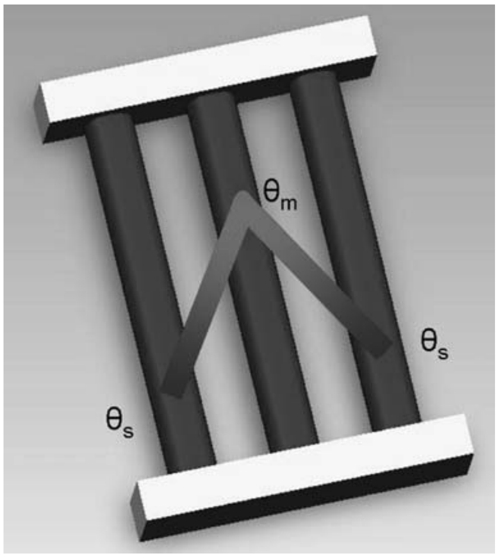


Fig. 5. Details of three bar analog for residual stress modeling

- Cracks always emanate from areas with high residual stresses. Thus residual stresses act as stress concentrators.
- The total stress in a part is a superposition of the stresses due to the externally applied load and the residual stresses. Hence, a factor of safety can be added while designing the component to take care of the extra stress (residual), provided the residual stress level or range is known.

It has been found that the residual stress that develops in the direction parallel to the weld is much greater than the stress in the perpendicular direction [19]. The three-bar analogy is a simple model that neglects the stresses perpendicular to the weld (see Fig. 5) and can be used to estimate the residual stresses produced by temperature gradients. In this model the weld region is divided into three bars with the middle bar representing the hot region closest to the weld line and the side bars representing the cooler zones away from the weld line. During the heating and cooling, the hotter regions are constrained by the colder regions. This constraint is represented by the movable rigid boundary. This constraint leads to the development of residual stresses which can be estimated using the three bar model. In a simple form, the center bar is heated to a temperature defined as θ_m, and the two outer bars are heated to θ_s. To reach equilibrium, the stress in three bars must sum to zero and the strains must be equal. Based on these fundamentals, it is possible to derive equations relating stress and strain to a wide range of thermal histories as detailed in previous work [19].

3 Friction Welding

3.1 Process Description of Friction Welding

There are four main variations of friction welding: linear, orbital, spin and angular welding. Linear and orbital welding are similar in that they are amenable to a wide range of geometries, while in contrast, spin and angular welding are primarily suitable for circular weld geometrics. All four processes rely on relative motion between the two parts that are to be joined, which re-

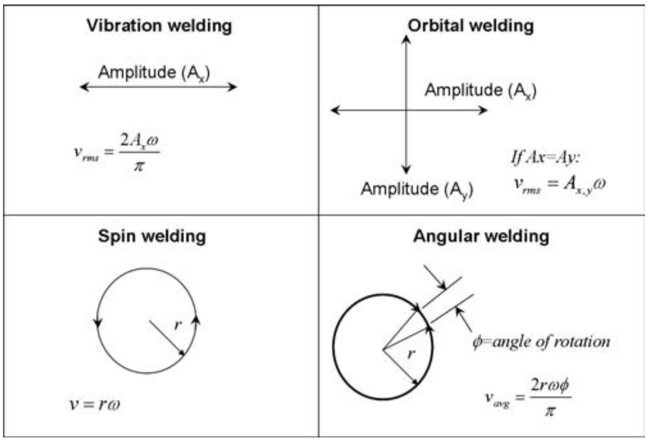


Fig. 6. Details of various modes for friction welding

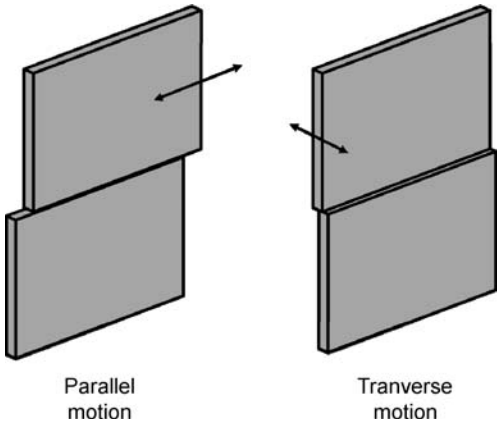


Fig. 7. Example of walls parallel and traverse to direction of motion

sults in frictional heating. The only major difference between these processes is the geometry of the relative motion. Fig. 6 details the various motions and the corresponding velocities. It is important to note that in all cases, the angular velocity (ω) of the displacement is in radians/s [20]. In addition, in the case of angular welding the angle of rotation is defined in radians. With the velocities, it is possible to estimate power dissipation based on the fundamental assumption that power is equal to velocity multiplied by friction force as detailed in previous work [1, 21].

Linear vibration welding allows welding of surfaces that are able to be moved in one direction. However, with linear vibration welding there is the risk that relatively weak welds can result with walls that are aligned transversely to the vibration direction, as shown in Fig. 7. This is due to that fact that without proper support, either internally with stiffening ribs or externally with built-in features in the fixtures, the walls can deflect and reduce the relative motion of the interfaces. Orbital welding, because of its elliptical or circular motion, produces a relatively constant velocity [21] assuming the amplitudes in both directions are equal. This constant velocity dissipates more energy at the joint for a given weld time and amplitude compared with linear vibration. In addition, because the motion is equal in all directions, assuming equal amplitudes in the x-and y-directions, the wall deflection, independent of orientation, is less of an issue.

Some of the key parameters for friction welding are detailed in Table 1. It has been shown that frictional welding has four distinctive phases [22, 23]. In the first phase, heating is generated by solid/solid interfacial frictional heating. This renders some thermoplastic materials with a low coefficient of friction such as fluoro-polymers not weldable with these processes. Other materials with such as PE (polyethylene) require relatively high clamping forces to generate larger friction forces. The second phase is the transition phase where solid frictional heating is replaced by viscous heating through shear deformation of the thin melt layer that formed at the interface. During the transition phase the thickness of the melt layer increases until the third phase, also known as the steady-state phase, is reached. This phase is usually considered the optimum phase

Process variable	Description
Velocity (spin)	Revolution per minute of welding head
Angle (angular welding)	Include angle of relative motion
Weld time	Length of time motion is activated
Hold time	Time parts are held under force after heating
Ramp time	Length of time the sonic ramp up during a weld cycle
Weld force	Amount of force applied to part
Melt down/collapse	Amount of weld down during weld
Mode	Primary process variable that defines weld cycle; such as time, or melt down

Table 1. Process parameter for friction welding

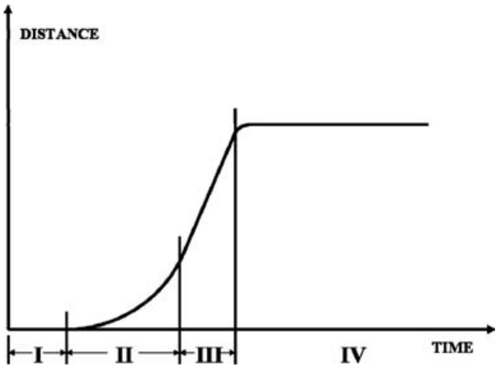


Fig. 8. Typical meltdown as a function of time for friction welding

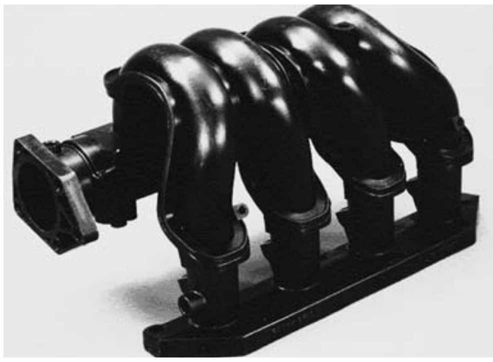


Fig. 9. Typical intake manifold assembled with vibration welding

to stop the motion because the melt generation rate equals the melt squeeze flow rate and thus additional melting does little to promote higher weld strength and only produces excessive weld flash. The final phase (phase four) is after the motion is discontinued and the material is allowed to solidify under the clamping pressure. The phases can be easily observed by measuring the melt down (displacement) as a function of time, as seen in Fig. 8.

Using the velocities detailed in Fig. 6 (Appendix 1), it is possible to estimate power dissipation for a constant coefficient of friction based on the fundamental assumption that power is equal to velocity multiplied by friction force as detailed in previous work [1, 21, 22]. Further more it is possible to use Eqs. 4 and 5 to predict temperature fields and estimate the degree of welding respectively.

3.2 Friction Welding Applications

One of the most familiar products assembled with friction welding are thermoplastic intake manifolds for the automotive industry, see Fig. 9. Historically, thermoplastic manifolds were manufactured as a single component with lost-core technology. While this process was expensive, it was attractive to the industry because the glass filled PA (polyamide) material allowed weight and costs saving, compared to aluminum components. By injection molding the component in two parts and joining the two halves, the lost-core technology was replaced by injection molding and linear vibration welding. One of the main challenges during this development was machine and tooling design that allowed intake manifolds for larger (V-8) engines to be manufactured. Still today, the welding of these large components requires the largest of the vibration welding systems available on the market.

Other applications range from household goods, such as small appliances, washer components and bumper assemblies for the automotive industry. In addition, non-rigid applications, such as carpet, are often vibration welded to thermoplastic substrates by using a comb like engaging fixture. Some of the advantages of the process that lead designers to select it for joining are speed of operation (typically less than 10 seconds cycle time), ability to weld internal walls and ability to weld relatively large components (not necessarily true for spin welding). Limitations often associated with friction welding processes, particularly for large systems, are capital investment for equipment and tooling. In addition, some materials, such as PC, can generate dust-like particulates that can present problems in some applications.

3.3 New Friction Welding Technologies

While the early friction welding systems (vibration welding) were simple, the basic system design is still the same, a resonance-tuned vibrator, driven by electromagnets (in early systems driven by hydraulics). However, there have been a number of advancements in controls and motion. For example, it has been shown that through neural networks it is possible to have the control system automatically detect the steady-state phase (phase three) and automatically discontinue the motion, making process optimization easier [24]. It is also possible to weld to a predetermined weld depth that allows relatively consistent part size after welding. Other newer controls include self-tuning systems.

Researchers have also used some of the understanding of squeeze flow and shear thinning to design new machines to reduce undesired molecular orientation and increase weld quality. For example, it has been shown that by applying a three dimensional cyclic motion, (Z-axis), better weld strength can be achieved. It is believed that this is due to better molecular alignment by reducing the shear thinning effects [25]. It has also been shown that greater weld strength can be achieved with vibration welding by stopping the motion between the two parts very quickly (dynamic breaking). This prevents shearing of the weld as the molten material solidifies.

In the original spin welding systems, the motion was produced by either electrical or pneumatic/air motors and often energy was stored in a fly wheel. Once the energy was dissipated, the motion ended. In newer systems, the motion is produced by servo-motors that allow faster acceleration and nearly instantaneous breaking. This reduces shear of the melt during solidification and allows final positioning of the two parts to be defined within in few fraction of a degree. This same technology then led to the development of angular welding where the circularity of the weld geometry is not critical and total rotation is not required.

One of the latest advancements in friction welding is the development of hybrid systems using IR heaters to pre-heat the faying surface. This approach reduces weld time and particulate generation [26]. It is believed that this approach softens the asperity peaks and allows them to deform without breaking free to form particulates during the initial phases of friction welding.

4 Hot Plate Welding

4.1 Process Description of Hot Plate Welding

Hot plate welding is one of the simplest welding techniques making it highly reliable and common place in industry. The process works by bringing the faying surfaces to be joined in contact with a heated tool. The tool can have relatively complex geometries to allow the welding of complex interfaces. In addition, the tool is often coated with a non-stick material (often PTFE, product name: Teflon) to act as a release agent. In the initial phase (matching phase), pressure is applied to promote squeeze flow of the faying surfaces to assure that the faying surfaces are well defined and all part irregularities are removed. Once sufficient matching displacement is achieved, the pressure is removed by mechanical stops or pressure regulators, so that a relatively thick melt layer is developed. After a pre-selected heating time, the parts are retracted from the tool, the tool is quickly displaced away from the parts and the parts are brought together to allow the two molten interfaces to weld. Again, the amount of displacement during the cooling phase may be limited by mechanical stops to prevent excessive squeeze out which would force the majority of melt out of the weld zone leaving a cold weld. The key parameters for heated tool welding are detailed in Table 2.

Variations of hot plate welding include high temperature hot plate welding and non-contact hot plate welding. Both processes address issues with sticking of residual material to the hot plate between welding cycles. In high temperature hot plate welding, the tool is not coated with any release agent and the tool is heated to 300 to 400 °C. In this case, the matching phase and heating are usually shortened. Once the parts are disengaged from the tool, any residual material is either oxidized away and/or mechanically removed from the heated tool. If even higher temperatures are used, the tool never makes contact with the parts, thus totally eliminating the issue of sticking or stringing of the melt to the tool. Stringing is a condition where filaments of melt are pulled between the heated tool and the molten interface. For non-contact hot plate welding, the parts are brought near to the tool (1 to 3 mm) and convection and radiation heating from the tool heats the faying surface. One of the major limitations to this approach is that there is no matching phase and thus part fit up must be good prior to welding.

During the matching and heating phases of contact hot plate welding the plastic part is brought in contact with the heated plate. Due to surface asperities on both the plastic part and the hot plate thermal contact resistance would reduce the heat flow into the part. The thermal contact resistance would gradually decrease as more melt is generated and the surface of the polymer conforms to that of the hot plate. Therefore, for precise predictions of the heat flow during contact hot plate welding the thermal contact resistance should be considered as well as the temperature dependence of the thermal properties of the polymer. However, in most cases, because the thermal contact resistance is low and the thermal mass of the heated tool is large compared to the parts being welded, the heat flow and temperature fields can be modeled by assuming a constant temperature boundary condition using Eq. 6, and the degree of healing can be estimated using the predicted temperature fields along with experimentally determined coefficient for Eq. 4.

Process variable	Description
Temperature	Temperature of heated tool
Matching time	Length of time parts are held against heated tool
Weld time	Length of time heated parts are held together
Ramp time	Length of time the sonic ramp up during a weld cycle
Matching force	Force applied while parts are held against heated tool
Matching displacement	Amount of displacement while parts are held against heated tool-controlled by mechanical stops
Weld force	Force applied while parts are held against heated tool
Weld displacement	Amount of displacement while parts are held together tool-controlled by mechanical stops
Switch over time	Time that is allowed to remove the parts from the heated tool and brought together

Table 2. Process parameter for heated tool welding

Fig. 10. Photograph of saddle point for pipeline installation using hot plate welding

4.2 Hot Plate Welding Applications

One of the well known applications associated with hot plate welding is that of PE pipe welding for drainage systems and gas line installations. In many cases, the pipe can be larger than 1 m in diameter. Hot plate welding is selected because it is amendable to field conditions where pipelines are installed, allows a wide range of diameters to be welded and it is a relatively robust process. It is also common place for saddle joints (Tee-s), see Fig. 10, to be welded to a main pipeline using hot plate welding.

Other applications include fuel tank assemblies for the automotive industry. Again, hot plate welding is selected because it is a robust process that allows poor fit of parts to be corrected during the matching phase and can produce hermetic and strong welds consistently. This is also why batteries are often assembled with hot plate welding. One major limitation to hot plate welding is cycle time. A typical cycle time is 30 to 90 seconds and with larger parts it can be as long as 30 minutes.

4.3 New Hot Plate Welding Technologies

As previously noted, hot plate welding of high temperature materials may result in sticking and stringing of the melt, which was addressed historically by high temperature welding. Based on visco-elastic properties of polymers, high speed translation systems (servo-driven tooling) have been developed to solve this issue. These systems pull the parts away from the heated tool fast enough so that the visco-elastic properties prevent stringing [27] by fracturing the polymer melt. This has become particularly useful in hot plate welding of polyamide components. In this case, the material is heated quickly by high temperature to reduce overall heating time and to prevent gravity driven melt flow. Then by very rapidly pulling the samples from the heated tool [27], relaxation of the melt is prevented and promotes brittle fracture at the melt/heated tool interface. Without the rapid motion, the melt would behave in a visco-elastic manner and stringing would occur. Often this rapid motion is achieved with linear of servo driven actuators.

Other advancements with hot plate welding include refined temperature control of the heated tool by use of PID controllers compared to conventional on/off controllers. In addition, automated retooling can be fitted to conventional heated tool welding systems so that multiple applications can be welded on one system by quick retooling.

5 Ultrasonic Welding

5.1 Process Description of Ultrasonic Welding

Ultrasonic welding is a very popular technique for fusion bonding of thermoplastics and thermoplastic composites. Welding is accomplished by applying low amplitude (1 to 250 μm) high frequency (10 to 70 kHz) mechanical vibration to parts. This results in cyclical deformation of the parts, primarily at the faying surfaces (joining surfaces) and surface asperities. The cyclical energy is converted into heat – within the thermoplastic – through intermolecular friction. This is similar to the heating that occurs in a metal wire that is bent back and forth repeatedly, or in general, to the effect occurring when materials are subjected to cyclical loading. The heat, which is highest at the surfaces (because asperities are straining more than the bulk), is sufficient to melt the thermoplastic and to fuse the parts. Usually, a man-made asperity in the form of a triangular protrusion is molded into one of the parts to improve the consistency of heating and welding (see Fig. 11). This protrusion, which is also called an energy director or concentrator, experiences the highest levels of cyclical strain producing the greatest level of heating. Therefore, the energy director melts and flows to join the parts. There is a wide range of joint designs that concentrate the energy at the faying surfaces, including shear joints, mesh joints, knife edge joints among others that can be used in conjunction with roughened surfaces to enhance welding [1]. It is beyond the scope of this paper to review these alternative joint designs.

Ultrasonic welding is often used in mass production because the welding times are relatively short (often less than 1 s). Ultrasonic welding is a flexible technique that can also be used for small lot size production – as long as the fixtures are designed to be flexible. It is applicable to both amorphous and semicrystalline thermoplastics. In some cases, the technique can even be used to bond dissimilar materials [28]. Because of these advantages, ultrasonic welding is one of the most common methods used in industry to join plastics.

Some of the limitations of ultrasonic welding are part size, part design constraints and possible part damage. Part size limitations are caused by the fact that the horn size is limited by design constraints. Here, the horn is defined as the tool that makes contact with the part and delivers the ultrasonic energy. Because the horn must be designed to resonate at the ultrasonic welding frequency, there are physical limitations to its size. Failure to consider these limitations during the design phase of the horn may cause undesired modes of vibration to develop that can lead to horn failure and/or poor welding. In addition to these limitations, the process and tools must be adapted to the materials to be welded. For example, amorphous materials tend

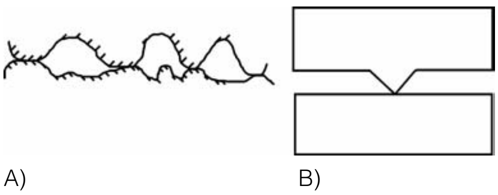


Fig. 11. Ultrasonic heating through cyclical deformation of (A) Surface asperities and (B) Man-made energy directors

Process variable	Description
Amplitude	Motion of horn at horn/part interface
Weld time	Length of time sonics are activated
Hold time	Time parts are held under force after sonication
Ramp time	Length of time the sonic ramp up during a weld cycle
Weld force	Amount of force applied to part
Trigger force	Force at which sonics are activated
Melt down/collapse	Amount of weld down during weld
Mode	Primary process variable that defines weld cycle; such as time, energy, melt down, or peak power

Table 3. Process parameter for ultrasonic welding

to attenuate the ultrasonic energy less compared to crystalline materials; thus, they are typically easier to weld. In addition, applications fabricated from a crystalline material tend to be limited to near field (defined below) ultrasonic welding. One of the reasons that crystalline materials tend to be more difficult to weld, is that they have a narrow transition temperature range. For example, some amorphous polymers such as polystyrene or ABS are relatively easy to weld because they have high energy dissipation or conversion of the ultrasonic energy into heat. In addition, amorphous polymers are generally easier to weld in far-field than semicrystalline polymers. One of the reasons that semicrystalline polymers tend to be more difficult to weld, is that they have a narrow transition temperature range. For example, during ultrasonic welding of these materials, any local region outside the weld zone that heats due to localized stress also experiences an increase in the loss modulus. This promotes local energy dissipation, which accelerates the heating. Once the melt temperature is approached (T_m), the mechanical properties rapidly decrease thereby preventing ultrasonic energy from being transmitted through this softened region and being delivered to the weld zone. In contrast, amorphous materials have a relatively wide transition in properties near the glass transition temperature (T_g). Therefore, they do not experience this rapid change in mechanical properties and tend to be less effected by local stresses. These local stresses can be the result of part design as well as asperity deformations.

Ultrasonic welding is usually divided into two major groups: near-field and far-field welding. Current industry practice, which is based on the most extensively used 20 kHz welding system, considers applications where the distance between the horn/part interface and the weld interface is less than 6 mm to be near-field welding. Far-field ultrasonic welding is used to describe applications where that distance is greater than 6 mm. At 20 kHz, the wavelength in the plastic component ranges between 6 and 13 cm depending on the specific polymer. Therefore, during near-field ultrasonic welding, the vibration amplitude at the weld interface is close to the amplitude at the horn face. For far-field welding, the amplitude of vibration at the weld interface depends on the ultrasonic wave propagation in the parts. Some of the key parameters for ultrasonic welding are detailed in Table 3.

Beyond simply welding plastic components, ultrasonic energy can be used to insert metal threaded bosses or other components into a thermoplastic part (ultrasonic insertion). When joining two dissimilar thermoplastics, which are not weldable, or when joining thermoplastic components to a second material such as metal, ultrasonic staking can be used. Ultrasonic swaging is similar to ultrasonic staking except that the profile is often larger and does not have a final appearance of a rivet. Ultrasonic swaging is used in a variety of applications, e. g., to reshape the end of thermoplastic tubes or rods to a desired shape for connection with a coupler. Ultrasonic energy can also be used for many other applications, including machining, cutting, sewing, degassing, separation of solids from liquids, nondestructive inspection, imaging and more [29].

Fig. 12. Example of application joined/sealed with ultrasonics (Courtesy Branson Ultrasonics Corp.)

Fig. 13. Example of hermetic seal made with ultrasonic welding from a semi-crystalline material (Courtesy Branson Ultrasonics Corp.)

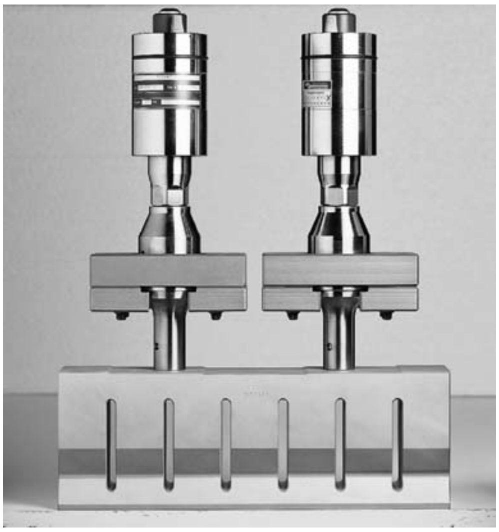


Fig. 14. Photograph of bar horn driven by multiple converts (Courtesy Herrmann Ultrasonics)

5.2 Ultrasonic Welding Applications

Because of its popularity, a large number of applications are assembled with ultrasonic welding, ranging from food packaging, computer components, consumer packaging (so-called blister) to continuous applications, such as feminine pads that are cut and sealed with ultrasonics, see Fig. 12.

One of the more challenging and critical applications on the market is the standard disposable butane lighter. This application is molded from a semi-crystalline material (acetal), a material that is relatively difficult to join with ultrasonics. Here, the bottom of the fuel container is sealed, thus the weld must be hermetic, strong, and the process must be robust so that there are no in-field failures, see Fig. 13.

5.3 New Ultrasonic Welding Technologies

In original power supply designs, it was critical to tune the electrical components to the resonant frequency of the mechanical system (horn, booster and converter). Because the resonant frequency often changes slightly with time as a result of heating and coupling of the parts to the stack during a weld cycle, it is often difficult to find a single frequency that allows the system to operate properly during the entire weld cycle. In newer systems, the power supplies are not only able to self-tune on start-up, but they track the frequency even during a single weld cycle with no intervention from the operators. In addition, new power supplies have the ability to change the amplitude through digital controls. This allows the operator to modify the welding amplitude without the need to disassemble the stack and change the booster. Prior to the implementation of this technology, the amplitude was determined by the mechanical gain of the booster and horn. In this case, the booster either amplifies or de-amplifies the vibration amplitude from the converter, which is the linear motor that converts electrical signals to mechanical motion, and transmits it to the horn. It is important to note that by changing the amplitude electronically, there is usually a reduction in the maximum power capacity of the power supply. For example, if the amplitude is set to 50 % of the full amplitude, the power supply can only deliver only 50 % of its rated power. This is often not an issue, since the power/unit volume dissipation of a typical plastic weld is governed by Eq. 7.

$$Q = \frac{\omega A_0^2 E''}{2}. \tag{7}$$

In this equation, the Q is the internal heat generation (W/m^3), ω is the welding frequency in radians/s, A_0 is the amplitude and E'' is the loss modulus of the plastic (which is frequency (ω)- and temperature-dependent). Thus, by reducing the amplitude (A_0) by 50 %, the power dissipated by the application will be reduced by a factor of 4. It is possible to estimate the power (P) dissipated during welding by multiplying the volume of energy director by Q. By assuming that the heat flows equally in both directions over the cross section area of the energy director, it is possible to calculate the heat flux $\dot{q}_0$ by dividing the power by the total weld area. Building on this further, it is possible to then use Eq. 4 to estimate the degree of healing based on experimentally determined coefficients.

Further building on temperature histories and the degree of welding, it has also been shown that varying the amplitude during welding can also improve the weld quality. For example, by reducing the amplitude (amplitude profiling) at the end of a weld cycle, there is a reduction in heating and shear thinning with amorphous materials, increasing weld strength and reducing weld flash [30]. In addition, because of the reduced shear thinning there is an increase in the degree of healing of the weld interface caused by increased molecular mobility. A similar approach using force profiling can increase weld strength in crystalline materials [31]. Amplitude profiling is less effective with crystalline materials because their viscosities are less temperature-dependent compared to amorphous materials.

Recently, newer converters can produce as much as 6 kW at 20 and 15 kHz, and therefore power limitations are less of an issue. This allows larger applications to be welded. In addition, multiple converters can be ganged together in parallel to drive a single horn, allowing even greater power capabilities [32], see Fig. 14.

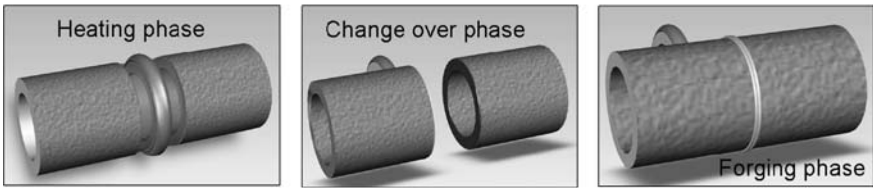


Fig. 15. Basic steps in the IR/Laser surface heating mode of welding

It has also been shown that improved consistency of weld quality is possible by using digital displacement-encoders and servo-driven actuators that can vary the weld force and travel distance. This has also allowed the development of clean-room friendly actuators [33]. Other actuator designs use stepper motor drives [34]. Displacement control of the stack has also been improved over the last few years by use of rigid mount boosters. In the past, the clamping ring (a ring located at the nodal point) of the booster decoupled the stack from the pressure actuator assembly with rubber O-rings. This decoupling allows the booster to be held without dissipation of the vibrations into the pressure actuator assembly. However, the O-rings allowed deflection and caused inconsistency between welds [35]. In applications where this can present a problem, specially designed boosters replace the rubber O-rings with metallic deflection springs that greatly reduce deflection thereby reducing the inconsistency between welds.

Many manufactures incorporate built-in SPC (statistical process control) features as well as self diagnostics that communicate automatically to the manufacturer via the Internet [36] when maintenance is needed or to prevent power supply failure.

6 Laser/IR Welding

6.1 Process Description of Laser Welding

While laser welding of plastics has been reported as far back at the late 60's [37], it has only become popular in the last decade, primarily due to the significant reduction in cost for laser energy. The current market prices for lasers is less than 10 \$/W, compared to 1000 \$/W just a decade ago. There are two basic modes of IR/laser welding [1]:

- Surface heating.
- Through Transmission Infrared (TTIr) welding.

While much less common surface heating can be used to weld subassemblies. Surface heating is very similar to heated tool (plate) welding as shown in Fig. 15. The surfaces of the components to be joined are heated by direct IR/laser exposure for a sufficient length of time to produce a molten layer, usually for 2 to 10 s. Once the surface is fully melted, the IR/laser tool is withdrawn from between the parts, the parts are forged together, and the melt is allowed to solidify. The heating source must be continuous thus either the laser/IR source must be achieved through continuous illumination or high speed scanning. That is to say, because surface heating relies on residual heat and melting at the faying surfaces, slow-speed scanning is not possible. For example, high-speed scanning can be used to build up a sufficient melt layer. In this case, the beam is can be split with a mirror to illuminate both parts simultaneously, as seen in Fig. 16. The rotating mirror usually dithers back and forth to direct the beam from one secondary mirror to the other. In addition, it is possible to rotate the secondary mirrors to increase the width of the heated area.

TTIr welding is based on the concept of passing IR/laser radiation (typically with wavelengths (λ) between 800 to 1100 nm) through one of the components to be welded while having the second component absorb the light at the interface (see Fig. 17). This absorption results in heating and melting of

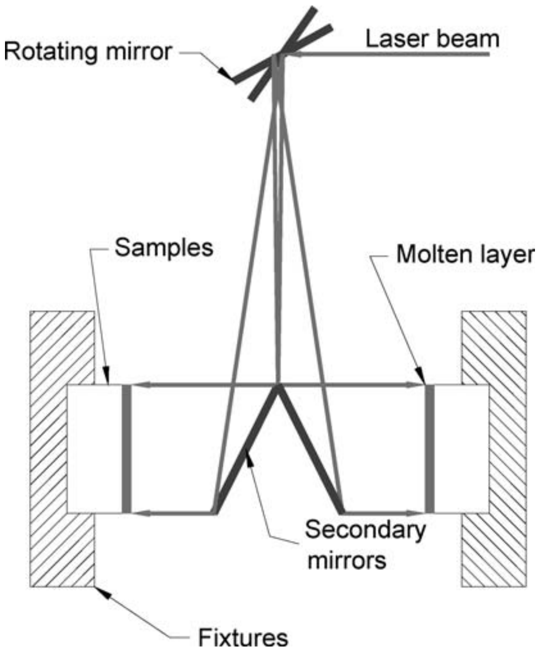


Fig. 16. Surface heating via scanning

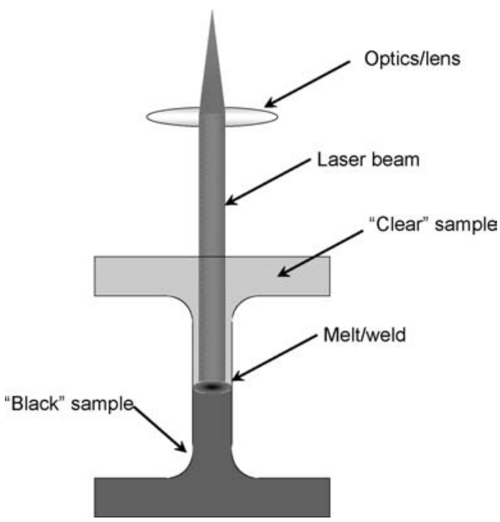


Fig. 17. TTIR welding of plastics

the interfaces and allows the parts to be welded. TTIr welding is used for such applications as automotive lamps and medical components. It is well suited for applications that require hermetic seals with minimal marking and low flash/particulate generation. In terms of laser welding of plastic, it is currently the most popular mode of operation, because it offers several additional benefits compared to surface heating. For example, it is a pre-assembled method. This means that the parts are placed into the machine in the same position and orientation as the final assembled position. For many applications this is critical to allow sub-components to be held in place during the welding process without complex fixtures.

Other benefits of TTIr include speed and flexibility. A typical cycle time ranges between 1 and 5 s, which is similar to vibration welding and much shorter than hot plate welding. The process can also weld unsupported internal walls with complex curvature if the optical properties allow illumination of the faying surface by IR/laser radiation. Applications with this type of geometry can be difficult to weld with vibration welding, a process that is considered relatively fast with cycle times of less than 10 s. Possibly one of the most important advantages of the TTIr process is weld quality. Because the process is non-invasive, the parts typically have excellent cosmetic properties. In addition, there are no excitation vibrations or large heated platens and only the weld area is heated and modified/melted.

One limitation of TTIr welding is material suitability. One of the components must be relatively transparent to the IR radiation. Since most systems on the market use a wavelength between 800 and 1100 nm, most unfilled polymers tend to be transparent. However, crystalline polymers, such as PE and PP, tend to promote internal scattering of the radiation. This often limits the “transparent” part to a thickness of less than 3 to 5 mm with scattering materials. In addition to requiring that one part is transparent to the radiation, the other part must be absorbent. Usually this is accomplished by the addition of carbon black or an IR absorbing dye. As previously mentioned, part fit up can be critical for some laser welding applications. In some cases small voids can be welded or sealed as a result of thermal expansion as the plastic heats and melts without melt down. The size of the void that can be fully welded or sealed depends on the welding parameters as well as on material properties, such as the coefficient of thermal expansion (CTE). It is has been reported that there is a significant loss in weld strength with defects as small as 0.25 mm [38] with crystalline materials. It should be noted that smaller gaps may be filled depending on the welding parameters, material and joint design. The allowable gap must be determined for each application experimentally. In some cases the limited melt down, such with slow speed scanning, can be an advantage because it reduces the amount of flash produced. For example, with micro fluidic or sensing devices, displacement or collapse of the substrates is not tolerated, as it will affect the fluidic channel size or final part height. Inherent to the slow speed scanning technique is the benefit of a built-in mechanical stop in the material that is not heated, providing identical and consistent stack heights before and after the welding process. There are four methods of introducing laser energy for TTIr, slow speed scanning, high speed scanning, continuous illumination [39] and mask welding.

The slow speed scanning technique involves translating an IR/laser source across the faying surface. This approach usually involves locating the parts in a fixture and translating the IR source with a robotic arm or similar type of automation. One of the main advantages of this approach is that a single welding machine can be easily re-programmed to weld a variety of part geometries. However, one limitation of this approach is that for TTIr welding the faying surfaces must be in intimate contact, because, as the IR source translates around the circumference of the part, the faying surface is only locally heated (see Fig. 18). Thus, unless the parts are compliant and can be locally deformed to force the faying surfaces together, any gaps between the faying surfaces can result in voids or weak welded regions. Gaps between the two parts can be the result of molding warpage, molding shrinkage, ejector-pin indentations, or variations in the mold cavities.

An alternative mode of slow speed scanning uses a light source/laser that is translated around the part at a high velocity so that the beam returns to any given point before the material is allowed to solidify. This allows for the entire faying surface to be melted during the weld cycle. Unless the part is relatively small, the minimum scanning rate requires the beam to be translated with galvanic mirrors or a very fast robotic system. If galvanic mirrors are utilized, the IR source is usually limited to a collimated laser source, such as YAG lasers (yttrium-aluminum garnet), in order to keep the beam collimated as it reflects off the mirrors. For TTIr welding, this mode has the advantage that melt-down or collapse is possible. Thus, virtually any defect size can be welded or sealed with the proper amount of melt-down. It also retains the benefit that a single welding machine can be easily re-programmed to weld a variety of joint geometries. If galvanic mirrors are used, the application must be relatively planar so that the beam can be translated around the part without being blocked by the part itself or by appendages, also known as “shadow” areas. That means that the part geometry must allow for the entire faying surface to be illuminated from a single point with the rotating mirrors. The typical diameter of an independent beam ranges from 0.6 mm to

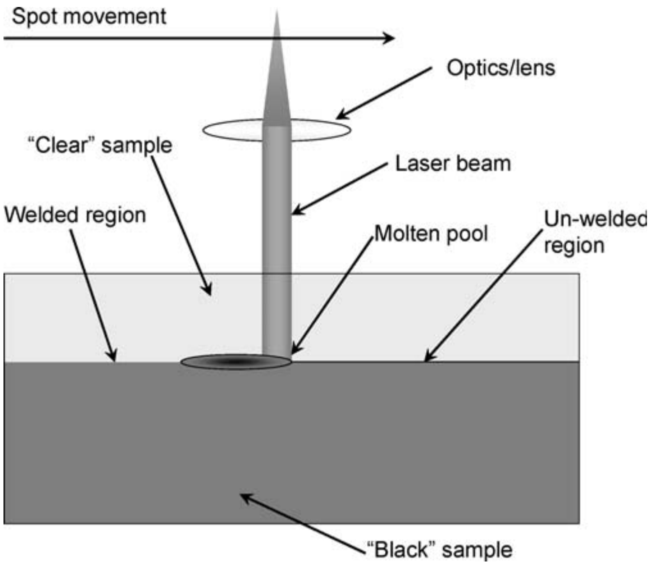


Fig. 18. IR/laser scanning and localized heating

2.6 mm, which allows the welding of intricate patterns as shown in Fig. 19. A basic square, circle, rectangle, or other contour can be sealed with travel speeds ranging from 10 to 50 mm/s. Multiple banks of laser heads can be used concurrently, allowing for batch processing and higher production speeds. When welding a square pattern, or any pattern with sharp turns or bends, the heating of the plastic in the corner or sharp contour areas will be higher. Proportional Integral Differential (P.I.D.) control can be utilized with the single beam method to control or reduce the intensity of the light as the beam passes over the intricate corners or contours. This can eliminate over-welding in condensed weld areas and ensure an even weld width throughout the weld pattern.

In the continuous illumination mode, there are numerous IR sources illuminating the entire faying surface during the weld cycle (see Fig. 20). As with high-speed scanning, for TTIr welding, part tolerance and fit-up are not as critical since melt-down is possible. In addition, complex geometries can be welded without the limitation of shadow areas and there are no problems with "run-on/run-off", which is defined as regions where the weld is started and stopped. These regions represent transition zones and often contain defects because of the transitions.

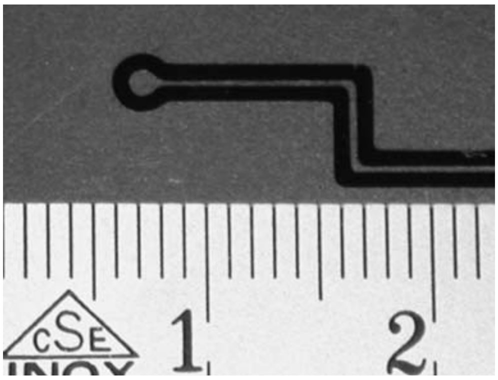


Fig. 19. Typical weld with scanning (Courtesy Leister Corp.)

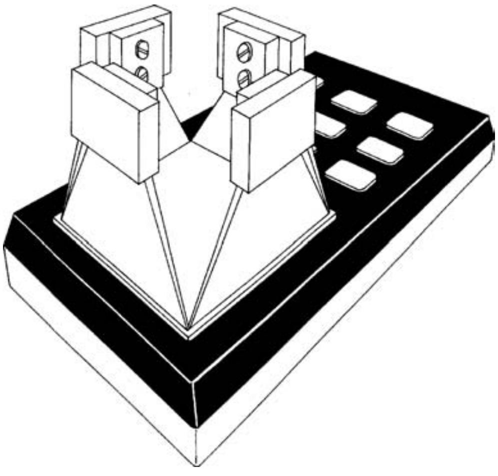


Fig. 20. Continuous illumination with IR welding (Courtesy Leister Corp.)

A fourth possible heating mode for TTIr is mask welding. This technique utilizes a typical continuous illumination curtain of light that is passed over a mask that blocks portions of the light, allowing only the pre-specified areas to melt and seal. An example of this method is shown in Fig. 21. This method is especially suited for complex, micro structure areas. With this method, micro welds as narrow as 100 μm can be achieved (Fig. 22). The correlation of light intensity, clamping force, and travel speed (the speed of the laser passing over the mask or the mask assembly passing under the laser) controls the amount of melt and edge definition.

Because of the large array of possible heating modes, it is not practical to list the key parameters for IR/laser welding,

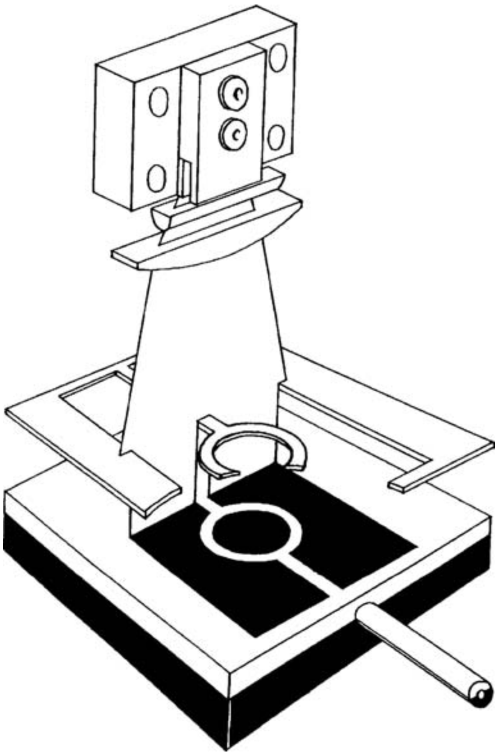


Fig. 21. Example of TTIr mask welding (Courtesy Leister Corp.)

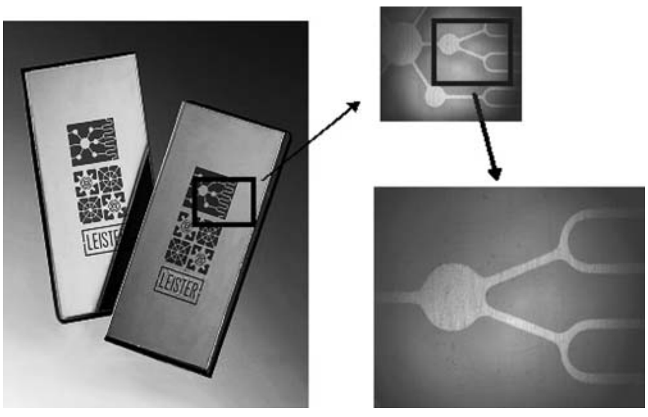


Fig. 22. Example of micro welds with TTIr mask welding (Courtesy Leister Corp.)

but some of the common parameters include, laser power (W), energy density of delivered laser power (W/m^2), wavelength and wavelength distribution, laser spot size and geometry, cycle time and clamp force.

As with the many welding technique it is possible to predict weld quality based on thermal models and interfacial healing. For example, if continuous or simultaneous welding is used, it is possible to calculate a heat flux $\left(\dot{q}_0 = \frac{P}{A}\right)$ based on the laser power (P) and total weld area (A) for <u>both</u> parts. By using Eq. 6, it is possible to estimate temperature fields within the welded components as a function of time; in addition, and Eq. 4 can be used to predict weld quality. Additional heating models that can be used are detailed in other articles [40, 41].

6.2 Laser Welding Applications

Because of the relative newness of the process there are a limited number of applications that use laser welding. In addition, because of the novelty, most users are hesitant to disclose their technology. However, some of the commonly known application that use laser welding are brake fluid reservoirs, ink jet cartridges and automotive marking lights. The main driving force for selecting laser welding for most of the applications is the lack of particulate generation. For example, with anti-locking brake systems (ABS), now a standard option on many new cars, it is critical that the reservoir does not contaminate the fluid with dirt or particulates often associated with friction welding processes that would lead to ABS failure. This is true for many micro-fluidic systems including bio-medical applications.

6.3 New Laser Welding Technologies

With the introduction of laser welding, the main technology developments are mostly related to laser energy delivery. For example, in early systems, a laser spot was directed and the faying surface and the beam was translated around the weld joint. However, by using light guides, multiple laser sources can be coupled together so that the entire surface is illuminated simultaneously, see Fig. 20.

In addition, it has been shown that by using diffractive optics, it is possible to reshape a spot into complex shapes (Fig. 23) [42] and even resize these shapes with standard optics to make micro welds. In Fig. 24, a circular pattern is welded with a resized diffractive image to make a weld with a width under 100 μm, and a circular pattern with a diameter of less than 300 μm [43].

It has also been demonstrated that TTIr laser scanning and clamping can be completed with a single head design which incorporates a rotating sphere acting as a lens as well as a pressure/force applicator, see Fig. 25. This technique has been labeled "Globo Welding" [44] and has the advantage that the laser and the applied pressure are inherently coaxial and the process is well suited for robotic applications where complex weld geometries can be followed.

Other newly developed aspects related to laser welding are dyes and pigments. IR dyes are available to make transparent parts appear black [45]. In addition, highly absorbing IR dyes were used to make clear parts absorb laser radiation. This allowed clear-to-clear parts as well as black-to-black parts to be welded. More recently, newer dyes are being developed that are increasingly thermally stable, allowing higher temperature materials to be welded with these configurations [46]. There are even dyes that are specifically wavelength sensitive so that

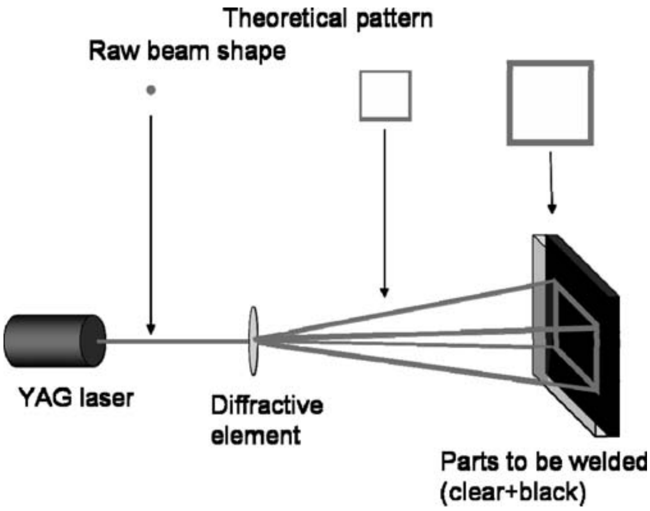


Fig. 23. Setup for welding with diffractive optical elements

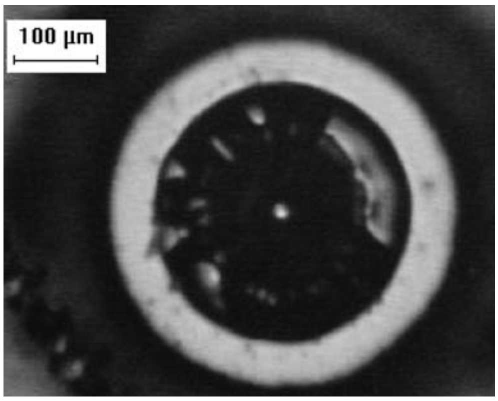


Fig. 24. Micro weld made with laser

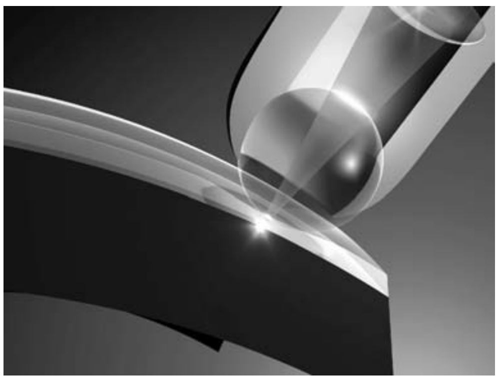


Fig. 25. Cartoon showing "Globo" welding (Courtesy Leister Corp.)

multiple wavelength sources can be used to weld multiple planes simultaneously.

Other developments include closed-loop feedback based on bondline temperature as well as intensity [47]. In addition, IR-assisted staking is also becoming common place [48].

7 RF Welding

7.1 Process Description of RF Welding

Radio Frequency (RF) welding, which is also often referred to as "dielectric welding" is a process that relies on internal heat generation by dielectric hysteresis losses in thermoplastics with polar side groups. In a rapidly changing electric field these polar groups try to orient themselves in the field resulting in intermolecular friction and heat generation. It is most commonly used to weld PVC bladders, such as intravenous drip bags for the medical industry. It is also used to weld books and binding covers. RF welding has the advantages that it is a relatively fast process with typical cycle times ranging from less than 1 s to 5 s. It also does not require any special joint designs and produces welds that are relatively appealing cosmetically.

RF welding is almost exclusively used for welding thin sheets or films. Thickness usually ranges from 0.03 to 1.27 mm (0.001 to 0.050 in), depending on the material and application. The limitation of welding films is due to the fact that a strong electric field must be generated and this can only be achieved when the welding electrodes are brought together in close proximity (0.03 to 1.27 mm). If the welding electrodes are significantly further apart, the electric field density is too low to effectively heat and melt the plastic. Another limitation of the process is that the materials being joined must have the proper electrical properties. One such property is a relatively high dielectric constant, typically > 2. This allows more current to flow through the material, which promotes heating at a lower electrode voltage. The other major material restriction for RF welding is that the material must have a relatively high dielectric loss. The basic concept relies on applying a relatively high electric field across the films to be joined. The electric field is concentrated by using raised electrodes adjacent the faying surfaces, Fig. 26A. The electrodes are connected to a high voltage, high frequency power (27.12 MHz) supply that is tuned to match the electrical impedance of the weld.

In many applications, the welding die or electrode trims or cuts the film/sheets to the final shape in addition to sealing them, see Fig. 26B. However, since the electrodes, even at the cutting edge, cannot be allowed to make contact while the electric field is applied (to prevent machine damage), there is usually a small amount of material remaining at the toe of the weld. The operator must tear the parts along this section of the weld. Some of the key parameters for RF welding are detailed in Table 4.

7.2 RF Welding Applications

As previously noted, all RF welded applications consist of welding relatively thin plates or films. In addition, the material must have relatively high dielectric loss, making PVC the most common material used. Common applications include blister packs for packaging (Fig. 27A) and medical applications (Fig. 27B). It is important to note that some applications, such as water bed mattresses, are relatively large.

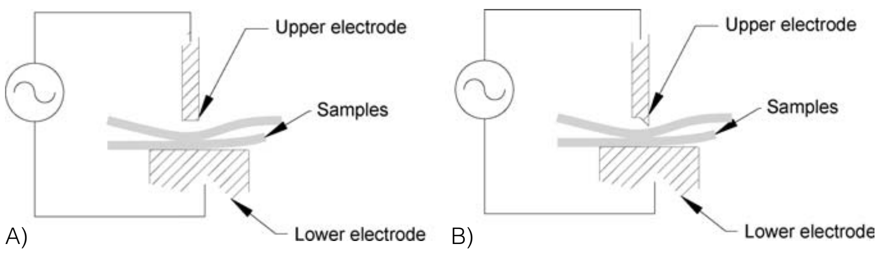
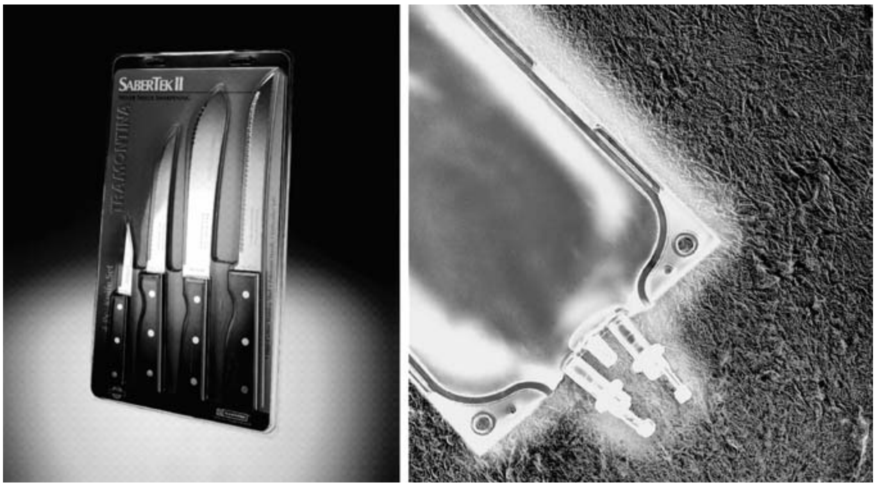


Fig. 26. Configuration for (A) Sealing and (B) Cut and seal

Process variable	Description
Voltage	Voltage at the electrodes
Frequency	Frequency of applied electric field
Hold time	Time parts are held under force after sonication
Material properties	Dielectric constant
Weld force	Amount of force applied to part
Electrode separation	Initially the thickness of materials and at end of weld cycle is the distance between electrodes

Table 4. Process parameter for RF welding



A) B)

Fig. 27. (A) Photograph of RF sealed blister package (B) RF sealed IV medical bag (Courtesy Alloyd Co.)

7.3 New RF Welding Technologies

Historically, RF welding has been limited to materials that have an inherently relatively high dielectric loss; however, recently, additives and consumables have been developed that allow even non-polar materials to be sealed with RF welding [49]. These additives can either be added to the faying surface locally as a film or compounded into substrates.

Other improvements include machine designs with automatic tuning of the power supply, which even tracks the changes in electrical impedance during the weld cycle as the gap between the electrodes change due to melt down during the welding cycle [50]. Other improvements include automated and quick change-over of tooling [51].

8 Hot Gas/Extrusion

8.1 Process Description of Hot Gas/Extrusion Welding

Hot gas welding is a process where heated gas or air is used to heat and melt base material as well as a filler (weld) rod that is pressed into the joint. It is a very flexible process which makes it well suited for short-runs or prototype welding of small items or for welding of large structures or tanks. Hot gas welding can be performed manually, in speed welding modes and automated modes. As shown in Fig. 28, in a manual operation, pressure is applied by pushing the weld rod into the joint area by hand. In speed welding, a tip with a pressure shoe or tongue is used to apply pressure enabling higher welding speeds. Automated welding is performed using custom equipment and is designed specifically for each application.

The filler rod should be made from the same material as the parts that are to be welded. Usually, the filler rod has a round cross-section, but it is also available in oval, triangular and rectangular cross sections. Like in metal welding, for large joints, multiple passes are used to fully fill the cavity. In some cases it may be desirable to use a small filler rod for the first pass to ensure complete penetration and then use larger rods for subsequent passes.

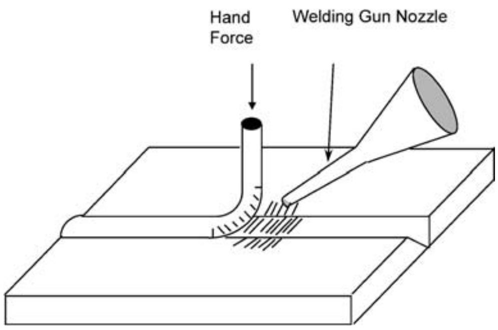


Fig. 28. Manual hot gas welding

Extrusion welding is very similar to hot gas welding except that the surface of the base material is heated by hot gas while the filler rod is extruded into the cavity. A welding shoe on the extruder is used to apply pressure. It is used in tank and pipe construction, welding of sheet liners, and sealing of geomembranes. Depending on the application, pellets or filler rod are fed into the extruder. The extrusion screw, which is turned by an electric motor, propels the pellets into the barrel, where they heat and melt. The melt is then extruded into the cavity. The welding shoe is attached to the nozzle of the extruder. It is used to apply pressure while keeping the extrudate from squeezing sideways out of the cavity. To minimize sticking and reduce friction, the welding shoe is either made from or coated with PTFE. Two types of extruders are used. For larger extrusion rates for welding of thicker sheets, a stationary extruder on wheels with a movable welding shoe is generally used. For smaller extrudate volumes and thinner sheets, a hand held extrusion welder is used. Hand held extruders are generally fairly large and heavy and they can be cumbersome to move. Some of the key parameters for hot gas and extrusion welding include are detailed in Table 5 and 6, respectively. It is seen that there are less variables with extrusion welding and thus extrusion welding is relatively easy to perform and tends to be more automated and consistent compared to hot gas welding.

Process variable	Description
Temperature	Temperature of hot gas existing nozzle
Gas	Composition of hot gas (Air or N)
Angle	Include angle between weldment and rod
Travel speed	Rate at which weld is being deposited
Weld force	Amount of force applied to filler rod
Filler rod	Composition of filler and diameter
Shoe	Design and size of welding nozzle

Table 5. Process parameter for hot gas welding

Process variable	Description
Temperature	Temperature of melt existing nozzle
Travel speed	Rate at which weld is being deposited-primarily controlled by extrusion rate
Extrusion rate	Rate at which material exist nozzle
Weld force	Amount of force applied to filler rod
Filler rod	Composition of filler, diameter geometry (rod or pellets)
Shoe	Design and size of welding nozzle

Table 6. Process parameter for extrusion gas welding

8.2 Hot Gas/Extrusion Welding Applications

Because hot gas welding is a relatively slow manual process, it is not used in mass production, such as parts for consumer products. However, because it can be easily tailored to work with large parts (over 3 m is size, see Fig. 29) with nearly any geometry, it is used to fabricate pipelines, pond liners, and a wide variety of vessels. Interior support sections for scrubbers are one popular application for hot gas welded thermoplastics. Wet benches for computer chip manufacturing and other equipment utilized in clean-rooms, where metallic construction is not suitable, require considerable hot gas weldments.

Fig. 29. Example of tanker container assembled with hot gas welding

8.3 New Extrusion and Hot Gas Welding Technologies

Most of the new developments in the area of extrusion welding are related to equipment design. For example, servo and DC motors are used to drive the extrusion screw making the extrusion more controllable and smoother. There are also hydraulic driven systems that can be operated continuously [52]. In addition, non-destructive evaluation (NDE) methods have been evaluated to confirm weld quality. NDE is critical for these processes because they are manual and operator skill can greatly affect weld quality and thus weld quality can only be assured through NDE testing. For example, ultrasonics has been used to measure melt thickness in real time as well as for post-weld evaluation [53]. Conventionally, high-voltage spark testers have also been used to evaluate welding quality.

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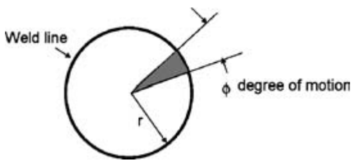
Appendix



Consider an angular friction welding of thin walled tubes where the velocity variation through the wall can be neglected. Based on the above notation of angular welding the distance (d) travel at some point in the middle of the weld is:

$$d(t) = r\frac{\phi}{2}\sin(\omega t).$$

It is important to note the peak-to-peak angular amplitude (φ) is divided by 2 to give the amplitude for the sinusoidal displacement function. Thus, the instantaneous velocity (v) is:

$$v(t) = r\omega\frac{\phi}{2}\cos(\omega t).$$

Therefore, the instantaneous heat flux that is generated at the interface for a constant friction coefficient f is,

$$q = \tau(t)\,|v(t)| = fp_0 r\omega\frac{\phi}{2}|\cos(\omega t)|.$$

Where, $\tau(t)$ is the shear stress at the interface and p_0 is the normal or clamping pressure. The average heat flux is then determined by averaging over a quarter of the period (T),

$$q_0 = \frac{4}{T}\int_0^{T/4} fp_0 r\omega\frac{\phi}{2}\cos(\omega t)\,dt$$

$$= fp_0 r\omega\frac{\phi}{2}\left(\frac{2\omega}{\pi}\right)\int_0^{\pi/2\omega}\cos(\omega t)\,dt = \frac{fp_0 r\omega\phi}{\pi}.$$

Similarly one can average the instantaneous velocity over a quarter of a period giving,

$$v_{avg} = \frac{4}{T}\int_0^{T/4} r\omega\frac{\phi}{2}\cos(\omega t)\,dt = r\omega\frac{2\omega}{\pi}\int_0^{\pi/2\omega}\cos(\omega t)\,dt = \frac{r\omega\phi}{\pi}.$$

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