Microwave Welding

PROCESS

Microwave welding uses high frequency electromagnetic radiation to heat a susceptor material located at the joint interface; the generated heat melts thermoplastic materials at the joint interface, producing a weld upon cooling. Microwave welding is a type of electromagnetic welding, in addition to induction welding and radio-frequency welding, but uses much higher frequencies - 2 to 10 GHz. [575]

Heat generation occurs in microwave welding through absorption of microwave energy by susceptor materials that contain polar groups as part of their molecular structure or that are electrically conductive. In an applied electric field, polar groups align in the field direction. In a microwave, the magnitude and direction of the electric field changes rapidly; polar molecules develop strong oscillations as they continually align with the field, generating heat through friction. [599]

Polyaniline (PAN) doped with an aqueous acid such as HCl is used as a susceptor in microwave welding. Doping with dilute aqueous acid introduces polar groups into the molecular structure and makes the material electrically conductive by providing free moving electrons. The amount of heat produced during welding is dependent on the conductivity. If the material is not conductive enough, mobility of free charges is low and very little heating occurs. If conductivity is too high, microwave energy is reflected, not absorbed, so that no heating occurs. PAN is an “A-B” type polymer with a conductivity ranging from that of an insulator to 400 S/cm, depending on the doping material used. For welding thermoplastics, acid-doped PAN powder and a thermoplastic material is compression molded into a gasket that is placed at the joint interface. Heat introduced during compression molding vaporizes some of the acid in the PAN powder, resulting in a loss of dopant. The conductivity of the gasket is therefore much lower than that of the PAN powder, and microwave absorption by the gasket is reduced. Bulk material in the parts being joined is not affected by microwave heating unless the molecular structure includes polar groups. [575, 599]

Absorption of microwave energy in polar, conductive materials is dependent on the conductivity (σ) of the material, the dielectric constant in a vacuum (ε_0), the frequency of the radiation (ω), the imaginary part of the dielectric constant (ε'') which accounts for dielectric loss through energy dissipation, and the real part of the dielectric constant (ε') which represents the ability of the material to store electrical energy: $\tan \delta = (\sigma / \varepsilon_0 \varepsilon \omega) = (\varepsilon'' / \varepsilon')$. Tan δ is the loss tangent, a measure of the ability of the material to absorb microwave energy. [599]

The dielectric constant and conductivity of polyaniline are a function of the radiation frequency, PAN temperature, and doping level. At low doping levels, microwave conductivity of PAN in an alternating current field is higher than direct current conductivity. Conductivity increases as the PAN temperature increases from 60^{o}C to 300^{o}C, and increasing doping levels increases the conductivity of the gasket. The form of PAN affects its conductivity: stretched films have higher conductivity than unstretched films and pellets. The conductivity of PAN changes during storage. [599]

The microwave energy dissipated in a material is used to melt the material during microwave welding. The amount of energy dissipated is a function of the electric field strength, frequency, and dielectric or effective loss factors (ε''_{eff}): $\varepsilon''_{eff} = \varepsilon''(\omega) + \sigma / \varepsilon_0\omega$. The average power dissipation in microwave heaters can be calculated from the electric field distribution in the medium: $P_{avg} = 0.5\ \omega\varepsilon_0\varepsilon''_{eff} \int (E^* \ E\ )\ dV$, where E* refers to the conjugate electric field strength and E to the electric field strength. In multimode microwave cavities, the electric field is continually changing, so that calculation of the average power dissipation is difficult. [599]

The microwave welding process consists of four steps. In step I (heat generation), heat is generated in the gasket by absorption of microwave radiation. In step II (heat conduction and melting), this heat is conducted from the gasket to the thermoplastic parts being welded, resulting in melting in the joint area. Flow of the molten plastic occurs in step III (flow and diffusion), resulting in intermolecular diffusion and chain entanglement as the parts come in intimate contact. In step IV (cooling), the microwave power is terminated; flow occurring at the beginning of this stage eventually stops as the weld interface and bulk material solidify. Pressure can be applied throughout the process or just in the cooling stage, to obtain maximum heating and minimize the amount of material squeezed out of the joint. [599, 575]

PROCESSING PARAMETERS

Important processing parameters in microwave welding are the heating time, power level, welding pressure, and percentage of conductive polymer in the gasket. These parameters affect the amount of heat generated and the weld strength. In welding experiments with HDPE bars (0.635 x 0.635 x 5.08 cm; 0.25 x 0.25 x 2.0 in.), gaskets were composed of HCl-doped PAN and HDPE; gaskets composed of 60% PAN had higher loss tangent and conductivity values than gaskets composed of 50% PAN, indicating that the 60% PAN gaskets can absorb more microwave energy and generate more heat than 50% PAN gaskets with the same thickness. Generation of heat depends on total PAN content and not only on %PAN, so that gaskets with a greater thickness have a greater PAN content and produce increased heat generation. The loss tangent was not sensitive to frequency in the range 8.976 to 12.335 GHz for either gasket. Increasing the thickness of film gaskets composed of d,l-camphorsulfonic acid, m-cresol-doped PAN and nylon or increasing the PAN concentration in the gasket increased the heating rate and temperature at the joint interface of nylon 6/6 bars in adiabatic heating. [599, 598]

Higher power levels (400 W to 1800 W in welding HDPE) result in higher temperatures, faster heating rates, and dramatically decreased welding times. Heating time should be carefully controlled in microwave welding; at high power levels, temperatures at the joint interface can exceed 200^{o}C in less than five seconds. In materials containing polar groups, such as nylon 6/6, high power levels or long heating times may lead to overheating and material degradation. Heating rate changes with temperature and decreases at higher temperatures due to a loss of PAN conductivity and a consequent irreversible loss in absorption. [575, 598]

Absorption of microwave energy is influenced by gasket orientation. The conductive gasket responds to the directional electric field generated in the microwave system. PAN-HDPE gaskets and PAN-nylon gasket films with the length placed parallel to the electric field displayed higher heating rates than gaskets perpendicular to the field, due to a greater tangential surface. [598, 575]

Joint strength is affected by changes in processing parameters. Joint strength increased with increased heating times in welding HDPE; at 15 seconds heating time (2400 W power, 1 MPa pressure), joint strength was 96% of that of the bulk material. In nylon 6/6 welds, increasing the heating time from 10 seconds to 14 seconds (at 2000 W, 1 MPa pressure) increased the joint strength from 50% to 87% of the bulk material. In other experiments, increasing the pressure from 0.3 to 0.6 MPa in HDPE welds (50% PAN, 0.5 mm gasket thickness) increased the joint strength and decreased the weld time necessary to attain a particular joint strength.

Increasing PAN concentration increased the joint strength in HDPE and nylon 6/6 welds. With 17.72% PAN (0.05 mm thickness, 2000 W, 10 seconds heating time, 1 MPa pressure), joint strength of nylon 6/6 welds was 97% of the bulk material. Increasing PAN concentration from 50% to 60% in HDPE welding increased heat generation at the joint interface, resulting in a larger molten layer and more melt flow. Melt flow squeezes out more of the gasket from the joint interface, resulting in direct contact and intermolecular diffusion between the two HDPE bars and producing a stronger weld. Photographs of welds produced with intact gaskets and with gaskets that were squeezed out during melt flow are shown in Figure 8.1. [599, 598]

Increasing the PAN gasket thickness from 0.5 to 1.0 mm (0.020 to 0.039 in.) in HDPE welds increased weld strength. Greater heat generation produced a larger molten layer thickness and greater melt flow, which squeezes gasket material out of the weld interface and produces a stronger weld. In nylon 6/6 welds, increasing gasket film thickness beyond 0.05 mm (0.002 in.) decreased joint strength, possibly due to an increased rate of temperature increase in the thicker films that dramatically lowers PAN conductivity. Decreased heat generation produces smaller molten layers and lowered joint strength. [598, 599]

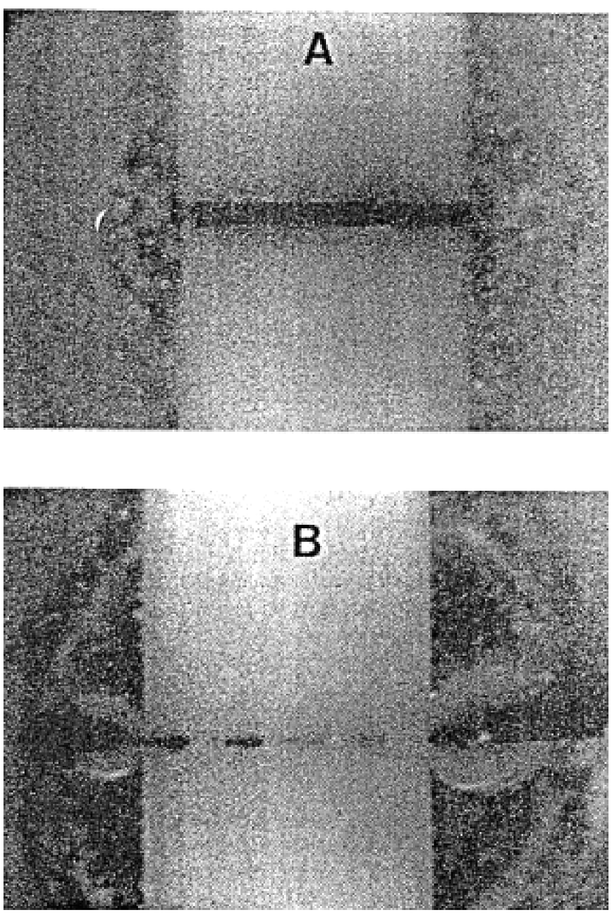

Figure 8.1 Photographs of microwave welded joints. In A, the gasket remained intact after welding; in B, gasket material was squeezed out of the joint during the welding process producing a stronger weld

In addition to effects on joint strength, squeezing out of gasket material affects recycling considerations. Performing the microwave welding process on a microwave welded part generates heat used in disassembling the weld. Disassembling the weld is easier if more conductive gasket material is present in the weld interface when welding is completed. Since joint strength increases as more gasket material is squeezed out, an optimal amount of gasket material remaining in the weld must be determined if recycling considerations are important. Conductivity of the gasket decreases upon reheating. [597, 598]

MATERIALS

Any material that contains polar groups in its molecular structure can absorb microwave radiation. In order to avoid overheating and material degradation, processing parameters and susceptor material must be adjusted. Temperature increases occurred in nylon 6/6 in the absence of susceptor material, especially at higher power levels. Temperature increase at the joint interface was insignificant at 100 W power; joint temperature was only slightly higher than bulk temperature. Temperature increased almost linearly with heating time at 1000 W (to 50^{o}C in 25 seconds) and increased exponentially at 2000 W power, to 180^{o}C in 25 seconds. Control of heating time, with computer control of power levels, is crucial in welding polar materials. [598]

In order to increase film conductivity for welding nylon 6/6, polyaniline was doped with d,l-camphorsulfonic acid in m-cresol solution. The combination of the two dopants increased film conductivity by several orders of magnitude. [598]

EQUIPMENT

Equipment for microwave welding can be as simple as a conventional microwave oven. A more sophisticated, single mode microwave system is shown in Figure 8.2. The microwave power source uses a magnetron to generate 3000 W power at a frequency of 2450 MHz. The power generator is connected to a three-port regulator or circulator which prevents reflected waves from damaging the power source. A four-stub tuner matches the impedance between the source and the load, and a dual power meter located between the circulator and tuner monitors forward and reflected power. Welding is performed in the double-slotted applicator connected to the tuner. A dummy load connected to the applicator converts transmitted energy into heat; water is used in cooling. This system produces a traveling wave pattern used in adiabatic heating. A wave traveling in one direction produces a non-uniform electric field in the applicator. This is an advantage in welding, in which localized heating is preferred; the electric field distribution can be determined for optimal part placement.

For generation of a standing wave pattern, the second power meter and dummy load are replaced by a solid plate to reflect generated waves. A standing wave pattern in a single mode microwave system produces a much higher field strength than a traveling wave pattern as a result of constructive interference of transmitted and reflected waves.

For welding materials containing polar molecular groups, control of power output can be achieved using a digital-to-analog data acquisition board for voltage control. Connection to a pressuring device consisting of a solenoid valve, air cylinder, and relay provides pressure regulation during welding. [598, 575, 599]

ADVANTAGES AND DISADVANTAGES

Microwave welding is a new process currently being developed. Advantages include the ease of disassembly, important in recycling considerations, and the ability to uniformly heat both large parts and multiple disconnected areas of a part simultaneously. The higher frequency used can result in faster heating than in radio-frequency-welding. A disadvantage is that materials containing polar molecular groups can heat up rapidly, causing material degradation if the heating rate and power level are not controlled. [575, 597]

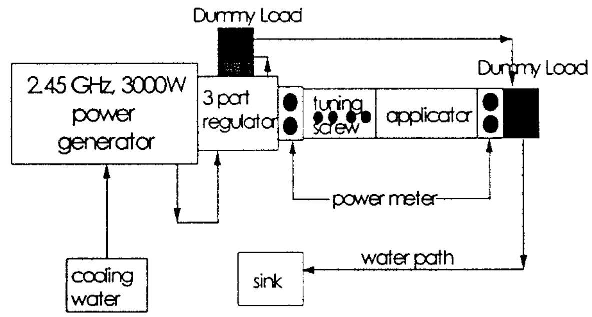

Figure 8.2 A single mode microwave system. A magnetron is used to generate 3000 W of power at a frequency of 2450 MHz. Reflected waves are prevented from damaging the generator by a regulator connected to the power source. A tuning screw matches the impedance between source and load, and a power meter monitors forward and reflected power. Welding is performed in the applicator, and dummy loads dissipate power by converting transmitted energy into heat.