Chapter 1

Heated Tool Welding

PROCESS

In hot tool or hot plate welding, a heated platen is used to melt the joining surfaces of two thermoplastic parts. After the interfaces of the plastic parts have melted, the heated platen is removed, and the parts are held together under low pressure to form a molecular, permanent, and hermetic seal. A hot plate is used for flat joining surfaces; for curved or irregular joining surfaces, complex tools that allow the hot surfaces to match the contours of the joint interface are required.

For accurate mating and alignment, holding fixtures (collets, gripping fingers, mechanical devices, vacuum cups) must support the parts to be joined. The joint surfaces should be clean and relatively smooth to the surface of the heated tool; weld quality is affected if the surfaces are contaminated by mold release agent or grease. Surfaces can be treated mechanically or chemically. For a butt joint weld (Figure 1.1), the two ends must be completely aligned before welding begins. [513, 495, 502]

In hot plate welding, the parts to be joined are pressed against the hot platen; platens can be coated with polytetrafluoroethylene (PTFE) to inhibit melt sticking. Welding can be performed in either of two ways, referred to as welding by pressure and welding by distance. Both processes consist of four phases, shown in the pressure vs. time diagram in Figure 1.2. [552, 521]

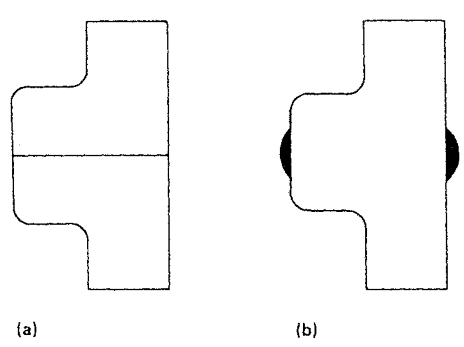

Figure 1.1 A butt joint used for hot tool welding, shown before and after welding.

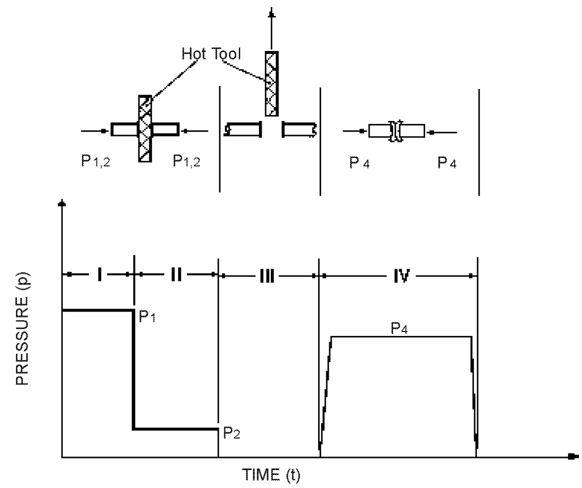

Figure 1.2 Pressure vs. time curve showing the four phases of heated tool welding. Parts to be welded are pressed against the hot tool in phase I, and heat is transferred to the parts by conduction. Melting begins when the melt temperature of the plastic is reached. In phase II, pressure is reduced in order to increase melt thickness. In phase III, the hot tool is removed, and in phase IV, the parts are brought together under pressure to cool and solidify.

In welding by pressure, the parts are brought in contact with the hot tool in phase I, and a relatively high pressure is used to ensure complete matching of the part and tool surfaces. Heat is transferred from the hot tool to the parts by conduction, resulting in a temperature increase in the part over time. When the melting temperature of the plastic is reached, molten material begins to flow. This melting removes surface imperfections, warps, and sinks at the joint interface and produces a smooth edge. Some of the molten material is squeezed out from the joint surface due to thermal expansion of the material. In phase II, the melt pressure is reduced, allowing the molten layer to thicken; the rate at which the thickness increases is determined by heat conduction through the molten layer. Thickness increases with heating time - the time that the part is in contact with the hot tool (usually 1 to 6 seconds).

When a sufficient film thickness has been achieved, the part and hot tool are separated. This is phase III, the changeover phase, in which the pressure and surface temperature drop as the tool is removed. Duration of this phase should be as short as possible (ideally, less than 3 seconds) to prevent premature cooling of the molten material. A thin, solid “skin” may form on the joint interface if the changeover time is too long, affecting weld quality. In phase IV, parts are joined under pressure, causing the molten material to flow outward laterally while cooling and solidifying. Intermolecular diffusion during this phase creates polymeric chain entanglements that determine joint strength. Because final molecular structure and any residual stresses are formed during cooling, it is important to maintain pressure throughout the cooling phase in order to prevent warping. For semicrystalline polymers, recrystallization occurs during this phase; recrystallization behavior is affected by cooling rates. Joint microstructure, which affects the chemical resistance and mechanical properties of the joint, develops during phase IV. [513, 520, 521, 495]

Welding by pressure requires equipment in which the applied pressure can be accurately controlled. A drawback of this technique is that the final part dimensions cannot be controlled directly; variations in the melt thickness and sensitivity of the melt viscosities of thermoplastics to small temperature changes can result in unacceptable variations in part dimensions. [366]

In welding by distance, also called displacement controlled welding, the process described above is modified by using rigid mechanical stops to control the welding process and the part dimensions. Parts are pressed against the hot tool under pressure, but the displacement of the parts as the molten material flows out during phase I is restricted to a predetermined distance using mechanical stops on the hot tool (melt stops) and on the holding fixture (holding or tooling stops). During melt flow, the part length decreases as molten material flows out laterally; when melt stops contact tooling stops in phase II, parts are held in place for a preset time to allow the molten film to thicken. The hot tool is removed in phase III, and mechanical stops are used again in phase IV to inhibit motion of the parts, allowing the molten film to solidify only by heat conduction and not by lateral flow. Cooling time is usually 3 to 6 seconds and ends when tooling stops on supporting fixtures come into contact. Total cycle time for hot tool welding is usually 20 seconds or less. Steps in welding by distance are shown in Figure 1.3. [495, 366, 511]

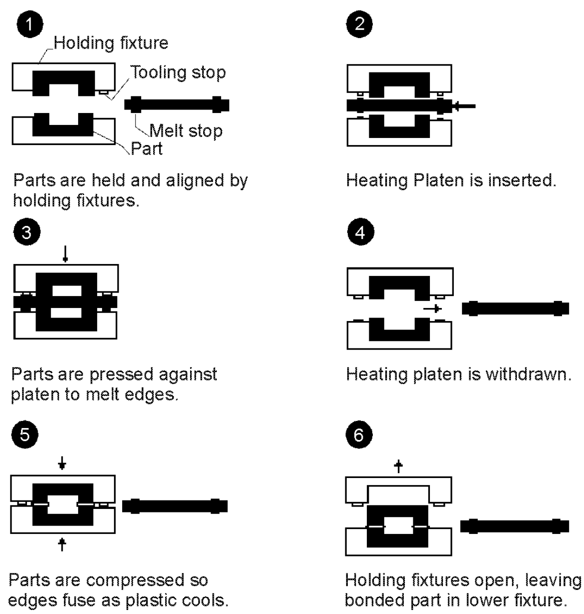

Figure 1.3 The hot tool welding process, showing displacement stops used in welding by distance. In step 1, parts are aligned in holding fixtures; tooling and melt stops are set at specified distances on the holding fixture and heating platen, respectively. The platen is inserted between the parts in step 2, and parts are pressed against it in step 3. Step 3 includes phases I and II of Figure 1.2. Molten material melts and flows out of the joint interface, decreasing part length until melt stops meet tooling stops. Melt thickness then increases until the heating platen is removed in step 4, the changeover phase (phase III in Figure 1.1). Parts are pressed together in step 5 (phase IV), forming a weld as the plastic cools; tooling stops inhibit molten flow. The welded part is removed in step 6.

PROCESSING PARAMETERS

Important processing parameters for hot tool welding are the hot tool temperature during phases I and II, the pressure during phase I (matching or heating pressure), heating time, displacement allowed during heating (heating displacement), melt pressure during phase II, changeover time, pressure during phase IV (weld, joining, or consolidation pressure), duration of phase IV (consolidation time or welding time), and displacement allowed during phase IV (welding displacement). In welding by distance, the parameters should be set so that the displacement (also called the penetration), the decrease in part length caused by the outflow of molten material, is large enough to control part dimensions. Initially in the welding process, there is very little molten flow, and the molten film thickens. The flow rate increases with heating time, eventually reaching a steady state at which the rate of outflow equals the rate at which the material is melting; at this point in welding by pressure, the penetration increases linearly with time. When displacement stops are used, however, the penetration ceases when the melt displacement stops come into contact with the hot tool displacement stops. Until the stops come into contact, the melt will flow out laterally; afterward, the thickness of the molten material increases with time.

Molten layer thickness is an important determinant of weld strength. If the thickness of the molten layer is less than the melt stop displacement, melt stops cannot contact holding stops, part dimensions cannot be controlled, and joint quality is poor due to limited intermolecular diffusion. In addition to contributing to weld strength, adequate displacement in phases I and II compensates for part surface irregularities and ensures that contaminated surface layers flow out before the joining phase. [514]

Melt thickness increases with heating time. For optimal molten layer thickness, heating time should be long enough to ensure that melt thickness is as large as the melt stop displacement. High heating pressures result in larger amounts of squeeze flow; displacement stops may not be reached if too much material is lost by being squeezed out of the joint, and the decreased molten layer thickness produces a brittle weld. If the molten layer thickness is greater than the melt stop displacement, molten material will be squeezed out, producing weld flash and an unfavorable molecular orientation at the interface; this reduces the quality of the joint. [512, 514, 510]

The effect of parameters on weld strength has not been investigated extensively. In experiments with polypropylene, tensile strength increased slightly with heating time (at 260°C, 500 °F) up to about 30 seconds, then leveled off; optimum molten layer thickness was reached, so that further increases in heating time had no effect on weld strength. At higher heating temperatures, weld quality was sensitive to variations in heating time. At 320°C, (608 °F) optimum heating time was 10 seconds; changes in either direction in heating time significantly decreased weld strength. At lower temperatures (200°C, 392 °F) weld strengths were not significantly affected by 30 second variations in heating time. Strength decreased with increased heating pressures (over 0.9 MPa, 131 psi) and decreased with increasing changeover times (0.5 to 3 seconds); the effect of changeover time was greater at heating times of 30 seconds than at 40 seconds. At a 60 second heating time, weld quality improved as changeover time increased to 10 seconds. Lower strengths were obtained when displacement stops were increased from 0.2 mm (0.0075 in.) to 0.4 mm (0.015 in.). Weld strengths increased slightly with increasing weld times, then leveled off at about 25 seconds. Highest weld strengths obtained were about 95% of the neat material. Displacement (penetration) generally increases with increasing temperature and heating time and decreases with increases in changeover time. [518, 510, 513]

High strength welds were obtained with acrylonitrile-butadiene-styrene (ABS). Weld strengths with flash retained were higher than those in which the weld flash was machined off; highest strengths obtained were 95% of neat ABS. Weld strength increased slightly as machine heating temperatures increased from 232°C (450 °F) to 246°C (475 °F) at heating times of 10 seconds; however, at 20 second heating times, temperature increases from 204.5°C to 218.5°C

(400.1°F to 425.3 °F) did not affect weld strength. [514]

Optimal parameter settings are dependent on the materials to be welded. Computer-aided parameter optimization is possible by monitoring the viscosity of the melt zone. [517]

Quality control in production can be implemented by monitoring parameters during the welding process; if one parameter is not within a specified tolerance range, the welding machine either produces a signal or stops the welding process. More sophisticated techniques include statistical process control, in which parameters and melt characteristics are monitored and compared throughout the welding cycle, and continuous process control (CPC), in which optimum parameters are continuously calculated, with the welding machine adjusting conditions as necessary throughout the welding process. [508]

MATERIALS

Hot tool welding is suitable for almost any thermoplastic but is most often used for softer, semi-crystalline thermoplastics such as polypropylene and polyethylene and for thermoplastic polyimides. It is usually not suitable for nylon or other materials with long molecular chains. The temperature of the molten film can be controlled by controlling the hot tool temperature, so that plastics that undergo degradation at temperatures only slightly above the melting temperature can be welded.

Properties of the plastics to be welded affect the strength of the weld. Within a polymer family such as high density polyethylene (HDPE), attainable weld strength may depend on the grade of the polymer and can be related to the structural parameters of melt index and density. Lower melt index polymers produce higher melt viscosities and can tolerate higher heating temperatures without melt sticking to the hot tool. As a result, the size of the heat affected zone (HAZ), the part area affected by heat, can be larger; a larger HAZ produces a higher strength joint. For a constant melt index, increasing polymer density results in joints with lower tensile strength. Higher density polymers have a greater proportion of crystalline regions, which melt in a narrower temperature range than polymers of lower crystallinity. As a result, a thinner HAZ and more brittle welds are obtained. [522]

In hygroscopic materials such as polycarbonate (PC), absorbed water may boil during welding, trapping steam and lowering weld strength. High weld strengths can be obtained by predrying materials; alternatively, processing parameters can be adjusted to compensate for absorbed water. High strength welds can be achieved in dried PC over a wider heating temperature range (250 - 400°C, 482 - 752 °F) than in undried PC (230 - 250°C, 446 - 482 °F). With increasing part thickness, the optimum temperature range shifts to higher temperatures. [521]

Dissimilar materials having different melting temperatures can be welded in hot tool welding; instead of a single platen with two exposed surfaces, two platens are used, each heated to the melting temperature of the part to be welded. Different melt and tooling displacements and different heating times for each part may be necessary, and due to different melt temperatures and viscosities, the displacement of each part will be different. Optimum processing conditions for each material must first be established, followed by optimizing process conditions for welding the two materials together. High strength welds equal to the strength of the weaker material can be achieved. [511]

WELD MICROSTRUCTURE

Weld quality is determined by the microstructure of the heat affected zone of the weld. The heat affected zone consists of three zones in addition to the weld flash. The stressless recrystallization zone consists of crystals with a spherulitic shape, indicating that cyrstallization occurred under no significant stress. This zone results primarily from reheating and recrystallization of the skin layer and the molten layer near the joint interface. The columnar zone consists of elongated crystals oriented in the flow direction; lower temperatures in this zone lead to an increase in melt viscosity, and crystals formed during melt flow aligned with the flow direction. In the slightly deformed zone, deformed spherulites are present, resulting from recrystallization under joining pressure. Higher heating temperatures result in larger heat affected

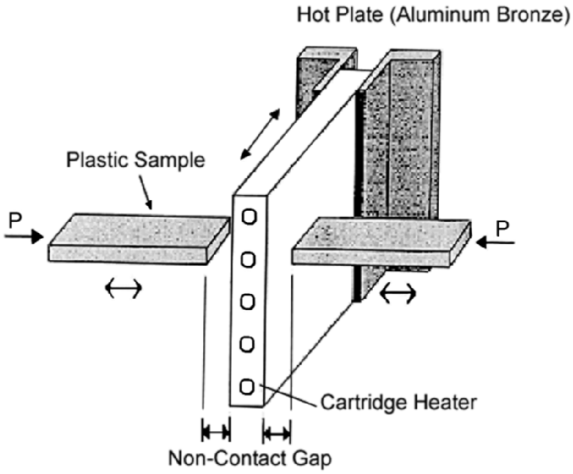

Figure 1.4. Non-contact hot plate welding. Parts being welded are placed near the hot plate, separated from it by a distance referred to as the non-contact gap. The hot plate is removed during the change-over phase, and pressure is applied to hold the parts in intimate contact during weld coolingand solidification.

zones and greater bond strength; however, too high a temperature or pressure results in void formation at the joint interface. [513]

Morphological investigation of polypropylene welds by differential scanning calorimetry (DSC) and Fourier transform infrared spectroscopy (FTIR) indicated that welds with low tensile strength correlated with the lack of a region of deformed spherulites between the weld and the bulk material, a wide weld region, and a reduction in the amount of melt flow in the weld direction. Low strength welds had a lamellar thickness distribution similar to that of the bulk material, but a wider distribution of lamellar thicknesses was present in high strength welds. [614]

EFFECTS OF AGEING ON WELD STRENGTH

Chemical and physical changes may occur in polymers during hot tool welding, affecting the durability of the weld. After air oven ageing at 120°C (248°F) at times ranging from 3 to 14 days, there was a significant reduction (>30%) in weld cross-sectional area in ABS welds, and degradation of the rubber segment of ABS resulted in yellowing. Elongation and tensile strength were reduced more than in the bulk material. After immersion for 7 days in 80°C (176°F) water, tensile properties and elongation deteriorated more in the weld than in the bulk material. Whitening occurred in the weld, possibly due to free radical and hydroperoxide formation during welding which subsequently initiate degradation reactions. Unsaturation in ABS decreased, along with an increase in carbonyl group concentration; both were more significant in welds than in bulk material. Ageing effects should be considered when welds will be exposed to aggressive environments. [516]

VARIANTS OF HOT TOOL WELDING

In direct contact hot tool welding, described above, parts are pressed against the hot tool. For high temperature polymers, the hot plate temperature required for melting is too high for non-stick surfaces to be used. In non-contact hot plate welding, parts are brought very close to the hot plate without actually coming into contact with it (Figure 1.4). Heat is transferred by thermal radiation and convection. The process is otherwise identical to hot tool welding: the hot plate is removed in the changeover phase, and pressure is applied to achieve intimate contact as the weld cools and solidifies.

Processing parameters that influence weld strength include the size of the non-contact gap, platen temperature, heating time, change-over time, and weld pressure and duration. Effects of change-over time and weld pressure and duration are similar to those in direct contact hot tool welding. In non-contact hot plate butt welding of polypropylene plates, using a 1 mm (0.04 in.) non-contact gap, weld strength approached or equaled bulk strength at optimal heating times which varied with hot plate temperature. Higher hot plate temperatures (480°C, 896°F) produced stronger joints at shorter heating times (40 s); however, joint strength decreased at longer heating times due to excessive squeeze flow of molten material out of the joint interface and an adverse molecular orientation.

Joint strengths increased with increasing duration of weld pressure up to 60 seconds, then remained constant or decreased slightly. Optimal weld pressure was about 0.35 MPa (50 psi); lower pressures allowed air entrapment in the joint, while higher pressures produced excessive squeeze flow out of the joint and an unfavorable molecular orientation during weld formation. [613]

EQUIPMENT

A hot tool welding machine consists of the hot tool assembly with two exposed surfaces, two fixtures for holding parts to be welded, tooling for bringing parts in contact with the hot tool and bringing molten joint surfaces together to form the weld, and displacement stops on the platen and holding fixtures. Dual platen hot tool welding machines are used for welding dissimilar materials. Welders can accommodate a range of varying part designs and sizes and can join parts in either a vertical or horizontal plane. In vertical heat platens, tooling can be lifted out of the top of the machine, both part halves can be loaded at the same time with a single cavity tool, and nests are in view for part loading. Some welding equipment can remove weld flash after the weld is formed. [576, 492, 493]

Equipment ranges from manually loaded and unloaded machines to semi-automated and fully automated in-line systems. Statistical control of weld cycles can be achieved through operator control panels that display all machine parameters and diagnostic functions, and pressure or displacement can be programmed throughout the welding cycle. Parts conveyors or drawer load features are optional equipment. Equipment is rugged and is designed to produce molecular, hermetic seals with consistent joint strength. A typical hot tool welder is shown in Figure 1.5. Tooling provides accurate mating and alignment of parts, and displacement stops control melt and weld dimensions. Tooling with displacement stops is shown in Figure 1.6. [514, 493, 492]

Figure 1.5 A typical vertical platen hot tool welder .

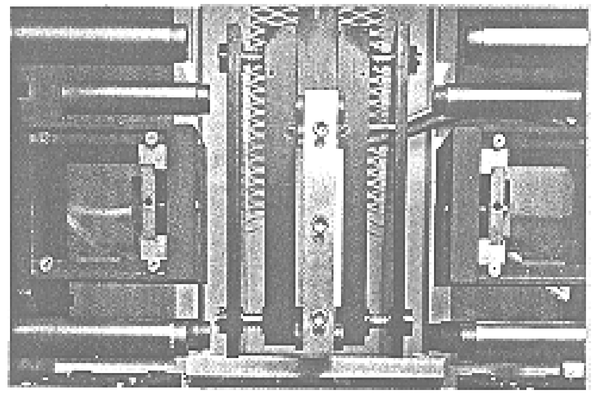

Figure 1.6 Tooling displacement stops in a hot tool welder, used to control melt and part dimensions.

ADVANTAGES AND DISADVANTAGES

Hot tool welding is a simple, economical technique in which high strength joints and hermetic seals can be achieved with both large and small parts. Joints with flat, curved, or complex geometries can be welded, and surface irregularities can be smoothed out during the heating phases (I and II). Dissimilar materials that are compatible but that have different melting temperatures can be welded using hot tools at different temperatures. Expensive plastics can be used for only critical part components; inexpensive plastics can be welded on to comprise the remainder of the part. Processing parameters can be monitored, and the welding process can be easily automated. Hot tool welding is used on compatible materials and does not introduce foreign materials to the part; as a result, plastic parts are more easily recycled. [517, 495, 513, 477, 450]

In non-contact hot tool welding, contamination of weld surfaces is minimized, heating is uniform, and a small weld bead is produced, providing good, consistent weld strengths. [613]

The major disadvantage is the long cycle time required, compared with vibration or ultrasonic welding. Welding times range from 10 to 20 seconds for small parts to up to 30 minutes for large pipes; typical cycle times are from 12 to 22 seconds. A second disadvantage is the high temperatures required for melting. Heat is not as localized as in vibration welding, and in some cases can cause plastic degradation or sticking to the hot platen. When hot melted surfaces are pressed against each other in phase IV, weld flash is produced. This must be hidden or removed for cosmetic reasons. In welding by pressure, part dimensions cannot always be controlled reliably due to variations in the molten film thickness and sensitivity of the melt viscosities of thermoplastics to small temperature changes. [511, 576, 552]

In the appliance industry, the welding of glass-filled polypropylene dishwasher pump housings, initially welded using hot tool welding, was converted to vibration welding due to reduced labor costs and lower power requirements. This is described in more detail under Vibration Welding, Applications.

APPLICATIONS

Hot tool welding can be used to join parts as small as a few centimeters to parts as large as 1.5 meters (4.9ft.) in diameter. It is commonly used in load-bearing applications and for welding large parts such as pipelines; special machines can weld large diameter pipes on site. [477, 518]

Cost reduction is possible by welding dissimilar materials. Automotive headlights, tail lights, and blinker assemblies are made by welding a clear polycarbonate or, more commonly, polymethylmethacrylate (PMMA) lens to an inexpensive plastic body made of ABS. Double cavity holding tools are used for welding rear lights. For high temperature applications, a fascia of a relatively expensive high temperature plastic can be welded to a less expensive subcomponent. An automobile headlight joined using hot tool welding is shown in Figure 1.7. [511, 493, 508]

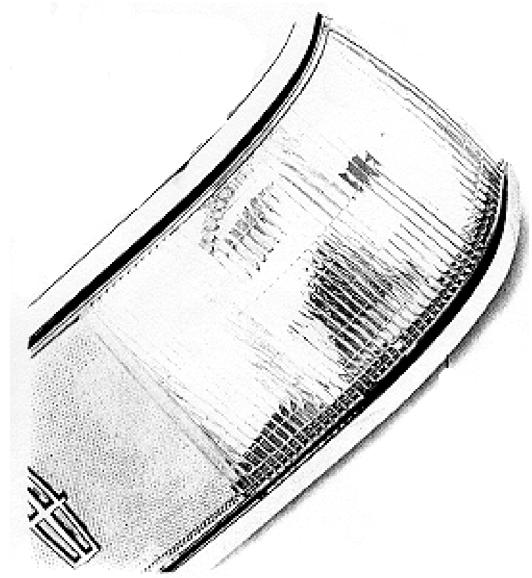

Figure 1.7 An automobile headlight; parts were joined using hot tool welding.

Stress cracking occurs in tail lights made from welding ABS to PMMA and is the most frequent cause of failure in tail lights. Welding induces internal tensile stresses below the yield point in PMMA which later cause cracks to form; the time before crack formation occurs varies. ABS is relatively insensitive to stress cracking due to the soft butadiene component. Exposure to surface active media such as methanol or windshield washer fluid accelerate crack formation by reducing the cohesive surface tension of the plastic. The mechanical stresses necessary for crack formation are then lowered to below the yield point, and cracks occur at low strain. Figure 1.8 shows stress cracking in a tail light. Higher internal stresses occur on the weld seams, which trigger cracks after exposure to a surface active medium and result in realignment of the break surface. Several small cracks are present on the welded lights, due to positioning constraints on the welded-on ABS housing. Susceptibility to stress cracking can be reduced by suitable processing conditions. In stress cracking experiments, susceptibility to stress cracking was significantly lower when either low (230°C) or high (420°C) hot tool temperatures were used. [616]

Other automobile parts, such as fluid reservoirs, fuel tanks, and vent ducts, are hot tool welded. Polypropylene air ducts and mounting brackets are hot tool welded to the main part of the instrument panel, made of glass mat reinforced polypropylene, on the Mercedes-Benz S-class automobile using mechanical stops to control part dimensions. In plastic fuel tanks, function parts, such as clips, vent lines, and filler necks, are hot plate welded to the blow molded tank; 29 parts are hot plate welded to the AUDI Quattro fuel tank. [508]

Plastic heat exchangers can be hot tool welded using a hot plate with deep heatable grooves that can be pressed against the bundles of thin-walled thermoplastic pipes. High pressure applied to the melted region results in molecular entanglement and high weld strength. Heat exchangers produced using this welding method display superior thermal performance, and production cost is competitive with traditional heat exchangers. [509]

Hot tool welding is also used in appliance tubs, agitators, and spray arms. Polyvinyl chloride is hot tool welded in medical products, life jackets, stationery products such as loose leaf binders, and blister packages, and plastic window frames are made by welding mitered, extruded profiles of a commercial grade of acrylonitrile-butadiene-styrene (ABS) developed especially for window frame applications. [514, 552, 495]

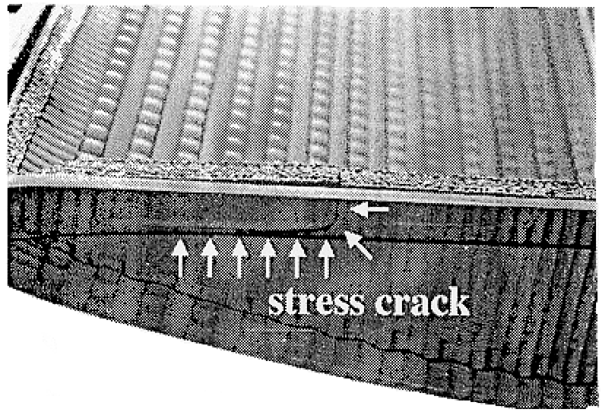

Figure 1.8 Stress cracking in tail lights. Welding induces internal stresses which later cause cracks to form.