Section VII

Plastic Joining

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1.0 Objective

Glue, nails, screws, welding and bolts are traditional means of assembling components, but the inherent properties of plastics allow many other options. All plastics can be deformed; thermoplastics resins can be melted and reformed. This makes processes such as staking, swaging, press fits, snap fits, and welding possible. The ability to mold intricate shapes, reform material after molding (with or without heat), and the wide range of strength and flexibility of resins all combine to make such operations possible. The advantages of these assembly methods over traditional methods are reduction in components (no additional screws or hardware), speed of assembly, reduced process time, and recyclability. All of these factors result in a lower overall cost of finished goods. If no metal or chemicals are used in the assembly, the entire finished product can be simply ground up and reused, without costly disassembly.

2.0 Staking

Staking, swaging, peening, and cold forming are all fastening methods involving the forming of plastics with a tool. Peening and cold forming are performed cold, whereas staking and swaging can be done either cold or hot. If staking is done cold, it is often referred to as cold heading. “Cold” operations may actually include heating the part, but to a temperature well below the melting point of the material. Typically heating to 30% of the melt temperature is considered “cold” working, temperatures above this are “hot” processes. There is also some heat crated in cold forming, through internal friction, which can reach temperatures high enough to melt the plastic and cause some degradation. These fastening methods are particularly suited to thermoplastics, but some thermosets can be cold formed or peened. All thermoplastic manufacturing methods can produce parts suitable for swaging and cold forming, while injection molding is ideal for creating the studs necessary for staking, peening, and cold heading.

In all of these processes, a plastic stud is deformed using pressure and/or heat. A stud is integrally molded to one piece of the assembly, and this stud inserted through a hole on the second part. The exposed side of the stud is then deformed to keep the latter piece from sliding off. Many different head geometries are possible depending on strength and aesthetic requirements.

2.1 Cold Forming of Stakes

Cold forming can theoretically be applied to all thermoplastics. It is particularly suited to acetal, nylon, and other materials with good impact resistance. This process relies on the application of compressive loads beyond the yield strength of the plastic. This load causes the stud to deform into a head for retention purposes. To avoid fracture, the pressure must be applied gradually to carefully controlled levels.

Cold forming of plastics is very similar to cold forming of metals. However, properties of plastic deformation and strain recovery, also known as ‘springback’, introduce a time dependence aspect. Some recovery will take place in cold-formed parts regardless of age, particularly if the assembly is exposed to heat in excess of the temperature levels at the time of forming. Holding the deformed section under pressure for a period of time following forming will reduce the amount of strain recovery, and will cause it to occur more slowly. For parts where exposure to elevated temperatures is expected, the use of heat is recommended in the deformation. This heat should be equal or greater than the expected future exposure so recovery will not be appreciable. On a molecular level, polymer strands will orient themselves along the direction along which principal strain took place. This will improve strength in the direction of molecular orientation and reduce strength in the cross direction. Cold formed parts are also more prone to crazing and chemical attack than hot formed parts.

The ideal dimensions of the stud are determined by a number of factors. Cold formed heads will exhibit tensile pull strengths that are approximately 50% of the material's shear strength. The stud diameter determines its length, as its unsupported length should not exceed twice the diameter. A longer stud will experience buckling during deformation. If a long stud is required, the deformation should be done in two stages, the first stage forms a cone shape and reduces the height to an acceptable level. Assembly speed, material, and temperature can also affect buckling of the stud. Head geometry will also affect stud length. The portion of the stud extending beyond the assemble components will become the finished head, so adequate material must be available. Different head geometries and appropriate stud dimensions are shown in Figs. 7.3 through 7.9. Tools are designed with a recess on the bottom surface identical to the head geometry. The stud should be dimensioned with the forming head in mind, as too much material will result in flash. Too little material will form an incomplete head, creating a weak joint and misshapen head.

Material	**Hot Air/ Cold Staking**	**Thermal**	**Ultrasonic**
ABS	Excellent	Excellent	Excellent
ABS/Polycarbonate	Excellent	Excellent	Good
ABS/PVC	No information	Good	Good
Acetal	Poor	Good	Fair to good
Acrylic	Good	Good	Fair
Acrylic multipolymer	No information	Good	Good
Acrylic/PVC	No information	Good	Good
Acrylic – impact modified	No information	Good	Fair
Butadiene-styrene (BDS)	Good	Good	Good
Cellulosics: CA,CAB,CAP	Fair	Good	Good
Flouropolymers	Poor to good	Not suitable	Not suitable
Liquid crystal polymer	Good	No information	Fair to good
Nylon	Fair	Good	Fair to good
PC-PET	No information	Good	Good
Polyarylate	No information	Good	Fair
Polycarbonate	Excellent	Good	Fair
Polyester			
PBT	Good	Good	Fair
PET	Fair to good	Good	Fair
Polyetherketone	No information	Good	Good
Polyetherimide	No information	Good	Good
Polyethylene			

Low and high density	Good	Excellent	Fair to good
Ultrahigh molecular wt.	No information	Not suitable	Not suitable
Polymethylpentene	No information	Excellent	Fair to good
Polyphenylene oxide	Good	Excellent	Good to Excellent
Polyphenylene sulfide	Good	Excellent	Poor
Polypropylene	Good	Excellent	Excellent
Polystyrene			
General purpose	Excellent	Good	Fair
Impact modified	Good	Good	Fair to Excellent
PVC			
Flexible	No information	Not suitable	Not suitable
Rigid	Good	Good	
SAN-NAS-ASA	Good	Good	Fair
Styrene-maleic-anhydride	No information	Good	Excellent
Sulfone polymers	Good	Good	Fair

Table 7.1: Process vs. Material Compatibility

2.2 Hot Air / Cold Staking

Hot air staking heats the stud before deformation to improve material flow and reduce springback after forming. The principle method of heating the stud is hot air. The air is preheated by an in-line heater and then forced through a tube on to the material Fig. 7.1A. Once the material has softened, the cold-forming die descends on the stud to form a stake Fig. 7.1B. The die remains in this position until the plastic solidifies. A pneumatic cylinder is typically used actuate the die. Care must be taken to apply the load gradually and with only enough force to achieve the forming. Excessive loading and speed can cause the stud to fracture. Cycle times for this process typically range 8 to 20 seconds, although multiple studs can be formed simultaneously.

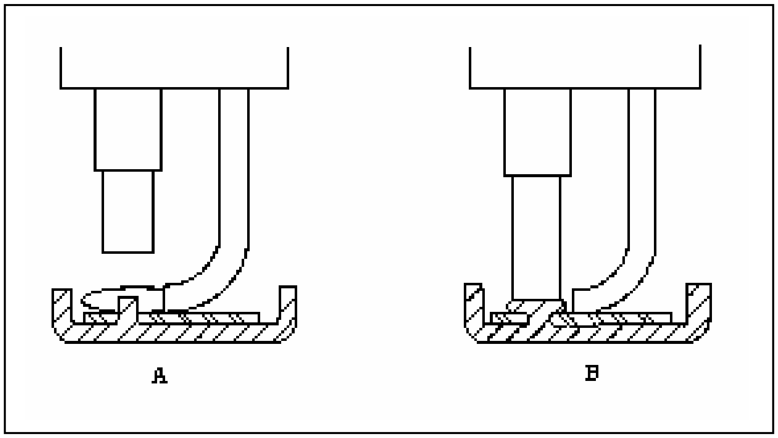

Figure 7.1: Hot Air Staking

Peening is a derivative of cold staking. Here, the die is heated, while the plastic is not. Peening is limited to resilient thermoplastics capable of withstanding the die impact without breaking.

2.3 Ultrasonic Cold Forming

Ultrasonics can also be used for cold forming. Called the “high pressure method”, this process uses ultrasonic vibrations to melt the material to a point at which the surface is softened but not melted. A high bearing load is transferred through a flat faced horn to press the softened material into a mushroom shape. The parts can be securely joined, or if the downward travel is controlled, the pieces may be set to permit relative motion. Resilient materials like ABS, high impact styrene, and polyolefins are well suited to this process. Acetal and polycarbonate can also be ultrasonically formed effectively.

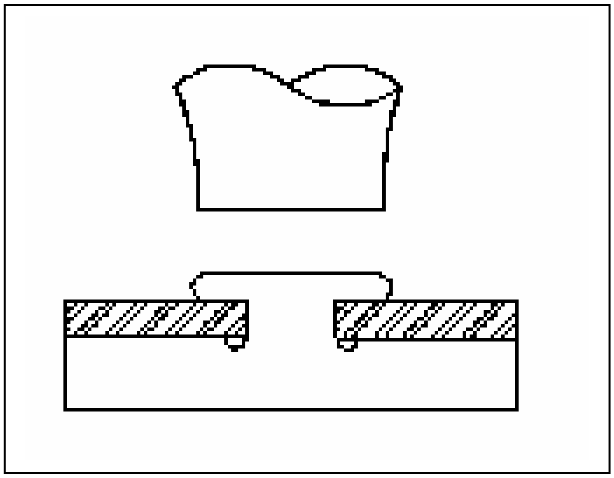

Figure 7.2: Cold Ultrasonic Staking

2.4 Thermal Staking

Hot die forming of stakes, or thermal forming, uses a heated die to raise the temperature of the plastic above its melting point. This heat helps to create tight assemblies and reduces springback of the material. The die transfers this melting heat to the plastic as it applies a downward force to the stud. Care must be taken to provide adequate heat for forming without causing degradation. If the stud is not sufficiently melted or deformation is too rapid, fracture can occur. Hot dies cannot be turned on and off like ultrasonics, so additional energy is consumed, however they are better suited to some materials. Brittle, or heavily glass-loaded polymers are more suited to thermal forming than ultrasonics. In addition, thermal staking will not damage sensitive electronic components as ultrasonics can.

2.5 Ultrasonic Hot Forming of Stakes

High frequency vibrations can be used to melt the top of the stud and reform it into the head of a stake. The shape of the head is machined into the tip of the horn, similar to hot die. As the vibrations melt the plastic, it gradually fills the contour of the horn, forming the head of the stake. When the limit of travel is reached, the horn is held in that position. This provides downward pressure on the joint until the head has cooled enough for the horn to be removed. If the horn is removed too quickly, the formed head may remain stuck in the staking cavity.

The main advantages of ultrasonic staking are increased strength and control. Unlike cold and hot die forming, there is no elastic recovery of the plastic following the operation. Ultrasonics can offer cycle times under one second, process reliability, and process control. This is possible because only the top of the stud is melted rather than the entire length. This is often accomplished by starting the vibration before the horn makes contract with the material, called 'pretriggering'. Ultrasonic staking is usually preformed using high amplitude and low pressure to permit the material to melt and flow into the cavity of the horn. The rate of downward travel must be carefully controlled so that it does not exceed the melt rate of the stud. Cracking and deformation are common if the speed is too high, pressure is too great, or amplitude too low.

2.6 Staking Geometries

2.6.1 Hollow Stake

- Works well with large diameter studs (no smaller than .080" O.D.)
- Produces a large strong head
- Does not have to melt a large amount of material (less time, less force)
- Avoids sink marks on the opposite side of molded component
- Enables parts to be re-assembled with self-tapping screws should repair or disassembly be necessary
- Aesthetically pleasing (can be made to look like it was "molded" on)

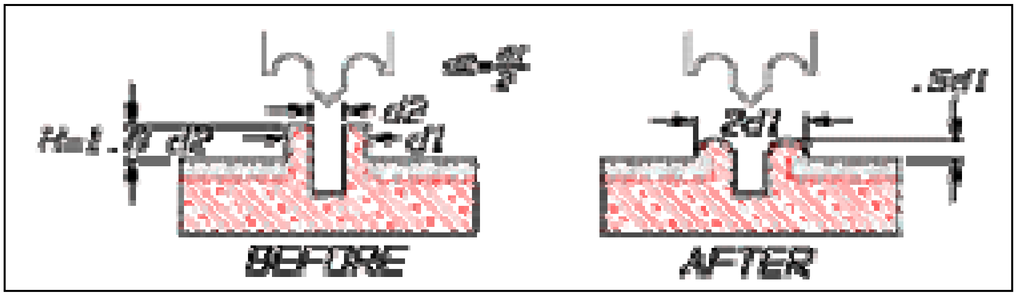

Figure 7.3: Hollow Stake

2.6.2 Rossette / Flared High Profile

- Recommended for large diameter posts
- Flares out material giving 360 degrees of even holding strength
- Stakes / moves more volume easily
- Slightly less staking forces required
- Slightly less cycle time as opposed to a dome stake on large studs
- Alignment to staking heads is critical
- Requires very accurate positioning so that center point of tip contacts center of stud
- Not generally recommended for use on heated platens (best on probes) because of thermal expansion
- Not generally recommended on small diameter studs
- Aesthetically pleasing (looks like a rivet)

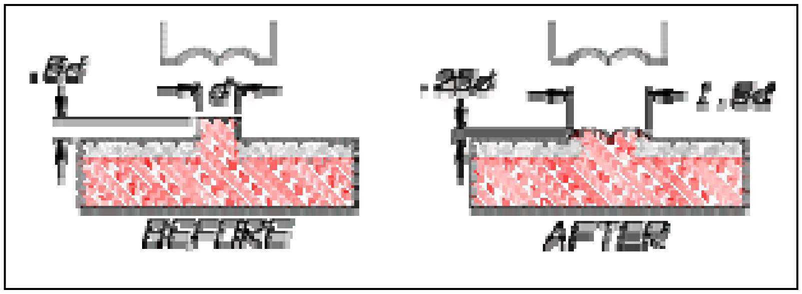

Figure 7.4: Rosette High Profile Stake

2.6.3 Knurled Stake

- Used where appearance strength is not critical
- Alignment is not an important consideration from an application standpoint
- Ideally suited for high volume production
- Three styles available: fine knurl, medium knurl, coarse knurl
- Generally the pitch/texture of the knurl is related to diameter of stud to be staked
- Can knurl a large tool and hit many stakes without alignment worries
- Good use on heated platens where thermal expansion is generally a problem
- Also works well when mating component has a countersink
- Greatly reduces cycle time

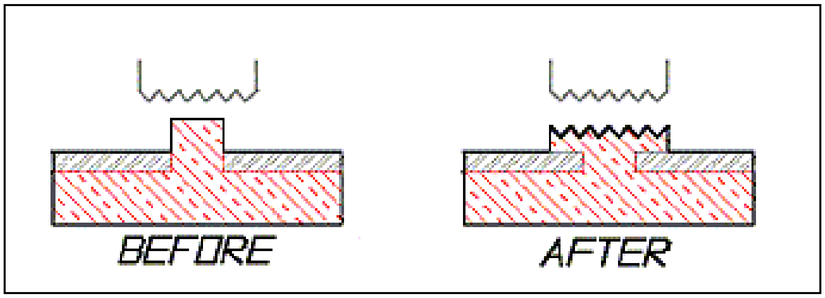

Figure 7.5: Knurled Stake

2.6.4 Rossette Low Profile

- Recommended for large diameter posts
- Flares out material giving 360 degrees of even holding strength
- Stakes / moves more volume easily
- Less staking forces required
- Slightly less cycle time as opposed to a dome stake on large studs
- Alignment is critical
- Requires very accurate positioning so that center point of tip contacts center of stud
- Not generally recommended for use on heated platens (best on probes) because of thermal expansion
- Not generally recommended on small diameter studs

- Aesthetically pleasing

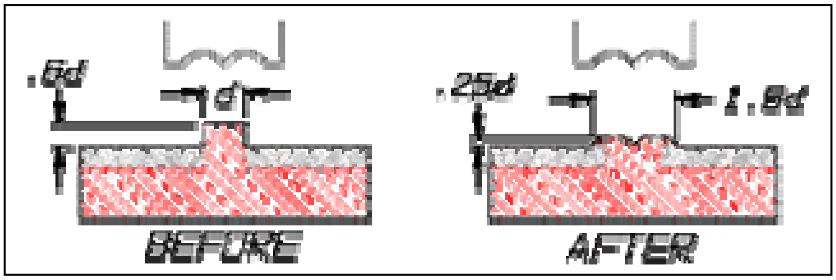

Figure 7.6: Rosette Low Profile Stake

2.6.5 Flush Stake

- Used for applications requiring a flush surface
- Requires that mating component has sufficient thickness for a countersink, counterbore, or a combination of the two
- Volume of the boss is crucial to fill the countersink properly

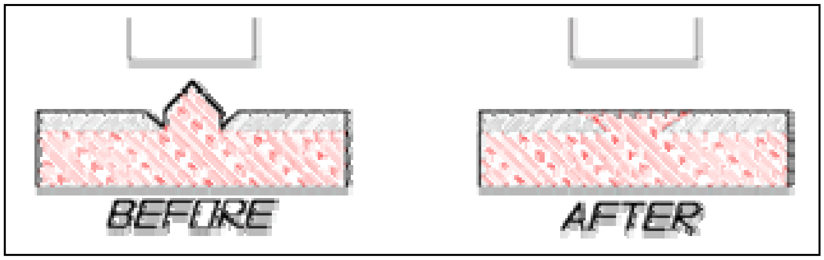

FIGURE 7.7: Flush Stake

2.6.6 Dome/Conical

- Generally used with bosses with an O.D. of 250" or less
- Aesthetically pleasing
- Produces a tight stake
- Recommended for crystalline material with sharp melting points such as 33% G.F. nylon, highly defined melting temperatures, (post cooling a must)
- Good for glass filled materials, or materials with abrasive fillers
- Good for materials that degrade easily (post cooling)
- Dome stakes come in two profiles: High and Low
- High Profile stake is typically .750" high or more
- Low Profile stake type is .375 or less
- Works well into counter bored holes

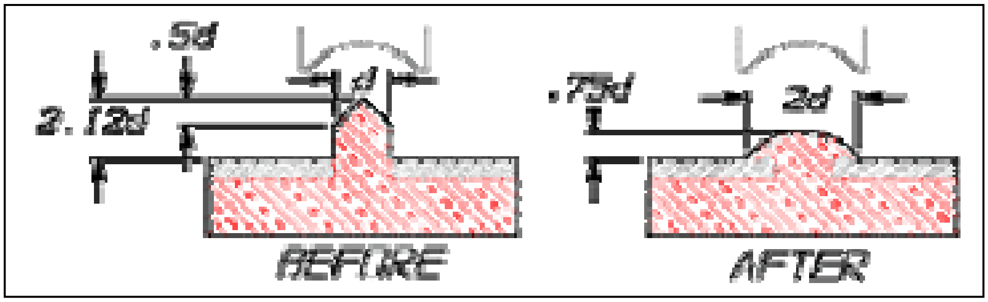

Figure 7.8: High Profile Dome

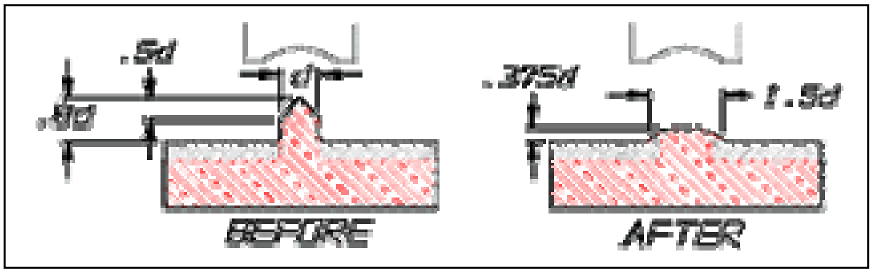

Figure 7.9: Low Profile Dome

3.0 Swaging

Swaging is the term applied to hot or cold forming, where an entire wall is displaced with a tool to entrap another part or parts. The assembly is created without a molecular bond. The entrapped part is nearly always a dissimilar material (metal, thermoset, or thermoplastic not compatible for welding to the original part). Swaging is essentially a permanent, non-flexible snap fit. The key advantage is reduction of mold costs, because there are no undercuts or studs are necessary in the mold. A tight assembly can be achieved without fasteners or adhesives in short cycle times, while producing minimal stress buildup in the components.

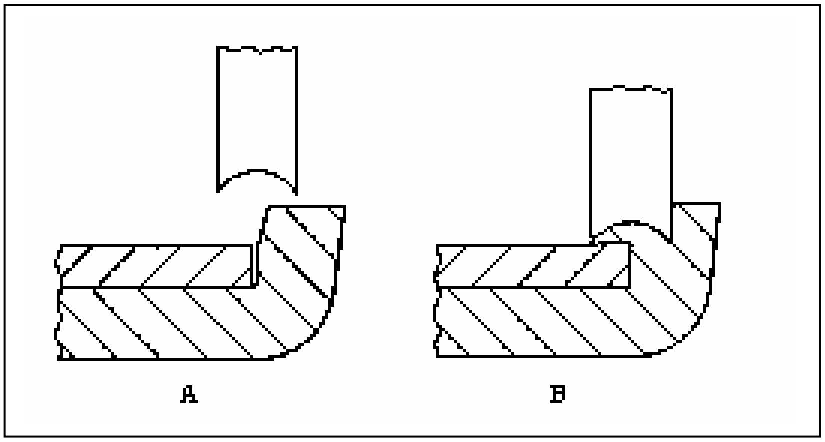

Figure 7.10: Swaging

An assembly before swaging has occurred is shown in Fig. 7.10A. Normally an undercut or stud would be required in the lower component for a snap fit or staking. The assembly is created when the die in Fig. 7.10B descends to displace material from the wall over the part to be entrapped. The principle process parameters are temperatures of the swaging tool and plastic component, downward pressure, and length of time the pressure is applied. Ultrasonic swaging is faster than hot die, and there is no stress buildup. However, a special tool is required and pretriggering should be used to ensure plastic melting occurs the instant the die makes contact with the wall. Once the material melts, the down force plows material over the entrapped part by the recess in the swaging tool. Heavy hold pressure is required to prevent elastic memory before the melted section cools and solidifies. Once the part is cool, the mating part is trapped in place.

Low to medium stiffness polymers are best suited to ultrasonic swaging because they permit cold forming of the material to begin prior to the melting from ultrasonic vibration. These include ABS, cellulosics, impact polystyrene, polyethylene, polymethylpentene, and polypropylene. Rigid thermoplastics can be swaged with greater difficulty. Cold swaging can be performed with softer materials, such as crystalline or tougher amorphous thermoplastics, which can withstand the large strains. These materials are more likely to exhibit elastic recovery than swaging with heat.

4.0 Ultrasonic Welding

Ultrasonic vibrations are sounds above the human hearing threshold. 18,000Hz is the limit of human hearing, and ultrasonic welding apparatus typically operates at 20-30KHz. The vibrations travel through a finely tuned horn and are transmitted to the plastic part. Within the part, the vibrations produce intermolecular friction between the polymer chains, and boundary friction at the joint interface of the parts to be welded. The plastic softens at the boundary, and this slows the transmission of the vibration to the distant areas of the part. This reaction accelerates the melting process, as a larger portion of the energy must be translated to heat rather than moved through the part. Temperatures rise until the melting point of both parts are reached. Vibrations are then halted, with downward pressure maintained until a molecular bond is formed across the joint and the plastic cools.

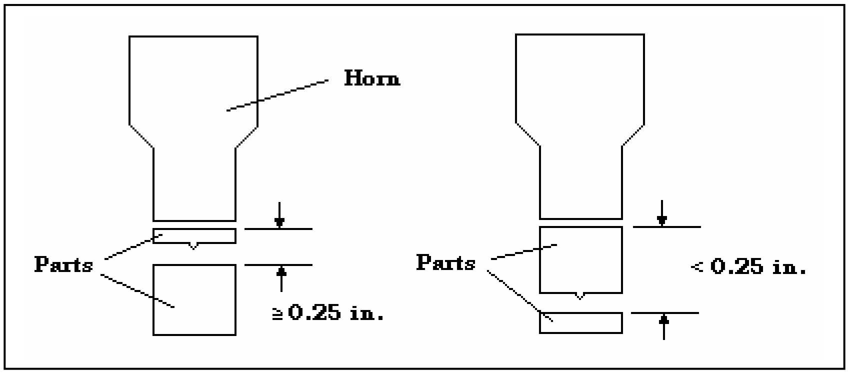

Figure 7.11: Near-Field and Far-field Welding

The closer the horn, or vibration source, is to the joint, the fewer vibrations are lost to absorption on their way to the joint. Who the horn is within 0.25" of the joint, the process is referred to as near-field welding Fig. 7.11A. Excellent results can be obtained with near-field welding, even with thin walls and crystalline or low stiffness polymers. Far-field welding Fig. 7.11B requires thicker walls and amorphous or high stiffness materials. Under ideal conditions, welds have been accomplished at distances up to 10" from the joint interface. Far-field welds require longer weld times, higher vibration amplitudes, and higher weld force to achieve the same quality of near-field welding.

Most ultrasonic welding makes use of energy directors. These small V shaped ribs placed on one side of the joint interface focus the vibrational energy. Concentrating this energy along a small area achieves rapid localized energy dissipation and therefore quick melting. Time and energy requirements are reduced for the weld, and the sharp tip results in less scuffing and flash along the joint. When welding similar materials, the location of the energy director is unimportant. If different materials are to be welded, the director should be placed on the part with the higher melt temperature.

Resin type is very important in ultrasonic welding. The vibrations must be transmitted through the material from the horn to the joint, without excessive loss. Stiff, rigid parts, whether through geometry or polymer type, are easier to weld. This is the opposite of staking, where softer plastics are easier. Amorphous thermoplastics have a random structure and transmit vibrations very effectively with little attenuation, or loss. Both parts should ideally be the same material, so that the interface will melt at the same temperature. In most cases materials are compatible only with themselves, but materials with similar molecular weights, and melt temperatures with 40°F may be welded to each other.

Hydroscopic materials, which absorb water from the air, can be difficult to weld. The moisture boils off during the welding and can create bubbles and porosity within the weld. This weakens the joint, causes degradation, and creates a frosty appearance. Obviously these materials should be dried prior to welding, or welded immediately after molding, before any absorption is possible. The principle hydroscopic materials are nylon, polycarbonate, polysulfone, polyester, and alloys containing these polymers.

Any additives to the virgin plastic can have negative effects on weldability. Fillers, glass fibers, impact modifiers all replace polymer material with unweldable material, producing weaker joints. Lubricants and mold release inhibit friction, thereby requiring additional vibrational energy to produce the necessary heat. Colorants and flame-retardants can reduce joint strength as well.

4.1 Joint Design

4.1.1 Butt Joint

This is the simplest joint. Using an energy director focuses the sonic energy on a smaller section of the part and reduces weld time. The material within the director becomes the sealant that is spread throughout the joint area. Standard textbook director geometry is 0.015” high with a 90° included angle. Practical considerations suggest a minimum height of 0.005”. When heights greater than 0.020” are indicated, multiple directors should be used, with the sum of the director heights equaling the formula dimensions.

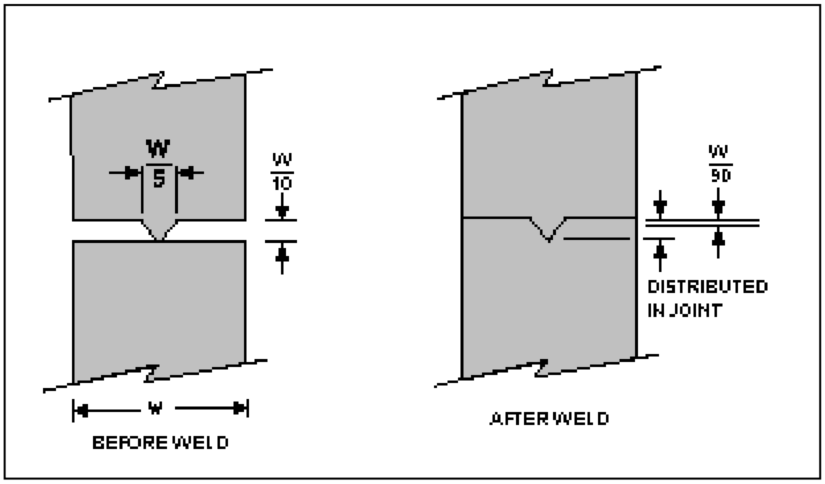

Figure 7.12: Butt Weld

4.1.2 Step Joint

A step joint is used to hide any flash or weld bead on the interior of the part. This joint is usually much stronger than a butt joint, since material flows into the clearance necessary for slip fit. This establishes a seal which provides strength in shear as well as tension.

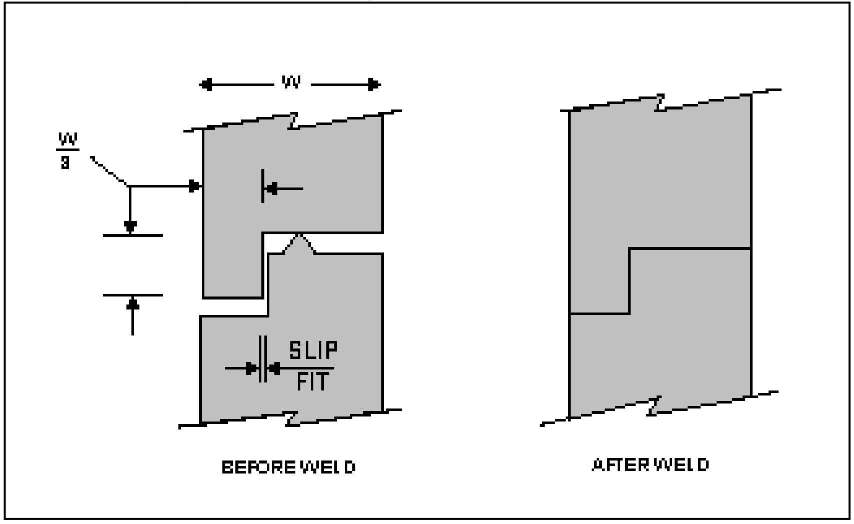

Figure 7.13: Step Joint

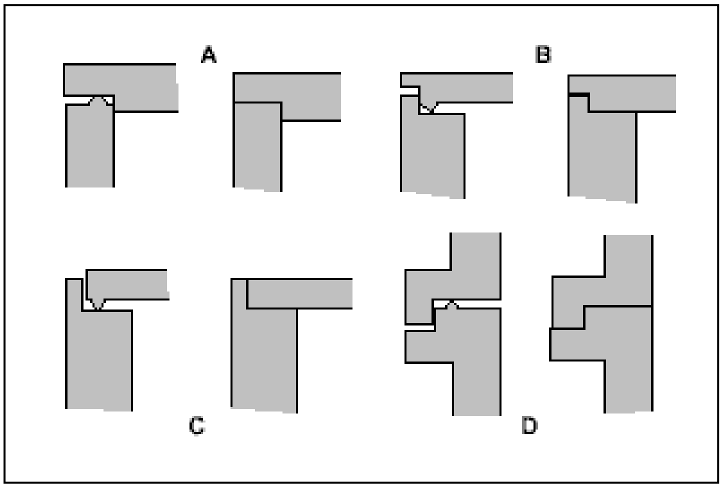

Figure 7.14: Step Joint Variations

4.1.3 Tongue and Groove Joint

A tongue and groove joint provides the greatest strength is both tension and shear. The need to maintain proper clearance on both sides of the tongue, however, makes this more difficult to mold. Draft angles can be modified concurrently with good molding practices, but interference between elements must be avoided.

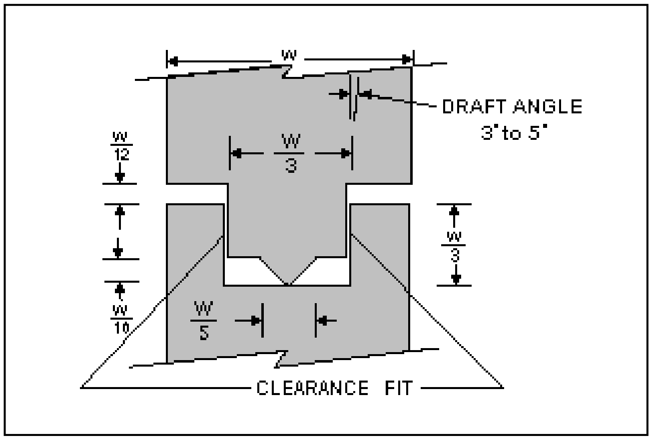

Figure 7.15: Tongue and Groove Joint

4.1.4 Interference Joint

Interference joints are used to provide a hermetic (air and water tight) seal with crystalline thermoplastics (nylon, acetal, polyethylene, polypropylene). Since crystalline resins (such as acetal and nylon) have a tendency of being watery in a motion state, the adjoining surfaces remain cool when the energy director has become molten. This results in little to no interaction of melted and unmelted surfaces. When an interference joint is used, weld strength in crystalline

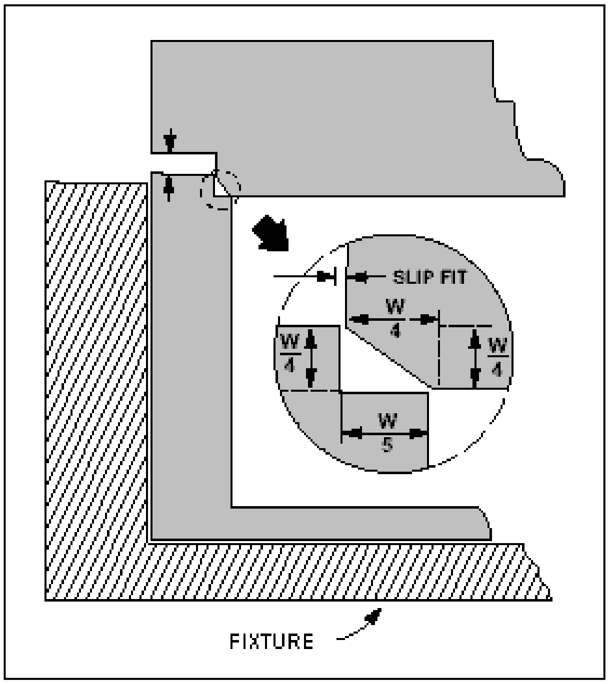

Figure 7.16: Interference Joint

materials approaches 95% of parent material strength. Energy director joints typically have strengths of 40-70%. The interference joint permits interaction between the two surfaces during the entire melt cycle by exposing more and more surface area as the two surface planes interfere under ultrasonic and clamp force. Adequate fixturing should be used for interference joining as the outer walls of the part may flex or distort if not contained by the nest.

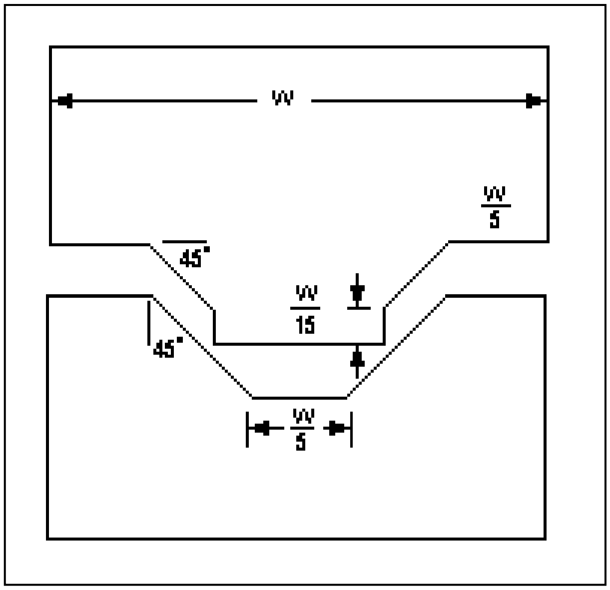

Figure 7.17: Hermetic Joint

4.2 Ultrasonic Tooling

Ultrasonic tooling is typically designed and produced by the welding equipment manufacturer. The tools are designed by acoustical engineers, made from aluminum or titanium and are precision calibrated, or tuned. Tooling consists of a booster which can be used to change the amplitude of the vibration, and the horn, which transmits the vibrational energy to the part. Boosters are designed to change the amplitude of the input signal. A 2 to 1 booster would increase a 20KHz vibration from the machine to a 40KHz vibration in the horn. The length and geometry of a horn are perfectly tuned to translate the full amplitude of the vibrational wave from the top to the bottom. The horn is driven at the top by the ultrasonic power supply, and then vibrates with one complete standing wave. In simplest terms, a horn with one wave form will transmit the input wave completely to the bottom of the horn, and at some point approximately midway down the horn, there will be no motion at all. This is the nodal point of the horn. Special custom horns may require setting up more than one complete waveform within the horn. A damaged horn that does not vibrate with one full wavelength can produce feedback into the wave generator and is potentially dangerous.

4.3 Booster Horns

The success of welding and staking of plastics or inserting metal into plastic depends upon the proper amplitude of the horn tip. Since it may be impossible to design the correct amplitude into the horn initially because of its shape, booster horns are necessary to either increase or decrease the amplitude to produce the proper degree of melt or flow in the plastic part. The choice of plastic, the shape of the part, and the nature of the work to be performed all determines what the optimum horn amplitude should be.

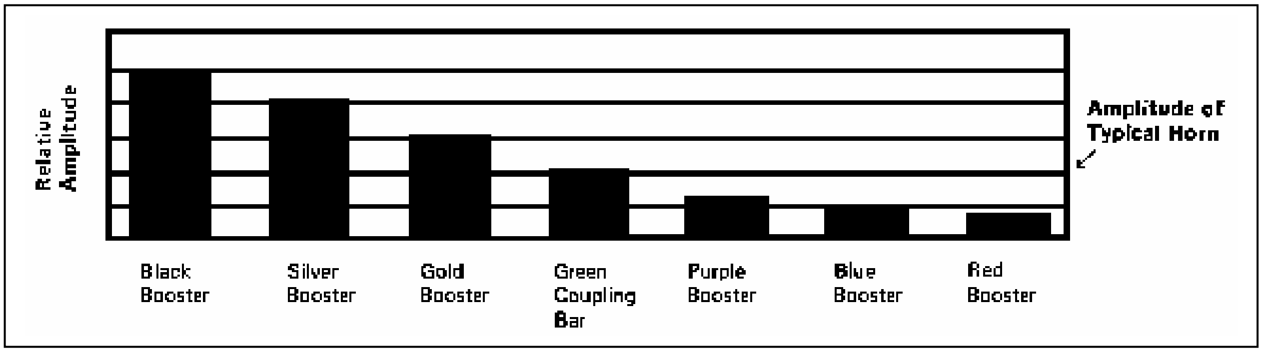

Figure 7.18: Booster Gains

Figure 7.19 further illustrates how a set of three amplitude-increasing boosters can change the pressure requirements of a typical exponential horn and power supply combination. With lower amplitude there is a greater force capability. For purpose of illustration, a high-amplitude horn might be compared to third gear in a car, which produces higher speed and low torque. Conversely a low-amplitude horn — similar to first gear which produces low speed and high torque — has tremendous force capabilities and will vibrate under hundreds of pounds of load. It is relatively easy to “stall” a high-amplitude horn by operating it under high pressure conditions, just as it would be easy to stall a car motor starting up a steep hill in third gear. Each horn-booster combination must be tailored to the specific application for optimum performance.

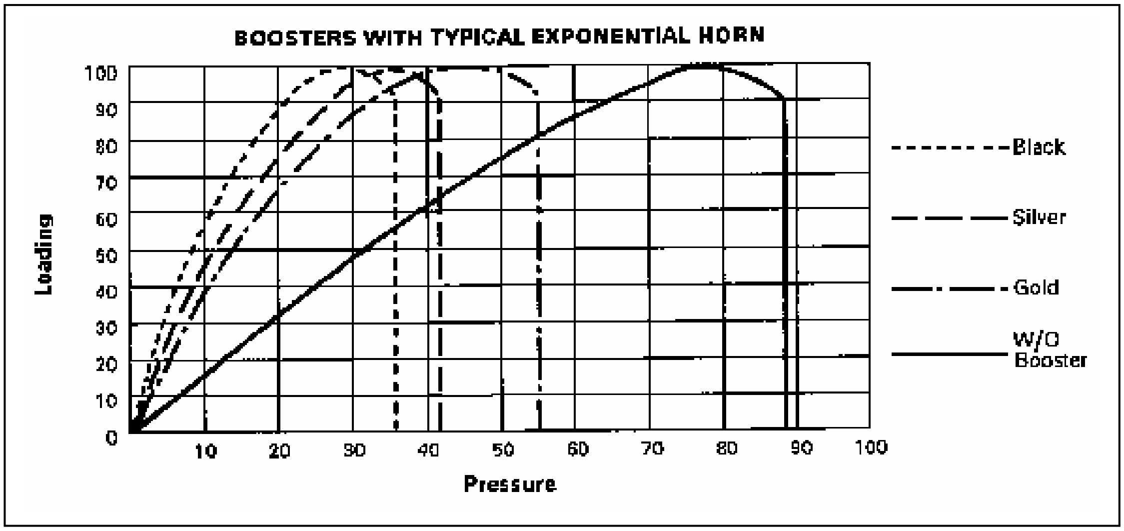

Figure 7.19: Booster Effects on Pressure

4.4 Horn Amplitude

When troubleshooting an ultrasonic welding process, the three parameters to be adjusted are downward pressure, horn amplitude, booster gain, and weld time. Typically, the larger the gain obtained through the booster, the lower required down pressure. The following suggestion can help to fine tune amplitude based on observed weld problems.

Increase Amplitude

- There is difficulty getting energy to joint resulting in a poor or slow weld.
- Energy is passing through the joint (vibration can be felt in nested part; part may show marking from nest).
- There is difficulty getting proper loading, or pressure required is beyond range of stand.
- Diaphraming occurs. (Burnout of circular parts.)
- If staking, melting occurs at base of stud instead of at surface.
- Marking of parts occurs because of excessively long weld times.

Decrease Amplitude
- System will not start or starts with difficulty.
- System stalls with low pressure.
- Excessive no load readings occur on power supply.
- Going from solid to tapped horn.
- Marking of parts occurs. High pressure provides better coupling of vibration into plastic.
- Plastic parts are shattered or metal inserts fracture.
- Excessive heat builds up near nodal area in horn.
- Diaphraming occurs.

5.0 Sources

Sonitek, 84 Research Drive, Milford, CT 06460, (203) 878-9321

<u>Joining of Plastics, Handbook for Designers and Engineers</u>, Jordan Rotheiser, SPE, 1999