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1. Introduction

Typical joining methods for plastic parts are screwing, snap- and press-fitting, gluing and welding. Welding is an effective method for permanently joining plastic components. There are various welding techniques such as spin-, ultrasonic-, friction-, laser- and hot plate welding. The friction or vibration welding process is ideally suited for welding of compatible thermoplastic parts along flat seams which have to be high strength, pressure tight and hermetically sealed. The process can also accommodate seams with small out-of-plane curvatures. The most effective analogy to demonstrate this process is pressing and rubbing your hands together to generate frictional heat. The same principle is applied for joining thermoplastic parts. It is the ability to control the frictional process that makes vibration welding such a very precise and repeatable process in serial production.

This technique offers a large number of advantages as well as some limitations:

**Polymer**
- Melted polymers are not exposed to open air, therefore no risk of oxidation of the polymer.
- No foreign material is introduced, so the weld interface is of the same material as the parts to be welded.
- Material transparency and wall thickness do not pose limitations to the process such as in laser welding.
- Welding is problematic for low-modulus thermoplastics such as Arnitel®
- Polymers with large differences in processing temperatures can not always be welded successfully.
- Heating is localized to a large extent therefore material degradation resulting from overheating is much less likely to occur.

**Process**
- Cost-effective process, short cycle times.
- Simple equipment.
- Suitable for mass production.
- Process works well for a variety of applications.
- Virtually no smoke or fume during welding.
- Requires fixturing and joint design.

- Product is exposed to vibrations during welding, sensitive components or parts may be damaged. Not suited for welding miniature components.
- Insensitive to surface preparation

**Appearance**
- Weld-flash is formed at the edges of the weld during the process. If this leads to an unacceptable appearance, a hidden joint or so-called flash traps can be used.
- Close contact between the parts is required over the whole weld surface. Otherwise warpage of parts could be problematic just as adhesion.
- Welding is limited to nearly flat-joint parts, although stepped parallel joints can also be welded.

Vibration welded airduct in Stanyl® TW200F6
2 The vibration welding process

2.1 Basic principles
In vibration welding, two plastic parts are in frictional contact with each other with a certain frequency, amplitude and pressure.

As a result of the friction between both parts heat is generated which causes the polymer to melt at the interface. Due to pressure, the molten polymer flows out of the weld-zone giving rise to flash, see Figure 1. After the vibration has stopped the layer of polymer melt solidifies and a joint is generated.

Four different stages can be distinguished in the vibration welding process, respectively solid friction stage, transient stage, steady-state stage and cooling stage, see figure 2.

In the **Solid friction** phase (1), heat is generated due to the friction energy between the two surfaces. This causes the polymer material to heat up until the melting point is reached. The heat generated is dependent on the frictional properties of the polymer and the processing parameters frequency, amplitude and pressure.

In the **Transient phase** (2) the molten polymer layer increases due to shear heating in the viscous (melt) phase. Heating decreases as the thickness of the viscous layer increases.

In the **Steady-state melt flow** phase (3) the melting rate equals the outward flow rate (steady state). As soon as this phase has been reached, the thickness of the molten layer becomes constant. The steady-state is maintained until a certain “melt down depth” has been reached at which the vibration is stopped.
Figure 3 schematically shows the flow profile of the molten polymer in the weld zone. The velocity of the outflowing material has a parabolic profile over the width and increases towards the edges of the part as a consequence of accumulating melt flowing from the center to the edges.

After stopping the vibration, the polymer melt cools and solidification starts; the Cooling stage (phase 4). The parts are allowed to solidify under pressure resulting in a permanent bonding of the parts. In order to impart a uniform weld, the entire weld surface must receive uniform energy input. Therefore, it is important for the entire weld bead surface to be in contact at the onset of, and throughout the welding process.

2.2 Process parameters
Vibration welding is generally used on large parts, yet smaller parts can be welded economically in multiple cavity tooling. A vibration welded air inlet manifold is a common example of large part welding, see figure 4.

The most important process parameters of vibration welding are frequency, amplitude, pressure, time and depth. Under optimized conditions, high weld strength can be achieved. However, the optimum weld parameters settings are depending on for example the kind of polymer, geometry, and cleanliness requirements.

Frequency
Most industrial vibration welding machines operate at weld frequencies of 100 – 240 Hz, although machines with higher frequencies are also available. Frequency is also depending on the mass of the upper tooling weight. The frequency has no significant influence on quality of the weld.

Amplitude
Lower weld amplitudes, (0.7 – 1.8 mm; 0.03 – 0.07 inches) are used with higher frequencies (240 Hz), and higher amplitudes (2 – 4 mm, 0.08 – 0.16 inches) with lower frequencies (100 Hz) to produce effective welds. See figure 5. Generally, high frequencies are used when clearances between parts are restricted to less than 1.5 mm (0.06 inches). High amplitude will reduce the welding time, but have a negative influence on cleanliness.

Pressure
Weld pressure varies widely (0.5 – 20 MPa; 72 – 2900 psi), although usually pressures at the lower end of this range are used (0.5 – 2.0 MPa; 72 – 290 psi). Higher pressures decrease the welding time;
however, increasing the weld pressure can reduce the strength of the weld by forcing out all of the molten plastic, resulting in a cold weld being formed. In general, weld strength is not very sensitive to the frequency and amplitude of vibration. Outside flow of molten material should be limited as much as possible due to change in glass fiber orientation (see chapter 4.3 Glass fiber reinforced materials). High viscosity materials can experience higher weld pressures but higher pressure can increase stronger dust generation in the start up phase.

**Time**

Vibration welding equipment is either time controlled or depth controlled. Where the equipment is depth controlled, the time is variable; time control corresponds with variable depth. Depth control is preferable. In this case the active welding time is the result of the settings.

**Depth**

The most important determinant of weld strength is the weld penetration or displacement. Static strengths equal to that of the parent polymer can be achieved when the penetration exceeds a critical threshold value, equal to the penetration at the beginning of the steady state phase; weld strengths decrease for penetrations below this value. Penetration greater than the critical threshold does not affect the weld strength of unreinforced polymer, glass-filled resins, or structural foams, but can increase the weld strength of dissimilar materials. As long as this threshold is reached, weld strengths are not very sensitive to welding frequency and amplitude; however, at a constant threshold value, weld strengths can decrease with increasing weld pressure.

More information about weld depth can be found in chapter 5.2 Weld depth.

**General recommendations**

Mentioned values are general limits for the welding process. Typical values are starting values for the process, from where optimization should take place. Exact welding settings are depending on for example the kind of polymer, geometry, and cleanliness requirements.

Typical start values for Akulon® from which to optimize:

- **Weld pressure**: 1.4 MPa (200psi)
- **Frequency**: 240Hz
- **Amplitude**: 1.8 mm

**Weld depth**: 1.5 mm
- **Time**: 3.5 seconds
- **Holding time**: 0.5 times welding time

**Figure 5**

Representation of amplitude and frequency (blue high amplitude low frequency, red low amplitude high frequency)

Vibration welded Air Inlet Manifold in Stanyl® TW200F6
3 Vibration welding equipment

3.1 Machine Basics
A vibration welder is basically a vertical machine press, with one moving element, one fixed element and a tooling fixture on both. A schematic drawing of the components is shown in figure 6.

The vibrator assembly (topside) is a moving element with no bearing surfaces and is driven by either hydraulic pistons or electromagnets. The vibration head and electrical drive deliver the power required to perform the frictional weld process. The ‘head’ is an electromechanical spring mass system, which typically has power delivered by electric coils acting upon opposing lamination stacks. With the tooling installed, the mass of the system determines its natural frequency. The drive sends power to the opposing drive coils switched at an electrical frequency tuned to match the natural frequency of the mechanical system, thus providing constant frequency vibratory motion. The amplitude \(a\) of the oscillation is a controllable parameter on the machine.

The fixed element is a lifting table (below) which brings the parts to be welded into contact, by raising the lower tooling and the part to meet those attached to the vibrator head. Guide rails ensure that horizontal positional accuracy is maintained. The lifting table controls the force \(F\) with which the parts are brought together and controls the penetration depth \(s\).

Both the vibrator head and lifting table are equipped with application-specific tooling fixture. The tooling must provide good support to ensure that an even pressure is applied to the weld interfaces during the welding. It is essential that there is no relative movement between the parts and tooling fixtures during welding, otherwise the amplitude between the weld interfaces will be reduced. If the amplitude falls below the threshold value, it will result in a poor weld.

The lifting table and hydraulic system are rigidly fixed to a machine frame and the vibration head is attached to the frame by means of isolation mounts, and therefore able to be moved by large forces. The mechanical system is surrounded by a sound enclosure with access doors to the working envelope for operation. A control cabinet houses the drive mechanism, electrical system and the PC control unit.

3.2 Tooling Basics
Tooling is application specific and will need to be designed uniquely for each program. It is therefore highly recommended that
the tooling be planned along with the part design, so that feasibility is covered from the start. The function of the welding tool is to provide constant, uniform pressure across the weld joint and to ensure that the parts sense the uniform relative amplitude generated by the welding machine. In order to satisfy these requirements the tooling must be able to rigidly support the entire weld joint, either through direct contact with the welding flange geometry or by transmission of the pressure through structural portions of the shell geometry itself.

Well designed tooling consists of an upper tool which is mounted to the vibration head and a lower tool which is mounted to the lifting table. The parts are placed into the fixtureing details of the tool at the start of each cycle. Tooling construction typically consists of hardened steel segments that are CNC cut to the part shape. These details may be on moving tool actions in the lower tool only. The upper tool cannot have any tool actions, as the forces imposed during the process would cause the tool to fail. It is important to understand these points for part design so that access to the weld joint on the part upper shell can be planned without tool actions.

An improper tool design that does not provide constant, uniform pressure across the weld joint or allows the parts to slip relative to each other, thereby not providing the uniform relative amplitude, will result in a loss of process control and the production of nonconforming parts.

3.3 Vibration Welding Systems
Vibration Welding systems (figure 7) are generally provided with fixed operating frequencies of 100 Hz, 200 Hz and 240 Hz or variable output frequencies (200 to 250 Hz). Almost every vibration welding machine is equipped with PC controlled process and data management.

Figure 7
Vibration Welding system (picture courtesy of Branson)
4 Materials

4.1 Thermoplastics
Thermoplastic polymers are made of molecules in which monomeric repeating units are attached together into long chains. An important property of thermoplastic polymers is that they soften and melt after heating and harden upon subsequent cooling. When two products made of a thermoplastic material are welded, the polymer chains diffuse across the interface and a bond is formed by entanglement of the chains, see figure 8. This applies to all welding techniques for thermoplastic materials. In simple overlap joints, flow of molten polymer is not necessary; the bond is formed by diffusion. Diffusion is not linked to viscosity.

The low thermal conductivity of thermoplastics keeps the cooling rate after melting sufficiently low for the formation of strong bonds. This is an important and advantageous difference with metals where heat is easily transported away from the weld area.

Almost any thermoplastic can be vibration welded: crystalline, amorphous, filled, foamed, and reinforced. Most DSM thermoplastics, such as Akulon®, Akulon® Ultraflow™, Akulon® Diablo, Stanyl®, Stanyl® ForTi™, Stanyl® Diablo, EcoPaXX™, Novamid™ and Arnite® can be vibration welded. Amorphous materials, for instance polycarbonate, are more easily vibration welded than semi-crystalline polymers. The process is less suitable for very flexible materials such as Arnitel®. Thermosets (thermosetting resins) in cured condition cannot be welded; no diffusion of molecules can take place since cross-linking of their molecules has occurred.

4.2 Type and composition of material
The weld performance is clearly influenced by the type of material but material specific additives can also significantly affect the weld strength.

Figure 8
Molecular diffusion and entanglement during welding

Figure 9
Effect of polymer type on weld strength
− Type of polymers. Figure 9 shows the influence of the polymer type on the weld strength of vibration welded testbars in a series of tests performed by DSM.

− Viscosity. Higher viscosity will lead to a better interlinking (diffusion and entanglement) of the polymer chains during the molten phase.

− Reinforcement. Explained in chapter 4.3

− Additives. Some additives can affect the crystallization rate. For instance Carbon Black accelerates the crystallization where Black Dye slows down the crystallization process. Generally, a slower crystallization rate is preferable for better weld quality as it allows more time for the interlinking of the polymer chains.

− Moisture content. Water absorption during storage increases the moisture content of some thermoplastics, which can sometimes lead to bubble formation in the jointed area and decreased weld strength. To avoid bubble formation, parts can be pre-dried or preferably welded immediately after molding.

4.3 Glass fiber reinforced materials
The welding behavior of polymers that contain fine particles such as glass fillers is similar to that of unfilled polymers, but achieving threshold penetration generally requires slightly increased welding times. For 30% glass fiber content, the weld strength is considerably lower than the bulk strength. Why does this happen? The decrease in mechanical properties is due to the reorientation of the fibers induced by the vibration movement. Because of the applied pressure the molten material is squeezed out laterally (see figure 3), the glass fibers are involved in the flow and at the end of the process glass fibers are oriented perpendicular to the tensile direction. This unfavorable orientation is the reason for the reduced strength of weld compared to the bulk strength of the material. The orientation perpendicular to the injection molding direction facilitates fracture through the weld zone. This is clearly demonstrated in figure 10, which reveals the fracture surfaces of respectively a welded PA6-GFR30 test-bar that has been subjected to a tensile test (A) and the fracture surface of a non-welded PA6-GFR30 test-bar (B). These SEM pictures demonstrate that the fibers in the weld-zone are mainly oriented in the plane of the fracture, in contrast to the non-welded material where the fibers are mainly oriented perpendicular to the plane of fracture, leading to substantial fiber pull-out and consequently high strength. Therefore the weld is not as strong as the rest of the material and it approaches properties of the unfilled PA6.

4.4 Compatibility of materials
As diffusion of molecules across the interface is required to form a strong bond, the molecular mobility in the molten weld, as well as the compatibility of the molecules on both sides of the weld are important. In general, it is advisable to use similar materials for the two parts to be welded. However, welding of dissimilar polymers is still possible provided the materials have some degree of compatibility. For example, PA6, PA66 and PA46 are miscible in the molten state and PBT and PET are miscible above their melting temperatures. DSM’s copolyesters (Arnitel®) are also miscible with PBT and PET, as long as the amount of soft fraction is limited. PC is only partially miscible with polyesters, but the compatibility is supported by the occurrence of a compatible chemical reaction (transesterification). It is therefore possible to weld PC on polyesters and copolyesters. Table 1 gives an overview of the option for welding of dissimilar polymeric materials.
Table 1
Overview of plastics that can be welded together (shown with +)

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Vibration Welding of Engineering Plastics 13
5.1 Joint
As with every other welding process, the design of the weld geometry is important for successful vibration welding. The joint design can be very straightforward such as a butt joint or advanced with several flash traps and U-flange. The choice of the joint design depends mostly on the requirements of the design of the part. A few basic joint designs are described below.

Butt joint.
The simplest joint design can be used on short walls or walls that are parallel to the vibration motion. To prevent the part from snagging, the joint faces must never be completely out of contact, so the amplitude is restricted to 90% of the wall thickness. Figure 11A illustrates a typical butt joint design.

Butt joint with U-flange.
A U-flange may be necessary for thin or long unsupported walls. It is designed to lock the component wall to the tooling fixture, thus preventing wall flexure. Walls as thin as 0.8mm (0.03 inches) have been successfully welded with U-flanges. See figure 11B.

Tongue and groove with U-flange.
It securely holds the flange in the tooling, aligns the mating parts to each other before welding, applies the weld force directly over the weld area and hides flash both internally and externally. A raised tongue is present on one part to provide material to melt and flow in the joint during vibration. In reality material is displaced from both parts during welding but convention usually adds weld material only to the tongue. The groove should be volumetrically sized to the amount of material displaced during welding. See figure 11C.

Double tongue and groove.
Comparable with tongue and groove with U-flange but especially used when maximum strength is needed and large flash containment is required. This joint design will produce the cleanest finished appearance. See figure 11D.

Tongue and groove with U-flange.

Double tongue and groove.

Joint design definitions for Bead-on-Bead design:
- The Weld Flange is the area on which the welding tool makes contact to transfer the welding pressure and impart the vibratory amplitude to the joint. This structure needs to be sufficiently stiff to transfer the pressure to the weld bead and provides a path to minimize stress concentration in the structure.
- The Weld Bead is really a ‘Bead-on-Bead’ design such that the narrow rib of the lower shell melts into the wider rib on the upper shell to create the bond. Having the bead-on-bead configuration provides a uniform heat sink area for the thermal process and acts as a deflector for the flash that is generated away from the opening.
- The Weld Depth is the amount of material displaced during the bonding process. It is removed from both shells and shown as a defined interference fit.
− The Flash Trap exists on either side of the weld bead to collect the flash that propagates during the process. A flash outside the weld line (see figure 11A and 11B) could create a safety issue for handling, an obstruction to airflow in the manifold core, or an appearance issue.

− The Gripper Tab or Return Flange is a feature used to help locate and retain the shell geometry on the steel details of the weld tooling. These features also provide a means with which to manage the distortion imparted on the shells during cooling.

5.2 Weld depth
Shell welded parts, for instance intake manifolds, need to meet certain structural requirements, such as the typical burst strength specification. Manifolds are typically made of glass reinforced polyamide materials to satisfy these requirements.

To meet the structural requirements, a particular wall thickness is specified. When stress is applied to the structure and the structure is split into shells that are joined together by welding, this weld joint becomes a localized area for stress concentration.

In the case of glass reinforced polyamide materials that are welded together by the vibration welding process, the material strength of a welded joint is approximated by the following curve of % parent material strength vs. weld depth for tensile test specimens of a constant thickness. (This graph is a compilation of various studies completed by material suppliers and represents a working model for purposes of part design.)

A few observations for figure 13:
− Maximum strength of a welded joint is approximately 75% of the parent material.
− Maximum occurs at 1.5mm of melt depth.
− The curve rises sharply to this maximum and falls off more gradually thereafter.
− In order to stay in a region of high strength, parts should be designed for a melt depth within a window of about 1.2mm to 2.2mm.
− To achieve strength equivalent to the parent material, it is necessary to make the weld tongue wider than the parent material. As a general rule, a weld tongue should be equal to the nominal wall thickness for unfilled materials and at least 1.2x the nominal wall thickness for filled materials, depending on weld strength requirements.

5.3 Welding line
The most challenging task when planning the design of a part to be vibration welded is to choose the splitting lines along which the injection molded shells will be joined. Because the welding tool opens and closes on the parts similar to the injection molds that made them, it is helpful to consider this when planning the splitting lines for the shells.

When choosing the splitting line(s) consider the following guidelines:
− The vibration weld Clamp Axis should be parallel (or as close to parallel as possible) to the injection mold die draw axis, or slide action axis that will create the weld joint geometry for each shell. This will permit the tooling access required to
support the shells in the tooling and will ensure that the weld joint geometry can be produced square; otherwise an additional correction will need to be made.

- The splitting line should be a 1D or 2D curve in a projected plane parallel to the clamp axis and perpendicular to the amplitude axis. This curve is extruded as a surface through the part such that motion between these two shells along the split surface is permitted along the Amplitude Axis. In general, a flat plane is easier to work with than a curved surface.

- Due to the robustness of the vibration welding process, it is possible to have a slightly inclined ‘ramp’ along the Amplitude Axis, or ‘in the line of vibration’, but this is limited to a 10° maximum over a relatively short distance.

- An orthogonal coordinate system consisting of (3) axes is now defined: the Clamp Axis, the Amplitude Axis, and an axis perpendicular to both in the Projection Plane that is approximately tangent to the projected splitting curve. It would be helpful to construct this coordinate system in the CAD model during the part design, and could be included as a feature of a ‘Knowledge Based Engineering’ software tool.

Limitation can occur with the presence of an inclined weld bead (weld bead with an angle versus the welding plane). The penetration depth and the effective pressure are lower with inclined weld beads. See figure 14. The angle (α) between the weld lines is limited to a 60° maximum. For duct sections such as a throttle body neck, the limit can be increased to 70°. To accommodate the reduced weld depth at these sections, increase the machine Melt Depth Setpoint. This will maintain the Weld Depth along the split line within the desired window for weld strength.

**Figure 14**
Inclined weld bead, displacement and pressure difference as a result of the angle.
6 Testing

Burst Pressure testing is a method of evaluating the structural integrity of the welded part. It is important to consider burst pressure when designing any sort of system pressurized with gas or liquid, whether that system is an intake manifold in a car or a municipal water system. There are two types of pressure testing: Quasi Static Burst Pressure testing and Dynamic Burst Pressure testing. These tests can be performed with virgin material and/or aged material (e.g. temperature, mechanical, chemical, etc.).

**Quasi Static Burst Pressure testing**

Pressure testing can be performed with water. The welded part to be tested is filled with water (room temperature) and the pressure is increased until failure. This means that if the object filled with water under high pressure fails and the welded part opens, the tank would not explode because the liquid is incompressible and would not suddenly expand under ambient conditions. An advantage of testing with water is that the object is not completely fragmentized and therefore the failure initiation area can be located.

Alternatively, pressure may be tested with air. Similar to testing with water, this can easily be implemented at different temperature but is destructive at failure and therefore the failure initiation area cannot always be located. The results of testing with air are generally 5-10% below those conducted with water.

**Dynamic Burst Pressure testing**

Explosive Back-fire testing: an engine backfire is being simulated by igniting a combustible air/fuel mixture inside the intake manifold. The pressure rise time is typically 5-15ms.

Compressed air testing: the combustible air/fuel mixture is replaced with pressure-vessel accumulated air. The pressure rise time is slightly slower than explosive testing (<30ms)

Explosive back-fire on engine: as close as possible to the real situation. Ignition of air/fuel mixture is created on an engine. This kind of testing is only performed at OEMs or engine test-centres.
7 Applications

Vibration welding is used on parts with a broad range of sizes. Large parts are usually welded one at a time, whereas smaller parts can be welded economically in multiple cavity tools.

Automotive assembly applications include door panels, intake manifolds, filter housings, instrument panels, air-conditioning and heater ducts, tail lights and lenses, fluid reservoirs, bumpers and spoilers. Aviation applications consist of HVAC ducts, air diverter valves, interior lighting and overhead storage bins.

Domestic device manufacturers make use of vibration welding for dishwasher pumps and spray arms, detergent dispensers and vacuum cleaner housings. Vibration welding is also used to assemble chainsaw housings and power tools.

Accessories applications are business and consumer toner cartridges, point-of-purchase displays, display stands and shelves.

Medical applications include surgical instruments, filters and I-V units, bedpans and insulated trays.
8 Process variants

Linear vibration welding with IR preheating
A feature associated with vibration welding is the formation of fine impurities or so-called fluffs causing optical impairment and mechanical degradation. Studies have shown that these fluffs are generated during phase 1 of the welding (see figure 2), as surface asperity at the joint line becomes sheared away. In some applications, such as media conveying parts and vessels for medical use, this soiling is unacceptable. The use of preheating (with IR emitters) to suppress the solid friction phase ensures that a melt film forms prior to the vibration welding cycle, resulting in a homogeneous weld flash and nearly no fluff formation during welding.

Orbital friction welding
In orbital friction welding, one part is rubbed relative to another in an orbital motion, under axial pressure, as shown in figure 15. Unlike linear vibration welding, the relative motion of the two parts at the interface is the same at all points around the contours, and constantly changes from transverse motion to longitudinal motion.

The orbital friction welding mechanism works as follows: the upper tooling plate is mounted on three central springs. Three electromagnets are positioned at 120° spacing around the center column. During operation, each electromagnet is energized in turn, pulling the tooling plate away from the center position. This continues throughout the weld cycle, producing an orbital motion. When the weld time is complete, the electrical energy to the magnets is switched off and the tool returns to its original central position, ensuring good part alignment. An axial load is applied throughout the welding and cooling cycles.

Because of the gentler motion created, and with amplitudes up to 0.7 mm (0.03 inches), the process is better suited for components with relatively thin walls (< 2 mm; < 0.08 inches) or unsupported vertical walls. It is also better for components containing sensitive electrical parts. In addition, cycle times tend to be shorter than for linear vibration welding.

Angular friction welding
Angular friction welding involves the rubbing together of components in an angular, reciprocating motion under axial force. The motion is indicated in figure 16. It is, in principle, similar to the linear friction welding process, except the motion is angular and is used for circular components. The angle of vibration is up to 15° with a frequency of up to 100 Hz.

The process was developed for circular components where the final joint configuration is critical; but it is not widely used in industrial applications these days, since the advent of spin welders with positional control.

High frequency vibration welding
Vibration welding was developed as a 120 Hz process, with one part moving in relation to the second part at amplitudes between 2-4 mm (0.08 - 0.16 inches). A more recent development is variable high frequency vibration welding, which reduces the required amplitude of motion. Typical vibration frequencies for this process range between 250 and 300 Hz, with vibration amplitudes for effective welding ranging between 0.7 – 1.5 mm (0.03 and 0.06 inches).

Several important benefits are realized at higher vibration frequencies: firstly, the higher frequencies at the same velocity of relative motion between parts, allow smaller displacement amplitudes. Smaller displacement means that the heat generated by the friction is confined to a narrower region and quicker melting results. Secondly, when wall thicknesses of the parts to be joined are comparable to the displacement amplitudes, reduced displacement amplitudes yield better coverage.