Manufacturability in UltraSonic Welding

- What is Ultrasonic Welding
- Materials to be joined
- Welding parameters
- Assembly critical things for ultrasonic welded parts
- Different ultrasonic welding joint types
- Other ultrasonic joining methods

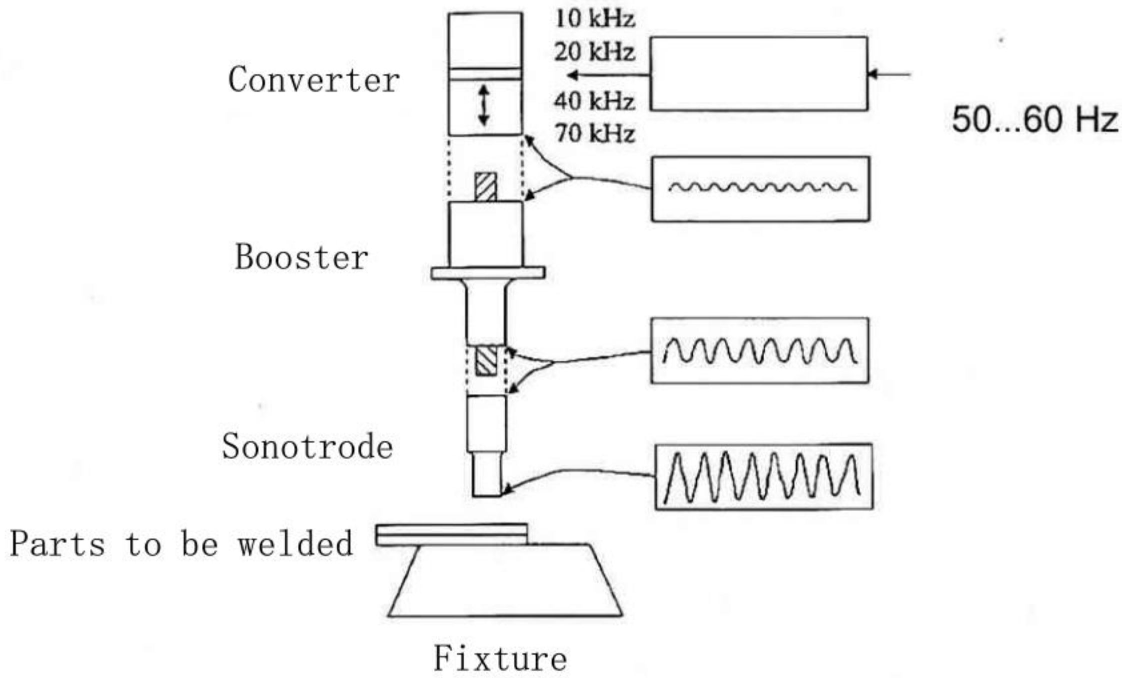
Ultrasonic Welding

- Principle of Ultrasonic Welding
  - Ultrasonic welding is based on combined effects of heat and pressure at the joint surface of parts.
  - Ultrasonic energy is brought through the upper part and focused with energy directors to the joining surface. Surface of joined parts heats because of the friction between polymer molecules (internal friction of polymer) and friction between joined surfaces.
  - Place where the biggest pressure is affected to the joint surface will start to melt first.
  - First requirement for the US weldability is that the material is melting → US welding is suitable for thermoplastics. Cold-set plastics do not melt (e.g. polyurethane, epoxy, melamine, etc.).

Main construction of Ultrasonic Welding equipment

- Frame and pressing mechanics
- Generator, which transform normal voltage frequency to high frequency (20 - 70 kHz) alternate current.
- Converter transfers high frequency electrical energy to mechanical oscillation.
- With help of booster the amplitude of oscillation, produced by converter, can be lengthen or shorten.
- Sonotrode is transmitting the oscillation (vibration) to the joined parts. Sonotrode is also transmitting pressing force to the joined parts and modifies the amplitude of oscillation if needed.
- Anvil / fixture is keeping the joined parts at right position.

Progress of the oscillation / vibration



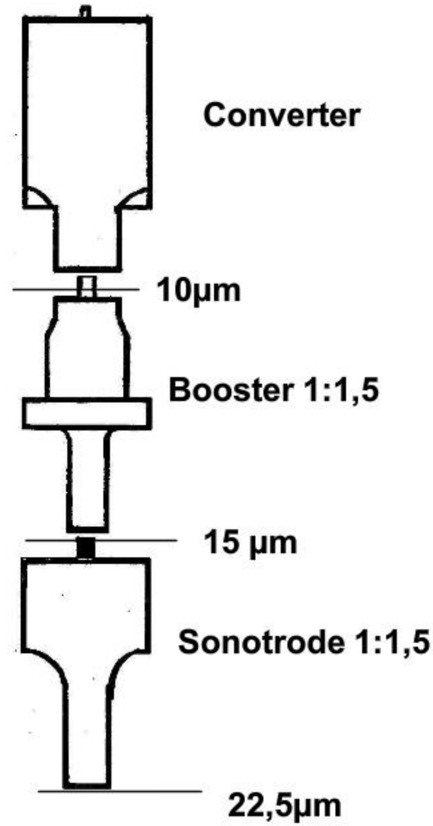
Amplitude formation

- Converter oscillation amplitude for example 10μm

- Booster transformation ratio 1:1,5 → Oscillation amplitude from booster to sonotrode is then 15μm.

- If cross-section area of sonotrode is changing for example 1:1,5 will the amplitude conducted to joined parts be in theory 22,5 μm (in practice the amplitude is a bit smaller due to losses from system).

- Straight (unchanging cross-section area) sonotrode transmits the amplitude without changes.

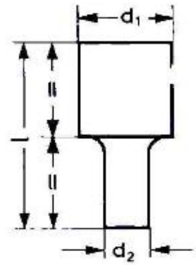


Sonotrode properties

- Sonotrode should have good fatigue resistance and small acoustic impedance (small power loss). Aluminium and Titan are typical sonotrode materials. Also tempered steel is used in special cases for example when inserting metall inserts with ultrasonic welding.

- Resonance length of sonotrode is normally half of the resonance systems total wave length. Small variations in sonotrode raw materials, etc. causes that every single sonotrode is individual instrument that has to be tuned carefully to work properly.

- With the sonotrode design the amplitude can be lengthen if needed.



Resonance length

$$l = \frac{\lambda}{2} = \frac{c}{2f}$$

Amplitude adjustment

$$\beta = \left(\frac{d_1}{d_2}\right)^2 = \frac{A_1}{A_2}$$

λ Wavelength
c Sound velocity
f Resonance frequency
A_1 Cross-section area 1
A_2 Cross-section area 2

For example:
Aluminium sonotrode:
c = 5100 m/s
f = 20000 1/s

l = 0.1275 m

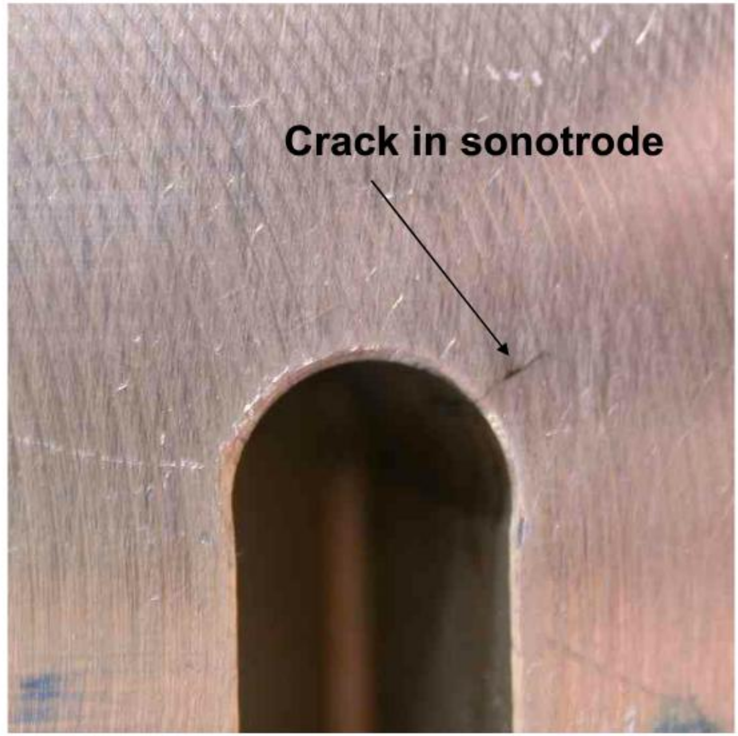
Sonotrode function check-out

If there is not proper equipments available needed for sonotrode manufacturing (like to measure resonance frequencies and phase difference), the possibilities to check sonotrode function is limited to following things:

- At least the the newer US welding equipments are directly informing the power loss of sonotrode in use. With small sonotrodes the power loss should be under 10 %. With bigger sonotrodes even 20 …25 % power loss can be still acceptable.
- Amplitude can be easily measured for example with a dial cauge having max. 2µm scale division.
- Cracks in sonotrode that are coming to the sonotrode surface can be get visible.
- Extraordinary / exceptional heating of sonotrode is also a sign for damages in sonotrode.

Cracks in sonotrode

- Cracks in sonotrode that are coming to the surface can be made visible for example by spraying some lubricant which is not containing oil (very low viscosity →penetrates easily to small cracks). After this the operating check of US system is done.
- Possible cracks should be seen as dark stripes.
- At the same time the sonotrode power loss can be noticed to be high.



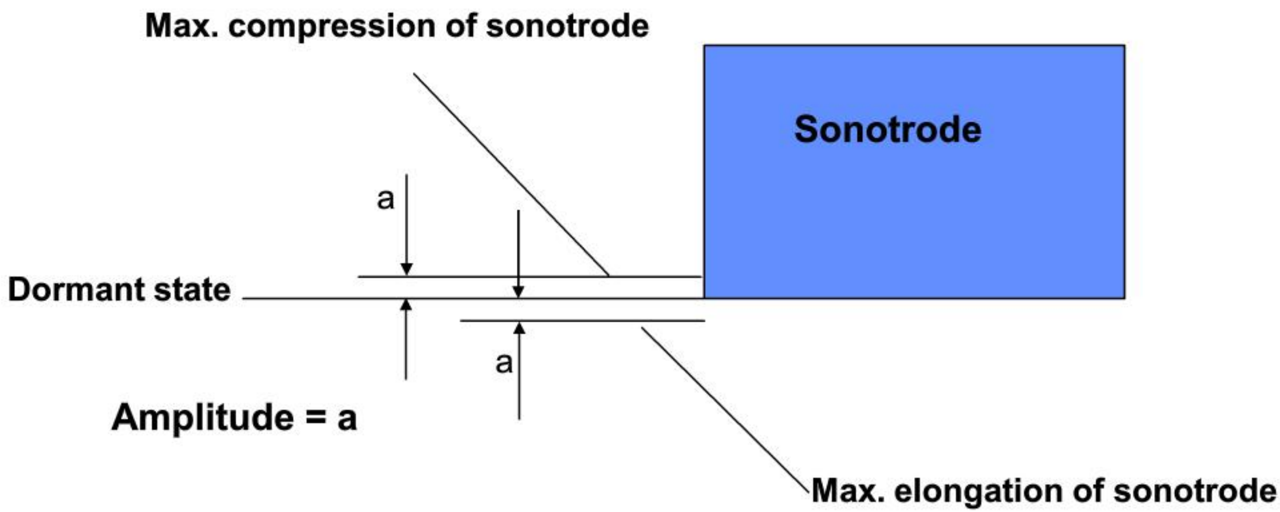
Measuring the amplitude

By using test set-up shown in picture, the amplitude of sonotrode can be measured directly from the sonotrode.

Measurement is done from the whole end face of the sonotrode with distances of couple centimeter.

(With this method it is however not possible to find the possible amplitude phase difference at the difference places of sonotrode end surface. This possibility is typical with big sonotrodes.)

Amplitude



Max. compression of sonotrode
Sonotrode
a
Dormant state
a
Amplitude = a
Max. elongation of sonotrode

Amplitudes for different materials

Because different plastics have different physical properties, it is important to use right amplitude for certain plastics to ensure proper welding.

Sometimes the shapes of welded parts can cause welding problem from the amplitude point of view.

If there are big differences in part height at welding areas causing that sonotrodes height differs according the shapes, the amplitude may not be same at the whole welding area.

To avoid this problem the welding area should be as flat as possible (welding joint at same height in the construction, no steps in height at joint).

Typical amplitudes for different plastics at 20 kHz frequency (μm) :

Source: Rinco

ABS	20...30 μm
PMMA	20...35
PC	25...40
PS	15...30
SB	20...35
SAN	15...30
PP	30...60
PE	25...60
PBTP	40...50
PA	35...60
POM	40...50

Material influence to the weldability

- Welded parts are one part of the vibrating / oscillating system.
- From the material welded, there is first requested as good throughput of oscillation energy as possible directed to the welding joint (with as low losses as possible) and after that the material should suddenly melt at joint (as big loss in oscillating energy as possible) enabling strong joint.
- Material properties has a big influence to the welding success and quality.
- With right material selection it can be helped the success of welding and with wrong selection the welding can be done very difficult.

General things from weldability of materials

- Only thermoplastics can be ultrasonic welded.
- Hard materials are better to be welded than soft materials.
- Most trouble-free is to weld same plastic grades together. If that is not possible , the melting temperatures of welded plastics should be as close to each other than possible.
- Amorphous polymers are easier to be ultrasonic welded than semicrystalline polymers (like PA, etc.).
- Most additives in plastic material are worsening weldability.
    - Color additives (especially titanoxide for white color, blue color).
    - Fire retardants.
    - Reinforcements (glass fiber, etc.).
    - Relief agent residues (if relief agents used during molding parts).
    - Etc.
- Humidity that is absorbed to the parts to be welded is worsening weldability of the parts.
- Surface treatments like painting, metallization, etc. at the joined surfaces are worsening the weldability.

Ultrasonic welding parameters

- Most important ultrasonic welding parameters:
  - Amplitude, which is based on welded material. Length of amplitude can be adjusted by different booster and sonotrode construction. At sophisticated welding machines, the amplitude can be adjusted by controlling unit.
  - Pressing force, which is adjusted according shapes of welded part, material of welded parts and used amplitude. Pressing force affects to the strength of joint and also to the scratches at the surfaces of welded parts.
  - Trigger force, which is used to adjust the switch-on timing for ultrasonic vibration. Right chosen trigger force is enabling adequate part movements related to each other at the very beginning of welding phase to ensure that they are at the right position related to each other.

Ultrasonic welding parameters

- Most important ultrasonic welding parameters (cont.):
  - Movement speed of sonotrode, which is affecting to the quality of the joint. Too big movement speed can brake the welded parts already before they are starting to weld together.
  - Welding time, energy and distance. Adjustments of these parameters is depending of the chosen welding method (time, energy or distance controlled welding).
  - Holding time after welding is affecting i.a. strength of joint. Too short holding time can weaken the joint strength. Too long holding time is prolonging the cycle time unnecessarily.

Control modes of welding process

- Time mode
  - Welding time is constant.
  - Welding energy can be used as monitoring value.
  - Most simple control mode and applicable especially when first time testing and looking parameters for new welded constructions.

- Energy mode
  - Welding energy is constant.
  - Min. and max. welding time settings used for monitoring.

Control modes of welding process

- Differential weld travel mode
    - Melting depth from triggering point during welding is constant.
    - Max. energy and max. time can be used for monitoring.
    - Slight distance variations at the welded parts in welding direction can be compensated.
    - Warped parts are easily welded only partly (from the first point where the joint construction is closed).

- Absolute weld travel mode
    - Welding distance from pre set zero - point is constant.
    - Max. energy and max. time can be used for monitoring.
    - Relevant for applications where the accuracy of the size / distances of finished object in welding distance is critical.

Assembly critical things for ultrasonic welded parts

- Parts to be ultrasonic welded should be rigid enough.
  - Sufficiently thick walls.
  - Normal pressure behind sonotrode about 1,4 - 2,8 bar (1,4 kg/cm^2 - 2,8 kg/cm^2), welded construction has to stand this pressure coming from welding direction.

- Good guiding and self locating elements between welded parts which are located outside of the welded / joining area.
  - During welding there is no friction between joined parts (only liquid plastic).
  - Guiding and self locating elements missing → parts sliding uncontrolled to wrong position related to each other.

Assembly critical things for ultrasonic welded parts

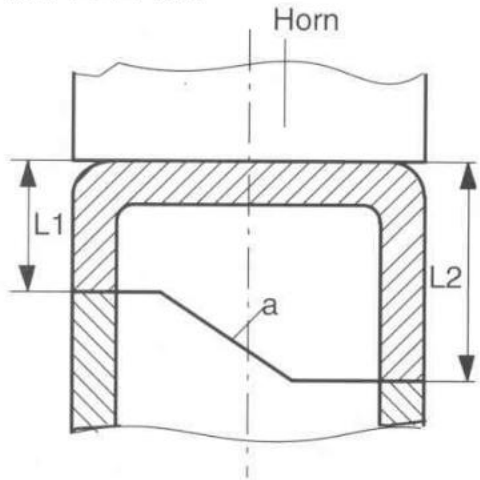
- Welding joint should be positioned so that the welding can always happen in exact vertical direction. Tilted welding directions and joints should be avoided because due the gravity force and "liquid / slippery connection" between joined parts during welding the welded parts are sliding to the other end of planned position.

- Avoid constructing parts, which has to be welded from more than one direction because it may lead to big strains in the joint after welding operation.

- The welded parts should not be tight fitted to each other before welding. There should be constructed suitable clearance (min. 0,05 - 0,1 mm) between welded parts.
  - Should be noticed when tolerating welded parts.
  - Shrinkage risk of the parts should be also noticed.
  - If too tight fitted, welding can happen at places where not planned.

Assembly critical things for ultrasonic welded parts

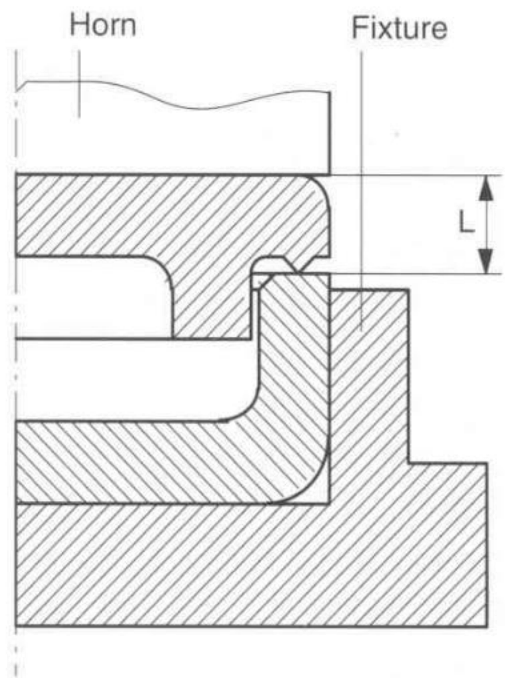
- Welding surface between parts should be as flat and straight as possible in welding direction (no rounded surfaces and/or stepped surfaces in welding direction)



Unequal distances L1 and L2; zone "a" not at right-angle to horn surface.

Assembly critical things for ultrasonic welded parts

- Welded construction should be as low as possible in the welding direction.
- Joint surface in welded construction should be as close as possible to the surface where welding energy is brought to the construction (surface which sonotrode is touching).



Near field welding, L less than 6 mm

Assembly critical things for ultrasonic welded parts

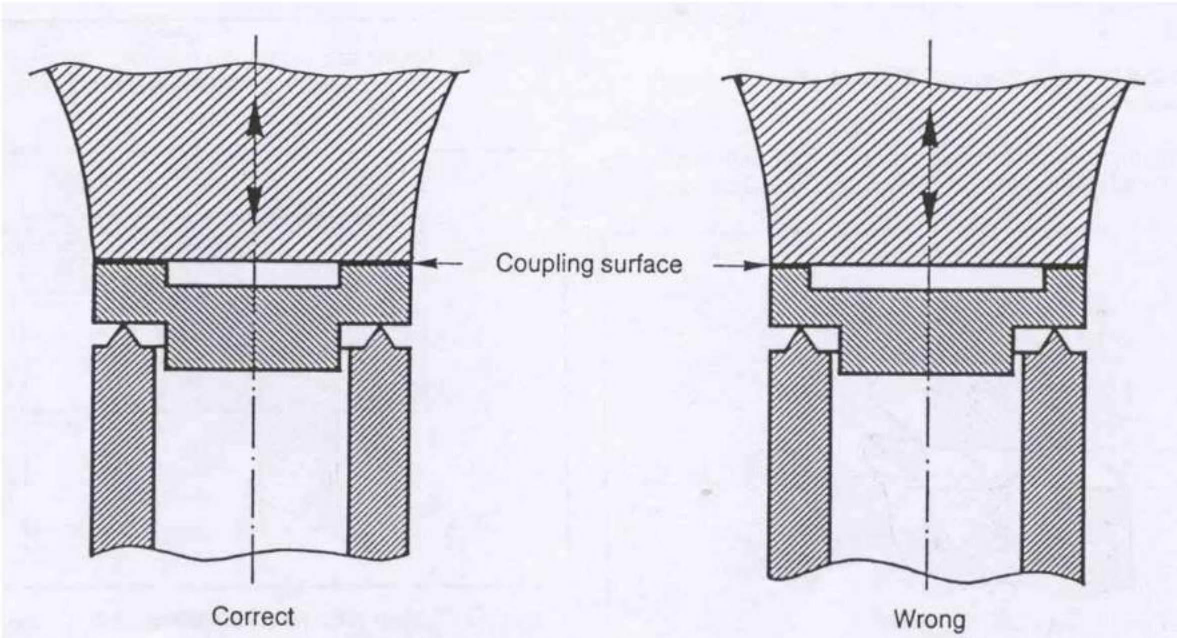
- Welding joint construction should be located horizontally at the same position / line where the welding energy is brought to the construction (i.e at the same horizontal line).

  If this is not followed, the welding energy is not lead / directed properly to the welding surface and the welding is not happening properly (welding energy is traveling in the material straight ahead and at the same direction as it is brought to the material).

- It is recommended to arrange so called coupling surface at the upper part at the location where the joint construction is located at parts. This will concentrate the welding energy properly from the sonotrode to the joint construction.

  Coupling surface should be located right above the joint construction and it should have same width as joined construction.

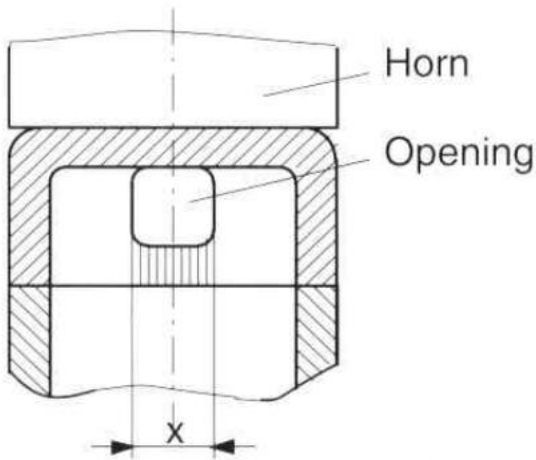
Assembly critical things for ultrasonic welded parts



- Welding joint construction location vs. sonotrode coupling area / surface.

Assembly critical things for ultrasonic welded parts

- There should not be any material discontinuities (holes, etc.) in the material between the place where welding energy is brought and welding surfaces. Discontinuities will cut the welding energy traveling and prevent welding at places where they exists.



Poor or no welding at all in zone X

Assembly critical things for ultrasonic welded parts

- Sharp corners should be avoided in part constructions to be welded. Minimum 0,5 mm corners are recommended.

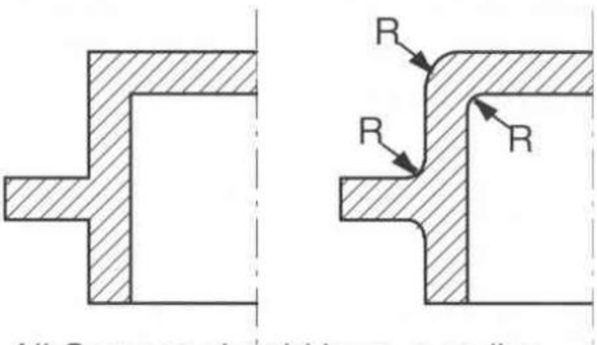
  If corner radiuses are smaller than 0,5 mm, there is big risk that the construction is broken at the sharp corners (notch effect) due to the strong vibration resonance coming from the ultrasonic welding vibration during welding.

  This is especially critical if the construction includes very thin ribs.

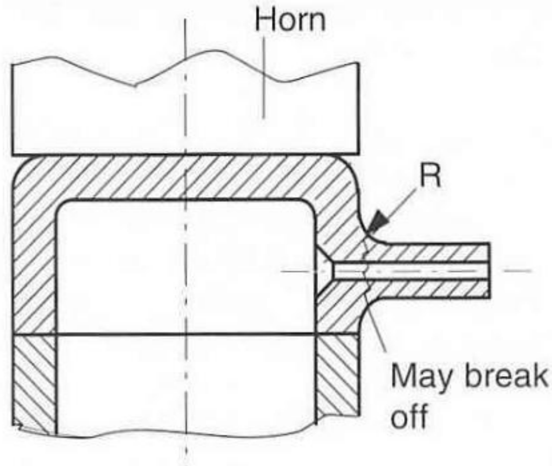
  It should be remembered that these vibration resonances are occurring even far from the place where the energy is brought to the construction.

Assembly critical things for ultrasonic welded parts

- Avoid sharp corners:



All Corners should have a radius.



Ultrasonically induced vibrations of extended parts

Assembly critical things for ultrasonic welded parts

- Free sinking path of the upper part

  - The upper part must be able to sink unhindered during ultrasonic welding.

  - No edges, ribs, bridges, etc. must be able to intercept the upper part during the sinking movement.

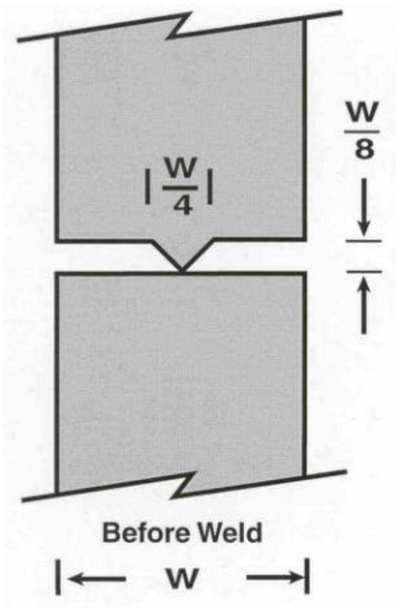
  - Also if there are any components in housing closed with ultrasonic welding, they may not intercept the upper part during the sinking movement. This includes also all spring forces coming from the connector springs.

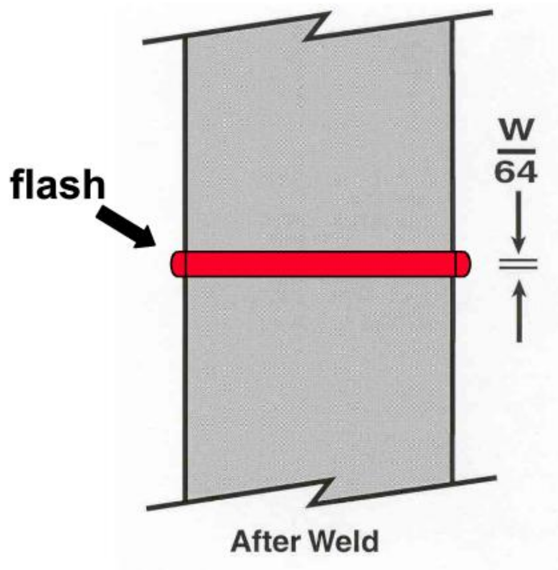
  - All forces intercepting the sinking movement will reduce the welding quality and cause problems during welding and if there is contacts from components closed in housing, they may very easily damage.

Different US joint constructions

- US joint constructions are roughly divided to following types:
  - US joint constructions with energy director:
    - Butt joint
    - Step joint
    - tongue and groove joint
  - Shear joints
  - In some applications shear joints may include also energy director.
- US joint constructions with energy director are very common (especially most simple butt joint), but there should always consider if for example shear joints are working better depending of the application.

Butt joint





Butt joint

- Angle of energy director 60° - 90°
  - Bigger angle stands better pressure affected by sonotrode before the energy director " ignites" .
- Height of the energy director 0,2 mm - 1,0 mm
  - Lower energy director for materials that are easy to weld.
  - Higher energy director for materials that needs more welding energy (difficult materials) like:
    - Semicrystalline polymers
    - Polymers that have low rigidity
    - Polymers that have high melting point temperature (like polycarbonate).
- Energy director tip has to be absolutely sharp to enable optimal welding start ("ignition").

Butt joint

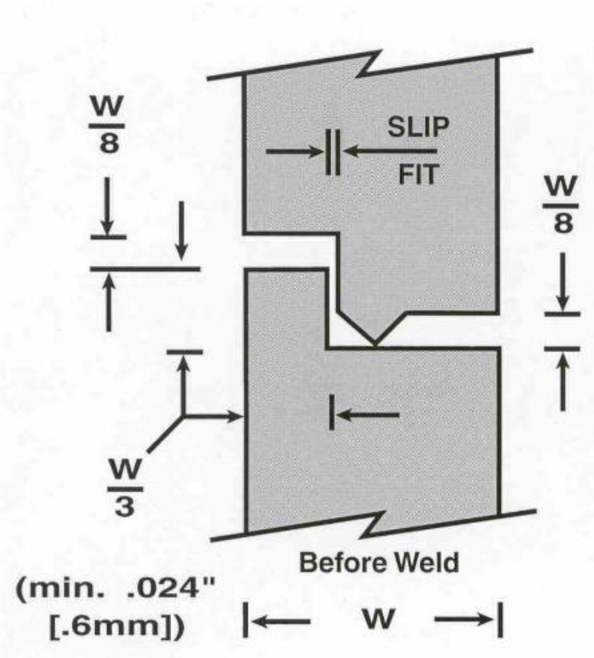
- Advantages:

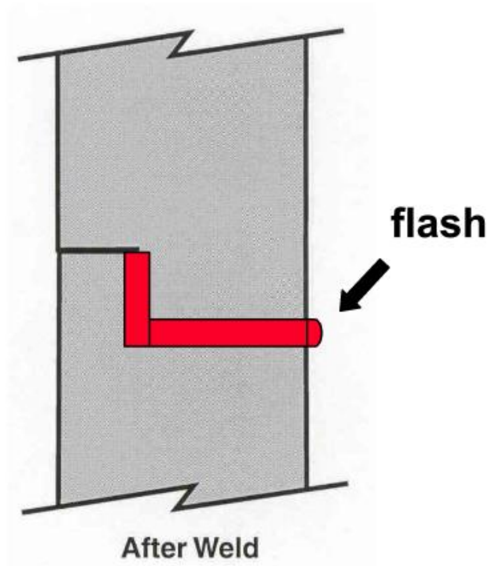
+ Quite simple construction to design in the construction and to manufacture in plastic tooling.

- Disadvantages:

– Welded parts are not self located by joint construction. Welded construction needs separate self locating features.
– Not suitable for joints that have high cosmetic requirements, because flashes arising during welding are easily coming visible especially if the energy director is close to the part edge.

Step joint





Step joint

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    - Polymers that have high melting point temperature (like polycarbonate).
- Energy director tip has to be absolutely sharp to enable optimal welding start ("ignition").
- There must be constructed clearance (slip-fit in picture) between the joint constructions vertical surfaces to avoid uncontrolled welding due too tight pre-fitting between welded parts. Recommended clearance 0,025 - 0,05 mm.

Step joint

- Advantages:

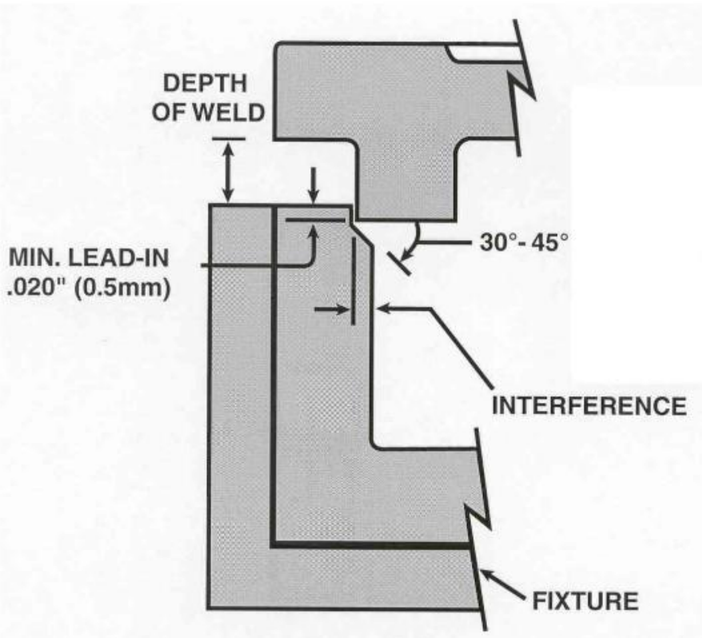
+ Stronger joint than butt joint.
+ Better joint than butt joint for joints where high cosmetic requirements → burr / flash normally coming only to the other side of the joint.
+ Welded parts are self locating themselves better than with butt joint.

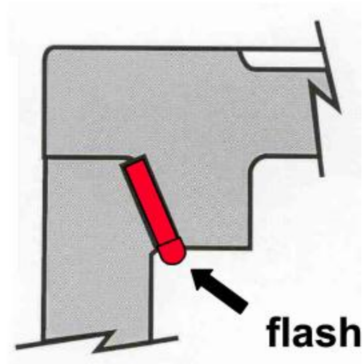
- Disadvantages:

– Implementation of the needed clearance (slip-fit) between the joint constructions vertical surfaces accurate enough increases the tool manufacturing and molding exactness (more difficulties / risks).

– Differences at the wall material thickness due to the joint construction may easily lead to the cosmetically problems at the outside surfaces of the parts (gloss differences).

Shear joint


DEPTH
OF WELD
MIN. LEAD-IN
.020" (0.5mm)
30°- 45°
INTERFERENCE
FIXTURE


flash

Shear joint

- Very strong and even hermetical joint possible to implement.
  - Strength of the joint is depending from the overlapping depth of joint.
  - To enable joint strength that exceeds part wall strengths, the overlapping depth should be min. 1,25 times wall thickness at joint area.
- Recommended especially for semicrytalline polymers (Semicrystalline polymers are changing from solid form to liquid form at very narrow temperature area. Normal energy director construction is not most optimized with semicrystalline polymers because melted plastic hardens before it will melt together with surrounding material).
- Shear joint constructions melting starts from small contact area (sharp edges) after which the melting continues at the vertical overlapping wall area "telescopically" during the joined parts thrusts inside each other.
- There should be good self locating features outside the welding joint area to ensure right positioning of the joined parts (the joint construction itself is not necessarily securing the right

Shear joint (cont.)

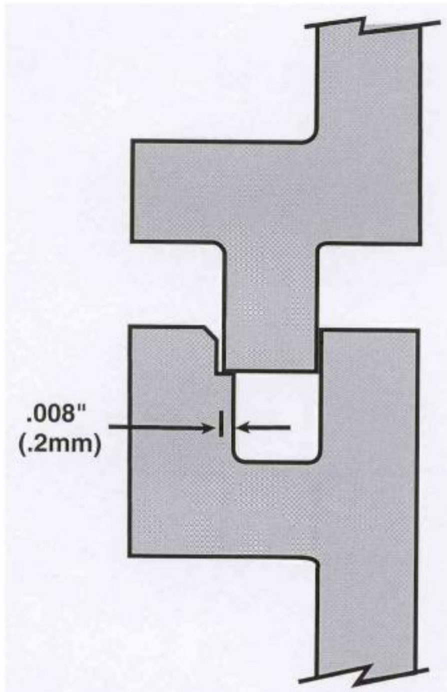
- Part in welding fixture has to be supported from outside up to the height where the joint is existing because the joint construction is forcing the parts walls at the area where the joining is happening outwards during the pressure from sonotrode is applied.

- Upper part against sonotrode has to be as low as possible because the joint construction is forcing the upper part inwards at the joint area during the pressure from the sonotrode is applied. Best would be if the upper part is a low lid type.

- Horizontal forces that are occurring during welding shear joints can be eliminated by using tongue and groove –modification of shear joint.

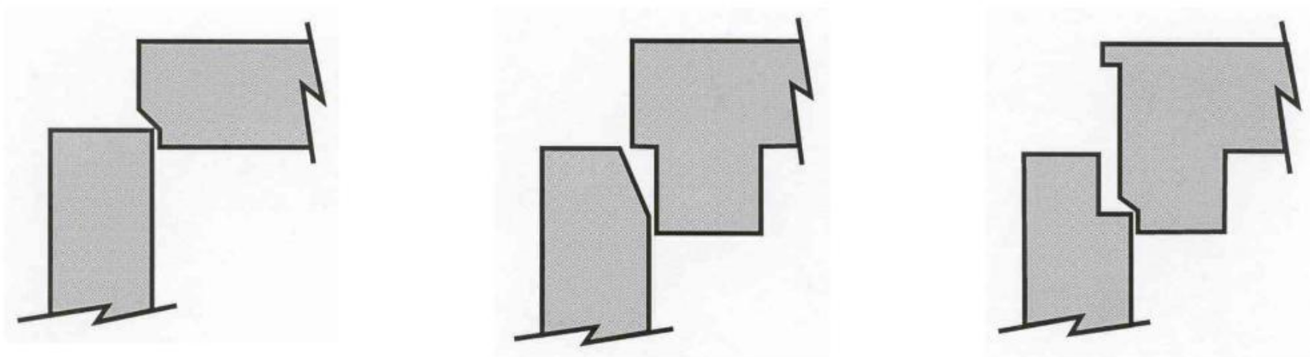
Shear joint

Tongue and groove –modification from shear joint, with which the horizontal forces to the construction during welding can be reduced.

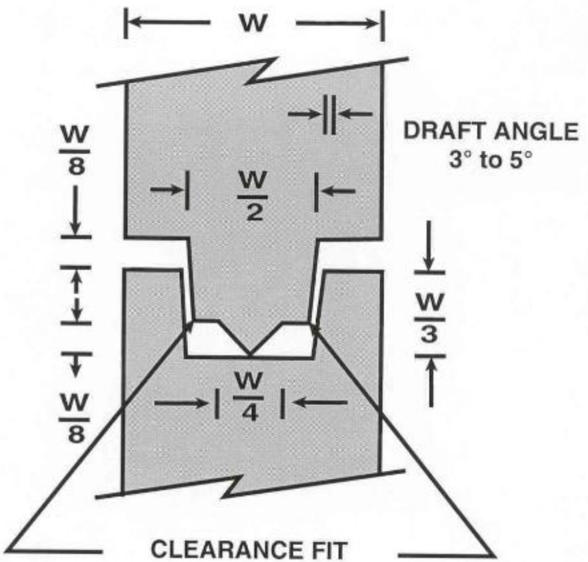


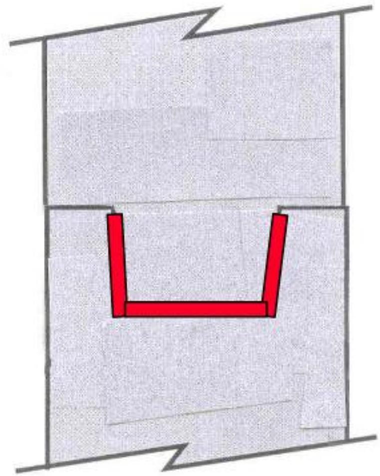
Shear joint

Different modifications of shear joint construction



Tongue and groove joint





Tongue and groove joint

- Angle of energy director 60° - 90°
  - Bigger angle stands better pressure affected by sonotrode before the energy director " ignites" .

- Height of the energy director 0,2 mm - 1,0 mm
  - Lower energy director for materials that are easy to weld.
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    - Polymers that have high melting point temperature (like polycarbonate).

- Energy director tip has to be absolutely sharp to enable optimal welding start ("ignition").

- There must be constructed clearance (slip-fit in picture) between the joint constructions vertical surfaces to avoid uncontrolled welding due too tight pre-fitting between welded parts. Recommended clearance 0,025 - 0,05 mm.

Tongue and groove joint

- Advantages:

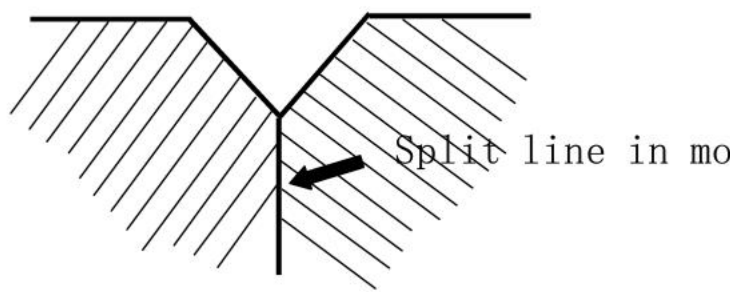
+ Strong joint, good strength properties.
+ God joint construction for joints with high cosmetic demands → normally burr / flash is left inside joint area.
+ Good self location of welded parts by the joint construction itself.

- Disadvantages:

– Implementation of the needed clearance (clearance-fit) between the joint constructions vertical surfaces accurate enough increases the tool manufacturing and molding exactness (more difficulties / risks).
– Differences at the wall material thickness due to the joint construction may easily lead to the cosmetically problems at the outside surfaces of the parts (gloss differences at surface areas where wall thickness changes).

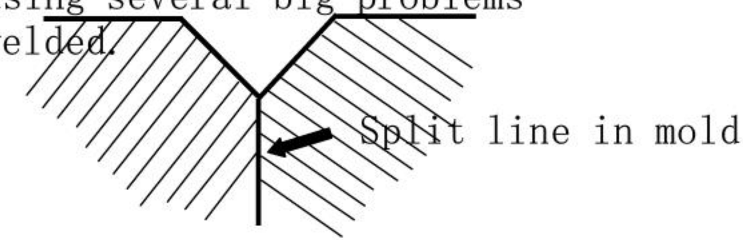
Energy director

- The tip of the energy director has to be absolutely sharp to enable proper welding start (ignition of energy director).
  - In tooling making the welded part, there has to ensure that the groove, which makes the energy director to the part, is absolutely sharp shaped at the bottom (making the tip of energy director to the molded parts). There is not allowed to be any radius (even small one) at the bottom of this groove in the mold.
  - The groove bottom sharpness in the mold can be secured for example by making split line in the mold at the place which is making the energy director tip.



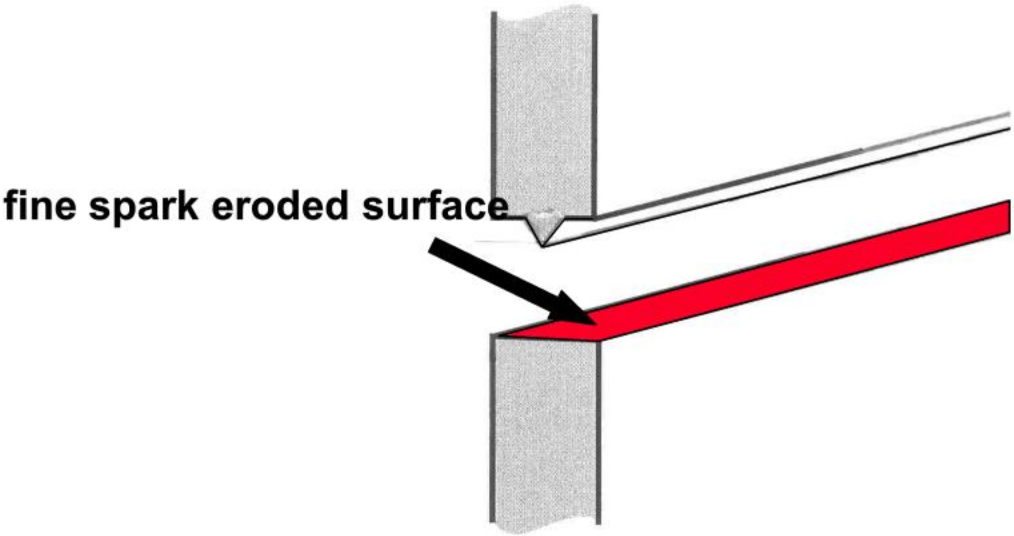
Energy director

- The tip of the energy director has to be absolutely sharp to enable proper welding start (ignition of energy director).
  - By implementing the split line in the tooling at the place which is making energy director to parts, there can be also avoided energy director tip un-sharpness affected by air trapped in the molding. Split line is enabling proper ventilation of tooling at this critical area.
  - When taking the mold in use it is very important to remember clean the split line carefully by disassembling the mold and washing the split line area carefully. If this is not done it is most obvious that all the storage oils / greases will raise from the split line during molding to the surface of the energy director of molded part and causing several big problems afterwards when the parts are welded.



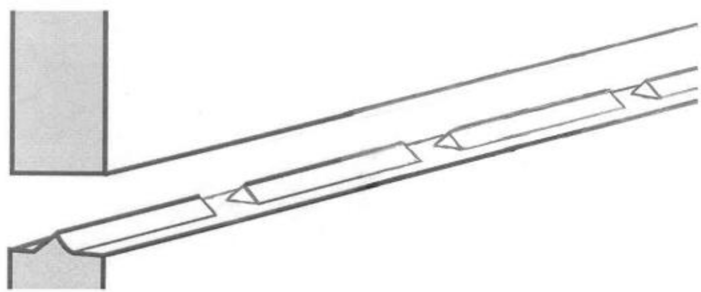
Energy director

- The surface which is coming towards the energy director is recommended to be smoothly coarse-textured (fine spark eroded surface). Welding is starting easier than if the surface against energy director is polished (there are more ignition points / more secure touch all over the joint).



Energy director

- Normally the energy director is designed uniform for the whole distance that is joined.
- In some cases it can be justified to use energy director that is split in length.
- If uniformed energy director is for reason starting to tear off the tearing can continue easily at the whole length of the joint. If the energy director is split in length also the joint is split in parts and possible tearing of joint is most obviously stopping at the place where the discontinuity is placed at the energy director line.



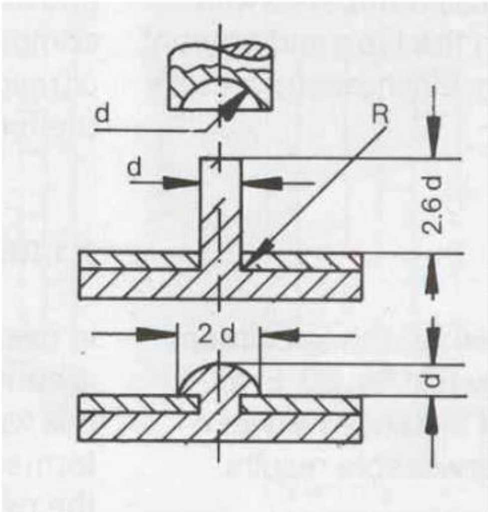
Other US joining methods

- US riveting
- US flanging
- US staking
- US insert assembly
- US spot welding

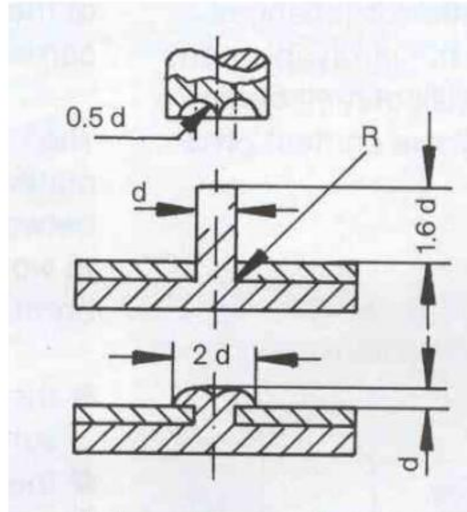
US riveting

- Enables part fixing between plastic part and non plastic part.
- Plastic pin is plasticized with oscillating / vibrating energy produced by sonotrode.
- Sonotrode is acting also as riveting mold with which the final shape of rivet head is formed.
- The volume of riveted plastic pin has to correspond to the planned volume of rivet head.
- It is important to ensure that the joined parts are pre-secured tight together before riveting to avoid any unplanned gaps between joined parts after riveting.

US riveting

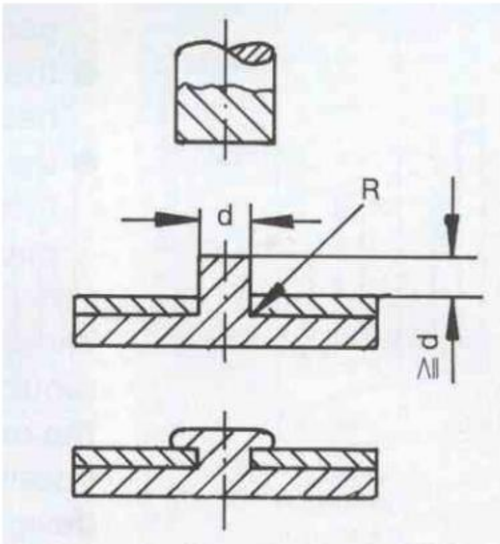


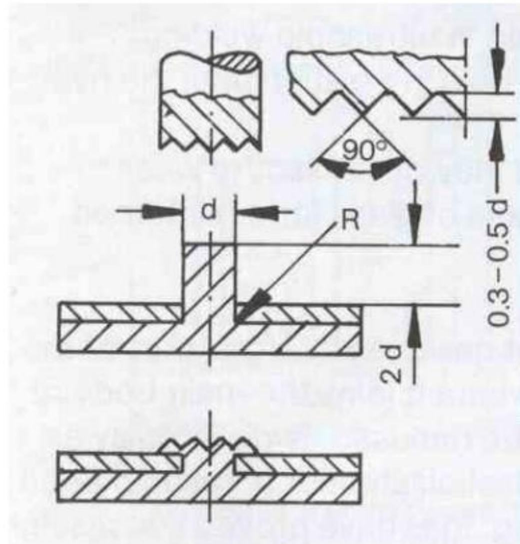
Recommended dimensions when the diameter of riveted pin is max. 3 mm



Recommended dimensions when the diameter of riveted pin is over 3 mm

US riveting

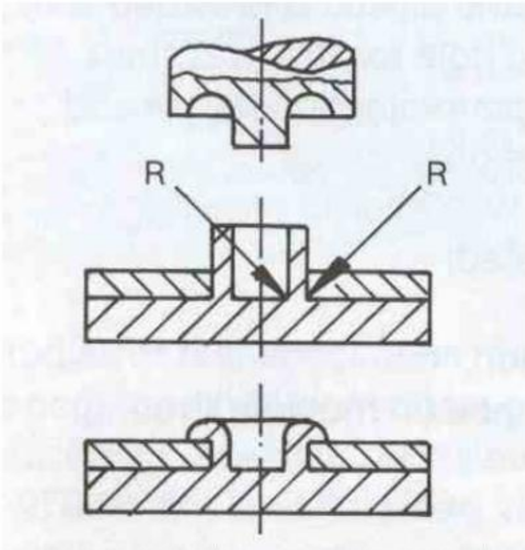


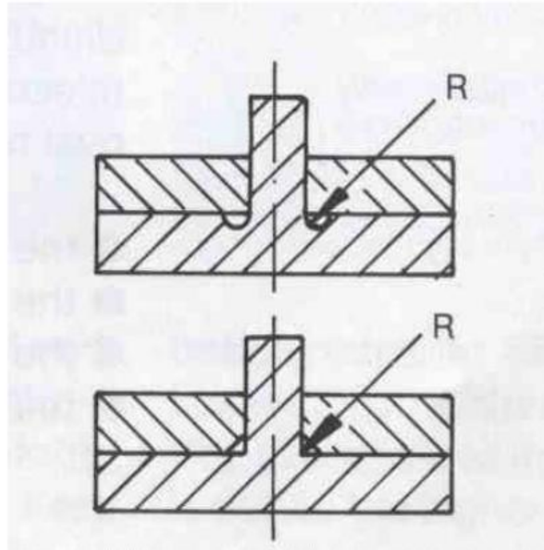


Recommended construction when several pins are riveted simultaneously with same tool where several riveting heads → allows slight inaccuracy between the horizontal distances of individual pins in multi-head tool.

Knurled surface of riveting head Allows slight inaccuracy also in t height location of individual pin l when several pins are riveted simultaneously with multi-head t

US riveting

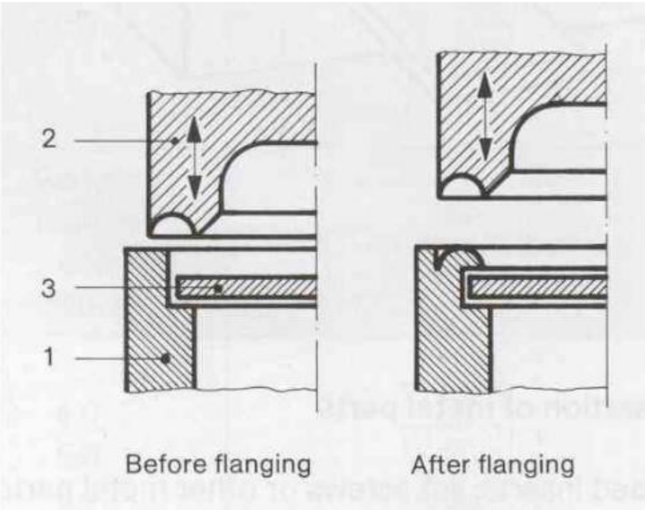


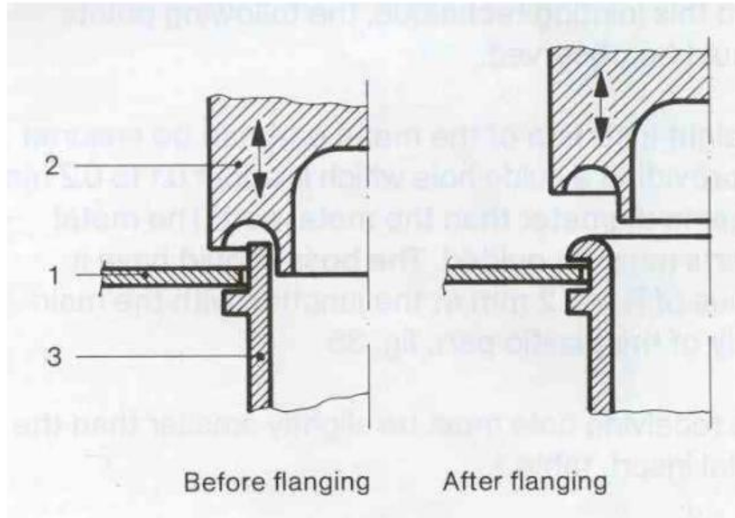


Recommended construction when riveted pin has large diameter (avoids sink-marks, etc.).

There has to be constructed adequa rounding at the pin root: R min. 0,3 r to avoid notch effect which leads to breakages of the pin.

US flanging





Inside flanging

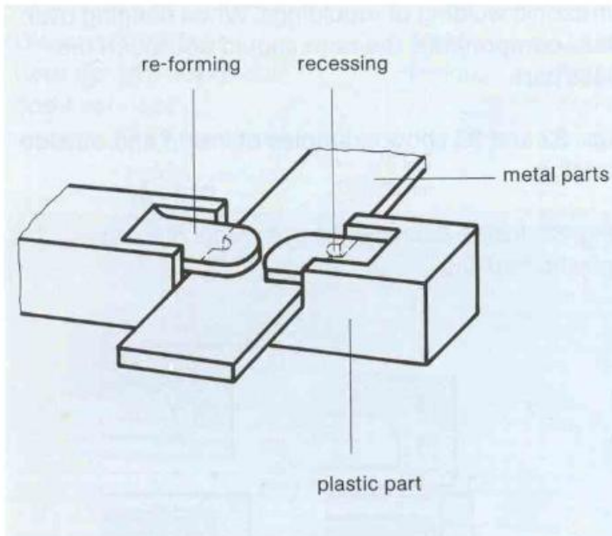
1 Plastic frame part
2 Sonotrode
3 Fixed part made from other material than plastic

Outside flanging

1 Frame part other material than pl
2 Sonotrode
3 Plastic part

US staking

- US staking is similar US joining method as US riveting and US flanging. At US staking method the plastic material is plasticised with ultrasonic oscillation / vibrating and forced to the locking shapes of joined parts (grooves, holes, etc.). After plastic is hardening it is forming fixed joint.

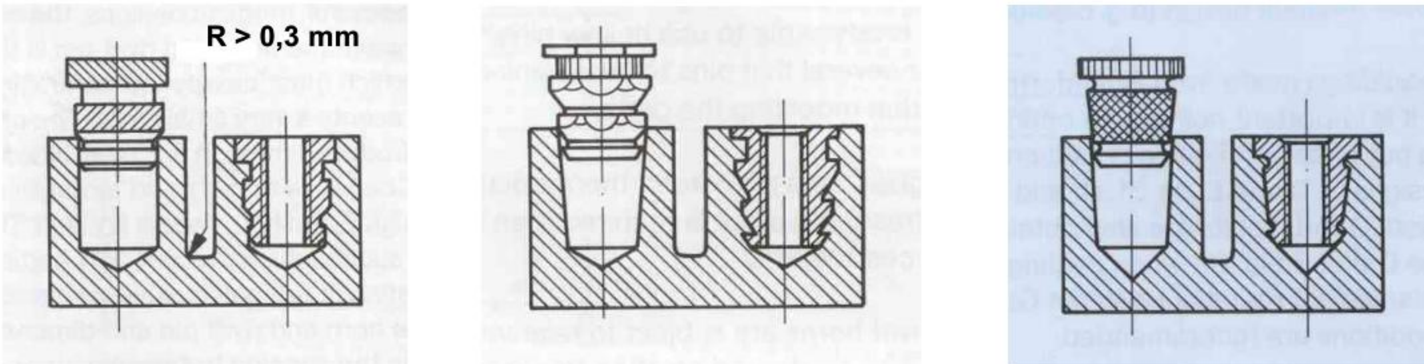


US insertion of metal inserts to plastic

- Different type of metal inserts can be embedded to plastic material with ultrasonic oscillation / vibrating energy.
- Depending of the construction and shape of the metal insert, it can be achieved very strong joint which stands well pull-out force as well turning / rotating forces.
- Critical things for joining construction:
  - There should be a guiding hole (lead- in counterbore) for insert, which diameter is 0,1 - 0,2 mm bigger than the diameter of the assembled insert.

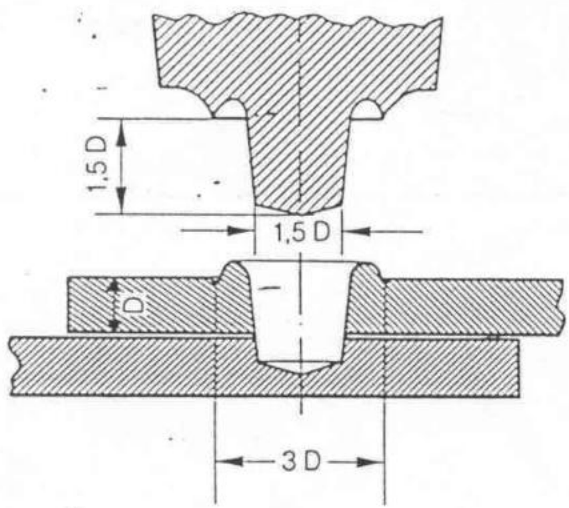
    Depth of the lead-in counterbore is depending of the insert construction. Important is that the insert is freely going to the hole deep enough to ensure right assembly angle (preventing insert to tilt during assembly).
  - If the assembly hole is blind (not through open) should the hole be about 2 - 3 mm deeper than the insert coming to the hole. This ensures that there is room enough for melting plastic which the insert is displacing during assembly.
  - If the insert is US inserted in hole at plastic tower, the material thickness at tower walls be min. 2 mm.

US insertion of metal inserts to plastic



Examples from assembly of different type of inserts.
Note the rounding of the sharp inner edges
to prevent notch effect.

US spot welding



US spot welding principle

US spot welding is used normally when flat shaped plastic parts are joined together and where there is for some reason not possible to use energy director construction (thermoformed sheets, blow molded parts, etc.).

During the US spot welding the tip shaped sonotrode is penetrating the upper material and thrusts partly to the lower material. Heat, which plastizes the plastic material, generates between the joining surfaces at welding area. After welding the material is cooling and the surfaces are fixed together.

Plastic material that the sonotrode displaces is flowing upwards and forming rounded shape bank around the hole. Normally there will not be any cosmetic marks / defects to the background surface opposite side where the sonotrode is pushed.

Thickness of the upper material is not recommended to be more than 8 mm.