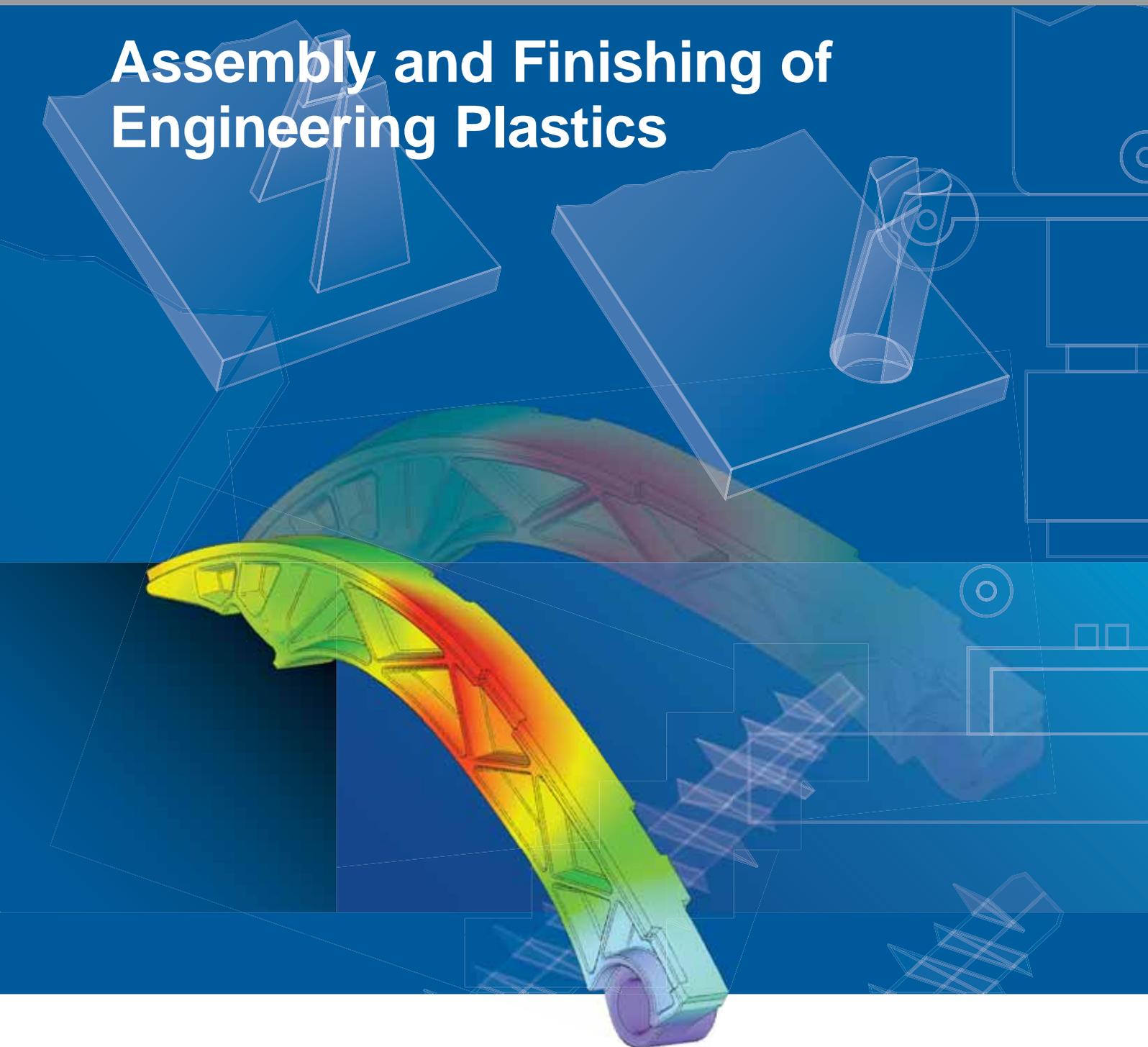


Secondary Operations Guide

Assembly and Finishing of Engineering Plastics



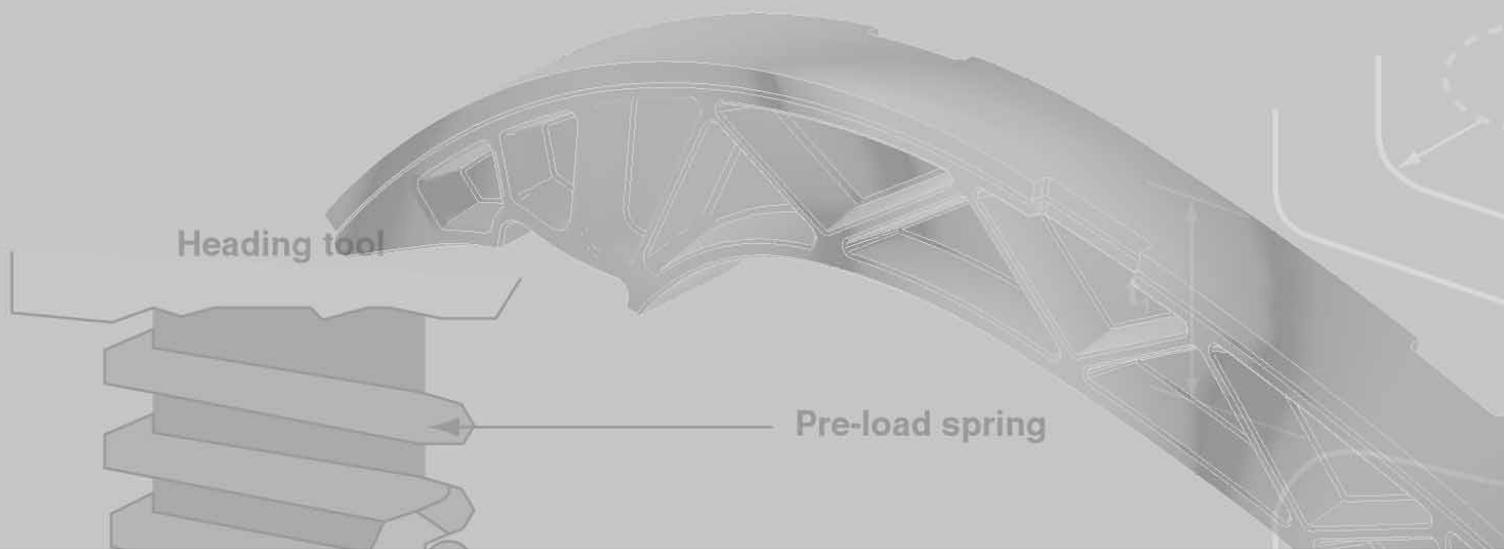
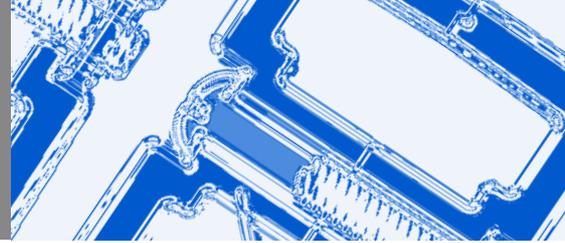


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1.1. Mechanical Fasteners

1.1.1. Introduction

Mechanical fasteners are generally used where connections can be easily assembled and disassembled.

1.1.2. Bolted Assembly

Bolted connections can be used when frequent assembly and disassembly of components are required.

Bolted connections are expensive and aesthetically are not the most elegant of connections due to the bolt head and nut being exposed. Since the bolts need tightening, which necessitates the use of tightening tools, the space available may be a constraint and has to be considered prior to designing.

Bolts and nuts are generally made of steel. The threads (both internal and external) can be molded in.

Bolts and nuts produced from thermoplastics are also available with standard machine threads. Thermoplastic bolts and nuts are ideally suited for applications where improved chemical resistance or electrical insulation is required. Thermoplastic bolts can solve the problem that may occur if steel bolts with a relatively low thermal expansion coefficient are used to join plastic components with a high thermal expansion coefficient.

To avoid overstressing during tightening, hollow bosses can be designed to accommodate the pre-stress, see figure 2. This also avoids the walls from buckling due to the high bending stresses.

To avoid stress concentration below the head of the bolt and the nut, washers should be used to distribute the load over a larger area. Bolts with conical heads lead to high tensile stresses under the head and must be avoided, see figure 3.

For information on calculating tightening torque and the stresses in a bolt see paragraph 1.1.4.

Figure 1 Possibility for frequent (dis)assembly.

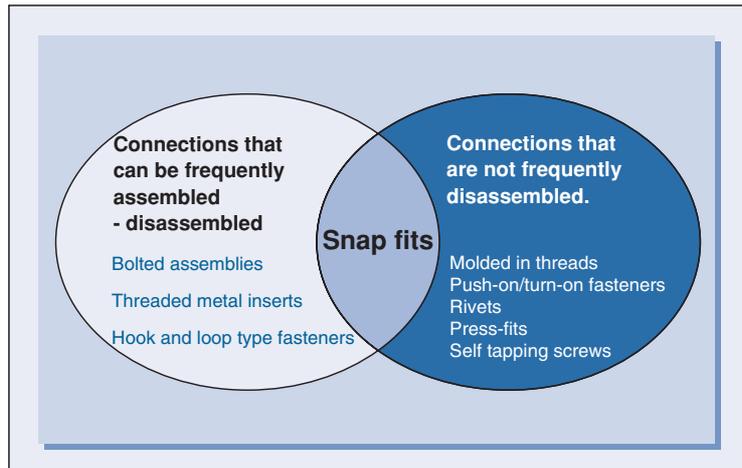


Figure 2 Hollow bosses are used to limit deflection.

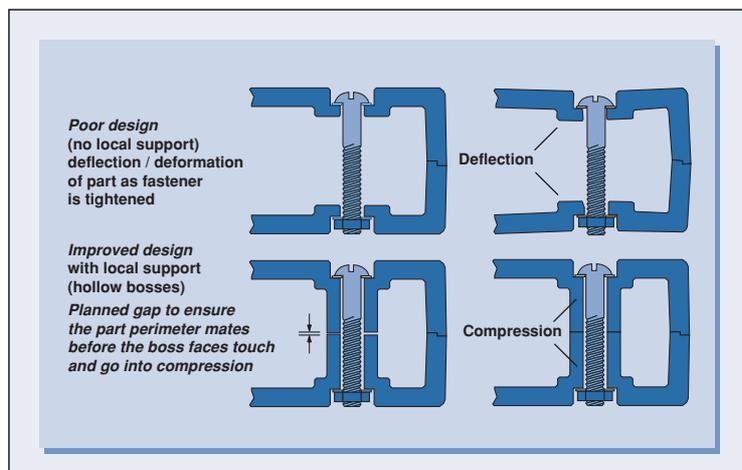


Figure 3 Bolts with a conical head should be avoided.

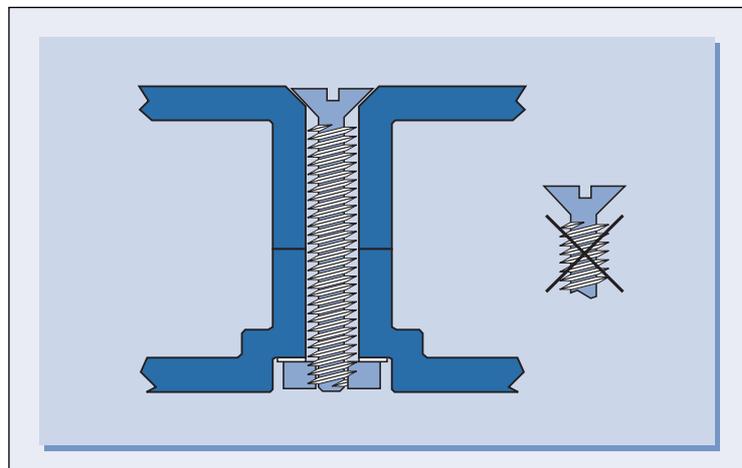
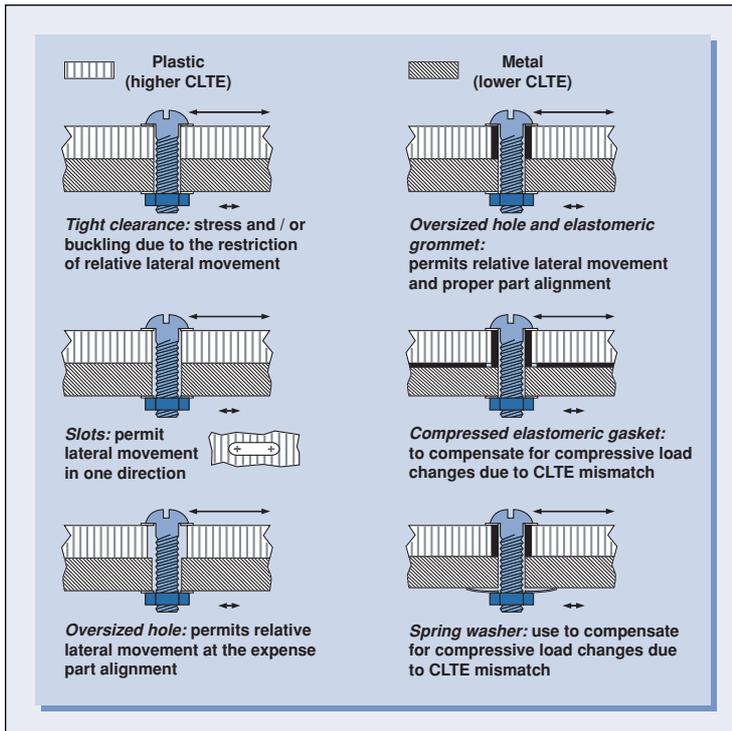


Figure 4 Several solutions for the thermal expansion mismatch.



Bolts should be tightened to the point where the compressive load and friction prevent relative motion.

Parts from dissimilar materials having different thermal expansion coefficients can be joined using expansion joints, slotted holes or with elastomeric grommets. Several solutions can be chosen to take care of thermal expansion mismatches, see figure 4.

When using bolted assemblies to join parts, the coefficients of thermal expansion (CLTE) of the different materials being assembled have to be taken in to consideration in the design. Since the CLTE for most plastics is greater than that of steel, loosening of the assembly at low temperatures and tightening of the assembly at high temperatures occurs. Under extreme conditions (very high temperatures), the compressive stresses in the plastic may increase above the yield strength due to the plastic expanding more than the bolt.

The difference in thermal expansion ΔL between the metal and the plastic can be calculated with the following formula.

$$\Delta L = (\alpha_{\text{plastic}} - \alpha_{\text{metal}}) \cdot L \cdot \Delta T$$

where

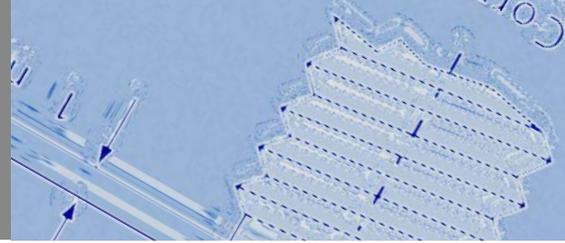
α_{plastic} = coefficient of linear thermal expansion of the plastic

α_{metal} = coefficient of linear thermal expansion of the metal

L = original length of the bolt between the head and the nut

ΔT = temperature increase.

If the temperature increases, the thermal expansion of the two materials leads to the elongation of the bolt and the compression of the plastic. This will increase pre-stresses in the bolt and the plastic, as shown graphically in figure 5.



The force-displacement diagrams of the plastic construction and the bolt are shown in the figures A and B respectively (see figure 5). The slope of the lines in these figures is determined by the stiffness of the bolt and the stiffness of the plastic construction. The two diagrams have been combined in figure C, whereby the distance between the origins of both curves is equal to ΔL . The resulting increase of the pre-stress can be determined.

The bolt head and the nut can be countersunk to improve appearance. Caps on the nuts are also a good way of improving aesthetics. Hexagonal shaped depressions can be molded into the parts to prevent the bolt head or nut from rotating, simplifying the assembly operation and also making the aesthetics of the assembly better.

1.1.3. Molded-in Threads

Design

Molded-in threads can be used when frequent assembly and disassembly are not required. Mechanical thread-forming operations are eliminated in that way. Both internal as well as external threads are commonly used.

When designing molded-in threads, the following rules must be taken into account.

- Maximise the root radius to reduce stress concentrations, see figure 6.
- Thread run-outs should preferably be rounded off to avoid cross threading and thread damage, see figure 7.
- Avoid tapered (pipe) threads, unless a positive stop is provided, see figure 8.
- Avoid very fine threads with a pitch smaller than 1 mm, considering mold filling and tolerances.
- Special attention must be paid to constructions in which metal and plastic mate. Differences in thermal expansion and stiffness may lead to high stresses or loosening of a connection. Sharp edges on metal threads may damage the plastic.
- The connection must be checked for high stresses due to tightening or loosening due to creep or stress relaxation.

Figure 5 Increase of the pre-stress in the bolt.

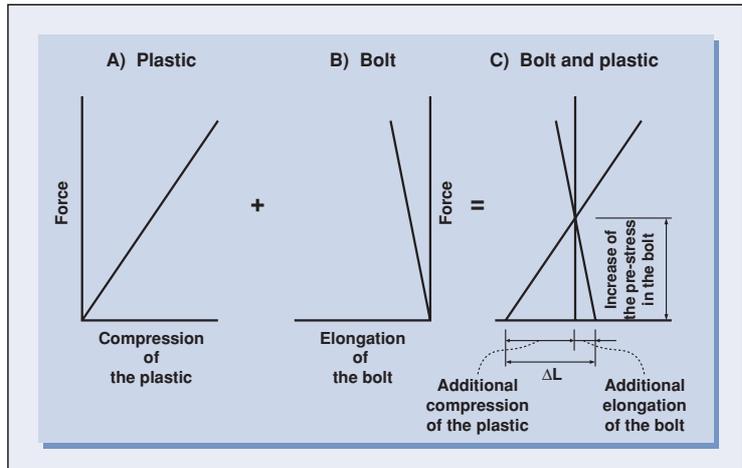


Figure 6 Typical root radius: $r = 0.14 P$ to $0.18 P$.

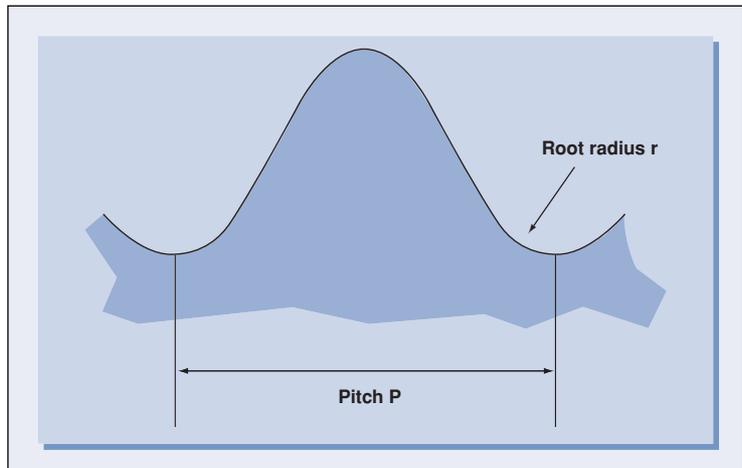


Figure 7 Avoid sharp edges.

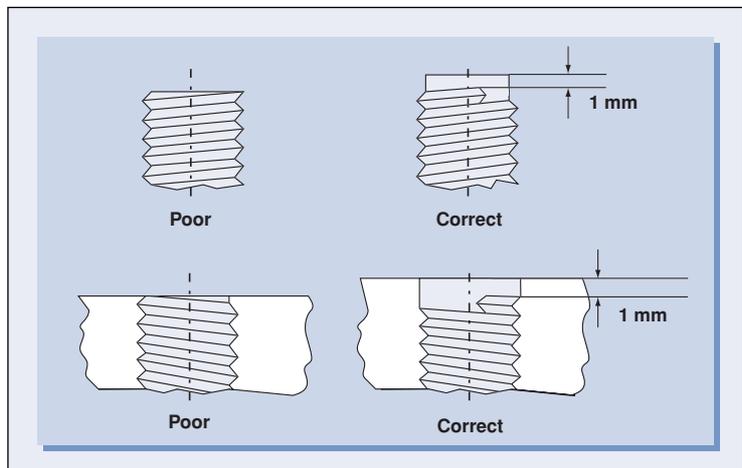


Figure 8 For tapered (pipe) threads, provide a positive stop.

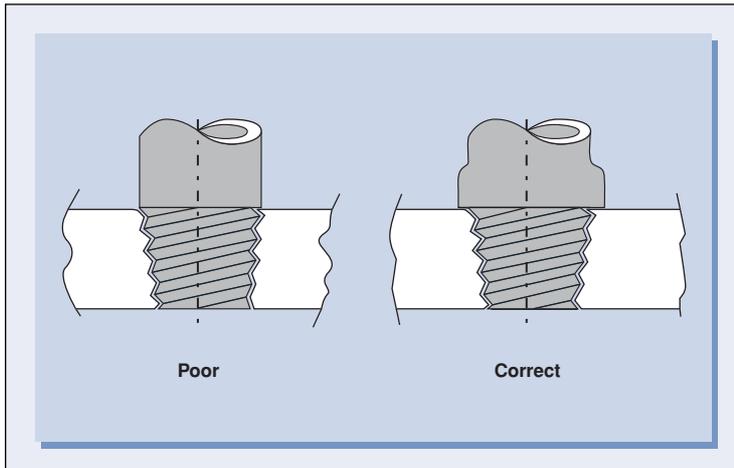
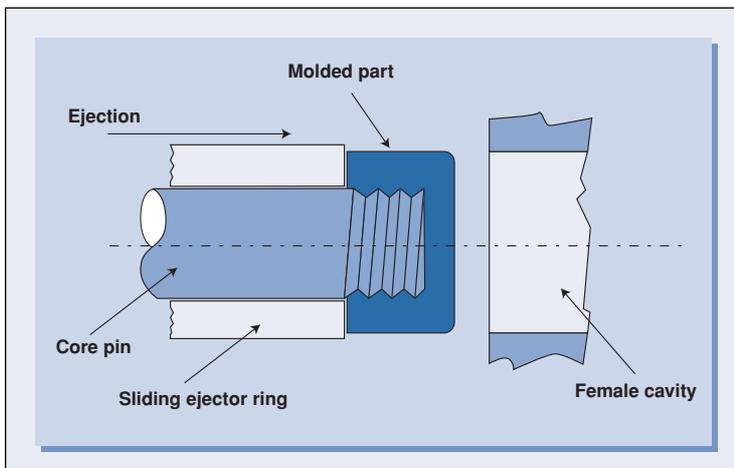


Figure 9 Stripping internal threads from the mold.



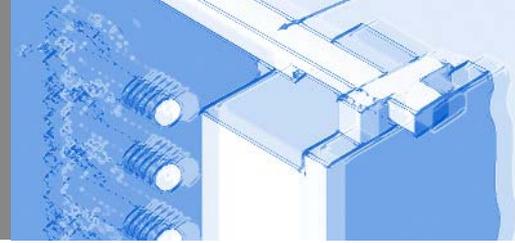
Molding internal threads

Internal threads can be molded in several ways:

- Stripped from the mold,
- Collapsible cores,
- Unscrewing devices,
- Hand loaded threaded inserts.

Stripped internal threads

The possibility to de-mold parts with internal threads by stripping them from the core is very limited and depends on the plastic type and the thread shape. Only thermoplastics with a low E-modulus and a high yield strain are suitable. During the stripping process the elastic limit must not be exceeded in the thread during ejection from the mold (see figure 9). For information about the maximum allowable short-term strain in the thread for DSM's thermoplastics, see par. 3. 2. Rounded threads are especially suitable for this option.



Collapsible cores

Collapsible cores are used for smaller parts, figure 10. Parting lines due to the segments of the split core will appear. Collapsible cores are wear-sensitive.

Unscrewing device for internal threads

High-quality threads can be produced in large production series using unscrewing devices, figure 11.

Hand loaded threaded inserts

Hand loaded threaded inserts are typically used for small production series and if a high precision is required. The inserts are removed from the mold together with the part.

Molding external threads

External threads can also be produced in several ways:

- In a mold with the thread in the parting plane,
- The thread can be stripped from the mold,
- Unscrewing devices can be used.

Figure 10 Collapsible core.

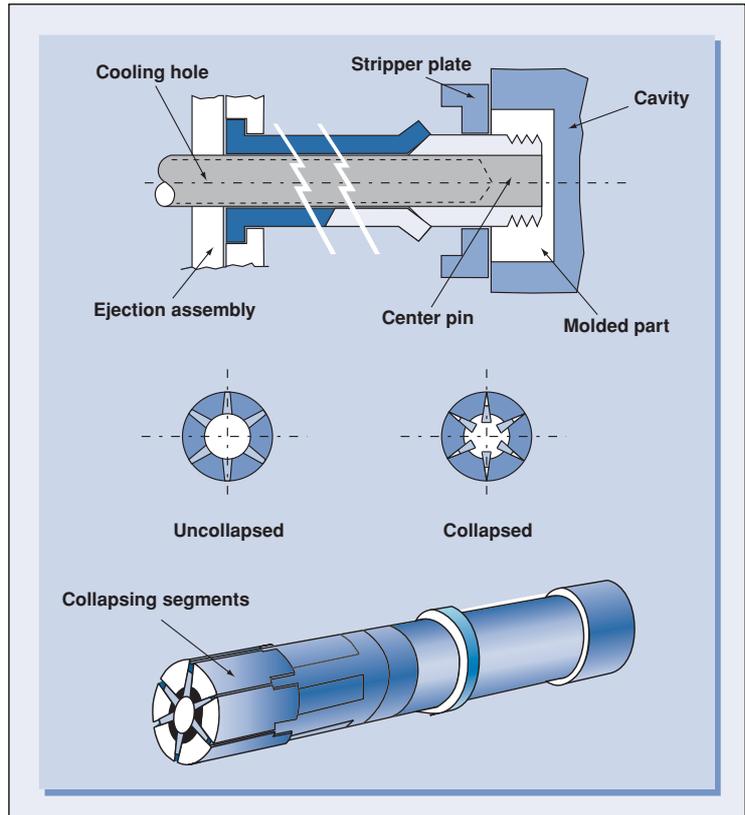


Figure 11 Unscrewing device for internal thread.

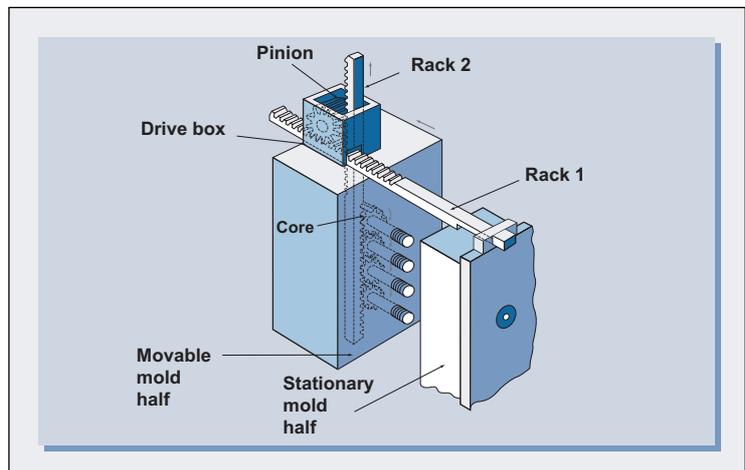


Figure 12 Mold without unscrewing device. The center line of the thread lies in the parting plane of the mold.

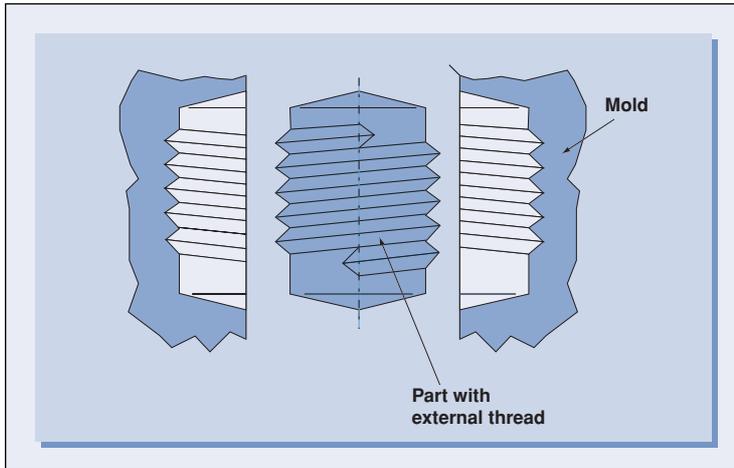


Figure 13 Stripping external threads from the mold.

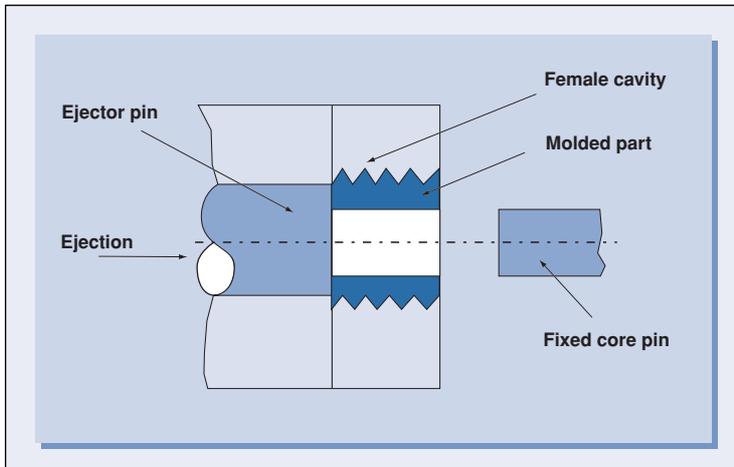
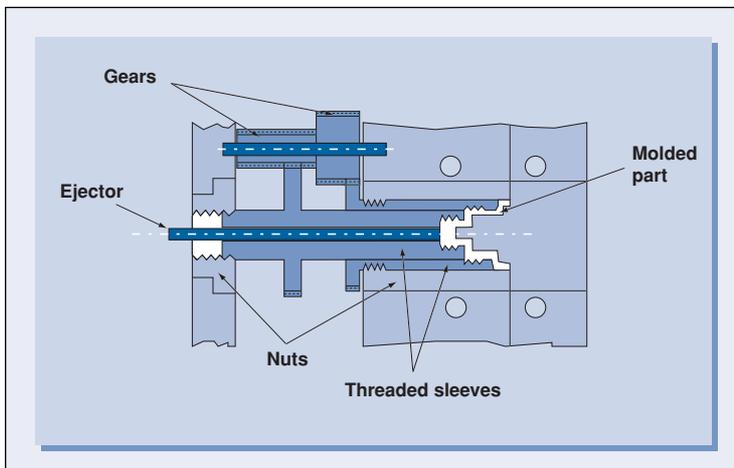


Figure 14 Unscrewing device for external threads.



Mold with the thread in the parting plane

The mold costs can be lowest if the center line of the thread lies in the parting plane of the mold, figure 12. An expensive external unscrewing device is not necessary in that case. A parting line will however be visible on the surface of the part.

If this is not acceptable, or if the center line of the thread cannot be located in the parting plane, for instance because the center line is in the mold opening direction, the part must be stripped from the mold, or an unscrewing device must be used.

Stripped external threads

Figure 13 shows the principle of stripping external thread of from the mold. The same considerations as for internal threads apply.

Unscrewing devices for external threads

An example of an unscrewing device for an external thread is shown in figure 14.

1.1.4. Calculation of Plastic Screw Threads

Tightening torque and torque in the thread

The required tightening torque M_h can be calculated with the following formula. (See also figure 15 for used symbols and dimensions.)

$$M_h = F \cdot \left(\mu_h \cdot R + \frac{\mu_t \cdot r}{\cos \alpha} + \frac{p}{2 \cdot \pi} \right)$$

where

- F = axial force in the screw
- R = average radius of the screw head contact surface
- p = thread pitch
- r = pitch radius of the thread
- α = thread flank angle in radial direction
- μ_h = coefficient of friction in the contact surface under the head
- μ_t = coefficient of friction in the thread

The first term in this expression represents the friction under the head and the last two terms represent the friction in the thread. So the torque M_t in the thread is:

$$M_t = F \cdot \left(\frac{\mu_t \cdot r}{\cos \alpha} + \frac{p}{2 \cdot \pi} \right)$$

The engineer must keep in mind that the coefficient of friction can show large variations, depending on the surface roughness, the lubrication conditions and the surface pressure etc. For information on coefficients of friction see par 3.3.

The stresses in cross-section A-A

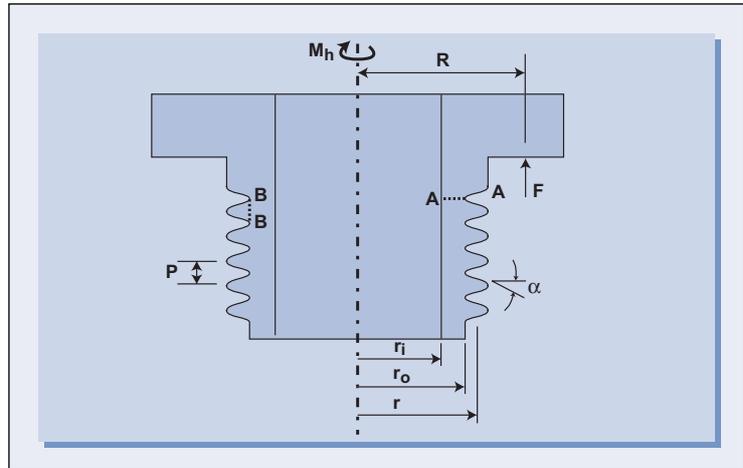
The nominal axial tensile stress σ_{ax} and the shear stress τ in cross section A-A of the shaft are:

$$\sigma_{ax} = F / A$$

respectively

$$\tau = r_0 \cdot M_t / I_p$$

Figure 15 Screw.



where

- A = surface of the cross-section of the shaft
= $\pi \cdot (r_o^2 - r_i^2)$
- I_p = polar moment of inertia of the cross-section = $\pi \cdot (r_o^4 - r_i^4) / 2$
- r_o = outside radius of the screw core
- r_i = inside radius of the screw core

The equivalent stress σ_{id} according to the von Mises failure criterion is:

$$\sigma_{id} = \sqrt{(\sigma_{ax}^2 + 3 \cdot \tau^2)}$$

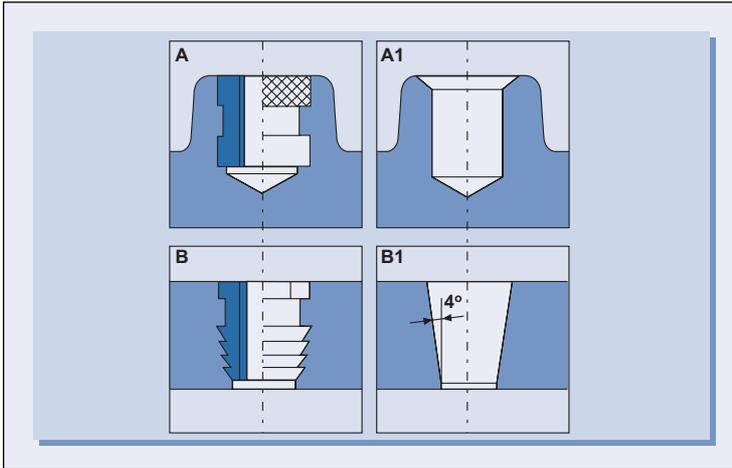
This equivalent stress must be smaller than or equal to the maximum allowable stress for the material:

$$\sigma_{id} \leq \sigma_{max}$$

The shear stress in cross-section B-B

It is a well-known fact that the load on a screw thread is not distributed uniformly over the windings. The first few windings of a thread take up by far the biggest part of the axial load F. In case of a plastic screw and a steel nut, or vice versa, the axial stiffness of the plastic part will be much lower than that of the steel part. The first winding will then bear as much as 50%

Figure 16 Inserts for ultrasonic insertion.



of the total load, which means that the stress level in the cross-section B-B should also be checked. The nominal shear stress τ is then:

$$\tau = (F/2) / (2 \cdot \pi \cdot p \cdot r_o) = F / (4 \cdot \pi \cdot p \cdot r_o)$$

and the equivalent stress σ_{id} according to the von Mises failure criterion is:

$$\sigma_{id} = \sqrt{(3 \cdot \tau^2)} = \sqrt{3 \cdot F / (4 \cdot \pi \cdot p \cdot r_o)}$$

Again this equivalent stress must be smaller than or equal to the maximum allowable stress for the material:

$$\sigma_{id} \leq \sigma_{max}$$

1.1.5. Threaded Metal Inserts

Insertion is a way to create a connection that can be assembled and disassembled repeatedly without problems. A metal part is inserted in the thermoplastic and the connection can be made using a standard screw or bolt.

Bosses are required in most cases. They should be properly designed to avoid sink-marks, internal stresses and warpage. Sink-marks will be less visible on dull surfaces, light colors, machined surfaces and round edges.

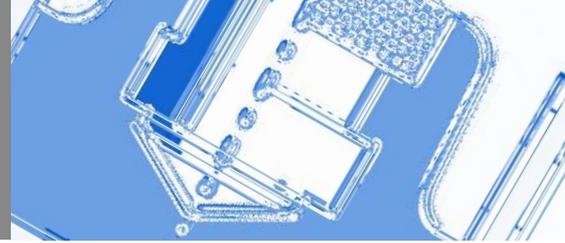
The different insertion techniques that are used will be discussed in more detail.

Ultrasonic insertion

The insert is pressed into a hole in the plastic by a horn that vibrates at ultrasonic frequency. The ultrasonic energy melts the plastic around the insert. Once the insert is pressed in, the plastic freezes off evenly around the insert.

Inserts as shown in figure 16 specially developed for ultrasonic insertion, are commercially available in various types and sizes.

Ultrasonic insertion gives a shorter molding cycle than parts with molded-in inserts. However, it also represents an additional manufacturing process. Care should always be taken to ensure the insert is solidly embedded in the substrate.



Heated inserts

A special press that pre-heats the insert is used for hot pressing-in. The inserts are pressed into the hole when they have reached the desired temperature. The heat-transfer melts the polymer and the molten polymer flows into the undercuts and secures the insert after cooling down.

The advantages are:

- strong connection, high loads can be absorbed
- low internal stresses in the plastic if well-designed and executed
- low equipment costs compared to ultrasonic insertion.

A longer insertion time is needed however, for heating-up and cooling-down the plastic.

Cold pressed-in inserts

Inserts can also be pressed directly into a hole. This can be done cold as well as hot. Pressing-in cold is done with a small press. The inserts are provided with knurls under an angle at the outside. It is the fastest and easiest way of insertion, but high stresses will be present in the material round the insert making the connection weak.

Molded-in inserts

The insert is put into the mold (cavity) during the injection molding cycle, figure 18. It is important to heat the inserts to a temperature close to the mold temperature before molding to remove differences in thermal expansion that can lead to a stress build up at the metal/plastic interface. It is also essential that the inserts are clean and free of any process lubricants.

Figure 17 Pressed-in Inserts.

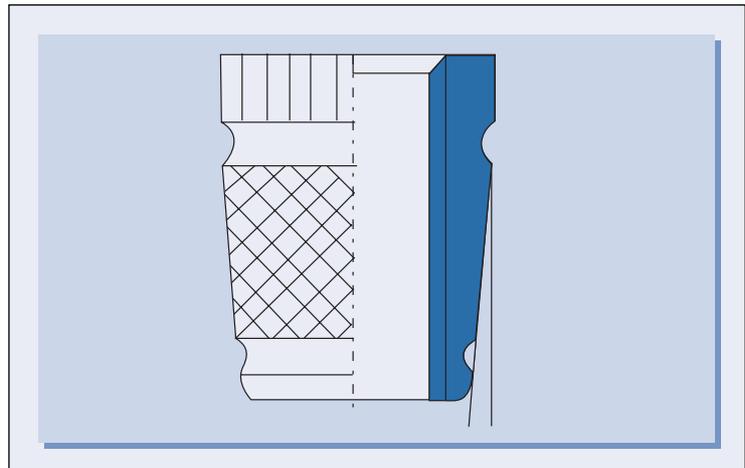
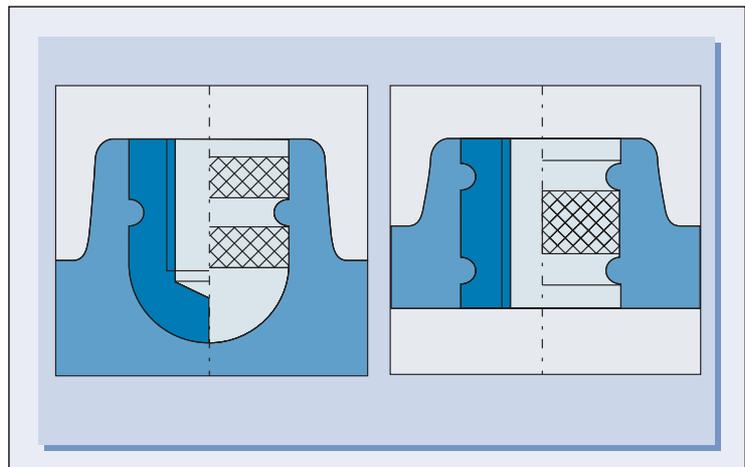


Figure 18 Molded-in inserts undercut with grooves and knurls.



Molded-in inserts have the following advantages:

- strong connection, high loads can be absorbed
- low internal stresses in the plastic if well-designed and executed.

There are some disadvantages in this process:

- a longer injection cycle is required to position the inserts in the mold
- heating of the inserts is necessary
- thermal stresses in the plastic if not well executed
- severe damage to the mold is possible if inserts move.

Figure 19 Coil insert.

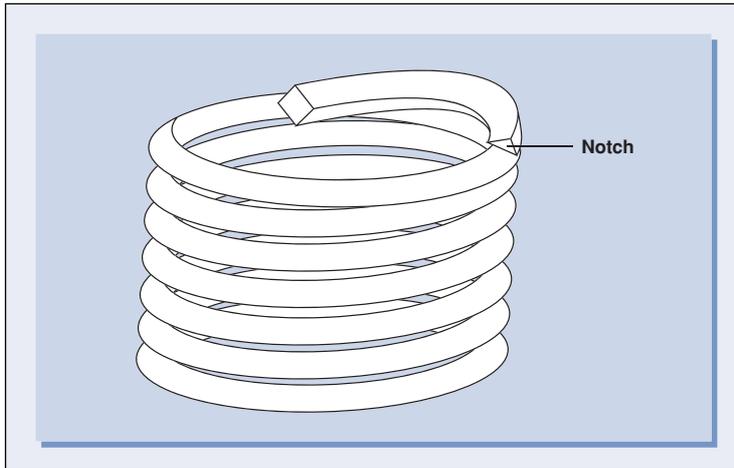


Figure 20 Thread-cutting inserts.

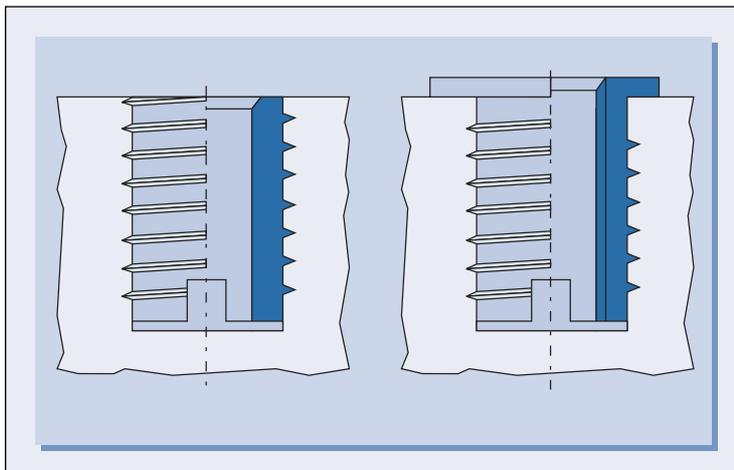
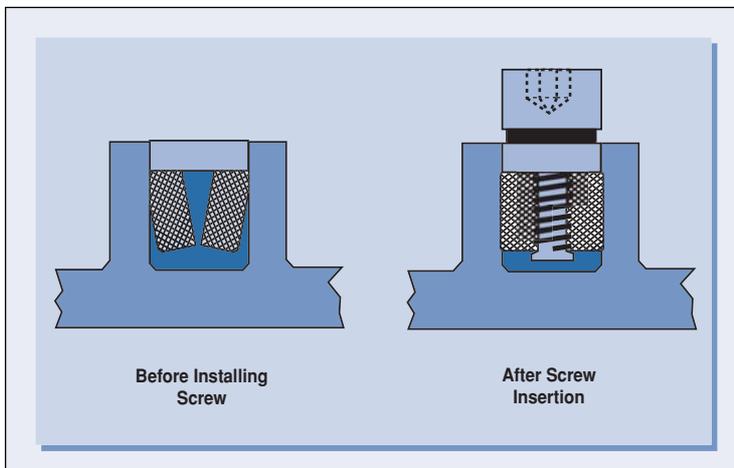


Figure 21 Expansion insert.



Coil inserts

Coil inserts (figure 19) offer a better wear resistance and strength than the surrounding polymer, but high stresses may be introduced into the boss. Coil inserts offer only limited connection strength.

Thread-cutting inserts

Thread-cutting inserts (figure 20) are comparable to self-tapping screws. The insert is screwed into a drilled or injection molded hole without internal thread. A cutting edge at the outside of the insert cuts a thread in the plastic.

Expansion inserts

Expansion inserts can simply be pushed into a hole in the product. They are provided with a saw cut at the bottom, thus forming separate segments. The two segments are spread after putting the insert in place, either before or during insertion of the screw (see figure 21).

Expansion inserts offer limited connection strength.

Recommendations:

- design simple inserts with undercuts for pull-out retention and grooves or knurls for torque retention
- avoid sharp corners
- use brass, stainless steel or plated steel inserts; raw steel inserts may rust
- use clean inserts to safeguard optimal interfacing between the metal and the thermoplastic (free from oil, grease, etc.)
- ensure that adjacent walls have sufficient thickness to prevent the insert from being pulled out during assembly
- keep knurls away from part edges for notch sensitivity.

1.1.6. Boss Caps

Boss caps (figure 22) are cup-shaped rings stamped from metal sheet which are pressed onto the top of hollow plastic bosses by hand, with a pneumatic device, or with a light press. The caps reduce the tendency of the bosses to crack by reinforcing the boss against the expansion force exerted by screws. The caps are used with thread forming screws and include a single thread for additional strength.

1.1.7. Push-on / Turn-on fasteners

Push-on and turn-on fasteners are self-locking and self-threading fasteners respectively that replace standard nuts. These fasteners are pushed or screwed onto studs molded into a part, capturing the mating component. They are easy to use, inexpensive and vibration resistant, and provide a light to medium duty assembly, where clamp load requirements are minimal.

The type of fastener in figure 23 produces a permanent assembly.

A removable assembly can be made with a Tinnerman® clip in combination with a stud with a D-shape cross-section.

The self threading nut in figure 25B also produces a removable assembly and allows for some control over the clamp force.

Figure 22 Sheet metal boss cap pressed onto the top of the boss to reinforce the boss and provide additional assembled strength.

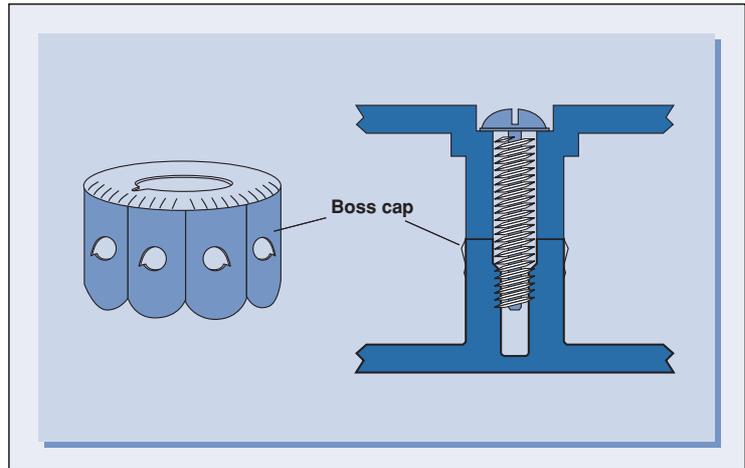


Figure 23 Push-on fastener for a permanent assembly.

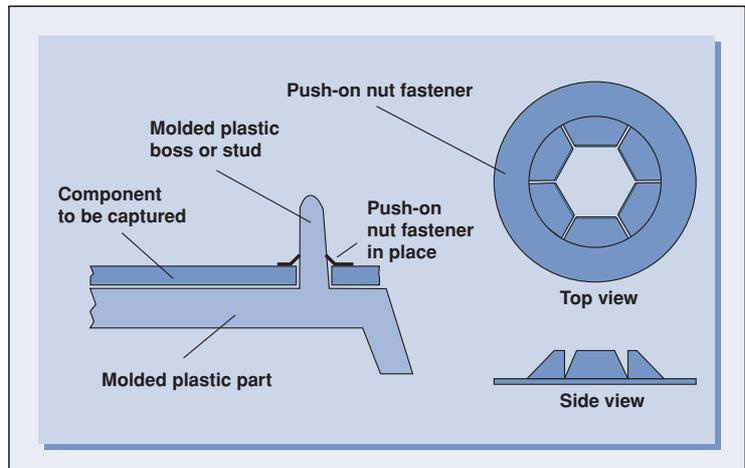


Figure 24 Tinnerman® clips for a removable or permanent assembly.

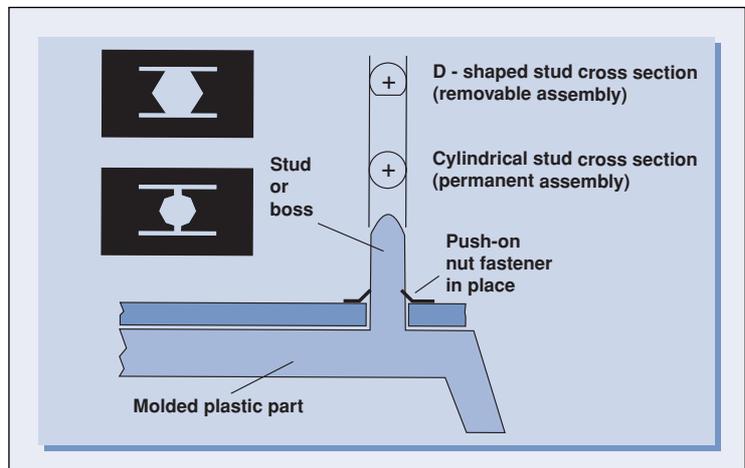


Figure 25 Push-on nuts (A) and self threading nuts (B).

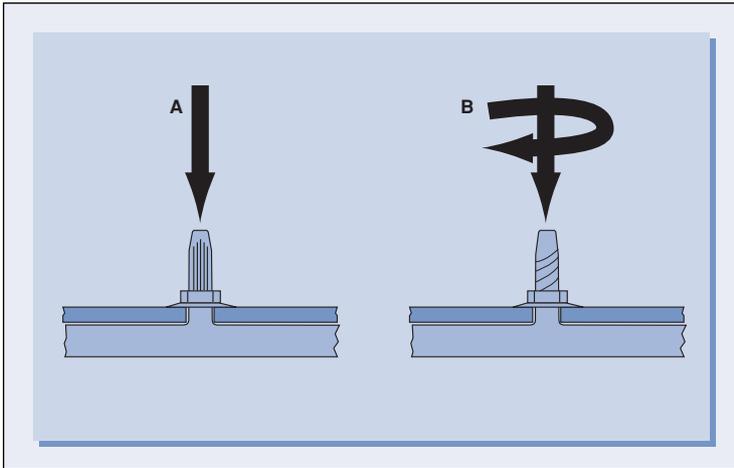
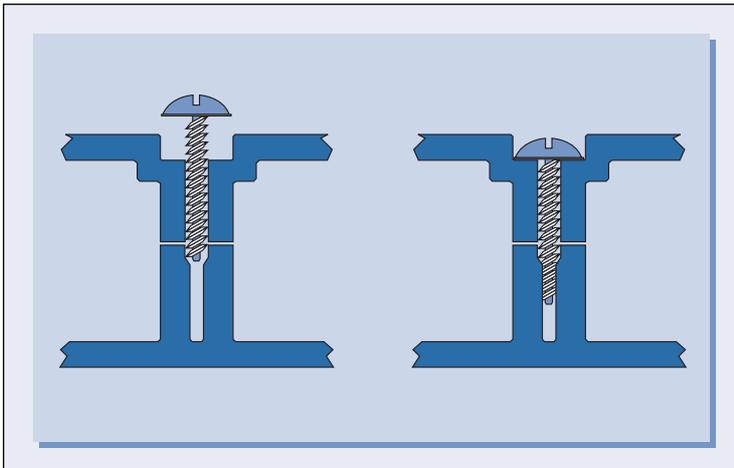


Figure 26 Typical self threading screw assembly.



A self threading screw assembly typically includes a through clearance boss and a boss with a pilot hole (figure 26). The holes can be molded-in or drilled through. The diameter of the pilot hole is greater than the root diameter of the screw, but smaller than the outside diameter of the screw.

Self tapping screws can be distinguished as either thread cutting screws or thread forming screws.

Thread cutting screws cut the thread during assembly. That means that every time the screw is assembled some material will be cut away. For that reason this type of screw is not recommended for repeated assembly and disassembly. In general, thread cutting screws are used for polymers with a low elongation at break and no ability to deform plastically. The relatively low hoop stress level associated with their use makes them suitable for use with glassy amorphous materials subject to crazing. As this type of screw generates small “chips” during the cutting process, space for the chips must be provided when blind holes are used. The chips can be a nuisance when through pilot holes are used.

Thread forming screws do not cut but deform the thermoplastic. Close to the screw the stresses can be high. Thread forming screws are generally used with lower modulus plastics, since ductility or cold flow is a prerequisite for their use. Thread forming screws can be used for repeated assembly and disassembly. In general, thread forming screws have higher drive and strip torque values than thread cutting screws.

1.1.8. Self-Tapping Screws

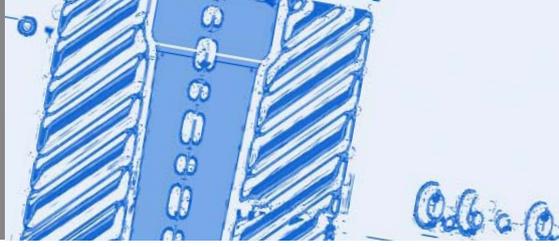
Self-tapping screws are used for assembling parts. Fewer parts need to be assembled compared to bolt-and-nut connections, with lower fastener and equipment costs. No nuts are required, so one smooth surface is obtained. Also the aesthetics of self tapping screws are better than bolts. Recyclability is good.

In self-tapping screw assemblies, mating plastic threads are formed directly on the part when the screw is tightened into the assembly. They have limited durability and repeated assembly is possible to a certain extent.

With regard to screw geometry the following requirements should be observed:

- thread flank angle must be as small as possible (30°) in order to obtain small radial and hoop stresses in the boss
- thread core design possibly profiled in order to allow a trouble-free material flow during the thread-forming process

In special cases the usefulness should be established by means of component tests.



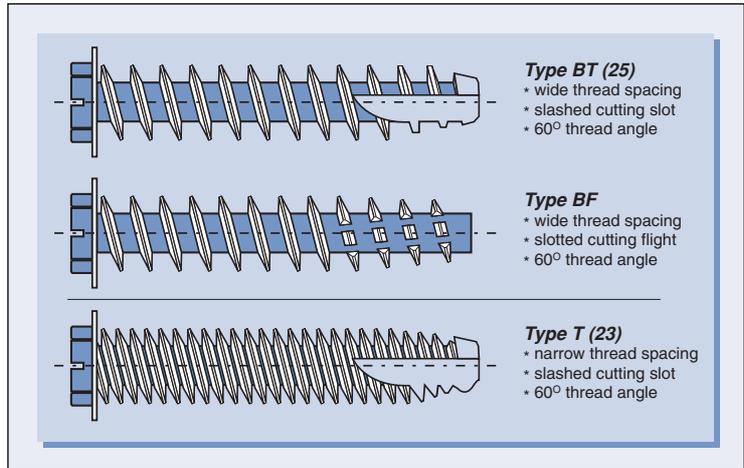
Standard thread cutting screws

Figure 27 shows some examples of standard thread cutting screws. These screws are provided with cutting slots.

The type BT (formerly known as type 25) screw is the most common standard thread cutting screw due to its wide thread spacing and generous cutting slot. The type BF screw also has wide thread spacing, but the slotted cutting flights may tend to clog when working with softer materials. The B series screws have been used with materials having a flexural modulus as a low as 1400 MPa.

The type T (or 23) is often useful with very high modulus glass reinforced materials with a flexural modulus greater than 7000 MPa.

Figure 27 Standard thread cutting screws.

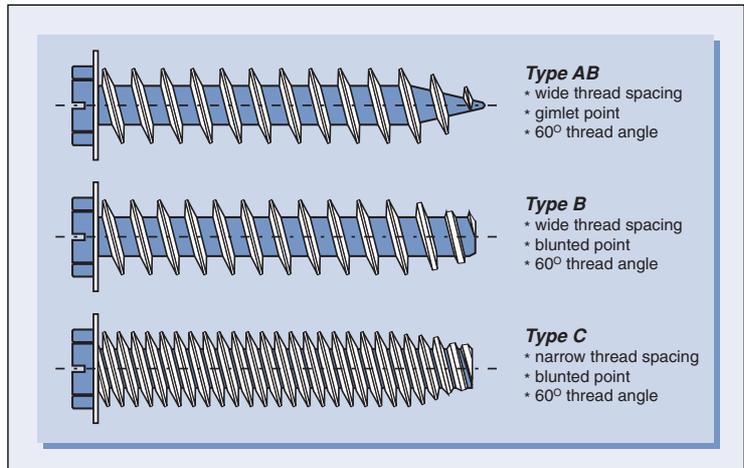


Standard thread forming screws

Thread forming screws do not contain cutting slots and do not produce chips. They are generally used with plastics with a modulus smaller than 3000 MPa. Figure 28 shows some examples.

These standard screws with their 60° thread angle generate relatively high radial and hoop stresses. The wider thread spacing of the types AB and B is recommended over the type C for most applications. The gimlet point of the type AB necessitates extra long bosses as the tapered point does not contribute to the strength of the connection.

Figure 28 Standard thread forming screws.



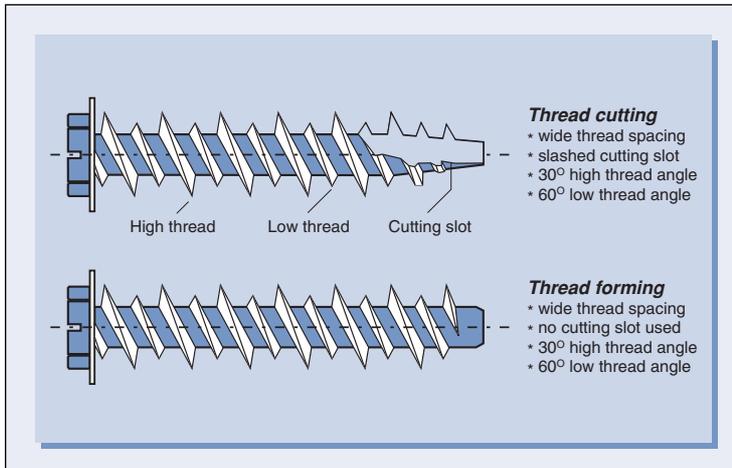
Self-tapping screws designed for plastics

HiLo® screws are designed with a double lead, consisting of a high and a low thread. The screw thread configuration has a smaller minor diameter than that of conventional screws and the high threads make a deeper cut into the material between the threads, contributing to greater resistance to pullout and stronger fastening. The high thread has a 30° thread angle and the low thread has a 60° thread angle.

The screws are available in thread cutting and thread forming varieties and with different point and head styles.

Plastite® thread-forming screws have a more or less triangular cross-section, which reduces the driving torque. After installation, cold flow of the plastic effec-

Figure 29 HiLo® screws.



tively locks the screw in place, increasing the resistance to loosening and making the screw ideal for vibration applications.

PT® screws, supplied by Ejot, are thread-forming screws with a 30° thread angle and a modified shank, which is said to improve plastic flow during the thread forming operation.

Polyfast® screws have an asymmetric screw profile. The widely spaced flights have a 35° leading edge and a 10° trailing edge.

Figure 30 Plastite® thread-forming screws.

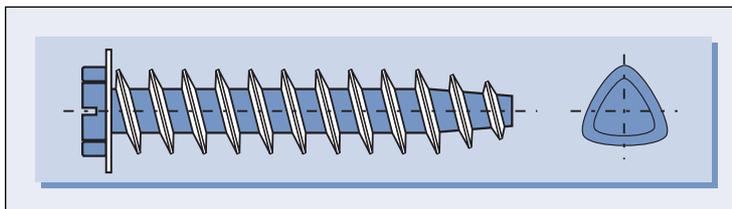


Figure 31 PT® screws for plastics up to 40% GF.

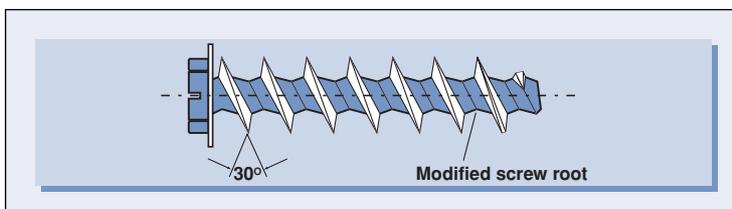
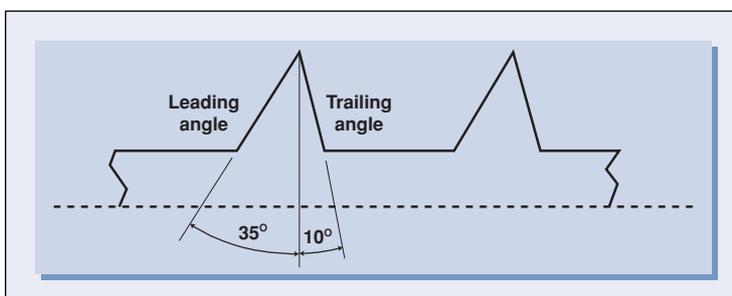
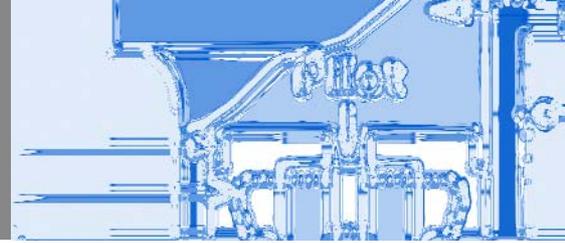


Figure 32 Polyfast® screws.





Bosses

Optimum bosses can be designed using recommendations given in the table 1.

A cylindrical lead-in counterbore should be considered in the design in order to reduce edge stress.

Tightening torque

When using screw assembly, a distinct difference can be noticed between the torque required to assemble and that required to over tighten the screw, see figure 34.

The torque gradually increases from point A to point B, due to friction in the thread and thread forming forces. The head of the screw touches the part at point B, after which the torque rapidly increases until point D, where the stripping torque is reached and the material starts to yield or break. The tightening torque (point C) should be chosen well below the stripping torque, at least a factor 2 smaller. The tightening torque and the stripping torque can best be determined experimentally.

During the assembly process a maximum speed of about 500 rpm should be observed. At higher speeds, the resulting friction may melt the material.

Figure 33

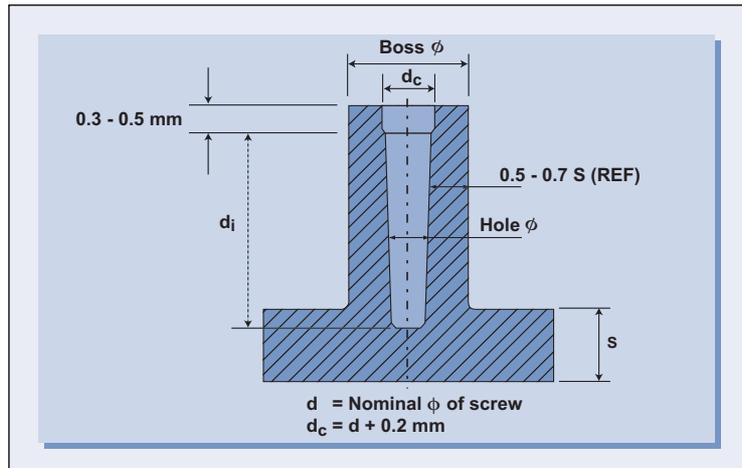


Table 1 Recommended boss design. (Source Ejot)

Material		PT Screw System Hole ϕ	Boss ϕ	Insertion depth d_i
Akulon	PA6 and PA66	$0.75 \times d$	$1.85 \times d$	$1.7 \times d$
	PA6 + 30% GF	$0.8 \times d$	$2 \times d$	$1.9 \times d$
Stanyl	PA66 + 30% GF	$0.82 \times d$	$2 \times d$	$1.8 \times d$
	PA46	$0.73 \times d$	$1.85 \times d$	$1.8 \times d$
Arnite	PA46 + 30% GF	$0.78 \times d$	$1.85 \times d$	$1.8 \times d$
	PET and PBT	$0.75 \times d$	$1.85 \times d$	$1.7 \times d$
Xantar	PET and PBT + 30% GF	$0.8 \times d$	$1.8 \times d$	$1.7 \times d$
	PC	$0.85 \times d$	$2.5 \times d$	$2.2 \times d$
Xantar C	PC + 30% GF	$0.85 \times d$	$2.2 \times d$	$2 \times d$
	PC + ABS	$0.8 \times d$	$2 \times d$	$2 \times d$

Figure 34 Torque versus number of screw turns.

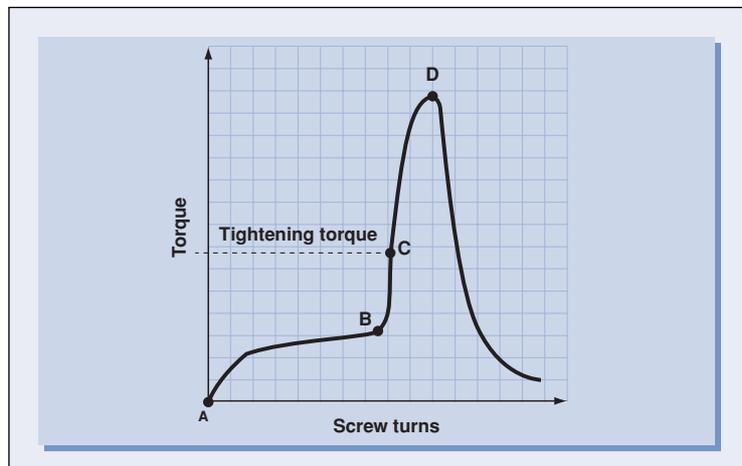


Figure 35 Different types of rivets.

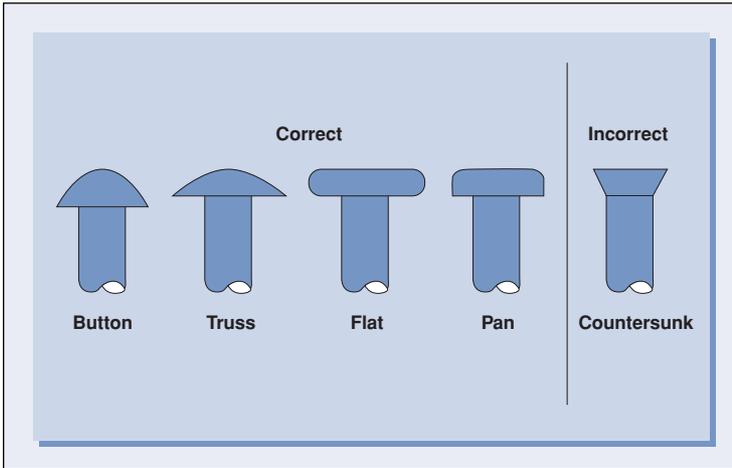


Figure 36 Heading tool.

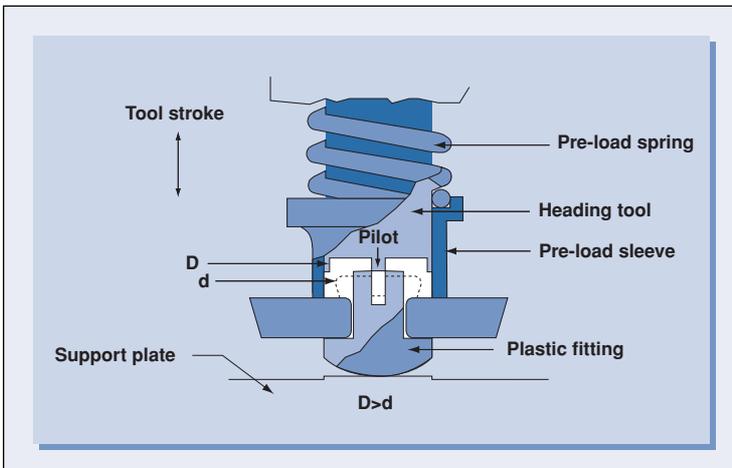
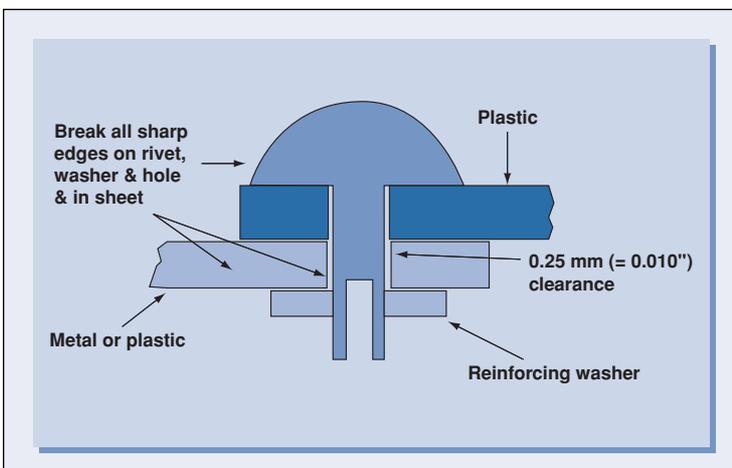


Figure 37 Reinforcing ring under the head of the rivet.



1.1.9. Riveted Assembly

Rivets provide a simple and economic assembly process, and produce a strong permanent mechanical joint. They are used to join thin sections of plastics, plastic to metal sheet or plastics to fabric. The process can easily be automated. Different types of rivet heads are available, as shown in figure 35.

The diameter of the head must preferably be three times the shank diameter to reduce the stresses in the parts by distributing the clamp force over a larger area. A conical head should not be used, as it produces high tensile stresses.

Rivets can be produced from metal or plastic. Aluminium and plastic rivets produce smaller compressive stresses in the parts.

A 0.25mm (0.010 inch) clearance between the rivet and the molded hole is recommended to account for tolerance variations and the coefficient of thermal expansion mismatch. A head is formed at the shank by plastic deformation of the material. The head can be made with a hand vice or a press.

Figure 36 shows a typical example of a heading tool. Load control devices should preferably be used during rivet installation to ensure correct clinching pressure and consistent assembly thickness.

A reinforcing washer under the head of the rivet helps to minimise the stresses in the parts, just like a shouldered rivet.

1.1.10. Hook-and-Loop Fasteners

Hook-and-loop fasteners are available in a variety of shapes, sizes and colors.

They can be opened and closed hundreds of times and can be used for many applications such as attaching doors and panels and other frequently removed parts, but also to attach electric cables, optical fibre cables, or hoses. Hook-and-loop fasteners are available either plain-backed or adhesive-backed. Plain-backed tape can be attached to a plastic part by rivets (see figure 39).

1.1.11. Press-Fits

Introduction

Press-fits are a simple and cost effective means to connect two parts. A press-fit is usually applied to connect a hub to a solid or hollow shaft, or to fix a bush in a housing. Interference between the two parts supplies the required pre-stress to enable the connection to transmit an axial force or a torque.

The hub and the shaft may both be of plastic, but a combination of plastic and metal is also possible. If different materials are used, attention must be paid to differences in thermal expansion, which may cause loosening of the connection or too high stresses.

Stress relaxation

Stress relaxation in the plastic may also lead to loosening of the connection. Isochronous stress-strain curves can supply information about the stress relaxation that will take place, see figure 40.

The stress level immediately after assembling is σ_0 in this example, at a strain level ϵ_0 . After a certain time the stress reduces to $\sigma(t)$, while the strain remains constant. This means that the relaxation modulus

$$E_r = \sigma(t) / \epsilon_0$$

should be used in the calculations to determine if the connection will still function during the design life time t .

Figure 38 Formed head on a rivet.

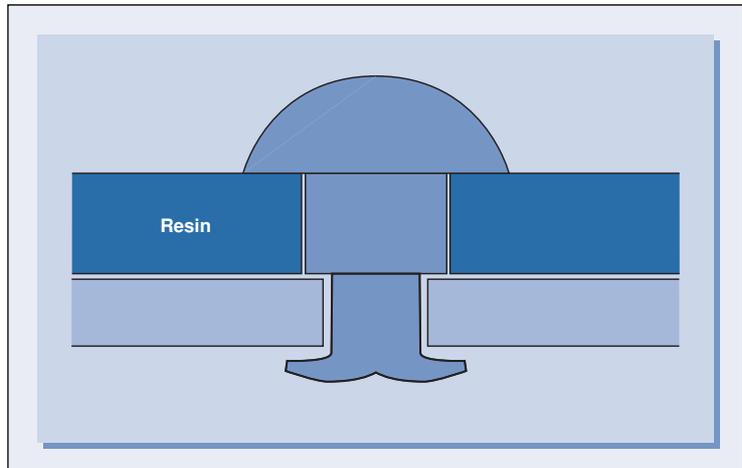
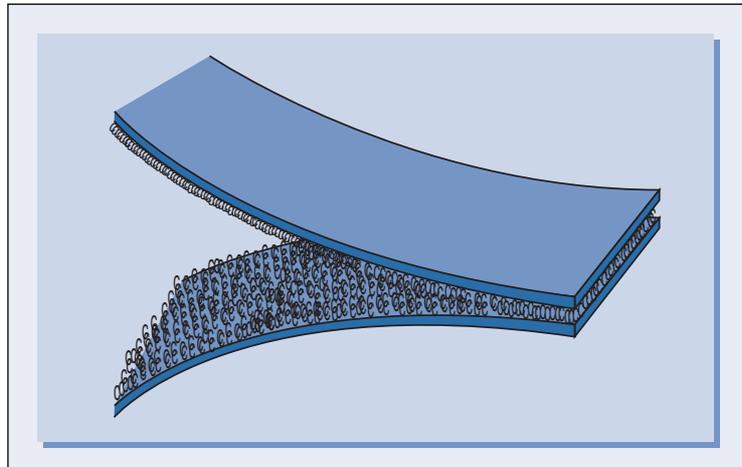
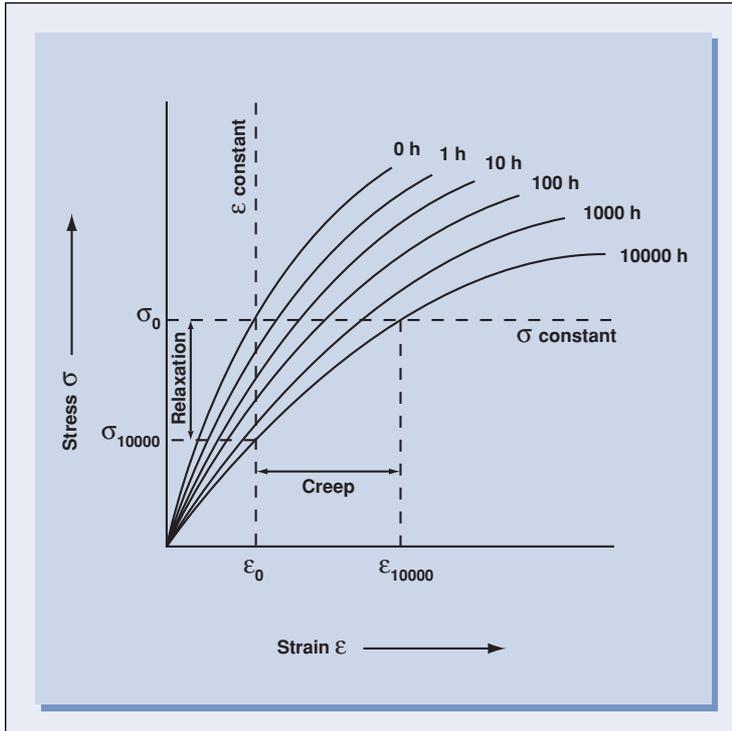


Figure 39 Hook-and-loop tape.



(Isochronous stress-strain curves can be found in the DSM product database on www.dsmep.com. Select a material grade first by clicking on the grade name, then click on "PROPERTIES" and "Fct" (functions). If the desired curves are not available for a material grade, the curves of a comparable grade can be used.)

Figure 40 Creep and stress relaxation.



Coefficient of friction

The external force or torque that can be transmitted by the connection depends on the coefficient of friction μ .

For information about this coefficient see par 3.3.

Poisson's ratio

Poisson's ratio must be known to calculate the surface pressure between the shaft and the hub, and the material stresses in the shaft and the hub.

For information about this ratio see par 3.4.

Surface pressure between the hub and the shaft

The theory for thick-walled cylinders is outlined below, neglecting edge effects.

General case

The surface pressure p between the hub and the shaft is:

$$p = \frac{i}{d_o} \cdot \frac{i}{(A - v_s) / E_s + (B + v_h) / E_h}$$

where A and B are geometry factors with

$$A = \frac{1 + (d_i / d_o)^2}{1 - (d_i / d_o)^2}$$

$$B = \frac{1 + (d_o / D_o)^2}{1 - (d_o / D_o)^2}$$

- d_i = inside diameter of the shaft
- d_o = outside diameter of the shaft
- D_i = inside diameter of the hub
- D_o = outside diameter of the hub
- E_h = modulus of the hub material
- E_s = modulus of the shaft material
- i = interference between hub and shaft
= $d_o - D_i$
- v_h = Poisson's ratio of the hub material
- v_s = Poisson's ratio of the shaft material

Plastic hub - metal shaft

The stiffness of plastics is very low compared to the stiffness of metals, so the deformation of the shaft will be negligible if a plastic hub is mounted on a metal shaft. The formula for the surface pressure p between the hub and the shaft is then reduced to:

$$p = \frac{i}{d_o} \cdot \frac{E_h}{B + v_h}$$

Metal hub - plastic shaft

The deformation of the hub will be negligible if a metal hub is mounted on a plastic shaft, as the stiffness of the plastic is very low compared to the stiffness of the metal. The formula for the surface pressure p between the hub and the shaft is then reduced to:

$$p = \frac{i}{d_o} \cdot \frac{E_s}{A - v_s}$$

Hub and shaft of the same plastic

If the hub and the shaft are of the same plastic with modulus E , the formula for the surface pressure p between the hub and the shaft is reduced to:

$$p = \frac{i}{d_o} \cdot \frac{E}{A + B}$$

Stresses

The stress distribution is shown schematically in figure 41. The maximum tangential stress $\sigma_{\phi h}$ in the hub will be the critical stress in many cases, as this is a tensile stress.

The highest radial stress is located at the contact surface between the hub and the shaft. This maximum radial stress σ_r is the same in the hub and the shaft, and the absolute value is equal to the contact pressure:

$$\sigma_r = -p$$

The maximum tangential stress $\sigma_{\phi h}$ in the hub is also located in the contact surface:

$$\sigma_{\phi h} = p \cdot B$$

The maximum tangential stress $\sigma_{\phi s}$ in a hollow shaft is located at the inside of the shaft:

$$\sigma_{\phi s} = -2 \cdot p / \{ 1 - (d_i / d_o)^2 \}$$

The tangential stress $\sigma_{\phi s}$ in a massive shaft is constant:

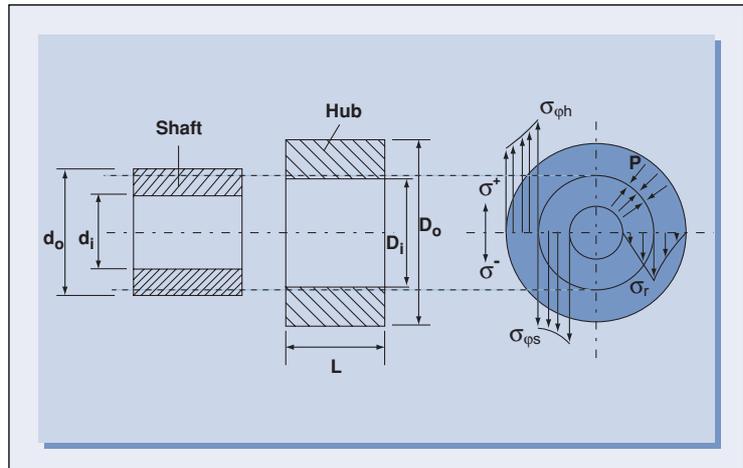
$$\sigma_{\phi s} = -p$$

Axial force

The axial force F required to press the two parts together and the axial bearing capacity of the connection can be approximated by the equation:

$$F = \pi \cdot d_o \cdot L \cdot \mu \cdot p$$

Figure 41 Hub and shaft.



where

d_o = outside diameter of the shaft

L = length of the press-fit surface

μ = coefficient of friction

p = surface pressure between hub and shaft

Torque

The maximum torque M that can be transmitted by the connection is approximately:

$$M = \pi \cdot d_o^2 \cdot L \cdot \mu \cdot p / 2$$

Assembling

Assembling can be made easier by warming up the hub and/or cooling down the shaft, thus reducing the interference. The change in diameter Δd can be calculated as follows.

$$\Delta d = \Delta T \cdot \alpha \cdot d$$

where

ΔT = temperature change

α = coefficient of linear expansion

d = initial diameter

Figure 42 Snap-fit cantilever beam type.

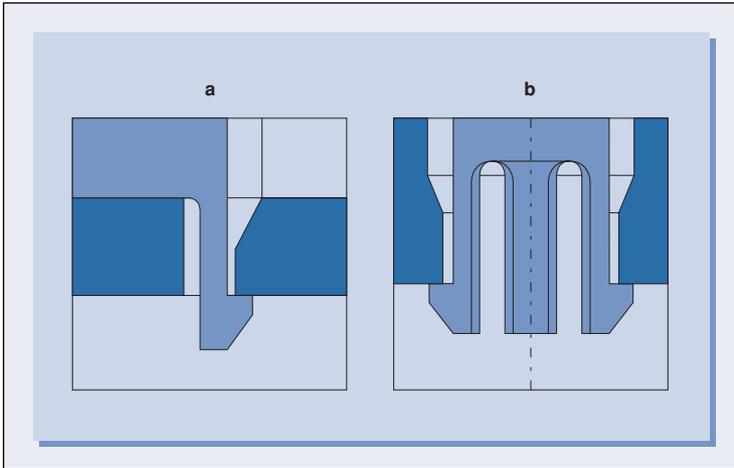


Figure 43 Snap-fit cylindrical type.

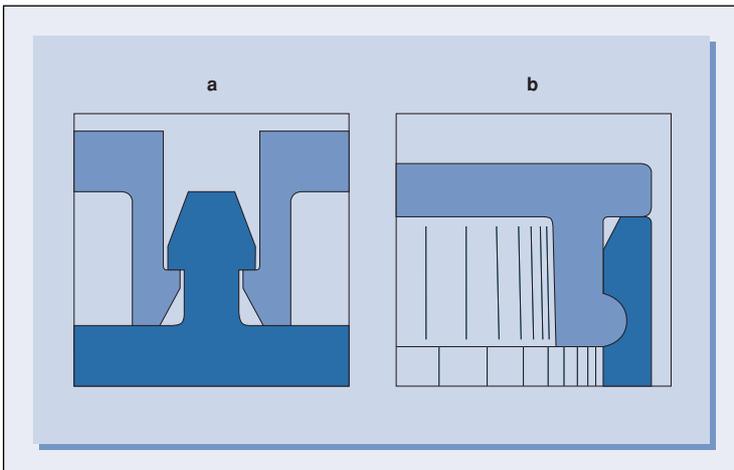
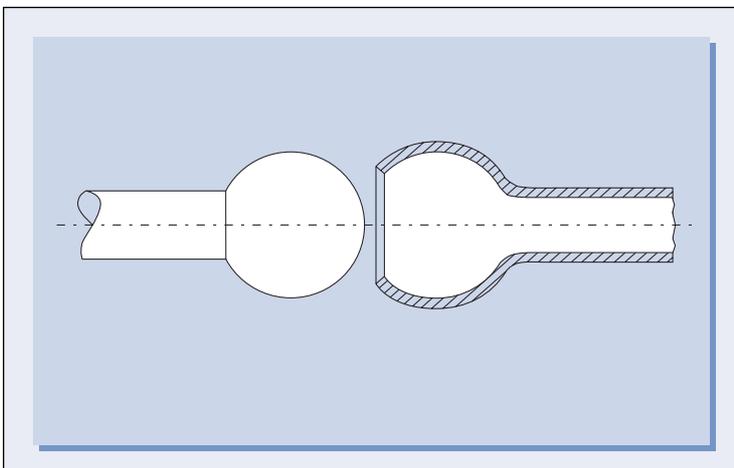


Figure 44 Snap-fit spherical type.



1.1.12. Snap-Fits

Introduction

A snap-fit is an effective method to design the fastening system into the product design itself. A snap-fit can be designed to allow parts to be either permanently fastened (or pre-determined to be broken off) or for frequent assembly and disassembly.

In combination with O-rings or proper seals, even gas and fluid tight connections can be made.

Designing a snap-fit is rather complex due to a combination of factors:

- the functional requirements of the product
- the assembly requirements
- the mechanical properties of the thermoplastic
- the design of the mold and notably part ejection.

Snap-fits can be found in a wide variety of shapes. Three examples are shown here (Figures 42, 43, 44).



The force-deflection diagram

In the general case, both parts will be deformed during assembling, see the example in figure 45. Part 1 is bent downwards over a distance y_1 , part 2 is bent upwards over a distance y_2 and a deflection force F_b acts between the two mating parts.

A force-deflection diagram as shown in figure 46 can be a useful aid for the engineer to determine how the total deflection will be distributed over the two parts.

The undercut h of the snap-fit determines the total deformation $y_1 + y_2$ in this diagram and the spring characteristic (stiffness) of both parts determines the deflection force F_b .

Secant modulus

The spring characteristic of the parts must be calculated from the part dimensions and the material stiffness E . Young's modulus E_0 may be used as long as the strains remain in the proportionality range of the stress-strain curve, but for larger strains the secant modulus E_s should be used. Figure 47 shows the definition of E_s .

The strain will vary from place to place, so that the calculation should in fact be done using several secant moduli. This is not feasible for a hand calculation, in that case the engineer will normally use an average secant modulus. One of the advantages of a finite element calculation is that the complete stress-strain curve of a material can be used as input, with the computer determining the strain and modulus for every point of the construction.

Maximum allowable short-term strain during assembling

If a snap-fit fails during assembly, the maximum deflection of the cantilever beam most likely exceeded the deflection limit of the thermoplastic used. The maximum strain that occurs during assembling can be calculated for both parts if the force-deflection diagram of figure 46 is known. For information about the maximum allowable short-term strain level ϵ in DSM thermoplastics see par. 3.1.

Figure 45 Both parts are deformed.

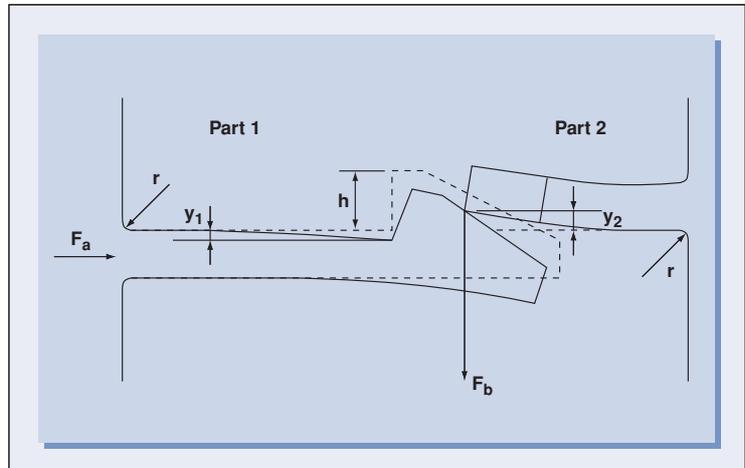


Figure 46 Force-deflection diagram.

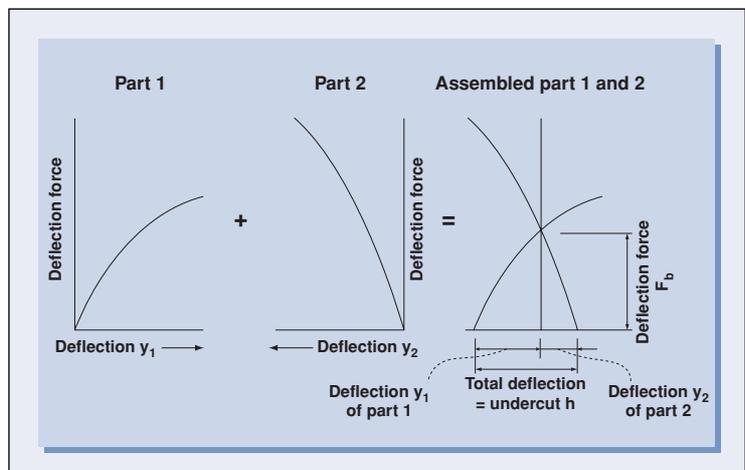
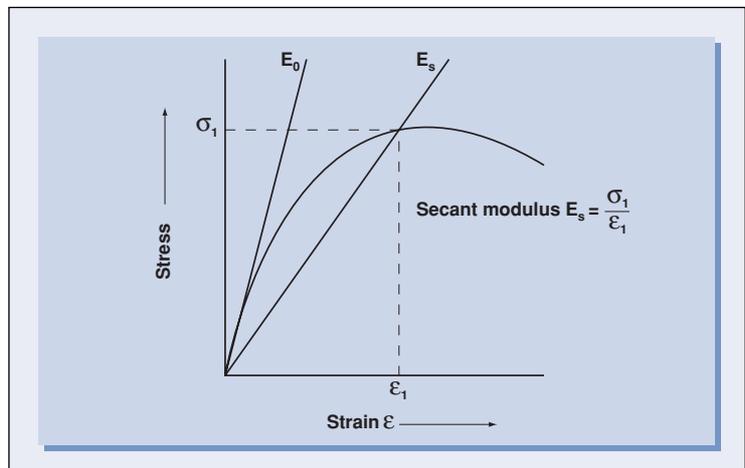


Figure 47 The definition of the secant modulus E_s .



Since the snap-fit is only a small part of a product, it is better to design snap-fit dimensions based on the selected thermoplastic rather than to choose a thermoplastic to make a specific snap-fit work.

Creep and stress relaxation

Internal loads in the snap-fit connection after assembly should be avoided if possible, due to possible creep and stress relaxation. A graph with isochronous stress-strain curves gives information about the creep and stress relaxation that will take place, see figure 40.

(Isochronous stress-strain curves can be found in the DSM product database on www.dsmep.com. Select a material grade first by clicking on the grade name, then click on "PROPERTIES" and "Fct" (functions). If the desired curves are not available for a material grade, the curves of a comparable grade can be used.)

If a certain pre-stress cannot be avoided, as the connection has to resist an external load, this pre-stress should be minimized. The designer should be aware that both the possibility of breakage and the required force to (dis)assemble can be dealt with independently. In most cases the number of snap-fits can be changed.

Stress concentrations

A common factor causing failure of a snap-fit is the inside radius r (see figure 45) in transitions or the lack thereof. An inside radius which is too small will induce stress-concentrations. These sections with high stresses are often weak because the strain limit is reached sooner. A radius $r = 0.5$ mm is satisfactory in most cases.

Coefficient of friction

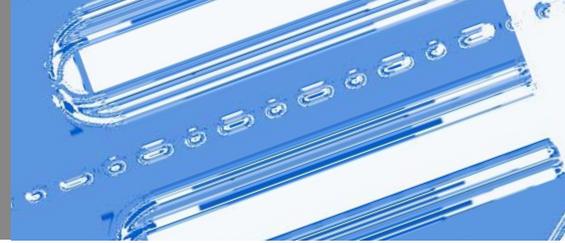
The mating force F_a required to assemble and the separation force F_d required to disassemble the snap-fit are determined by several parameters. One of them is the coefficient of friction μ , which characterises the friction forces which must be overcome.

For information about this coefficient see par.3.2.

Poisson's ratio

Poisson's ratio must be known to calculate the surface pressure and the stresses in a cylindrical snap-fit.

For information about this ratio see par. 3.3.



Lead angle and return angle

The lead angle α_1 and the return angle α_2 determine the required mating and separation forces respectively, in addition to the dimensions of the snap-fit, the material stiffness and the friction coefficient.

The lead angle α_1 is normally between 15° and 30° .

The return angle α_2 determines the maximum load that the snap-fit can take up. The maximum load bearing capacity is reached for a return angle of 90° . The return angle determines if the connection will be separable or inseparable, see figure 48.

$\alpha_2 + \rho < 90^\circ$: separable joint

$\alpha_2 + \rho > 90^\circ$: inseparable joint

$\mu = \tan \rho$ = coefficient of friction

Mating force and separation force

The mating force F_a required to assemble can be calculated with the following formula.

$$F_a = F_b \cdot \frac{\mu + \tan \alpha_1}{1 - \mu \cdot \tan \alpha_1}$$

where

F_b = deflection force

μ = coefficient of friction

α_1 = lead angle

The same formula is used for the separation force F_d required to disassemble, but then with the return angle α_2 instead of α_1 .

How F_b can be calculated is explained in the following paragraphs.

Cantilever beam snap-fits

Cantilever beam type snap-fits can be calculated with the general beam theory. However the calculations are a simplification. In general, the stiffness of the part that the snap-fit connects to is important. The formulas mentioned only roughly describe the behavior of both the part geometry and the material. On the other hand, the approach can be used as a first indication of whether a snap-fit design and material choice is viable or not.

Figure 48 Separable and inseparable joints.

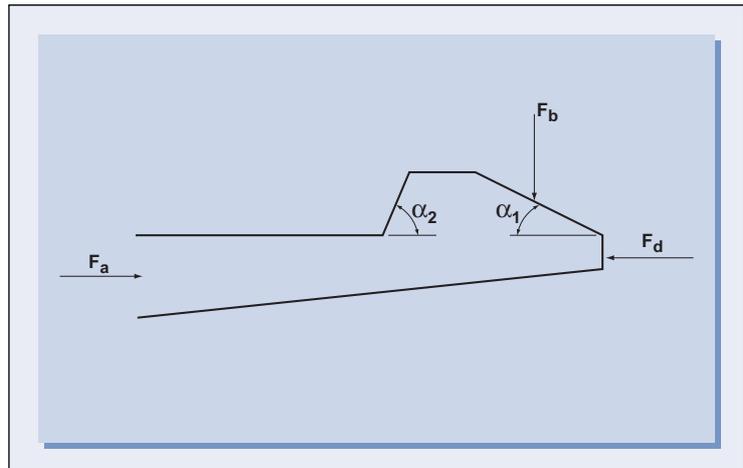
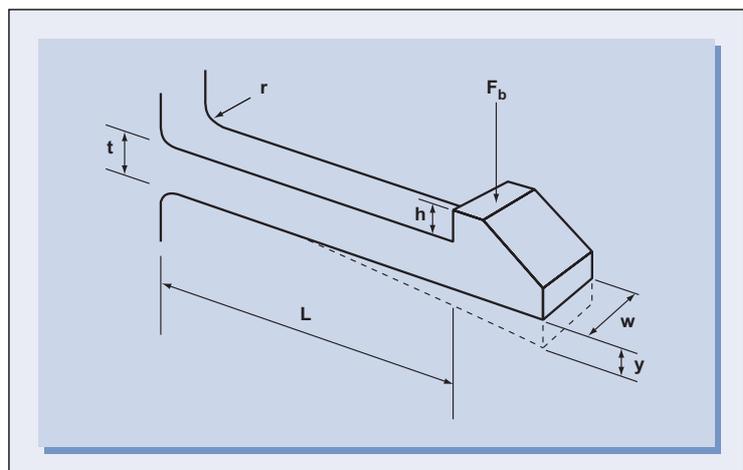


Figure 49 Cantilever beam with constant rectangular cross section.

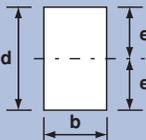
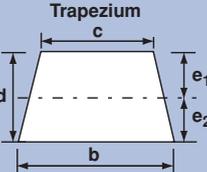
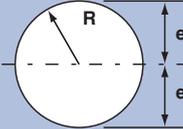
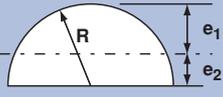
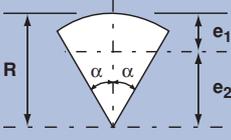
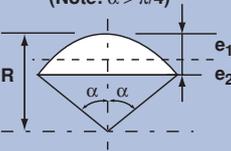
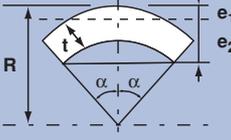


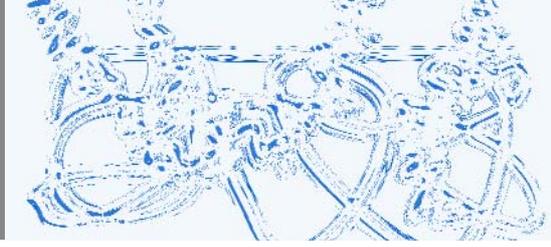
Cantilever beam with constant rectangular cross section

A simple type of snap-fit, the cantilever beam, is demonstrated in Figure 49, which shows the major geometric parameters of this type of snap-fit. The cross section is a rectangle and is constant over the whole length L of the beam.

The maximum allowable deflection y and deflection force F_b can be calculated with the following formulas if the maximum allowable strain level ϵ of the material is known.

Table 2 Moment of inertia and distance from centroid to extremities.

Form of section	Area and distance from centroid to extremities	Moment of inertia
<p>Rectangle</p> 	$A = b \cdot d$ $e = \frac{d}{2}$	$I = \frac{1}{12} \cdot b \cdot d^3$
<p>Trapezium</p> 	$A = d \cdot (b + c) / 2$ $e_1 = \frac{d}{3} \cdot \frac{2b + c}{b + c}$ $e_2 = d - e_1$	$I = \frac{d^3}{36} \cdot \frac{b^2 + 4 \cdot b \cdot c + c^2}{b + c}$
<p>Solid circle</p> 	$A = \pi \cdot R^2$ $e = R$	$I = \frac{\pi}{4} \cdot R^4$
<p>Solid semicircle</p> 	$A = \frac{\pi}{2} \cdot R^2$ $e_1 = 0.5756 \cdot R$ $e_2 = 0.4244 \cdot R$	$I = 0.1098 \cdot R^4$
<p>Sector of solid circle</p> 	$A = \alpha \cdot R^2$ $e_1 = R \cdot \left(1 - \frac{2 \cdot \sin \alpha}{3 \cdot \alpha}\right)$ $e_2 = \frac{2 \cdot R \cdot \sin \alpha}{3 \cdot \alpha}$	$I = \frac{R^4}{4} \left(\alpha + \sin \alpha \cdot \cos \alpha - \frac{16 \cdot \sin^2 \alpha}{9 \cdot \alpha}\right)$
<p>Segment of solid circle (Note: $\alpha > \pi/4$)</p> 	$A = R^2 \cdot (\alpha - \sin \alpha \cdot \cos \alpha)$ $e_1 = R \cdot \left[1 - \frac{2 \cdot \sin^3 \alpha}{3 \cdot (\alpha - \sin \alpha \cdot \cos \alpha)}\right]$ $e_2 = R \cdot \left[\frac{2 \cdot \sin^3 \alpha}{3 \cdot (\alpha - \sin \alpha \cdot \cos \alpha)} - \cos \alpha\right]$	$I = \frac{R^4}{4} \cdot \left[\alpha - \sin \alpha \cdot \cos \alpha + 2 \cdot \sin^3 \alpha \cdot \cos \alpha - \frac{16 \cdot \sin^6 \alpha}{9 \cdot (\alpha - \sin \alpha \cdot \cos \alpha)}\right]$
<p>Sector of hollow circle</p> 	$A = \alpha \cdot t \cdot (2 \cdot R - t)$ $e_1 = R \cdot \left[1 - \frac{2 \cdot \sin \alpha}{3 \cdot \alpha} \cdot \left(1 - \frac{t}{R} + \frac{1}{2 \cdot t/R}\right)\right]$ $e_2 = R \cdot \left[\frac{2 \cdot \sin \alpha}{3 \cdot \alpha \cdot (2 \cdot t/R)} + \left(1 - \frac{t}{R}\right) \cdot \frac{2 \cdot \sin \alpha - 3 \cdot \alpha \cdot \cos \alpha}{3 \cdot \alpha}\right]$	$I = R^3 \cdot t \cdot \left[\left(1 - \frac{3 \cdot t}{2 \cdot R} + \frac{t^2}{R^2} - \frac{t^3}{4 \cdot R^3}\right) \cdot (\alpha + \sin \alpha \cdot \cos \alpha - \frac{2 \cdot \sin^2 \alpha}{\alpha}) + \frac{t^2 \cdot \sin 2\alpha}{3 \cdot R^2 \cdot \alpha \cdot (2 \cdot t/R)} \cdot \left(1 - \frac{t}{R} + \frac{t^2}{6 \cdot R^2}\right)\right]$



$$y = \frac{2}{3} \cdot \frac{L^2}{t} \cdot \epsilon$$

$$F_b = \frac{w \cdot t^2 \cdot E_s}{6 \cdot L} \cdot \epsilon$$

where

E_s = secant modulus

L = length of the beam

t = height of the beam

w = width of the beam

ϵ = maximum allowable strain level of the material

The four dimensions that can be changed by the designer are:

- the height of the snap-fit lip h is directly related to the performance of the lip.
Changing the height might reduce the ability of the snap-fit to ensure a proper connection.
- the thickness of the beam t is uniform over the length of the beam in this example. A more effective method is to use a tapered beam.
The stresses are more evenly spread over the length of the beam. This type of beam is discussed.
- increasing the beam length L is the best way to reduce strain as it is calculated to the power of 2 (squared) in the equation for the allowable deflection.
- the deflection force is proportional to the width of the snap-fit lip w .

Beams with other cross sections

The following general formulas for the maximum allowable deflection y and deflection force F_b can be used for cantilever beams with a constant asymmetric cross section, such as the example in figure 42b.

$$y = \frac{L^2}{3 \cdot e} \cdot \epsilon$$

$$F_b = \frac{E_s \cdot I}{e \cdot L} \cdot \epsilon$$

where

E_s = secant modulus

I = moment of inertia of the cross section

L = length of the beam

e = distance from the centroid to the extremities

ϵ = maximum allowable strain level of the material

Normally tensile stresses are more critical than compressive stresses. Therefore the distance from the centroid to the extremities, e , that belongs to the side under tension is used in the above-mentioned formulas.

The moment of inertia and the distance compressive stresses. Therefore the distance from the centroid to the extremities is given in table 2 for some cross sections.

Figure 50 Tapered beam, rectangular cross section, variable height.

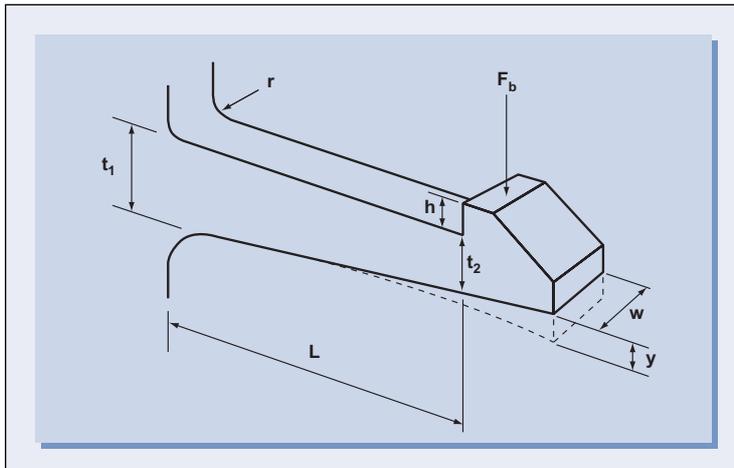


Table 3 Multiplier c as a function of the height.

t_2 / t_1	0.40	0.50	0.60	0.70	0.80	0.90	1.00
c	1.893	1.636	1.445	1.297	1.179	1.082	1.000

Figure 51 Tapered beam, rectangular cross section, variable height.

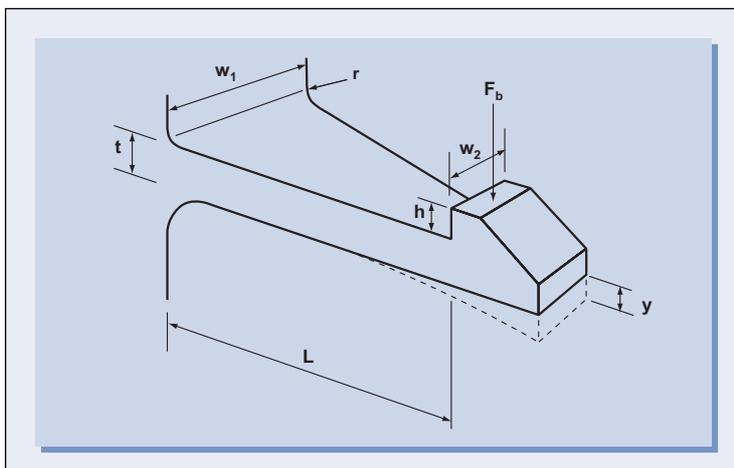


Table 4 Multiplier c as a function of the width.

w_2 / w_1	0.125	0.25	0.50	1.00
c	1.368	1.284	1.158	1.000

The following formulas can be used to calculate the maximum allowable deflection y and the deflection force F_b for a tapered cantilever beam with a rectangular cross section. The height of the cross section decreases linearly from t_1 to t_2 , see figure 50.

$$y = c \cdot \frac{2 \cdot L^2}{3 \cdot t_1} \cdot \epsilon$$

$$F_b = \frac{w \cdot t_1^2 \cdot E_s}{6 \cdot L} \cdot \epsilon$$

where

E_s = secant modulus

L = length of the beam

c = multiplier

w = width of the beam

t_1 = height of the cross section at the fixed end of the beam

ϵ = maximum allowable strain level of the material

The formula for the deflection y contains a multiplier c that depends on the ratio t_2 / t_1 , see table 3, where t_1 is the height of the beam at the fixed end and t_2 is the height of the beam at the free end.

The following formulas can be used to calculate the maximum allowable deflection y and deflection force F_b for a tapered cantilever beam with a rectangular cross section. The width of the cross section decreases linearly from w_1 to w_2 , see figure 51.

$$y = c \cdot \frac{2 \cdot L^2}{3 \cdot t} \cdot \epsilon$$

$$F_b = \frac{w_1 \cdot t^2 \cdot E_s}{6 \cdot L} \cdot \epsilon$$

where

E_s = secant modulus

L = length of the beam

c = multiplier

w_1 = width of the beam at the fixed end of the beam

t = height of the cross section

ϵ = maximum allowable strain level of the material



The multiplier c depends on the ratio w_2 / w_1 , see table 4, where w_1 is the width of the beam at the fixed end and w_2 is the width of the beam at the free end.

Cylindrical snap-fits

One must distinguish between a cylindrical snap-fit close to the end of the pipe (figure 52) and remote from the end (figure 53).

More material must be deformed if the snap fit is remote from the end, and the deflection force F_b and mating force F_a will be a factor 3.4 higher. The snap-fit is regarded as being remote if

$$l > 1.8 \cdot \sqrt{(D \cdot t)}$$

where

l = distance to the end of the pipe.

The following symbols are further used:

D = average diameter of the pipe

$$= (D_o + d_o) / 2$$

D_o = outside diameter of the pipe

d_o = outside diameter of the shaft

d_i = inside diameter of the shaft

$\Delta d / 2$ = height of the bulge on the shaft

= depth of the groove in the pipe

E_s = shear modulus of the plastic

t = wall thickness of the pipe

$$= (D_o - d_o) / 2$$

μ = coefficient of friction

ν = Poisson's ratio of the plastic

The formula for the deflection force F_b is given in table 5 for both a rigid (metal) shaft with a flexible pipe, and a flexible shaft with a rigid (metal) pipe. Four cases can be distinguished. (see table 5)

If the deflection force F_b according to table 5 has been calculated, the mating force F_a is found using the expression:

$$F_a = F_b \cdot \frac{\mu + \tan \alpha_1}{1 - \mu \cdot \tan \alpha_1}$$

Figure 52 Cylindrical snap-fit close to the end.

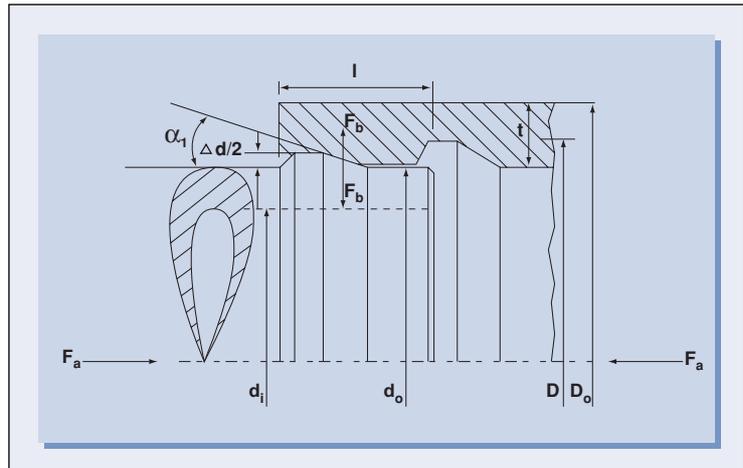


Figure 53 Cylindrical snap-fit remote from the end.

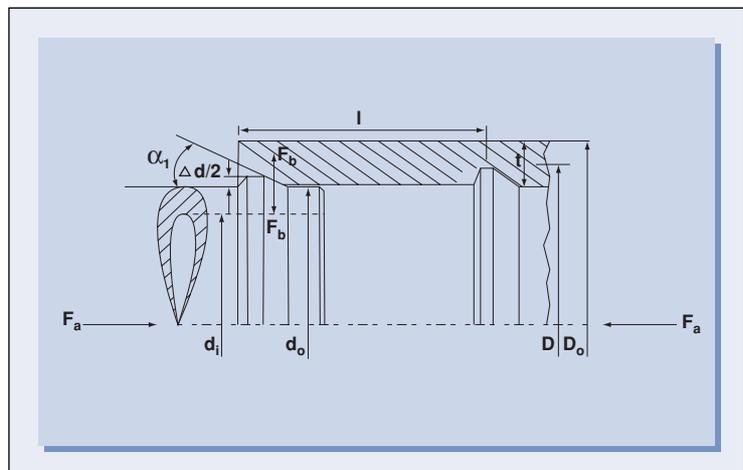
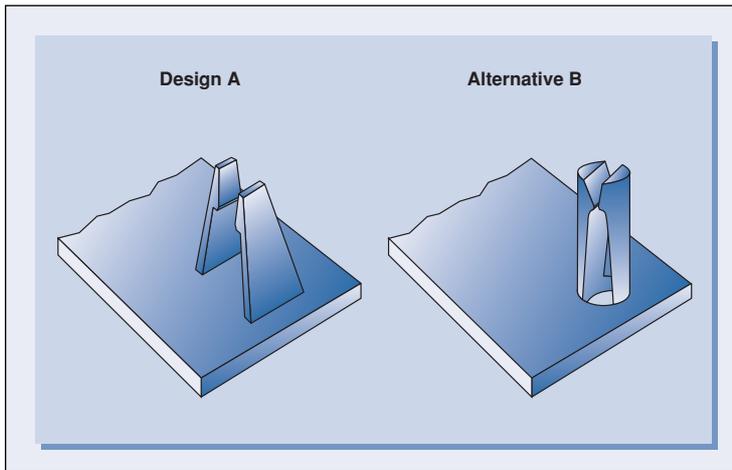


Table 5 Deflection force F_b .

Snap-fit	Shaft	Pipe	Formula
Snap-fit close to the end	Rigid shaft	flexible pipe	$0.62 \cdot \Delta d \cdot d_o \cdot \frac{\sqrt{[(D_o / d_o - 1) / (D_o / d_o + 1)]}}{[(D_o / d_o)^2 + 1] / [(D_o / d_o)^2 - 1] + \nu} \cdot E_s$
	Flexible shaft	rigid pipe	$0.62 \cdot \Delta d \cdot d_o \cdot \frac{\sqrt{[(d_o / d_i - 1) / (d_o / d_i + 1)]}}{[(d_o / d_i)^2 + 1] / [(d_o / d_i)^2 - 1] - \nu} \cdot E_s$
Snap-fit remote from the end	Rigid shaft	flexible pipe	$2.1 \cdot \Delta d \cdot d_o \cdot \frac{\sqrt{[(D_o / d_o - 1) / (D_o / d_o + 1)]}}{[(D_o / d_o)^2 + 1] / [(D_o / d_o)^2 - 1] + \nu} \cdot E_s$
	Flexible shaft	rigid pipe	$2.1 \cdot \Delta d \cdot d_o \cdot \frac{\sqrt{[(d_o / d_i - 1) / (d_o / d_i + 1)]}}{[(d_o / d_i)^2 + 1] / [(d_o / d_i)^2 - 1] - \nu} \cdot E_s$

Figure 54 Design B has mold cost advantages over design A.



The highest tangential strain ϵ_{φ} in the plastic is approximately:

- Rigid shaft, flexible pipe:
 $\epsilon_{\varphi} = \Delta d / d_o$ (tension in the pipe)
- Flexible shaft, rigid pipe:
 $\epsilon_{\varphi} = - \Delta d / d_o$ (compression in the shaft)

The highest axial bending strain ϵ_a in the plastic is about a factor 1.59 higher:

$$\epsilon_a = 1.59 \cdot \epsilon_{\varphi}$$

(tension at one side and compression at the other side)

The calculation procedure where both parts are flexible and both are deformed is explained in the paragraph "the force deflection diagram" (p. 22). As a first approach, for flexible materials with a comparable stiffness, one can assume that the total deformation Δd is equally divided between the two parts.

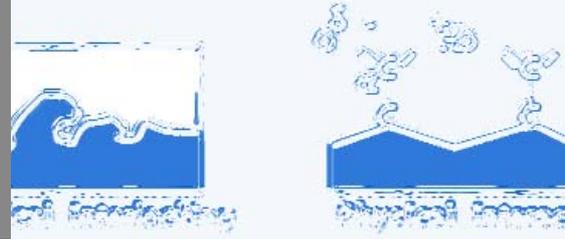
Spherical snap-fits

The spherical snap-fit (figure 44) can be regarded as a special case of the cylindrical snap-fit. The formulas for a cylindrical snap-fit close to the end of the pipe (figure 52) can be used.

Mold construction

The engineer must realise that mold construction costs are highly affected by the design of the snap fit, compare design A and alternative B.

An expensive slide in the mold is required for design A and the flat surfaces of design A require expensive milling. No slide is required for alternative B and the cylindrical outside surface of alternative B can furthermore simply be drilled.



1.2. Glueing

1.2.1. Introduction

Glueing for assembly of plastic parts is an effective method of making permanent connections. This method produces aesthetically clean looking joints with low weight and sufficiently strong connections. This is a very effective joining method for heat sensitive plastics that would normally deform if welded.

1.2.2. Solvent Bonding

Solvent bonding or solvent welding is a process in which the surfaces of the parts to be joined are treated with a solvent. This swells and softens the surface and by applying pressure to the joint and with the evaporation of the solvent, the two surfaces bond. Adhesives are not used. The process is commonly used with amorphous thermoplastics such as Xantar.

Specific advantages of solvent bonding are:

- homogeneous distribution of mechanical loads
- good aesthetics / no special requirements to hide the bond
- economic assembly
- low weight, no heavy screws, bolts and nuts
- heat sensitive constructions or materials, which welding would distort or destroy, can be joined
- good sealing and insulating properties.

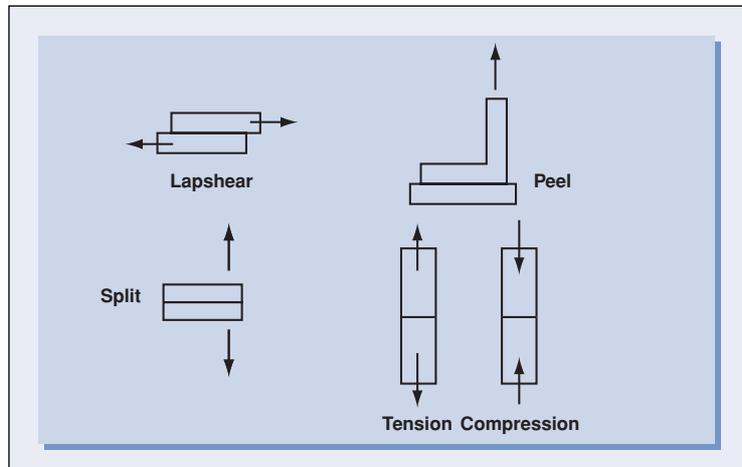
Potential limitations are:

- entrapment of solvent in the joint
- stress cracking or crazing
- dissimilar materials can only be joined if both are soluble in a common solvent or in a mixture of solvents
- differences in thermal expansion of components are not compensated in a thick adhesive layer if dissimilar materials are bonded
- reproducibility / process control
- curing time
- no disassembly possible
- assembly hazards such as fire or toxicity.

Table 6 Suitable solvents for some DSM products.

DSM Products	Polymer description	
Akulon	PA6 & PA66	Formic acid Alcoholic calcium chloride Concentrated aqueous chloral hydrate Concentrated alcoholic phenol/recorcinol
Stanyl	PA46	Formic acid Aqueous phenol solution (88%) Resorcinol/ethanol (1:1)
Xantar	PC	Methylene chloride Ethylene dichloride
Xantar C	PC + ABS	Methylene chloride Ethylene dichloride

Figure 55 The load can be applied in several ways.



Solvents

Suitable solvents for bonding selected DSM products are given in the table 6. Arnite and Arnitel are generally bonded by other techniques such as adhesive bonding.

Different solvents can be mixed to produce a mixture with optimal properties. For instance, if two dissimilar materials are to be joined, a mixture of two miscible solvents specific to the different polymers can be used. A mixture of methylene chloride and ethylene dichloride is sometimes used for Xantar polycarbonate and polycarbonate blends. Methylene chloride evaporates faster than ethylene dichloride. A

Figure 56 The relation between the surface contact angle and wetting of the surface.

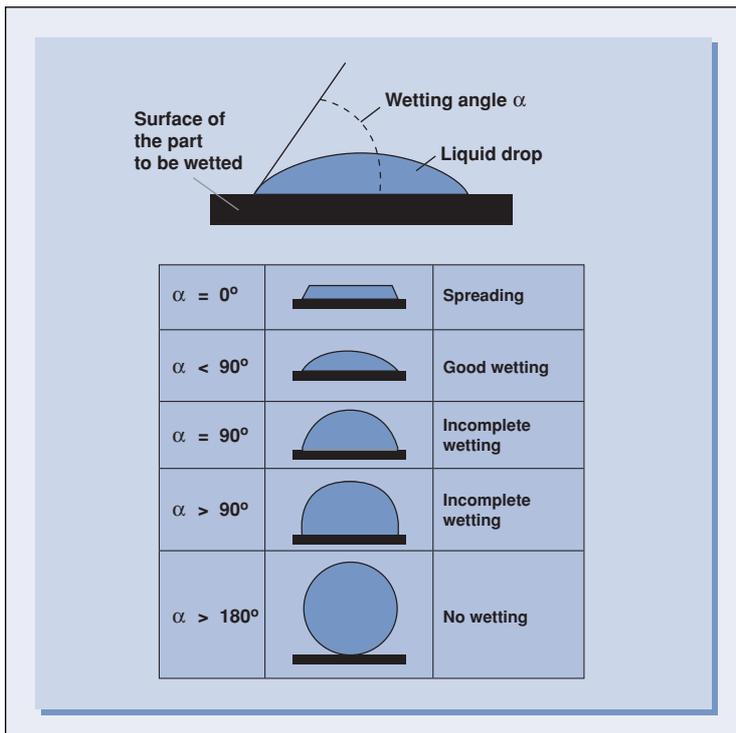
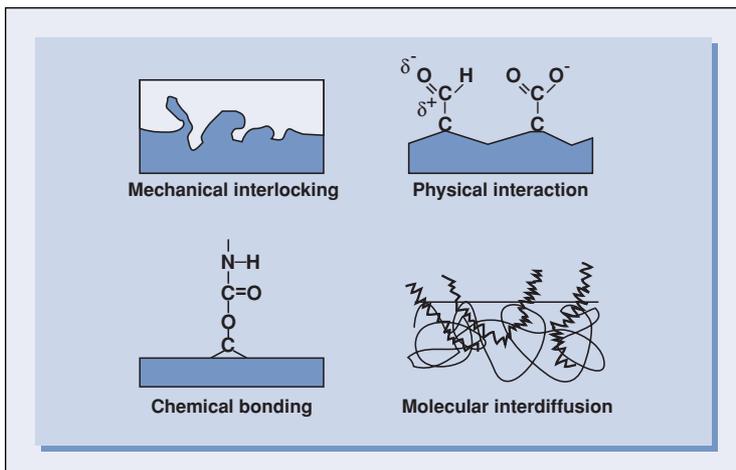


Figure 57 Different adhesion mechanisms.



longer assembly time is therefore required if ethylene dichloride has been added.

A slurry made of solvent and up to 25% of the base resin can be used to produce a smooth filled joint when the mating parts do not fit perfectly. Adding base resin makes the solvent easier to use.

It is important to consult the Material Safety Data Sheet of the solvent used, for health and safety information and for proper handling and protection equipment.

Procedure

The mating surfaces must be clean and free of grease before bonding. Cleaning with a suitable solvent may be necessary, see par. 2.1.11. Parts having a single joining surface are simply pressed against a sponge or felt pad that has been impregnated with solvent. The quantity of solvent used should be kept to a minimum to avoid drips and crazing. More complex multiplane joining surfaces require contoured solvent applicators made from wood or a metal. It may be necessary to allow a few seconds to ensure sufficient swelling. The parts are then clamped together with a moderate pressure. The parts are removed from the clamping equipment and must not be used for a period of 24 to 48 hours to ensure that full strength has been achieved. Heat can be used to accelerate the overall rate of evaporation and reduce the cycle time.

Design for solvent bonding

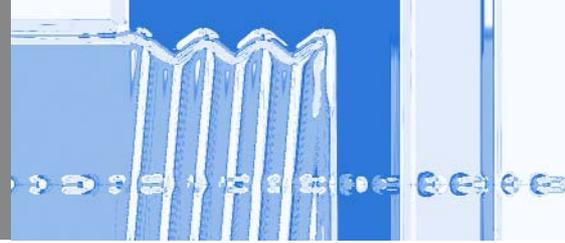
The load on the assembly can be applied in several ways as indicated in figure 55.

General design guidelines are:

- design for lap shear loads
- maximize the bonding surface; for instance, use a scarfed or a dovetail joint
- avoid stress concentrations at thick-thin sections
- ensure that there is sufficient venting.

Scarfed or dovetail joints should be relatively shallow, so that solvent entrapment is avoided. Entrapped solvent can cause crazing over time and lead to part failure. The parts should be molded with a minimum of internal stress, or can be annealed or stress relieved prior to assembly (see par. 2.3).

Gates should be located away from the areas to be bonded. Caution should also be exercised when working with "closed" parts, to avoid getting solvent trapped inside the part.



1.2.3. Adhesive Bonding

The main criteria for achieving good adhesive bonding are surface wetting and curing of the adhesive. Important variables for the application of adhesive and distribution on a substrate are surface contact angle (see figure 56), adhesive viscosity and chemical resistance of the substrate to adhesive.

In general, adhesion is based on various mechanisms as shown (see figure 57).

Molecular interdiffusion is limited by crystallites, therefore it is more difficult to achieve good adhesion on semi-crystalline compared to amorphous thermoplastics. Adhesion on non-polar thermoplastics, e.g. polyolefins, will improve considerably when the surface is pretreated using corona, UV, plasma or flame treatments.

Poor bonding occurs when the adhesive layer does not stick properly to the substrate. Pretreatment, e.g. cleaning, degreasing and sanding, may be helpful.

Specific advantages of adhesives are:

- application on various substrates like thermoplastics, thermosets, elastomers and metals
- homogeneous distribution of mechanical loads
- differences in thermal expansion of components can be compensated by using a thick adhesive layer
- good aesthetics / no special requirements to hide the bond
- economic assembly
- low weight, no heavy screws, bolts and nuts
- heat sensitive constructions or materials, which welding would distort or destroy, can be joined
- no thermal stresses introduced
- good sealing and insulating properties.

Potential limitations are:

- long term behavior may not be very good
- stress cracking or crazing of the plastic may take place
- dissimilar materials can only be joined if both are compatible with the adhesive

Table 7 Lap shear strength (MPa).

DSM Products		Epoxy		Polyurethane	Acrylic	Cyanoacrylic
		2 comp.	1 comp.			
Akulon	PA6 UF/GF	3 - 10	6	7	10	10
	PA66 UF	4	8	3	10	5
	PA66 GF	4	8	4	-	10
Arnite	PBT UF	1	6	3	-	1
	PBT GF	2	9	4	-	5
	PET UF	2 - 6	10	5 - 7	- 8	2
	PET GF	4 - 10	10	7 - 10	1 - 10	8
Xantar	PC UF/GF	10	-	7	5	7
Xantar C	PC + ABS UF	4	-	7	-	9

UF = unfilled, GF = glass fiber

- reproducibility / process control
- curing time can be dependent on the adhesive
- no disassembly possible
- assembly hazards such as fire or toxicity.

Adhesive types

A wide variety of adhesives are commercially available. The performance on some DSM products is shown in table 7. The values indicated are based on lap shear strength (in MPa).

Epoxy

Various epoxy adhesives are available, with different characteristics and properties. The different curing mechanisms are:

- 2 component hot or cold curing
- 1 component hot curing
- UV-curing.

Standard epoxy adhesives are brittle and show low peel strength. To improve toughness, modified epoxy adhesives have been developed. The use temperature varies between - 40°C and 80°C (-40°F - 180°F) for cold curing systems. Hot curing epoxies can normally be used up to 150°C (300°F).

In general, large deviations in lap shear bonding strength are found, depending on the particular combination of adhesive and material.

With some plastics, pretreatment can give a considerable improvement. Oils and grease negatively affect the adhesion of epoxies.

Polyurethane

Polyurethane adhesives are relatively inexpensive and show good adhesion. Varieties exist from elastomeric to rigid. Several types of curing mechanisms are available:

- 1 component thermosetting
- 2 component catalyzed
- reactive hot melts.

Polyurethane adhesives are tough and show a high peel strength. They can be used at temperatures between -80°C and 100°C (-110°F - 210°F).

Adhesion on engineering plastics is good. Degreasing is often sufficient to obtain the required bonding strength.

Acrylic

Acrylics are flexible and tough. Fast curing takes place at room temperature. Care should be taken when joining amorphous thermoplastics such as Xantar, as environmental stress cracking may occur.

Several systems are available:

- 1 component UV-curing used for transparent plastics
- 2 component premix
- 2 component no-mix.

Use temperature is between -55°C and 120°C (-70°F - 250°F). Acrylics show excellent peel strength and are tough.

Good adhesion is obtained on amorphous thermoplastics. Pretreatment may improve the lap shear bonding strength considerably.

Cyano-acrylic

Cyano-acrylics are fast curing systems but rather brittle, which results in low peel strength and impact properties in the joint. Rubber modified cyano-acrylics have been developed to improve toughness.

A very high lap shear bonding strength can be obtained with most engineering thermoplastics. Unfilled polyesters (Arnite PET and PBT) show moderate results. Effective primers are available to

improve the bonding strength on polyolefins.

Silicone

Silicone adhesives react under the catalytic effect of water. Humidity in the air or some moisture on the surface of the parts is sufficient. The reaction times are relatively long, compared to cyano-acrylics. Silicone adhesives offer a high elasticity.

UV Cure

UV curable adhesives use ultraviolet light to initiate polymerization and contain no solvents. Curing time is short, typically 3 to 10 seconds. UV curable adhesives have a high bond strength and can easily be applied to transparent materials like Xantar polycarbonate.

Hot melt

Hot melt adhesives are thermoplastics, available as pellets, or in block, tape or foil shape. The adhesive is heated above the melting temperature and applied to the surfaces to be bonded with special equipment like rollers, nozzles or calendars. The bond is formed after the melt cools to a solid. The operating equipment must operate fast for effective bonding. These adhesives are fairly viscous, solvent free, and have good gap filling abilities.

Recommendations for DSM products

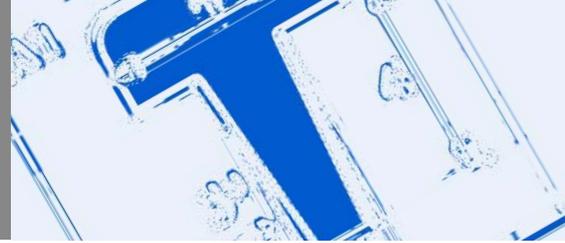
The surfaces to be joined should be clean prior to bonding. Cleaning in a compatible solvent may be necessary to remove oil, grease, mold release agents and other foreign materials, see par 2.1.11.

Akulon (PA6 and PA66)

Epoxy, urethane, cyano-acrylic, silicone and hot melt adhesives are suitable for bonding Akulon PA6 and PA66.

Stanyl (PA46)

Although many different glues can be applied to polyamides, only a few can be recommended for use in Stanyl at high temperatures of 120°C - 150°C. A selection of possible adhesives for Stanyl is listed below (see table 8).



The peel strength of glued Stanyl parts depends on:

- The moisture content of the polyamide parts: dry as molded parts give higher peel strengths than conditioned parts.
- Environmental conditions (chemical attack), size and kind of loading, size of the gap between the mating parts.
- The application of a pretreatment: peel strengths measured on parts which are not pretreated, are in the range of 3-4 MPa, while pretreatment shifts this range to 10-17 Mpa.

Applicable pretreatments are:

- Abrading the surface with medium grit (80-150) emery paper or grit blasting (especially effective for polyurethanes and acrylates)
- Etching the surface (3 minutes at 20°C) with a mixture of sulphuric acid (90%), potassium dichromate (4%) and water (6%)
- Priming the surface by means of a mixture of resorcinol, ethanol and p-toluensulfonacid, a nitrilphenol based solution or by means of a resin based on resorcinformaldehyde
- Plasma or UV/ozone pretreatment (especially effective in combination with glues based on epoxies)

The adhesive forms the weakest link in a glued Stanyl component due to the lower temperature resistance of the adhesive. Consequently adhesive bonding is not a preferred joining technique for Stanyl. More stable systems are achieved using welding techniques or mechanical fasteners.

Arnite (PBT and PET)

Ethylcyanoacrylate, methacrylatelastomer, ethyl, methyl, polyurethane, epoxy and silicone type adhesives are suitable for Arnite PBT and PET. Hot melt adhesives can also be applied. The area to be joined should be lightly roughened and free of grease. The adhesion strength obtained, however, will be below the specified product strength.

Arnitel (TPE)

Good bonding results can be achieved on Arnitel components with polyurethane adhesives. Normally two-component systems are used, with isocyanate or di-isocyanate hardeners.

Table 8 High temperature resistance adhesives for Stanyl.

Trademark	Type	T _{max} (°C)	Cured at
Bostik M890	Acrylate, mod.	125	Room temperature
Vantico:			
Araldit AV118	Epoxy	130	High temperature
AW139/HV998	Epoxy	120	Room temperature
Degussa:			
Agomet P79	Epoxy, mod.	120	Room temperature
Delo:			
Delo ESP	Epoxy	130	High temperature
Delo Katiobond 050	Acrylate	120	High temperature
GE:			
SEA210	Silicone	150	Room temperature
RTV 118,387,399	Silicone	150	Room temperature
3M:			
Jetmelt 3779	PA	150	Hot melt
EC 2214 HT	Epoxy	150	High temperature
E 1000	Cyano-acrylate	130	Room temperature
Henkel:			
Macromelt	PA	150	Hot melt
Loctite:			
Loctite 152-50	Acrylate	140	High temperature
Loctite 5910	Silicone	150	Room temperature
Marston:			
Hyloglue Plus 405	Ethyl	150	Room temperature

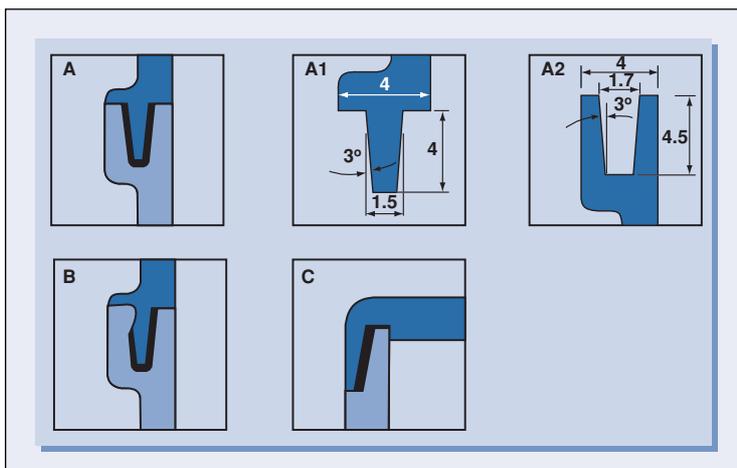
Laminating Arnitel (e.g. to fabric) can be done with a TPU (thermoplastic Polyurethane) hot melt adhesive. The high temperature during melting of the adhesive activates the hardener in the hot melt.

Xantar (PC), Xantar C (PC + ABS) and Stapron E (PC + PET)

A variety of adhesive types can be used for bonding Xantar PC and PC-blends: epoxy, urethane, cyano-acrylic, acrylic, methacrylic, silicone and hot melt. UV-transparent grades can also be bonded with UV-cure types. Being amorphous materials, Xantar PC and PC-blends are relatively sensitive to stress cracking induced by solvents, or to degradation due to specific chemical substances like amines. The best results are generally achieved with solventless materials.

Reactive adhesives make it possible to bond Xantar to many other materials. The application of reactive adhesives is simple and fast compared to adhesive solvents and the requirements to accurately align the joint areas are not as high. Reactive adhesives with elastic properties after curing are used in the automotive industry (e.g. for gluing lenses of transparent PC to metallized surfaces or to opaque PC).

Figure 58 Designs for adhesion bonding.



Reactive adhesives for Xantar based on epoxy resin must be free of low molecular weight amines. Polymeric amino amides can be used as hardeners. The possible reaction of residual amino groups with Xantar must be avoided by ensuring that the amino groups react completely with the epoxy groups.

Two-component and one-component polyurethane adhesives have also proven successful in joining PC, but they must be free of solvents and amines.

Silicone adhesives are particularly suitable as joint-gap-filler systems (e.g. for glazing of industrial and greenhouse windows).

Cyano-acrylic adhesives, should be used only to bond stress-free parts that will not be subjected to hydrolytic loads during use.

Mild surface abrasion (sanding) may improve adhesion by providing an increase in both surface area and the potential for mechanical coupling.

Design for adhesive bonding

The load on the assembly can be applied in a similar way to solvent bonding, see figure 55.

Thin layers are advised in case of lap shear. Peel and split loads are best taken up by a thick layer of adhesive.

General design guidelines are:

- design for lap shear loads
- maximize the bonding surface; for instance, use a scarfed or a dovetail joint
- avoid stress concentrations at thick-thin sections
- take care of sufficient venting on substrate.

Recommended joint designs are given in figure 58. Hermetic seals required for containers and bottles are achieved with the designs shown in figure A and B. Joint C is more universal.

To ensure successful joining with adhesives it is important to know the functional requirements of the assembly and the possibilities and limitations of the adhesive in combination with the substrate.

The following checklist might prove useful:

- product: design joints specifically for adhesives
- mechanical load: lap shear, peel, split or tensile
- life of joint: use temperature, environment, relative humidity
- thermoplastic substrate: mechanical properties, wetting, moisture absorption
- adhesive: temperature and chemical resistance
- pretreatment: cleaning, etching, sanding, oxidation, primer
- safety: MSDS (Material Safety Data Sheet) chart.

The moisture content of polyamides does not strongly influence the bond strength. It is advisable however to do some bonding tests with conditioned parts prior to production.



1.2.4. Double-Sided Tape

Double-sided coated tapes are adhesive-coated on both sides of paper, film or tissue. This increases the adhesive's dimensional stability for easy handling and application. Double-sided pressure sensitive tapes are available with a variety of carriers, adhesives and load bearing capabilities.

Specific advantages of double-sided tapes are:

- homogeneous distribution of mechanical loads
- dampen vibrations and noise
- absorb impact
- join dissimilar materials
- resist plasticizer migration, avoiding stress cracking problems
- good aesthetics / no special requirements to hide the bond
- economic assembly / minimal application training / no investment in major equipment
- low weight, no heavy bolts and nuts
- differences in thermal expansion of components can be compensated in a thick adhesive layer

- heat sensitive constructions or materials, which welding would distort or destroy, can be joined.

Potential limitations are:

- stress cracking or crazing caused by the adhesive
- reproducibility / process control
- disassembly.

Adhesive transfer tape consists of a pressure-sensitive adhesive pre-applied to a special release liner. The tape is simply applied to a surface and the liner is peeled off. This leaves a clean, dry strip of acrylic adhesive for joining of lightweight materials.

Pressure-sensitive tapes require a clean surface for optimal strength. Cleaning of the part may be necessary to remove oil, grease, mold release agent and other foreign materials, see par 2.1.11.

Figure 59 Schematic representation of the flow profile in the weld zone.

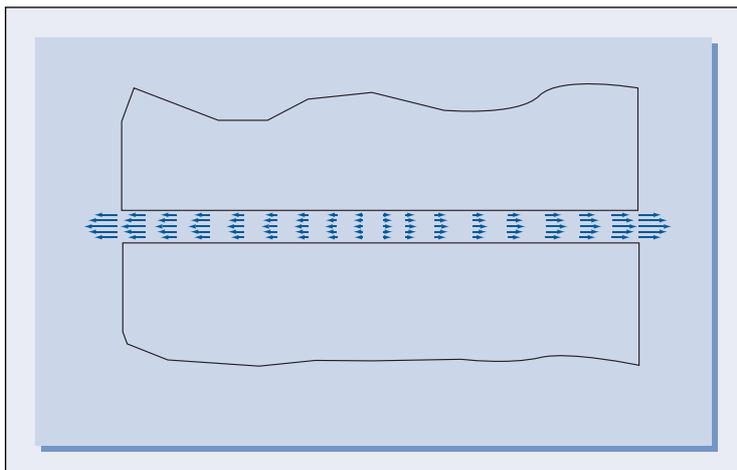
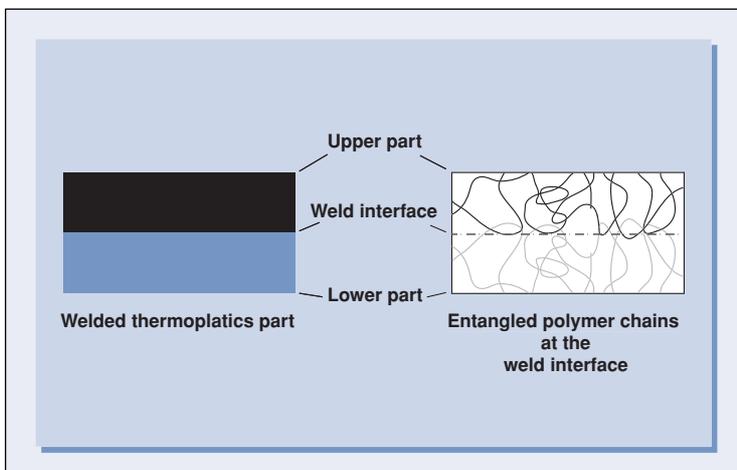


Figure 60 Molecular diffusion and entanglement during welding.



1.3. Welding

1.3.1. Introduction

Welding is an effective method of permanently joining plastic components. There are various welding methods.

Welding works on the principle of a phase change from solid to liquid (melt or in solution) followed by a solidification phase at the interfaces to be joined. In several welding processes, some material will be squeezed out of the weld by the pressure on the mating surfaces. The velocity of the out flowing 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 centre to the edges, figure 59.

The flow direction of the polymer melt is perpendicular to the direction of injection molding. After the polymer solidifies, this unfavourable orientation remains in the weld zone, which is the reason for the reduced strength of the weld compared to the bulk strength of the material.

Welding is aesthetically clean, and forms a very strong bond which is more-or-less permanent.

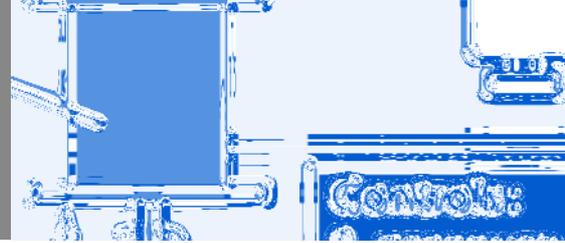
Welding of thermoplastic parts is based on interdiffusion of molecular chains, figure 60. It requires elevated temperatures, pressure and time to achieve a good mechanical bond.

Welding techniques

There are a variety of welding techniques. Generally these techniques can be distinguished into two basic types.

In **friction welding** the required heat energy is generated by friction between the two parts due to relative motion, as in vibration welding, spin welding and ultrasonic welding.

An **external heat source** is used in case of hot plate welding, laser welding, radio frequency welding (or dielectric or high frequency welding), induction



welding (or electromagnetic welding), resistance welding and hot gas welding.

The major advantages and disadvantages of the various welding methods are given in table 9.

Staking (par. 1.3.11) is not a welding process, but there are some similarities. In this process one part is provided with studs, which protrude through holes in the other part. The studs are then deformed through the cold flow or melting of the plastic to form a head which mechanically locks the two components together. Staking is specially suited to connect parts made from dissimilar materials (e.g. plastic to metal).

Costs

One of the decisive factors in the selection of the optimal welding technique is the welding cost per part. This cost depends on the batch size, as shown in figure 61. The effect of the batch size on the cost per part is not the same for every welding technique. This means that the most cost-effective process also depends on the batch size.

Figure 61 Welding costs.

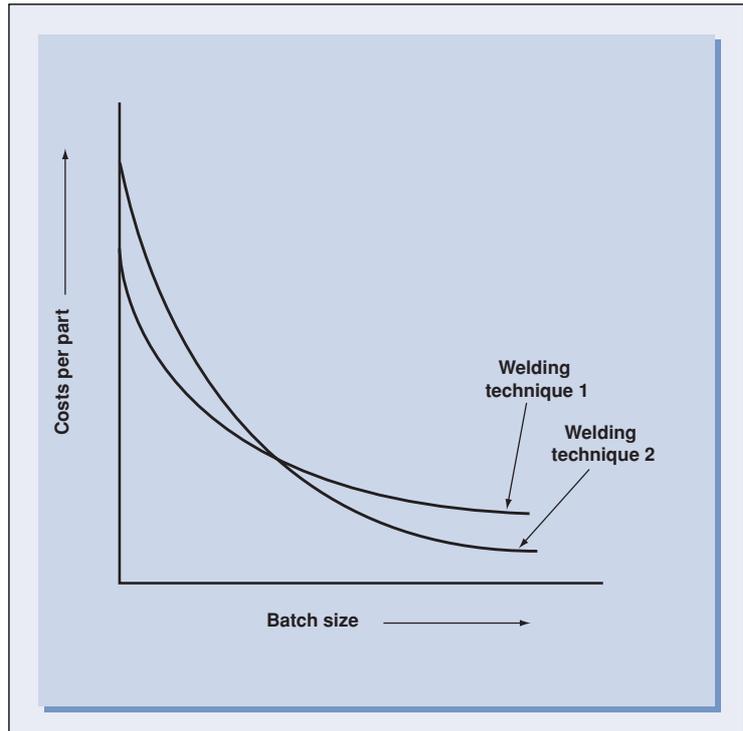


Table 9 Welding techniques.

Advantages	Disadvantages
Vibration Welding	
<ul style="list-style-type: none"> - cost-effective - short cycle times - large batch sizes possible - melted polymer not exposed to open air - strong bond 	<ul style="list-style-type: none"> - welding thermoplastic elastomers is problematic - product is exposed to vibrations during welding - much flash is formed - 3D-contours cannot be welded - materials with big difference in melt temperature cannot be assembled
Spin Welding	
<ul style="list-style-type: none"> - efficient, simple process - simple equipment - short cycle times - large batch sizes possible - melted polymer not exposed to open air - strong bond 	<ul style="list-style-type: none"> - welding thermoplastic elastomers is problematic - only circular contours can be welded - 3D-contours cannot be welded - relative position of the parts cannot be adjusted - materials with big difference in melt temperature cannot be assembled
Ultrasonic Welding	
<ul style="list-style-type: none"> - cost-effective - very short cycle times - large batch sizes possible - melted polymer not exposed to open air 	<ul style="list-style-type: none"> - welding thermoplastic elastomers is problematic - product is exposed to vibrations during welding - restricted to small and medium-size parts - materials with big difference in melt temperature cannot be assembled
Hot-Plate Welding	
<ul style="list-style-type: none"> - cost-effective - large batch sizes possible - suited for soft materials (thermoplastic elastomers) - different materials can be assembled in many cases - no electrical fields, no mechanical vibrations - strong bond 	<ul style="list-style-type: none"> - long cycle times - melted polymer exposed to open air (oxidation) - not well suited for PA66 and PA46
Laser Welding	
<ul style="list-style-type: none"> - short cycle times - no or hardly any flash is formed - ideally suited for miniaturization and very large products - thermoplastic elastomers can be welded - small heat-affected zone, built-in stresses not large - sensitive parts close to the weld not affected - no electrical fields, no mechanical vibrations - small series and mass production possible - strong bond 	<ul style="list-style-type: none"> - one part must be transparent to infrared radiation, the other part must be absorbant
Radio Frequency Welding (or Dielectric or High Frequency Welding)	
<ul style="list-style-type: none"> - suited for high polarity polymer films like PVC, EVA and polyurethane 	<ul style="list-style-type: none"> - only high polarity plastics can be welded; other plastics can only be welded using polar additives - not suitable for parts containing electromagnetic sensitive items (metal inserts)
Induction Welding (or Electromagnetic Welding)	
<ul style="list-style-type: none"> - short cycle times - 3D weld surfaces are possible - thermoplastic elastomers can be welded - can be used for highly filled materials - welding process is reversible (repair, recycling) - tolerances on part dimensions not tight 	<ul style="list-style-type: none"> - electromagnetic welding gasket material is required - not suitable for parts containing electromagnetic sensitive items (metal inserts)
Resistance Welding	
<ul style="list-style-type: none"> - simple and fast process, minimal equipment requirements - very large products can be welded 	<ul style="list-style-type: none"> - heating wire remains in part after welding, adding to process costs and possibly reducing welding strength
Hot Gas Welding	
<ul style="list-style-type: none"> - suitable for very large products - suitable for field assembly, repair and prototypes - inexpensive, simple equipment, generally portable 	<ul style="list-style-type: none"> - weld quality is operator dependent - often a limited weld strength - slow process - weld remains visible



1.3.2. Vibration Welding

In vibration welding, the plastics parts to be joined are vibrated (rubbed) against each other at a chosen frequency, amplitude and pressure which results in frictional heating of the surfaces, causing the polymer to melt at the interface. The molten polymer flows out of the weld-zone giving rise to flash, see figure 62. When vibration stops, the weld cools down and solidifies. Vibration welding is a cost-effective process, with short cycle times.

Vibration welding has the advantage that the polymer melt is not exposed to open air, which can be important for materials that are susceptible to thermooxidative degradation. With this process, strong connections can be made, however the product is exposed to vibrations during welding, which can be a disadvantage for certain applications.

The welding process

Four different phases can be distinguished in the vibration welding process, namely the solid friction phase, transient phase, steady-state phase and cooling phase, see figure 63.

In the solid friction phase, the heat generated due to frictional energy between the two surfaces (frequency of vibration, amplitude, and pressure) causes the material to heat up and melt.

In the second phase 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 third phase, the rate at which melt is formed becomes equal to the outward flow rate (film drainage) and this comes to a steady state (the thickness of the molten layer becomes constant). Vibrations are stopped at this point.

The polymer melt starts to cool, the cooling phase, and solidification results at the interface of the joint. Film drainage will continue while the joint is held under pressure. When solidification is complete the pressure is withdrawn and the joint is formed.

Figure 62 Schematic representation of the welding process.

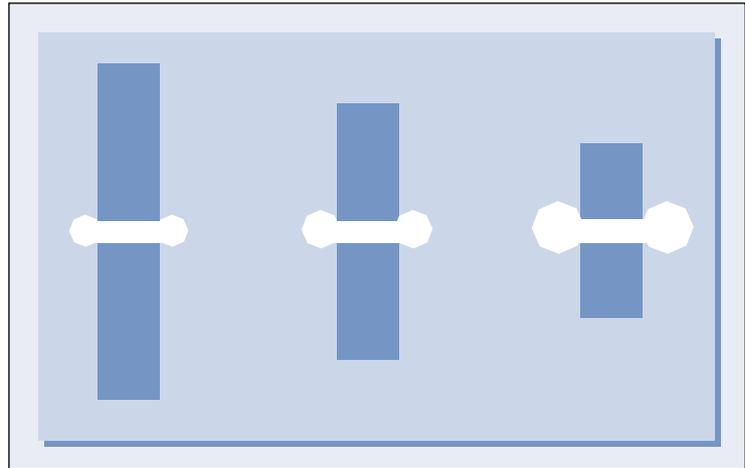


Figure 63 The phases of the vibration welding process.

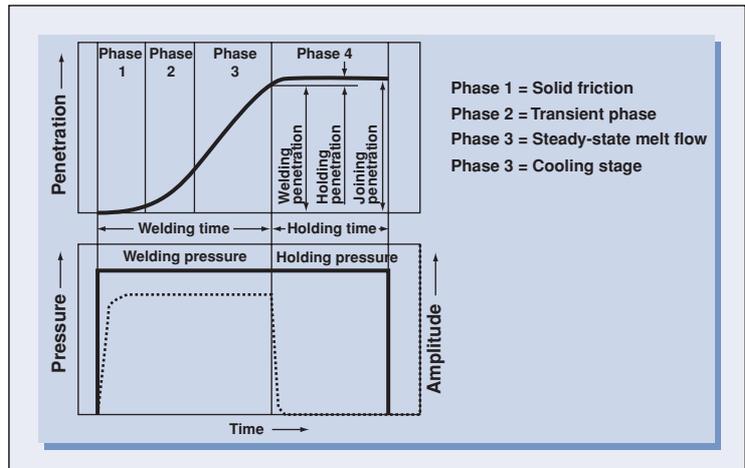


Figure 64 Air inlet manifold of Akulon K224-HG6.



Figure 65 Vibration welding equipment.

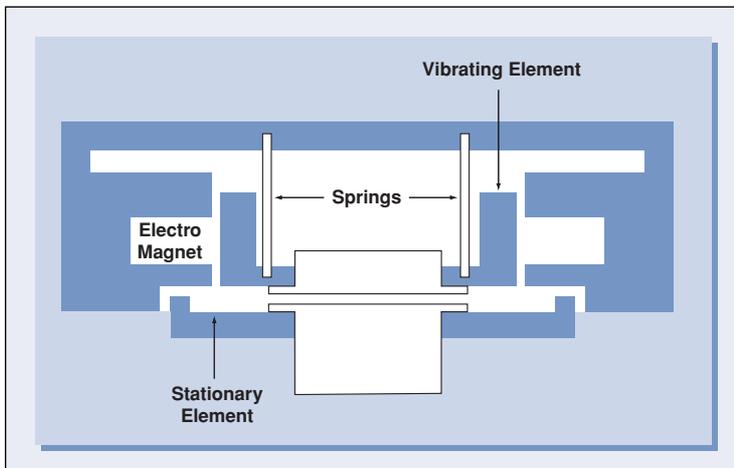
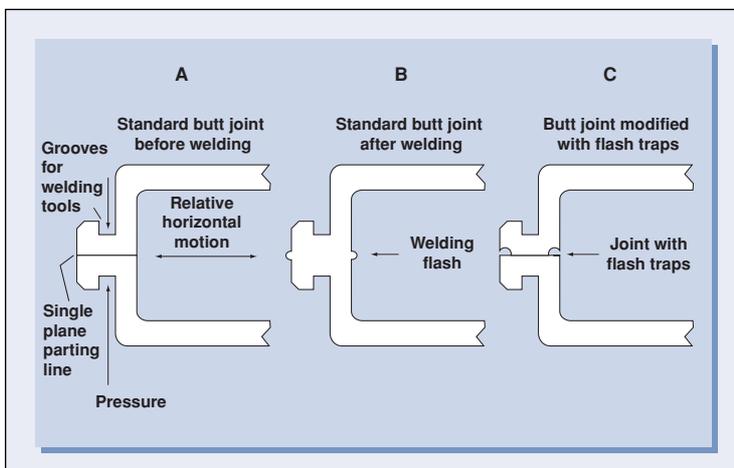


Figure 66 Typical joint designs for vibration welding.



Process parameters

It is possible to weld components that are very large. Usually products larger than 200 mm (8 in) are joined with this technique, see figure 64.

Typical process parameters are:

- frequency: 100-400 Hz
- amplitude: 0.5-2.5 mm (0.02-0.10 in)
- cycle time: 10 seconds
- weld pressure: 0.5-5 MPa (70-700 psi)

Materials

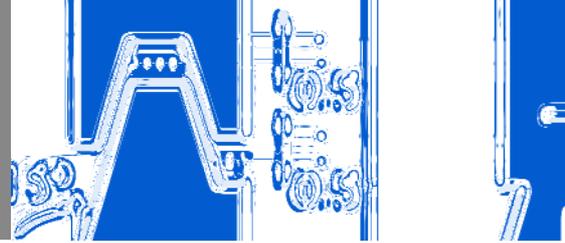
Most DSM thermoplastics, such as Akulon, Arnite, Stanyl and Xantar, can be vibration welded. Amorphous materials, such as Xantar, are more easily vibration welded than semi-crystalline polymers. The process is not suitable for very flexible materials such as Arnitel.

Equipment

During welding a special fixture is required to hold the components. The vibrations are generated by electro magnets, as in the example shown (see figure 65), or electric motors.

Part design

The mating surfaces must be parallel. Three-dimensional contours are not possible due to the vibratory motion. If visible flash is not acceptable, the joint can be provided with flash traps, see figure 66 part C.



1.3.3. Spin Welding

The two parts to be welded are pressed together and while one part is held fixed the other rotates at high speed. The friction between the two parts generates heat which causes the polymer to melt at the interface. The molten polymer flows out of the weld-zone giving rise to flash, see figure 62.

When rotation stops, the weld cools down and solidifies. Spin welding is an efficient, simple and fast process, with short cycle times.

Spin welding has the advantage that the molten polymer is not exposed to air, which can be important for materials that are susceptible to degradation or oxidation. Strong connections can be made.

The welding process

Four different phases can be distinguished in the vibration welding process; the solid friction phase, the transient phase, the steady-state phase and the cooling phase (see figure 67).

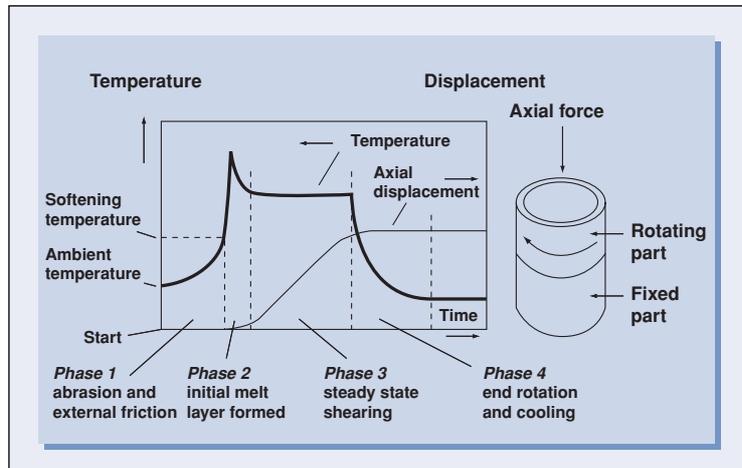
In the solid friction phase, heat is generated as a result of the friction between the two surfaces. This causes the polymer material to heat up until the melting point is reached. The heat generated is dependent on the applied tangential velocity and the pressure.

In the second phase, a thin molten polymer layer is formed which grows as a result of the ongoing heat generation. In this stage heat is generated by viscous dissipation. At first only a thin molten layer exists and consequentially the shear-rate and viscous heating contribution are large. As the thickness of the molten layer increases the degree of viscous heating decreases.

Thereafter (start of third phase) the melting rate equals the outward flow rate (steady state). As soon as this phase has been reached, the thickness of the molten layer is constant. The steady-state is maintained until a certain "melt down depth" has been reached at which point the rotation is stopped.

At this point (phase 4) the polymer melt cools and solidification starts, while film drainage still occurs

Figure 67 The phases of the spin welding process.



since the welding pressure remains. After all the material has solidified, drainage stops and the joint is formed.

Process parameters

Spin welding is restricted to cylindrical parts with a maximum diameter of about 250 mm (10 in). 3D-contours cannot be welded and the relative position of the parts cannot be adjusted. Typical process parameters for spin welding are:

- tangential velocity: 3-15 m/s (10-50 ft/s)
- rotational speed: 1000-18000 rpm (depending on the part diameter)
- welding time: 0.25-1s
- holding time: 0.5-1s
- cycle time: 1-2 seconds
- weld pressure: 2-5 MPa (300-700 psi).

Figure 68 Spin welding equipment.

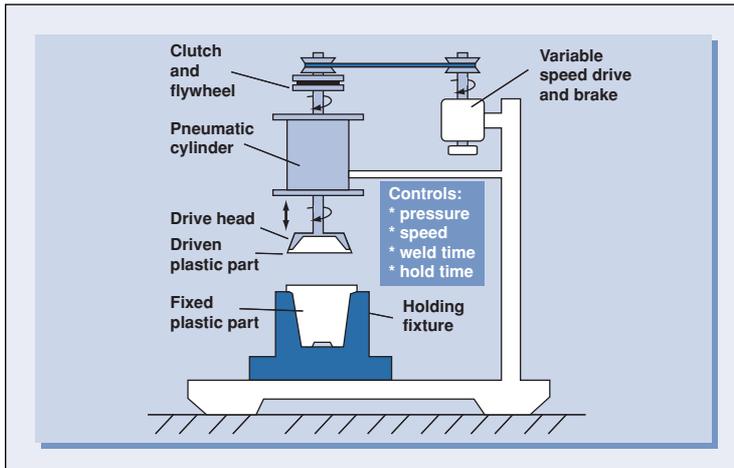


Figure 69 Gusset plates for improved torque transmission.

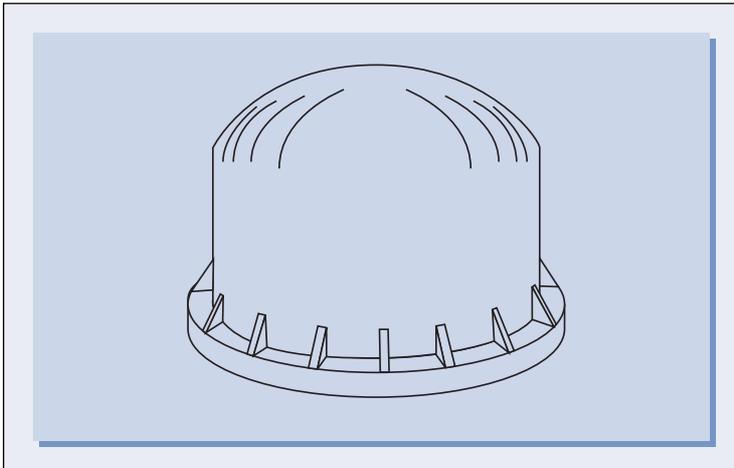
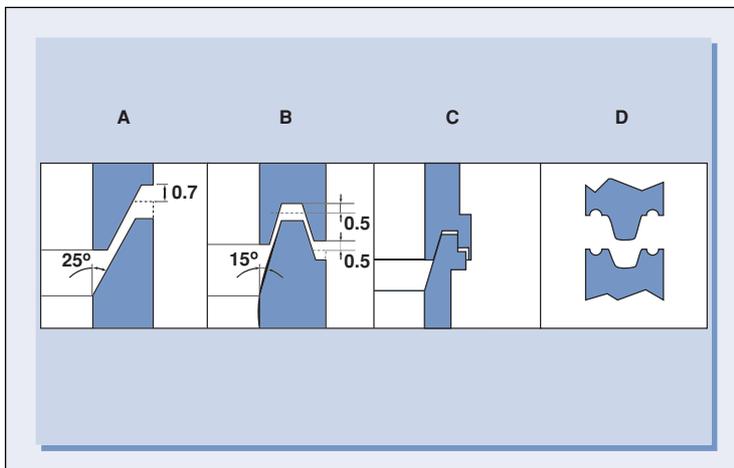


Figure 70 Typical weld designs for spin welding.



Materials

Most DSM thermoplastics, like Akulon, Arnite, Stanyl and Xantar, can be spin welded. Spin welding of soft plastics, such as Arnitel, is problematic.

Equipment

Welding equipment can range from a simple modified drill press or lathe for prototype work or pre-production runs, to more automated and expensive production machines. Figure 68 shows the principle of more sophisticated equipment.

A flywheel is accelerated to the desired rotational velocity using a motor. The motor is disengaged at the start of the weld cycle, and the kinetic energy stored in the flywheel is converted into heat energy during welding. The pneumatic cylinder generates the welding pressure.

Part design

To prevent part deformation during welding it is common practice to design a flange at the weld surface. Due to the weld, a loss in the overall length of 0.2-0.4 mm (0.01-0.02 in) should be taken into account when designing the component. Correct alignment of the components is important. Gusset plates can be added on the flange of the part for improved torque transmission.

A simple butt joint is possible, however in figure 70 parts A and B show some typical weld designs, which are stronger and self-centering.

Proper welds will always show flash. For aesthetic purposes the part can be designed to hide the weld (figure 70 part C) or flash traps can be used (figure 70 part D).



1.3.4. Ultrasonic Welding

Ultrasonic welding is a fast and cost-effective welding technique for small and medium size parts. Cycle times are very short.

The process uses low amplitude, high frequency (ultrasonic) vibrational energy. One of the two parts to be joined is fixed firmly within a stationary holding jig, while the mating part is subjected to a sinusoidal ultrasonic vibration normal to the contact area. As a result of the friction between the parts and internal friction in the parts, heat is generated. This causes the polymer to melt at the interface. When vibration stops, the weld cools down and solidifies.

Ultrasonic welding has the advantage that the melted polymer is not exposed to air, which can be important for materials that are susceptible to degradation or oxidation. The product is exposed to vibrations during welding, which can be a disadvantage for certain applications.

The welding process

Four different phases can be distinguished in the ultrasonic welding process; the solid friction phase, the transient phase, the steady-state phase and the cooling phase, see figure 71.

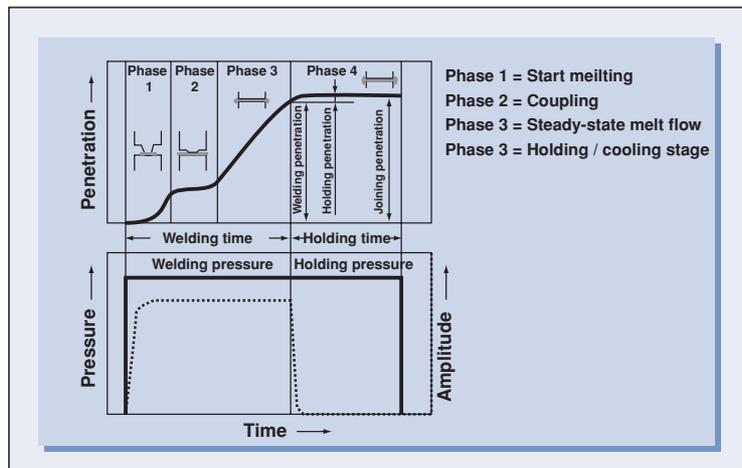
In the solid friction phase, heat is generated as a result of the frictional energy between the two surfaces and the internal friction in the parts. This causes the polymer material to heat up until the melting point is reached. The heat generated is dependent on the applied frequency, amplitude and pressure.

In the second phase, a thin molten polymer layer is formed which grows in thickness as a result of the continuous heat generation. In this stage heat is generated by viscous dissipation.

At first only a thin molten layer exists and consequently the shear-rate and viscous heating contribution are large. As the thickness of the molten layer increases the degree of viscous heating decreases.

At a certain point (start of third phase) the melting rate equals the outward flow rate (steady state). As soon

Figure 71 The phases of the ultrasonic welding process.



as this phase has been reached, the thickness of the molten layer is constant. The steady-state is maintained until a certain "melt down depth" has been reached at which the vibration is stopped.

At this point (phase 4) the polymer melt cools and solidification starts, Film drainage still occurs since the welding pressure is maintained. After solidification of all the material, no further drainage occurs and the joint is formed.

Process parameters

In general products with a weld joint smaller than 200 mm (8 in) in length are joined with this technique. Large batch sizes are possible. Typical process parameters are:

- frequency: 20-40 kHz
- amplitude: 10-50 μm (0.0004-0.002 in)
- cycle time: 1 second
- weld pressure: 1-10 MPa (145-1450 psi).

Materials

Most DSM thermoplastics, like Akulon, Arnite, Stanyl and Xantar can be vibration welded. Semi-crystalline polymers are generally more difficult to weld using ultrasonic energy when compared to rigid or semi-rigid amorphous thermoplastics. The process is not suitable for very flexible materials such as Arnitel.

Figure 72 Ultrasonic welding equipment.

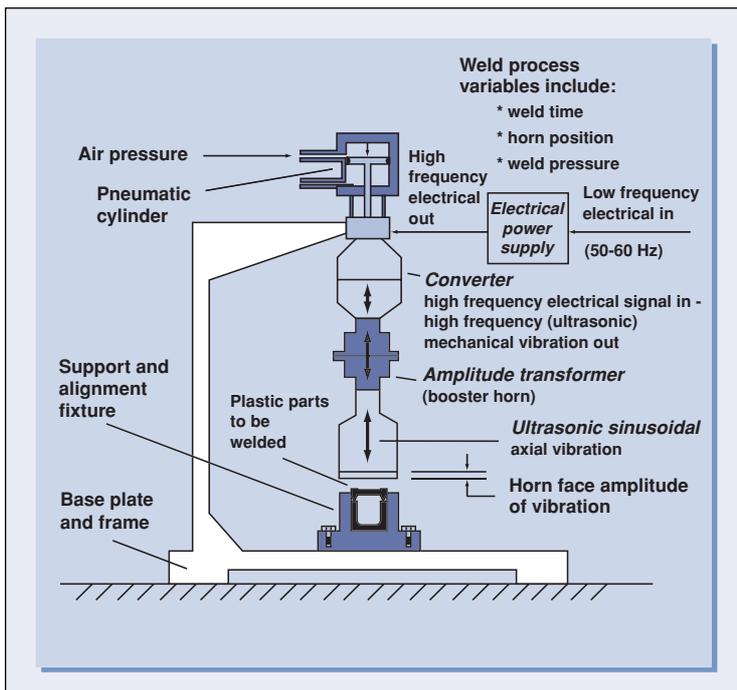
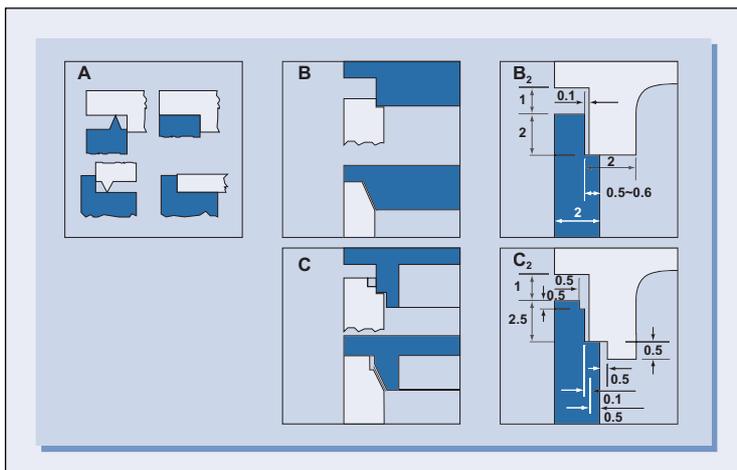


Figure 73 Designs for ultrasonic welding.



Drying before welding is not always necessary to obtain a higher quality weld. DSM drying guidelines for injection molding can be followed. If the effect of moisture is unclear, it is advisable to first test its influence on welding strength. Components may be conditioned for testing by immersing them overnight in water in advance of welding.

Equipment

Welding equipment consists of an ultrasonic generator, a booster for amplification and a horn to transfer energy to the component, figure 72. The combination of booster and horn is unique for each design. When using glass fiber reinforced thermoplastics, the horn needs a special surface treatment to prevent abrasion.

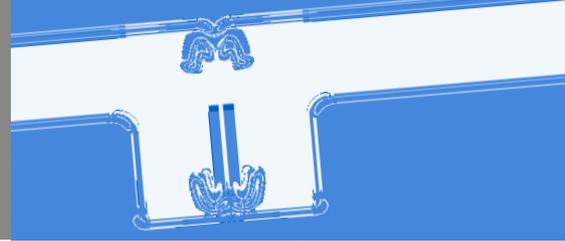
Part design

Melting takes place at the weakest part of the component. Therefore, it is often advised to use a line contact at the welding surface. Standard shapes are depicted in figure 73: the energy director principle (A) and the shear joint (B & C).

The weld zone is melted instantaneously by internal friction. The mechanical strength of an ultrasonic weld may reach a value of 70 to 80% of the original strength of the material, however the actual strength depends on the specific geometry and the materials being welded.

In general, a shear joint is advised for semi-crystalline thermoplastics because of their short melting range. Note that the weld can be hidden either on the inside or on the outside corner to improve appearance. The efficiency of energy transfer to the weld surface depends largely on the type of thermoplastic. Stiff parts with low mechanical damping properties can be easily welded. The distance between horn and weld surface may be larger than 6 mm (0.24 in) (distant welding). Parts with a relatively low stiffness should be welded under near field conditions [less than 6 mm (0.24 in)].

Internal sharp corners cause stress concentrations. The use of fillet radii is strongly advised when using ultrasonic assembly. Proper welds always give flash.



1.3.5. Hot-Plate Welding

Hot plate welding uses thermal energy to melt the welding zone through heat conduction. It is a cost-effective process and large batch sizes are possible. However, the process is time consuming; typical cycle times being 10 to 60 seconds. This results in a strong bond that can bear heavy mechanical loads. The molten polymer is exposed to air during the process, which may reduce the weld strength, due to oxidation of the polymer.

The welding process

The welding process comprises six steps, see figure 74.

Process parameters and materials

The welding pressure is relatively low, 0.1-0.5 MPa (15-73 psi). Part size is unlimited.

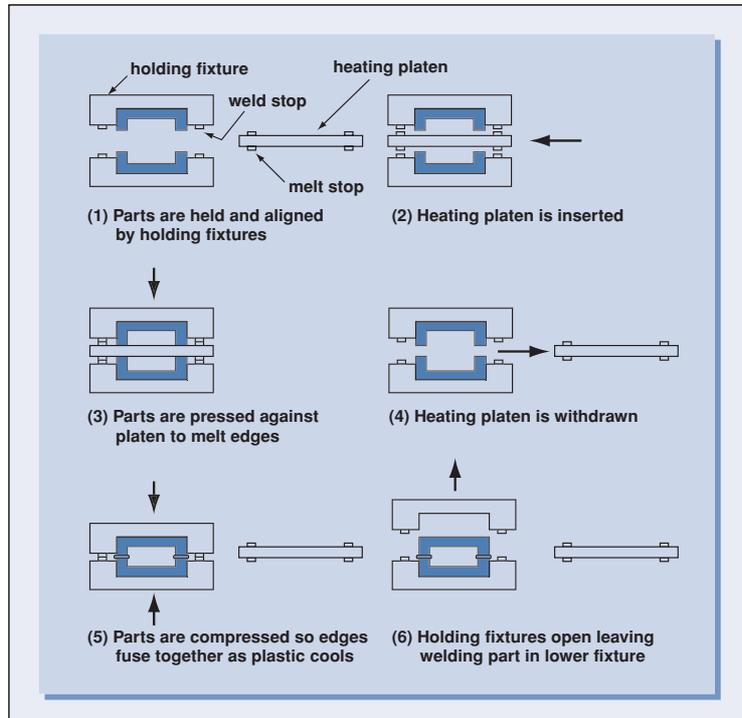
DSM's thermoplastic materials can be hot plate welded and the process is even suitable for very flexible materials such as Arnitel, but the process is less suited for Akulon PA66 and Stanyl. It is difficult to achieve a satisfying weld strength with PA66, due to oxidative degradation of the molten polymer. Stanyl has a very low melt viscosity, which causes dripping.

One of the strong points of hot-plate welding is that different materials can be assembled, e. g. amorphous and semi-crystalline polymers, or polymers with a big difference in melting point.

The recommended plate temperature depends largely on the specific thermoplastic. Amorphous plastics require a temperature 100°C-160°C (212°F-320°F) above the glass transition temperature (T_g). Semi-crystalline materials are best welded at 40°C-100°C (100°F-210°F) above melting temperature (T_m).

A PTFE coating on the hot plate is often used to prevent parts sticking to the hot plate. In that case, the temperature of the hot plate should be limited to 260°C, as the PTFE will begin to fume off at a temperature of 270°C - 275°C. The maximum temperature for a hot plate without PTFE is 450°C. PTFE coated hot plates have the following features:

Figure 74 The hot plate welding process.



- less sticking of the parts to the hot plate
- lower temperature results in less degradation of the polymer
- lower temperature results in longer cycle times
- limited life of the PTFE coating.

Sticking of the parts to the hot plate can sometimes be avoided by choosing a higher hot plate temperature. High temperature hot plate welding of PC should be done above 300°C.

Non-contact welding is another way to prevent sticking. In that case, the plastic parts and the hot plate are separated by a small gap and the heat is transferred by radiation instead of conduction. The hot plate temperature must therefore be considerably higher. Temperatures up to 450°C can be used.

Oxidative degradation of the molten surfaces, which leads to a reduced weld strength, can easily occur in non-contact welding.

Table 10 Indication of hot plate temperature for DSM's products.

DSM-products	Polymer description	Hot plate temperature (°C) (*)
Akulon	PA6	240-300
Arnite	PBT	240-350
	PET	270-350
Arnitel E	TPE	250-300
Arnitel P	TPE	275-325
Xantar	PC	250-400 (**)
Xantar C	PC + ABS	220-400 (**)
Stapron E	PC + PET	250-400 (**)

(*) Higher temperatures, even up to 450°C, might be used for non-contact welding, or to reduce cycle times, but oxidation of the molten surfaces can easily lead to a reduced weld strength.

(**) When welding without a PTFE coating on the hot plate, use temperatures above 300°C to prevent parts sticking to the hot plate.

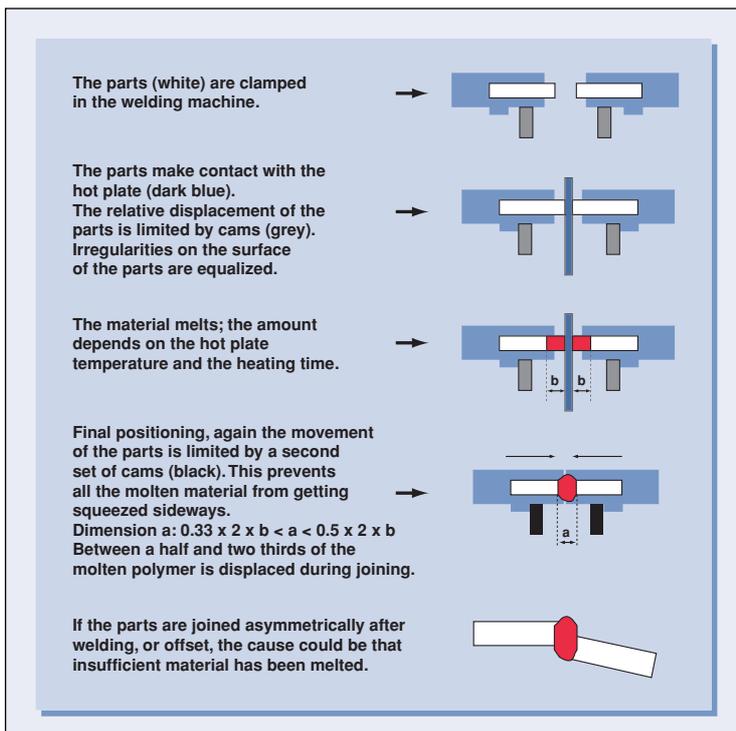
Recommended hot plate temperatures for DSM polymers are listed in table 10.

It is important that the relative displacement of the parts and the welding pressure are carefully controlled. If the welding pressure is too high, the molten polymer will be completely squeezed from the weld seam and the weld strength may be too low. There are two basic principles to control the weld penetration: "welding by pressure" and "welding by distance". In the first type, the pressure is controlled throughout the process.

The most frequently used principle however is welding by distance. In that case rigid mechanical stops are used to control the dimensions, see figure 75.

The change-over time between melting of the polymer and assembling of the parts should be as short as possible to avoid premature cooling and to limit oxidation of the molten film as much as possible.

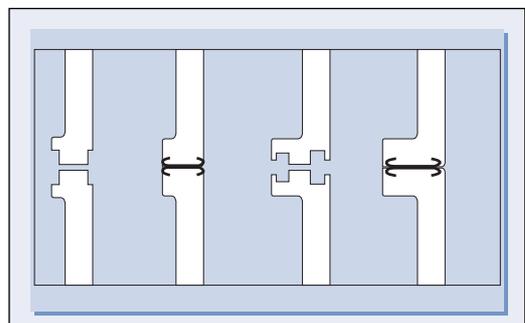
Figure 75 The welding by distance principle.

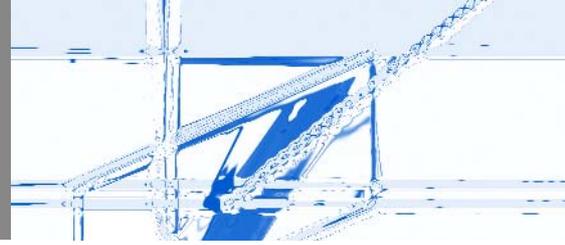


Part design

Proper welds will give rise to flash. To improve appearance the flash may be trapped as indicated in figure 76. A loss in overall length due to welding should be allowed for.

Figure 76 Typical weld designs for hot plate welding.





1.3.6 Laser Welding

Laser welding is an emerging technology among welding methods. It offers several advantages over other welding methods as follows:

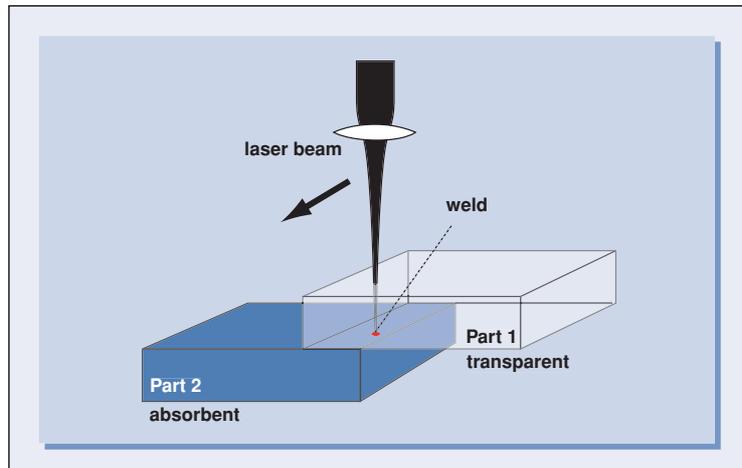
- Improved visual appearance of the welded surface due to negligible weld-flash formation
- Little visible damage or deformation to the product because limited mechanical loads are used during welding
- The process is very flexible and adapts quickly to suit different production rates
- It can be applied to products with a wide variety of sizes, from very small to quite large, due to the widely variable weld line width possible
- 3D shaped welding contours can be joined
- Thermoplastic elastomers can be welded
- Physical performance of the product is minimally affected since the heat treated area is small, leading to lower built-in stresses
- Sensitive components can be welded as no electrical fields or mechanical vibrations are generated

Weld strengths achieved with laser welding are similar to those on parts welded using other methods. Laser welding is inherently a flexible process and by selecting the right welding equipment, switching between different products is facilitated.

There are some boundary conditions to be met on materials and product design if the process is to be effective. One important material condition is that one product part should be transparent to laser radiation, whereas the other part has to be absorbent. The geometry of the weld region is an important aspect in the product design, nevertheless a large number of shapes can be used and still give optimum welding results.

The recently introduced diode lasers are relatively inexpensive and are an attractive option for industrial laser welding applications. Even though their optical beam quality is less than of conventional laser systems, this does not affect their performance in welding polymers.

Figure 77 Overlap welding.



Potential laser welding applications can vary from miniature components for optical information storage and biomedical applications to encapsulation of electronic components, housings of personal electronic products, automotive components and double walled window systems.

Laser welding process

There are two process variants for laser welding of polymers: overlap welding and butt-welding.

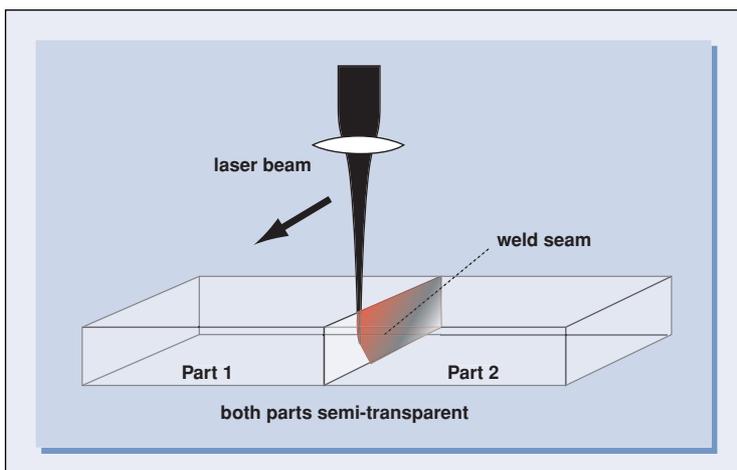
Overlap Welding

The parts to be welded are held together with a moderate clamping force. The laser beam passes through one of the parts (part 1) which is transparent to laser radiation with a wavelength in the near infra-red region between 800 and 1100 nm. See figure 77.

The laser radiation is absorbed in the top-layer of the other part (part 2). This top-layer is heated and heat is transferred to the upper part. The surface layers of both parts melt, and after cooling and solidification a reliable bond is formed.

In general, parts that are transparent to near infra-red laser radiation are also visibly transparent, whereas laser-absorbing parts usually have an opaque appearance (colored or black). However, there are a few exceptions to this and these can be used to increase design freedom with regard to color.

Figure 78 Butt welding.



Butt welding

Due to the low thermal conductivity of polymers (contrary to metals) only those parts of the work piece where the laser energy is absorbed will be molten, figure 78. In order to achieve a strong weld seam, a melt has to be created throughout the whole joining volume. This puts important restrictions on the laser absorption of both parts, and consequently on their pigmentation.

For this reason, butt welding is not an ideal configuration for polymer welding.

Process parameters for laser welding

Laser welding is suitable for both small-series and mass production and for micro-components as well as very large products, like double-walled window systems. The process time can be < 0.5 seconds for small products. In practice, laser welding can be as fast as ultrasonic welding.

The typical wavelength of the light used is 800-1100 nm.

Materials

The most important material properties for laser welding are the optical properties of the parts to be joined. In most cases overlap welding is used. For this type of laser welding, one part has to be transparent and the other should absorb the laser. Since most polymers are transparent to infrared laser radiation, absorbent additives are needed in the absorbing

part. For colored parts which do not absorb in the IR spectrum, special IR absorbent additives should be used with a low level of visible color. The most well-known organic IR absorbent material is carbon.

The IR laser radiation penetrates the transparent part and irradiates the interface between the product parts. In many materials, there are several phenomena that lead to scattering of the incoming IR radiation. Sources of light scattering are mineral fillers, glass fibers or polymer crystallite structures. An example of a strongly scattering material is Arnite PBT. All these phenomena result in a broader intensity distribution at the weld area. Welds of dissimilar materials can be made as long as the materials have some degree of compatibility. For more details please see the laser welding handbook on www.dsmep.com.

1.3.7. Radio Frequency (or Dielectric or High Frequency) Welding

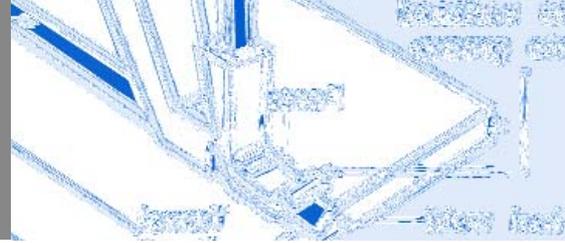
Radio frequency (RF) welding, also called dielectric welding or high frequency (HF) welding, uses electromagnetic energy to generate heat and bond two parts together under pressure. The resulting weld can be as strong as the original material. RF welding is used to connect polymer films for healthcare, medical, industrial and consumer products, where a strong fluid proof seal without needle holes is needed.

The welding process

The parts that must be bonded are placed in a varying, radio frequency electromagnetic field. The heat results from electrical losses that occur in the material located between two metal plates or bars, called electrodes. These electrodes also act as pressure applicators during heating and cooling. The dynamic electric field causes the molecules in some thermoplastics to oscillate, due to their dipole moment. The oscillating movement of the molecules makes the polymer melt. When the electromagnetic field is switched off, the weld cools down and solidifies.

Materials

Only certain materials, which contain molecules with a dipole moment (polar polymers), can be RF welded. The most widely used material is Polyvinyl Chloride (PVC).



Nylon sheeting can be RF welded if preheated electrodes are used. Other plastics can only be welded with the use of polar additives.

1.3.8. Induction (or Electromagnetic) Welding

Induction welding, also called electromagnetic welding, uses inductive energy to heat the plastic and reach the fusion temperature in the area to be joined. The process requires a magnetically active bonding material in the shape of a preform or a gasket that is laid into the groove on one of the parts to be welded to form a hermetic seal. The process is reversible, which permits repair of misaligned joints and defective components, and also improves recyclability.

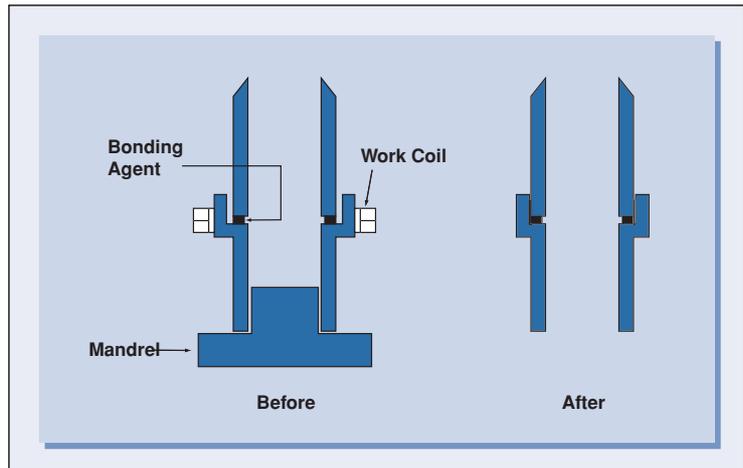
The welding process

The electromagnetic welding equipment consists of a radio frequency generator, watercooled coils and fixtures to contain and align the parts that must be joined. The generator creates a high frequency current in the coils, producing an oscillating magnetic field in the joint area. The parts to be joined must be transparent to the magnetic fields. The high frequency magnetic field generates eddy currents in the bonding material through induction and the hysteresis loss in this process is responsible for the heat generation. The bonding material melts and the parts are joined under low pressure. The plastic solidifies again as soon as the magnetic field is switched off.

The bonding material can be supplied as extruded tape, strand or other profile, or as a molded gasket for complex geometries or for ease of handling. The bonding material is normally produced from the same polymer as the parts or from a compatible polymer, and is filled with finely dispersed micro particles of ferromagnetic material, such as iron, iron oxide or stainless steel. The loading of the ferromagnetic powder is generally less than 15% by volume.

Hygroscopic thermoplastics, such as Akulon and Stanyl, may need to be dried to eliminate moisture related welding problems.

Figure 79 The induction welding process.



Process parameters

Complex 3D-contours can be welded. The electromagnetic field typically has a frequency between 2 and 8 MHz. The cycle time can vary from 3-10 seconds, for small parts, to 30 seconds for large assemblies.

Materials

Akulon, Arnite, Stanyl and Xantar can all be electromagnetically welded. The process is specially suited to welding soft plastics, such as Arnitel TPE.

Part design

The most commonly used joints are the tongue and groove joint and the step joint, see figure 80. The shear joint is the strongest connection, as externally applied forces only result in shear stresses in the weld.

The dimensions of the gasket and the groove are designed in such a way that an overfill of about 5% is achieved, so that the space between the parts is completely filled with melted polymer.

The tolerance requirements for the parts are not very tight, due to the capacity of the welding material to fill gaps or voids.

Figure 80 Typical joint designs for electromagnetic welding.

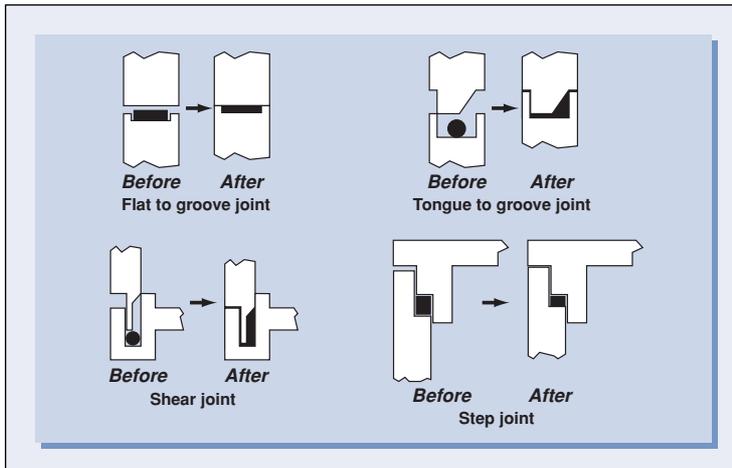
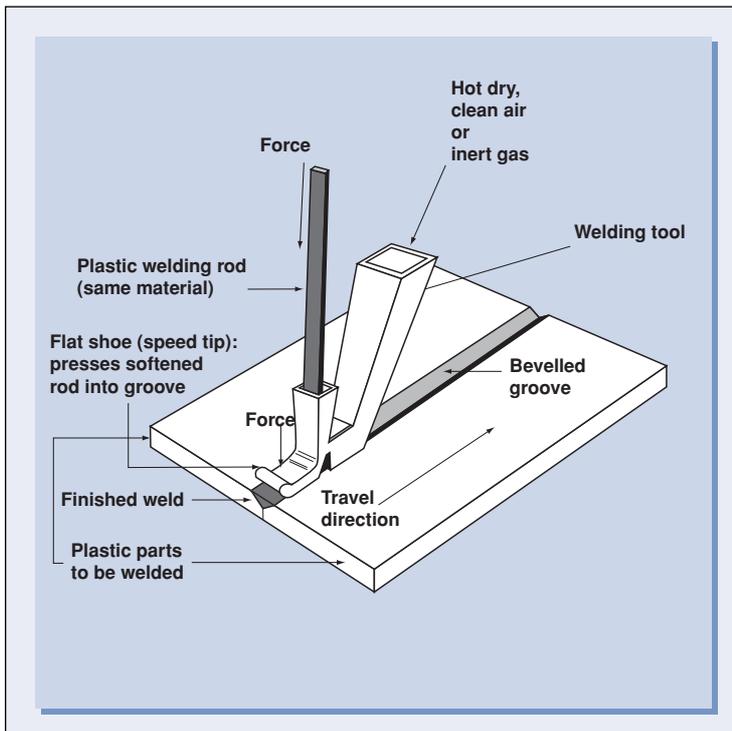


Figure 81 Hot gas welding.



1.3.9. Resistance welding

Resistance welding is a simple and fast process used to join plastic parts using an electric current. An electrically conductive wire or braid is placed in the joint interface. The wire is connected to an electric circuit and an electric current generates heat in the weld zone through resistance losses. The heat generated depends on the electrical resistance and is expressed by the equation

$$E = I^2 \cdot R \cdot t$$

where

E = the heat energy,

I = the current,

R = the electrical resistance of the wire

t = the time that the current is applied.

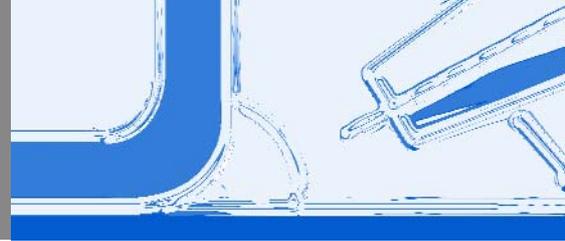
The two parts are joined under pressure and the plastic that surrounds the wire is softened or melted by the heat. The plastic solidifies when the electric current is switched off and the bond is formed.

The process is suitable for very large parts due to the minimal equipment requirements, but has the disadvantage that a sacrificial heating wire is required, which remains in place after welding, adding to the process costs. It is a reversible process, which permits repair of misaligned joints and defective components, and also improves recyclability. The presence of the wire in the weld may have a negative influence on the weld strength.

1.3.10. Hot gas welding

Hot gas welding uses a hot dry gas to simultaneously melt the surface of the parts to be joined and a plastic welding rod. The melt from the welding rod fills a groove or corner between the two parts and forms a bond after solidification, figure 81.

The process is extensively used for assembling large parts produced from thermoplastic plates, tubes or profiles. Hot gas welding is specially suited to field assembly and repair, and for prototyping. Injection molded parts are normally not hot gas welded, as many other more automated and more economic



welding processes are available, mostly with a better controlled weld quality.

Hot gas welding is a slow process.

The weld quality is operator dependent and the weld strength is often limited, due to

- residual stresses in the weld zone caused by shrinkage
- notch effects at the bottom of the groove
- incompatibility of the welding rod material with the part's material
- dirt particles, grease, oil or moisture in the weld
- gas inclusions.

The welding process

The hot gas that is used can be air, or, for materials that are sensitive to oxidative degradation, an inert gas like nitrogen. The gas as well as the parts must be dry and free of dirt, oil and grease. The edges of the parts are chamfered prior to the welding, or the two parts form a corner. Both parts are clamped or placed in a fixture to ensure proper positioning. Hot gas welding is generally done manually.

The welder holds the welding tool in one hand and pushes the welding rod into the weld area with his other hand. It is clear that the weld quality highly depends on the skill of the welder. Welding tools modified with shoes or rollers increase both the speed and quality of welding by providing improved control over the welding pressure.

Extrusion welding

Extrusion welding is similar to hot gas welding, except that the filler material is separately heated in an extruder. The melted material is then extruded through a PTFE die into the joint. The joint is pre-heated using a hot gas nozzle mounted on the extruder barrel.

Process parameters and materials

Most DSM thermoplastics can be hot gas welded. For optimum weld strength, the welding rod must be made from the same material as the substrate.

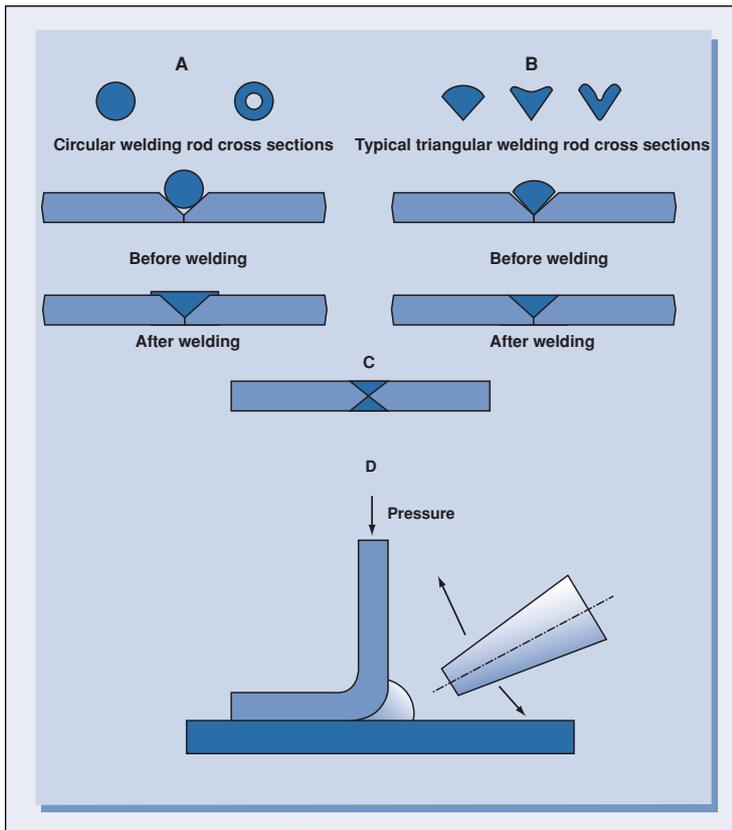
- The hot gas temperature for Xantar is typically 350°C (660°F). The hot gas temperature for semicrystalline materials is typically between 80°C and 100°C above the melting point.
- The travel speed of the welding tool is normally between 0.1 and 0.3 m/minute. Good results can be obtained when the welding gun is moved in a pendulum fashion along the joint axis.
- The angle between the welding rod and the parts to be welded should be approximately 90°.
- Typical gas flow rates are in the range 16-60 litre/min.

Equipment

The equipment for hot gas welding consists of a heater unit to heat the gas and a nozzle to direct the gas onto the workpiece. A range of nozzle shapes are available and selection is based on the type of weld preparation. The equipment is generally cheap, simple and portable, although more automated and expensive large scale production machines are available.

Hazardous hot fumes can be developed during hot gas welding. Proper ventilation and exhaust equipment may be necessary.

Figure 82 Examples of joint designs and welding rod cross-sections.



Part design

V-welds are shown in figure 82 with the most commonly used round welding rod and a welding rod with a triangular cross-section for improved heat transfer and flow. The double V-weld in figure C offers a stronger connection, as stress concentrations at the bottom of the groove are avoided. The solution shown in figure 82D has the advantage that no chamfering is required.

1.3.11. Staking

Staking is a process that is specially suited to connect parts made from dissimilar materials (e.g. plastic to metal, figure 83). One part is provided with studs, which protrude through holes in the other part. The studs are then deformed through the cold flow or melting of the plastic to form a head which mechanically locks the two components together. It is a quick and economical technique and it has the advantage that no consumables such as rivets and screws are required.

A variety of stud head designs are feasible by changing the probe tip design.

The general purpose stake is recommended for studs with a diameter between 1.6 and 4 mm (1/16-5/32 inch). The dome stake is recommended for small studs with a diameter smaller than 1.6 mm (1/16 inch). The flush stake is used where a flat surface is required. The hollow stake minimises sink marks and shrinkage voids and is used where the stud has a diameter greater than 4 mm (5/32 inch).

Staking is widely used, in many fields like

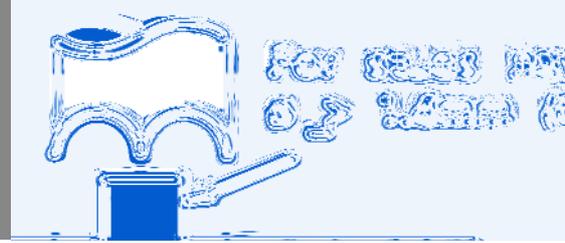
- automotive industry
(attaching parts to door panels)
- telecommunications
- electronics (printed circuit boards)
- medical equipment
- consumer appliances.

Cold staking

In cold staking, the stud is deformed through the application of high pressure. Cold flow subjects the stud region to high stresses and consequently it is only suitable for use with the more malleable plastics.

Heat staking

In heat staking, the compression probe is heated so that less pressure is required to form a head on the stud, giving lower residual stresses in the head. This widens the application of staking to a broader spectrum of thermoplastic materials than is possible with cold staking, including glass-filled materials. The quality of the joint is dependent on the control of the



processing parameters: temperature, pressure and time. A typical cycle time lies between 1 and 5 seconds. Heat staking has the advantage that parts can be disassembled in many cases.

Hot air staking

In thermostaking or hot air staking, heat is applied to the stud by means of a stream of superheated air, delivered through a tube which surrounds the stud. A separate cold probe then lowers to compress the stud head.

Ultrasonic staking

In ultrasonic staking, the stud is melted using ultrasonic energy supplied through a welding horn. During the continued pressure of the horn, the melted stud material flows into the cavity within the horn to form the required head design. Cycle times are typically less than two seconds and welds may be performed with a hand-held welding head.

Figure 83 Stake designs.

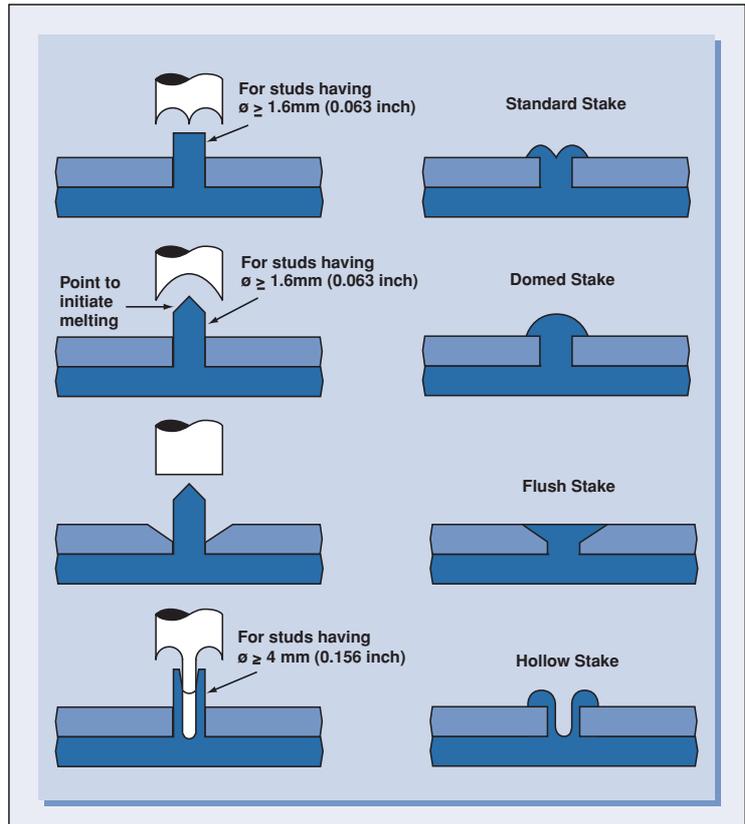
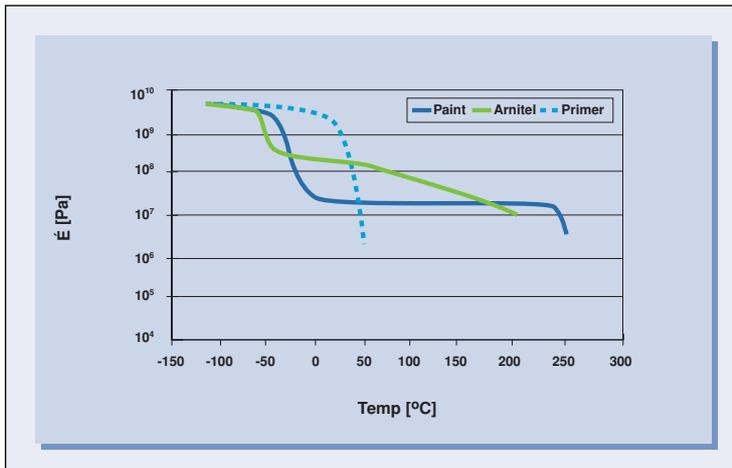


Figure 84 Ductile behaviour of Arnitel substrate at -35°C and brittle behaviour of paint and primer at -35°C.



2.1. Finishing & Decoration

2.1.1. Introduction

Components manufactured using engineering plastics are frequently used in assembly with other components. Enhancing or conforming to the aesthetic beauty of the assembly becomes very important. A commonly used method is through surface decoration of these parts.

This section on finishing and decoration of plastic parts explains the methods that are normally employed in doing so and the recommendations for employing these methods on engineering plastics.

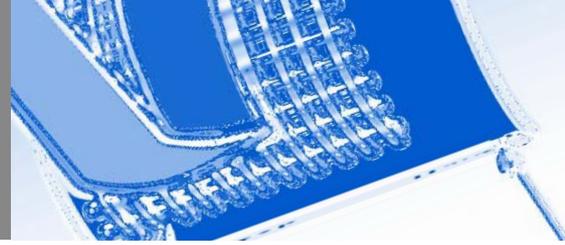
2.1.2. Painting and Coating

Although parts can be made with molded-in color, painting and coating are nevertheless done for a number of reasons such as:

- Aesthetics: to hide irregularities in the substrate; free choice of color-gloss-structure; color matching with adjacent parts
- Improved chemical, abrasion or UV-resistance
- Electrical conductivity
- Electromagnetic shielding
- Styling versatility
- Manufacturing convenience

The use of paint can on the other hand have an important drawback. It is often observed that a paint and/or primer on a ductile plastic results in brittle fracture during impact loading, whereas the unpainted part tested under the same conditions deforms in a ductile manner. The paint layer can result in a 40-fold reduction of the fracture energy, especially when too rigid a paint is used. On loading the part, the brittle paint fractures first and the crack may propagate through the substrate. An extreme example of a big difference in modulus between substrate, paint and primer is shown in figure 84.

Additionally solvents in the paint might lead to environmental stress cracking. High internal stresses in the part near gates, weld lines and wall thickness



transitions, but also stresses due to external load, in combination with aggressive solvents may cause cracks in the surface of the substrate.

Pretreatment

The surfaces to be painted/printed must be clean and free of oils, grease and mold-release sprays for good adhesion of the paint and cleaning the parts may be necessary (see par. 2.1.11). Painting/printing should be done in a dust free environment.

Apart from cleaning, several other pretreatments exist to enhance adhesion of the paint to the substrate:

- Flaming is a simple and widely used process, in which a gas flame is moved a few centimeters above the surface of the part. The speed with which the flame is moved is in the order of 0.1 m/sec. Propane, butane and natural gas can be used to fuel the flame.
- Low pressure plasma treatment is specially suited for complex parts, with surfaces that can not easily be reached in flame or corona treatments. In this batchwise process, the parts are exposed to gas discharge at low pressure.
- Corona treatment is an electrical discharge process. A high voltage, high frequency electrode is moved over the surface of the part at a distance of 1 to 2 mm, activating the surface through oxidation and ozone formation. This process is normally used for parts with flat surfaces and is specially suitable for sheet material.
- Priming.
- Sanding.

Figure 85 Electrostatic spraying.

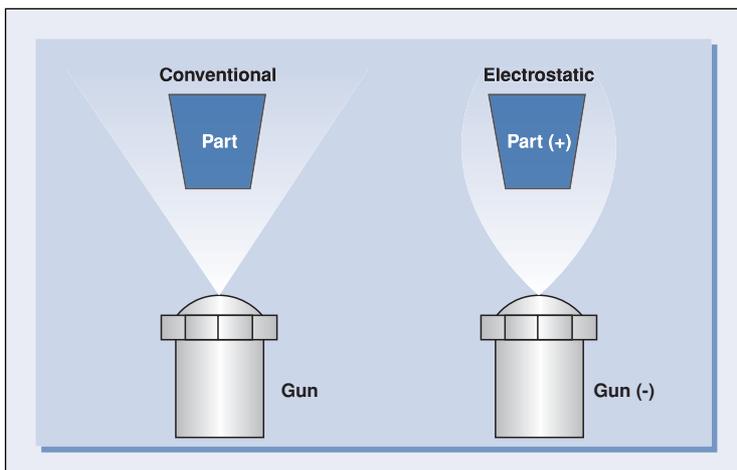
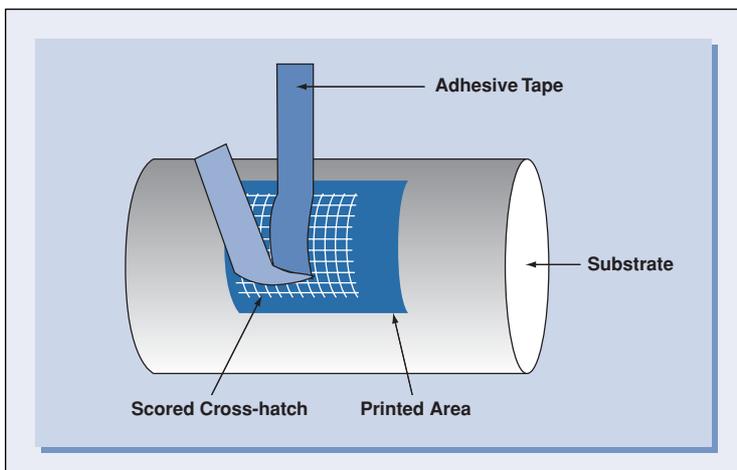


Figure 86 The crosshatch and tape pull-off test.



Paint application

Good wetting and distribution of the paint on the substrate surface can be achieved when the surface tension of the wet paint is lower than the surface tension of the substrate.

Further, no additives or color-masterbatches should be used in molding the part where there is a chance that ingredients migrate to the surface and reduce the surface tension. This can lead to an irregular paint thickness distribution.

Spraying is the most common painting process for parts, and it can easily be automated with robots. Conventional spraying processes make use of com-

pressed air to force the paint through a spray nozzle, whereas airless processes use a pump. Electrostatic spraying is a process in which the paint droplets and the parts to be painted have an opposite electrical charge as shown in figure 85. Good paint coverage and less over-spraying are the advantages.

The paint droplets must blend together on the surface of the part and form a smooth layer with a uniform thickness. Premature evaporation of the solvent during spraying must therefore be prevented, otherwise an effect called "dry spray" may occur. The climatic conditions, like temperature and humidity, should be well-controlled for a good, reproducible coating result. An undesirable temperature rise during hot days can lead to the dry spray effect.

The paint can also be applied with a brush (stripe painting), a roller, a resilient pad (decorative figures), by dipping or by dyeing (fibres and fabrics). A mask can be used if the surface of a part is only partially to be covered with paint. The painting process can also be integrated with the injection molding process in several ways, avoiding the need for a separate painting line, see paragraph 2.1.7.

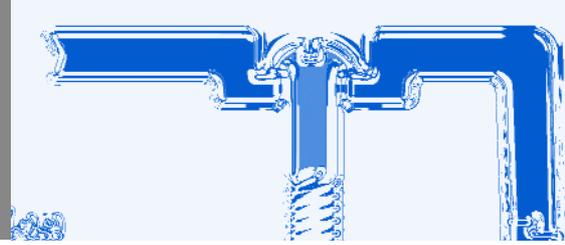
Foam molded parts cannot be painted immediately after molding. The gases produced by the foaming agents must first reach equilibrium with the ambient air. This outgassing may require 24 to 48 hours, depending on temperature and humidity. Painting before this equilibrium is reached may cause blistering.

Testing

Adhesion testing

The adhesion of the paint/ink layer to the substrate can be tested in several ways. In a scratch test (Kratzprobe), the painted/printed part or test specimen is provided with scratches in a regular pattern. The paint/ink layer will not come off near the scratches if adhesion is good. Poor adhesion on the other hand will result in paint/ink particles that separate from the substrate.

The crosshatch + tape pull-off test (Gitterschnitt) is a combined scratch and peel test, figure 86.



Scratches are made in the printed/painted surface in two perpendicular directions and an adhesive tape is then stuck to the surface. The tape is pulled off and the ratio between the area of the undamaged surface and the area where the paint/ink has peeled off with the tape is established visually.

Depending on the specific application, additional exposure tests may be requested, like:

- Humidity exposure
- Water soak
- Heat aging
- Thermal shock
- Steam jet
- Stone chipping

Chemical resistance testing

The stress crack resistance of the substrate to a particular paint/ink system can be tested by coating tensile bars while they are subjected to a strain of up to 1%. Uncoated tensile bars and tensile bars that were coated without an applied strain are used as a reference. The tensile bars are subjected to a tensile test after the coating process and the stress-strain curves of the test bars are compared with the curves of the reference bars.

Impact testing

Impact performance after painting/printing can be tested by various methods, such as a puncture test or a falling dart test.

Scratch resistance

The scratch resistance can be established e. g. in the Taber abrasion test, where the amount of haze is established after a number of abrasive cycles. The scratch resistance can also be determined quantitatively by measuring the weight loss after a number of sanding cycles (see DIN 53754). The pen test according to ISO 1518 determines the indentation caused by a sharp pencil applied with a defined force.

Paint types

Paints generally consist of four components:

- a resin that bonds the color particles after curing
- pigments used for the color

- a solvent or carrier that enables application of the paint in the liquid state
- additives for enhancing adhesion and appearance.

The paint selection is determined by the desired decorative effect, the functional demands, the application technique and local regulatory restrictions. A variety of paints have been developed, based on different chemistries and polymers. The following generic paint types can be distinguished.

- Acrylic paints give a brittle, scratch resistant coating and resist most common oils. Transparent acrylic coatings (compact discs) can be applied for UV-protection.
- Epoxy paints typically provide a hard, tough and glossy coating
- Formaldehyde / alkyd resins
- Polyester
- Polysiloxane coatings have good chemical and scratch resistance. Transparent types with glass-like optical properties and good UV-protection have been developed
- Polyurethane paints are flexible cold-curing coatings
- Vinyl paints typically produce a soft, rubbery coating.

Paints can be divided in two main groups: conventional paints with an organic solvent and waterborne paints. Paints based on organic solvents generally have better adhesion to substrates than waterborne paints, but solvents may be attack the substrate and cause stress cracking.

Waterborne paints have superior properties in relation to environmental, health and safety matters.

Curing of the paint can take place in several different ways:

- Air-curing paints harden due to the evaporation of the solvent, while the resin polymerizes.
- Heat-curing paints require elevated temperatures for curing. The use of these paints systems is limited by the high curing temperature that the plastic must be able to withstand.
- Two-component paints have the big advantage

- that no volatile components evaporate during curing. Pot-life after mixing is however limited.
- UV-curing paints.
- Oxygen-curing paints.

Paints systems should always be tested on prototype parts over an extended period of time, to establish the compatibility of the paint.

Recommendations for DSM thermoplastics Akulon (PA6 and PA66)

The relatively high heat deflection temperature and solvent resistance of Akulon PA6 and PA66 make them excellent resins for paint applications. However, the ability of polyamides to withstand the required paint-curing temperature should be checked. Acceptable mold release-agents and moisture levels should be ascertained.

Stanyl (PA46)

Stanyl does not usually require any form of pretreatment. Primers applied to polyamides to be used outdoors or where high gloss and/or extremely good adhesion is required, are in general based on two-component isocyanate systems. Coating the Stanyl part in the dry-as-molded state increases the adhesion of the lacquer to the substrate. Suitable paints/lacquers for Stanyl are based on:

- nitrocellulose
- vinylchloride copolymers
- polyisocyanate resins
- polyurethane resins
- formaldehyde/alkyd resins

These coatings can be recommended for Stanyl, provided that the temperature resistance of the lacquers is similar to that of the base material. The reinforcements and flame retardants used in Stanyl may influence the adhesion behaviour of the lacquer to the substrate, which might necessitate a primer step.

Arnite (PBT and PET)

Arnite can be coated with practically all known coating systems. The chemical resistance of polyester is so good however, that these coatings generally have poor adhesion to the surface of the part. A primer should be used for all standard coatings.

Standard coatings for metals normally have low elasticity compared to plastics, which may lead to a reduced impact strength. An elastic primer that serves as a buffer between the part and the topcoat can help to reduce premature failure. Highly elastic PUR coatings are especially suitable for the retention of properties of elastomer-modified Arnite.

The high heat resistance of many Arnite types makes them suitable for on-line top-coating of automobile bodies with standard coatings.

Surface preparations, like sanding or filling are not normally necessary, but cleaning (par. 2.1.11.) of molded parts is generally necessary.

Arnitel (TPE)

Arnitel is easily coated, provided that no silicone containing mold release agent, or other products with an adverse effect on adhesion, are used during injection molding. No special adhesion promoters are necessary. Most paints are based on a two-component PUR systems as manufactured by Mankiewitz, ISL, Herberts, Peter Lacke, Wörwag, Beckers etc.

Xantar (PC), Xantar C (PC + ABS) and Stapron E (PC + PET)

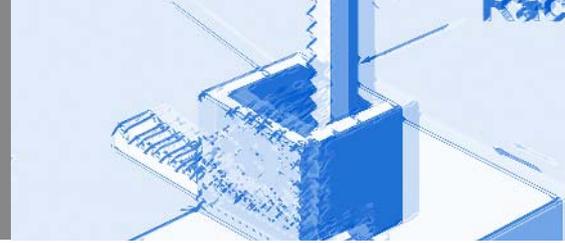
If no mold-release is used and the parts are not touched with bare hands, the only necessary cleaning operation might be blowing with clean air. Cleaning with a compatible solvent is necessary if parts have been contaminated with oil, grease, mold-release or other foreign materials, see par. 2.1.11.

A variety of conventional as well as waterborne paints have been developed for Xantar PC and blends.

Common types include:

- Acrylic
- Epoxy
- Polyester
- Polysiloxane
- Polyurethane

It should always be checked that the paint system is not too aggressive. Organic solvents may cause stress cracking. Chlorinated and aromatic solvents, as well as ketones, should generally be avoided,



although they may sometimes be used in other solvent systems as adhesion promoters to etch the surface. Solvents should evaporate easily and leave the painted part completely. Waterborne paints and paints based on aliphatic hydrocarbons (mineral spirits, heptane, hexane and alcohols) are generally compatible with PC.

Second-surface painting of transparent parts is a way to protect the paint layer with a clear layer of tough PC. The front side of the part is covered with a mask and the reverse side (= second surface) is painted.

Special coatings with glass-like optical properties have been developed. These offer a significant improvement in chemical and/or scratch resistance, or reduce yellowing under the influence of UV light. Hard coats can also be applied on opaque parts to give them a wet-glossy appearance. Silicone and acrylic hard coats are the most widely used. The hard coat system commonly consists of a primer and a topcoat.

Hot curing temperatures up to 120 °C (250 °F) are commonly used for Xantar and its blends.

2.1.3. Metallization

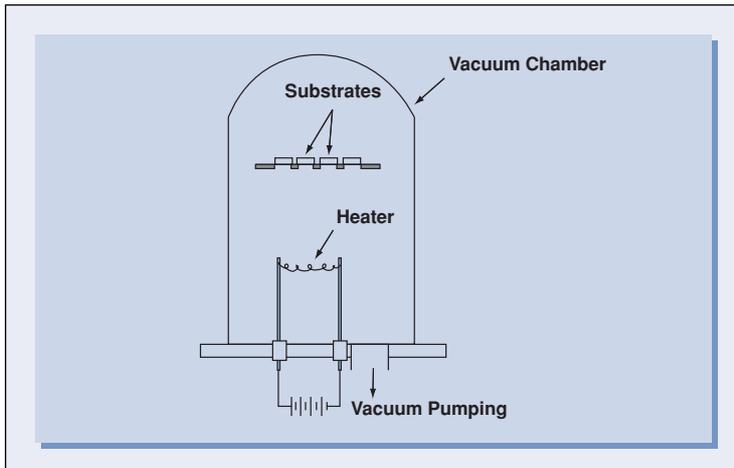
Introduction

Plastic parts can be metallized for decorative or functional purposes. A thin metal coating can give parts a glossy appearance, enhanced reflectivity, improved abrasion resistance, or high electrical conductivity, or to provide electromagnetic shielding. Metallized plastic parts have several advantages over comparable plated metal parts, such as low weight, corrosion resistance, greater styling possibilities, ease of assembly, controllable electrical conductivity and low costs.

Several metallization techniques can be used on DSM products. Metallization can either be done in a direct process, like vacuum metallization, plating, flame or arc spraying and painting (par. 2.1.2.) or in an indirect process, in which a transfer film is pre-metallized by vacuum metallization. The metal layer is then transferred onto the part by means of hot transfer (par. 2.1.5.), hot foil stamping (par. 2.1.6.) or in-mold decoration (par. 2.1.7.).

Painting with a coating that contains metal particles can give plastic parts a metal-like appearance and special electrically conductive paints can provide electromagnetic interference (EMI) shielding.

Figure 87 The principle of vacuum evaporation metallization.



Vacuum metallization

Vacuum metallization, sometimes also called 'Physical Vapour Deposition' (PVD), is widely used to deposit a thin aluminium layer on plastic parts. Applications include automotive interior parts, car lighting components, plumbing accessories, jewellery components, packaging foils etc.

The metallic coating can be deposited on the outside of a part, or on the inside of transparent Xantar PC parts. In the latter case, the metallic coating is protected by a layer of plastic. The ultra thin metallic coating on the outside of a vacuum metallized part must be over coated with a transparent topcoat to improve its abrasion resistance and to protect it against environmental influences, like humidity. Gold and other colors can be obtained by dyeing the topcoat.

High-heat thermoplastics used for car lighting can withstand the high temperatures inside the lamp unit, but can outgas volatile materials that condense on the cooler areas within the reflector, leading to a hazy appearance that impairs optical performance. A high surface energy, haze preventing topcoat may be deposited by thermal SiO_x evaporation from a heated boat or a crucible placed in the vacuum chamber. Arnite XL is an exception to this and does not outgas and a topcoat is not required.

In order to obtain a high-gloss and highly reflective aluminium layer on a matt or glass- or mineral filled plastic part, the plastic surface must be undercoated with a lacquer.

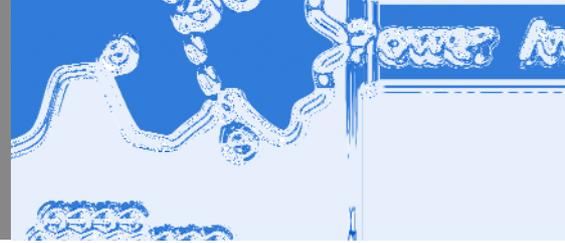
a. Vacuum evaporation

In vacuum evaporation the metallic coating is usually aluminium, but other metals can also be deposited by evaporation, see figure 87.

The metal is heated to the point at which it evaporates. The vapor then migrates through the chamber and condenses on the cold plastic part. The process takes place in a vacuum to allow the metal vapor to reach the plastic surface without being oxidised. The parts to be metallized are held in a fixture that can be rotated to expose all the surfaces to be metallized.

Several power sources can be used for metal evaporation, such as resistance heating, induction evaporation, electron beam guns, or a vacuum arc. Resistance heated tungsten filaments are used most often. The filaments are placed in the required position to obtain uniform coverage, and aluminium chips or staples are placed on the filaments. The metal to be evaporated can also be placed in a thermally heated boat or a crucible.

Evaporation coating is normally done batchwise in a cylindrical coating chamber. The coating chamber may have a diameter of up to several meters, depending on the size and number of parts to be coated. The parts may make a planetary movement around the vapor source in order to equally coat all sides of the parts with a metal layer. If desired, the areas not required to be coated can be masked, usually with metal sheets.



b. Sputtering

Sputtering is a vacuum coating process, in which atoms of the coating material are displaced by impact with an inert gas plasma, which is normally ionised argon, see figure 88.

A high-voltage electric field is created between the fixture of the plastic part and a negative electrode, the metal target (e.g. aluminum, or an alloy) that serves as a donor of metal atoms. The positively charged gas ions are attracted by the negative metal electrode and are accelerated in its direction. They transfer their kinetic energy to the metal atoms when they hit the negative electrode, thus enabling metal atoms to escape from the solid metal target. The plastic part is bombarded by these metal atoms and is coated with a thin metal layer.

More refined, high rate sputtering processes make use of an additional electromagnetic field (magnetron) to deposit the metal atoms at higher rates.

Sputter coatings have a better adhesion and are more resistant to abrasion than vapour deposition coatings, due to the higher kinetic energy of the deposited metal atoms. Also, sputtered coatings can easily be applied over large surface areas with a uniform layer thickness.

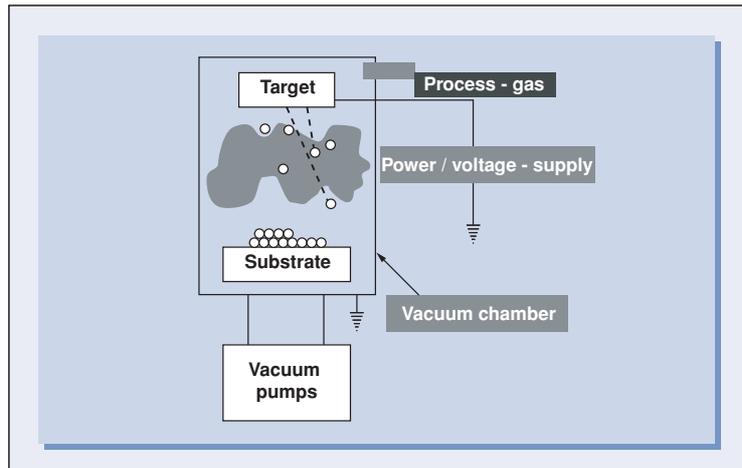
Sputter coating can be done batchwise or in line with the injection molding process. A well-known application is compact discs, which are sputter coated in line, with a cycle time of less than 2 seconds. Also reflectors for car lights are often sputter coated one by one, in line with the molding machine.

c. Reactive sputtering

In reactive sputtering, also called 'Plasma Enhanced Chemical Vapour Deposition' (PECVD), a chemical reaction is incorporated in the vacuum metallization process.

A gas can be used to react with a metal, like nitrogen with titanium to yield a titanium nitride coating with a golden appearance and high hardness, used for jewellery for instance. Another example reacts oxygen with aluminium to yield an aluminium oxide coating.

Figure 88 The principle of sputtering deposition.



Lacquering steps can be replaced by plasma polymerisation of a topcoat, eg siloxane to prevent corrosion, or depositing an aluminum adhesion promoting layer in the same coating chamber. A monomer is let into the vacuum chamber and is precipitated as a polymer coating under the influence of the ionised gas particles.

Plating

Plating processes can be divided into electroless plating processes, without a galvanic electric current, and electroplating, where an electric current is used in a galvanic process. Plating in general yields better adhesion than vacuum metallization, but the process is less environmentally friendly and less safe, and also expensive.

d. Electroless plating

In electroless plating, a metallic coating is deposited on electrically nonconductive plastics. Nickel and copper are the metals most frequently deposited in this way. The surface of the part to be plated is first etched with a strong oxidizing solution that partially erodes the plastic surface, creating microscopic holes. The enlarged surface area created makes the surface hydrophilic, enhancing the bonding of the plastic to the deposited metal. After etching, the part is immersed in a solution and a metallic coating is formed in a chemical reaction between the reducing agent present in the solution and metal ions.

The following steps can be distinguished in the process.

- (1) Predips may be used prior to etching to overcome two problems in parts. The first reason is to improve the surface of poorly molded, highly stressed parts. By slightly swelling the surface, a more uniform surface attack in etching is possible, reducing non-uniform etch conditions and improving overall adhesion. Secondly, a predip is used to facilitate etching on normally hard to etch plastics, e.g. Xantar polycarbonate. This is also done by attacking and swelling the surface. A different solvent is needed for each polymer and high molded-in stresses should be avoided as they may lead to cracking during pre-dip.
- (2) Etching if the plastic contains butadiene rubber particles, which serve as an impact modifier, the etchant may be chromium acid, permanganate, chromium trioxide, or sulphuric acid. The butadiene is selectively removed, thus leaving small ball shaped holes or bonding sites for mechanical interlocking.
- (3) After etching, the parts are rinsed in water and then put into a neutraliser, such as sodium bisulphite. Care must be taken that all etchants are completely removed, with no traces left in blind holes, as this may lead to poor metallizing if the etchant bleeds out in subsequent metallization steps.
- (4) In the next step a catalyst (or activator) is applied by submersing the part in a palladium tin colloid bath. Palladium is deposited during the following reaction.



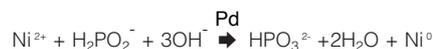
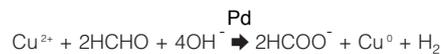
Palladium serves as a catalyst for the deposition of the nickel or copper.

- (5) After rinsing following the catalysis step, metallic palladium is present on the surface of the part surrounded by hydrolyzed hydroxide. The excess stannous hydroxide must be removed from the part in an organic or mineral acid bath before the

palladium can act as a catalyst.

- (6) Finally an adherent metallic film, usually copper or nickel, is deposited on the plastic surface by a reduction reaction. This is accomplished using a semi-stable solution containing a metal salt, a reducer, a metal complexer, a stabilizer and a buffer system. When a palladium-bearing surface is introduced into the solution, a chemical reduction of the metal occurs on the palladium sites, and, through autocatalysis continues until the part is removed.

The basic reactions for copper and nickel are:



Electroless plating is widely used to produce a conductive coating for subsequent electroplating.

e. Selective electroless plating

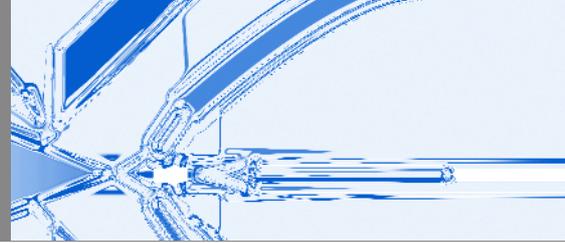
The surfaces of a part can be selectively electroless plated. This is done by replacing the etching step and the catalysis step by applying a lacquer that contains the catalyst onto the surfaces to be plated. The copper or nickel are only deposited where the lacquer is present.

f. Electrolytic plating

Electrolytic plating is the deposition of a metal on a conductor using an electric current. A plastic surface must first be made conductive in order to be electrolytically plated. This can be done through electroless plating or by the use of conductive additives such as carbon. The part to be electrolytically plated is immersed in a solution of metal salts connected to a cathodic direct current source, and an anodic conductor is immersed in the bath to complete the electrical circuit. Electric current flows from the cathode to the anode, and the electron flow reduces the dissolved metal ions to pure metal on the cathodic surface. The anode usually is made from the same metal, which dissolves during the electroplating process, replenishing the plating bath.

g. Flame and arc spraying

Flame and arc spraying are easy, low-cost metalliza-



tion processes, where a hand-held or automated pistol is used to spray liquid metal onto a part. The metal layer produced is thick compared to other metallization techniques and the deposition rate is high. However, the coatings prepared with these processes are quite porous, coating adhesion is lower and the surface roughness of the metal layer is relatively high. Both processes are well suited to electromagnetic shielding purposes and the metal layer can be applied selectively on different surfaces of the part. The oxide content of the metal layer is relatively high, due to the oxygen in the combustion gases and the ambient air.

In flame spraying, a metal powder or a wire is heated and propelled onto the plastic substrate by a stream of hot gases (see figure 89).

A fuel gas, usually acetylene or propane, is fed through a central nozzle and supplies the necessary energy to melt the metal. A second outer annular gas nozzle feeds a stream of air or an inert gas around the combustion flame, which accelerates the spray particles towards the substrate and focuses the flame.

Arc spraying is comparable with flame spraying, but in arc spraying a DC electric arc is used. The arc is struck between two continuous consumable wire electrodes that form the spray material, figure 90.

Molding for metallization

Good metallisation starts with the design of the mold. Many visual defects can be avoided with proper mold design.

The following guidelines should therefore be followed.

- Gates and parting lines should be put in non-appearance areas
- Integral parts should be used to avoid welded joints
- Ribs and bosses should be designed to eliminate sink marks
- Texturing can be used to break up large flat surfaces and hide any defects, such as scratches
- The mold should be designed with generous release angles to avoid the necessity to use mold release agents, which generally have a

Figure 89 The principle of flame spraying.

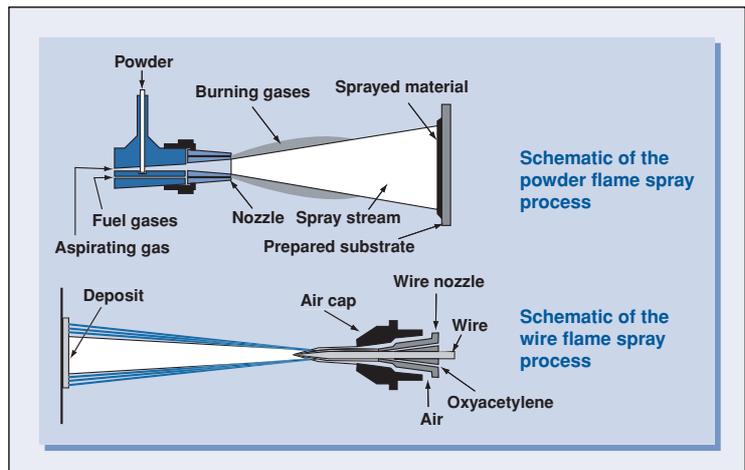


Figure 90 The principle of arc spraying.

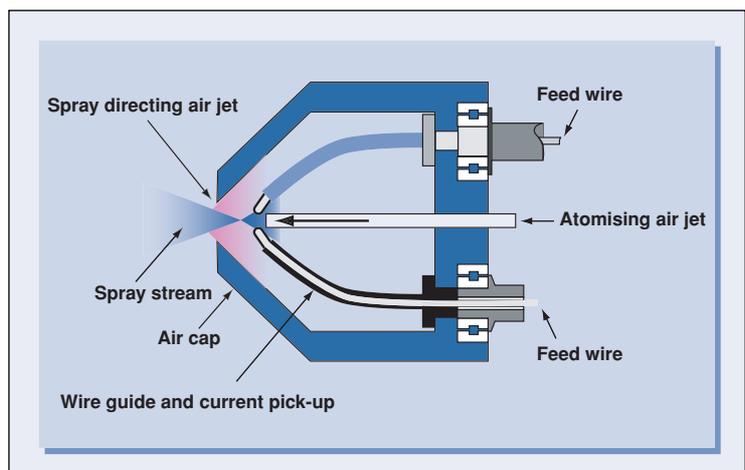
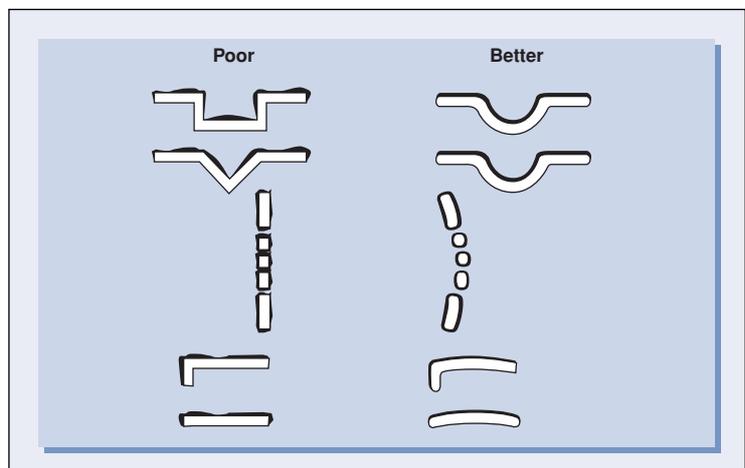


Figure 91 Sharp edges and large flat surfaces may lead to poor plating uniformity.



- negative effect on adhesion. Silicon-type mold releases are difficult to remove in a cleaning operation. If it is essential to use a mold release, a stearate or soap type can be chosen.
- Wall thicknesses should be sufficient to ensure rigidity.
 - In the case of electrolytic plating, the plating uniformity is the result of the current density distribution, and must be considered in the initial design. Do not use right angles or V-grooves, keep letters close to the surface, make angles as large as possible, and crown large flat surfaces, see figure 91.
 - The mold should be highly polished.

Furthermore, the following recommendations for molding conditions can be given.

- The plastic should be properly dried before molding to avoid splay or delamination on the part, which may result in blistering.
- The temperature of the melt should be sufficiently high as to avoid molded-in stresses, which could cause uneven etching in electroless plating or lead to cracking if swelling in a solvent is applied.
- Too fast a fill speed can overpack the mold, making the part surface harder to etch and may result in a loss of adhesion.

Cleaning

In general, parts must be clean and free from oils and greases before metallization and must receive a cleaning treatment if necessary (see par. 2.1.11.). The different metallization techniques are not all equally sensitive to contamination. For electroless plating, cleaning prior to etching is optional and generally not used if parts are reasonably clean. If parts are not touched with bare hands and contamination is avoided during handling, cleaning might not be necessary.

Recommendations for DSM's engineering plastics

Akulon (PA6 and PA66)

Vacuum metallization, electroless plating and electroplating are the techniques that are most frequently used for Akulon. Predrying of parts before metalliza-

tion is not always necessary, depending on the metallization process and the moisture content.

Arnite (PBT and PET)

Vacuum metallizing is the best metallization technique for Arnite. To improve adhesion, the application of a cellulose primer coat is desirable. To protect the metal layer, a cellulose topcoat may be used.

Arnitel (TPE)

Vacuum metallizing is the best process for Arnitel. With regard to the low flexibility of the metal film, it is best not to use soft Arnitel grades and always run a test first.

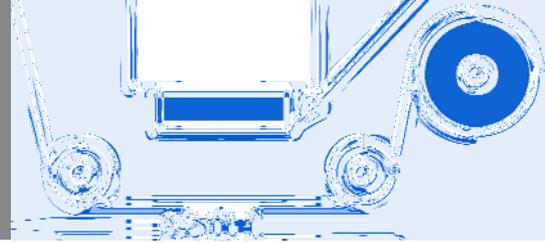
Stanyl (PA46)

The most important metallization techniques for Stanyl are electroplating (3-D PCB's) and vacuum metallization (reflectors).

In electroless plating of Stanyl, chemical roughening of the surface can be done using a CaCl_2 solution at 40°C; etching can also be done by using carefully selected concentrations of hydrogen chloride, chrome-sulphuric acid, potassium hydroxide and lactones.

Xantar (PC and its blends)

Vacuum metallizing, plating and spraying can all be used for Xantar PC. Great care must be taken when swelling solvents are applied to enhance adhesion. Environmental stress cracking due to molded-in stresses may occur. Stresses can be detected in transparent Xantar PC grades using polarized light. Electroless plating is especially suitable for rubber modified PC grades and PC/ABS grades (Xantar C).



2.1.4. Decals

Decals can be either decorations or labels with instructions or information. They are made of a pre-printed and pre-cut carrier, like a polymer film or paper, with a pressure sensitive adhesive backing and a release sheet. The release sheet is removed just before applying the decal to the surface of the part to be decorated and the decal is then pressed into place.

As in adhesive bonding, the surface of the part must be clean and free of oils, grease and mold release for good adhesion. Cleaning (par. 2.1.11) may be necessary. The abrasion, scratch, UV and chemical resistance should preferably be tested on prototype parts, under representative conditions.

The compatibility of the adhesive and the polymer film to the plastic must be checked. Some adhesives for example, but also the plasticizers in PVC decals, may cause environmental stress cracking in Xantar polycarbonate and polycarbonate blends.

2.1.5. Hot Transfer

Hot transfers can be used to provide parts with a decorative pattern or lettering. They consist of a pre-printed transfer film, on which the design has been applied. A hotplate is used to transfer the color coating from the film onto the part under pressure.

The difference with the hot stamping process (par. 2.1.6.) is that the transfer film already contains the complete design, before it goes onto the part. In hot stamping, the decorative pattern is in the raised pattern on the die or the part. Pre-printing the film makes the hot transfer process relatively expensive compared to hot stamping. Hot transfers are specially suited to complicated multi-color images.

Hot transfers require a smooth part surface for good adhesion. As in all decorative processes, the parts should be clean, and free of oils, grease and mold release. Cleaning (par. 2.1.11.) of the parts may be necessary before applying the film. The compatibility of the coating with the part material must be checked, and careful pretesting is recommended.

Figure 92 Standard hot stamping, with a raised pattern on the heated die.

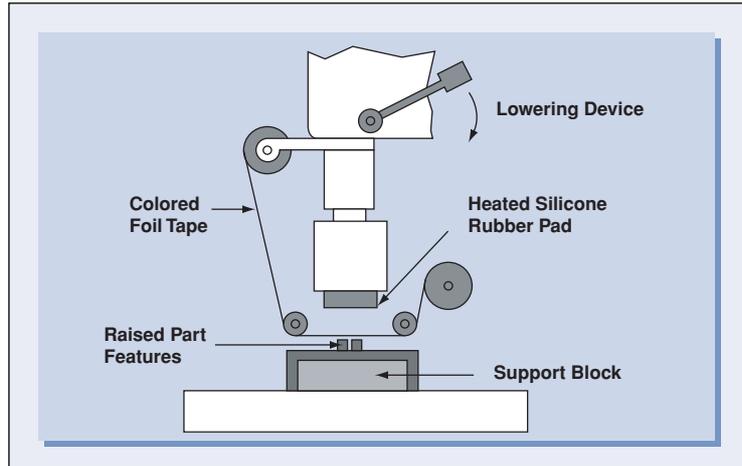
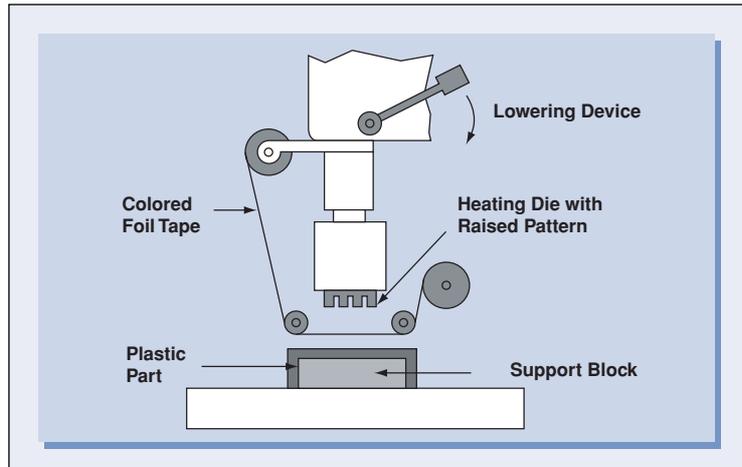


Figure 93 Dome printing, with a raised pattern on the part.

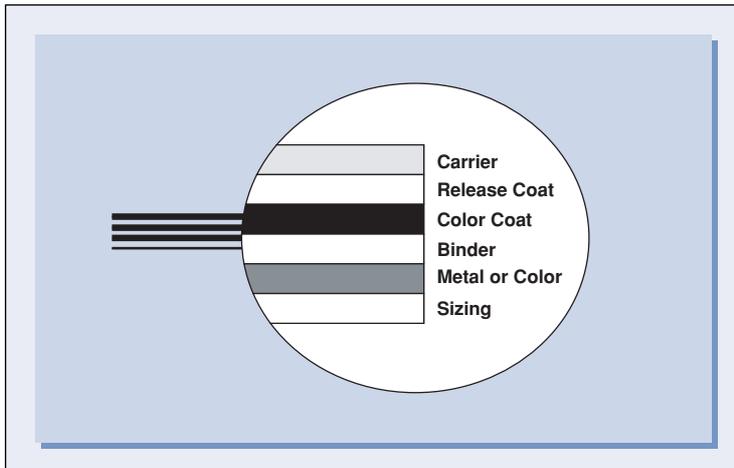


2.1.6. Hot Stamping

Hot stamping is a fast and easy process to provide parts with a decorative pattern or lettering. The image is transferred from a carrier foil to the part with the help of a heated stamping press as shown in figure 92 & 93. It is a dry process and the parts can be handled immediately after stamping.

In standard hot stamping, the stamping press is provided with a heated die with a raised pattern, as shown in figure 92, whereas dome printing uses a raised pattern on the part, see figure 93.

Figure 94 Example of a stamping foil.



The difference with the hot transfer process (2.1.5.) is that the film does not contain the complete image in advance of the stamping process, whereas the hot transfer foil has already been pre-printed with the final image before it goes on the part. The hot transfer process is more expensive and is especially suited to complicated multi-color designs.

During the hot stamping process, the pressure on the part requires the part and to be firmly supported and designed to withstand the stamping forces. The stamping die must be designed in such a way that no air can be entrapped between the die and the part. For good adhesion, parts must be clean and free of oil, grease and mold release. Cleaning in a suitable soap solution or a solvent may be necessary (par. 2.1.11.).

A wide variety of stamping foils is available, with a color coating, a layer of metallic foil, or a combination of the two. They can be used to provide parts with a colored pattern or a thin metallic layer. Wood grain patterns are also possible.

Figure 94 shows an example of a stamping foil. The release coat allows the easy separation of the carrier and the color coat at the end of the stamping process, and the sizing provides the adhesion to the part.

The compatibility of the color coat, the binder and the sizing with the part material should be checked (e. g. environmental stress cracking of polycarbonate and polycarbonate blends). It is advisable to consult the

stamping foil supplier on this issue and to perform prototype tests.

2.1.7. In-Mold Decorating

The decorating process can be integrated with the injection molding process in several ways.

In-mold decorating processes offer one or more of the following advantages over conventional coating procedures:

- lower costs, no separate painting line,
- reduced or eliminated emissions of volatiles,
- many problems related with solvent-substrate compatibility are avoided,
- no heat-curing restrictions and
- multi-color patterns possible.

On the other hand, in-mold decoration makes the injection molding process more complicated. Several methods are available.

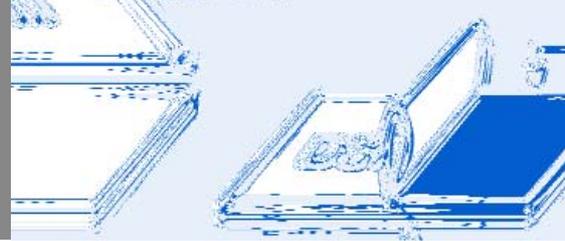
Film-insert molding

Film-insert molding makes use of a preprinted film, which can be decorated with figures, text or symbols. The film is inserted into the mold during the mold-open phase and becomes an integral part of the injection molded product at the end of the molding cycle. The film can either be flat, or preformed. Flat film is either cut into sheets with a shape that corresponds to the mold cavity and electrostatically kept in place in the mold, or the film is fed into the mold on an indexed roll, figure 95.

Excess film at the edges of the part is removed after ejection from the mold.

Three-dimensional preforms can also be made from the film by pre-heating the film and subsequent vacuum forming or high-pressure forming.

The film can be single-layer or two-layer. The patterned color layer is vulnerable to abrasion, scratching and UV-degradation if the decorative pattern is printed on the outside of a single layer film. If the decorative pattern is printed on the inside, the pattern is in contact with the hot polymer melt during the injection phase, and this may lead to distortion at hot spots. A two-layer



system is sometimes used, with the pattern layer between the two film layers. However this is a more expensive system.

DSM has developed a special patented stretchable Arnitel film, which eliminates the need of preforming in many cases, reducing decorating costs. Arnitel film is easily printed and soft touch types are available.

In-mold transfer decoration

In-mold transfer decoration, see figure 95, makes use of a preprinted film in which the patterned layer is transferred from the film to the part during the melt injection phase under the influence of heat and pressure. The transfer film is separated from the part at the end of the injection molding cycle and is discarded.

In-mold transfer has the disadvantage that the patterned layer lies on the outer surface of the injection molded part, which makes it vulnerable to damage and UV-degradation.

Powder coating

Powder paint can be sprayed onto the mold surface in the mold-open phase. The powder melts during the thermoplastic resin injection phase and forms a bond with the surface of the part during the cooling phase.

2.1.8. Water Transfer

Water transfer is a process for decorating three-dimensional products, by applying an ink pattern to a water-soluble role of film (see figure 96). The pattern is released on the surface of a tank of water, with the ink side up, (figure a). The part is dipped into the water (figure b) and the pattern is transferred to the part. The part is removed from the water and the remains of the film are rinsed off the part (figures c and d).

A wide variety of preprinted films is available, for example woodgrain, marble, fur, leather, camouflage and carbon fiber fabric patterns. The process can be used for parts with a three-dimensional shape, with curved surfaces and round corners, such as car interior parts, computer housings, telephones etc. Sharp corners must be avoided, as they tend to break the film. The parts are provided with an all-over pattern and precise positioning of the pattern on the part is not possible.

Figure 95 The film (1) is fed into the mold (2) on a roll.

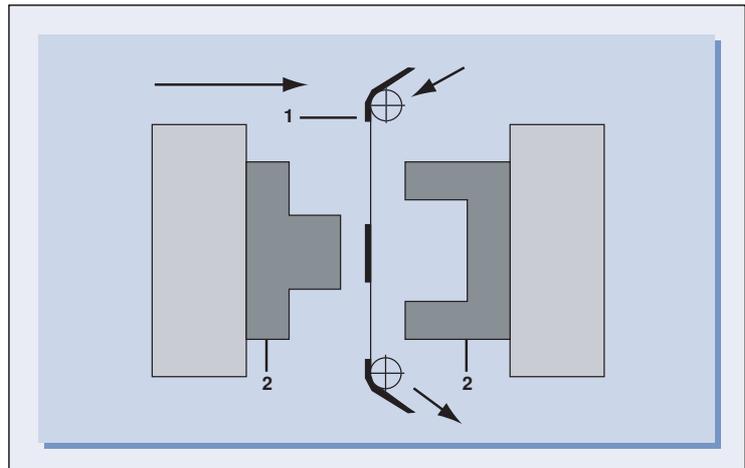
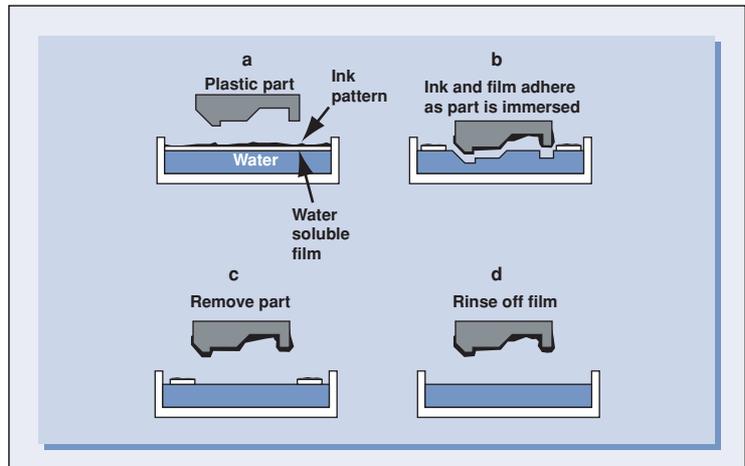


Figure 96 The water transfer process.



A colored primer is sometimes used. Products with a carbon design can for example be primed black and parts with a woodgrain design can be primed brown. A protective transparent topcoat is normally applied for abrasion and UV protection.

The compatibility of the coating with the part material should be checked and prototype testing is recommended.

The parts must be clean in advance of the decoration process, free of oil, grease and mold release, and must receive a cleaning treatment (par. 2.1.11.) if necessary.

Figure 97 Pad printing with a cliché plate.

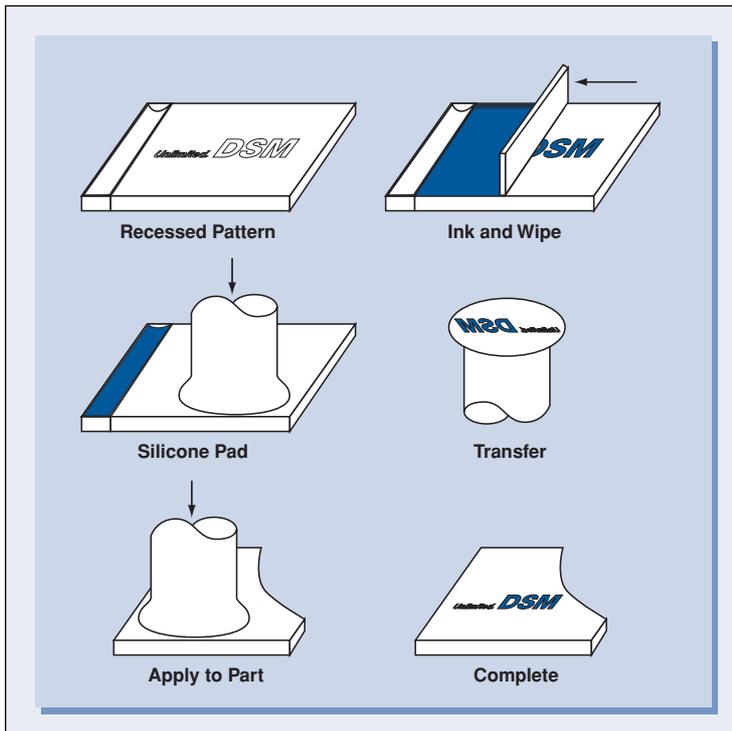
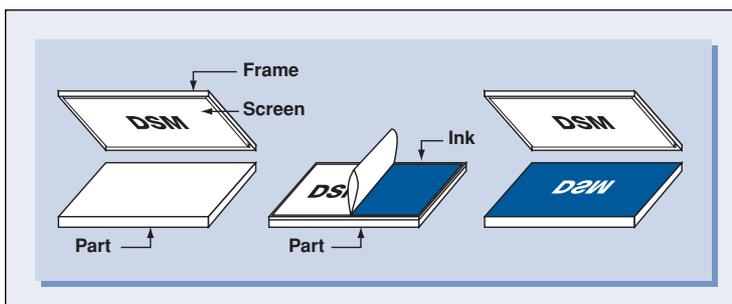


Figure 98 Screen printing.



2.1.9. Printing

Parts made from DSM's engineering plastics can be printed to provide them with a decorative pattern, logos or lettering. Some of the common types are discussed in this section.

The use of ink can have a drawback. It is often observed that a coating on a ductile plastic results in a brittle fracture during impact loading, whereas the uncoated part tested under the same conditions deforms in a ductile manner. The ink layer can result

in a 40-fold reduction of the fracture energy, especially when a rigid ink is used. On loading the part, the brittle ink fractures first and the crack may propagate through the substrate.

Additionally, solvents in the ink might lead to environmental stress cracking. High internal stresses in the part near gates, weld lines and wall thickness transitions, but also stresses due to external loads, which in combination with aggressive solvents, may cause cracks in the surface of the substrate.

Printing techniques

a. Pad printing

The ink can be applied onto the part with a soft silicone rubber pad, whereby two methods can be distinguished.

In the first method, the pad is provided with the decorative pattern in relief. The pad is first pressed onto a transfer plate covered with a layer of ink, deposited by a roller. The pad picks up the ink from the plate and is then pressed onto the part to be printed.

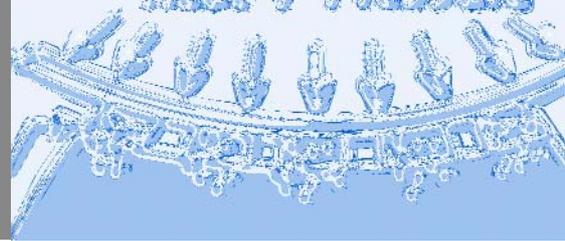
In the second method, the pattern has been etched in a cliché plate, as shown in figure 97.

A layer of ink is applied onto the plate and the excess ink is wiped off with a blade. The ink only remains in the recess areas of the plate. The rubber pad with a flat surface is then pressed on the cliché plate and picks up the design. Finally the pad is pressed onto the part.

Pad printing is a relatively simple and cheap process for printing in one color. Multi-color designs can however be made by sequentially overprinting with fast curing inks. Color registration is fair to good, depending on the equipment. The resolution of detail is fine to medium.

b. Screen printing

A fine-mesh screen, made of silk, polyester or stainless steel, is used for screen printing. The screen is held in a frame, figure 98. A stencil containing the design is placed in the frame, covering the holes in the screen where no ink is desired. The stencil is often produced with a photographic process.



The screen is placed on the part and ink is deposited in the frame. The ink is then forced through the screen by moving a blade across the screen. The screen is lifted and the part is finally allowed to dry.

Screen printing is an inexpensive process and fine details are possible. As with pad printing, multi-color designs can only be made by overprinting in sequential steps, with intermediate drying. Ink can be applied in thick layers if desired and the screens can be made of any size. The registration of colors can be good, depending on the equipment.

c. Sublimation printing

Sublimation printing, also known as diffusion printing, is commonly used for keyboards and calculator keys and is characterised by the fact that the ink sublimates from the solid state into the gas state during the printing process, without going through the liquid state, figure 99. The ink pattern is first applied on a transfer film. This carrier is positioned over the part and is heated under pressure. The ink sublimates into the gas state and the vapors penetrate the surface of the part to a depth of up to 0.2 mm. The ink is sealed into the surface of the part as soon as the material cools down.

d. Flexography

Flexography is a high-speed printing technique, used for printing film, see figure 100.

A rotating rubber ink take-up roller, which is partially immersed in an ink reservoir, picks up the ink and transfers it onto a steel roll. Both the rubber roll and the steel roll have a surface without a profile and serve only for ink dosing. A rubber plate, attached to the plate roller, contains the printing designs in profile. The plate roller picks up the ink from the ink coated steel screen roll and transfers it onto the film, which is supported by the back up roll. The film finally cures in the drying oven.

Multi-color designs can be produced with several successive printing stations such as the one described.

Figure 99 Sublimation printing.

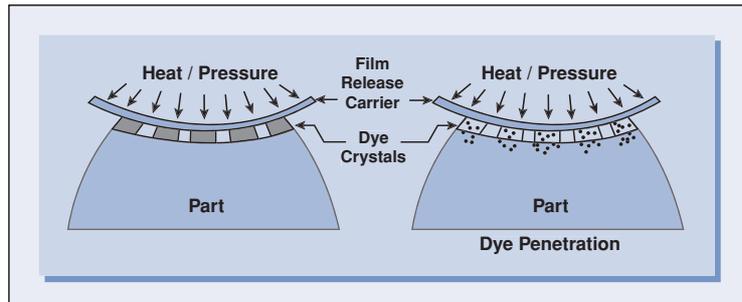


Figure 100 Flexographic printing.

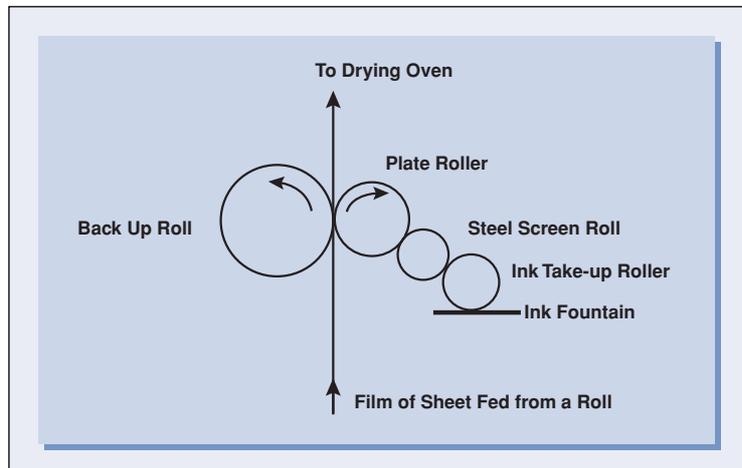


Figure 101 Offset printing.

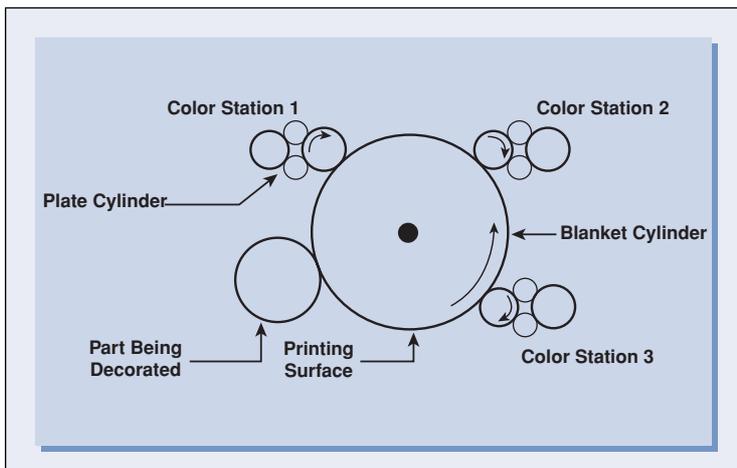
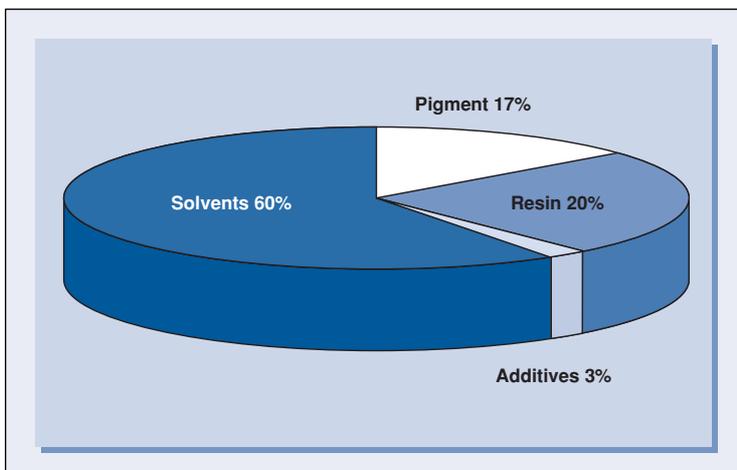


Figure 102 Typical components of solvent-based pad-printing inks.



e. Dry offset printing

Dry offset printing is a low-cost, high-speed process, which is normally used for printing round objects, like containers, with a diameter up to 300 mm (12 inch), see figure 101.

An etched plate on the plate cylinder contains the printing pattern. This cylinder is coated with ink by rollers and it transfers the pattern onto an intermediate roller, called the blanket cylinder. Several color stations can be placed around the blanket cylinder for multi-color designs. The blanket cylinder transfers the ink onto the part to be decorated.

The process is characterised by thin, transparent ink films on a white or cream substrate. Fine details are possible and the registration of colors is very good. The different colors are printed wet on wet, and are then dried.

In-mold decoration

The printing process can also be integrated with the injection molding process in several ways, avoiding the need for a separate printing line, see par. 2.1.7.

Ink types

Inks generally consist of four components, figure 102.

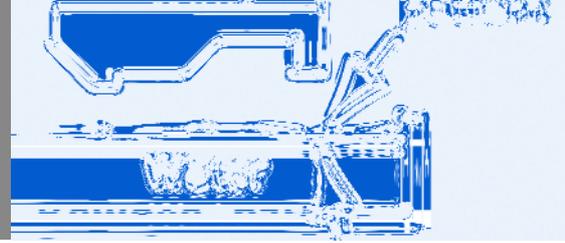
- resins
- pigments or dyes
- solvents or a carrier
- additives.

The resin forms the finished ink layer and bonds the color particles after curing. Typical resins include polyvinyl chloride, alkyd, polyester and epoxy. The resin selection is determined by the desired decorative effect, the functional demands, the application and curing technique and local regulatory restrictions. A variety of inks exists, based on different chemistries and polymers.

Pigments give the ink the desired color and opacity. They are normally supplied in powder form and incorporated into the ink by a mechanical dispersion process. Dyes are sometimes used instead of pigments, for instance in sublimation inks, and for transparent coatings.

Solvents or carriers enable inks to be applied in the liquid state. Inks can be divided into two main groups: conventional inks with an organic solvent and waterborne inks. Inks based on an organic solvent generally have better adhesion to substrates than waterborne inks, but solvents may attack the substrate and cause stress cracking. Generally, no single solvent has all the desired properties and a mixture of solvents is therefore used. Waterborne inks have superior properties in relation to environmental, health and safety matters.

Special additives can be used to give the ink the desired flow properties in the application phase or an



improved flexibility after curing. Some additives enhance adhesion and appearance.

Pad printing inks have formulations comparable to screen printing inks, but there are some differences. Pad printing inks are formulated for rapid solvent evaporation, whereas screen printing inks are designed to resist rapid evaporation so that they don't dry in the screen. Furthermore, screen printing inks are sometimes applied as a very thick film, unlike pad printing inks.

Different types of inks can be distinguished according to the way curing takes place:

- Air-curing inks harden due to evaporation of the solvent, while the resin polymerizes. They dry rapidly and are the most commonly used ink type.
- Heat-curing inks require elevated temperatures for curing. The use of these ink systems is limited by the high curing temperature that the plastic must be able to withstand.
- Two-component inks have the big advantage that no volatile components evaporate during curing. Pot-life after mixing is limited.
- UV-curing inks are widely used for screen printing. The curing process is fast and environmental problems are smaller than for solvent-based systems. Small changes in ambient conditions have little influence, which makes the printing process very stable.
- Oxygen-curing inks have a limited use, as they dry slowly. The polymerization takes place under the influence of oxygen absorption.
- Sublimation inks are heated at a temperature of about 200°C (392°F) during the application process, so that dyes in the ink sublime and are absorbed by the polymer surface while they are in the gas state. Sublimation inks are in the solid state at ambient temperature, like a wax, and become fluid when raised to 80°C (176°F) in the ink reservoir and cliché.

Ink systems should always be tested on prototype parts over an extended period of time to establish the compatibility of the ink.

Pretreatment

The surfaces to be printed must be clean and free of oils, grease and mold-release agents for good ink adhesion and cleaning of the parts may be necessary (par. 2.1.11.). Painting/printing should be done in a dust free space.

Apart from cleaning, several other pretreatments exist to enhance the adhesion of the ink to the substrate, see par. 2.1.2.

Surface wetting

For all printing techniques, the surface energy of the wet ink should be lower than the surface energy of the substrate to achieve good surface wetting and a uniform ink distribution. If the surface energy of the ink is higher than the surface energy of the substrate, the contact angle of the liquid will be large and the liquid beads up and forms into globules, so that the wetting of the surface will be poor, see figure 56. If on the other hand, the surface energy of the substrate is equal to or higher than the surface energy of the liquid, the contact angle will be low and the ink can be spread evenly across the surface.

Special kits are available to test the surface energy of the substrate by applying liquids with known surface energy levels and watching the reaction. The test kits normally contain six to eight fluids, and are available in felt-tip pen form.

It is important that no additives used in the substrate or added color masterbatches, can migrate to the surface. This may affect surface tension in a negative way and lead to an irregular thickness distribution.

Climatic conditions, like temperature and humidity, should be well-controlled for a good, reproducible printing result.

Foam molded parts cannot be printed immediately after molding. The gases produced by the foaming agents must first reach equilibrium with the ambient air. This outgassing may take 24 to 48 hours, depending on temperature and humidity. Premature printing may cause blistering.

Testing

For a description of the different tests, such as adhesion testing, chemical resistance testing, impact testing and scratch resistance testing see paragraph 2.1.2.

Recommendations for DSM products

Akulon (PA6 and PA66)

The relatively high heat deflection temperature and solvent resistance of Akulon PA6 and PA66 make them excellent resins for printing and drying at elevated temperatures. Pretreatments are normally not necessary, due to the strongly polar character of the material. However, acceptable mold release-agents and moisture levels should be ascertained.

Stanyl (PA46)

Due to its strongly polar character, Stanyl does not usually require any form of pretreatment. Printing should however take place on dry-as-molded products. Together with a thermal after treatment (i.e. curing) this ensures that sufficient adhesion between the inks and the polyamide substrate is achieved.

Solvent containing inks suitable for Stanyl consist of solvents based on ketones, glycol ethers, alcohols and/or esters, binding agents based on nitrocellulose, vinyl chloride copolymers or thermoplastic polyamides, and pigments based on azo and phtalocyanine compounds.

Arnite (PBT and PET)

Arnite can be printed with practically all known printing systems. The chemical resistance of polyester is so good, that inks generally have a poor adhesion to the surface of the part. A primer should be used for all standard inks.

Arnitel (TPE)

Arnitel is easy to print, provided that no silicone-containing mold releases agents or other products with an adverse effect on adhesion are used. No special adhesion promoters are necessary. Arnitel can be printed with several printing techniques, including sublimation printing.

Xantar (PC), Xantar C (PC + ABS) and Stapron E (PC + PET)

If no mold release is used and the parts are not touched with bare hands, the only necessary cleaning operation might be blowing with clean air. Cleaning with a compatible solvent is necessary if parts have been contaminated with oil, grease, mold-release or other foreign materials (par. 2.1.11.).

It should always be checked that the ink system is not too aggressive. Organic solvents may cause stress cracking. Chlorinated and aromatic solvents, as well as ketones, should generally be avoided, although they may sometimes be used in other solvent systems as adhesion promoters to etch the surface. Solvents should evaporate easily and leave the printed part completely. Waterborne inks and inks based on aliphatic hydrocarbons (mineral spirits, heptane, hexane and alcohols) are generally compatible with PC.

Hot curing temperatures up to 120°C (250 °F) are generally acceptable for PC.

f. Laser Printing & Marking

The traditional method of writing on plastics is printing with ink. Direct ink printing puts an image on the surface whereas laser marking can provide an indelible, high contrast mark under the surface.

With laser marking there is no direct contact with the plastic other than through the laser beam.

Laser marking is the most flexible way of marking plastics and yields legible and sharp images. Lasers can mark products with various geometries in a fully computer-controlled process with high reproducibility and reliability.

For more details please see the laser marking brochure.



2.1.10. Vapor Polishing

Minor scratches and other small surface irregularities can be removed from Xantar PC parts by vapor polishing. The process is performed with a chemical vapor, which attacks the surface of the plastic and smoothes it. When done properly, vapor polishing can provide optical quality finishes.

Methylene chloride vapor is normally used in the process for PC. The vapor is created by heating a container with methylene chloride to the boiling point. The parts are exposed to the methylene chloride vapor for less than three seconds. The whole process must be performed in a closed and well ventilated room, that prevents the operator from coming in contact with the fumes. Parts must not come in contact with liquid methylene chloride.

After the polishing process, parts must be allowed to dry, in order to evaporate all methylene chloride. Finally the parts are gradually heated in an air circulation oven and kept at 120°C (250°F) for one hour to release surface stresses and to evaporate the entrapped methylene chloride.

Dirt particles and all foreign matter, such as oils and greases should be removed from the parts by carefully cleaning (par. 2.1.11.) and drying before polishing.

Because of the risks involved, this process must only be performed by an experienced person. The chemical vapors are harmful if inhaled; special equipment must be employed to avoid that the operator comes into contact with the chemicals. In addition, various government agencies have strict regulations concerning the exposure limits to this group of chemicals. Please refer to the MSDS provided by the chemical supplier.

2.1.11. Cleaning

The surfaces of parts that must be painted or joined together by a gluing process, like solvent or adhesive bonding, must be clean and free of foreign materials, such as dirt particles, oil, grease, or mold release agent in order to achieve a strong bond.

Table 11 Cleaning solvents for Akulon (PA6 & PA66).

Alcohols	Butanol Ethanol Isopropanol Methanol Propanol
Aliphatics	Heptane Hexane
Aromatics	Benzene Toluene
Ketones	Acetone Methyl ethyl ketone
Chlorinated hydrocarbons	Methyl chloride Tetra chloro methane
Others	Mild solution of soap (pH between 4.5 and 7.5)

Table 12 Cleaning solvents for Stanyl (PA46).

Alcohols	Butanol Ethanol Isopropanol Propanol
Aliphatics	Heptane Hexane
Aromatics	Benzene Toluene
Ketones	Acetone Methyl ethyl ketone
Chlorinated hydrocarbons	Methyl chloride Tetra chloro methane
Others	Mild solution of soap (pH between 4.5 and 7.5)

If the plastic pellets do not contain a mold release agent and if no mold release agent has been sprayed in the mold during the injection molding process and the parts were not touched with bare hands, cleaning in an air bath to remove dust particles may suffice.

The need to use a mold release agent can be avoided by designing the parts with generous release angles.

If necessary, persistent contaminants can be removed by washing in a suitable solvent. Tables 11 to 15 give some examples of solvents that can be used for DSM's thermoplastics, assuming that the parts will not be exposed to the cleaning solvents for more than 10 minutes.

Table 13 Cleaning solvents for Arnite (PBT and PET).

Alcohols	Butanol Ethanol Isopropanol Methanol Propanol
Aliphatics	Heptane Hexane
Aromatics	Benzene Toluene
Ketones	Acetone Methyl ethyl ketone
Ester	Ethyl acetate Methyl acetate
Chlorinated hydrocarbons	Methylene chloride 1,1,1-Trichloro ethane
Chlorinated fluorocarbons	Trichloro trifluoro ethane Trichloro trifluoro methane
Others	Mild solution of soap (pH between 4.5 and 7.5)

Some solvents may cause environmental stress cracking in polycarbonate and polycarbonate blend parts which are subjected to internal or external stresses. Chlorinated and aromatic solvents, as well as ketones, should therefore be avoided for these polymers.

It is important to consult the Material Safety Data Sheet of the solvent used, for health and safety information and for proper handling and protective equipment.

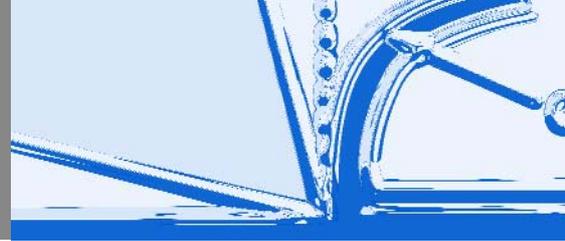
An automated cleaning line may be useful to speed up the cleaning process and improve quality control. An ultrasonic bath or a spraying installation can be considered.

Table 14 Cleaning solvents for Arnitel TPE.

Alcohols	Ethanol Isopropanol Methanol Propanol
Aliphatics	Heptane Hexane
Ketones	Acetone Methyl ethyl ketone
Others	Mild solution of soap (pH between 4.5 and 7.5)

Table 15 Cleaning solvents for Xantar (PC), Xantar C (PC + ABS) and Stapron E (PC + PET).

Alcohols	Butanol Ethanol Isobutanol Isopropanol Propanol
Aliphatics	Heptane Hexane
Others	Mild solution of soap (pH between 4.5 and 7.5)



2.2. Machining

2.2.1. Introduction

Machining is often necessary for blow molded and extrusion fabrication processes. Injection molded parts do not normally require any machining operations, apart from the removal of sprues and flash in some cases.

The following are recommended for machining plastic parts.

- Standard HSS (high speed steel) tools or carbide tools used for machining metals can generally be used, although specially designed tools for plastics may sometimes allow higher production rates and have better chip removal capabilities. Carbide tipped tools and diamond tools offer a longer tool life and are especially suitable for filled polymers.
- Cutting oils and cooling liquids used in the metal industry should generally be avoided, as they may not be chemically compatible with plastics and must be removed afterwards. A forced air stream can best be used for cooling, or if more intensive cooling is necessary, a water spray mist or a water soluble cooling liquid can be used.
- When machining plastics it has to be remembered that the heat conductivity of these materials is only one hundredth to one thousandth of that of metals. A high cutting speed and a low feed speed are therefore customary, and sharp and well polished tools are required to avoid local melting and gumming. Cutting tools must have a generous back clearance to minimise frictional heating.
- Plastics generally have a high thermal expansion coefficient, up to a factor twenty higher than that of metals. The dimensions of machined parts should therefore be measured after allowing the parts to cool down.
- Internal mechanical stresses are built up in the plastic part during machining. Annealing may therefore be considered in critical cases, where environmental stress cracking can be expected. This can be critical for Xantar PC, see par. 2.3.
- Skin contact and dust inhalation must be avoided, as dust may cause irritation. Check the material safety data sheets for any required precautions.

Figure 103 Cutting tools for plastics should have a generous back clearance to prevent overheating.

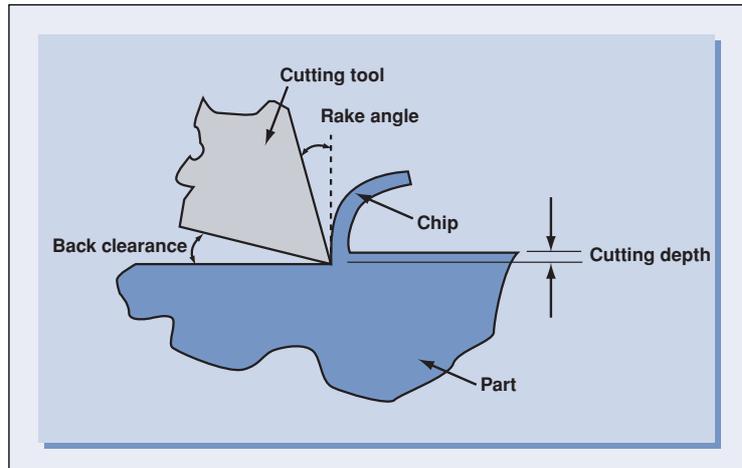


Table 16 Drilling conditions.

	Xantar PC	Stamylan UH	Other Plastics
Rake angle	0 - 5°	15-25°	> 0
Clearance angle	5 - 15°	about 16°	10 - 15°
Cutting speed	5 - 40 m/min (16 - 130 ft/min)	40-70 m/min (130-230 ft/min)	30 - 120 m/min (100 - 400 ft/min)
Feed speed	0.025 - 0.040 mm/rev (1 - 1.5 mils/rev)	0.1-0.3 mm/rev (4-12 mils/rev)	0.025 - 0.5 mm/rev (1 - 20 mils/rev)

2.2.2. Drilling & Reaming

For holes with small diameters, drilling is often a good option. This is also the case if molded-in holes would require expensive slides in the mold.

A standard high speed drill used for metals with a 118° nose angle can normally be used, but special drills for plastics may allow faster production rates. These drills are characterised by smaller nose angles, smaller helix angles and larger flutes, for better chip removal, and a larger back clearance to minimise friction.

Note, whereas many plastics require a positive rake angle, drills for Xantar PC must have a rake angle of 0-15° for a scraping rather than a digging action.

Table 16 gives some guidelines for drilling conditions. The values shown are only a rough indication, as optimal conditions depend on the specific polymer

Figure 104 Stepped drill for drilling a smooth hole.

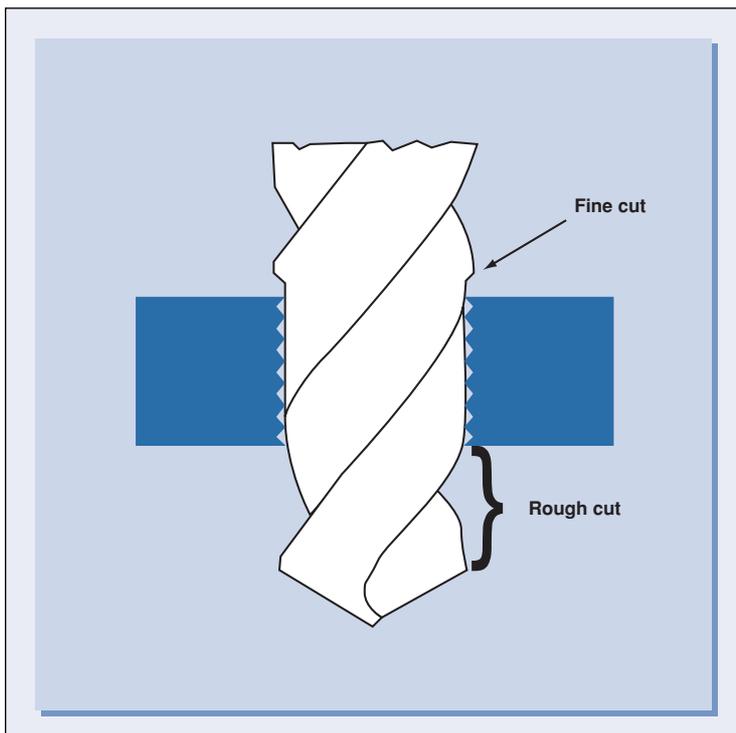


Table 17 Sawing conditions.

	Xantar PC	Stamylan UH	Other plastics
Circular saw			
Rake angle	5-15°		5-15°
Clearance angle	10-25°		10-25°
Pitch	2-4 mm (6-13 teeth/in)		3-6 mm (4-8 teeth/in)
Cutting speed	1000-3000 m/min (3000-10000 ft/min)	3000-4000 m/min (10000-130000 ft/min)	<3000 m/min (<10000 ft/min)
Feed speed		0.1-0.2 mm/tooth (4-8 mils/tooth)	
Band saw			
Rake angle	0-8°		0-8°
Clearance angle	20-40°		20-40°
Pitch	2-5 mm (5-13 teeth/in)		2-8 mm (3-13 teeth/in)
Cutting speed	600-1000 m/min (2000-3000 ft/min)	1000-1500 m/min (3000-5000 ft/min)	300-1500 m/min (1000-5000 ft/min)
Feed speed		0.1-0.3 mm/tooth (4-12 mils/tooth)	

grade and the fillers used. A lower feeding speed must generally be used for drills with small diameters.

A smooth hole can be produced by first drilling a hole with a diameter that is slightly smaller than the desired size, and then finishing the hole with a second drill. A stepped drill (figure 104) can also be used and offers a faster alternative.

2.2.3. Threading and tapping

Parts made of more rigid engineering plastics such as Akulon, Arnite, Stanyl and Xantar can be provided with a screw thread by threading or tapping with conventional steel working equipment. Very fine threads with a pitch smaller than 1 mm should however be avoided and the root radius must be maximised to reduce stress concentrations. Threading can be done on a conventional lathe by removing material in successive cuts of less than 0.25 mm (10 mils). Low spindle speeds must be applied for tapping, with a feed speed between 6 and 24 m/min (20-80 ft/min).

2.2.4. Sawing

DSM's thermoplastics can be cut with band saws, circular saws and jig saws. The saw blades should however have a generous set to minimise friction. Typical conditions are shown in the table 17.

2.2.5. Milling

In both milling and sawing, the cutting action is discontinuous compared to other processes such as turning. The tool and work piece are subjected to alternating mechanical and thermal loads. Besides abrasion, thermal degradation is a further cause for tool wear. Cutting speeds that are too high relative to a low feed rate will melt the polymer along the cutting line. On the other hand, if the chosen feed rate is too high, it can cause rough surfaces or even lead to breakage, regardless of the cutting speed. To efficiently remove heat that develops during milling, single-edge cutters or cutters with a low number of edges are recommended so that sufficient chip space is available. Mills with four cutting flutes produce good results for most plastics.

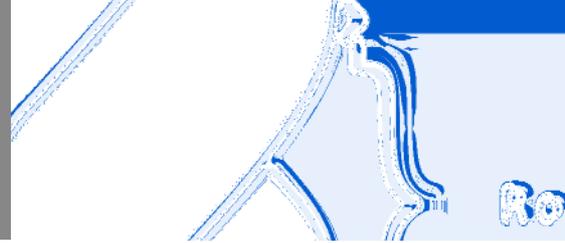


Table 18 lists generic milling conditions. The data shown does not represent optimal values, but are guidelines to achieve acceptable results.

Milling is often done in two steps. In the first step a high cutting depth is used to remove material at a fast rate and in the second finishing step, a small cutting depth and high cutting speed are used to produce a smooth surface.

2.2.6. Turning and boring

Turning and boring of DSM thermoplastics can be done on conventional lathes, as used for metals and is often used to produce round parts from bar stock. A minimum nose radius of the cutting tool of 0.4 mm (15 mils) is recommended to produce parts with a small surface roughness. Table 19 suggests turning conditions that will generally yield good results.

To achieve a smooth surface, the finishing cut is done with a small cutting depth and high cutting speed.

2.2.7. Punching, blanking, and die cutting

Punching, blanking, and die cutting are techniques that can be applied on ductile plastics with a limited toughness. Filled plastics and Xantar PC are therefore less suited. On the other hand these techniques give good results when used on thermoplastic elastomers such as Arnitel. Cutting tools must be very sharp and preheating the part or sheet material to soften the plastic can be considered. Sharp corners in cut out sections should be avoided.

2.2.8. Laser cutting

Laser cutting is a technique that is rapidly gaining acceptance and its use is growing. Round holes or holes with an irregular shape can be cut in plastics with a laser beam, usually of the carbon-dioxide type, operating in the infrared region. The laser beam may either be continuous or pulsed. Laser cutting has the big advantage that the machined surfaces are free of machining grooves, which when present might lead to stress concentrations. Furthermore, laser cutting can

Table 18 Milling conditions.

	Xantar PC	Stamylan UH	Other plastics
Rake angle	0-15°	5-15°	15°
Clearance angle	5-20°	5-15°	5-20°
Cutting speed	30-60 m/min (100-200 ft/min)	200-800 m/min (650-2600 ft/min)	70-2000 m/min (230-6600 ft/min)
Feed speed	50-250 mm/min (2-10 in/min)	about 0.3 mm/rev (12 mils/rev)	160-250 mm/min (6-10 in/min)
Cutting depth	0.1-3.0 mm (5-125 mils)		1.5-6.0 mm (60-230 mils)

Table 19. Turning conditions.

	Xantar PC	Stamylan UH	Other plastics
Cutting speed	40-120 m/min (130-400 ft/min)		60-1000 m/min (200-3300 ft/min)
Feed speed	0.1-0.3 mm/rev (0.004-0.012 in/rev)		0.1-0.5 mm/rev (0.004-0.02 in/rev)
Cutting depth	1.5-3 mm (60-120 mils)		1.5-3 mm (60-120 mils)

often be applied in areas that are inaccessible for conventional techniques or when firmly supporting the workpiece is problematic.

2.2.9. Filing

A file can be used to remove flash or for rounding sharp edges. Single hatched files must be preferred, as cross hatched files have a tendency to clog. Tough plastics, like unfilled Akulon and Stanyl, require files with relatively coarse teeth.

2.2.10. Sanding and grinding

Sanding can either be done by hand, or mechanically on an endless belt or with a disc sander. The heat conductivity of plastics is low making them easily susceptible to softening. The sanding speed should therefore be low and wet sanding can be considered, as this reduces the chance of gumming.

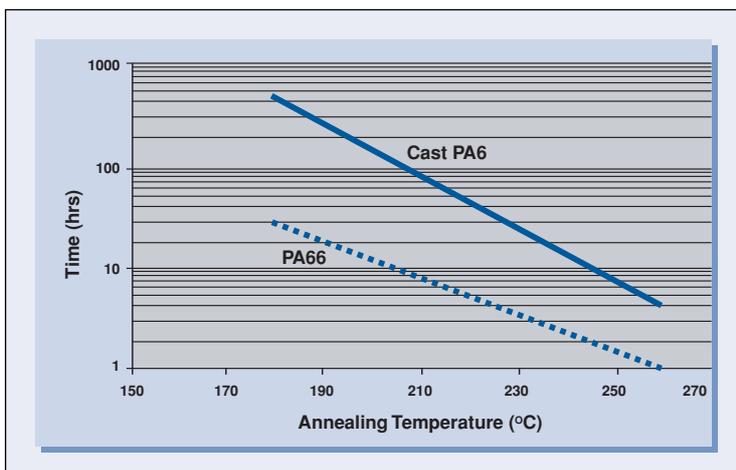
Abrasive discs rotating at high-speeds on a hand grinder, can also be used to remove material fast.

2.2.11. Polishing and buffing

Engineering plastics which are rigid (Stanyl PA46, Arnite PET and PBT, Akulon PA6 and PA66, and Xantar PC) can be buffed on standard buffing equipment, in order to bring the surface to a desired roughness level and give parts an appearance that may vary from a dull satin finish to a highly polished look. Buffing is done on a rotating wheel made of layers of cotton or muslin, that are kept dressed with a buffing compound.

A slurry of pumice and water can be applied to remove the surface irregularities and provide a satin finish. Special polishing compounds give parts a high gloss. Polishing is done in several steps, the last treatment being wiping off the polishing compound with a dry, soft wheel.

Figure 105 Unfilled Stanyl annealing conditions giving water uptake levels similar to PA66 or cast PA6.



2.3. Annealing

Annealing is a high temperature after-treatment of an injection molded part.

2.3.1. Annealing Stanyl

Important morphological changes occur in Stanyl during annealing. The crystalline phase undergoes a further optimization and there is a reorganization of the amorphous phase into a denser structure. These result in a further increase in Stanyl's high-temperature, mechanical properties and a reduction in its moisture uptake.

Stanyl is annealed when heat treated above its glass transition temperature [T_g 80°C], but below its melting temperature [T_m 295°C], preferably at temperatures between 210 and 240°C for 4 - 12 hours. The effects obtained through annealing are irreversible. Annealing can be carried out in standard industrial ovens. At the indicated annealing temperatures (>210°C), a nitrogen atmosphere is recommended to avoid any thermal oxidation of the material. Stanyl parts will anneal at lower temperatures - e.g. when operating at continuous temperatures around 150°C, but the process will take longer. As a planned heat treatment in a production process, the higher temperatures mentioned above should be used.

Annealing can typically lead to the following property improvements in Stanyl:

- High temperature strength and stiffness (above T_g) can be increased by up to 50%
- The fatigue performance can be considerably improved
- Wear resistance may be improved by as much as 50%
- There is a substantial reduction in moisture uptake, leading to better dimensional stability. Reducing water uptake by annealing is UNIQUE for Stanyl. Depending on the chosen time/temperature combination, water uptake in Stanyl can be brought down below PA66 and PPA levels, and to the level of cast PA6, see figure 105.



An important practical aspect of these mechanical property improvements is that annealed Stanyl parts can carry and transmit higher loads. For instance, smaller gears can be designed to transmit the same torque as current larger designs: annealing allows for MINIATURIZATION.

For more information, see the guideline "Annealing of Stanyl".

2.3.2 Annealing Xantar

Parts made of Xantar PC can be annealed to relieve the internal material stresses that are introduced during injection molding or machining, in order to prevent environmental stress cracking.

This can be done by heating the parts for approximately half an hour at a temperature 20°C (36°F) below the Vicat softening temperature. For most Xantar PC grades this means that the annealing temperature should be around 128°C (262°F).

Mechanical properties may be affected by the heat treatment. Impact strength may be especially reduced. This negative effect is less after annealing at lower temperatures: e.g. at 80 - 95°C (176 - 203°F) for at least 12 hours.

If necessary, parts must be well supported during the heat treatment, to prevent deformation due to gravitational forces acting on the part.

Table 20 Typical values for the maximum allowable short-term strain at 23°C.

DSM Products		Polymer description	ε (%) Dry / conditioned
Semi-crystalline materials	Akulon	PA6 and PA66	2.5 / 10 (*)
		PA6 and PA66 + 15-35% GF	1.8 / 2.8
		PA6 and PA66 + 40-50% GF	1.5 / 2.0
		PA6 and PA6.6 + GF + IM	2.3 / 4.0
	Stanyl	PA46	7.0 / 10 (*)
		PA46 + FR	3.5 / 10 (*)
		PA46 + IM	10 / 10 (*)
		PA46 + 15% GF	2.0 / 4.0
		PA46 + 15% GF + FR	1.5 / 3.0
		PA46 + 30% GF	2.0 / 3.5
		PA46 + 30% GF + FR	1.3 / 1.8
		PA46 + 40% GF	1.5 / 3.0
		PA46 + 40-45% GF + FR	1.0 / 1.5
		PA46 + 50% GF	1.4 / 2.5
	Arnite	PBT	2.5 (*)
		PBT + FR	3.2 (*)
		PBT + IM	2.8 (*)
		PBT + 15-30% GF	1.5
PBT + 15-30% GF + FR		1.3	
PBT + 20% GF + IM		2.0	
PBT + 35% GF		1.3	
PET		2.8 (*)	
PET + 20-35% GF		1.3	
PET + 30-33% GF		1.0	
Amorphous materials	Xantar	PC	4.2
		PC + 10% GF	3.5
		PC + 20% GF	2.0
		PC + 30% GF	1.0
		PC + 40% GF	0.8
	Xantar C	PC + ABS	3.0
	Stapron E	PC + PET	4.2

FR = flame retardant
GF = glass fibre
IM = impact modifier

3.1. Introduction

The important tables required for making calculations related to secondary operations are:

- Maximum allowable short term strain
- Coefficient of friction
- Poisson's ratio
- Unit conversion factors

3.2. Maximum Allowable Short-Term Strain

The maximum allowable short-term strain in plastics must be known to calculate the maximum permissible deformation, for instance of:

- snap fits during assembly and disassembly,
- threads during stripping from the mold,
- parts with undercuts during ejection from the mold etc.

The maximum allowable short-term strain is:

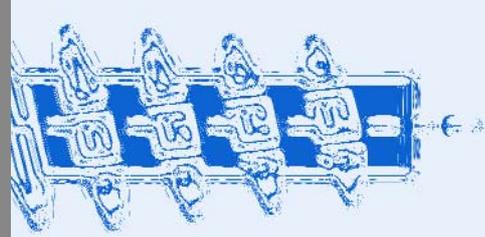
70% of the yield strain for materials with a clear yield point. (*)
50% of the strain at break for materials that break without yielding, as is the case for most most glass filled materials.

Table 20 gives some typical values at a temperature of 23°C. Because values are temperature dependent and different temperatures can be encountered during the various manufacturing steps, real values at those temperatures should be used.

The yield strain and the strain at break can be found on www.dsmep.com. Select a material grade first by clicking on the grade name, then click on "PROPERTIES" and "Mech" for the mechanical data.

For applications where repeated loading and unloading is experienced, 60% of the above-mentioned values is recommended.

(*) Note, even higher strains, close to the yield strain, could be accepted for unfilled semi-crystalline thermoplastics with a clear yield point. Although no breakage will occur, this might result in unacceptable plastic deformation.



3.3. Coefficient of Friction

The coefficient of friction must be known for the calculation of constructions such as bearings, snap fits and threads. The coefficient of friction depends on several factors:

- the material,
- the hardness of the counter surface,
- the surface roughness,
- the service temperature,
- the surface pressure,
- the sliding velocity,
- running-in phenomena, elapsed time and
- additives.

Frictional properties of plastics differ markedly from those of metals. The rigidity of even the highly reinforced resins is low compared to that of metals; therefore, plastics do not behave according to the classic laws of friction. Metal to plastic friction is characterized by adhesion and deformation of the plastic, resulting in frictional forces that are proportional to velocity rather than load. In thermoplastics, friction actually decreases as load increases.

It is a characteristic of most thermoplastics that the static coefficient of friction is less than the dynamic coefficient of friction.

Running-in phenomena normally do not play a role in applications such as snap fits and threads, and the temperature will generally be close to room temperature. The coefficients of friction in the table can be used for these applications. Table 21 gives values for various plastics when tested either against itself or against steel.

The equilibrium dynamic coefficient of friction at elevated temperatures, after several hours running, is of importance for bearings. The temperature increase is the result of the heat generated by the friction.

3.4. Poisson's Ratio

Poisson's ratio ν is a measure of the lateral contraction of a material if it is subjected to a tensile stress in

Table 21 Coefficients of friction at 23°C, without running-in.

DSM Products	Polymer description	On itself	On steel
Akulon	PA6 & PA66	0.15 – 0.45	0.20 – 0.50
Stanyl	PA46	0.15 – 0.45	0.20 – 0.50
Arnite	PBT	0.20 – 0.40	0.20 – 0.45
	PET	0.20 – 0.30	0.15 – 0.25
Xantar	PC	0.30 – 0.50	0.25 – 0.50
Xantar C	PC + ABS	0.30 – 0.50	0.25 – 0.50

Table 22 Poisson's ratio at 23°C.

DSM Products	Polymer description	Dry	Conditioned
Akulon	PA6 & PA66	0.38	0.45
Stanyl	PA46	0.38	0.45
Arnite	PBT	0.44	
	PET	0.43	
Arnitel	TPE	0.45 – 0.49	
Xantar	PC	0.38 – 0.42	
Xantar C	PC + ABS	0.36 – 0.42	
Stapron E	PC + PET	0.36 – 0.42	

the longitudinal direction. It is defined as follows:

$$\epsilon_l = -\nu \cdot \epsilon$$

where

- ϵ_l = strain in lateral direction,
- ϵ = strain in longitudinal direction.

Note that the strain in the lateral direction ϵ_l is negative, as contraction occurs.

Poisson's ratios lie between 0.3 and 0.5 for most polymers. Incompressible polymers, like rubbers, have a Poisson's ratio 0.5. Other polymers have lower values.

The Poisson's ratio of polymers depends on:

- the temperature
- the moisture content in case of nylons
- the fibre content and the fibre orientation in case of filled polymers.

The values in table 22 can be used for mechanical calculations.

Table 23

Length	1 in = 25,4 mm 1 ft = 12 in = 0,304 8 m 1 yd = 3 ft = 36 in = 0,914 4 m 1 mile = 5280 ft = 1 609,344 m 1 Å = 10 ⁻¹⁰ m
Surface	1 in ² = 6,451 6 cm ² 1 ft ² = 0,092 903 06 m ² 1 yd ² = 0,836 127 m ² 1 mile ² = 2,589 988 km ² 1 acre = 4 046,856 m ²
Volume	1 in ³ = 16,387 064 cm ³ 1 ft ³ = 28,316 8 dm ³ 1 yd ³ = 0,764 555 m ³ 1 gal (UK) = 4,546 09 dm ³ 1 gal (US) = 3,785 41 dm ³ 1 pt (UK) = 0,568 262 dm ³ 1 liq pt (US) = 0,473 176 dm ³ 1 fl oz (UK) = 28,413 1 cm ³ 1 fl oz (US) = 29,573 5 cm ³ 1 barrel (US) = 158,987 dm ³
Velocity	1 ft/s = 0,304 8 m/s 1 mile/h = 0,447 04 m/s
Acceleration	1 ft/s ² = 0,304 8 m/s ²
Mass	1 lb = 0,453 592 37 kg 1 oz = 1/16 lb = 28,349 5 g
Density	1 lb/ft ³ = 16,018 5 kg/m ³
Force	1 lbf = 4,448 22 N 1 dyn = 10 ⁻⁵ N 1 kgf = 9,806 65 N
Dyn. viscosity	1 lb/(ft s) = 1,48816 Pa.s 1 P = 1 dyn.s/cm ² = 0,1 Pa.s
Kin. viscosity	1 ft ² /s = 0,092 903 0 m ² /s 1 St = 10 ⁻⁴ m ² /s
Moment	1 ft.lbf = 1,355 82 N.m 1 kgf.m = 9,806 65 N.m
Pressure	1 lbf/in ² = 6 894,76 Pa 1 kgf/m ² = 9,806 65 Pa 1 Torr = 133,322 Pa 1 at (technical) = 98 066,5 Pa 1 atm (standard) = 101 325 Pa 1 mmH ₂ O = 9,806 65 Pa 1 mmHg = 133,322 Pa
Energy	1 ft.lbf = 1,355 82 J 1 cal = 4,186 8 J 1 BTU = 1 055,06 J 1 kgf.m = 9,806 65 J 1 erg = 1 dyn.cm = 10 ⁻⁷ J
Power	1 ft.lbf/s = 1,355 82 W 1 hp (fps-system) = 745,700 W 1 hp (metric) = 735,499 W 1 kgf.m/s = 9,806 65 W 1 erg/s = 10 ⁻⁷ W
Temperature	1°C = 1 K T / K = t / °C + 273,15 1°F = 0,5556°C = 0,5556 K t / °C = (5/9) . (t _F / °F - 32) T / K = (5/9) . (t _F / °F + 459,67)

3.5. Unit Conversion Factors



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