

## Manufacturing – Forming

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## 3 Forming

### 3.1 Mastering aluminium cold forming technologies

**Mastering aluminium forming technologies**, especially those performed at room temperature, is the key to successful high volume lightweight automotive engineering.

While the principles of cold forming are equally applicable to all common metals, it is important to appreciate the differences as well.

It is the objective of this Section to summarise the important cold forming technologies applicable to aluminium and point out the potentials and limits.

- ⤴ **Sheet forming** of inner and outer closure panels summarises the experiences in part and tool design.
- ⤴ **Bending of tubes and shapes** has become a key technology field in the development of space frames and other structural application using tubes and especially extruded shapes as starting materials for complex shaped components.
- ⤴ **Hydroforming** of tubes and extruded shapes has developed as important cold forming technology for aluminium components, particularly with respect to minimising tolerances.
- ⤴ **Impact forming** is of particular significance for aluminium extrusions, since it permits to obtain local increases in cross-section, which otherwise must be attached by joining techniques.
- ⤴ **Semi-hot forming** - a necessity for magnesium - dramatically extends the forming limits of aluminium. It may well become of more significance in the future.

## 3.2 Sheet forming

### 3.2.1 Approach and contents

Aluminium alloy car body sheet materials can be cold formed using the same investments in equipment as for forming of steel sheet. However, aluminium sheet requires special attention due to its lower formability (when compared with mild steels), higher springback and surface sensitivity in contact with forming tools.

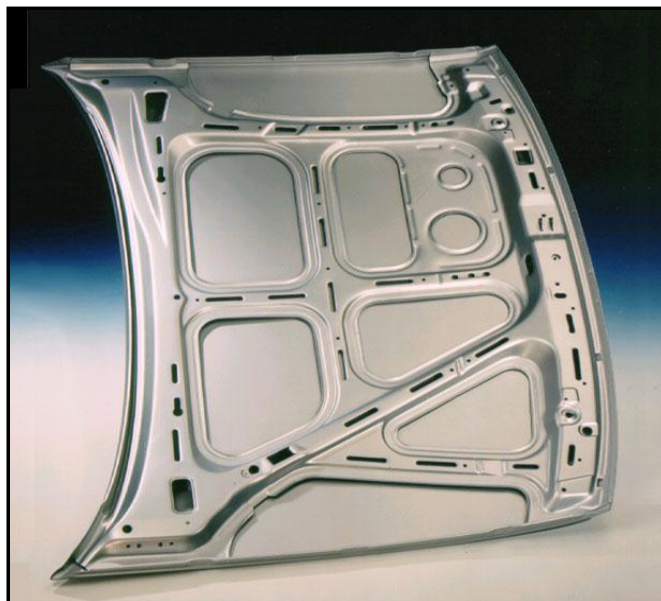
For difficult part designs the approach is to use special car body sheet qualities and shapes, adhere to allowable tool design features, select the right lubrication and follow established aluminium sheet forming strategies.

Tips & tricks for successful aluminium car body sheet forming are summarised in this Section by **DO-s** and **DON'T-s** with respect to

- ⤴ **Forming methods**
- ⤴ **Tooling**
- ⤴ **Tribology** and
- ⤴ **Forming practice.**

The contents are intimately related to information given in other sections of this Manual:

- ⤴ see: Rolled products,
- ⤴ see: Flow curve and formability,
- ⤴ see: Joining
- ⤴ see: Surface finishing.



### 3.2.2 Forming methods

#### General remarks on forming aluminium sheet

See also:

- ⤴ AAM – Products – 1 Rolled products > Flow curve, formability data

Specific **DOs** and **DON'Ts** are presented for the following **aluminium sheet forming methods**:

- ⤴ Blank preparation
- ⤴ Drawing
- ⤴ Stretching
- ⤴ Bending
- ⤴ Flanging
- ⤴ Hole expansion
- ⤴ Embossing
- ⤴ Feature lines
- ⤴ Roll forming
- ⤴ Handling

Design of each operation must consider

- ⤴ Springback

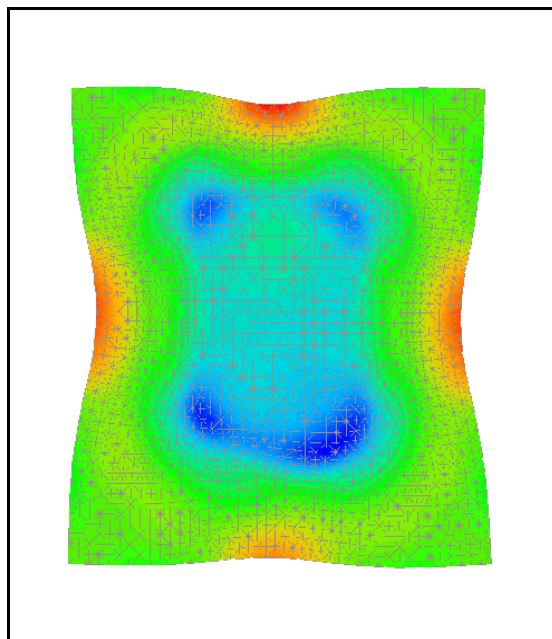
#### DO

- ⤴ use processes specifically designed for aluminium
- ⤴ use geometries and methods suitable for aluminium

#### DON'T

- ⤴ use straight substitution of steel by aluminium

See also chapter "Flow curve & formability".



**Strain distribution in aluminium product as simulated by DiekA**

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### Blank preparation

Literature:

- ⚡ Furrer, P. and Bloeck, M.: Aluminium-Karosseriebleche. Landsber: Verl. Moderne Industrie, 2001, (Die Bibliothek der Technik; Bd. 220) ISBN 3-478-93250-5

Blank preparation concerns blanking, washing, etc.

### DO

- ⚡ For critical stampings use EDT finish of < 1.5 mm. EDT reproducibly shows better forming and paint appearance.
- ⚡ Use developed blanks rather than rectangular ones to improve formability and springback predictability.

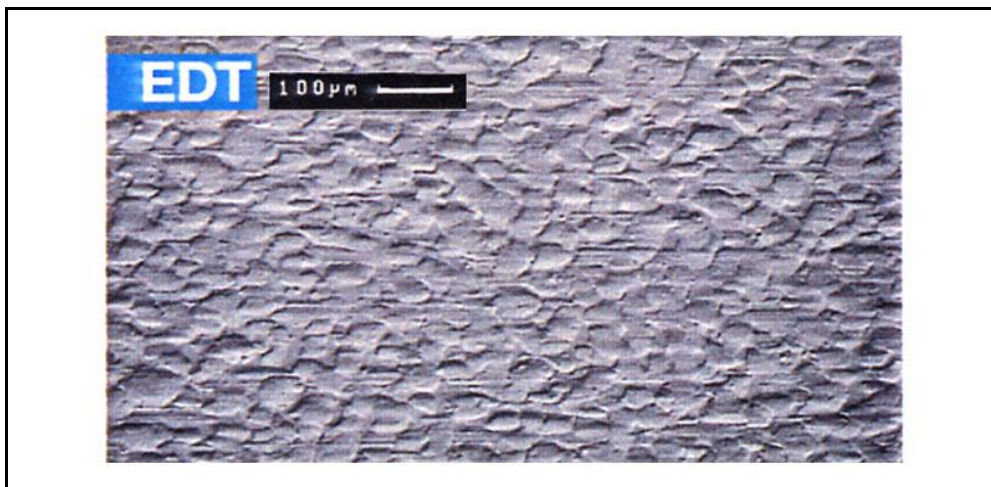


**Developed blank**

**Source: Alcan**

### DON'T

- ⚡ Use more than 1.5 mm of roughness: it will cause blanks to fret and paint appearance will worsen.



**EDT surface topography**

**Source: Corus Group**

## Drawing

### Literature:

- ⤴ Schuler GmbH: Handbuch der Umformtechnik. Berlin: Springer-Verlag, 1996. ISBN 3-540-61099-5
- ⤴ K. Siegert (Hrg.), Neuere Entwicklungen in der Blechumformung. Symposium Stuttgart 1992., Oberursel: DGM Informationsgesellschaft-Verlag, ISBN 3-88355-182-1
- ⤴ Siegert, K. (Hrg.), Neuere Entwicklungen in der Blechumformung Symposium Stuttgart 1996, Oberursel: DGM-Informationsgesellschaft-Verlag, 1996

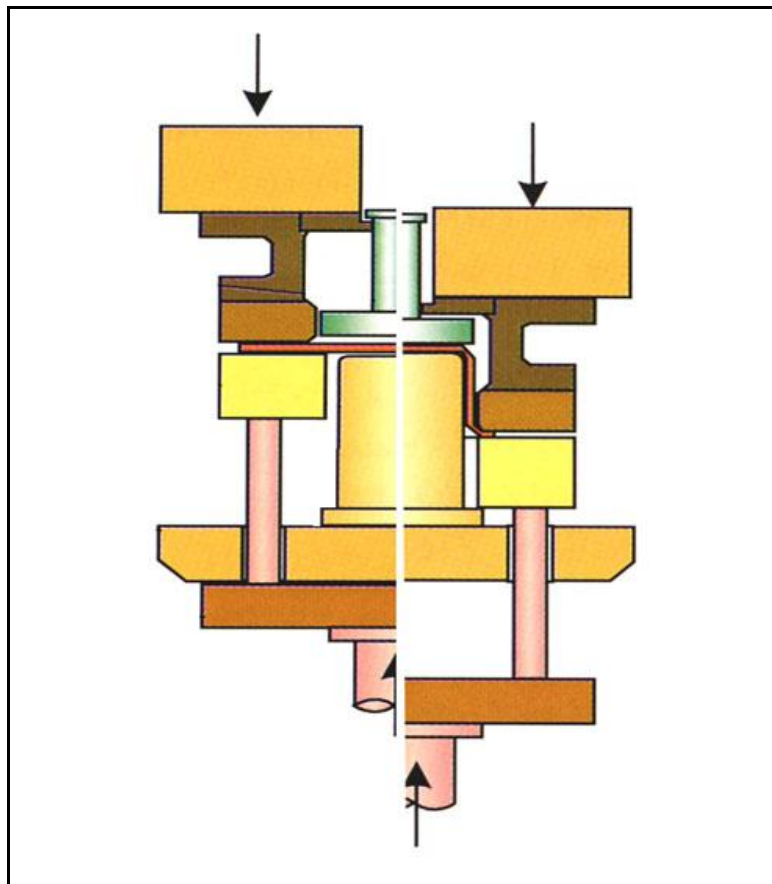
Drawing, or deepdrawing, is a forming method, where the shape is stamped into a sheet by means of dies allowing for the material to flow inwards.

### DO

- ⤴ Use of a developed blank minimises formability and springback problems.
- ⤴ Drawbeads can be used to control material flow.

### DON'T

- ⤴ Be careful not to induce too much strain in areas where flanges will be later on. Both for flanging and for clinchability



**Single acting drawing tool setup**

**Courtesy: Schuler GmbH**

## Stretching

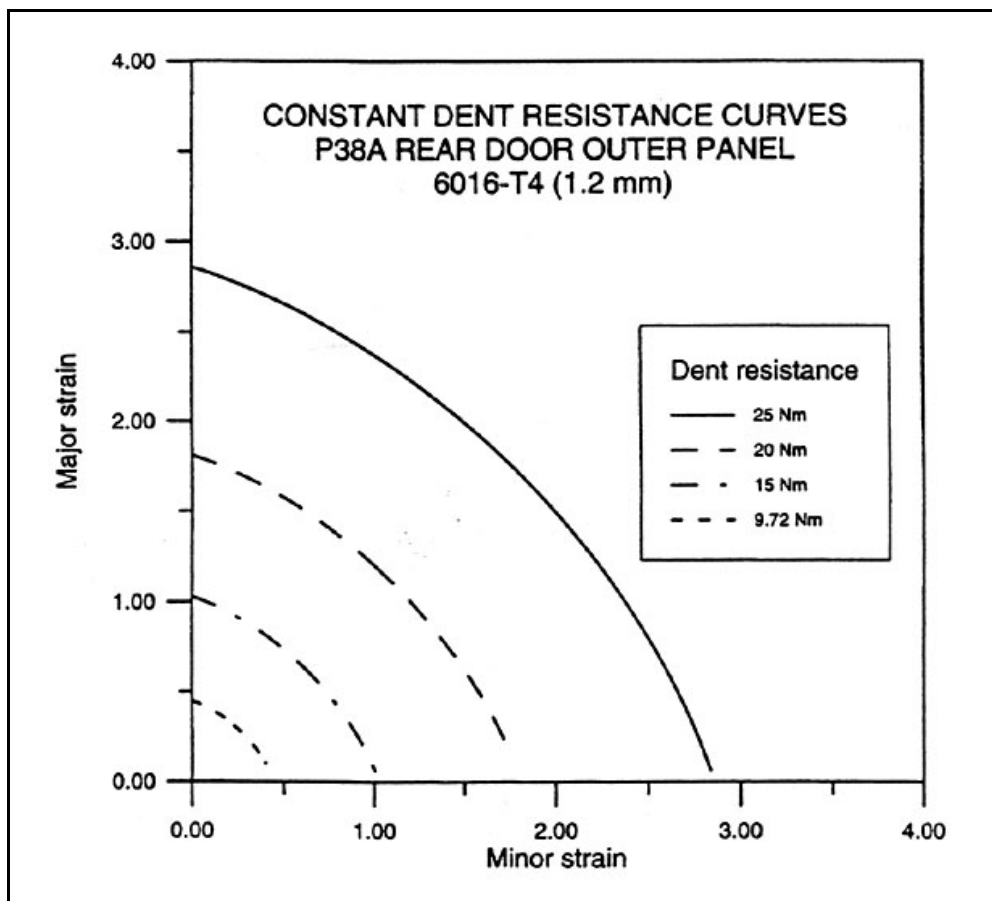
Stretching, is a forming method stamping the shape into a sheet by means of dies restricting the material from flowing inwards.

### DO

- ⤴ Make sure a minimum strain of 1-2% is obtained in the whole panel for dent resistance and tightness. Use lockbeads wherever possible to achieve this
- ⤴ However, using bakehardenable material the dent resistance will be largely independent of strain
- ⤴ Try and achieve uniform strain distribution for dimensional quality and predictable springback

### DON'T

- ⤴ Be careful not to induce too much strain in areas where flanges will be later on. Both for flanging and for clinchability



**Increase in dent resistance of exterior panel with plastic strain**

**Source: Corus Group**

## Bending

Bending is a forming method in which positive strain develops on one side and negative strain on the other. Average strain is zero, so length remains intact.

Bending can be done in several ways:

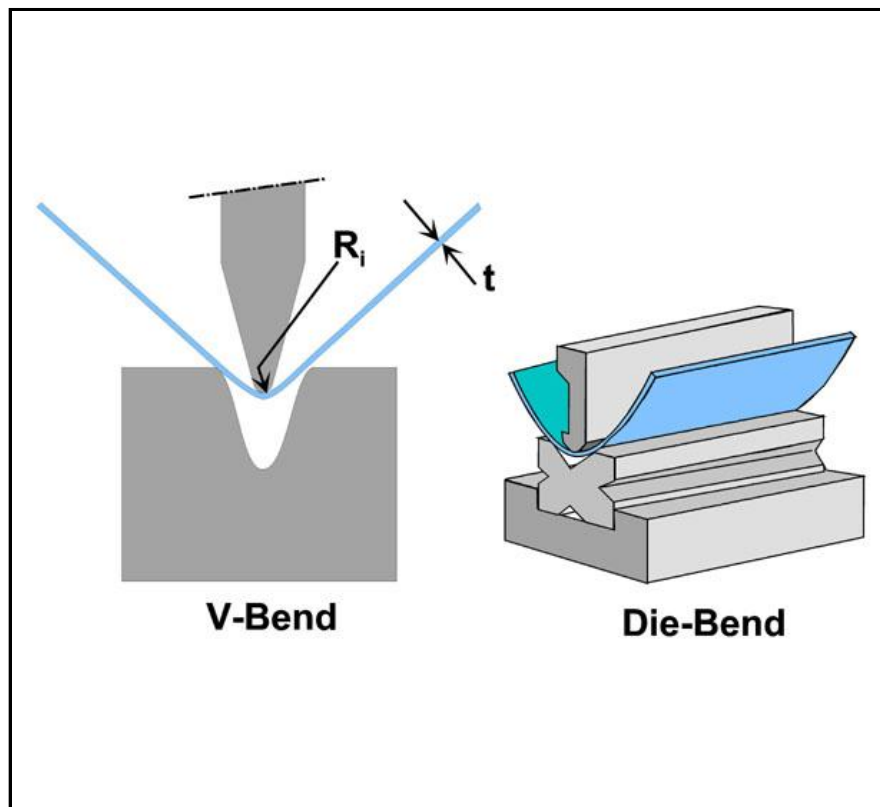
- ⤴ free bending (here),
- ⤴ die bending (here) or
- ⤴ flanging (next page).

## DO

- ⤴ Layout cutting process such as to have the cut edge on the outside radius of the bend, i.e. the burr on the inside
- ⤴ Set inner radius to  $>3t$  if in doubt of capabilities of the alloy of choice

## DON'T

- ⤴ Bend along a line in rolling direction (RD) if you can avoid it. Because this will increase orange peel



V-bending (left) and die-bending (right), schematically



### Straight flanging

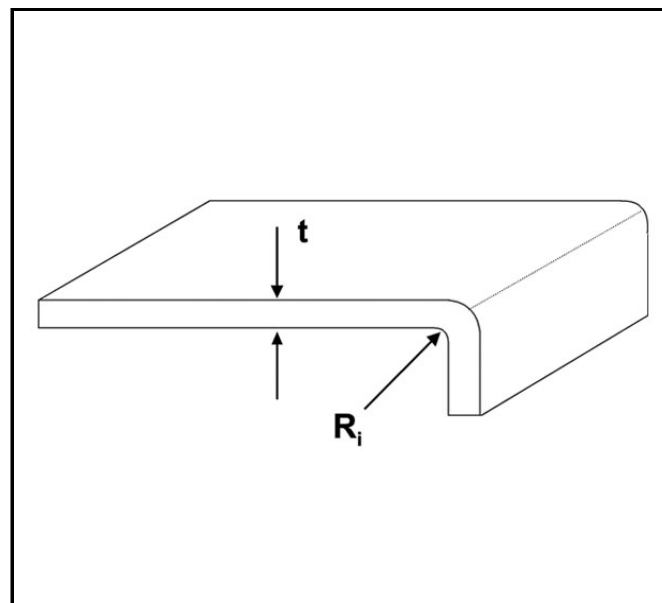
Flanging is the forming (bending) of flanges to a panel using stamping techniques.

#### DO

- ⤴ Calculate the outside strain by  
 $\epsilon_{\beta} = 1/2 \ln(1 + t/R_i)$   
This accounts for the shift of the neutral plane in bending. Thickness is  $t$  and inner radius of flange is  $R_i$
- ⤴ Compare the strain  $\epsilon_{\beta}$  to the uniaxial elongation  $A_{80}$ . When  $\epsilon_{\beta}$  is smaller than  $A_{80}$ , there is absolutely no problem. This criterion is very conservative and hence higher strains might be allowed with care
- ⤴ Have a nominal clearance of 5% of  $t$

#### DON'T

- ⤴ Use downflange radius less than  $2 \cdot t$ , if panel is to be hemmed 180 degrees (smaller radii can however be reached with optimised aluminium products)



Schematic straight flange

### Stretch flanging

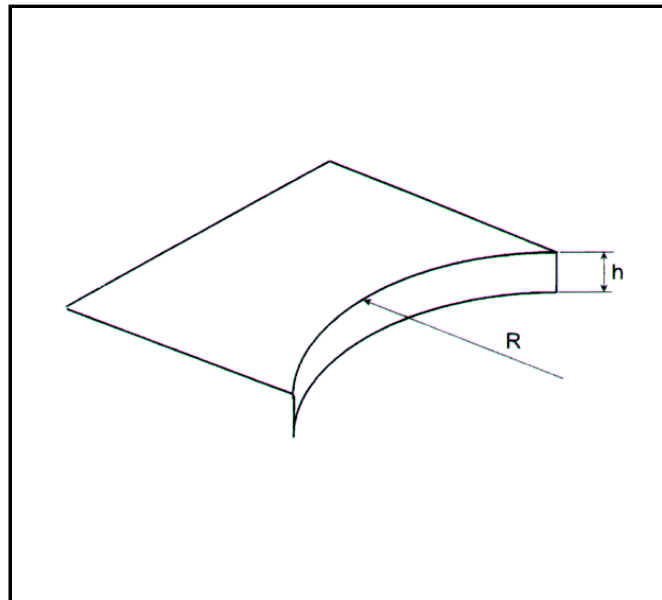
Stretch flanging is the flanging operation performed on a (partial) hole.

#### DO

- ⤴ Calculate maximum strain at edge of the hole from  $\epsilon = \ln(R_2/R_1)$ . Where  $R_1$  is inner radius of hole prior to flanging;  $R_2$  is radius after flanging
- ⤴ Make sure this strain is less than elongation  $A_{80}$ . Unlike in straight flanging this is **not** a conservative criterion

#### DON'T

- ⤴ If the flange is to be hemmed 180 degrees subsequently, the final strain will be twice the now calculated one



Schematic stretch flange

### Shrink flanging

Shrink flanging is a flanging operation on a concave edge.

#### DO

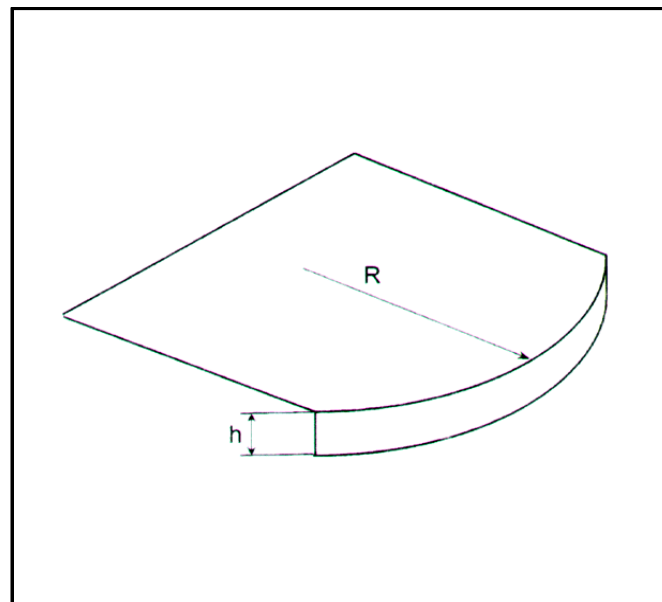
- Shrink flanges are prone to wrinkling. Critical strain is limited to:

$$\varepsilon_{cr} = \left[ \frac{1}{3} \left( \frac{t}{R} \sin \alpha \right)^2 \frac{E}{1-\nu^2} \frac{1}{K} \right]^{\frac{1}{n+1}}$$

R is radius of panel,  $\alpha$  flange angle (usually 90 degrees), K and n stem from Hollomon's law. E is the elastic modulus and  $\nu$  Poisson's ratio.

#### DON'T

- Subsequent hemming to 180 degrees will set  $\sin \alpha$  to 2 in the formula on the left



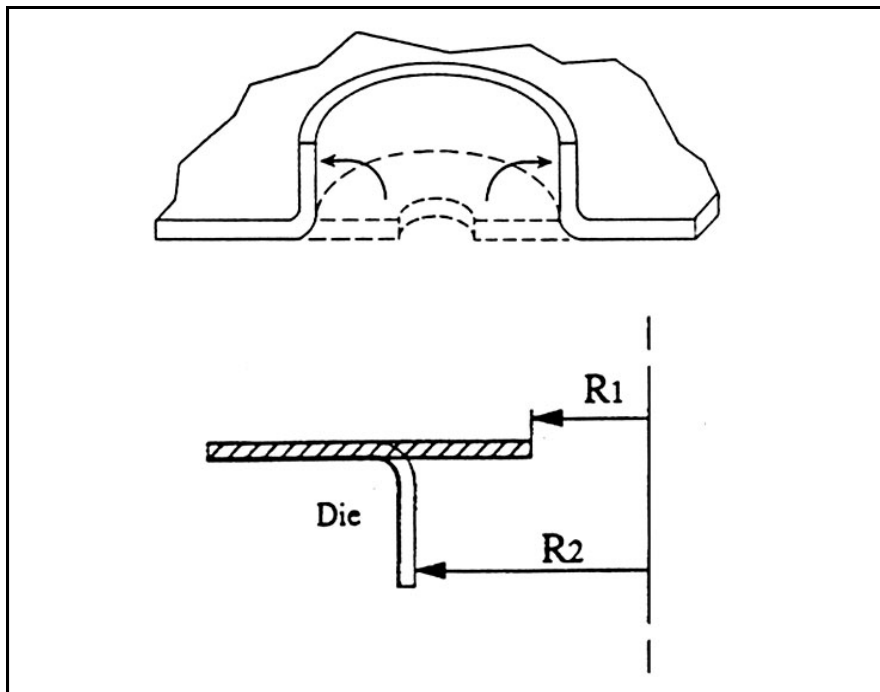
Schematic shrink flange

### Hole expansion

Hole expansion is comparable to stretch flanging. However, it can also be achieved using a conical punch (JFS-T1001-1996).

#### DO

- ⤴ For high hole expansion ratios in aluminium use a conical punch comparable to the one used in the JFS norm.
- ⤴ Calculate maximum strain at edge of the hole from  $\varepsilon = \ln(R_2/R_1)$ . Where  $R_1$  is inner radius of hole prior to flanging;  $R_2$  is radius after flanging.



### **Embossing**

Embossments are brought in local features pressed in at the end of the forming process by pure stretching.

#### **DO**

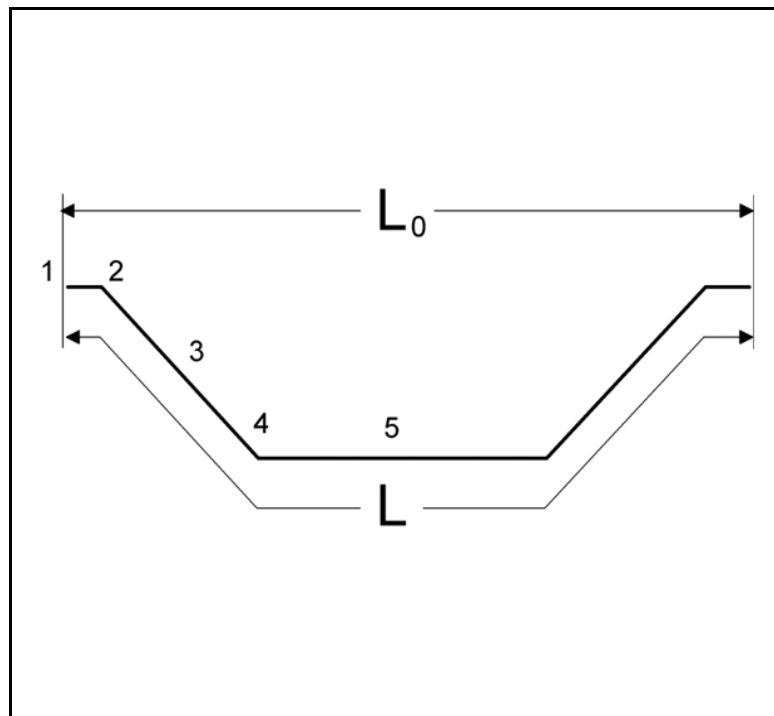
- ⤴ Estimate strain from surface change between flat sheet and embossment. Make sure this strain is well below FLD.

**Feature lines**

Feature lines, or plane strain embossments are stretched in only one direction.

**DO**

- ⤴ Assuming no movement outside the feature: calculate line length along feature  $L$  and line length without feature present  $L_0$ .
- ⤴ Estimate strain from these lengths as  $\epsilon = \ln(L/L_0)$ . Make sure this strain is less than  $1/2 \text{ FLD}_0$ .



**Example length calculation over feature line**

## Roll forming

Roll forming is the continuous forming of sections through subsequent roll sets.

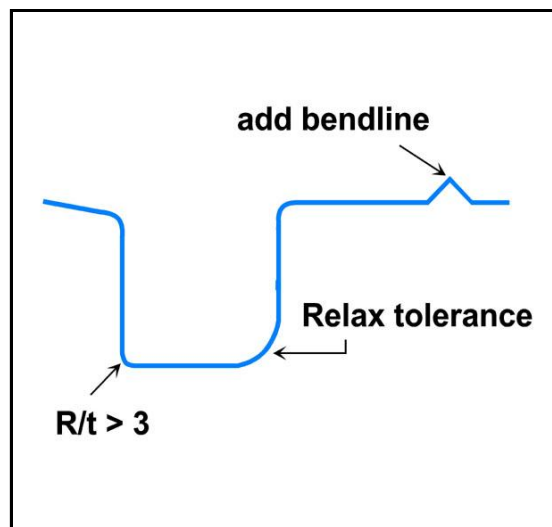
Aluminium profiles are often extruded but sheet alloys can be stronger.

### DO

- ⤴ Obey minimum bending radii as found in suppliers data sheets. In general  $R/t > 3$  is considered to be safe
- ⤴ Set relaxed tolerances on large radii in the cross section, because they are difficult to maintain
- ⤴ Stiffen wide sections by adding local bendlines

### DON'T

- ⤴ Use extruded profiles where strength is needed
- ⤴ Try forming short legs with roll forming
- ⤴ Use narrow high rolls if it can be avoided, to prevent breaking



Schematic of roll formed profile

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### Handling

Handling refers to all secondary processes in transport of material in between forming steps.

#### DO

- ⤴ Take care in handling aluminium. It easily scratches.
- ⤴ Preferably use a dry-film lubricant to avoid scratches instead of a paper interlayer.

#### DON'T

- ⤴ Simply use steel handling installations available.



### Springback

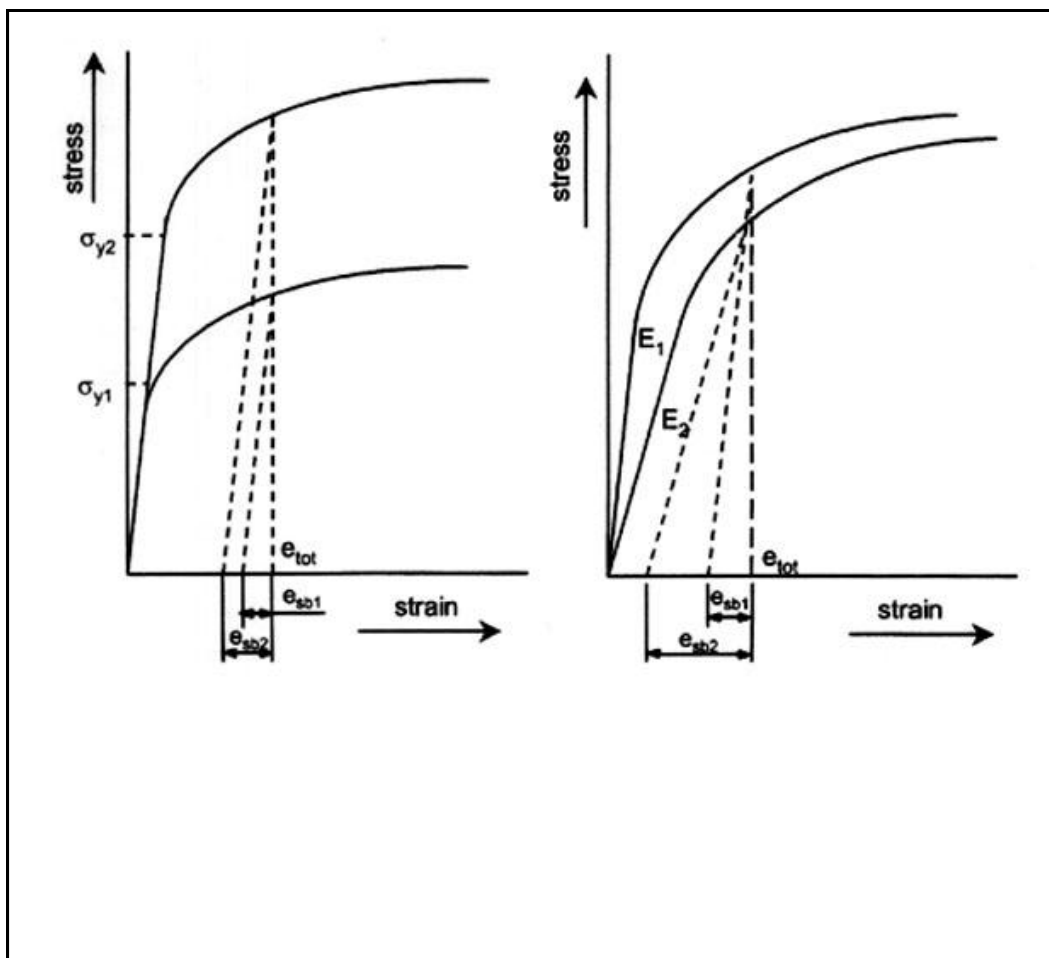
Springback refers to the phenomenon of shape change after forming due to residual stresses.

#### DO

- ⤴ Use drawbeads / lockbeads to induce 1-2% strain in the whole of the panel.
- ⤴ Induce some stretching to alleviate springback due to bending stresses.

#### DON'T

- ⤴ Overlubricate, this will reduce friction so less strain can be induced and springback will be worse.



**Springback scales linearly with stress level and elastic modulus  
However, larger thickness reduces bending springback**

### 3.2.3 Tooling / tool surface

#### Draw beads

Draw beads are used to restrict the material flow into a die cavity. By restricting the flow, more stretching strain can be induced in the centre of panel, and a tighter appearance is achieved.

#### DO

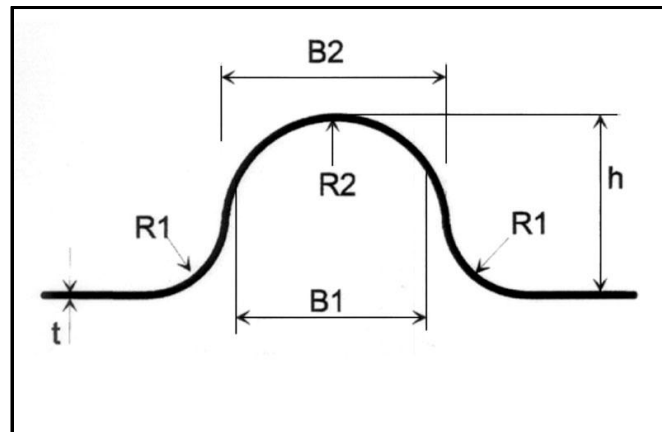
Use the following general design rules:

Typical radii used in draw beads for aluminium body panels:

$R1 = 3$  to  $6t$ ;  $R2 = 6t$ ;  $B1 = 12t$ ;  $B2 = 15t$ ;  $h = 6$  to  $10t$ .

With:  $t$  = sheet thickness

The centre of the draw bead is traditionally placed about 25 times the sheet thickness from the side of the draw die (punch opening line). The radius at this side should be 5 to 10 times the sheet thickness



### Lock beads

Lock beads are used to completely stop the material from flowing into the die cavity. In this way all deformation is stretching deformation. This ensures ensuring a panel to be as tight as possible.

### DO

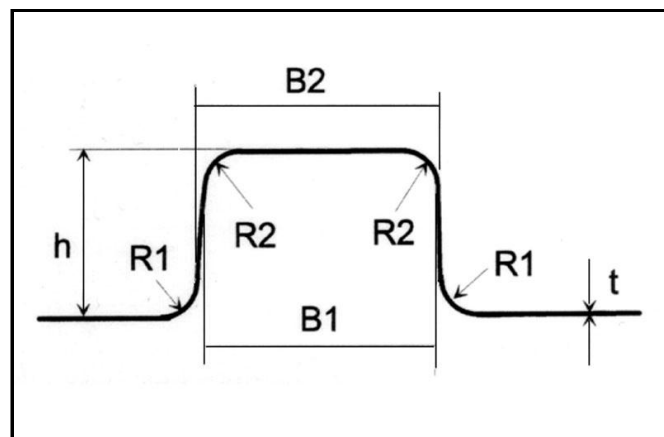
Use following general design rules:

Typical radii used in lock beads for aluminium body panels:

$R1 = 3t$ ;  $R2 = 2t$ ;  $B1 = 12t$ ;  $B2 = 15t$ ;  $h = 6t$ .

With:  $t$  = sheet thickness

The centre of the lock bead should be placed about 24 times sheet thickness from the side of the draw die (punch opening line). The radius at this side should be at least 9 times sheet thickness.



### Radii

Die and punch radii should generally be chosen a bit larger when compared with radii for steel sheet of the same thickness.

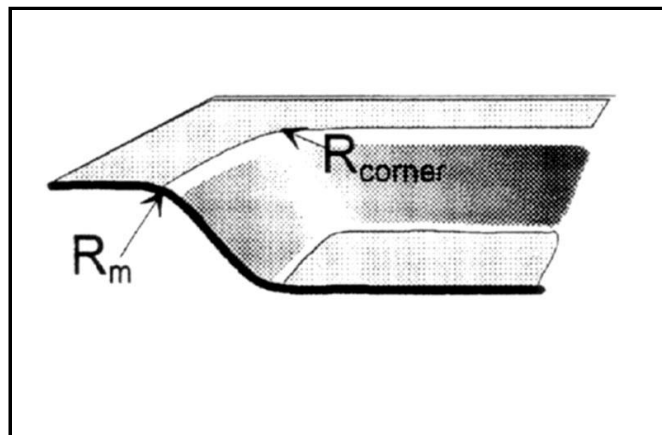
### DO

Use following general design rules:

$R > 10$  times sheet thickness for low ribs ( $h < 20$  mm)

$R > 15$  times sheet thickness for high ribs ( $20 < h < 30$  mm)

$R_{\text{corner}} > 20$  times sheet thickness



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### Tool material & coating

Choice of tool material is wide, coating is most important for performance.

#### DO

- ⤴ Preferably use cast steel as tool material
- ⤴ Consider using a coating on the tooling: Japan & North America commonly use chrome plating. Alternatively nitriding, or titanium nitride, vanadium nitride or titanium carbide may be applied. Also consider DLC coatings as an alternative.

#### DON'T

- ⤴ simply use flame hardened cast iron. Cast iron has a porous surface which will cause marks on the sheets when drawn.

Overview tool material and coatings				
TOOL BASE MATERIAL		SURFACE LAYER		REMARKS
	examples	Reactive coatings	Deposited coatings	
<b>CAST IRON</b>	GG25 (Japan) GGG60 GGG70 (Europe)	Nitriding, Nitrocarburizing, Chromating, Boriding	Hard chromium plating*	commonly used, not suitable for ceramic PVD/CVD coatings because of soft and porous structure.
<b>CAST STEEL</b>	Meehanite, GS 42CrMo4, SAE J435/0050A	Nitriding, Nitrocarburizing, Chromating, Boriding	Hard chromium plating*	commonly used, not suitable for ceramic PVD/CVD coatings because of soft and porous structure.
<b>TOOL STEEL</b>	DIN 1.2379, ARNE steel, D2 alloy steel	Nitriding, Nitrocarburizing, Chromating, Boriding	Hard chromium plating*, CrN (PVD), CrC (CVD), Ti(C,N) (CVD/PVD), DLC (PACVD)**	more expensive, usually used for inserts and draw beads

\* Coating can be repaired locally in the press shop.  
\*\* Promising coating for aluminium deep drawing with reduced amounts of lubricants

### 3.2.4 Tribology

#### Issue of the tool / sheet interface

See also:

- ▲ AAM – Manufacturing – 4 Surface finishing > Pre-conditioning of Al-forms > Sheet / strip

Tribology is concerned with the behaviour of the tool / sheet interface. It includes friction, lubrication and wear topics of the sheet / tool interface.

Tribological aspects (can) have a major influence on the forming characteristics of a part.

Information on important tribological factors and phenomena can be found under the following topics:

- ▲ Friction
- ▲ Galling
- ▲ Lubrication
- ▲ Surface roughness

#### DO

- ▲ Use lubrication, suitable for processing aluminium.
- ▲ Consider using a dry-film lubricant.
- ▲ Use optimised surface roughness texture, eg. EDT.
- ▲ Take into account that Aluminium generally shows lower friction than steel.
- ▲ Take into account all sheet-lubricant- tool-process parameters when analysing the frictional behaviour of the sheet/tool interface.

#### DON'T

- ▲ Use the same tooling used for steel panels regardless. These are very likely to be unsuitable for friction, wear and due to more general formability issues. Dedicated tooling material and/or geometry is usually required.

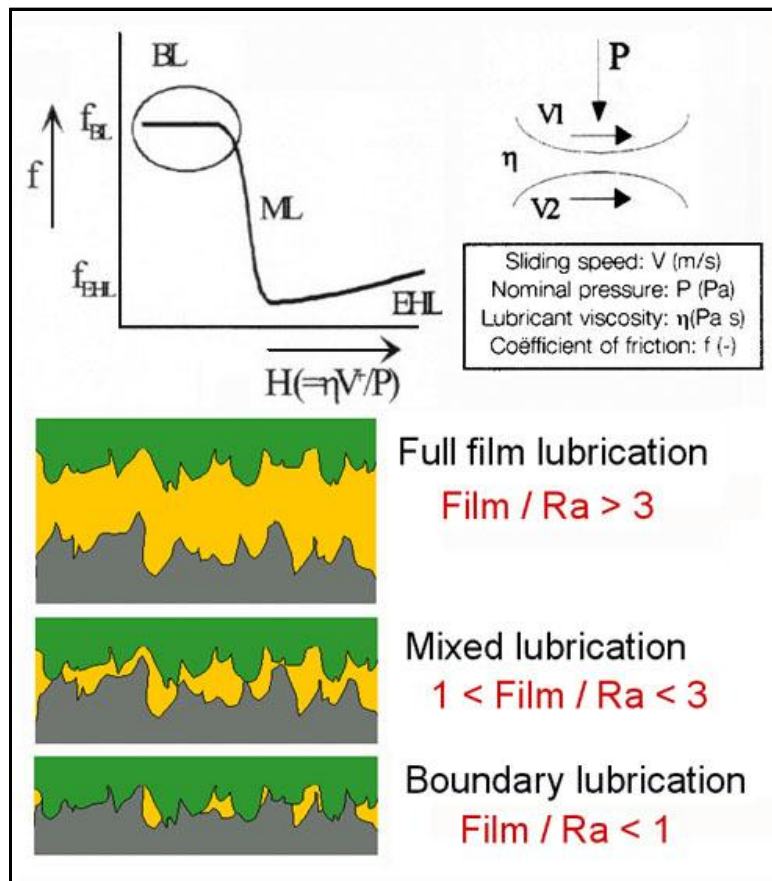
**Friction**

The friction and wear behaviour is clearly a **system** characteristic. **The** friction and **the** wear of an aluminium sheet material do **not** exist.

Friction under sheet metal forming conditions is mildly dependent on contact pressure and sliding speed. However, **all** properties of sheet material and the tool (mech. properties, coatings, roughness, geometry) and also lubricant properties and operational (process) conditions (e.g. temp.) should be taken into account.

Different kinds of surface textures that influence the friction (MF, EDT) can be applied to aluminium.

The friction coefficient is mainly determined by the lubrication regime. In case all the normal load is carried by the lubricant film (i.e. full film lubrication) then friction is relatively low (EHL = elasto-hydrodynamic lubrication). However, in case the entire load is carried by direct metal-to-metal contact of tool and sheet metal (i.e. boundary lubrication, BL) then friction is much higher. Commonly, the lubrication regime during deep drawing of aluminium is somewhere between full film and boundary lubrication (i.e. mixed lubrication, ML).



**Stribeck diagram, illustrated with different ratios of film thickness to roughness  $Ra$**

**Source: Corus**

### Galling

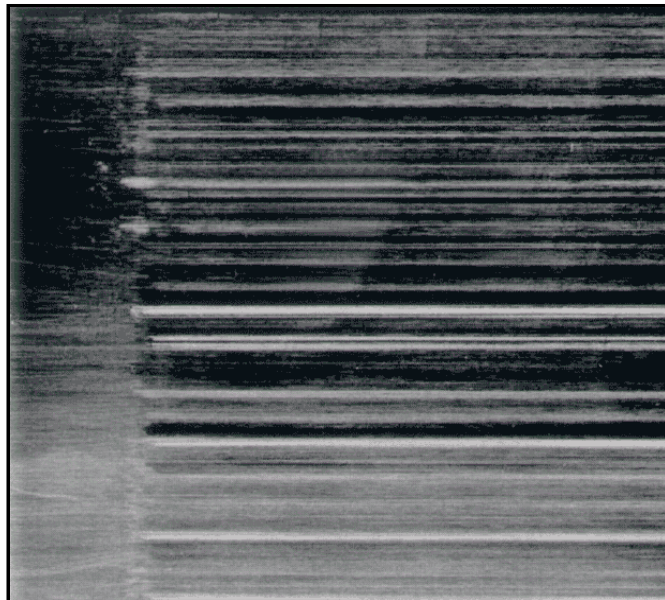
Galling is the type of wear in which transfer of material from one contact surface to the other takes place. In Sheet Metal Forming: from sheet to tool. Ultimately this will cause severe damage to the sheet surface.

Severe scratches in the direction of sliding arise from the ploughing of tiny sheet material particles, sticking to the tool surface.

Galling also implies more frequent tool inspection and thus production interruption.

Galling can be reduced by avoiding direct metal-to-metal contact between the sheet and the tool. This can be achieved by pre-coating aluminium or alternatively by applying sheet with a certain roughness, which is capable of generating micro-pockets containing lubricant. These micro reservoirs may act as a source of extra lubrication in the process of severe asperity flattening. This favours certain surface textures like EDT above MF.

Avoid sharp edges and radii (i.e. high pressures), apply tool coatings. Polish the surface.



**Typical scratch pattern on sheet as a result of galling**

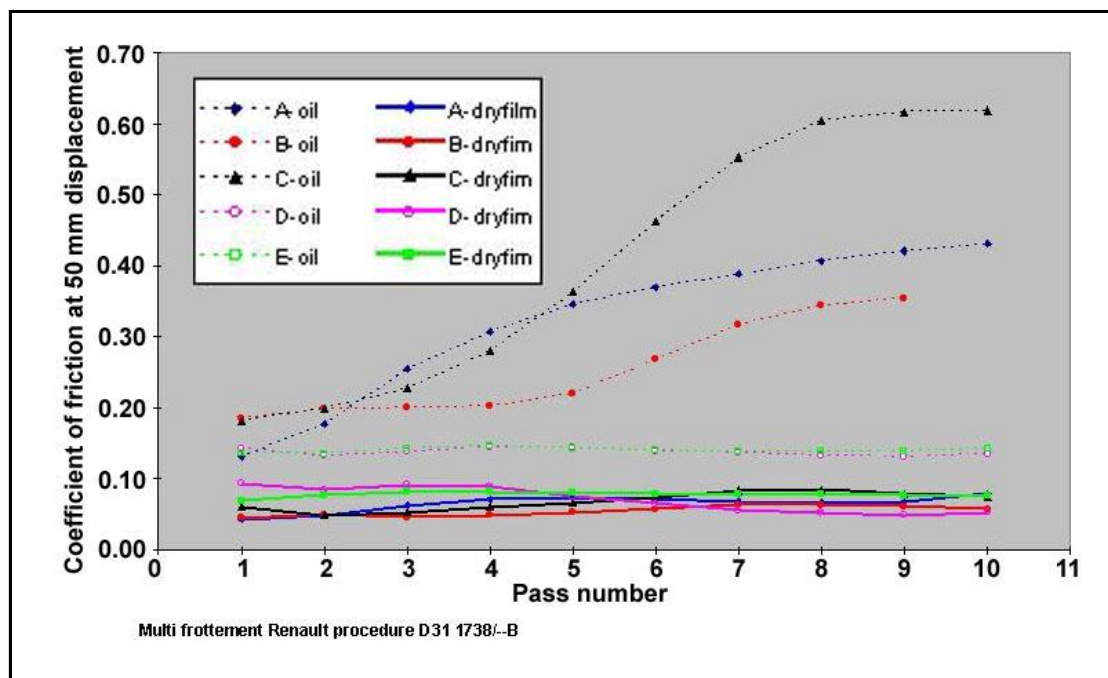


**Lubrication**

Some form of lubrication is usually needed to reduce friction and avoid galling. This can be liquid based, usually mineral oil based. Alternatively, dry-lubricants are gaining popularity.

Severe flattening of the asperities under friction causes this different behaviour of aluminium compared to uncoated steel. Due to this flattening, a small amount of lubricant is already sufficient to induce mixed lubrication. As a result of all this, in deep draw operations the friction in the blank holder can become extremely low if sufficient lubricant is applied. Pure boundary lubrication is hard to obtain.

Dry lubricants show a more stable frictional behaviour than mineral fluids. Regardless of conditions these systems retain the same friction coefficient (s. fig. below). This is usually good for process stability. The frictional behaviour is hardly influenced by minor process variations.



**Dryfilm lubricant vs 'oil' on different materials in the Renault Multifrottement test**

Fig. (above): Multi-friction-test, number of passes between flat and cylindrical tool. Steep increase of Coeff. of Friction for mineral fluids demonstrates the effect of galling.

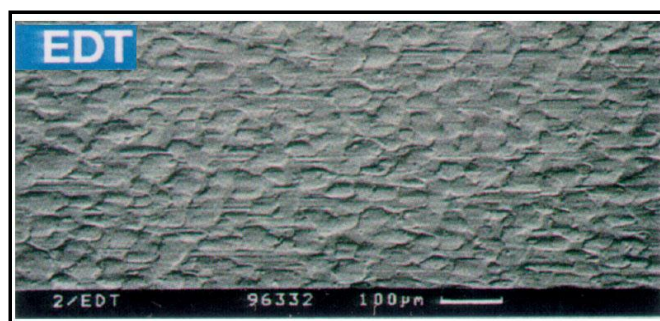
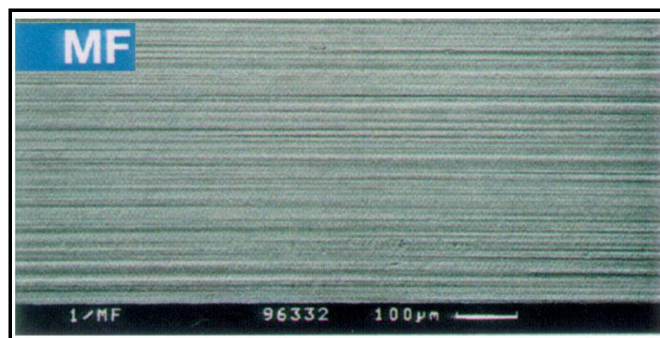
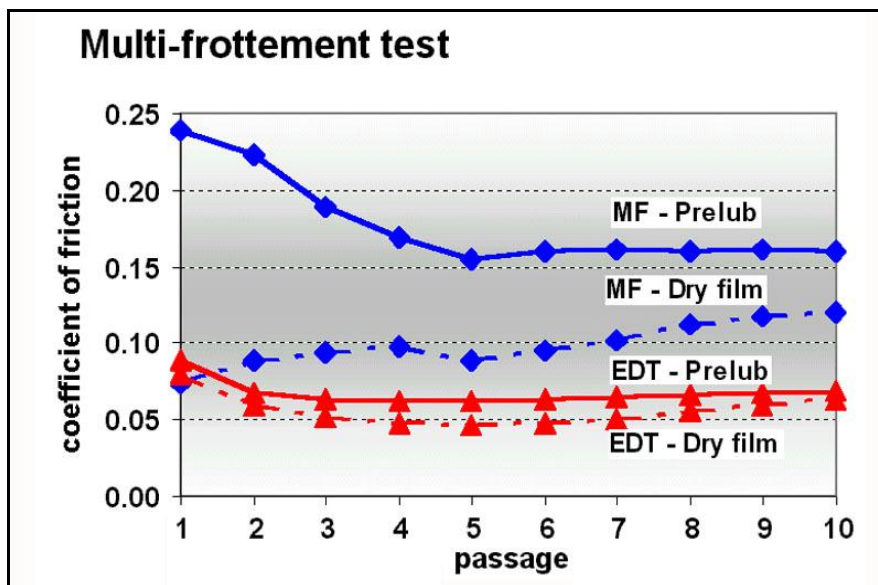
**Surface roughness**

Roughness and waviness have an impact on paint appearance of sheet material.

Apart from that, it also has an influence on the frictional and wear behaviour during forming.

The difference in frictional behaviour of EDT and MF is due to the difference in roughness level (EDT:  $R_a \approx 1\mu\text{m}$ , MF:  $R_a \approx 0.4\mu\text{m}$ ), the directionality of MF and the difference in closed void area fraction / volume (3D roughness).

One would expect a lower friction for lower  $R_a$  values. However, the fig. below demonstrates that this is not true. The randomness and the higher content of closed voids of EDT compared to MF are of major influence on the level of friction. Therefore, 3D roughness cannot be neglected in understanding tribological behaviour.



### 3.2.5 Forming practice

#### Tips & tricks

Forming practice is concerned with the practical tips & tricks to get the forming process to deliver the panels and deliver them with the desired quality.

#### DO

- ⤴ All practical forming principles for steel equally apply to aluminium.
- ⤴ As aluminium is generally less formable than the traditional low strength steels more care in process design is needed.
- ⤴ The emphasis on some questions may be different in aluminium than in steel. For instance springback will be a larger problem in aluminium. On the other hand press tonnage will generally be less.

#### DON'T

- ⤴ use an existing tool for drawing steel panels to evaluate the (possible) performance of aluminium.

## Minimum strain

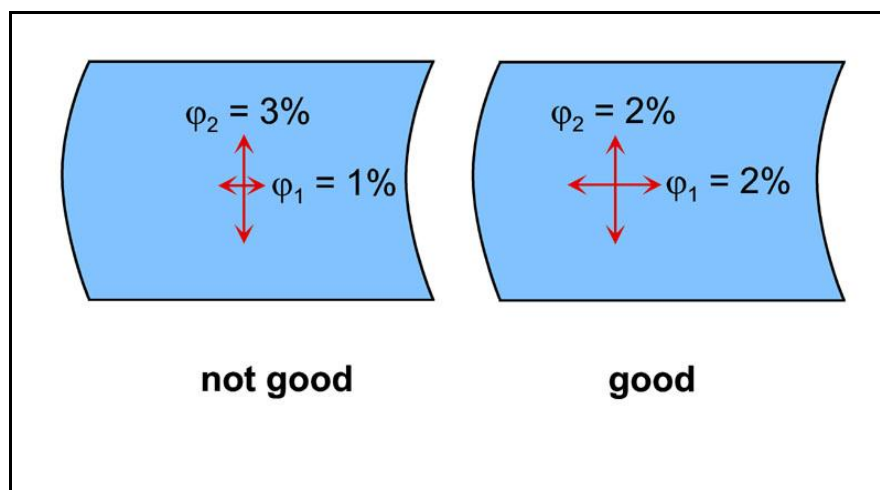
For a tight appearance, especially important in outer panels, a minimum equivalent strain of 2% is recommended.

### DO

- ⤴ use drawbeads or lockbeads to achieve minimum required strain. Controlling strain by beads is more robust than by blank holder force (BHF).
- ⤴ Static dent resistance also increases with a strain and more than 2% may be favourable from this point of view.
- ⤴ Edges are easily stretched. Extra lubrication on the punch may put more strain in the middle of the panel as well.

### DON'T

- ⤴ try inducing the minimum strain by stretching in one direction. Equibiaxial stretching is needed for best results.



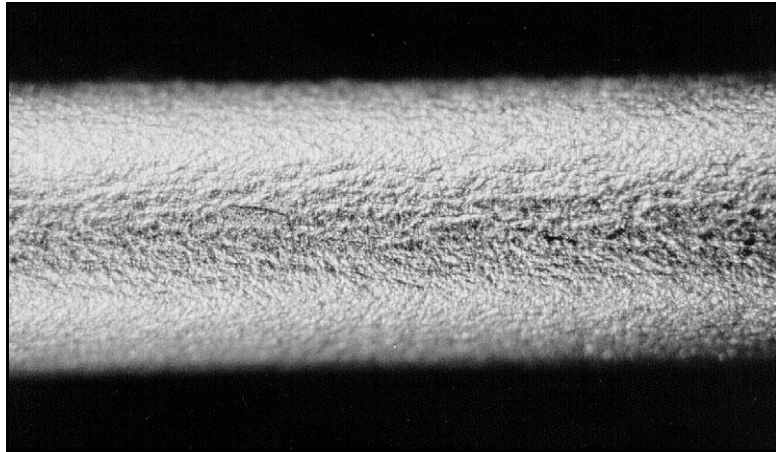
Schematic strain distribution

## Flanging

Flanging induces high strain levels in the material. If flange areas had been deformed significantly in the previous operations, tearing problems may occur.

### DO

- ⤴ Avoid excessive straining on points where later on flanges will be formed.



**Surface of a flat hem of sheet alloy 6016-T4**

**Source: Corus Group**

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### Storage

Storage of material also influences formability.

#### DO

- ⤴ In winter: bring material in a room temperature environment appr. 24 hrs before pressing. Low temperatures decrease ductility markedly.
- ⤴ Scratches occurring during transport of blank on e.g. a pallet can be avoided by specifying dry lube's. These provide much higher resistance to scratching than oil does.

#### DON'T

- ⤴ carelessly transport aluminium blanks without any inter sheet protection. They will easily scratch. A paper sheet, some oil or (preferably) dry lube is much better.

### Developed blanks

In applications which are critical due to limited formability for aluminium (when compared to low strength steel) developed blanks (also called form blanks) are recommended.

#### DO

- ⤴ Use a developed blank when splitting problems are experienced.
- ⤴ Make sure the cutting edges of the tool used to cut the developed blank are sharp and clean. Otherwise build up or galling eventually produces slivers which will scratch and cause pimples in the drawing operations.

#### DON'T

- ⤴ save on washing & re-oiling after blanking. Even with sharp knives the old contamination will get on the sheet leading to pimple problems in drawing.

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### Extra lubrication

Use of extra lubrication in the process will add cost but makes the process more robust.

#### DO

- ⤴ Add extra / controlled amount of lubricant if much variation in process performance is seen or expected. This may be due to redistribution of oil during transport.
- ⤴ Oiling both sides of the blank reduces the risk of fretting during transport.

#### DON'T

- ⤴ use manual application or redistribution of oil using a cloth. This may contaminate sheet surface and cause pimples in drawing.



### Strain uniformity

Strain uniformity enhances predictability and dimensional accuracy.

#### DO

- ⤴ Aim for as uniform a strain as possible. Strain distribution can be measured by optical measurements of grid patterns. Commercially available systems include circle grid, ASAME and PHAST™.
- ⤴ This will increase dimensional quality, as well as the predictability of springback, though not necessarily the amount of springback.

#### DON'T

- ⤴ try to achieve low springback at the cost of strain uniformity. Even if springback is lower, its variability is higher and control is more difficult.

## 3.3 Bending

### 3.3.1 Methods, materials and tempers

Links:

- ⤴ AAM – Manufacturing – 3 Forming > Semi-hot forming
- ⤴ AAM – Materials – 2 Alloy constitution > Heat treatment > Retrogression heat treatment
- ⤴ AAM – Manufacturing – 3 Forming > Hydroforming (tubes)

Automotive tubing and extruded profiles are rarely used in as-fabricated straight lengths. To comply with design requirements, various forming techniques are employed. The most frequent forming operation is **bending** - often succeeded by mechanical local reforming, calibration and sometimes **hydroforming**.

Bending of tubes and extruded shapes can be performed with various **methods** suitable for the purpose.

To achieve the required end form and tolerances, attention must be paid to **tooling techniques**, but also to the **shape design** required for optimum forming behaviour. Bending of tubes and shapes is mostly done by **cold forming**. Depending on the formability requirements the material must be supplied in a suitable temper.

For large degrees of cold forming the following **tempers** may be selected from:

- ⤴ Non-heat-treatable alloys (3xxx and 5xxx): soft tempers (O, H111, H112)
- ⤴ Heat-treatable alloys (6xxx, 7xxx): solution annealed, quenched and naturally aged (T4). If in-line process heat treatment facilities are available, the as-quenched (W) temper, RHT or re-solution heat treatment procedures may be used.

While cold forming is usually preferred, forming at moderately high temperatures, sometimes by localised heating, can be used to improve the material's formability.

Note, however, that any thermal treatments during processing change the microstructure and properties. Therefore, care should be exercised to avoid detrimental effects on design properties.

**Post-bending re-shaping** may offer a variety of solutions for part forming and must be considered in the design of the cross-section shape.

### 3.3.2 Combining additional forming during bending of extruded shapes

Bending of tubes is a well established technology and due to their rotational symmetry, tubes can be bent with equal force and spring back around any axis. As regards non-tubular shapes, the situation is different. Therefore, high volume (> 10000 pcs./yr.) production until now, to a large extent, has been bending around one axis - 2D. However, high volume 3D bending of profiles is under development.

Bumper beams (s. figure at right) have for years been 2D bent in high volumes in high speed forming lines. Included in the forming lines are also:

- ⤴ pre-cutting (removing material before bending),
- ⤴ solution heat treatment (applied to 7xxx-series alloys)
- ⤴ punching holes and removal of external webs and flanges, various embossments, and calibration operations,
- ⤴ mounting of fastening elements like steel nuts,
- ⤴ mechanical joining of various brackets.



**Bumper beams**

**Courtesy: Hydro Automotive Structures**

### 3.3.3 Estimating deviations from design due to bending

Bending defects like **sagging** or local **buckling** (wrinkling) of flanges, undesirable **wall-thinning** or **elastic spring back** are estimated by simple design formulas or determined more accurately by use of Finite Element Analysis.

Design formulas for predicting bendability are especially useful for quick and relatively accurate estimates of hollow sections.

An overview of important parameters with respect to bendability of rectangular hollow sections follows below (pure bending):

$$\begin{aligned} \text{Sagging depth} &\propto \frac{b^4 h}{f^2 R^2} \\ \text{Buckling depth} &\propto b \sqrt{\frac{h}{nR}} \\ \text{Spring back curvature} &\propto \frac{\sigma_{0.2}}{EI} f(h, b, t, n) \\ \text{Radius at critical thinning} &= \frac{h}{2n} \\ \text{Ovalisation of circular tubes} &\propto \frac{D^5}{f^2 R^2} \end{aligned}$$

**Design formulas for pure bending**

where:

$b$  = width of section

$h$  = height of section

$t$  = wall-thickness

$R$  = bending radius

$E$  = Young's modulus

$I$  = second moment of inertia

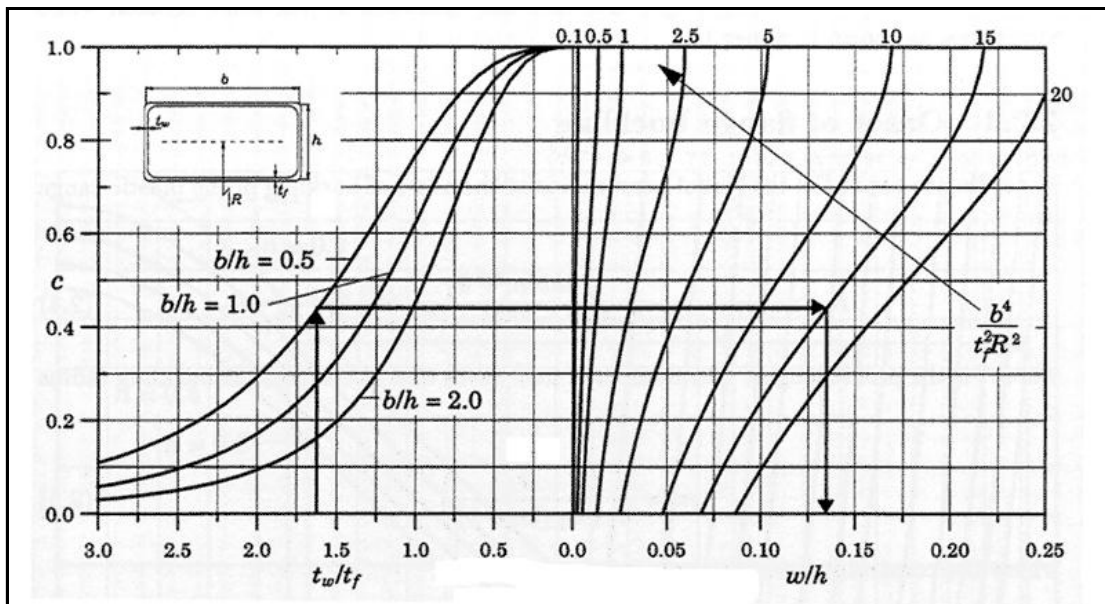
$\sigma_{0.2}$  = yield stress (0.2% offset)

$n$  = hardening coefficient

$D$  = diameter of tube

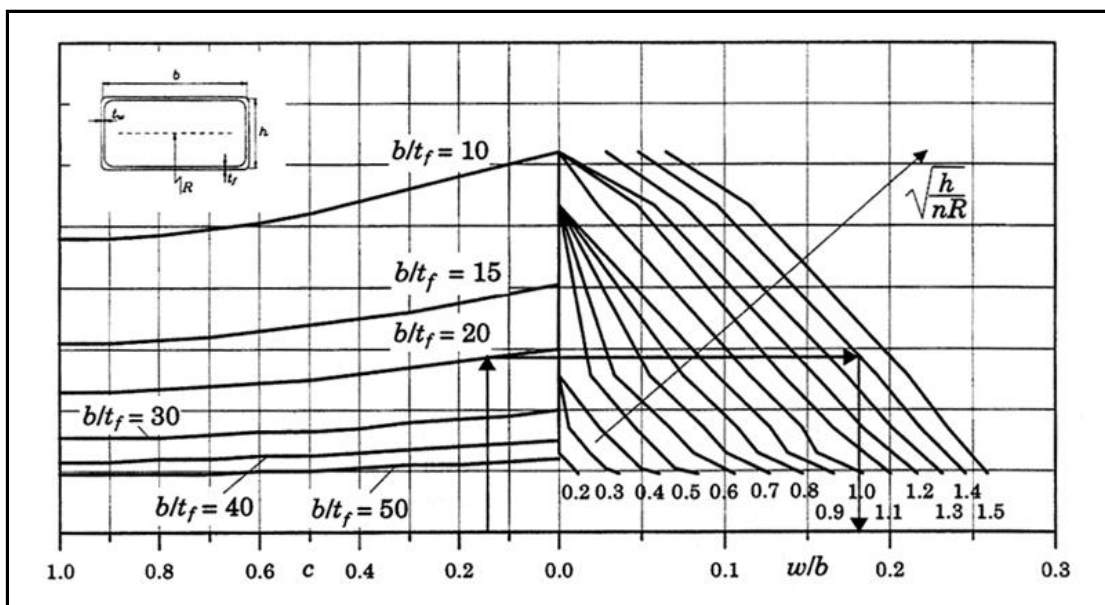
Examples of the design formulas for rough calculation of sagging and buckling depth of a single chambered hollow section are incorporated in the design diagrams shown on next page.

Example of diagram for determining flange sagging of a rectangular hollow section:



Flange sagging deflection  $w$  normalized with height  $h$  of the section

Example of diagram for determining flange buckling of a rectangular hollow section:



Post buckling depth  $w$  normalized with width  $b$

### **Influences on dimensions and tolerances**

The amount of wrinkling and the sagging depth are sensitive to variations in material parameters and dimensions of the extrusion going into the bending process.

A process with fluctuating sagging or wrinkling affects elastic spring back, which in turn affects dimensions of the final product.

The impact of variations from the extrusion process are determined by Finite Element Analysis or estimated by use of design formulas.

The dimensional tolerances set on a location of a point, a line or a surface on the product must reflect possible variations in the bending process.

Tolerance requirements are often ruling the forming process and thus also cost. For instance, simple press forming is, due to die cost, less costly than stretch forming. If the product can be accepted with wrinkling, high degree of sagging, and in general lower tolerances, it can be formed at lower cost. In small series production like frames for niche cars, low cost forming processes are usually used, but more work is required in the joining process to meet frame tolerances.

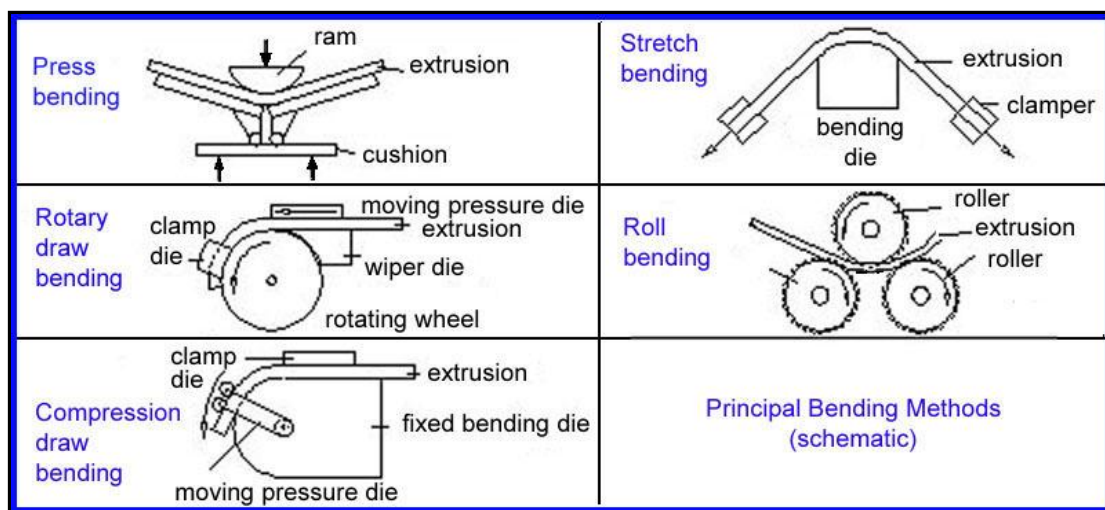
### 3.3.4 Forming methods

#### Bending methods for tubes and extruded shapes

Most common industrial bending methods are:

- ⤴ Press bending
- ⤴ Rotary draw bending
- ⤴ Compression bending
- ⤴ Stretch bending
- ⤴ Rotary stretch bending
- ⤴ Roll bending

The following slides give a brief description and **pros** and **cons**.



Source: Hydro

### Press Brake Bending

#### Description

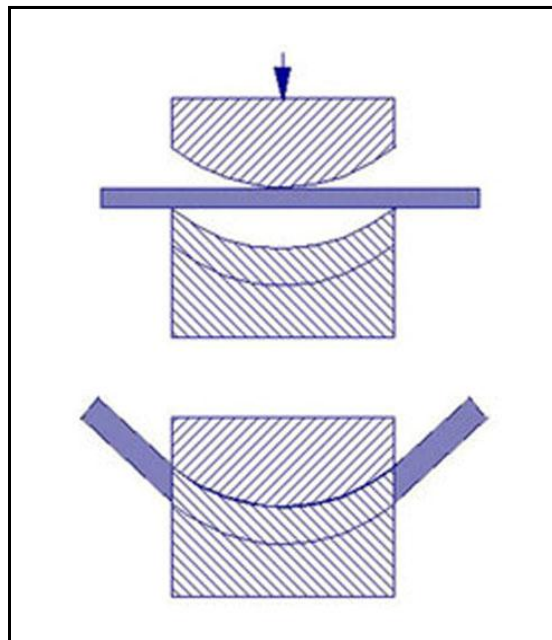
The tooling consist of a two die half (male and female part) that is mounted into a standard hydraulic press. The dies are basically a negative imprint of the part to be produced. The shape is normally supported laterally in the bending area to reduce local distortion. The profile / shape is positioned into the lower die half, and the tooling closes.

#### Pros

Relative low tooling cost. Suitable for high volume production as well as low due to high productivity (low cycle time) and low to medium die cost.

#### Cons

Limited repeatability with respect to spring-back and problems with wrinkling in the compressive side due to limited control of the material flow. Sections to be bent using this methods require strict control with material properties and geometrical cross-sectional shape. Very often it is necessary to use an internal support (i.e. flexible mandrel) to reduce local distortion.



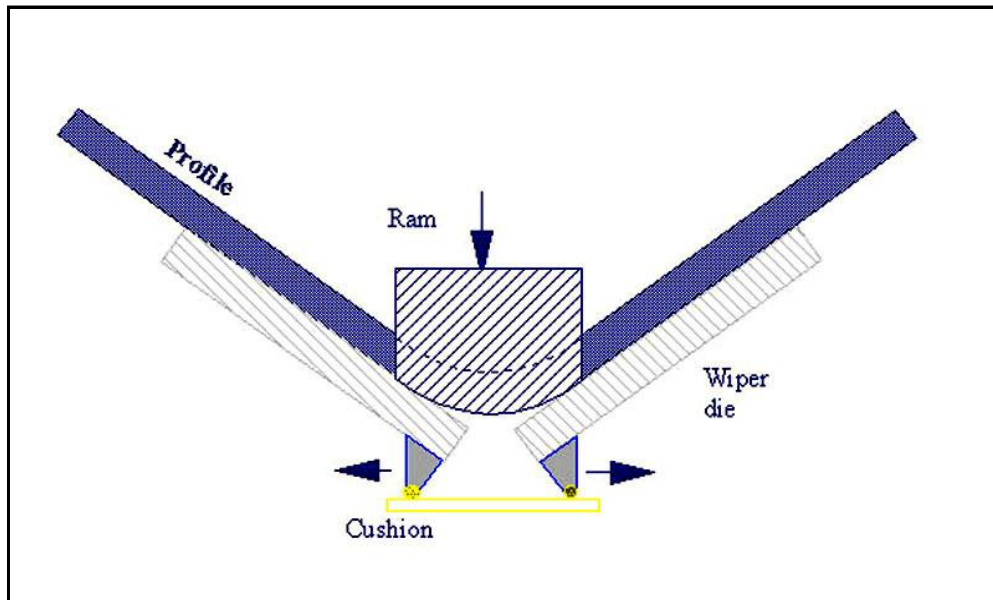
Press brake bending (schematic)



### Ram Press Bending

Another tool concept for the press bending process is where wiper dies are used instead of a stationary lower die.

This concept gives better possibilities for supporting the section during bending and may reduce local distortion of the cross-section.



Source: Hydro

## Rotary Draw Bending

### Description

A clamp die clamps the tube or profile to the rotating form. The rotating form defines by its dimension and rotating angle the bend radius and bend angle respectively.

A pressure die is used to support the tube at the outside and to guide material into the bending area. At the inside of the bend a wiper die is used to prevent tubes from collapsing.

A mandrel can be placed in the tube to support the tube from collapsing and wrinkling. The mandrel can be extended with balls, so called ball mandrel.

The free tube end can be pushed in the bend to reduce wall thinning and sagging. In this case we speak of a positive end boost.

A tool stack may be used when bending different radii at the same tool set-up.

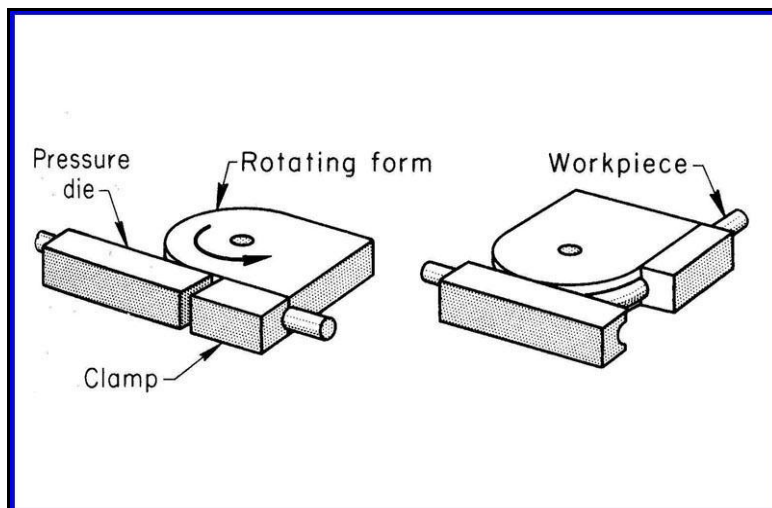
### Pros

Rotary draw bending has been used for relatively small bending radii, down to 1D (the radius of the bend equals the diameter of the tube or profile)

Both 2D, 21/2D and 3D bending is applicable.

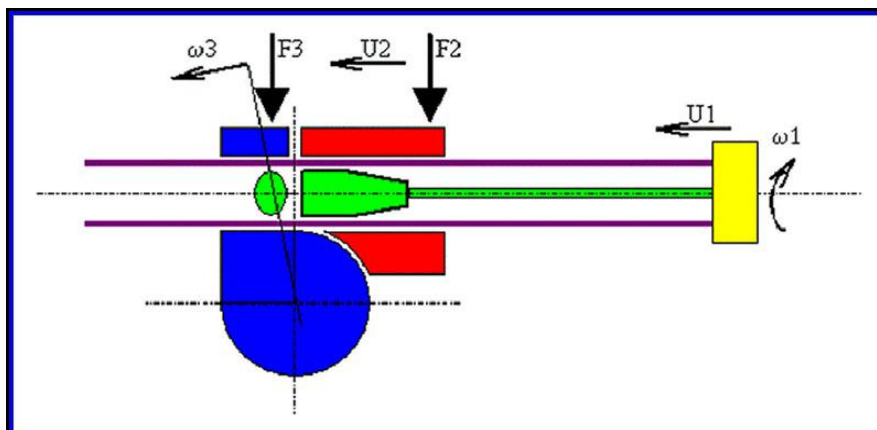
### Cons

Another important parameter is the diameter thickness ratio of the tube ( $D/t$ ). The larger the  $D/t$ -ratio the more difficult the bending process is.



Rotary draw bending

Source: Metals Handbook, vol. 13, ASM, 1988



Source: Corus

## Compression Bending

### Description

The tool set-up for compression bending looks similar to rotary draw bending. For compression bending the clamp has been exchanged by a wiper shoe. The bending die is fixed.

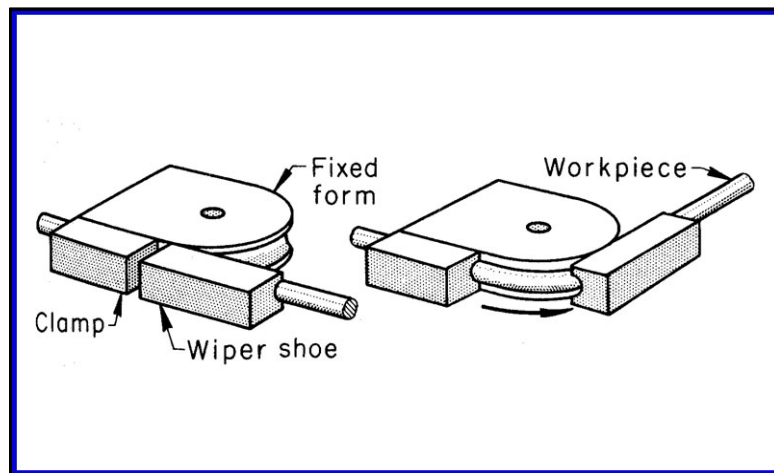
The tube has been bent by a movement of the wiper shoe around the bending die.

### Pros

Bending large radii (large R/D)

### Cons

No sharp bends



Source: Metals Handbook, vol. 13, ASM, 1988

### Ram Stretch Bending

#### Description

The equipment consists of a stationary ram (die) where the section is forced / stretched over the ram normally using force control. Additional stretching after bending may be used to increase repeatability with respect to springback.

#### Pros

Good repeatability with respect to global shape (springback) and no / limited problems with buckling.

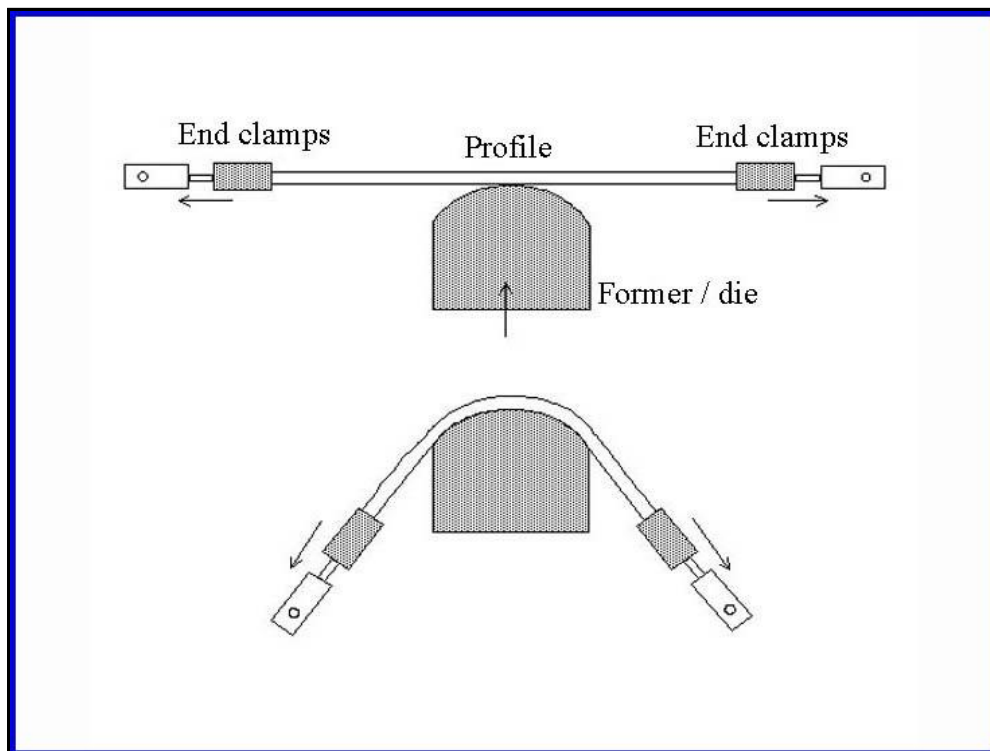
Relatively simple and thus low cost of the tooling.

Possible with 2D or 3D shapes.

#### Cons

Sagging or ovalisation tendency increases if excess stretch is applied. This, however, strongly depends on the cross-sectional geometry. An internal support might be used to reduce sagging.

Relative low productivity.



Source: Hydro

## Rotary Stretch Bending

### Description

In principle this is a rotary draw bending process with a negative end boost. The profile is clamped to the die using a clamping device. The tool is then rotated while restraining the other end of the profile. In case of symmetrical parts or producing left and right hand side parts simultaneously two counter-rotating dies might be used.

This variant of the rotation stretch bending process is commonly used for high volume production of simple/ 2D bending. Highly mechanised lines makes this process run at cycle times down to 12 s/cycle. Local forming/ reforming, punching, machining etc. are done later in the line.

Again, pressure die and mandrel might be used to support the tube.

### Pros

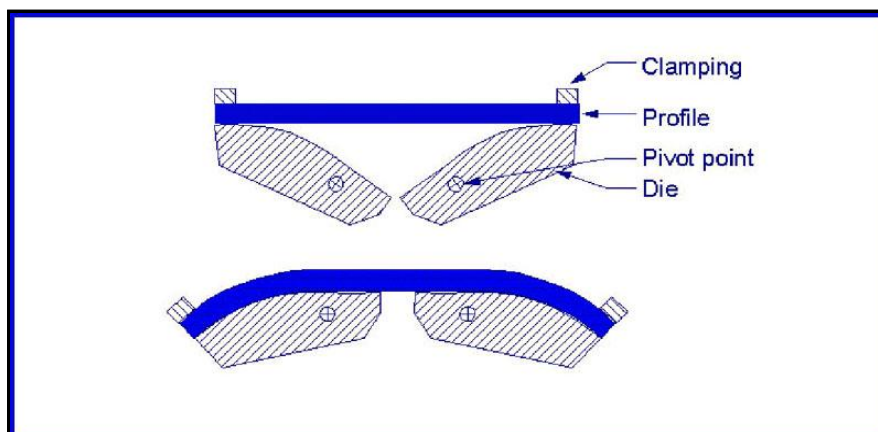
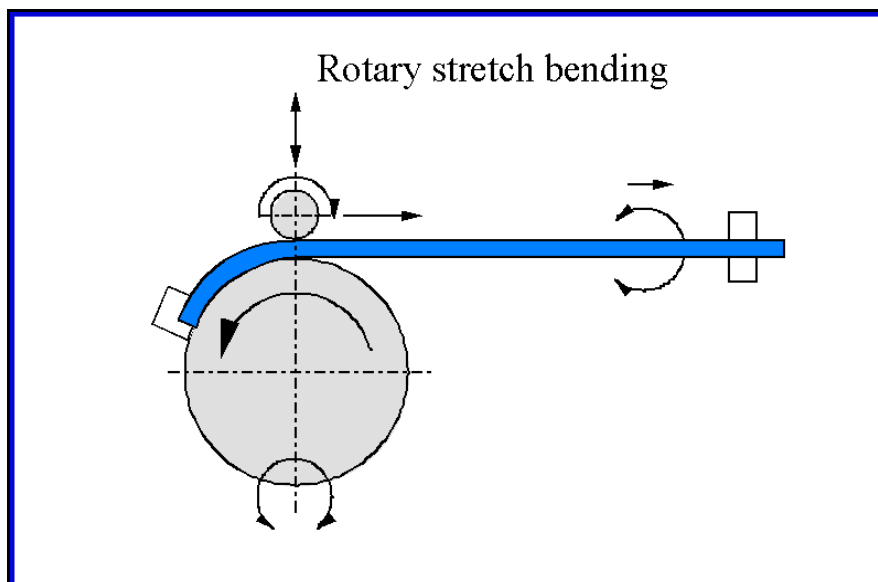
Very good control with overall shape control due to the stretch applied. Limited spring-back.

No or limited tendency of wrinkling.

Counter rotating dies applicable for high volume production using press line technology.

### Cons

Due to the stretch, sagging tendency is increasing.



Source: Hydro

### Oscillating Collet Bending

#### Description

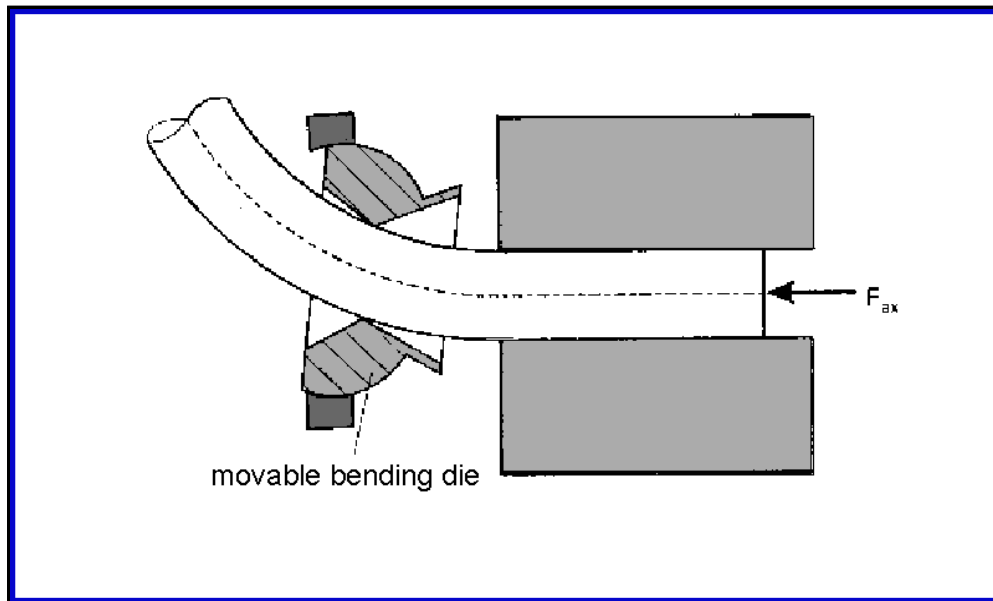
The tube has been pushed through a movable bending die. By shifting the bending die out of the centre of the tube, the tube has been bent.

#### Pros

Because no fixed bending die has been used varying bending radii can be applied. The bending radii can be changed continuously to achieve a 3-dimensional bend.

#### Cons

The bending radii can't be too sharp, minimum bending radii to 3D are possible, 3 times the tube diameter.



Source: Vollertsen et. al.; J. Mat. Proc. Tech.; 87, 1999

### Roll Bending

#### Description

The profile is placed onto two fixed rolls and is bent by an additional vertically movable roll between the other two rolls. By turning the rolls the material is moved in the axial direction and bent continuously. The local curvature can be varied by the indentation depth of the centre roll.

The method is used to make framework for windows and doors to the building sector and more rarely for cars.

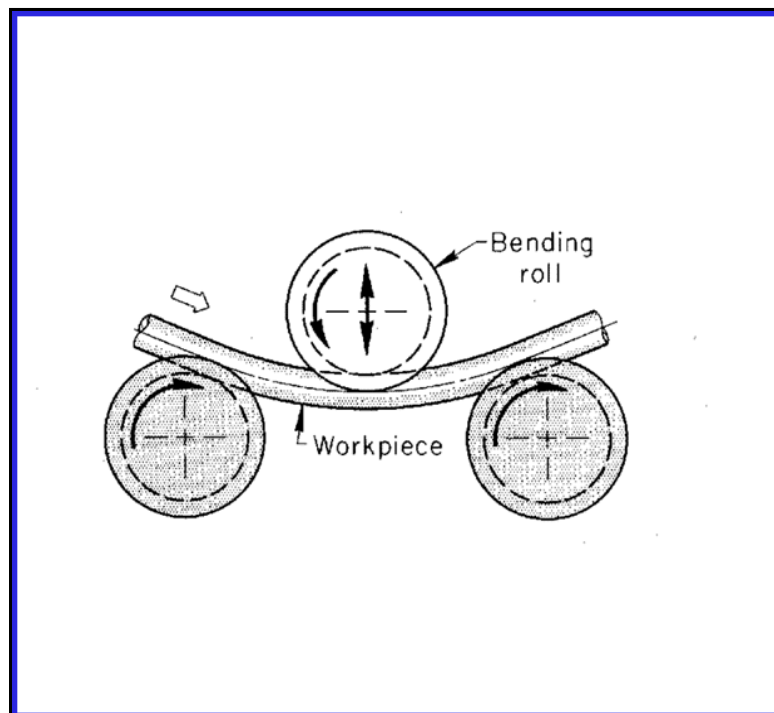
#### Pros

The advantage of four-roll compared with three-roll bending is the enhanced accuracy of the cross section of the bent part.

The accuracy of the cross section will also be improved by using a mandrel inside the profile.

#### Cons

Roll bending is a forming method that is suitable for larger radius where the demands on accuracy are less important.



Courtesy: Metals Handbook, vol. 13, ASM, 1988

### 3.3.5 Tooling mandrels

#### Internal support mandrel

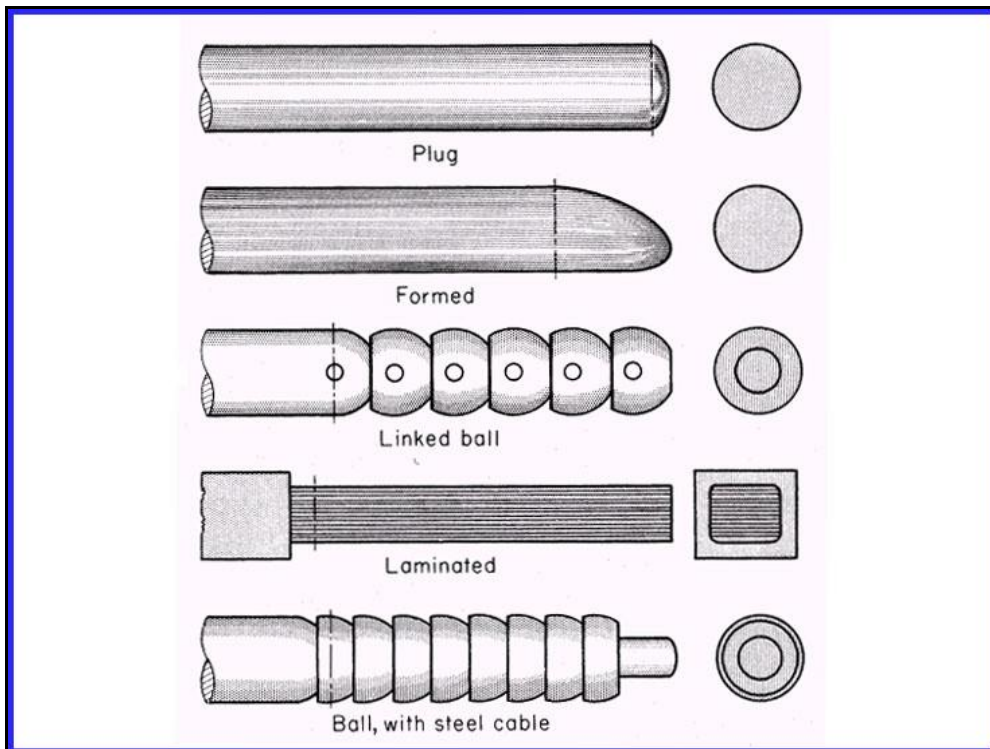
During bending, deformation of the ideal cross section of the extrusion can occur like sagging, bulging or wrinkling.

Basically there are two possibilities to avoid or minimise distortion in cross-section - either by use of a **mandrel** or by use of a **filler material**.

Mandrels are a part of the tool having an outer shape almost identical to the inner shape of the unbent extrusion. The mandrels are inserted into the extrusion before the bending operation and are pulled out when bending is finished.

A linked or laminated mandrel will be bent together with the extrusion compared with a plug that will not.

The elements of the link mandrel are connected by flexible joints. This design avoid very effectively change in cross section. The drawback of linked mandrels may increase production cost due to more handling.



Courtesy: Metals Handbook, vol. 13, 1988

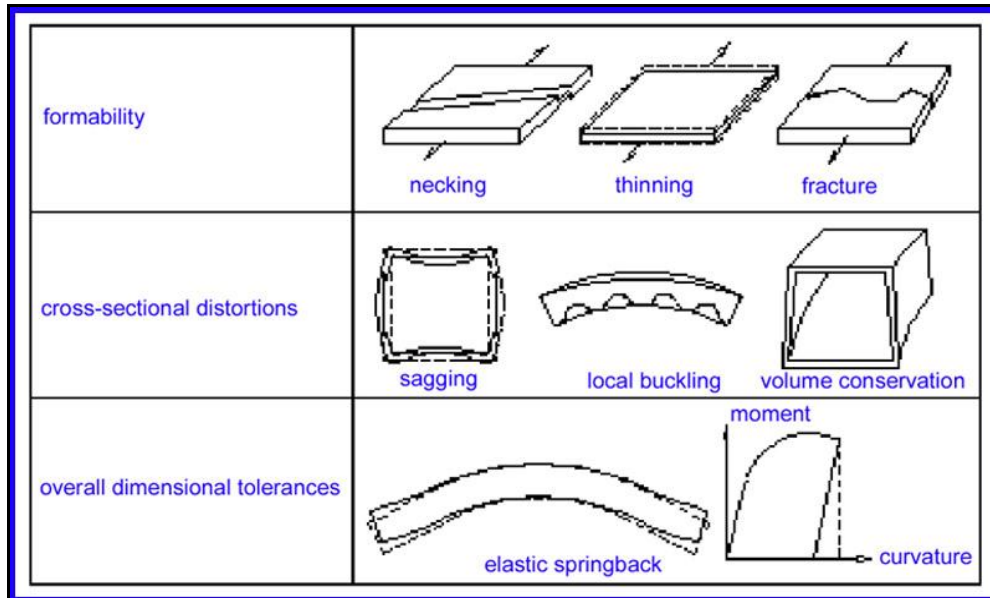


### 3.3.6 Phenomena during bending

#### Bendability

Bendability covers the ability of the tube or profile to be bent into a given shape:

- ⤴ without exceeding the formability of the material
- ⤴ with a minimum of local distortion
- ⤴ within the tolerance requirements specified by the product



Phenomena occurring during bending

Source: Hydro

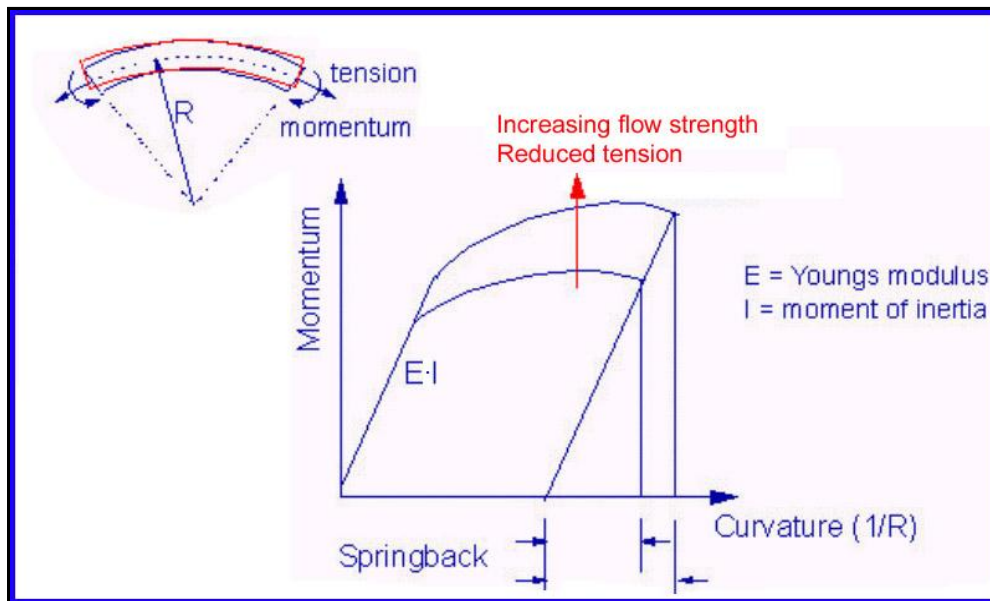
## Elastic Springback

Elastic springback is due to relaxation of elastic stresses imposed by the bending tool when the component is released.

Elastic springback is

- ⤴ reduced by increasing tension
- ⤴ increased by increasing flow strength and hardening of the material
- ⤴ increased by decreasing bending stiffness ( $E \cdot I$ )

Elastic springback can be foreseen and variations depend on variations in geometry and material properties.



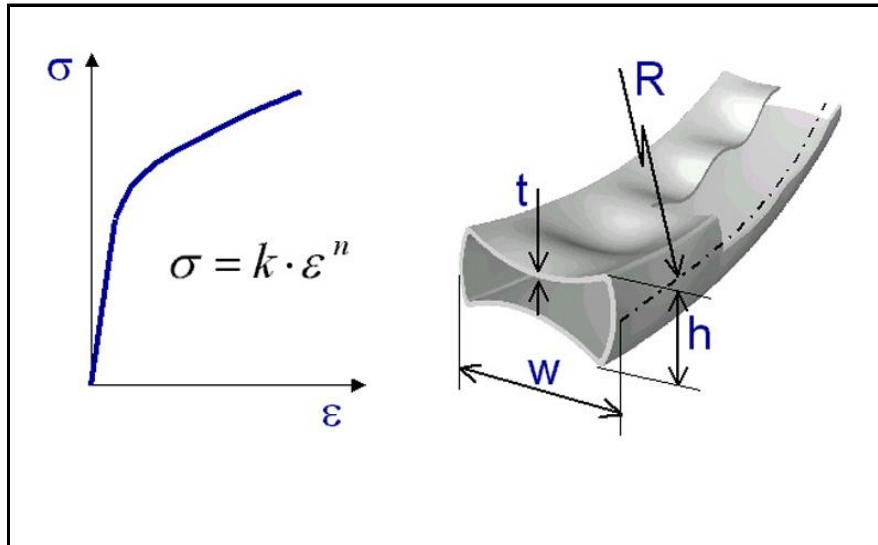
Source: Hydro

## Wrinkling

Wrinkling is buckling of the inner flange during bending. The behaviour reflects the stability of the flange due to compressive forces.

Wrinkling tendency is

- ⤴ reduced by increasing external tension
- ⤴ increased by increasing width of flange and height of web
- ⤴ decreased by increasing bending radius
- ⤴ decreased by increasing strain hardening and initial yield strength.



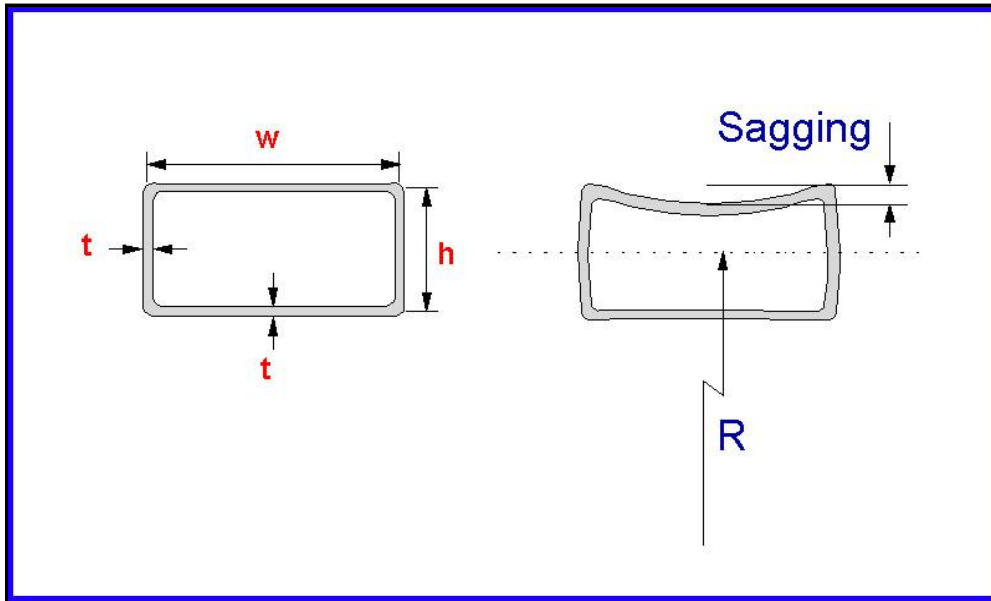
Source: Hydro Aluminium AS

## Sagging

Sagging is movement of the outer flange towards the neutral plane during bending. It is a result of inwardly directed components of the bending stress

Sagging is

- ⤴ reduced by reduced width to thickness ratio of the flange
- ⤴ increased by increasing flange height and decreasing radius
- ⤴ increased by increasing tension (decreasing radius)
- ⤴ altered by changing plastic anisotropy



Source: Hydro

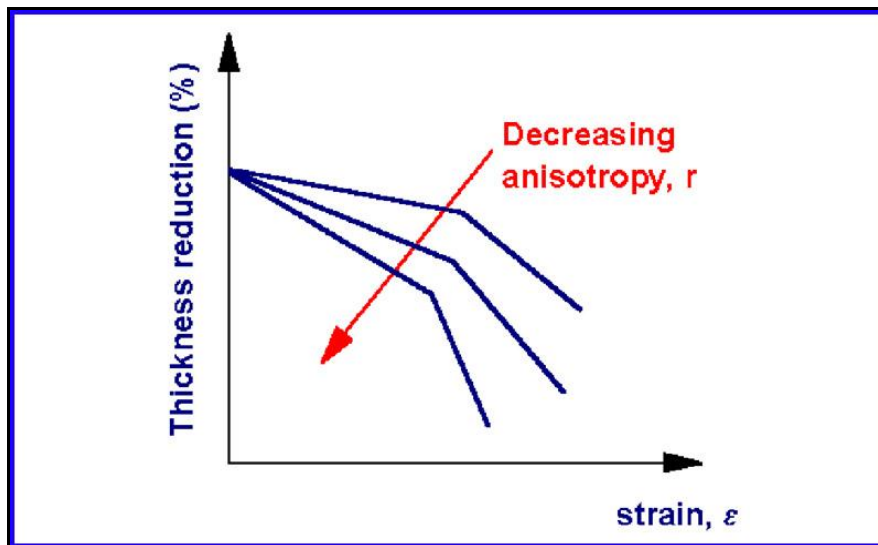
## Thinning

Thinning is reduction of thickness of the material in the tensile flange during bending due to volume conservation.

Necking is localised thinning in the tensile flange. It is a consequence of the materials lack of ability to compensate for increased strain due to thinning by strain hardening.

Thinning and necking tendency is

- ⤴ increased by increasing plastic anisotropy
- ⤴ increased by increasing tension and by restraining sagging by mandrels



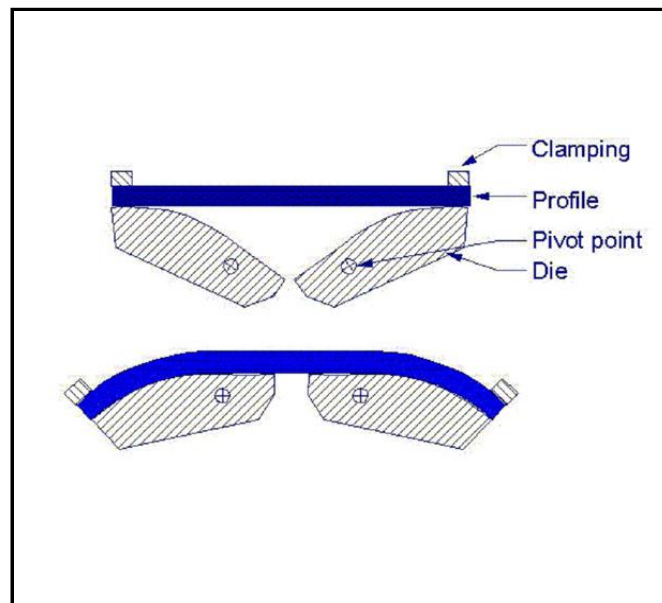
Source: Hydro

### 3.3.7 Forming practice

#### Stretch bending – Manufacturing sequence

See also:

- ⤴ AAM – Manufacturing – 3 Forming > Bending > Forming methods > Press Brake Bending
- ⤴ AAM – Manufacturing – 3 Forming > Bending > Forming methods > Rotary Stretch Bending
- ⤴ AAM – Manufacturing – 3 Forming > Bending > Post-bending reshaping



#### Forming Practice

In the following, some examples of forming practice will be described. The processes mentioned are:

- ⤴ Stretch bending
- ⤴ Press brake bending
- ⤴ Rotary swaging
- ⤴ Beading
- ⤴ End forming operations of tubes

#### Stretch Bending

Stretch bending is the most frequently used forming method in high volume forming. See pros and cons under forming methods. With this method different bend radii can be obtained along the profile. Typical manufacturing sequence is:

- ⤴ Pre-cutting webs and top flange close to ends
- ⤴ Solid solution heat treatment (heating to SS temperature, and quenching which should be done softly to minimise distortion. Applied to 7xxx-alloys and 6082 and other highly alloyed 6xxx-alloys.)
- ⤴ Lubrication

## THE Aluminium Automotive MANUAL

- ⤴ Global bending
- ⤴ Local forming (various embossments)
- ⤴ Material removal (punching of holes and removal of external webs and flanges)
- ⤴ Possible calibration operations
- ⤴ Final end cutting and deburring
- ⤴ Washing
- ⤴ Artificial ageing

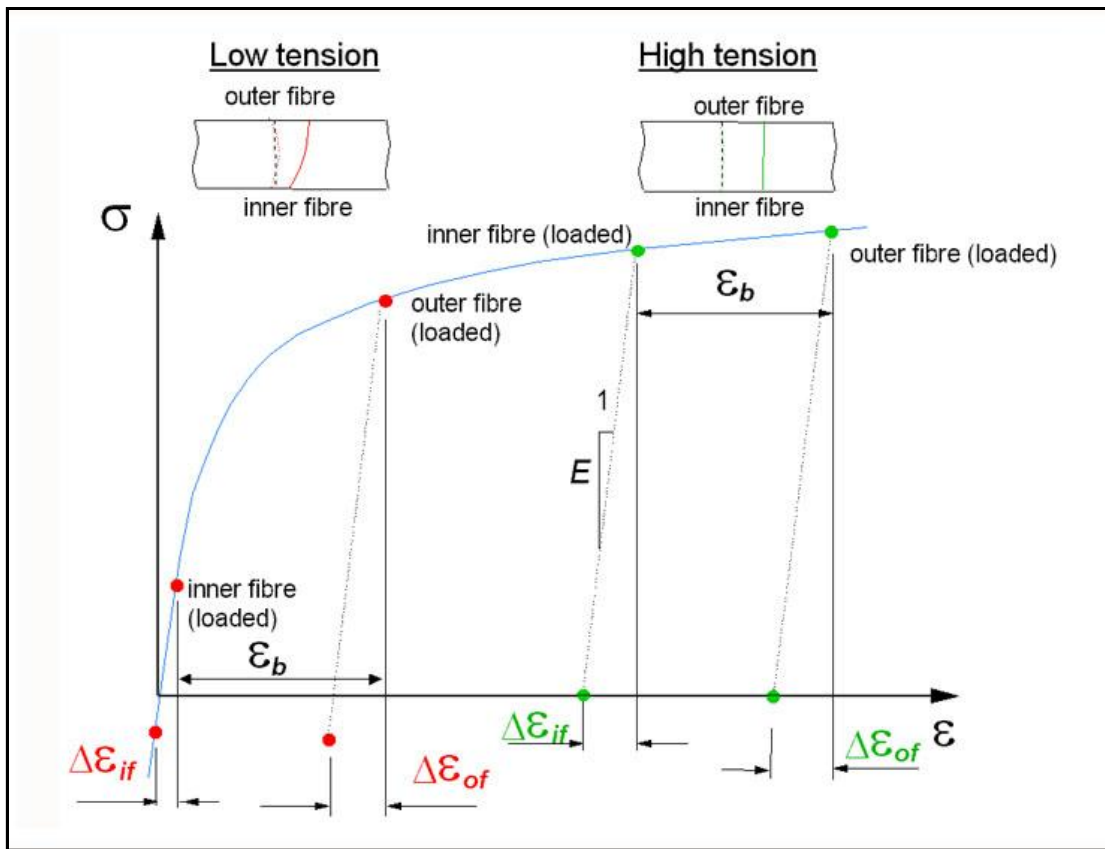
**Stretch Bending – Minimising Spring Back**

See also:

- ▲ AAM – Manufacturing – 3 Forming > Bending > Phenomena during bending > Wrinkling

In stretch bending, the amount of elastic spring back can be controlled by adjusting the degree of superimposed stretching in the process, as illustrated in the figure.

The net bending strain,  $\epsilon_b$  i.e. the difference in straining between the inner and outer fibre of the section, is directly proportional to the curvature ( $1/R$ ). The corresponding difference in stress depends on the slope of the stress-strain curve. In the case of a high level stretching, the stress and strain state is far to the right on the stress-strain curve, thus giving small stress gradients through the section and a correspondingly low degree of spring back.



Differences in spring back under high and low tension



## Stretch bending – Alloy temper and tolerances

See also:

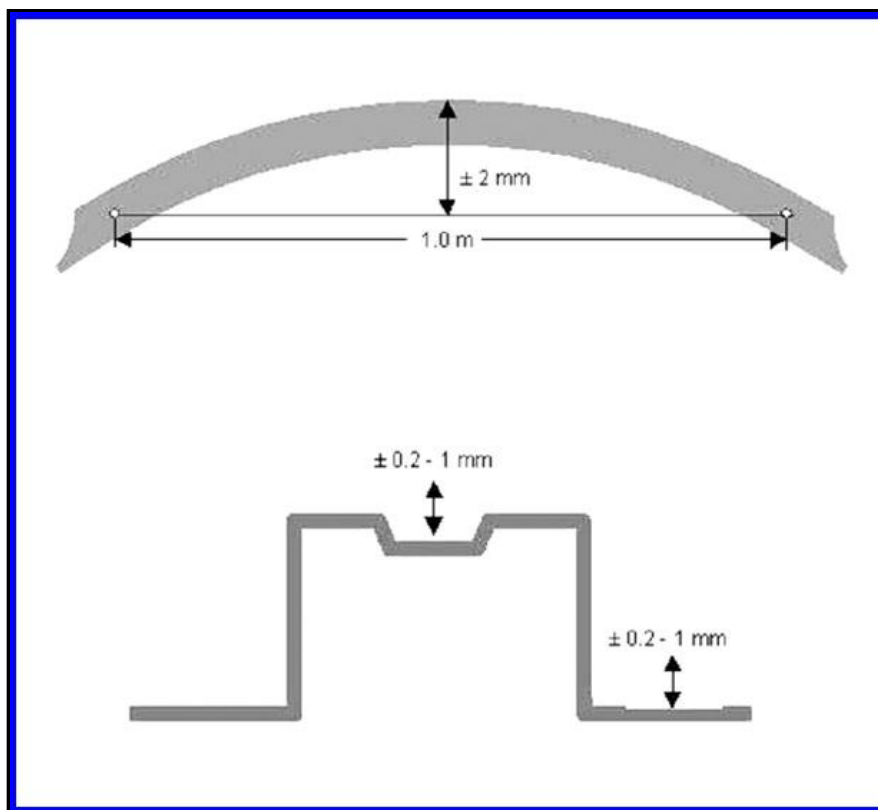
- ▲ AAM – Manufacturing – 3 Forming > Bending > Phenomena during bending > Wrinkling

### Temper

The forming is preferably done in the best formable temper. Lower alloyed 6xxx-series alloys can be formed in temper T1 (press quenched and stored at ambient temperature). The 7xxx-series alloys start age hardening within less than half an hour and are therefore usually solution heat treated just before forming. This is also the case with the high alloyed 6xxx alloys.

### Tolerances

Tolerances of formed products are very much depending on profile tolerances, microstructure and flow stress during forming, and friction condition between die and profile. Typical tolerance measures in e.g. bumper applications are as shown in the figure; global bending:  $\pm 2$  mm, local reference surfaces:  $\pm 0.2 - 1$  mm. These surfaces refer to two basic points as shown in this case, two bolt holes. In this case tolerances are tightest in the x-direction (vertical in the drawing).

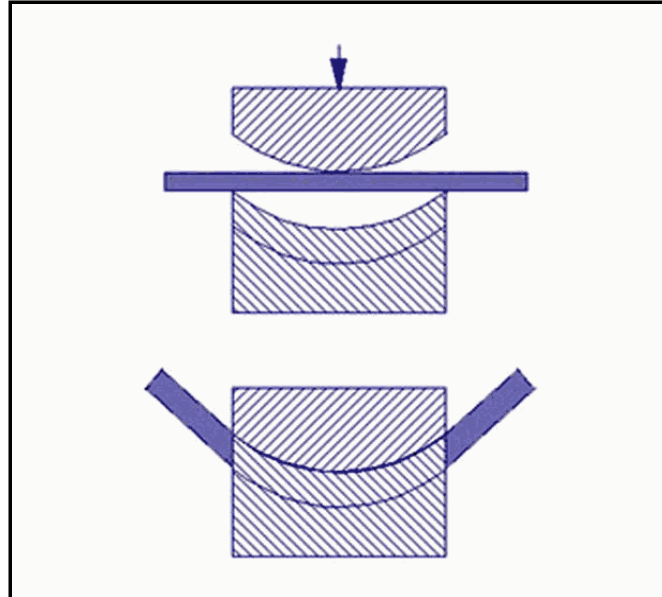


Typical tolerance measures of bent and formed profiles

### Press Brake Forming – Manufacturing Sequence

See also:

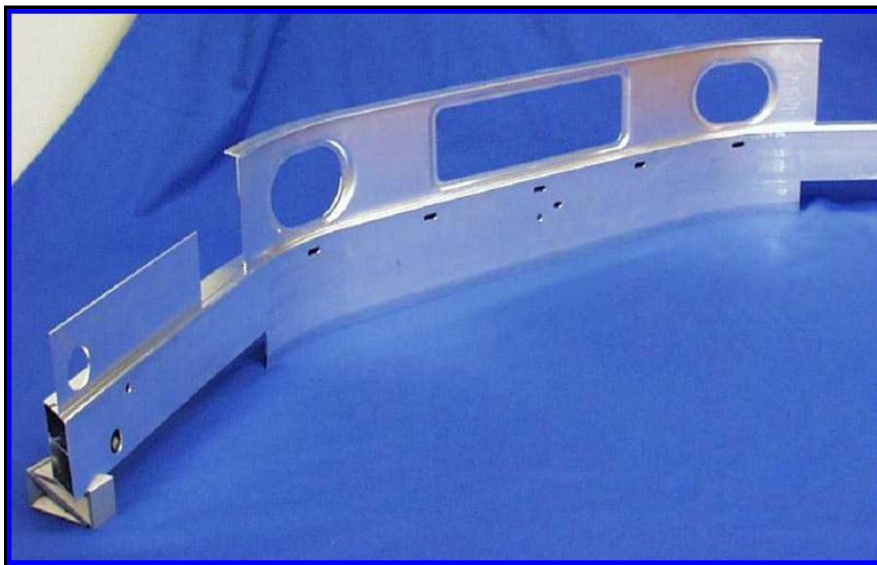
▲ AAM – Manufacturing – 3 Forming > Forming methods > Press Brake Bending



**Press brake forming** is frequently used for very small series.

This particular example has two rather sharp bends, several holes and parts of the webs are cut away. To prevent sagging at the bends, the profile is filled with water, and frozen. It is subsequently press brake bent with ice as an internal support. Ice is an adequate material for this purpose, but much additional handling is needed which means additional cost, thus limiting the method to use in prototypes or very small series only.

Essentially the same bending principle is in practice applied in numerous other processes. Some of these are applicable for high volume applications, but all suffer from a poorer global shape precision, than stretch bending.



**Part of rear structure of a low volume car**

### Rotary Swaging

**Rotary swaging** is a chip-less forming process to make net shape tolerances and reduce diameter of a bar or tube.

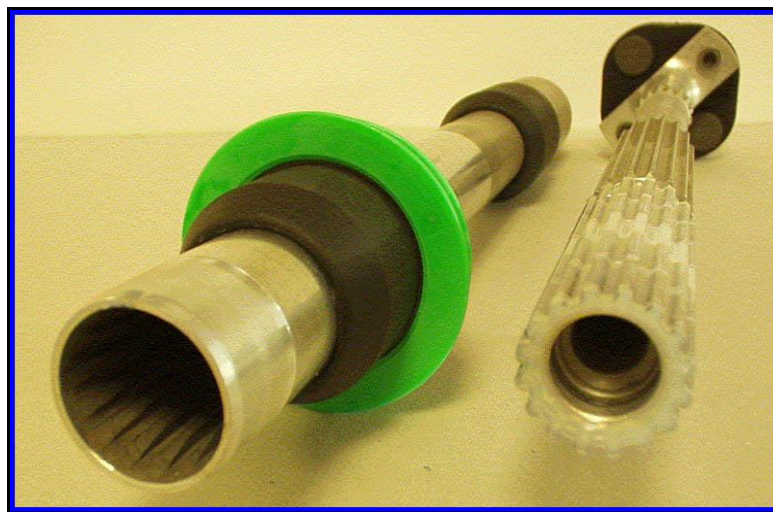
Usually four sets of dies (two to eight is possible) perform small, high frequency radial movements whilst rotating around a centre. The work piece is fed in axial direction, simultaneously rotating, but at a lower speed than the dies. Every inward movement of the work-piece reduces a small part of the diameter or wall-thickness, and makes it a little bit longer.

Through swaging over a mandrel, non-cylindrical internal geometry like hexagonal or splined sections can be made.

Non-cylindrical outer shapes can be maintained through stopping the rotation of work piece and dies. The number of dies will have to correspond with the required shape, and the method is not very often used.

When swaging aluminium, outer tolerances are between  $\pm 0,03\text{mm}$  and  $\pm 0,1\text{mm}$ , depending on size and geometry of the part. Inner tolerances are  $\pm 0,02$  till  $\pm 0,05\text{mm}$ , in splined sections also.

The commonly used material is alloy 6082, although 7000-series is used where high strength is required.



**Source: Steertec**

Figure: Rotary swaged steering shaft part, which has been swaged over a mandrel with longitudinal teeth.

For assembly, adjustment and collapse reasons, the tube is fit into a shaft with corresponding plastic coated teeth.

### Tubes convolutions

Convolutions angular to the centre line are created by a hydro forming technique. The applied inner pressure is created either by liquid or an elastomer, and the geometry of the enclosing die constitutes the outer shape. At sufficient pressure, the material plasticizes and flows in such a way that it fits into the die cavity.

This example is applied on impact extruded tubes, but the technique can be used to extruded tubes as well.

The figure shows a steering shaft tube with convolutions. The convolutions help the tube meet requirements on compression force and bending, and also to keep its integrity in a crash.



**Steering shaft with convolutions**

**Source: Steertec**

## End forming operations – Magnetic pulse forming

See also:

- △ AAM – Applications – 1 Power train > Liquid lines

Tube endforming is made by applying inner and outer tools to have very tight control of tolerances.

Threaded connections are often based on various bead shapes.

There are a number of fittings that need various endforming shapes. Bead shapes are also needed for Hose to tube connections like

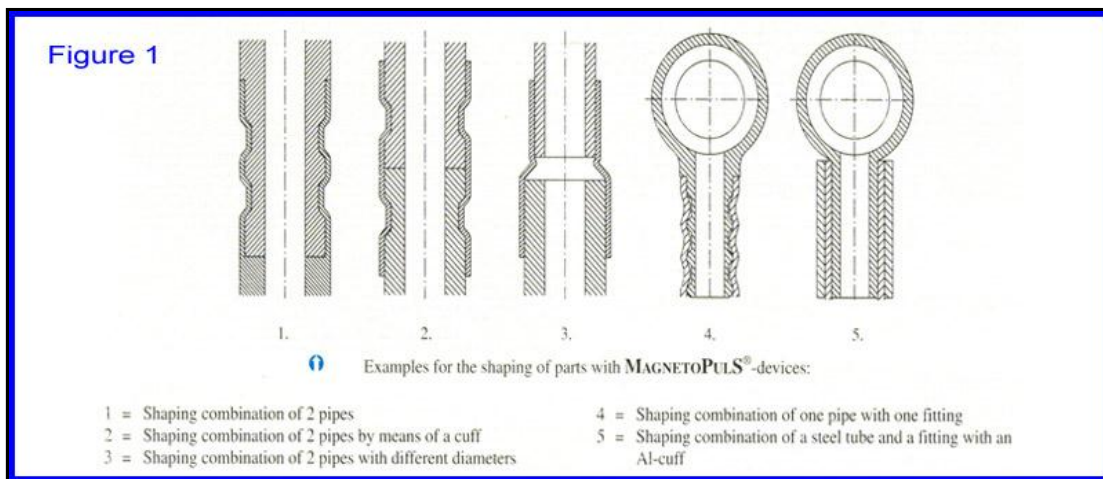
- △ Hose crimp shell connection
- △ Hose clamp connection

Magnetic Pulse Forming (MPF) is described under Application/ Power train/ Liquid lines. This method is used when crimping tubes to various fittings.

This contact-free shaping is mainly used for tubes and rings. Possible coatings of the parts are not damaged, and it is also an ecologically beneficial process.

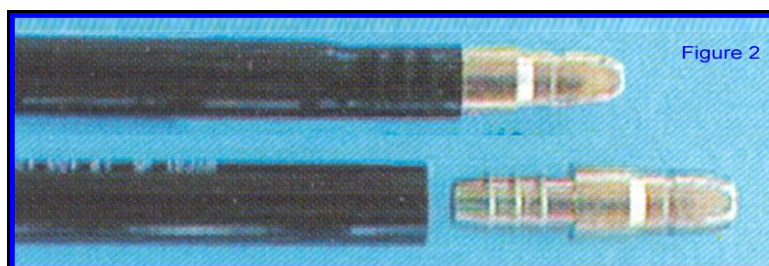
Fig. 1 shows examples of shaping and crimping of parts.

Fig. 2 shows before and after crimping (MPF) of tube to fitting.



### MPF forming, shaping of tubes or rings

Source: Pamphlet: Magnet-Physik Dr. Steingroever GmbH



A HYCOT tube (nylon coated tube) crimped to a steel fitting by MPF

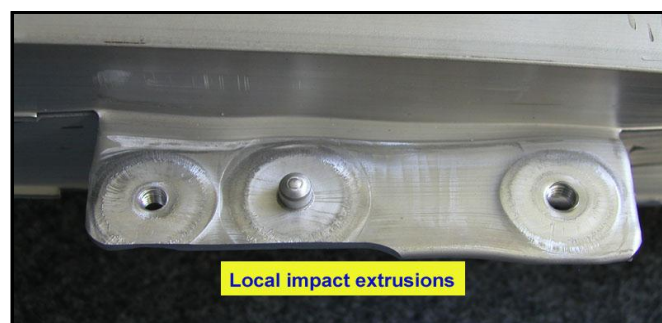
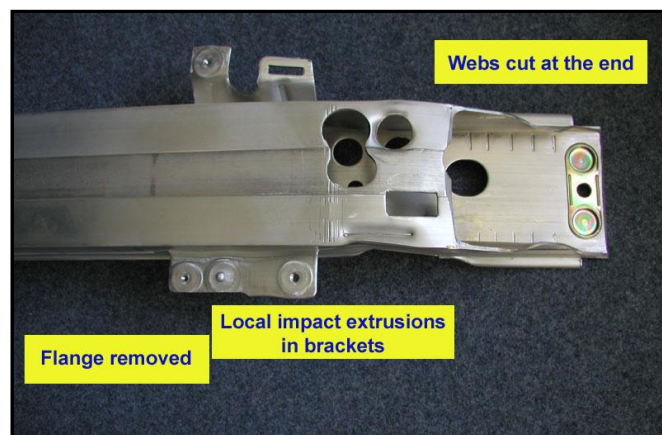
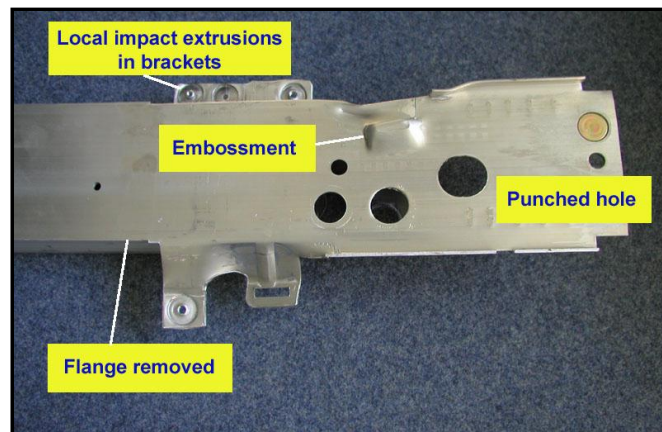
Source: Hydro

### 3.3.8 Post-bending reshaping

#### Post-Bending processes

Post-bending and reshaping processes described in the following screens are:

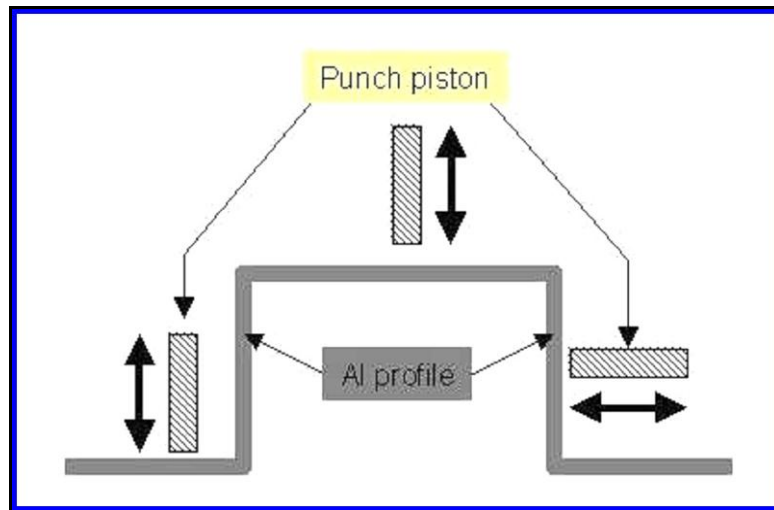
- ⤴ Punching (holes, removal of webs and ribs)
- ⤴ Embossment and various calibration operations
- ⤴ Local impact extrusion/ Local impacting
- ⤴ Machining and deburring
- ⤴ Forming / bending of webs, twisting of webs



Some of the processes involved in a bumper forming line

Source: Hydro

## Punching

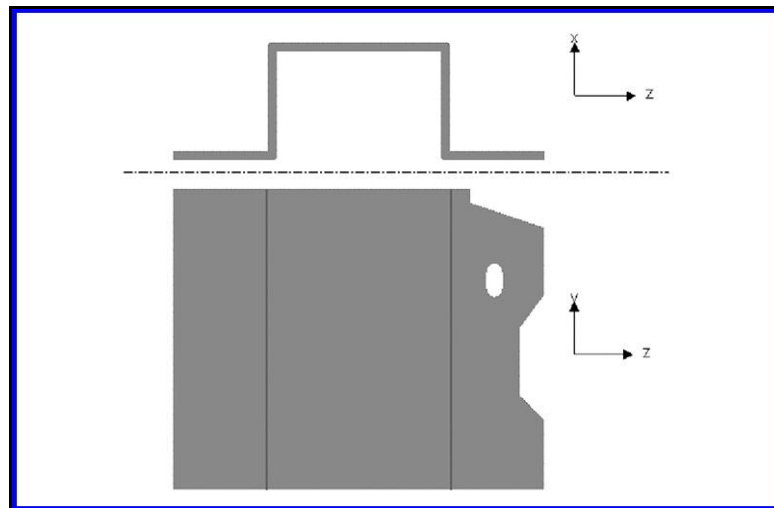


**Hole punching**

**Source: Hydro**

Punching is a cost efficient way of making holes.

Circular, oval, rectangular and many other shapes can be punched in one stroke, and in more than one direction.

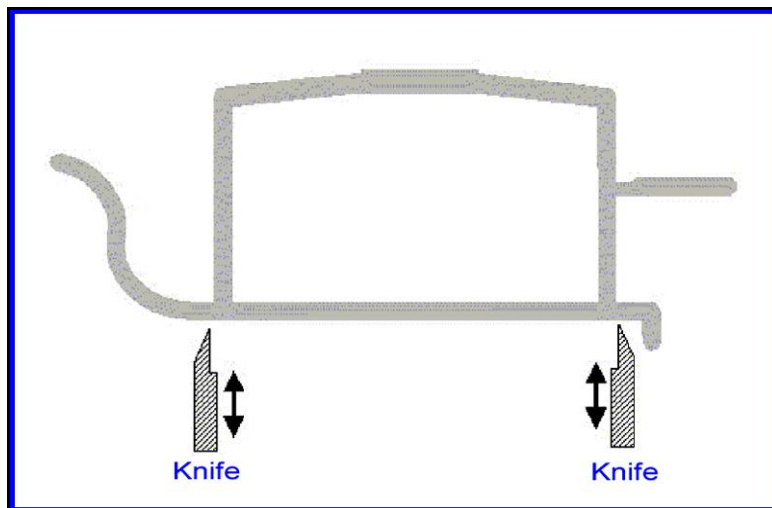


**Contour punching**

**Source: Hydro**

Moreover, contour punching of webs can be done.

Please note that aluminium tends to stick to steel, and special attention should be paid to tool design. Softer qualities tend to stick more than hard ones.



**Knife cutting of webs**

**Source: Hydro**

Knife cutting of webs is frequently used for removing webs not needed in certain areas.



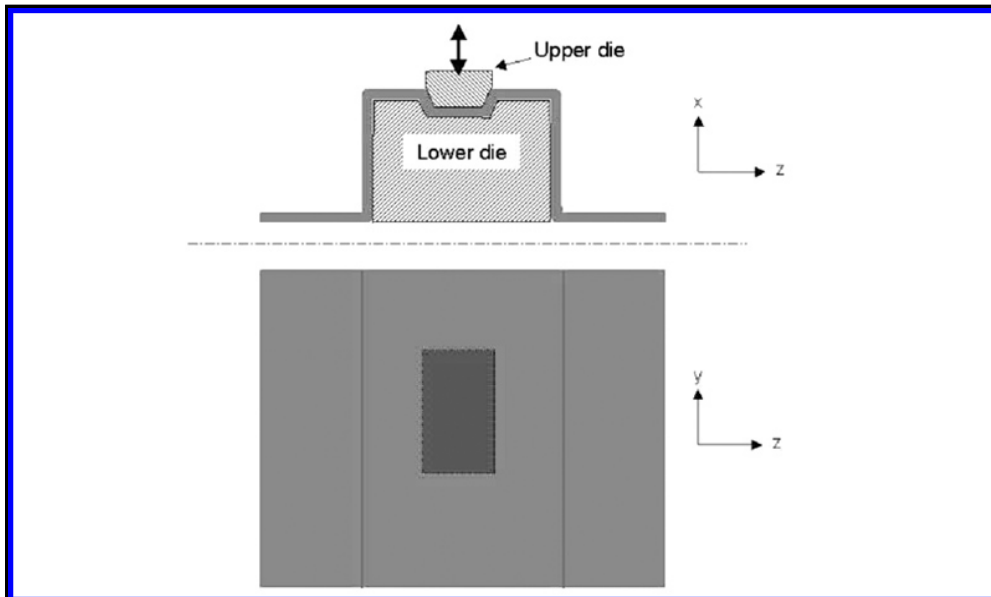
## Embossment

See also:

- ▲ AAM – Applications – 3 Car body > Bumpers > Beams / armatures > Closed Flexible Beam

Embossments are generally used for changing the profile section locally where functionality calls for such change. Also, it may create reference surfaces to be used in assembly, and are thus means of calibration.

High local strains are frequently involved when making embossments. Embossment as well as die design is therefore critical in order to minimise local strains. Strain to fracture when making embossment is lower than it would be in unbent extrusions. The material in the outmost fibre is stretched when bent, and therefore some of the strain capacity is already used. Local heating or local soft annealing, which is rarely necessary, will improve strain to fracture.



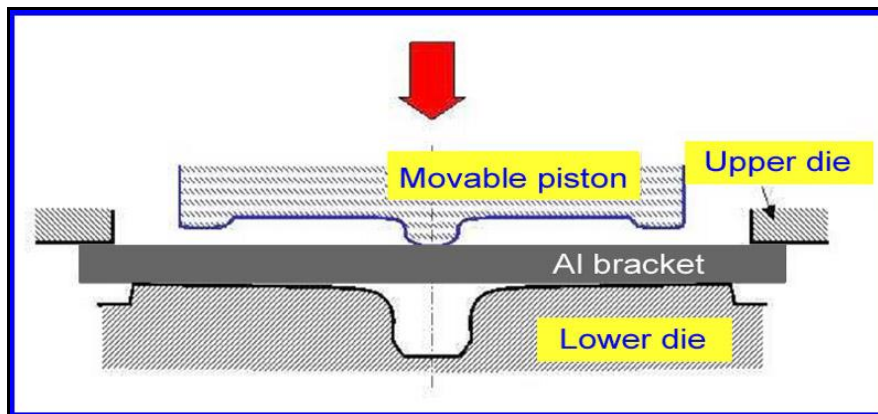
**Embossment - local reforming**

**Source: Hydro**

**Local Impact Extrusion (Local Impacting)**

Local impact extrusion is not frequently used, but it demonstrates some of the design possibilities with aluminium in general and extrusions particularly. Material is taken from the surroundings and impact extruded forwards or backwards.

The guide pin, which is the impact extruded detail in this case, is essential for assembly. In a corresponding steel design, this pin is mechanically joined to the part.



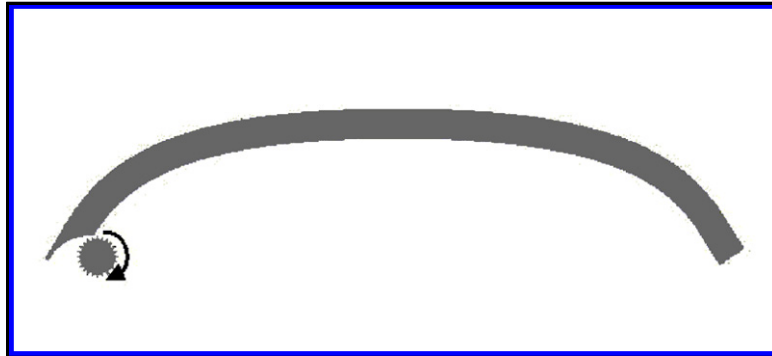
**Principal drawing of local impact extrusion**

**Source: Hydro**

### Machining / Deburring

Machining and end trimming is frequently part of the post bending processing. For larger series, end trimming is done by robotic milling, for smaller series, lower degree of automation is used. In cases when support from below is difficult or impossible (closed sections), holes are drilled or milled, rather than punched during forming.

Deburring by various methods is used to remove sharp edges and thus prevent handling injuries.



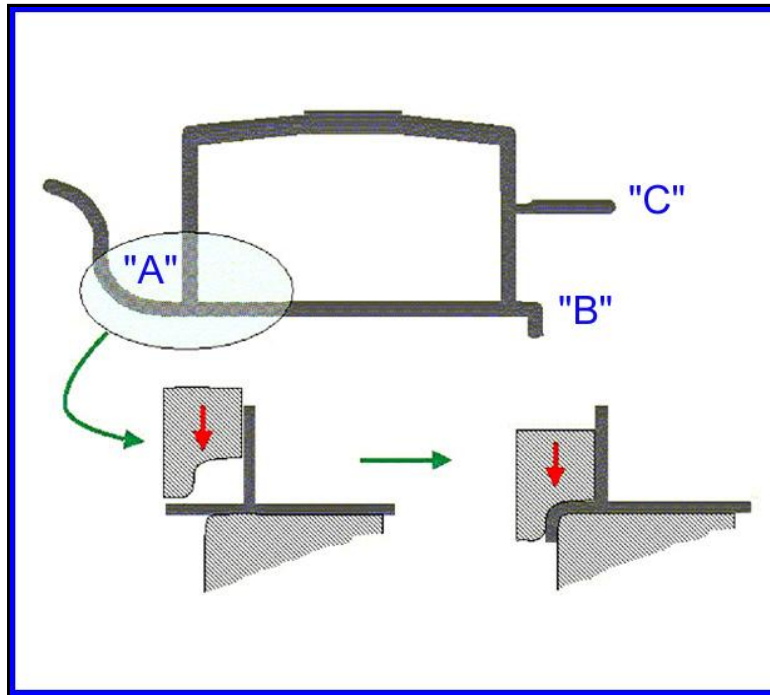
**End trimming of bent bumper beam**

**Source: Hydro**

**Bending / Reshaping of webs**

The curve shaped web of the extrusion to the right - Detail "A" - is removed over part of the extrusion, some part of it is reshaped and becomes a bracket. If this web was intended to have this bracket function only, it would be extruded to this shape like the one in the lower right corner of the profile - Detail "B" -, but other parts of it is used for other purposes (other types of brackets).

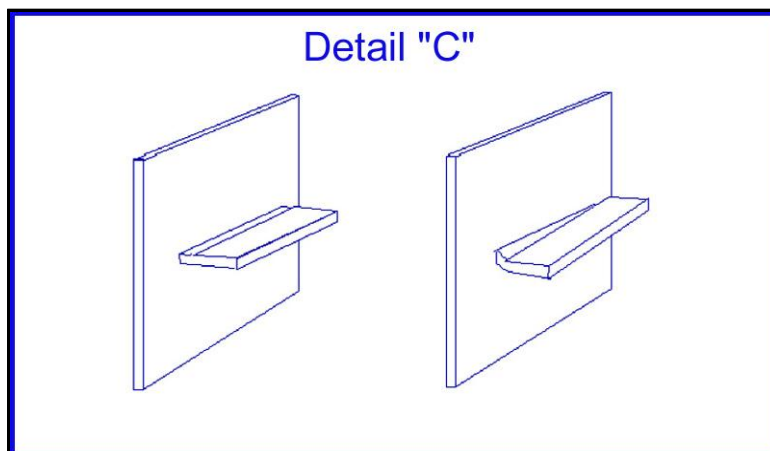
The bending operation shown in the figure is included in the forming line operations.



**Reforming of web**

**Source: Hydro**

Webs like the one of the extrusion below - Detail "C" - can be twisted to meet bracket needs.



**Twisting of partial web**

**Source: Hydro**

### 3.4 Hydroforming (tubes)

#### 3.4.1 Hydroforming of tubular shapes



Source: BMW, VAW

**Hydroforming** is an efficient means for manufacture of automotive components of complex shapes and with close tolerances.

In this context, hydroforming of hollow sections is becoming an established manufacturing technology as a cost-effective process for the production of car components.

Whereas steel initially played a totally dominant role in this relatively new production technique, aluminium has in the recent period gained importance as a feed material.

This is largely due to the favourable strength to weight ratio of modern aluminium alloys as well as recent advances in formability and joining properties, not to mention the known advantages offered by aluminium in terms of corrosion resistance and recyclability.

A major advantage of complex shaped closed section structures is the high stiffness-to-weight ratio in bending and torsional loading as compared to open section structures. While this general benefit is independent of feed material, the achievable stiffness-to-weight ratio of an aluminium component is higher than a comparable steel version.

#### Benefits

- ⤴ Forming of 3D-components in a single operation,
- ⤴ Excellent component stiffness-to-weight ratio,
- ⤴ Material savings and overall reduction in number of components,
- ⤴ High precision ready to install components
- ⤴ Suitable for volume production.

#### Drawbacks

- ⤴ Hydroforming equipment prompts high investments
- ⤴ Manufacturing process is rather complex

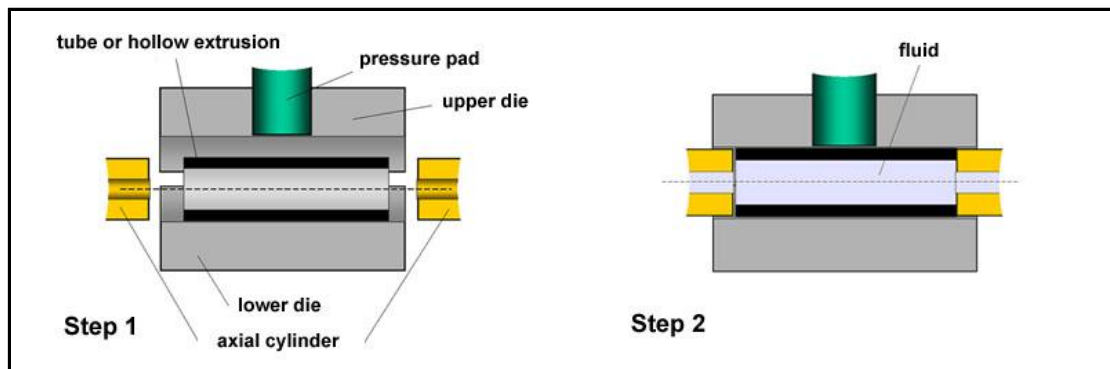
### 3.4.2 Hydroforming in general

#### What is hydroforming?

#### The hydroforming process principle

**Step 1.** A hollow section (tube or hollow extrusion) is placed into a die.

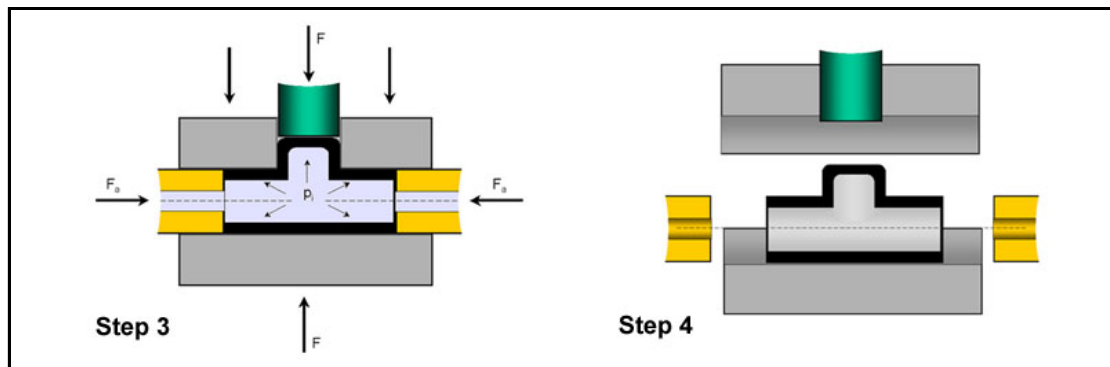
**Step 2.** After closing the die, the hollow section is sealed by axial cylinders and filled by a pressure medium (water or water emulsion).



Schematic hydroforming process, steps 1 and 2

**Step 3.** Under high pressure the hollow section expands into the cavity of the die. Material flow into the expanding areas may be assisted by end feeding with the axial cylinders, and/or by retreating pressure pads.

**Step 4.** Opening of the die.



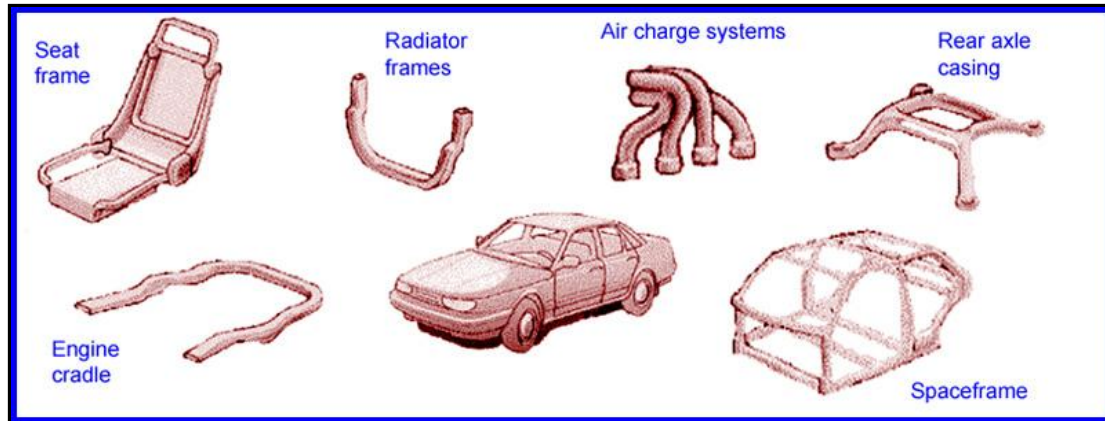
Schematic hydroforming process, steps 3 and 4

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### Application overview

See also:

- ⤴ AAM – Applications – 3 Car body > Seats
- ⤴ AAM – Applications – 1 Power train > Heat exchangers > Radiators
- ⤴ AAM – Applications – 2 Chassis > Structure and components > Subframe / Rear axle
- ⤴ AAM – Applications – 3 Car body > BIW > Space frame > Audi A2 (1999)
- ⤴ AAM – Applications – 2 Chassis > Structure and components > Engine cradle / Front axle



### 3.4.3 Hydroforming tools

#### Hydroforming equipment

The two main elements of the hydroforming equipment are the

- △ **hydroforming press**

which opens and closes the die, provides the clamping force and supplies of the pressure medium for the forming process, and the

- △ **hydroforming dies**

which define the shape of the part to be formed.

Hydroforming dies usually consist of an upper and a lower die. The dies may feature integrated operations such as

- △ flange cutting,
- △ hole piercing or
- △ trimming.

In addition to the dies the **axial cylinders** are directly involved in the hydroforming process. They are used for sealing the component to build up and maintain the internal forming pressure, and, most often, for end feeding to assist the material flow into the expanding areas.

An integral part of the hydroforming press is the **hydraulic equipment** for supply of the pressure medium and for operating the press and the incorporated features. Details on the hydraulic equipment such as pumps, valves, hydraulic cylinders or pressure intensifiers are beyond the scope of this compendium and should be discussed with suppliers of hydroforming equipment.



### General description

Finally, a central role is played by the generally computerized control system for control of the fluid pressure, the movement of the axial cylinders and other operations including their interaction. Especially the control of the interaction between pressure build-up and axial cylinders has crucial significance for a successful hydroforming process. The pressure and the axial cylinders can either be simply operated by independently prescribed functions over time or more sophisticated by dependent control of pressure and axial cylinders, where for example, the pressure is increased depending on the force (or displacement) controlled movement of the axial cylinders.

### Cost factor clamping force

A decisive cost factor is the clamping force, since it defines the size of the press, a fact which should be taken into account when designing a hydroformed component. Typically the clamping force is provided by hydraulic means. However, efforts to reduce costs have also lead to the ongoing development of mechanically assisted clamping systems.



Example of a standard four column press (25.000 kN clamping force)

## Sealing systems

### Sealing systems

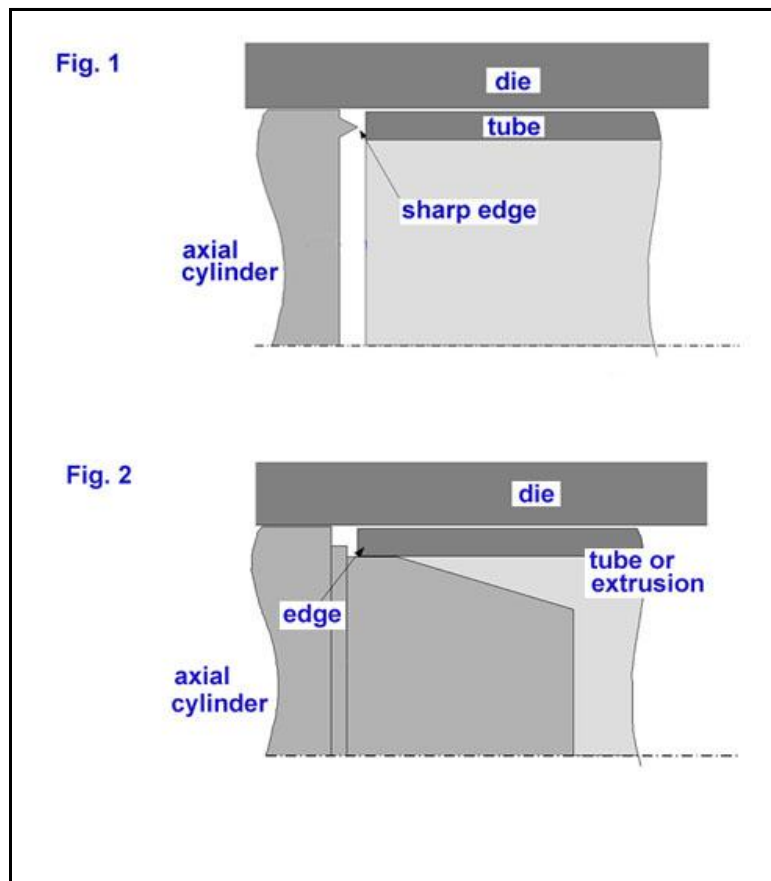
Metal-metal, polymer, or elastomer seals are used to build up and maintain the internal forming pressure with minimal fluid leakage.

Simple elastomer seals can be used at lower pressures, but are prone to mechanical damage.

Metal-metal seals or specially designed polymer-metal seals are needed for higher pressures. Most seals are designed for round tube where the sharp sealing edge engages the wall near midradius as shown in figure 1.

For thin wall aluminium extrusions with a more complex shape, special sealing methods as depicted in figure 2 have been developed.

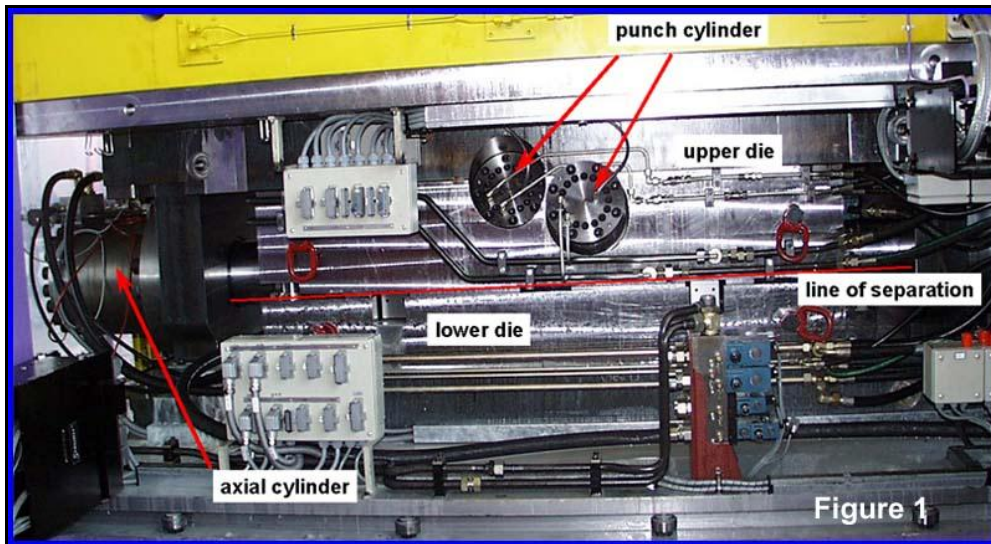
Since the work piece material is an integral part of the seal, its dimensional tolerances and mechanical properties must be taken into consideration.



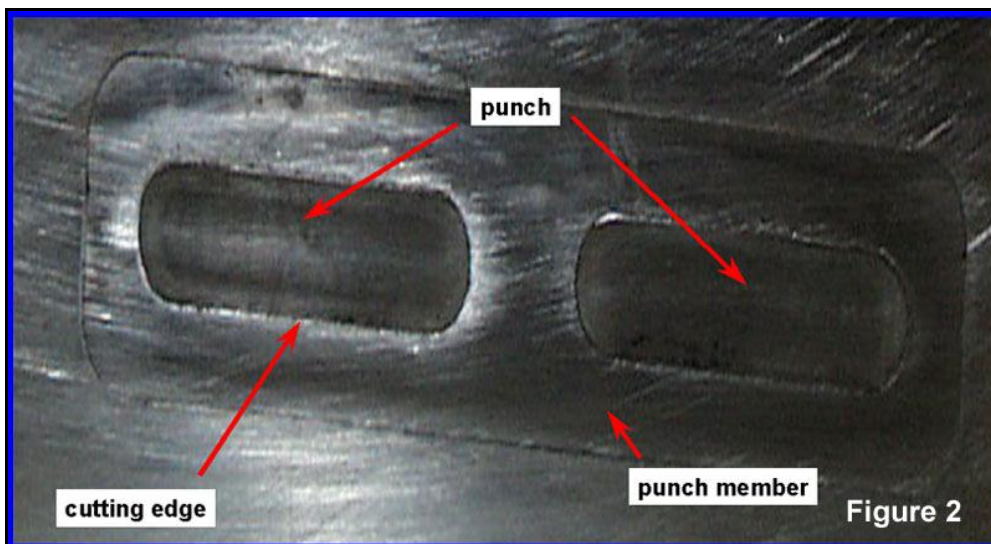
### Integrated hole piercing

#### Hydroforming with integrated hole piercing

Hole piercing can be integrated in the hydroforming process for improved efficiency of the production process. Two piercing methods can be differentiated, active hole piercing and passive hole piercing.



Hydroforming tool for integrated hole piercing  
Note the punch cylinders on the upper die

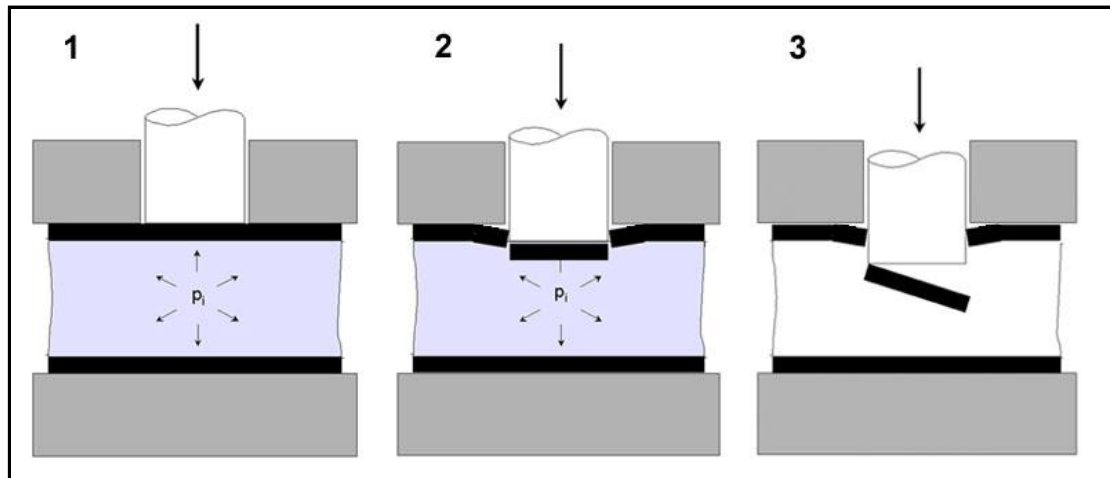


Inner surface of upper die with punches for integrated hole piercing

### Integrated hole piercing – Active piercing

As depicted in the process scheme below, the hole is pierced by the punch intruding the work piece. Active hole piercing has the following benefits:

- ⤴ Other than in a passive piercing process the piercing force is independent of the internal fluid pressure resulting in almost no limitations with respect to the minimal size of a hole.
- ⤴ The slug remains in the work piece and does not need to be removed within the cycle time of the press.
- ⤴ On the other hand there are some drawbacks to active hole piercing:
- ⤴ There will be an indentation of the work piece at the vicinity of the hole, depending on the level of the stabilizing internal fluid pressure.
- ⤴ Automated slug removal from the work piece is difficult.



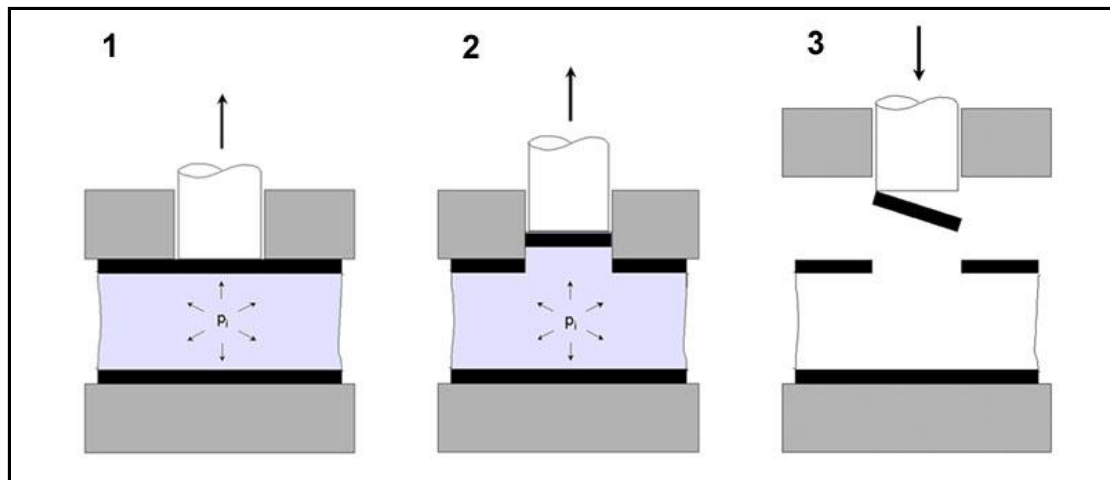
### Integrated hole piercing – Passive piercing

With this method the punch controlling the piercing process retreats and the hole is pierced by the internal pressure. Passive hole piercing has the following benefits:

- ⤴ The geometrical accuracy in the vicinity of the hole is better compared to active hole piercing.
- ⤴ Automated slug removal from upper die is easily achieved by controlled ejection of the punch.

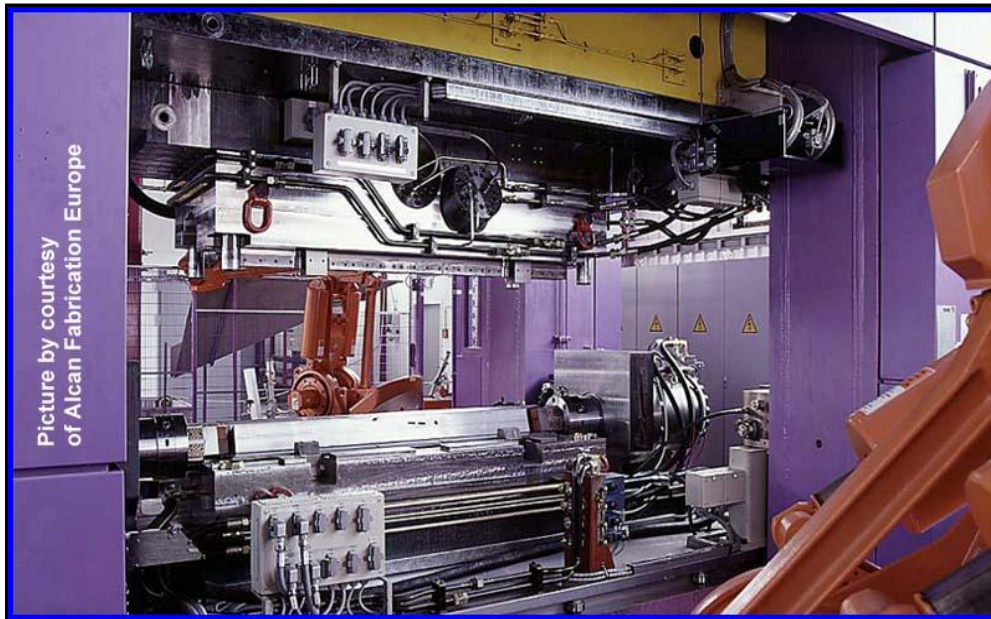
On the other hand there are some drawbacks to passive hole piercing:

- ⤴ The minimal hole size is limited depending on the internal pressure, wall thickness of the part and strength of the pierced material.
- ⤴ Automated slug removal from lower die is difficult.



### System for volume production

A system for volume production of hydroformed automotive parts may consist of bending equipment (e.g. rotary draw bending or stretch bending) and/or other pre-forming equipment, a hydroforming press for the key forming procedure and possibly other integrated operations (e.g. hole piercing), and, finally a cutting station for end trimming (e.g. laser cutting equipment or a CNC-processing centre which can perform additional milling operations). To reduce cycle time, thus costs per part, the hydroforming unit is typically automated. Since the hydroforming unit is the main cost factor, the remaining units are designed to match the cycle time of the hydroforming press.



**Robot-automated 35000kN hydro-forming press for series production of Audi A2 components at Alcan in Dahen- feld, Germany**

### 3.4.4 Hydroforming feedstock

#### General overview of options

See also:

- ⤴ AAM – Products – 3 Automotive tubes > Available forms and thicknesses > HF-welded (incl. Clad) > HF-welded tubes for structural applications
- ⤴ AAM – Products – 3 Automotive tubes > Available forms and thicknesses > Laser welded

#### Hydroforming feedstock

Usually aluminium alloys used in hydroforming are either

- ⤴ work hardening 5xxx-series or
- ⤴ precipitation hardening 6xxx-series alloys.

Typically the **5xxx-series feedstock** is produced from sheet as seam welded tube whereas the **6xxx-series feedstock** is produced as extruded stock. Accordingly, two types of feed material for internal pressure hydroforming can be differentiated:

- ⤴ **Roll formed and seam welded sheet material** and
- ⤴ **Extruded hollow aluminium sections.**

A very common alloy for seam welded aluminium hydroforming stock is AlMg3.5Mn, supplied in a soft temper to provide maximum formability. For similar reasons, 6xxx-series extruded hollows are supplied in a solutionized temper that will respond to age-hardening by natural or artificial means after hydroforming.

For hydroforming feedstock from

- ⤴ Longitudinally HF-welded and Laser-welded tubes, refer to section Automotive Tubes.
- ⤴ Extruded hollow sections, see next pages.

### Aluminium extrusions as feedstock

See also:

▲ AAM – Products – 2 Extruded products

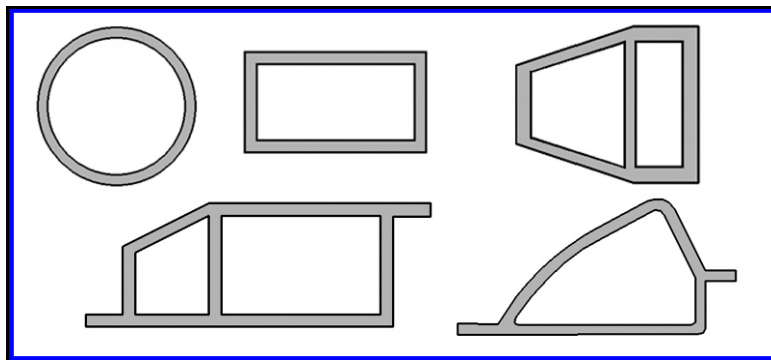
The main driving forces for automotive component hydroforming are weight and cost reductions. Hollow aluminium extrusions provide additional benefits. The decisive advantage offered by extruded sections is the fact that there are virtually no limits to the shape of the starting section. Features, such as varying wall thickness, flanges, or multi-section extrusions permit the production of even more complex components, i.e. cost-effective, integrated solutions, resulting in a further reduction of parts.

Moreover, extremely tight radii can easily be formed by extrusion of cross-sections with corners.

Generally, some component zones will be subject to much stronger forming during the hydroforming process than others, even in conjunction with less complex components. According to the local degree of forming these zones become thinner. If the final component is subjected to heavy loading under operating conditions in these locations, the starting material must be sufficiently thick. With extruded sections the distribution of material thickness can be tailored to the local requirements so as to accomplish an optimum weight of the component. Hence, extrusions represent tailored tubes without limitations!

The dimensional tolerances of extruded stock are typically inferior to sheet material. As an additional benefit of hydroforming the dimensional tolerances of extrusions can be significantly enhanced.

Extrusions provide a variety of options in designing hydroforming feed stock, only limited by the hydroforming process itself.



### Notes on temper conditions of extruded 6xxx-series alloys for hydroforming

Typically, the extruded hollows for hydroforming are precipitation hardening 6xxx-series alloys. To provide maximum formability, they are supplied in a soft temper that will respond to age hardening by natural or artificial means after hydroforming. Since natural age hardening can influence the formability, the feedstock should either be supplied in stabilized temper condition or hydroforming must be performed within a short time period after the extrusion process.

The ability to change the material properties of 6xxx-series alloys with heat treatment provides some advantages: The hydroforming process can be performed at a temper condition with low strength and high formability. Then, with an ageing heat treatment the strength of the material can be increased according to the requirements of the component.

The table shows typical mechanical properties of EN-AW 6014:

The material is hydroformed in the stabilized T4 condition. After the hydroforming process



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within a heat treatment process the mechanical properties can either be tuned to maximum strength (T6) or crash-worthiness with considerable strength and ductility (T7).

Typical mechanical properties of EN-AW 6014 (AlMgSi0.5V) at various temper conditions

Temper	YS [Mpa]	UTS [Mpa]	A <sub>g</sub> [%]	A <sub>50</sub> [%]	Z [%]	
AA 6014 T4*	106	206	20.4	26	37	⇐ formability
T6	220	265	10.7	12.8	17	⇐ strength
T7	201	233	7.6	11	31	⇐ crashworthiness

T4\* stabilized with respect to aging

See also chapter "*extruded products*" for further information on extrusions, available alloys and general notes on cross section design.

### 3.4.5 Development of components

#### Simple design recommendations

##### Some simple design recommendations for hydroformed components

Owing to the complexity of hydroforming processes, the optimum design solutions must be developed on a case-by-case basis.

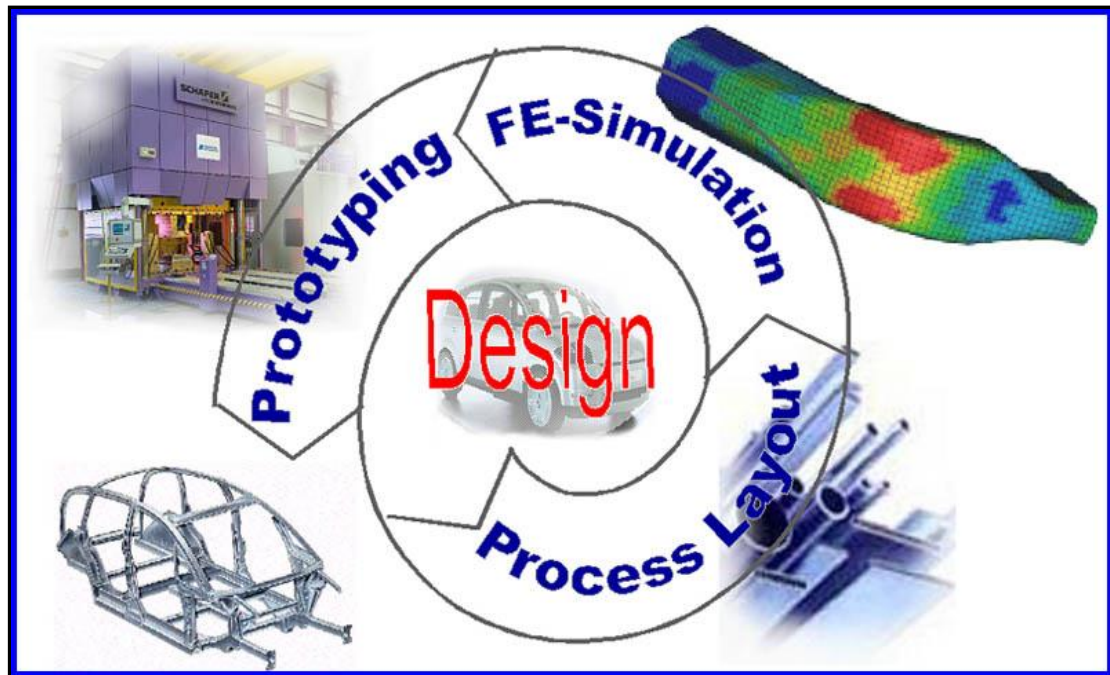
Nevertheless, there are a few simple design recommendations:

- ⤴ Less problems arise if the cross sections of the component are designed with approximately constant circumference.
- ⤴ Tight corner radii are prone for necking. Furthermore, they need higher internal pressure, thus implying higher capital investments in hydroforming equipment. Extremely small radii can be formed using extrusions with corners; however, changes in cross section will then be limited.
- ⤴ Sharply bent components imply high strains in the pre-forming process, limiting the formability in the hydroforming process.

### General development process

Compared to deep drawing processes, the deformation process in hydroforming has normally less constraints. As a consequence, the layout of a reliable hydroforming process tends to be quite difficult, i.e. the definite feasibility of a forming process is often not foreseeable at an early stage of development. Accordingly, the development of a hydroforming process is frequently an iterative process.

After an initial layout of the basic process including the choice of the feed material, it is recommended for most hydroforming components to check the initial layout in a virtual process by **FE-simulation** before entering the prototyping phase. The results of the virtual process might indicate that design changes are necessary. Only if the virtual process is successful, should the actual prototyping phase be entered.

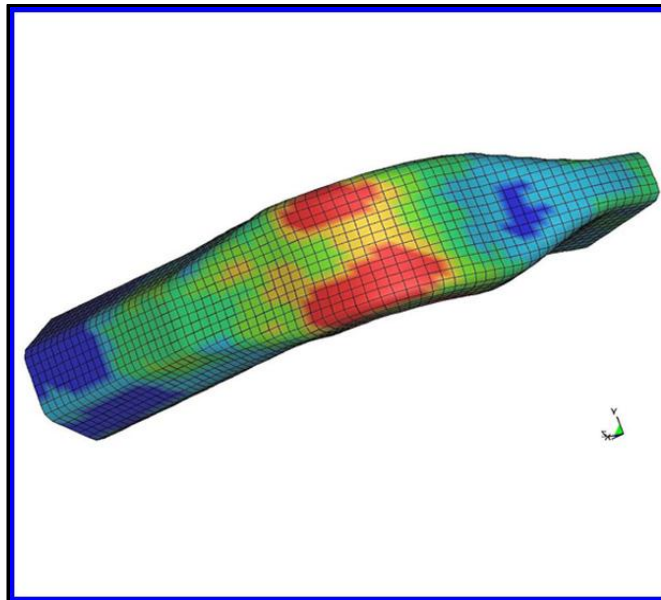


### Computer Aided Engineering

#### Why is CAE essential for successful development of hydroformed automotive components?

The observation of hydroforming procedures by way of direct experimenting is very difficult. Owing to the complexity of the forming process and the high investment costs associated with hydroforming tooling, the purely experimental design of hydroforming processes, i.e. the selection of feed material, design of the forming operations and the determination of process parameters, is time-consuming, cost-intensive and risky.

Hydroforming applications are therefore a prime example for the successful use of computer aided engineering (CAE). Besides the optimization of hydroformed components in terms of strength or crash behaviour, the simulation of hydroforming processes is of special interest. In FE-simulations, process parameters can be changed and the effects analyzed at comparatively low expense. Feasibility of a part fabrication, i.e. forming limits and other problems, can be foreseen, possibly resulting in design changes at an early stage of the design phase and prior to investments in hydroforming equipment. Only if the virtual hydroforming process looks promising, the prototyping phase should be entered.



**FE-simulation of a combined roll bending and hydroforming process**

#### Difficulties of hydroforming simulations

The mechanical model, upon which a hydroforming simulation is based, represents an extremely sophisticated problem, generally involving nonlinear material behaviour, finite deformation, frictional contact with large scale sliding, deformation-dependent external forces and also instability problems due to buckling. For this reason the expertise required for the successful performance of process simulations should not be underestimated.

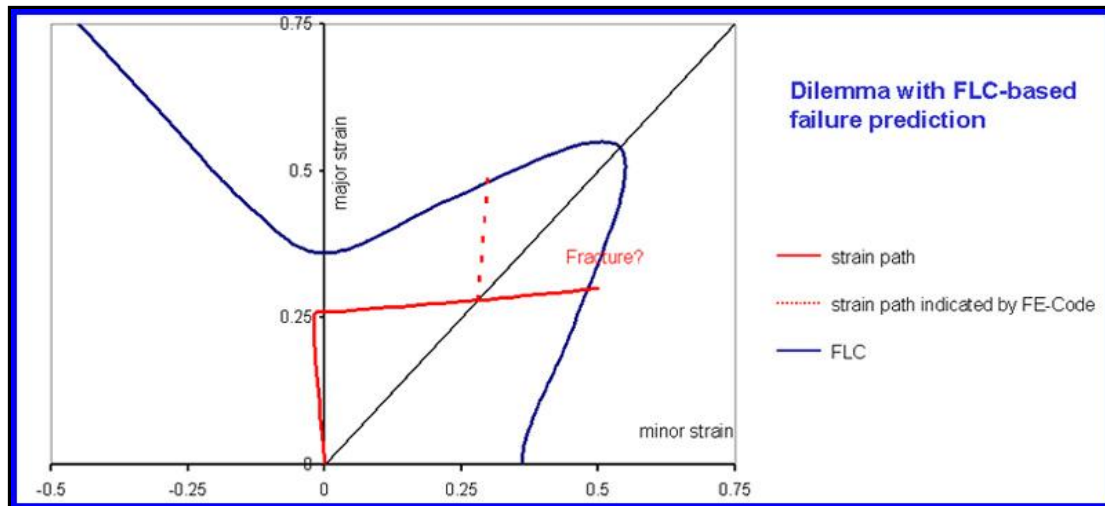
Although failure prediction based on forming limit curves (FLC) is common practice in hydroforming simulation, one should be aware of the involved dilemmas.

At first, for hydroforming feed material **FLCs** are difficult to determine, e.g. the manufacturing process for roll formed tubes significantly influences the actual forming limit, and, since tubes do not possess sufficiently large flat areas, standard FLC-testing is not possible. Furthermore, a **proportional strain path**, the precondition for the validity of a FLC, is a rare exception in hydroforming. Typically, strain paths are non-proportional, see example shown in the **figure (next page)**, where rotary draw bending results in a close to plane strain deformation and the subsequent circumferential deformation in the hydroforming process produces a radical 90°

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turn of the main strain direction. Finally, necking is not the only failure mechanism in hydroforming. Material failure in bending cannot be predicted by FLCs.

Besides the difficulties of failure prediction, an additional challenge is the appropriate consideration of the **actual friction conditions**, which can have significant influence on the outcome of a hydroforming process. Coulomb friction is by far the most popular model for frictional contact and often the only model provided by a simulation code. Nevertheless, ongoing research indicates that the assumption of Coulomb friction with a constant coefficient of friction and no rate-effects does not match up with reality in hydroforming.



### **Tribology**

Friction conditions can have significant influence on the outcome of a hydroforming process. Therefore, the quality of lubrication is a decisive factor on how the material slides within the die as the internal pressure rises. Once the internal pressure reaches a level that provides a significant degree of work piece-die surface interaction, sliding is retarded and strains tend to localize upon subsequent expansion. Without adequate lubrication, hydroformed parts neck or fracture prematurely during the forming process.

A number of commercially available lubricants have been successfully utilized with aluminium. Final selection of a lubricant for a particular hydroforming application requires consideration of starting material, effects on subsequent operations, lubricant removal and environmental aspects.

### 3.4.6 Examples of forming practice

#### BMW rear axle

See also:

- ⤴ AAM – Products – 3 Automotive tubes
- ⤴ AAM – Manufacturing – 3 Forming > Hydroforming (tubes) > Hydroforming feedstocks

Literature:

- ⤴ N.N.: Precision tubes, VAW alutubes GmbH, Hannover, 2001
- ⤴ Glockner, Kulka, Meyer, Oberloher: Aluminium-Fahrwerk der neuen BMW 5er Baureihe. ATZ Automobiltechnische Zeitschrift 98 (1996)

#### BMW 5 series rear-axle subframe

Made from HF longitudinally seam-welded tubes

Process chain longitudinal member:

1. Bending: CNC-Rotary-draw bending machine
2. Pre-Forming: Special press
3. Hydroforming:  
Closing force hydroforming press = 16.000 kN  
Calibration pressure = 1.100 bar

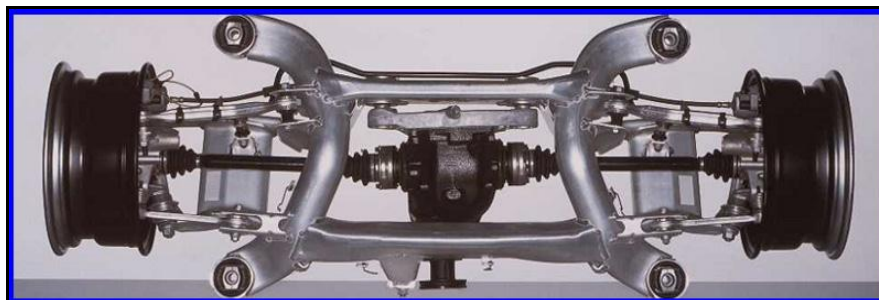
Advantages due to hydroforming:

- ⤴ Complex shape in one forming step after bending
- ⤴ Complete plastification of the components
- ⤴ Narrow dimensional tolerances

Alloy: AlMg3,5Mn

*Tube dimension: Diameter*  
82, 89, 95 mm

*Tube manufacturer:*  
VAW alutubes GmbH



**BMW 5 Series rear axle subframe**

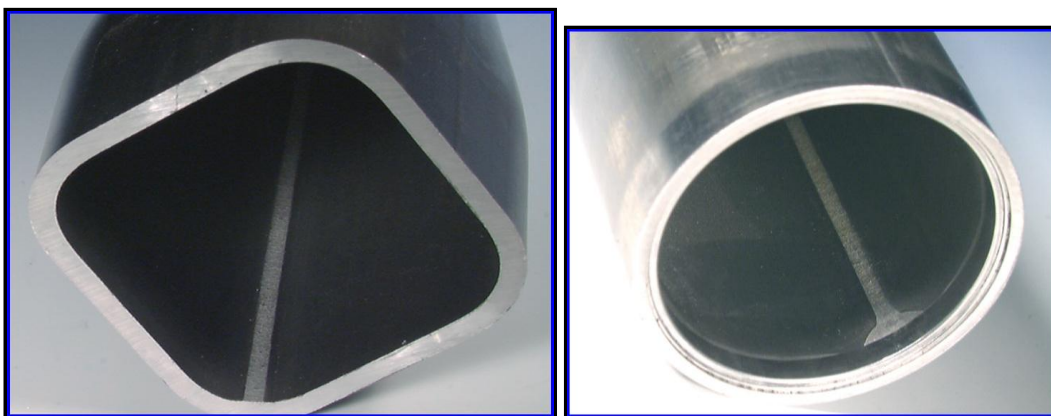


**Longitudinal member made from HF longitudinally seam-welded tubes**

#### Forming properties of HF-seam-welded tubes

Test sample:

- ▲ Alloy AlMg3,5Mn
- ▲ Tube dimension: 60,5x4 mm
- ▲ Circumference expansion of 20 %
- ▲ Forming of square cross section
- ▲ Constant wall thickness in forming area due to axial feeding
- ▲ Closing force hydroforming press: 12.500 kN
- ▲ Calibration pressure: 1.300 bar
- ▲ Axial feeding: 30,5 mm
- ▲ Tube manufact.: VAW alutubes GmbH
- ▲ square cross section
- ▲ Welding seam on purpose in main forming area
- ▲ tube end with piston formed welding seam and formed tube end due to sealing system



**Test sample of formed HF longitudinally seam-welded tube with 20% circumference expansion**



**Volvo air charge tubes**

Feed material: EN-AW 5049

Nominal force of hydroforming press: 25.000 kN

Forming operations: Multiple step rotary draw bending

Hydroforming at 1300 bar

Other information:

The socket is welded to the tube after the forming process.



**Source: Alcan Fabrication Europe**

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### Audi A2 roof frame

Feed material: EN-AW 6014

Nominal force of hydroforming press: 35.000 kN

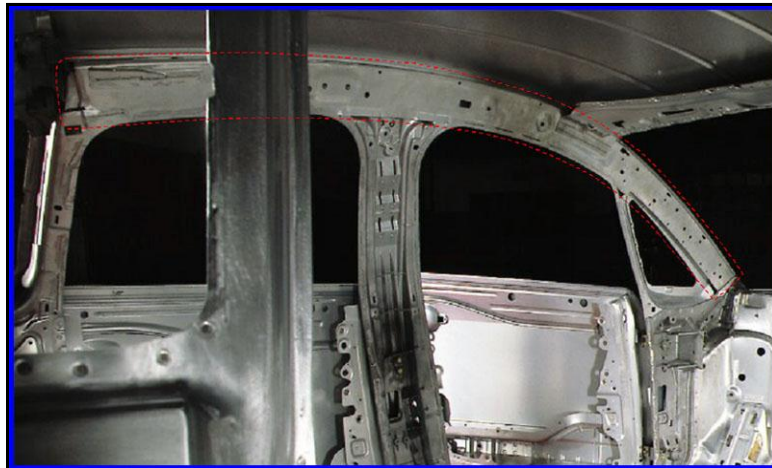
Forming operations: Stretch bending

Hydroforming at 1700 bar

Other information:

The hydroforming process includes punching up to 33 holes

Interior of Audi A2 body in white, marked section shows roof frame.



Source: Alcan Fabrication Europe

### **3.5 Impact forming**

See also:

- ^ AAM – Manufacturing – 3 Forming > Bending > Post-bending reshaping > Local Impact Extrusion (Local Impacting)

Cold impacting of aluminium, especially of extruded profiles, but also of pressed sheet parts, is a most fascinating forming technology. It helps to attach functional form elements to extrusions and sheet parts, often by local impacting. One well known example is the back extrusion of tube connectors in extruded manifolds for heat exchangers (Hydro Aluminium). Other examples are local extrusions in profiles as substitution of rivets or screws.

This work is in progress!

### 3.6 Semi-hot forming

#### Materials behaviour

Literature:

- ⤴ Schmoeckel, D. und Heller, C.: Umformen von Aluminiumblechen bei erhöhten Temperaturen. DFB-Forschungsbericht Nr. 34. Hannover: Europäische Forschungsgesellschaft für Blechverarbeitung, 1988
- ⤴ Heller, C. und Schmoeckel, D.: Umformen von Aluminiumblechen bei erhöhten Temperaturen. Aluminium 64 (1988) 4, p. 398-406

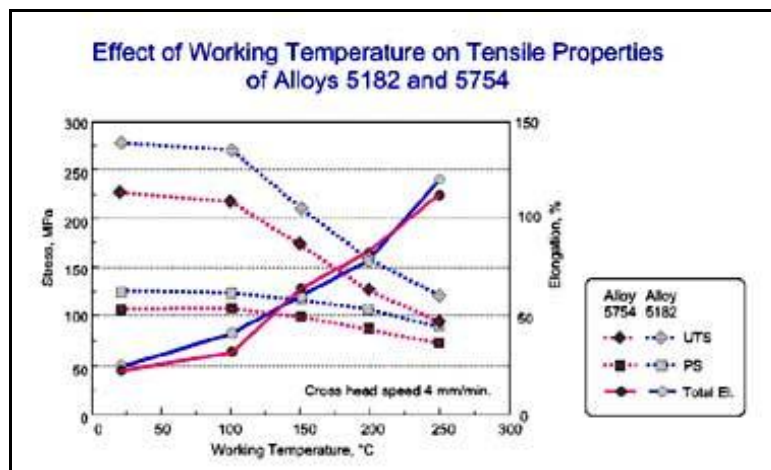
#### Plastic formability of aluminium can increase sharply at temperatures above 50°C

At ambient temperatures aluminium alloys have less plastic elongation capacity compared to common steels.

However, at temperatures above 50°C the plastic elongation capacity increases considerably.

#### Characteristics of 5000 series alloys:

Particularly alloys of the 5000 series family (Mg) exhibit an increase of total plastic elongation with rising temperature to more than 100% at 250°C, s. figure below.



Source: Alcan Deutschland GmbH

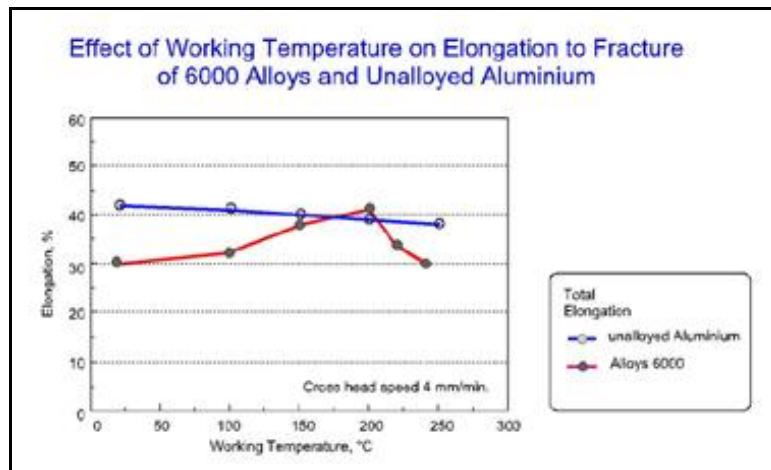
Remarks: As indicated, flow stress and work hardening rate decrease with increasing temperatures. On the other hand, flow stress and formability limits become increasingly sensitive to the **rate of deformation**, s. Lit. Schmoeckel et al.

The effects of working temperature on formability depend on the type of alloy.

#### Characteristics of 6000 and 1000 series alloys:

In comparison to 5000 series alloys plastic elongation of the age-hardening alloys of the 6000 family (MgSi) increases to a lesser extent with rising temperatures. Unalloyed aluminium (1000 series family) remains practically unaffected, s. figure below.

## THE Aluminium Automotive MANUAL



Source: Alcan Deutschland GmbH

### Principal methods – Forming with hot tools

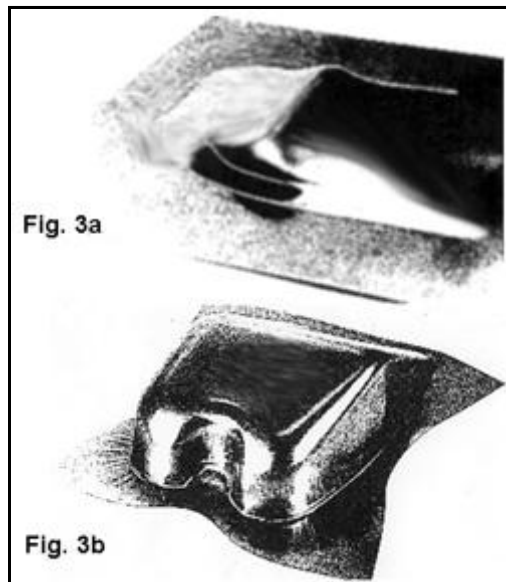
Literature:

- ▲ Schmoeckel, D. et. al.: Temperaturgeführte Prozeß-Steuerung beim Umformen von Aluminiumblechen. DFB-Forschungsbericht Nr. 55. Hannover: Europäische Forschungsgesellschaft für Blechverarbeitung, 1994
- ▲ Schmoeckel, D., Liebler, B.C. und Speck, F.-D: Deep drawing of aluminium in partially heated tools. Production Engineering 12 (1994), p. 55-58

High thermal conductivity of aluminium permits efficient heat transfer from hot tools to thin-gauged parts like sheet metal components.

Depending on the forming process partial heating of tools allows to apply heat only in sections, where the effects are most beneficial (e.g. under the blank holder in deep drawing).  
Example of forming with partially heated tools:

The figure below shows the forming limits of 1.2 mm thick 5182-0 sheet  
a. at room temperature (note crack line)  
b. between 140 and 180 °C (part is fully formed).



**Source: Schmoeckel et al.: Temperaturgeführte Prozess-Steuerung beim Umformen von Aluminiumblechen, EFB-Report No. 55**

Remarks: When using cold tools, pre-heating of sheet aluminium blanks is normally not sufficient for semi-hot forming operations, because heat is dissipated very quickly to the colder tool material.

### Principal methods – Hydroforming or blow forming with hot media

Literature:

- ⤴ Rösch, F.: Wärme macht Alu dehnbarer als Stahl. NC-Verlag, Blech 4 (2000) 6, p. 18-21
- ⤴ Geiger, M., Vollertsen, F. und Hein, P.: Neue Wege der Innenhochdruckumformung. EFB-Kolloquium, Tagungsband T16. Hannover: Europäische Forschungsgesellschaft für Blechverarbeitung, 1996
- ⤴ Alcan Patent DE-PS 195 31 035

A hot pressurised medium (gas or liquid) is used

- ⤴ to heat the work piece and
- ⤴ to generate flow stresses in the material during forming into the tool cavities.

Hollow sheet metal components can be hydroformed with hot media by pressurising a sealed assembly of two blanks. Sealing of flat, clean sheet blanks may be easily done by welding, brazing or roll bonding.

An example of a very complex shaped fuel tank is shown in the figure below and demonstrates the advantages of semi-hot forming processes for aluminium sheet metal components.



Source: Alcan Deutschland GmbH

## Advantages and disadvantages of methods

### Forming with hot tools

- + Greatly improved formability
- + Producibility of parts, which otherwise could not be produced
- Tool costs and dimensional accuracy
- Maintenance of dies and presses
- Lubrication of dies and work piece
- Influence of heat on forming presses
- Handling

### Hydroforming with hot media

- + Greatly improved formability
- + Producibility of parts, which otherwise could not be produced
- + Use of non-heated tools
- + Little influence of heat on tools, dies and forming presses
- Hot hydroform media
- Controlling temperatures of media
- Equipment for using hot media

### Sheet metal forming with hot media

- + Greatly improved formability
- + Producibility of parts, which otherwise could not be produced
- + Use of non-heated tools
- + Very little influence of heat on tools, dies and forming presses
- + Forming process control by varying temperature and binder pressure
- + For deep drawing and stretch forming
- Hot hydroform media
- Controlling temperatures of media
- Equipment for using hot media
- Fully sealed sheet assembly needed

### Possible applications of semi-hot forming:

- ⤴ A- and B-posts
- ⤴ door and door frames
- ⤴ single-part car body floors from tailored blanks
- ⤴ shock absorber towers
- ⤴ fuel tanks