# The Basics
# of Tube & Pipe Bending

**Tracto-Technik GmbH Spezialmaschinen**
Plant II • Rohrumformtechnik
Hunold-Rump-Straße 76-80
D-57368 Lennestadt

Tel.: +49 (0) 27 25 / 95 40-0
Fax: +49 (0) 27 25 / 95 40-33
E-mail: tubomat@tracto-technik.de
Website: http://www.tracto-technik.de

by Dipl.-Wirt.-Ing. Michael Rohrmann

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## C O N T E N T S

## 1. Reshaping by Bending

According to German standard, DIN 8580, the production methods are divided into the six main groups *original forming, reshaping, joining, separating, coating* and *altering the material properties* (*fig.1*). Reshaping means working a stable body by ductile (plastic) alteration of the shape, while maintaining the mass and the material cohesion. The reshaping methods are divided into sub-sections according to the main stress, this has been regulated in DIN 8582. Characteristic for reshaping by bending: the ductile condition (flow) is mainly carried out by bending stress. We differ between bending with *straight-lined tool motions* and *rotating tool motions.*

From single to series production, not only sheet metal, but also pipes, wires, rods and profiles with different shaped cross-sections can be bent, using a multitude of different methods. Normally, the work pieces are bent under cold conditions. The work piece has to be heated only when working with very thick sheet metal or very small bending radii, in order to keep the required bending forces down and to avoid brittleness of the material due to low temperature.

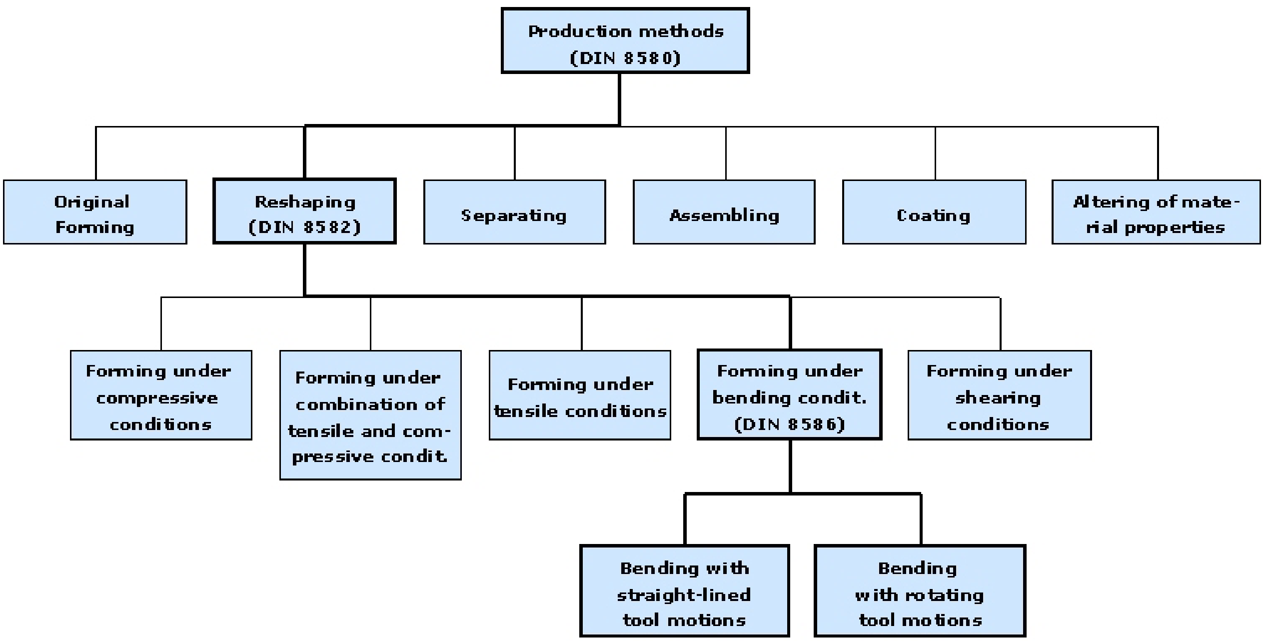
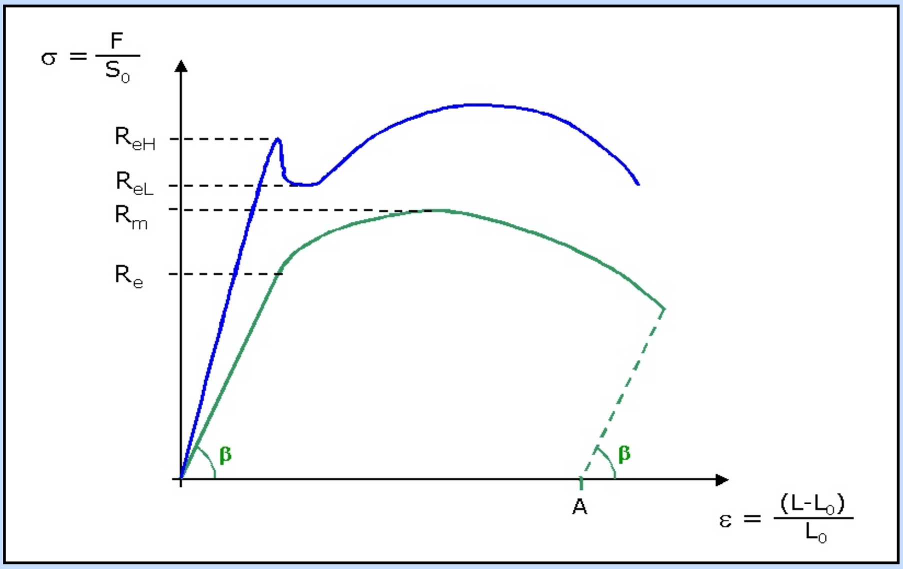



*Figure 1: Classification of the production methods according to DIN 8580.*

## 2. Theory of the Bending Process

When metallic working materials are bent in cold condition (below their recrystallization temperature), at first an elastic shape alteration takes place, which is replaced by a ductile shape alteration from a certain degree on. If the reshaping capacity is run down, the work piece breaks. This elastic-plastic behaviour of metallic materials is reflected in the stress-strain-diagram (*see fig.2*) determined by tensile tests. Within the range of the elastic line (Hooke's law), a tensile sample is reshaped elastically; as soon as the strain is relieved, the body returns to its original shape. However, if the applied tension exceeds the elasticity limit, the shape of the sample is permanently altered. The degree of resiliency after the strain has been removed, results from the elastic part of the shape altering process, which has been stored in the sample as potential energy beforehand. The alterations of shape occuring when metal pipes are being bent are mainly deter-




$\sigma$ = stress | $F$ = tensile force | $S_0$ = initial area

$\varepsilon$ = strain | $L$ = actual length | $L_0$ = initial length

$R_e$ = yield point | $R_m$ = tensile strength | $A$ = elongation at break

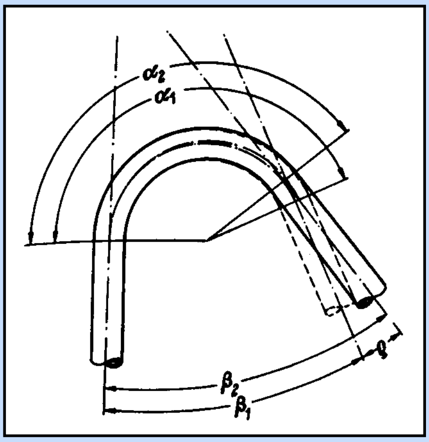
$R_{eH}$ = upper yield point | $R_{eL}$ = lower yield point

*Figure 2: Stress-strain-curve.*

mined by the material-specific parameters *modulus of elasticity* and *yield stress*.

Due to the elastic-plastic behaviour of metallic materials, the pipe springs back by a certain angle after every bending attempt. Besides the resiliency, there are also other inevitable phenomena to regard, where shaping by bending is concerned: the spring-back of the radius, oval deformation of the cross section (round pipes and tubes) as well as changes in the length of the work piece and formation of wrinkles.

The elasticity is the reason for the spring-back of the pipe after the bending process has been completed (*fig.3*). While in the valid range of "Hooke's law" (elastic line), the shaping energy is completely given back as work of elastic strain in the form of resiliency. But after the external strain has been re-moved, it is partly dissipated as work of plasticity when performing the elastic-plastic shaping. In this case, the extent of spring-back is only caused by the elastic (reversible) part of the shaping work, which is stored in the pipe as potential energy during the bending process. Spring-back is an inevitable phenomenon of bending, and can only be compensated by overbending the work piece.



Spring-back of the bend:

$$\rho = \alpha_1 - \alpha_2 = \beta_2 - \beta_1$$

Rate of spring-back:

$$\kappa = \frac{\alpha_2}{\alpha_1} = \frac{\text{bending angle after springback}}{\text{bending angle before springback}}$$

*Figure 3: Spring-back (acc. to W.D. Franz).*

In the so-called bending curve (*see fig.4*) the spring-back, depending on the bending angle with otherwise identical bending parameters, is displayed. Always the same typical progression is recognisable. A steeply rising linear phase (purely elastic forming) is followed by a non-linear phase (elastic-plastic bending phase, plasticizing in cross section) and then by the weak linear rise of a further range (plasticizing in the longitudinal section only) up to the end of the bending process. Spring-back of the pipe after relief of the strain is also followed by a slight increase of the bending radius, but this can already be considered when fabricating the bending tools.

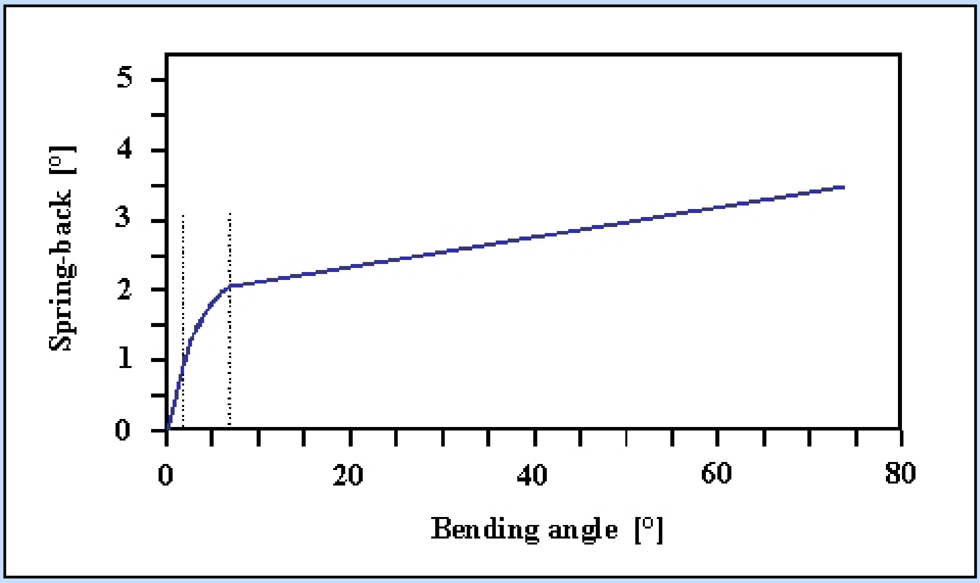
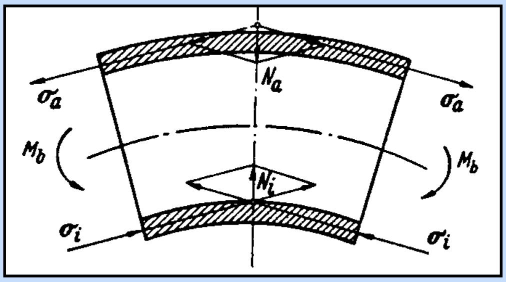



*Figure 4: Behaviour of the bending curve (spring-back curve) in general.*

While bending round pipes, radial components of the longitudinal bending stress lead to oval distortion of the circular pipe cross section. The outer side of the bend has an inclination to the central line, thus flattening the pipe.

Regarding the equilibrium of forces active during the bending process (*see fig.5*) you can see, that the pressure forces resulting from the bending moment in the inner area of the pipe bend and the traction forces in the outer area of the pipe bend work in opposite direction, thus favouring a compression of the original circular cross section. The measuring size for oval distortion is the eccentricity. The oval distortion grows stronger, if thinner pipe walls and smaller bending radii of the work piece have been selected. The alteration of the cross section shape has an influence on the free circulation cross-section and the consistency of the pipe when exposed to inner pressure.



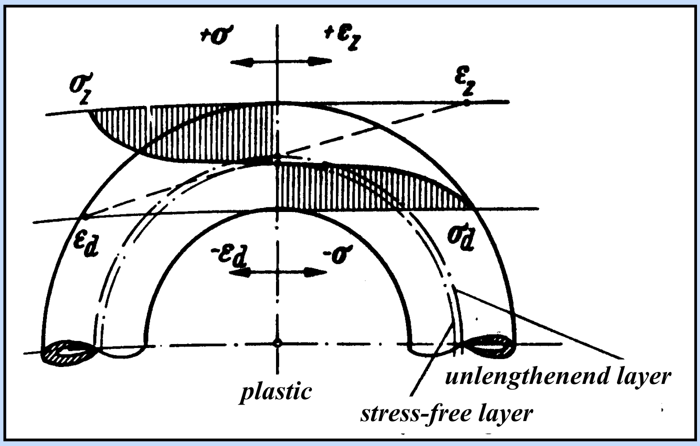

Ovality:

$$u = \frac{D_{\max} - D_{\min}}{D_0} \cdot 100\%$$

$D_{\max}$ maximum outer pipe diameter after bending
$D_{\min}$ minimal outer pipe diameter after bending
$D_0$ initial outside pipe diameter

*Figure 5: Forces during the bending process (acc. to W.D. Franz).*

With every bending process, the inner layers of the work piece suffer pressure stress in connection with material compression, while the outer layers are exposed to tensile stress and stretched in the direction of the leg. Under the consideration of plastic bending, we must differ between the unlengthened layer (neutral axis) and the stress-free layer.

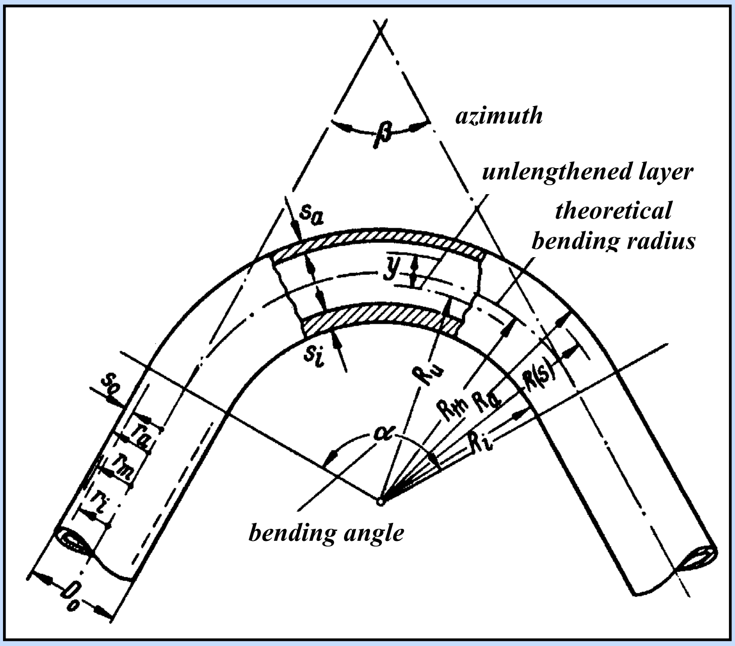



| | | | |
|---|---|---|---|
| $\varepsilon$ | strain | $\sigma$ | stress |
| $\varepsilon_d$ | compressive strain | $\sigma_d$ | compressive stress |
| $\varepsilon_z$ | extension strain | $\sigma_z$ | tensile stress |

*Figure 6: Stresses at the bend (acc. to W.D. Franz).*

The unlengthened layer has maintained its original length after the bending process is completed, permanent stretching equals zero. The position of this layer does not correspond with the neutral circular arc layer (theoretical bending radius), but is displaced indirection of the bending axis. For this reason, every pipe suffers a certain elongation during the bending process, but it is possible to approximately determine the corresponding cutting length with the help of mathematical calculation. The stress-free layer is positioned even further inside, it is the layer, which shows no longitudinal stress at all after ductile forming. An overview of the geometric terms and relationships concerning bent pipes can be seen in *fig.7*.

If thin-walled pipes are bent to small radii using the rotary draw bending method, the material on the inside of the bend is pressed back behind the line of tangent, where it is no longer supported by the bend die and therefore susceptible to wrinkling. This unwanted phenomenon is best avoided by using a wiper die (*comp. fig.11*). The wiper die is a form part, which is mounted inside the bend behind the bend die and has a sharped-edged end, which is placed in positive fit into the pipe groove of the bend die and pushed to the line of tangent as closely as possible, however without exceeding it. Flow of the material behind the line of tangent is avoided, thus minimising wrinkling. However, if wrinkles have already been formed, they cannot be eliminated after bending.




| | | | |
|---|---|---|---|
| $\alpha$ | bending angle | $\beta$ | azimuth |
| $D_0$ | initial outside pipe diameter | $r_a$ | external pipe radius |
| $r_i$ | internal pipe radius | $r_m$ | average pipe radius |
| $R_a$ | external bending radius | $R_i$ | internal bending radius |
| $R_{th}$ | theoretical bending radius | $R_u$ | radius of the unlengthened layer |
| $R(S)$ | radius of a layer „S" | $s_0$ | initial wall thickness |
| $s_a$ | wall thickness at a location of the stretched layer | | |
| $s_i$ | wall thickness at a location of the compressed layer | | |
| $y$ | distance of a layer „S" to the unlengthened layer | | |

*Figure 7: Geometrical dimensioning at a bend (acc. to W.D. Franz).*

A first proposition, whether a pipe with defined dimensions (outer diameter and wall thickness) can be bent at all, can be drawn from material-specific graphs like in *fig.8*.

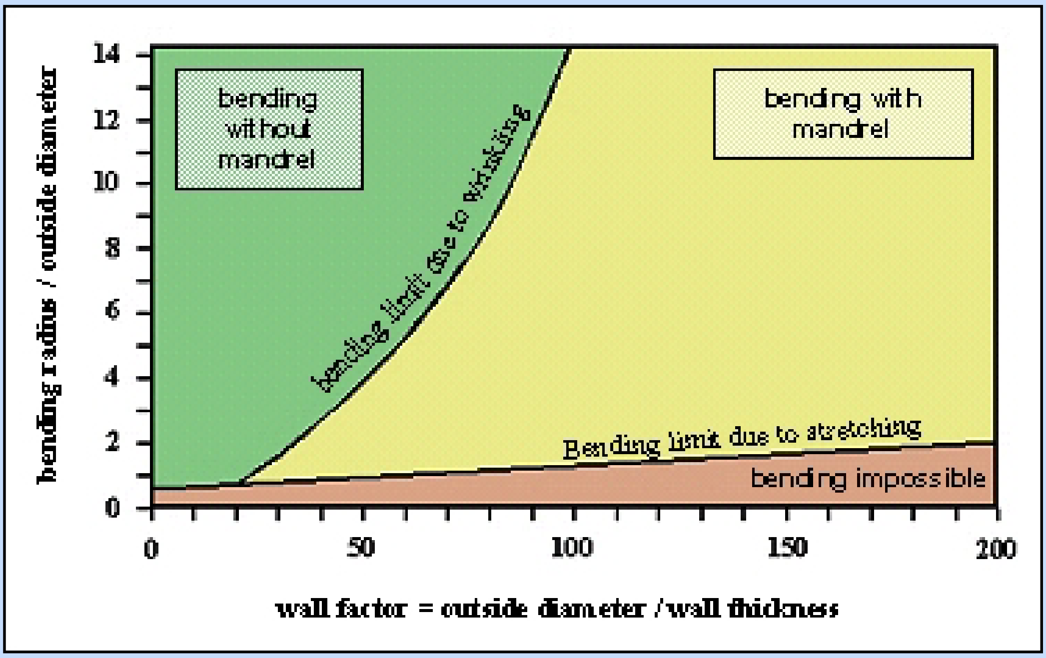



*Figure 8: Technical limits of the bending process.*

Bending is impossible below the bending limit determined by stretching and it comes to work piece failure as a result. The bending limit due to wrinkling separates the range, where bending with mandrel (and wiper die) is possible, from the range, in which the pipes can also be bent without a mandrel. The larger the relation between the outer diameter and the wall thickness of the pipe and the smaller the bending radius, the stronger is the inclination of the pipe to gather wrinkles while bending.

## 3. Pipe Bending Methods

Different methods can be used for bending pipes, depending on the material in use and the required finishing precision. *Press bending* (*ram bending*) belongs to the most common procedures, also *3-roll-bending*, *compression bending* and *rotary draw bending* (*round bending*).

When press bending is applied, the bending tool with the inwrought bending radius is pressed against two counter-rollers, either manually or by means of hydraulics. This motion forces the pipe inserted between the radius block and the counter-rollers to bend around the radius. The pipe cannot be supported from within, therefore this method is suitable for thick-walled pipes and large bending radii only.

Also 3-roll-bending is used for producing work pieces with large bending radii. The method is similar to press bending, but the working cylinder and the two stationary counter-rollers rotate, thus forming the bend.

Compression bending is carried out with a sliding carriage and a stationary bend die, between which the pipe is clamped. The sliding carriage, which rotates around the radius block, bends the pipe according to the radius of the bend die.

Considerably more precise than the three methods mentioned above is rotary-draw-bending. With this method the work piece is fastened between the bend die and the clamp die and formed by the rotation of both tools around the bending axis.

## 4. Rotary Draw Bending

When using rotary-draw-bending, the pipe is inserted in the bending machine and fastened between the bend die and the clamp die. The rotation of both tools around the bending axis bends the pipe according to the radius of the bend die *(fig.9).* The pressure die (slide piece) serves the purpose of receiving the radial stress, which is generated during the forming process, and supports the straight pipe end from outside. If mandrel and wiper die are applied additionally (mandrel bending), a high work piece quality can be achieved even with thin-walled pipes and tight bending radii.

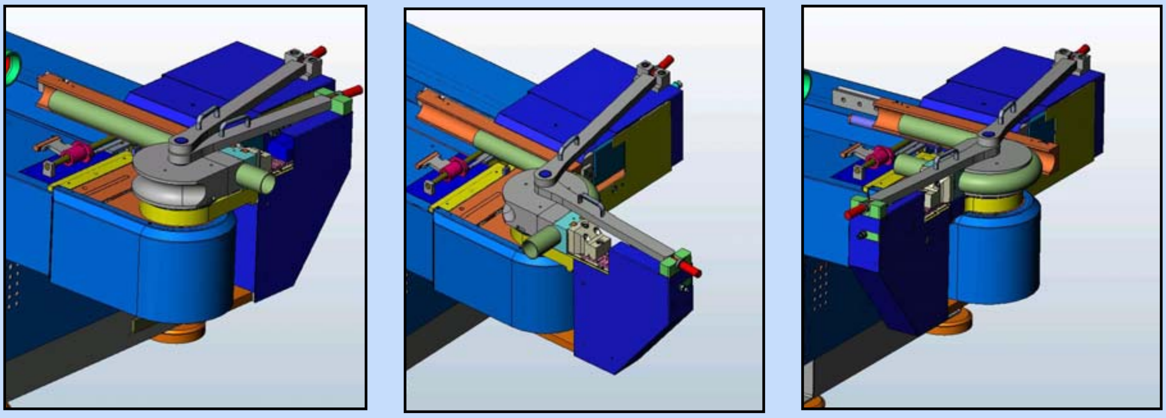
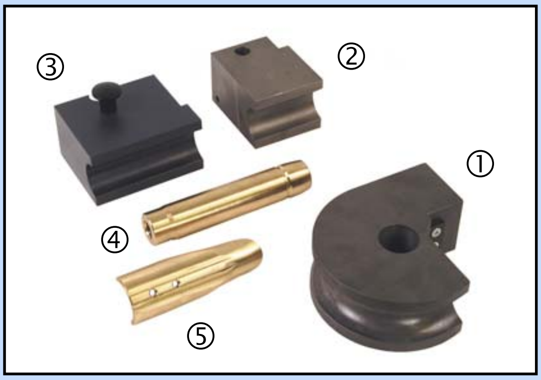


*Figure 9: Rotary draw bending.*

With modern mandrel bending machines, almost any kinds of cold-formable pipes - depending on the applied material - can be bent to bending radii of approximately 1xD to 5xD (referring to the outer diameter of the pipes), safely and in the desired precision. Even bending radii smaller than 1xD can be formed according to the present state of technique. But the forming possibilities are not limited to bending round pipes at all.

Oval pipes, flat and mono-block material can be formed just as well as bending square or other open profiles. Depending on the shape of the work piece, the required forming tools (bend die, clamp die, pressure die, mandrel and wiper die, see *fig.10*) are adapted accordingly.




Tool set for rotary draw bending, consisting of:

- ① Bend die
- ② Clamp die
- ③ Pressure die (slide piece)
- ④ Mandrel
- ⑤ Wiper die

*Figure 10: Tool set for rotary draw bending.*

Today the main differences of rotary-draw-bending machines are the maximum workable outside pipe diameter and the degree of automation of the various functions. Only the bending function of the so-called "1-axis controlled bending machines" is automatic, feeding and contortion are carried out manually. For the user of CNC or bending machines with fully automatic control, however, all functions are available automatically. These bending machines can be supplemented with automatic feeding and unloading systems for the production of large series without any problems.

## 5. Application Fields of the Pipe Bending Technology

In our everyday lives, bent pipes are required for the transportation of all kinds of fluids or gases and are also used as construction elements in almost any industrial branch. They are just as wide-spread in the car, aviation and shipbuilding industry as they are in the chemical industry, refrigeration and air-conditioning technology, furniture industry, steel constructions or machine technology and plant engineering. In general, all materials, which can be used for forming in cold condition, are suitable for pipe bending, i.e. steel, stainless steel, copper, brass, titanium, aluminium or CuNiFe. Not only circular cross sections, but also square and oval pipes, flat and mono-block material as well as profiles with all kinds of cross section shapes can be processed with the bending machine. Often, already bent steel pipes are used as basic semi-finished material for a subsequent hydro-forming process (i.e. for exhaust systems). The various application fields greatly differ, but so do the demands made on the bent work piece and its forming.

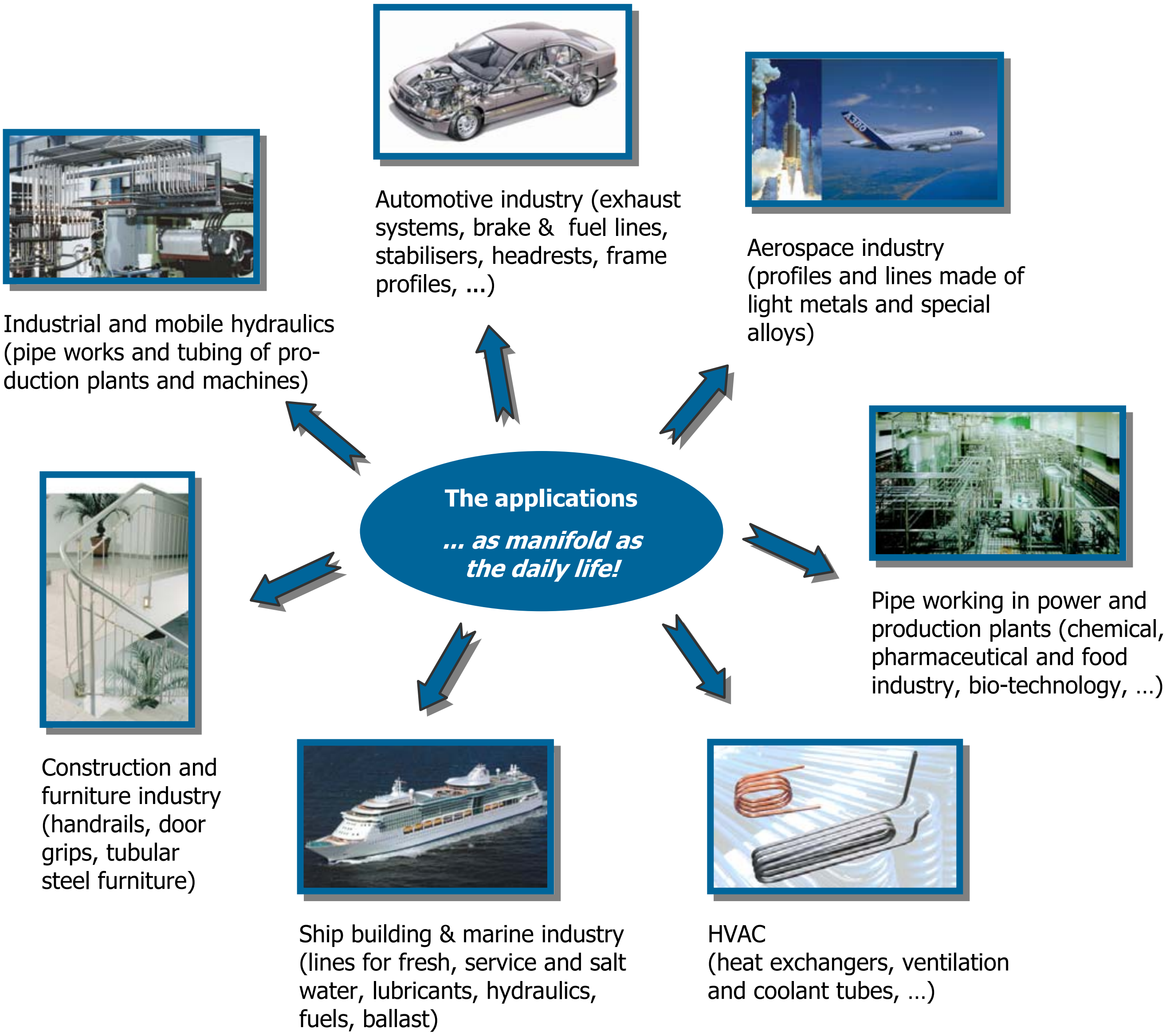



*Figure 11: Examples of tube/pipe bending applications.*

## 6. Advantages of Tube/Pipe Bending

Our present state of technology allows the production of complex construction elements rationally and precisely in one single working step by forming under bending conditions. But particularly in pipeline construction or in the installation business, where bending as a production method has been neglected for a long time and conventional - often expensive - connection techniques (i.e. welding) were used instead, bending has gained importance in the past years, due to its large variety of advantages. This is because the modern pipe bending machines have made it possible to optimally combine processing precision with productivity - not forgetting the high operation comfort.

In comparison with welding, the bending technology shows up with several economical as well as production-technological advantages. For example, by saving expensive fittings, not only material costs, but also the expenses for acquisition and storage can be lowered immensely. Production time and costs for bending are also clearly lower than those for welding connections (including preparation of the welding seam and finishing works). Production failures, which often occur when welding, are completely avoided with the application of the bending method. Furthermore, due to lower pipeline resistance, the fluidic behaviour is improved in bent pipes, compared to conventional fittings. By eliminating connection parts, which always represent critical construction elements, potential danger zones in the pipeline system are reduced to a minimum, which finally results in a longer service life of the pipeline system.

## 7. Influences on Pipe Bending

The bending results are determined by the properties of the original pipe, the quality and nature of the bending tools, the different parameters, which can be set at the bending machine as well as all kinds of environmental influences, and last, but not least, by the operator himself. Fluctuation of the material quality from one pipe producer to the other or even from different charges already has a definite influence on the results. As a rule you can say, the cheaper the production of the original pipe, the larger its tolerances. Fluctuations can be found in the material itself (e.g. where the chemical composition, the yielding point, ultimate tensile strength, annealing condition, hardness or welding seam structure are concerned), but also in the dimensions of the pipe (diameter, wall thickness, position and thickness of the welding seam). In order to maintain constant dimensions and properties of the basic material, it is important to obtain the pipes necessary for the production of a single order from one supplier, and if possible, even from the same charge. The acquisition of pipes, which are extremely expensive at first glance, but also of a high quality, may quickly prove its value, when you find the consecutive shaping works completely problem-free.

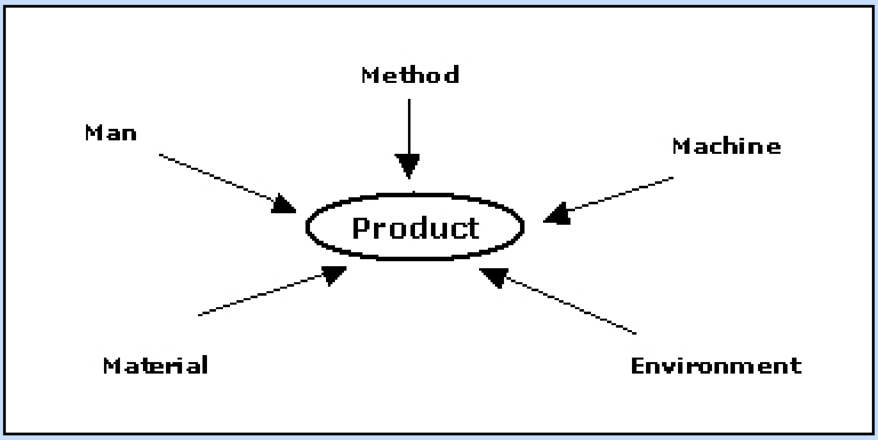



*Figure 12: Influences on Tube/Pipe Bending.*

Additional to the material influences are the influences affected by the machine. Here we must name, among others, the bending angle, bending radius, bending speed, shape and position of the mandrel, plane of bend (that means the position of the welding seam when bending lengthwise welded pipes), state of the pressure die (rigid, travelling or with boost) and lubrication, which altogether have an influence on the quality of the bended part. Finally, the experience of the machine operator also has to be taken into account, the sensitive touch, with which he sets up the bending tools and the bending parameters, is important for successful work.

## 8. Quality of bent Tubes/Pipes

The general quality term nominates the totality of properties and characteristics of a unit, referring to its ability to fulfil determined or presupposed requirements. The product quality can be judged either by metrical (determinable by measuring) or attributive (classification either as good or bad) quality characteristics. If you look at a bent pipe shape, you can judge the product as "good, if neither collapse of the cross-section, cracks, wrinkles, bulges nor any similar faults can be detected. Metric quality properties are bending angle, straight lengths, wall-thickness, ovality or roughness of the surface. Given tolerance ranges as a precondition allow separation of the pipes in good products or rejects, according to these properties.

# ACKNOWLEDGEMENTS / LITERATUE

*Bauer, D. / Khodayari, G.*
Rohrrückfederung beim Biegen prozessbegleitend kompensieren, in: Bänder, Bleche, Rohre. 33. Jahrgang (1992), Nr. 7 - Juli, S. 27-37. Würzburg: Vogel-Verlag.

*Bauer, D. / Weber, M.*
Rückfederungskompensiertes Biegen von Stahlrohr. Sonderdruck aus: Stahl 93 (1993), Heft 1, S. 90-92. Düsseldorf: Verlag Stahleisen.

*DIN 8586*
Fertigungsverfahren Biegeumformen. Einordnung, Unterteilung und Begriffe. Berlin: Beuth-Verlag.

*Franz, W.-D.*
Maschinelles Rohrbiegen, Verfahren und Maschinen. Düsseldorf: VDI-Verlag, 1988.

*Khodayari, G.*
Rückfederung, Ovalisierung und Wanddickenänderung beim Rohrbiegen. Universität Siegen, 1998.

*Khodayari, G.*
Untersuchungen zum elastisch-plastischen Biegen von Stahlrohrprofilen. Dissertationsschrift, Universität Siegen, 1993.

*Marczinski, H.-J.*
Kaltbiegen von Rohren, in: VDI-Berichte Nr. 357, S. 109-112, Hamm 1979.

*Seidel, P. / Richter, W.*
Streng geheim und doch beherrschbar, in M&T Metallhandwerk, Heft 1-2003, S. 11-13, Lübeck: Coleman-Verlag.

Stange, E.P.
The Skinny On Tight-Radius Rotary Bending, in: Tube & Pipe Journal, Heft 6-2000, S. 22-25.

*Stange, R.R.*
Rohrbiegetechnik. Grundsätze - Methoden - Biegewerkzeuge - Verfahren - Entwicklungen. Tools for Bending Inc., Denver (Colorado), 1997.

*Tapper, J.A.*
Optimize Your Tube-Bending Operations. Tooling and Equipment Setup - Keys to Success, in: Metal Forming, Ausgabe Juni 2000, S. 66-72.

*Tingley, W.Q.*
Building a better tube bend-ing en-cy-clo-pe-di-a, als Fortsetzungsartikel erschienen in: Tube & Pipe Journal, Heft 7-2002 bis Heft 5-2003.