Ball Bearing

Bar Extrusion

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Synonyms

Extrusion; Extrusion of sections

Definition

Pushing a billet enclosed in a container through a die to form an extrudate.

Theory and Application

Introduction

Bar extrusion is a process in which a block of metal (billet) is forced to flow by compression through a tool (die) opening of a smaller cross-sectional area than that of the original billet. There are two basic types of bar extrusion: direct and indirect. The most important and common method used is the direct extrusion (Lange 1988). Figure 1 shows the principle of direct bar extrusion where the billet is placed in the container and pushed through the die by moving a ram towards the die (Saha 2000).

In indirect bar extrusion, the die at the front end of the hollow ram moves relative to the container, but there is no relative displacement between the billet and the container as shown in Fig. 2. Therefore, indirect extrusion is characterized by the absence of friction between the billet surface and the container. The absence of friction leads to reduced axial extrusion forces compared to direct extrusion. Therefore, indirect extrusion is used for the forming of heavy extrudable alloys. But the major disadvantage of the method is the strong limited die design due to the required hollow ram geometry.

A third type of bar extrusion, which is rarely applied, is hydrostatic bar extrusion. This process utilizes a hydrostatic medium and there is no direct contact between ram and billet (Fig. 3). The pressure of the ram is transferred through the hydrostatic medium to the billet. In hydrostatic extrusion, friction as well as shear forces...
take place only between the billet and the die (Bauser et al. 2001; Sheppard 1999). It is difficult to seal the container, which is a drawback of the hydrostatic extrusion.

**Stages of Bar Extrusion**

In the most common direct extrusion process, pressure reaches a maximum when the material filled the container. The process can be described with three different phases:

1. The billet is upsetting and pressure rises to its peak value.
2. The pressure decreases as the billet length is decreasing.
3. The pressure shows a sharp rise as the discard material is compressed (usually the process ends at this point and the rest material is removed).

A typical force-displacement curve is shown in Fig. 4.

The parameters that influence the force can be given as:
- Temperature of container, die, and associated tooling
- Billet material
- Extrusion temperature
- Extrusion speed
- Extrusion ratio
Neglecting the shear forces at the die interface, the total extrusion force in direct bar extrusion can be calculated as:

\[ F_{\text{total}} = F_{\text{ram}} = F_{\text{ideal}} + F_{\text{shear,container}} + F_{\text{shear,die}} \]

\[ F_{\text{ideal}} = C \cdot \ln \left( \frac{A_{\text{container}}}{A_{\text{extrudate}}} \right) \cdot A_{\text{container}} \cdot \sigma_{fm} \]

where \( C \) is a constant, \( A_{\text{container}} \) and \( A_{\text{extrudate}} \) are cross-sectional areas of container and extrudate, respectively, and \( \sigma_{fm} \) is the mean flow stress.

Maximum shear force can be calculated as

\[ F_{\text{shear,max}} = \pi \cdot D_{\text{container}} \cdot \tau \cdot \left( l_0 - l_{\text{rest}} \right) \]

Materials and Products of Bar Extrusion

Materials with high formability are suitable for bar extrusion: aluminum and its alloys, copper, etc. The common materials and their extrusion temperatures are listed in Table 1 (Bauser et al. 2001).

Utilizing bar extrusion, long profiles can be produced (Ostermann 2007; Fritz and Schulze 2008). The variety of producible profile cross sections is immense: solid sections of bars and rods and hollow sections with open and closed profiles as well as tubes (Fig. 5). Closed hollow profiles and tubes can be further processed by hydroforming and bending for the manufacturing of profile structures.

Material Flow

In Fig. 6 deformation zones in bar extrusion of AlMgSi0.5 can be seen. With the help of AlSi5.5 pins embedded in AlMgSi0.5, the material flow, i.e., shear and dead zones, is made visible (Schikorra et al. 2006).

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Material</th>
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<tr>
<td>100–260 °C</td>
<td>Lead</td>
</tr>
<tr>
<td>150–300 °C</td>
<td>Zinc</td>
</tr>
<tr>
<td>300–400 °C</td>
<td>Magnesium</td>
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<tr>
<td>350–500 °C</td>
<td>Aluminum</td>
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<tr>
<td>550–1,000 °C</td>
<td>Copper</td>
</tr>
<tr>
<td>1,000–1,200 °C</td>
<td>Steel</td>
</tr>
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Bar Extrusion, Table 1 Ordinary bar extrusion materials with suitable extrusion temperatures

Bar Extrusion, Fig. 5 Typical bar extrusion products: solids, open and closed hollow profiles, and tubes
Bearing

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Synonyms
Aerostatic bearing; Angular contact ball bearing; Ball bearing; Electromagnetic bearing; Hybrid bearing; Hydrodynamic bearing; Hydrostatic bearing; Roller bearing; Spindle bearing

Definition
A bearing facilitates the low-friction relative motion between two machine elements while simultaneously transmitting the forces between them as well as guiding and positioning them relative to each other.

Theory and Application

Introduction
Bearings allow relative rotational and translational motion between two machine parts. Apart from transmitting radial and axial forces (in rotary bearings) and forces and moments transverse to the direction of motion (in linear bearings), they define the relative positions of the machine elements supported by the bearings.

Bearings are core components of all production machines and are often of great importance for the performance of these machines. In a machine tool, for example, different types of bearings are used for different applications: Linear guidings are used for feed axes. Rotary bearings are used for rotary axes, threaded spindle drives for linear axes, and bearings for main spindle shafts, among other things.

In machine tools, the load capacity, the stiffness, and the speed capabilities of the bearings determine the cutting performance. The stiffness also affects the achievable machining accuracy. Bearing friction, in turn, contributes to the machine’s energy consumption, and bearing life can directly affect the downtimes of the entire system.

Bearing Types
As shown in Fig. 1, the same basic bearing principles can be used in rotational and translational applications.

In hydrostatic and hydrodynamic bearings, a lubricant film separates the contact surfaces of the two mated elements. Whereas the necessary oil pressure is provided by a pump in hydrostatic
bearings, in hydrodynamic bearings the lubricant film is only formed during operation through the relative motion of the two surfaces. The main advantage of a hydrostatic bearing is that a stable lubricant film is present regardless of the operating state and hence the bearing is also suitable for low speeds or regular acceleration and braking operations. The disadvantage is the additional need for a pump and pipes. Hydrodynamic bearings, in contrast, are only suitable for applications with adequately high speeds and infrequent acceleration and braking because they would otherwise often run in mixed friction mode and wear would accordingly occur. Both bearings share a limited suitability for extremely high speeds due to the relatively high friction between the driven components and the lubricant.

In aerostatic bearings, which are basically designed in the same way as hydrostatic bearings are, air or any other gas is used for separating the supported elements. This produces very low bearing friction due to the significantly lower viscosity of the gas and the high volumetric flow rate, making these bearings suitable for extremely high speeds. On the other hand, given comparable dimensions, these bearings exhibit much lower load capacity, stiffness, and damping than hydrostatic bearings do. Application areas for these bearings include ultrahigh-precision machines in which low machining forces are generated at very high speeds (Weck and Brecher 2006).

Magnetic bearings use electromagnets to transmit forces between two machine elements and position them relative to each other. Because the gap between the two components is filled with air here, too, these bearings exhibit a similarly low amount of friction as aerostatic bearings do and are hence likewise suitable for extremely high speeds. At the same time, the bearing control
system allows bearing properties such as stiffness or damping to be adapted during operation. In this way, the vibration behavior of a main spindle can be actively manipulated, for example, to suppress chatter (Tamisier et al. 2001).

In sliding (or plain) bearings, the two mating elements are separated by an intermediate layer made of a material with a minimum coefficient of friction with respect to the supported machine elements. This is extremely important because, in these bearings, solid-state friction always occurs between the two machine parts and the intermediate layer, which in many cases is made of a polymer or a nonferrous metal. This friction severely limits the maximum relative surface speeds. However, these bearings are also suitable for applications with especially high demands on cleanliness due to the complete lack of lubrication.

The most commonly used bearings are roller bearings. Rolling elements are arranged between the parts to be supported, yielding a rolling motion between the supported machine elements and the rolling elements. This ideally results in pure rolling friction; in reality, however, there can be sliding-rolling friction overlaps due to factors such as the bearing design or the operating conditions. The widespread application of this bearing principle can be explained by the comparatively low costs, the ease of use, the high degree of standardization, and the diversity of properties that can be obtained with different roller bearing designs, among other things. Accordingly, further discussion will focus on roller bearings.

Table 1 provides an overview of the various bearing types and their main characteristics.

There are three main types of roller bearings used in machine tool main spindles: Angular contact ball bearings (so-called spindle bearings) with a contact angle between 15° and 25° can carry radial and axial loads and are mainly characterized by the best speed capabilities of all roller bearings. Tapered roller bearings can also carry combined loads and have a higher load capacity and stiffness than spindle bearings of comparable size do. Due to the line contact between the rolling elements and the raceways and the greater amount of friction arising from it (in comparison with the point contact occurring in spindle bearings), the suitability of these bearings for high-speed applications is limited. Cylindrical roller bearings are extensively used in combination with spindle bearings in applications in which high radial stiffness and load capacity are required. However, their internal
geometry makes bearings of this type very sensitive to differences in the thermal expansion of the inner and outer ring and restricts their range of applications (Butz 2007).

**Properties and Operational Behavior of Roller Bearings**

Because the operating behavior of the bearings has a significant effect on the operating characteristics of the overall machine, the suitability of the selected bearings for the planned application case must be investigated carefully. The main criteria in the first phase of bearing selection are the load capacity and the speed capabilities. The load capacity of a bearing mainly depends on the materials used, the inner and outer geometries as well as the size of the bearing, the number of rolling elements, and the bearing type. The relationship between the load rating and the bearing loads expected in operation can be used to estimate the bearing life. This is a statistical value, which gives the probability of survival of the bearing for a given number of load cycles (revolutions).

The limiting speed $d_{ln}$, also called high-speed coefficient or realizable speed coefficient, is often expressed by the multiplication of bearing rotational speed ($n$) and bearing pitch diameter ($d_m$). It represents the limit up to which a bearing can be operated. It depends on various factors and is mainly influenced by the bearing friction, which increases with increasing speed and load, and the associated heating up of the bearing. This increase in temperature can cause damage to the lubricant and the bearing’s polymer components and, in extreme cases, even the steel used in the bearing. In grease-lubricated bearings, the maximum allowable speed can also be limited by the maximum allowable shear stress for the grease or the ability of the grease to reliably supply the bearing gap with lubricant, even at high speeds (not always the case due to the limited flow of the grease). At very high speeds, the additional bearing load arising from the centrifugal forces acting on the rotating parts must also be taken into account. Depending on the bearing type, the bearing properties may also change with changing speed. For example, in spindle bearings at high speeds, the rolling elements undergo radial and axial displacement, resulting in a decrease in the contact angle at the outer ring and hence a decrease in the axial bearing stiffness.

Whereas the load capacity of a bearing only provides information about whether or not and how long a specific load can be withstood, the bearing stiffness and concentricity are especially decisive for applications in which accuracy plays a major role, for example, in machine tools. They are a measure of the magnitude of the relative displacement of the bearing machine elements under the operational loads.

A large number of bearing properties relevant to reliable operation can today be calculated, and hence incorrectly designed bearings are rarely directly responsible for bearing failure today. As shown in Fig. 2, in most cases, bearing failure can be attributed to the tribological system of the bearing, which is mainly affected by the lubricant. In addition to the causes specified in the figure, spontaneous overloading of the bearings resulting from tool collisions plays a role as a cause of failure, especially in main spindle bearings.

**Bearing Arrangements**

Especially in the case of high-precision bearings or at high speeds, the bearing arrangement is decisive for the operating properties of the entire bearing assembly. More detailed information on the various ways of arranging and preloading bearings and on the effects on operating conditions can be found in the entry entitled “Spindle.”

**Bearing Lubrication**

As mentioned above, lubrication of bearings is key to the reliable operation of the bearings and hence the entire machine. The task of the lubricant is to form a stable film between the two mated rolling parts, thereby preventing direct contact between the parts and hence minimizing wear and friction. In addition, certain lubrication types are suitable for transporting wear particles and especially heat out of the bearing. At the same time, however, contact between the lubricant and the rotating bearing elements also generates friction and heat.
Approximately 90% of all roller bearings used are grease lubricated (Schaeffler Technologies 2004). The main advantage of grease lubrication is the ease of use. However, in lifetime-lubricated bearings, the grease service life can limit the bearing life. In addition, grease-lubricated bearings are not suitable for extremely high speeds due to the poor heat dissipation and especially due to the danger of insufficient lubrication.

Whereas $dn$ factors ($n \cdot dm$) of up to $2 \times 10^6$ mm/min can be achieved with grease lubrication, oil-air lubrication, in which an air stream conveys oil droplets into the bearing, is suitable for $dn$ factors of up to $3 \times 10^6$ mm/min. Limitation of bearing life by the grease service life and the risk of inadequate lubrication are no longer relevant because, for example, the lubricant can be supplied directly through the outer ring, and hence reliable supply of lubricant can be ensured even at extremely high speeds (Table 2).

Whereas oil-air lubrication basically allows no heat to be dissipated from the bearing via the lubrication medium or the air stream, oil jet lubrication utilizes the volumetric flow of the lubricant to cool the bearing. This method produces considerably more lubricant friction than is the case with other lubrication variants. Nevertheless, combined with sufficient cooling it also yields the highest $dn$ factors, that is, up to $4 \times 10^6$ mm/min (Brändlein 1995). As it is the case for all other lubrication methods with external lubricant supply, a disadvantage is the expenditure required for additional components such as pumps, seals, and oil lines.

Recent Developments

In recent years, developments in spindle bearings have focused on improving the speed capabilities (among other things). The use of smaller balls has allowed the centrifugal effects such as ball displacement and the resultant decrease in stiffness to be reduced. A similar effect is obtained with the use of ceramic balls. The much lower density of ceramic balls in comparison with that of conventionally used steel results in a much lower weight, leading to lower centrifugal loads. In addition, steel-ceramic contacts have considerably better tribological properties than steel-steel contacts do, resulting in lower bearing friction and wear. Because of the ceramic’s higher Young’s modulus, bearings with ceramic balls exhibit higher stiffness than that of conventional bearings of the same design. However, this also leads to increased normal stresses at the rolling element-raceway contacts (Abele et al. 2010).

The use of high nitrogen steels (HNS), in which at least part of the carbon in the steel is substituted by nitrogen, allows for the production of bearing rings with superior corrosion resistance and higher load ratings, leading to a longer life under identical loading conditions (Harris and Kotzalas 2007).

In various areas, coatings can improve the performance characteristics of roller bearings. The achievable effects especially include a reduction in friction and wear or an increase in corrosion resistance (Schaeffler Technologies 2009). For example, coated spindle bearings
have been shown to exhibit considerably improved operating characteristics in insufficient lubrication conditions. One challenge for future developments in this area is to solve the problem of coating detachment (Brecher et al. 2007) (Fig. 3).

To avoid the described ball displacement caused by centrifugal forces in spindle bearings and the related changes in stiffness, so-called three- and four-point bearings in which there is a second contact point between the ball and the outer ring or additionally a second contact point between the ball and the inner ring were developed. This variation in geometry prevents the migration of the balls toward the vertex of the outer ring raceway with the above-described consequences but also results in increased bearing friction due to the additional rolling contact(s) (Brecher et al. 2007; Abele et al. 2010) (Fig. 4).

In cylindrical roller bearings, modifications to the rolling elements and the raceway geometry enabled the radial stiffness and consequently the sensitivity to stresses resulting from differences in expansion between the inner and outer rings to be lowered. This improves their suitability for high speeds. Additional improvements can be achieved through the use of ceramic roller bearings, which contribute the advantages described above (Brecher et al. 2007; Butz 2007).
Bending (Sheets)

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Synonyms

Folding (for 180° bends in thin materials only)

Definition

Bending is a forming process in which a blank is locally formed along a bending line as result of applying a bending moment. Starting from a flat blank, complex 3D parts can thus be formed, composed of flat flanges and semi-cylindrical bend connections. Below 15 mm thickness the process is known as sheet metal bending, while for blanks above 15 mm plate bending is the more common terminology.

Theory and Application

Bending Methods

Different methods can be applied to impose a bending moment on a sheet metal blank (Lange 1985). The most common techniques consist of positioning the sheet to be formed with the bend line coinciding with the centre line of a V-die and pressing a punch tool in the orthogonal direction (Fig. 1 right). The force...
exerted during this operation is typically delivered by a press brake (Fig. 1 left). Two main variants of this method can be distinguished. When the sheet is formed by imposing forces via line contacts at the shoulders of the die and the punch tip, the process is referred to as air bending, also known as three point bending (Fig. 2a). When the sheet to be formed is in full contact with both the punch and the die in de bending zone, the process is referred to as bottoming (Fig. 2b). Compared to bottoming, air bending offers a higher flexibility since different angles can be formed with the same tool set (a punch and die with a tool angle for the punch that is significantly higher than the V-die angle: Fig. 1 right) by controlling the Y axis displacement of the ram of the press brake. Bottoming offers better dimensional accuracy of the
resulting parts since springback can be limited in this process variant, resulting in an achievable bend angle accuracy of $\pm 15\%$ (Serruys 2006).

In wiper bending (Fig. 2c) and swivel bending (Fig. 2d) one of the two flanges bordering a bend line is clamped and the bend is formed by respectively a translating movement of a wiper tool or a rotational movement around a fictitious bend centre line.

**Stress: Strain**

In principle the different bending methods result in planar strain deformations. This planar strain deformation is only a correct assumption at sufficient distance from the ends of the bend lines (a multiple of the sheet thickness) where strains in the bend line direction are restricted by symmetrically behaving neighbouring material. The stress and strain components in this case are shown in Fig. 3. Near the ends of a bend line this assumption is not valid and the so called anticlastic effect can be observed (Fig. 4).

During a bending operation the moment imposed by the tooling results in the inner part of the cross section of the sheet in the deformation zone to be under pressure while the outer part undergoes tensile stresses. Releasing the work-piece causes elastic springback, resulting in a new equilibrium typically characterised by residual stresses in $x$ direction as depicted qualitatively in Fig. 5. The degree of springback severely depends on the elasticity limit and the strain hardening behaviour of the material to be formed.

**Bending Strain**

In case of large radius of curvature the strain can be assumed as a linear function of the distance from the middle surface (Marciniak 2002), the middle surface being defined as the surface characterised by $\sigma_x = 0$. However, in case of bending with small radius of curvature the middle surface changes position during deformation. In general the strain distribution is:

$$\varepsilon_1 = \ln \left( \frac{l_s}{l_0} \right) + \ln \left( 1 + \frac{y}{\rho} \right)$$

(1)

In this formula $l_s$ stands for the length of middle surface after deformation, $y$ for the distance from the middle surface and $\rho$ for the radius of curvature.

**Bending Force**

For air bending the following formula can be used as an approximation for the bending force $P(N)$:

$$P = \frac{1.42 \cdot L \cdot Rm \cdot s^2}{V}$$

(2)

In this formula $L$ stands for the bend length (mm), $Rm$ for the tensile strength of the material (N/mm$^2$), $s$ for the sheet thickness and $V$ for the V-die opening (mm).

For bottoming significantly higher forces are used, resulting in a higher load on the applied tooling.

Local heating allows to significantly reduce the bending force (Duflou and Aerens 2006).

**Blank Design: Unfolding Calculation**

As an effect of the bend radii the unfolded dimensions of a blank cannot be determined as the sum of the over measured flange dimensions. The difference between both is referred to as the bend allowance ($BA$). The BA can be determined experimentally. For mild steel the DIN6935 standard also offers a series of heuristic formulas. The standard uses the assumption that the neutral fibre (fibre with no effective strain) is showing
a constant radius of curvature. The radius is expressed as:

\[ R_i + k \cdot \frac{s}{2} \]  

(3)

with \( R_i \) the internal bend radius and \( s \) the sheet thickness. Setting factor \( k \) equal to 1 corresponds to the situation with the neutral fibre situated in the middle of the material. Coefficient \( k \) can be determined as follows (Fig. 6):

\[ k = \frac{s_i}{s_{0/2}} \]  

(4)

Additionally for \( k \) the following experimentally determined expression can be used for steel:

\[ k = 0.65 + \frac{1}{2} \cdot \log \left( \frac{R_i}{s} \right) \]  

(5)

The length of the folded part \( L_0 \) is usually defined as follows (Fig. 7):

\[ L_0 = a + b + \Delta L \]  

(6)
factor $k$. For acute angles $A$, $BA$ can be determined as follows:

$$BA = \pi \cdot \frac{180 - A}{A} \left( R_i + k \cdot \frac{s}{2} \right)$$  \hspace{1cm} (7)

The formula for obtuse angles is:

$$BA = \pi \cdot \frac{180 - A}{A} \left( R_i + k \cdot \frac{s}{2} \right) - 2 \cdot (R_i + s) \cdot \tan \left( \frac{180 - A}{2} \right)$$  \hspace{1cm} (8)

For bend angles higher than $165^\circ$, $BA$ is assumed to be negligible.

Bend Modelling

In order to guarantee bend angle accuracy the punch displacement (Y-axis in a CNC press brake) corresponding to the correct bend angle after springback needs to be known as input for the operation in a conventional bending approach.

In the 1990s several research efforts on bend modelling were reported. In the results published by Lutters et al. (1995), the described Equilibrium Model assumes a plane strain situation. The influence of shear stress and variable orthogonal reaction forces at the contact points with the die, as well as friction forces are incorporated in the model. The reported deviations between calculated and measured punch displacements, are of order of magnitude 0.1–0.2 mm, once the parameters in the constitutive law have been adjusted to the behaviour of the used material.

The required punch displacement value is highly sensitive for the exact material thickness and the material properties (elasticity limit and hardening behaviour). For correctly known material parameters the bend shape and springback, and thus the required punch displacement, can be determined with resulting bend angle and springback prediction accuracies of respectively approximately $1.0–0.3^\circ$ (Aerens 2000). Typical variations in material properties and thickness are thus that an accurate input of these data would require detailed material testing for individual sheets (Streppel et al. 1997). For example, sheet thickness variations of 0.15 mm are considered within tolerance (DIN1541) for 1.5 mm thick sheets. Consequence of these observations is the need for adaptive bending in order to assure bend angle tolerances smaller than $+/-1^\circ$.

Most recent achievements on the modelling of sheet metal bending can be categorized into following groups (Wagoner et al. 2013):

1. Plastic constitutive equations (Roters et al. 2010)
2. Variable Young’s modulus (Sun and Wagoner 2011)
3. Through-thickness integration of stresses (Wagoner and Li 2007)

Consideration of the aforementioned features of materials results in more accurate prediction of bending line, bending force and springback.
Adaptive Bending

In adaptive bending the predicted bend angle as a function of the punch displacement is compared to the instantaneous bend angle obtained during the bend stroke. Based on the observed deviation an updated target punch displacement can thus be determined. Several in-process measurement systems have been developed for this purpose. An overview of different measurement principles can be found in (Duflou et al. 2005): see Fig. 8.

With a sufficiently high sampling rate for the in-process measurement system, adaptive bending can be performed without significant productivity loss. Adaptive control allows to control bend angles with a precision of $\pm 20'$ (Serruys 2011).

Cross-References

▶ Bending (Tubes, Profiles)
▶ Springback

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Bending (Tubes, Profiles)

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Synonyms

Pipe bending; Profile bending; Section bending; Tube bending

Definition

According to DIN 8586 bending is the forming of a solid body, in which the plastic state is mainly induced by a bending load. The further processing of tubes and profiled semifinished products by bending processes to workpieces with different shapes, such as rings, segments, and 3D shapes, is referred to in this context as tube and profile bending. Tubes are considered as special profiles with circular cross sections.

Theory and Application

Introduction

Bending is one of the most commonly used procedures in sheet metal processing industry and is used in different application areas. Also various profiled semifinished products with different cross-sectional shapes can be produced and further processed by bending. In addition to sheet metals, wires, strips, rods, tubes, profiles, and preformed components can be shaped by bending on various forming machines.

In the literature, the bending procedures for tubes and profiles are often classified in the same way as the sheet metal bending processes. However, tube and profile bending processes are to be treated differently because of their special features. This is mainly due to the fact that the cross sections have special features that must be preserved after bending (Chatti 1998).

Application Fields of Bent Profiles

The use of bent profiles with their diverse cross sections, different contours, and multifunctional properties opened up new design opportunities for innovative lightweight construction products in the past and promises to be the basis of lightweight construction perspectives in the future. Profiles allow the construction of structures with low weight and little joining and cutting efforts showing improved space saving and aerodynamic properties (Jeswiet et al. 2000; Kleiner et al. 2003).

The application fields of such structures will be found where lightweight construction allows a higher acceleration capacity at the same driving power or energy savings. This is why bent profiles have been used more and more in various fields of traffic engineering (automobile industry, utility vehicles construction, railway...
manufacturing, shipbuilding) as well as in aircraft construction. Other further advanced application fields can be found in civil engineering, in mechanical and apparatus engineering, in the furniture industry, in the material-handling technology, as well as in lifting and conveying systems (Fig. 1). But even in the fields of architecture or design, for example, in the furniture industry, the use of structures made of bent tubes and profiles opens a wide range of innovative opportunities.

These selected examples show that profiles with straight and curved contours are well suited for the use in lightweight construction (Chatti 2005). They offer a great potential for the integration of functional features and allow the design of thin-walled cross-sectional shapes with high stiffness. Especially the possibility of the application of bent profiles offers considerable advantages in comparison with the traditional proceeding of the assembly of many individual components. Bent profiles, in addition, offer a great freedom of design and are capable of meeting a large number of structural requirements. Through the high flexibility in shaping of 2D and 3D bent profiles, also new ways for lightweight construction can be opened up (Chatti et al. 2010; Hermes 2012). Especially in traffic systems, this leads to lower energy consumption and CO₂ emissions.

**Classification of Profile Bending Procedures**

Bending of profiles is an important part of workpiece manufacturing in the metalworking industry. The profiles can be formed either in a closely limited segment with continuous or discontinuous feed or along their whole length. Machines for profile bending have already been used since the beginning of the twentieth century. With these machines, almost all profile cross-sectional shapes can be formed to different workpiece shapes. Due to the great number of possible profile cross sections, bending shapes, demands on the component, and the lot sizes of mass production, a variety of different bending procedures have been used in practice. These can be subdivided into methods of “form-closed shaping” (shaping with shape-defining rigid tools) and such of “kinematic shaping” according to the way they are used to form the desired shape. A second
subdivision according to DIN 8586 concerns the kind of tool motion, which can be linear or rotary.

The first group comprises the procedures stretch bending, wiper bending, and tube bending (with and without mandrel), having a rotary tool motion to execute the bending operation, and the procedures profile bending with presses, bending under internal pressure, Hamburger procedure, axial roll bending in a die, and shear bending, which work with a linear tool motion (Fig. 2).

Form-closed shaping is here defined as forming with shape-defining rigid tools that contain the desired workpiece geometry, especially with respect to the curvature, and considering for springback of the profile during unloading. Due to the fixed geometry of the tool, the geometry of the workpiece is also fixed, leading to a high reproducibility and a shorter processing time in many cases (Geiger and Sprenger 1998).

The second group of kinematic definition of the bending contour can also be subdivided into procedures with rotary and linear tool motion. The roll-bending procedures (three-, four-, and multiple-roll bending), incremental tube forming, sweeping, and other process combinations and variants are grouped according to the principle with rotary tool motion. Three-point bending, free-form bending, bending with extrusion, bending with expansion, and profile bending with an elastic pad follow the principle of linear tool motion (Fig. 3).

The presented procedures can be further differentiated by variants in practice. An exception here is laser bending and thermal-induced bending that belong to neither of the two main groups. These are forming techniques which allow the forming of profiles by thermal residual stresses instead of external forces.

The kinematic bending processes are more flexible than the form-closed processes. The final shape of the part is not determined by the shape of the tool, but rather by the relative movements of tool and workpiece. Normally, the final shape is produced by a number of successive steps that can be changed easily from workpiece to workpiece, yielding the high flexibility of these processes.

There are other classification strategies of the profile bending procedures like the subdivision according to the applied type of load or form of

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<thead>
<tr>
<th>Form-closed contour</th>
<th>Rotary tool motion</th>
<th>Linear tool motion</th>
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<tbody>
<tr>
<td>Stretch bending</td>
<td>Wiper bending</td>
<td>Profile bending with presses</td>
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<td>Tube bending with mandrel</td>
<td>Tube bending</td>
<td>Bending under internal pressure</td>
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<td></td>
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<td>Axial roll bending in a die</td>
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*Bending (Tubes, Profiles), Fig. 2* Profile bending procedures with form-closed definition of the bending contour
energy to produce the plastic bending. The active principles of all processes primarily focus on the following objectives:

- Avoidance or reduction of springback of the bent parts to increase the bending accuracy
- Minimization of the cross-sectional deformation and the thinning or thickening of the wall thickness, especially for small bending radii
- Increase of flexibility in the design for a freely definable bending contour
- Increase of process reliability and production velocity to reduce costs

The first step of a new bending problem always consists of choosing the best suitable manufacturing procedure. The selection of the best bending process and the suitable tools is influenced by the following technical and economic criteria:

- Kind of the profile cross section (hollow or open profile)
- Kind of the bending contour (two-/three-dimensional, small/large bending radii)
- Demands on the profile surface
- Number of pieces
- Machine, tool, and bending costs

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*Bending (Tubes, Profiles), Fig. 3* (left) Profile bending procedures with kinematic definition of the bending contour, (right) Thermal-induced bending procedures
Requirements on Bent Profiles

Bent profiles as structural parts imply highest quality requirements regarding dimension and shape accuracy. The time and cost situation in mass production makes such demands on a trouble-free assembly and automatic joining of bent profiles particularly necessary. Thus, the maintaining of certain repetition accuracies is indispensable for the industrial usage of bent profile manufacturing processes. The rapid determination and compensation of disturbances during the manufacturing of bent profiles becomes, therefore, significant. In addition, the time, cost, and resource consuming experimental determination of optimal manufacturing parameters are to be reduced to an absolute minimum.

In some application fields, e.g., in the automotive industry, high tolerances of curved profiles are required which cannot be achieved by conventional bending procedures or only at large expenditure. This forces the use of new and/or improved forming techniques combined with calibration procedures. Only innovative procedures and/or procedure combinations can meet the requirements. Hydroforming is often used as calibration procedure for hollow profiles. With this procedure, complex three-dimensional curved profiles can be manufactured in a single manufacturing step with a reproducibility of highest quality claims. The quality of the hydroformed workpiece and the reliability of the process are, however, defined by the material and geometrical properties of the initial parts.

As final parts or as semifinished products for hydroforming, bent profiles have to meet the following requirements (Chatti 2005):

- Accurate contour (constant radius or radii distribution)
- Absence of cross-sectional deformations
- As constant as possible wall thickness
- Sufficiently high remaining formability
- Quasi homogeneous material structure
- Status of low residual stresses
- Minimum surface damage

If one of these requirements is not fulfilled, neither a successful completion of hydroforming nor the desired quality of the product can be achieved. This has to be considered in each step of the process chain for bent profiles.

Problems of Profile Bending Procedures

A large number of process parameters and their interdependencies affect the profile bending processes and complicate their analysis, simulation, and realization (Fig. 4). This is one of the reasons why some of the profile bending processes still have a low grade of automation and bending processes are still planned in an empirical way. Some of the problems in profile bending relevant for subsequent manufacturing steps and also relevant for the design process of structures are the inaccuracy of the profile contour due to the influence of parameters specific for the workpiece, for the material, and for the tools.

It is very difficult to describe the forming behavior of profiles in an exact way, especially when plastic deformations are considered. Among the influencing factors are the manufacturing method itself of the profiled semifinished product and the residual stress state of the profile before the bending process. Bending processes themselves are characterized by tensile and compressive stresses. Bent profiles therefore show an inhomogeneous distribution of the true strain which is a cause for residual stresses. The cross-sectional shape of the profile and the profile material are subject to different changes before and during the bending process and depend strongly on the profile manufacturing method itself. The deformations of the profile cross section are generally the major problem in profile bending. This problem becomes more crucial with increasing complexity of the profile cross section and higher demands of quality. Due to the elastic–plastic material behavior, springback resulting in geometrical deviations cannot be avoided. In principle, it is possible to compensate springback by overbending. With conventional solution methods, this requires, however, a large number of bending tests to determine the tool adjustment in procedures with kinematic shaping and a remachining of the tools in procedures.
with form-closed shaping and leads to increased manufacturing costs and to higher scrap rates.

Well-known approaches from the field of sheet metal bending with regard to general investigations of the bending procedure consider the sheet metal as a workpiece with the cross-sectional shape of a broad beam. The integrals arising in the bending theory are relatively easy to solve because of the simple geometry or can be evaluated numerically. The cross-sectional area of a profile is more difficult not only with respect to its geometrical treatment, but it also implies a considerably more complicated displacement field during loading. This makes an exact mathematical description of the bending behavior of profiles problematic in comparison with the sheet metal bending, which is mainly given by the following influences (Chatti 2005):

- The ideal case of pure bending moment does usually not occur, since the bending is frequently accomplished by lateral forces or combined stress situations.
- The profile cross-sectional shape is often complex and must be discretized accordingly.
- With increasing profile height, larger strains result at the external fiber than at the internal fiber. The assumption of the equality of tensile and compressive strains over the profile cross section is not valid anymore in the case of profiles contrary to thin sheet metals.
• The profile cross section changes with large true strains by lateral contraction of the zone under tension and by lateral extension of the zone under compression. The assumption that the profile walls remain plane during bending loses its validity in particular in the case of hollow profiles with thin wall thicknesses.

• Contrary to sheet metal bending, the shift of the neutral axis and the forming limit is more distinct.

• With the effect of the cross-sectional deformation, longitudinal, lateral, and shear stresses superpose, whereby a three-dimensional stress state is reached.

• The most important bending factors, e.g., the elastic springback, depend, among other things, on the stress state (therefore on the bending procedure) and on the cross-sectional deformations.

• The bending of asymmetrical profiles has to be treated separately. When bending such profiles, shear stresses arise which cause a twisting of the profiles during the bending process. The cause is the deviation between the center of gravity and the shear center of the cross section in the case of asymmetrical profiles (Fig. 5). In contrast to symmetrical profiles, springback does not take place any longer in the bending plane but in another plane inclined with a certain angle (Fig. 6).

• The kind of workpiece guidance or the measures for the reduction of cross-sectional deformation change the stress state or the friction state between profile and tools. The influences of such effects on the bending process can be analyzed in most cases only with difficulty.

• Through the high bending resistance of profiles, high forming forces are usually required in profile bending. As a consequence, high frictional forces possibly occur between profile and tool leading to comparatively high machine deflections which cannot be neglected anymore.

Besides the similarities between sheet metal bending and bending of profiles, the problems which occur only in profile bending are summarized in Fig. 7. These are as follows:

- Instability of the profile walls (wrinkling)
- Large local strains, especially in the outer layers of the profile
- Large deformations of the cross sections
- Poor accuracy of the semifinished products, i.e., the material properties and the cross section
- Large variety of possible cross sections of the semifinished products
- High stiffness of the semifinished products
- Twisting of the profile cross section in bending asymmetric profiles or symmetric profiles along axes that are no principle axes
- Demand of machines with a large number of controlled axes

**Computation of the Bending Moment**

Given the case of pure bending with plastic deformation (Fig. 8) and taking into account the following assumptions:

- No cross-sectional deformation
- No shift of the neutral fiber
- Constant stress along the profile width
- Profile plane remains planar
Homogeneous and isotropic material properties in cross section and along the longitudinal axis
- Tangential stress component $\sigma_t$ and shear stress neglected
- Plane stress condition ($\sigma_0$; $\sigma_t$)

the stress distribution and the bending moment can be determined according to following equations:

$$ M_b = \int_{-R}^{R} \sigma_0 \cdot r \cdot dA $$

$\sigma_b$: Bending stress
$\sigma_t$: Tangential stress
$\sigma_0$: Normal stress
$R$: Radius of curvature

Bending (Tubes, Profiles), Fig. 6 Springback behavior of profiles

Bending (Tubes, Profiles), Fig. 7 Specific problems in profile bending (Vollertsen et al. 1999)

- Crack
- Collapse
- Wrinkles
- Bulging
- 3D-shift
- Deviation from ideal cross-section
- Torsion
- Local curvature
- Accuracy
or

\[ M_b = 2 \int_0^R \sigma_\theta \cdot r \cdot dA \]  \hspace{1cm} (2)

with

\[ \sigma_\theta = E \cdot \varepsilon_\theta \]  \hspace{1cm} (3)

for the elastically deformed zone

and

\[ \sigma_\theta = C \cdot \varphi_\theta^n \]  \hspace{1cm} (4)

simplified for the plastically deformed zone.

The shape of the profile cross section and the height of the elastically deformed zone are essential in profile bending. For the hollow profile given in Fig. 9, two cases have to be distinguished during the computation of the bending moment:

Case 1: \( R - s \leq r_e \leq R \) (cp. Fig. 9)

The bending moment can be calculated as follows as sum for the moments causing elastic and plastic deformation:

\[ M_b = M_{b,\text{elast}} + M_{b,\text{plast}} \]  \hspace{1cm} (5)

\[ M_b = 2 \int_{r_e}^{R-s} \sigma_{\theta,\text{el}} \cdot r \cdot dA_1 + 2 \int_{r_e}^{R} \sigma_{\theta,\text{pl}} \cdot r \cdot dA_2 \]  \hspace{1cm} (6)

Bending (Tubes, Profiles), Fig. 8  Stress distribution during pure bending with plastic deformation

Bending (Tubes, Profiles), Fig. 9  Height of elastically deformed zone \( r_e \) in case 1
Cross-References

- Bending (Sheets)
- Hydroforming (Sheets and Tubes)
- Residual Stress (Forming)
- Springback

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Definition

Bonding (referred to as adhesive bonding) is a joining method that joins two or more materials by applying and solidifying adhesives.

Theory and Application

Theory

The adhesive bonding is a complex physical and chemical process that creates attractive forces between the substrates (base materials) and adhesive. As shown in Fig. 1, the adhesive bonded joint consists of three areas: cohesion, transition, and adhesion zone. In the cohesion zone, cohesive forces are a result of a number of molecular forces such as intermolecular interactions, mechanical bonds, or chemical bonds within the adhesive. The transition zone is an interphase boundary layer or inter-diffusion segment with nonuniform composition formed by interacting adhesive and the substrate surface. The thickness of the transition zone differs from nanometer to millimeter ranges. In the adhesion zone, adhesive forces are determined by various chemical, mechanical, and electrical interactions at the interfaces.

A number of adhesion theories have been proposed to identify the formation of adhesive forces. The contributed adhesion mechanisms are (1) chemical bonding such as chemisorption theory; (2) physical interaction such as polarization, electrostatic, and diffusion theory; (3) thermodynamical interpretation such as adsorption theory; and (4) mechanical interlocking. No single theory exists to explain the entire property of adhesion on various substrates and adhesives. However, those theories may provide a guideline to understand the principle of the adhesion as the following details (Fig. 2).

*Chemical bonds* by chemical reactions can be formed across the interfaces at the time of contact or during the curing process. The chemical bonds such as covalent and ionic bonds are stronger and more durable than other physical interactions and adsorptions. Thus, the chemical bonds are called as primary bonds, while physical interactions are considered as secondary bonds. *Physical adsorption* can be created by van der Waals forces or the acid–base interaction based on intimate and molecular contacts between the adhesive and substrates. Behaviors of these contacts can be explained in “wetting” theory. The wetting is a contact characteristic of the adhesive and the wetting characteristic can be also explained by spreading behavior of the adhesive. For good wettability, the surface energy of the substrates must be higher than the adhesives. Substrates such as metals, glass, and polymers have higher surface energy than most adhesives. When the...
substrate surfaces are contaminated, the bonding strength can be weakened due to poor wetting by low surface energy of the substrate surface and undesired interactions. In addition, some plastics have a low surface energy. Thus, surface treatment is required to clean the substrate surfaces and to wet and flow the adhesive on the substrate surface well. Inter-diffusion can occur where both the substrate and adhesive are polymer. Sufficient movement of molecules with long chain segments in the polymer create inter-diffusion bonding by intertwining the molecules. Mechanical interlocking can be created that the adhesives penetrate into porous surfaces on the substrates as shown in Fig. 3. To create mechanical interlocking, surface treatment is required to introduce micro-roughness on the substrate surface. The surface roughness can also improve the bonding strength by increasing contact areas between the adhesive and the substrate and to create highly reactive surface which the forces of adhesion can develop. (Jennings 1972)

Figure 4 shows failure types of the adhesive bonded joint under a pull strength test. The cohesive failures in Fig. 4(a) and (b) occur when fracture is developed either within the adhesive and substrate, while the adhesive failure in Fig. 4(c) separates the substrate and adhesive at the interface.

As shown in Fig. 5, the general adhesive bonding line consists of: (1) surface preparation to clean and roughen the substrate surface, (2) preparation of the adhesive, (3) applying and spreading the adhesives on the substrate surfaces, (4) assembly, (5) clamping to support appropriate contact pressure between the substrates and adhesive, (6) curing to solidify the adhesive, and (7) inspection of the bonded joint. Joint design,
surface preparation, selection of adhesive, adhesive application, and curing processes are explained further as follows.

- **Joint Design**: The adhesive bond joint must be considered to provide compressive stress rather than tensile stress and reduce stress concentration and peeling in the bonded joints (Lees 1984).

- **Surface Preparation**: Surface treatment is an essential process to clean and roughen the bonding surface for good wettability of the adhesive. Surface treatment can be performed by mechanical, chemical, physical, and electrical methods. Protection of prepared surfaces is also recommended to prevent re-contamination (Brockmann et al. 2009).

- **Selection of Adhesive**: Selection must be considered with substrate materials, substrate surfaces, curing time, pressure, and temperature.
- **Adhesive Application**: Adhesives are formed as paste, liquid, film, or powder and that status determines an application method. Adhesives are applied in various forms such as spot, line, and surface by spraying, immersion, dripping, rolling, pouring, brushing, coating, knife coating, and stamping depending on viscosity (Habenicht 2008).

- **Curing**: In the curing process, the adhesive molecules are cross-linked to create a strong adhesive joint. To solidify the adhesives, several methods are utilized such as heat, pressure, time, catalyst, vulcanizing, reactivation, and radiation based on characteristics of adhesives (Fig. 6) (Cognard 2006).

### Applications
- Electronics
- Automotive
- Furniture and other woodworks
- Medical devices
- Textile
- Package materials

### References


### Bonding Materials

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### Synonyms

Binder; Bond; Bond systems; Matrix

### Definition

The bonding material is the material that secures the abrasive grain relative to each other in order to form the shape and structural integrity of the abrasive tool such as a grinding wheel, bonded abrasive segment, or abrasive belt.

### Theory and Application

The DIN 8589 classifies processes such as grinding, belt grinding, honing, lapping, free abrasive grinding, and abrasive blast cutting under the grouping of “machining with geometrically undefined cutting edges.” A further clustering of the aforementioned processes can also be presented, namely, that of machining with bonded abrasives encompassing grinding, belt grinding, and honing, with the remaining processes largely falling under the category of free or unbonded abrasive machining. Therefore it is clear that the science underpinning bonding materials is core to the development of bonded abrasive tools (Jackson and Davim 2011; Webster and Tricard 2004).

It can be seen from Fig. 1 that the bonding material holds the grains in place and holds the grains in contact with the backing material in the case of superabrasives or on abrasive belts. The bond can be seen to link individual grains, and this is often referred to as the bond “bridge” or bond “post,” and the various connections are often termed the bond “web.” The bond web must hold the grains in place until the forces in the bond web are exceeded in which case the grain is allowed to detach, exposing new sharp grain contact points. The forces that cause the bond web to break may result from blunt grains, bond wear, or the dressing process. The role of the bonding material includes the following:

- Provide adequate grain retention, during the high loading and high temperatures experienced in the material removal process.
- Allow controlled bond erosion, leading to gradual exposure of new cutting points.
- Provide sufficient strength and stiffness to ensure optimal transfer of the grinding forces from the spindle to workpiece.
• Provide adequate heat dissipation.
• Facilitate the structure of the inter-grain spacing with voids and fillers as necessary to achieve the appropriate abrasive tool characteristics.

It is recognized that in practice, the wear of the abrasive tool can proceed only as fast as the bond fracture occurs. Prior to bond fracture, pieces of the abrasive are lost by fracture of the grain and to a lesser extent by attritious wear (Rowe 2009; Jackson and Hitchiner 2013). The structure and composition of the abrasive tool is therefore complex and has been presented in the form of a “grinding wheel phase diagram” or “triple-coordinate system” to enable visibility of the interactions that can occur between the volume of grain, \( V_k \); volume of pores, \( V_p \); and the volume of the bond, \( V_B \). The regions for conventional and superabrasives such as cBN are shown below.

Figure 2 shows the triple-coordinate system for the interaction enabled by the bond, namely, the ability to structure the abrasive (Klocke 2009). Moving outside the limits highlighted above requires special measures to be undertaken, for example, the inclusion of burnout materials to create larger pores, or hot pressing to close the bond structure and reduce or eliminate pores.

The standard classifications of the bonded abrasives clearly place high emphasis on the bond type, and categories of grade and structure are also a function of the bonding system.
The diagram below shows the classification for conventional grinding wheels where it can be seen that bonding material is identified explicitly but that wheel grade and structure are also functions of the bonding (Fig. 3).

**Vitrified Bond**

Vitrified bonds are formed by mixtures of natural silicate clays, kaolin, and feldspar, as well as quartz. Additives such as frits which are man-made and therefore better controlled can be added to enable lower temperatures during the firing of the bond material when manufacturing the abrasive tool. This allows for temperature control of viscosity and surface tension and eventual structuring of the bond material, e.g., pore size, during firing which can occur at temperatures between 800 °C and 1,350 °C. At the firing temperature, adhesion between the bond and the grain occurs with surface tension pulling the grains together, and chemical reactions occur at the grain melt interface. On cooling, glassy necks known as bond “posts” or bond “bridges” are formed resulting in mechanical and chemical bonds between grains and bond material.

**Resin Bond**

Resinoid bonded abrasives are formed by mixtures of phenolic thermosetting resins and plasticizers. The mixtures together with the grain are molded into the abrasive tool shape and cured at temperatures between 150 °C and 275 °C. Bond properties such as hardness can be controlled by addition of plasticizers, and fillers can be used to embed dry lubricant and change wear resistance or heat conductivity. Resinoid bonded abrasives can also be reinforced with glass fibers to increase strength. In synthetic resin bonds, the abrasive is generally coated with a nickel or copper coating in order to improve heat conductivity and adhesion. Alkaline cooling lubricants are known to negatively impact on bond strength and hardness due to the penetration of water molecules in particular OH ions into the interface between the grain surface and the resin bond (Klocke 2009).

**Other Bonds**

Rubber bonds consist of vulcanized natural or synthetic rubber-rubber bonds are relatively cool-grinding bonds, as the dulled grains can break off relatively easily and early, limiting frictional heat transfer into the abrasive tool.
Silicate-bonded abrasives are manufactured by mixing sodium silicate with abrasive and molding. The processing temperatures are lower in comparison to vitrified bonded wheels and processing times are shorter. This is similar to magnesite bond whereby magnesite or burned magnesium is combined with water to form Magnesium hydroxide producing a soft grinding wheel and used for finishing cutlery (Klocke 2009).

Shellac dissolved in alcohol or mixed with alkalines is rarely used any longer due to prevalence of resin bonds with similar characteristics of flexibility for abrasives such as cutoff wheels.

**Bonding in Superabrasives**

The bonding material in superabrasives can be classified as single-layer bonded systems or multilayered (Fig. 4).

Single-layer bonding systems can be further classified as metal bonded or electroplated. The most common form of metal bonded is the use of sintered bronze. Grade control of the abrasive tool is achieved by altering the bronze composition. Nickel and iron can also be used. We-Co bonds are used in diamond abrasive tools for geological drilling (Malkin and Guo 2008).

Electroplating is used to hold single layers of diamond or cBN on a hub using a layer of nickel. The nickel thickness is usually 30% of the grain dimension. Chemically precipitated nickel phosphorus alloys present an alternative to electroplated/electrolytically precipitated nickel and exhibit higher strength. Strongly wetting active solders are another option for bonding abrasives to metal bodies although this is a more costly option due to the high temperatures required in the processing equipment.

Multilayered superabrasives can also use the sintering approach or use resinoid and vitrified bonds also (Marinescu et al. 2012).

**Bonding in Belt Grinding**

In a broadly similar manner to the bonding in abrasive tools such as grinding wheels and abrasive segments such as honing stick, the abrasive...
material must be secured to the flexible backing material in the case of belt grinding or abrasive belt finishing. The bond in this case is often referred to as the “binder.” In the case of belts, the bond is applied in two layers: the base bond is the interface between the belt backing material and the abrasive. Hide glues can be used as the base bond, offering good adhesion and rapid solidification during processing. Synthetic resins can be used as a top coat or top bond layer which is insensitive to cooling lubricants.

**Cross-References**

- Abrasive Material
- Dressing
- Grinding
- Honing
- Superabrasives
- Superfinishing

**References**


**Broaching**

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**Definition**

Broaching is a material removal process using a multiple-edged tool whose cutting edges are arranged in a line and with an offset \( h_z \) (also known as “rise per tooth” (RPT)), which determines the depth of cut per tooth. The tool is moved in one direction only; the feed and width of cut is hereby determined by the tool geometry. The size and shape of the final teeth corresponds to the desired geometry of the workpiece. After one single pass of the tool through the workpiece (broaching stroke), the operation is complete and the workpiece’s surface is finished at the same time. In general, the translational motion is run by the tool at a stationary workpiece (Ostwald and Muñoz 1997; Bralla 2007; Klocke 2008; CIRP (ed) 2004) (Fig. 1).

**Theory and Application**

**Classification of Broaching Processes**

High material removal rates can be achieved by a single broaching stroke. This is due to the fact that in most cases, several teeth are in contact with the workpiece. Furthermore, high surface qualities and tolerances up to IT 7 can be achieved. High tooling costs in production and preparation limit broaching processes to mass production applications since one tool is applicable only for a certain geometry (Yankee 1979; Klocke 2008).

A subdivision of the broaching process into internal and external broaching is of particular importance due to the design of broaching machines and broaching tools.
Internal Broaching
Internal broaching is characterized by (symmetrical) geometries in inner diameters. The broaching tool is thereby pulled or pushed through the workpiece. Through-holes as well as a sufficient minimum wall thickness to prevent deflection due to the radial cutting forces are preconditions for internal broaching. Broaching into solid material and into blind holes is not possible. Furthermore, the broach must pass through the workpiece completely (Yankee 1979). The supporting surface of the workpiece holder has to be perpendicular to the cutting direction and must not change under load throughout the operation (Fig. 2).

External Broaching
External or surface broaching is broaching of an outer surface of a workpiece. In general, every workpiece can be broached on the outer surface, unless the normal vector of the surface to be machined is arranged perpendicular to the cutting direction and no flange is present which would obstruct the tool’s cutting motion (Hoffmann 1976). If the tool is enclosing the workpiece on all sides when broaching external surfaces, it is also called tubular or peripheral broaching. Another variant of external broaching is chain broaching: several workpiece holding fixtures are attached to a continuous chain which draws the workpieces through a stationary broaching tool (CIRP (ed) 2004) (Fig. 3).

Classification According to DIN 8589-5
In addition to internal and external broaching, the process can further be subdivided according to DIN 8589-5 as follows (see Fig. 4):
- Face broaching
- Circular broaching
- Broaching of helical grooves
- Profile broaching
- Contour broaching (externally only)

In the next paragraphs, these processes will be described separately.

Face Broaching  Broaching with a linear cutting motion to create a plane surface oriented parallel to the cutting direction.

Circular Broaching  Broaching using a circular broaching tool with a linear cutting motion to create a cylindrical surface. This is also called circular profile broaching.

Broaching of Helical Grooves  Broaching operation in which the cutting motion is a combination of linear and circular motions. The circular motion is produced either by rotating the broaching tool or the workpiece.
Profile Broaching Broaching with a linear cutting motion to create a predefined geometry which is given by the broaching tool, i.e., broaching of a groove on an external surface. A polygonal shape is broached from a cylindrical through-hole as displayed in Fig. 4. Profile broaching using a cylindrical tool is called circular broaching.

Contour Broaching Contour broaching is for external surfaces only and can itself be subdivided into two techniques: In pivot broaching, the broaching tool has a rotating cutting motion at a stationary workpiece. In external cylindrical broaching with a rotary tool, the outer surface of a rotating cylindrical workpiece is machined by a rotating broaching tool.
Broaching Machines
The main demands of broaching machines are high accuracy, good dynamic behavior, low noise emission, reliable operation, and simple automation (Hoffmann 1976). The elementary construction and exactly defined load requirements make broaching machines to be highly reliable machine tools. It can be differed between the following types of construction:
• Vertical broaching machine
• Horizontal broaching machine
• Chain broaching machine

The vertical and horizontal machines can itself be divided into internal and external designs. In general, the vertical designs are preferred. They require less space, they can be inserted into transfer lines, and there is no deflection due to its own weight. A disadvantage is the pit which is needed for installation. For machining rotor blades of steam or gas turbines, the broach usually consists of several parts which are put together and result in lengths of broaches up to 80 m. Therefore, these machines are equipped with movable tables to attach clamping devices and to machine different types of geometries. Additionally, automatic tool change systems are applied to ensure low stand by times and high accuracy of the finished profile. Figure 5 shows a vertical broaching machine including a tool magazine with a capacity of 78 m of tool length. In Fig. 15, a vertical solution with tool changer and magazine is presented. The cutting speed depends on the tool material used and the workpiece material to be machined. Typical values range from 2 to 4 m/min using high speed steel tools on hard-to-machine materials up to 40 m/min using carbide inserts. If the materials are unalloyed or low-alloyed steels, the cutting speed ranges from 2 to 25 m/min (Hoffmann 1976).

A special design of broaching machines is the chain broaching machine. Here, several workpieces on holding fixtures are attached to a continuous chain and drawn through a set of stationary broaching tools (Fig. 6).

At conventional broaching machines, one idle return stroke per workpiece is necessary. In contrast, chain-type broaching machines allow continuous external machining of workpieces, such as screw wrenches, feet of rotor blades, and brake calipers for disk brakes. One chain-type broaching machine can replace multiple external broaching machines and is easy to automate.

Broaching machines are driven either electrically or hydraulically. Electromechanical drives are stiff and require less space, whereas high costs and power demand as well as low dynamics are disadvantages. Hydraulic drives are characterized by high dynamics, high possible loads, and low costs (Yankee 1979). On the other hand, flexible drive and high space demands are disadvantages. Additional, oil leakage may cause problems in dry machining processes.

Broaching Tools
Broaching tools (broaches) are special multi-edged tools representing a specific geometry and are designed and manufactured per workpiece geometry. Analogously to the broaching machines, broaching tools are
differentiated between internal and external application. Their lengths depend among other things on the maximum length of stroke of the machine and are in the range of 100–1,000 mm (Klocke 2008). The tool is made out of one or more parts, depending on geometry to be broached or of the size of the workpiece.

As Fig. 7 shows, an internal broach consists of the shank, front pilot, tooth portion, and the retrieval end. The broach is inserted into the workpiece and attached to the retrieval end. After self-centering, supported by the front pilot, the broach is clamped at the shank. The machining is then initiated when the broach gets pulled or pushed through the workpiece hydraulically or electromechanically. The last section of the broaching stroke is accomplished by the broach released from the retrieval end and without upper guidance. Hereby, the broach is fully pulled out of the workpiece. After the machining operation, the workpiece is removed, and the shank holder still clamping the broach moves back to the upper position interlocking the retrieval end. Subsequently, the shank is released to be inserted into the next workpiece again.

Generally, every broaching tool (broach) consists of three sections. The tooth portion itself consists of roughing and finishing teeth, followed by a set of spare teeth. The teeth are arranged with an offset $h_z$, where the amount of the offset determines the undeformed chip thickness per tooth. The roughing teeth usually take a relatively heavy cut, whereas the finishing teeth take a relatively light cut. The reserve teeth produce the final size required. Additionally, they are for maintaining dimensional accuracy when the tool is reground. This improves economic operational capability. The tooth portion relocates on regrinding toward the reserve set so the former first reserve tooth becomes the last finishing tooth.

The offset characterizes the manner in which the teeth are arranged and material is cut. It can be designed in different ways as shown in Fig. 8.
The offset in depth is defined as a vertical increment in height between one cutting tooth and the next successive one. The depth of cut is only little since the cutting edges penetrate the workpiece on the whole width perpendicular to the surface. The offset in width (lateral offset) is the offset of subsequent cutting edges parallel to the machined surface. In contrast to the offset in depth, the undeformed chip thickness is high. This combination is particularly suitable for casted or forged materials due to less tool loads (Fritz and Schulze 2008). A special design is wedge-type offset. It is a combination of lateral offset and offset in depth. Usual offset values are 0.03–0.3 mm per cutting edge and depend on the surface to be machined and the required surface quality.

An important dimension in design of broaching tools is the tooth pitch $t$. It defines the distance between two successive cutting edges measured in cutting direction and depends on the offset, chip formation of the workpiece, and the maximum length of the broach. High offset values and unbroken chips (ductile materials) require large chip space gullets and a large pitch (Fig. 9). In DIN 1416, the design guidelines for width of the chip gullet, the clearance land width, and the foot radii in dependence of the tooth pitch are given. The pitch also should be chosen in a way such that multiple teeth are in operation at the same time. This minimizes machine vibrations and leads to better surface qualities.

Further, the tool’s geometry is predefined by shape and size of the desired workpiece profile as well as by the clearance angle ($\alpha$) and the rake angle ($\gamma$). Most important factors on these angles are the material to be machined, the offset, and cutting lubricant (see “Cutting Fluid”) as well as cutting speed. Recommended values are $\alpha = 1–2.5^\circ$ and $\gamma = 6–15^\circ$ for high offset values and low cutting speeds smaller than $v_c = 15 \text{ m/min}$. At cutting speeds higher than $15 \text{ m/min}$, recommended values are $\alpha = 2–4^\circ$ and $\gamma = 18–25^\circ$. Despite the stability of the decreased cutting edge due to increased angles, the cutting pressure and the portion of friction decrease (Hoffmann 1976; Tschätsch 2009). Additionally, the clearance angle $\alpha$ should be kept small to enable multiple regrinding and therefore increase the economical use of the tool. The offset $h_z$ in broaching corresponds to the feed and therefore is integrated in the tool. Depending on the material to be machined, the offset is specified from $h_z = 0.02–0.04$ mm in the roughing portion, whereas in the finishing portion
it is clearly smaller from $h_z = 0.0025–0.02 \text{ mm}$ (Hoffmann 1976). Special applications using carbide inserts perform offsets of $h_z = 0.25 \text{ mm}$ using cutting speeds of up to 60 m/min. Another important angle is the inclination angle which states that the cutting edges are arranged at an angle $\lambda$ or are arranged perpendicular to the cutting direction ($\lambda = 0$). Its advantage is the avoidance of abrupt tool immersion and tool exit as well as the damping of vibration amplitudes and noise level. Disadvantages are increased width of the cutting edge, appearance of shear forces, and a difficult tool production.

Figure 10 shows an application for production of external tooth gear wheels for automotive industry. The workpiece to be machined is enclosed on all sides by a cup-shaped tool which is why it is also named cup broaching, pot-broaching, or tubular broaching. The fabrication of helical gearing is also possible in which case the workpiece undergoes an additional rotation. This process is not widely used yet because of its very high tool costs.

Cutting Material and Tool Wear
As like other machining processes, cutting materials must meet multiple requirements like high hardness, toughness, bending and compressive strength, tempering resistance, red hardness, and resistance in temperature changes. Low susceptibility to diffusion, corrosion, and scaling increases wear resistance are further demands. Some requirements like high hardness at concurrent maximal toughness are contrary and cannot be realized within one material. So, a consideration and a trade-off are needed.

In broaching cast iron and hard machining, primarily carbides are used. Brazed carbide tips or carbide inserts are seldom used on conventional steel parts and forgings. The main reason is the low cutting speed of most broaching operations which do not exhaust the advantages of carbide tooling. When broaching cast irons, its advantage is due to carbide’s resistance to abrasion on the rake surface. The main cutting materials for broaching in soft machining are high speed steels (HSS). The high speed steels applied in soft machining are mostly produced through powder metallurgy (HSS-PM). In contrary to smelted materials HSS-PM can contain greater proportions of alloyed elements with a homogeneous microstructure providing isotropic properties. The hard phases are evenly distributed with a defined grain size. To ensure low prices and a good utilization of raw materials, near-net-shape raw parts can be produced with little oversize. HSS-PM combine high hardness with highest values of toughness and can be grinded more easily than smelted HSS (see “Grinding”). To further enhance performance and efficiency of expensive broaching tools, coatings were developed which clearly enhance tool life (see “Coated Tools”). Especially, TiN coatings have established in industrial applications. High micro hardness leads to a minimization of wear, the chemical resistance reduces built-up edges as well as material adhesion, and a small friction coefficient reduces the
thermal load of tools. Especially for dry machining, multiple coatings were developed which mainly consider temperature resistance. In particular, super nitrides and nano-composite layers feature high capabilities. Further development of the TiN layers led to new coatings like TiAlN or AlCrN with enhanced red hardness values (Holland-Letz 2005).

Wear is a progressive loss of material at a surface caused by mechanical, chemical, or thermal stress. Wear occurs due to friction between broaching tool, workpiece, and unrolling chip. It depends on the process parameters, especially on combination of tool material and material to be machined (see “Wear Mechanisms”).

Mainly occurring types of wear in broaching is corner wear (CW), flank wear (VBz), rake face wear (VBγ), and rounding of the cutting edge. Due to relatively low cutting speeds and therefore little development of temperature compared to other machining processes, crater wear does not occur (Hoffmann 1976).

Hard-to-Machine Materials

Hard-to-machine materials are high-strength steels, super alloys, and titanium-based alloys. Reasons for low machinability are interalia, high strength and work hardening characteristics, and low thermal conductivity which leads to high cutting edge temperatures as well as conserving the workpieces mechanical properties at high temperatures.

For example, turbine disks for steam and gas engines are made of the nickel-based super alloys or the titanium alloy Ti-6Al-4V. Here, the broaching process is used to produce the “fir-tree”-shaped slots on turbine disks. These profiles are quite complex, and up to 100 slots have to be broached depending on size and type of the turbine (Bralla 2007; Hoffmann Räumtechnik GmbH, Pforzheim).

The slots are manufactured in different sections to achieve the final geometry. Due to high material removal rates and highly desired surface quality, mostly a notch is broached first (Figs. 11 and 14), followed by machining the final shape (Fig. 12). In doing so, the final surface can be machined in one stroke, guaranteeing high precision and quality. Another advantage of broaching is the increased operating life of the tool compared to other machining processes. Each tooth of the broach is in contact to the hard to machine material only once.

In general, horizontal external broaching machines are used to machine turbine disks due to very long tools (up to 80 m). Therefore, the broaching tools are made as a set of segments. Every segment is responsible for a defined geometry of the fir tree. Differing due to use and size of the disk, a broaching tool can consist of 12–50 segments, whereas a segment has 3–60 teeth. Tool lengths can reach up to 1 m or more and weights of up to 15 kg. Another reason for
segmentation is the possibility of replacement of a segment if one is damaged or its wear is too high (Fig. 13).

Figure 14 shows schematically the tool segmentation consisting of several different segments. For example, segment one through nine is for roughing to shape the rough contour, and segment ten accomplishes the finish cuts. This last segment creates the workpiece’s final surface, integrity, and quality.

As explained in Chap. 3.3, the feed within the tool is realized by the offset $h_z$ of successive teeth. When changing tool segments, the offset between the last teeth of a roughing broach and the first teeth of the successive broach is normally negative. The aim is to prevent the next broach from impacting the workpiece right from tool entry.

The finishing segments are rising both in depth and width so that they can consequently produce the finish contour. The notches are manufactured radial to the turbine disk or with a small angular inclination as can be seen in Fig. 15.

The last sets of teeth of all finishing broaches have calibrated teeth which allow a burnishing
finish. These teeth do not feature an offset since their task is to burnish the surface to realize better surface roughness and compressive residual stress. Additionally, the pitch is larger than a “normal” cutting tooth which allows the elastic deformed machined material to retract before the next tooth enters so that it produces a smoothing “cut.”

Cross-References

- Coated Tools
- Cutting Fluid
- Gear Cutting
- Grinding
- Wear Mechanisms

References

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Polishing

Burr

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Definition

There are several definitions for burrs, but they all describe the same phenomenon. Burrs are undesired but mainly unavoidable. A burr is a material accumulation, which is created on the surface during the manufacturing of a workpiece. It extends over the intended and actual workpiece surface and has a slightly higher volume in comparison with the workpiece (Beier 1999). Burrs are uncut material remaining on the workpiece after being machined. Burrs occur at the workpiece surface in cutting as well as in shearing operations at the workpiece edges. Further, laser machining can lead to burrs as well. This essay focuses on burrs of machining and shearing processes.

Burrs are of great industrial relevance as they interfere with the workpiece performance and functionality. Ideally, workpieces would be free of burrs, but, as this is often not the case, burrs can only be reduced either by changing the machining parameters, tool path, or tool. Alternatively, the burrs will have to be removed by time consuming and expensive deburring processes.

Theory and Application

History

Burrs are an economically very important issue in many machining operations. Therefore, a lot of research has been done in the last 50 years to understand, control, and minimize burr formation. The first published works on burrs cover
burr formation in punching. Pekelharing (1964) was the first to describe burr formation mechanisms in metal cutting processes. He described the chip formation process and closely interlinked burr formation to chip formation. First fundamental work describing an analytical model of burr formation, which enables to predict burr properties, was done by Gillespie et al., published in 1976 (Gillespie and Blotter 1976). After a basic understanding of the burr formation mechanisms was gained, research activities turned to the topic of deburring. In 2009, CIRP published a keynote paper on burrs by Aurich et al. (2009). The paper gives a review of the topic of burrs in machining operations.

**Burr Classification**

There is no overall classification of burrs. However, classifications of burrs defining the edges of workpieces, for example, in drilling or milling as well as an ISO standard, are available. CODEF (the Consortium on Deburring and Edge Finishing) classified five drilling burr types (Fig. 1). Gillespie introduces four types of burrs: poisson burr, rollover burr, tear burr, and cutoff burr (Fig. 2) (Gillespie 1999). The ISO 13715 standard defines the edges of workpieces as sharp, free of burrs, rounded, chamfered, or with burr (Fig. 3) (ISO 13715). Nevertheless, many companies use an in-house classification, as an overall accepted burr classification is lacking (Aurich et al. 2009).

**Burr Formation**

A lot of research focuses on understanding burr formation and revealing the parameters influencing burr formation. Pekelharing is the first to publish results on the investigation of burr formation. He interlinks burr formation to chip formation, as the burr formation depends on the chip formation mechanism (Pekelharing 1964). Gillespie states six physical processes which form burrs. The processes (1) lateral flow, (2) bending of material, and (3) tearing of chips from the workpiece result in plastic deformation of workpiece material. The (4) redeposition of material occurs in recasting processes. The fifth process regards the incomplete cutoff of material. The last process treats burrs produced in molding or shaping processes, when the material flows into cracks (Gillespie 1999). Hashimura et al. have issued a schema of burr formation (Hashimura et al. 1999). In his model, the burr formation mechanism is influenced by cutting conditions, tool and workpiece geometry, as
well as by the mechanical properties of the workpiece material. Schäfer (1975), Beier (1999), and Thilow et al. (2008) did a lot of work on burr formation. They all observed that a burr occurs at the tool entry or exit if the workpiece material evade the cutting process.

To gain a better understanding of the burr formation process and to be able to predict burr formation, the finite element method analysis can be applied. In Leopold et al. (2005), the state of research and future developments in modeling and simulation of burr formation are highlighted.

**Burr Measurement**

A large number of burr measuring and detecting methods are available. The choice of the measuring system depends on the burr values to be measured (e.g., burr height or thickness), the requested measuring accuracy, the application conditions (e.g., within the production process), or the research purpose. The measuring methods can be categorized into:

- Destructive methods
- Mechanical systems
- Optical systems
- Electrical measuring methods

Destructives methods are mainly chosen for research purposes, as the workpiece is destroyed afterward. With destructive methods, as for example the preparation of metallic cross sections, very detailed information about the burr can be obtained. It is possible to measure burr thickness, burr height, as well as the micro hardness in the burr.

Mechanical, optical, and electrical systems are mainly used to detect burrs. The stylus method, a mechanical system, can measure burr height, but optical methods can also be applied for this purpose. Among the most important optical systems are microscopes, autofocus methods, laser triangulation, and camera systems. For automatic burr detection in a production process, an electrical measuring method, for example, an inductive sensor system, can be applied.

**Burr Control Strategies**

As burrs cannot always be avoided, there are several burr control strategies to (at least) reduce burr formation. Burrs can be significantly influenced by the choice of tool, tool geometry, tool material, and tool coating. The tool or tooling best applied depends on the machining situation and the workpiece material. Several investigations on this topic have been conducted. The application method of coolants, the coolant media, and the application location of coolants influence burr formation likewise significantly. A proper combination of cutting parameters can reduce burrs notably. Changing the workpiece material can lead to less burrs or a more preferable burr type. Further, a change of workpiece design or a change of the order of machining processes can help to avoid burrs. A helpful approach is a targeted tool path planning.

**Deburring**

There are several techniques for deburring, which is the process applied to remove burrs from workpieces. They range from simple hand deburring to elaborated surface finishing by NC controlled robots (Aurich et al. 2009), Gillespie (1999) grouped the numerous deburring operations into the following four main categories:

- Mechanical deburring operations
- Thermal deburring operations
- Chemical deburring operations
- Electrical deburring operations

Mechanical deburring operations are very common, for example, abrasive flow machining,
milling, or dry blasting. The burrs are removed or reduced by mechanical abrasion. In thermal deburring operations, the workpieces are heated at very high temperatures for a very short period of time. Thin material accumulations, for example, burrs, are removed. In chemical deburring, chemical substances are applied to remove the burrs. Further, electrical fields can be applied to reduce or remove burrs. The choice of the deburring operation depends on the workpiece material, burr dimensions, and burr position as well as process costs.

Cross-References

▶ Chip-forms, Chip Breakability and Chip Control
▶ Cutting, Fundamentals
▶ Drill Milling
▶ Drilling
▶ Grinding

References


Business Management

▶ Management of Production Enterprises