1

Forming Processes

1.1. Introduction

The field of metal forming comprises a wide range of semifinished and finished products. Each requirement of the acquisition criteria is defined, justifying the use of various forming processes. A number of recurring characteristics can be observed in the desired shapes. The latter should respond with the best dimensional precision possible and the most suitable surface condition for its usage. The final product must meet material health conditions for usage properties with the least possible continuity defects. There is, therefore, an interest in what the most appropriate macro- and microstructures are.

1.2. Different processes

Metallic materials offer a rich range of independent or combined forming methods. Among the large families, the following processes are identified:

– smelting;

– machining;

– powder metallurgy;

– hot or cold plastic strain forming.

Each of these processes present characteristics of optimal quality, variable depending on the material being used, on the dimensions and on the desired accuracy, on the metallurgical quality, on the final cost and on the quantity. The choice is oriented according to specific criteria:

– the abilities of the material in relation to the different processes (particular attention should be given to the difference between a foundry alloy and alloys deemed “wrought”) regarding the form and the dimension of the product;

– the defined metallurgical health (limitation of defects such as cracks, porosities and chemical segregations);

– the usage properties of the product in the mechanical field;

– the desired surface condition (in terms of cleanliness, roughness, of residual stresses, etc.).

1.2.1. *Smelting*

The metal or the alloy is melted inside a crucible and then it is poured into a specific mold inside which it will solidify when cooled down. Complex forms can be obtained often linked with a minimum of induced thickness. Large variations of the latter involve consequences on the development of the final properties. Casting workpieces are produced from simple and often fairly cheap traditional techniques. This results in obtaining monobloc parts whose quality and mechanical properties are lower than those of wrought products (products having undergone hot hammering in order to obtain the desired properties often in a compulsory direction). There are numerous and very varied molding techniques depending on shape, quantities and on the quality requirements:

– The mold is made up of sand and inside it a cavity can be found that will represent the resulting piece. The first operation consists of building a pattern generating the shape of the desired casting by integrating the machining allowances and the useful drafts. The pattern represents the mold cavity left in the sand when the mold is closed. The mold is opened to extract the pattern therefrom and closed to the molten metal. When solidification is achieved after slow cooling, the mold is broken in order to retrieve the final product. One casting is thus obtained per mold.

– The mold is in metal and thus is reusable. The cooling proves to be much faster than the sand casting process. The pattern is obtained by machining the mass and with respect to the hollow parts, they can be achieved with eventually destructible cores.

– Die-casting integrates a metal mold but the filling of the pattern is ensured by means of a piston that pushes the liquid at high speed in a short period of time (a few $1/10$ of a second). A slight overpressure can be maintained in the mold, which has the effect of properly feeding the pattern, while avoiding the design of a hot-top to perform this function. The mechanization of the process is total. On the other hand, the tools undergo very significant repeated efforts, which reduces their life expectancy (20, 000–50, 000 parts depending on the nature of the cast alloy).

– Centrifugal casting concerns all so-called revolution parts. The fundamental difference lies at the level of the introduction of liquid material, which is carried out along an axis around which the mold revolves. The centrifugal force promotes uniform filling. The structural composition is finer and full.

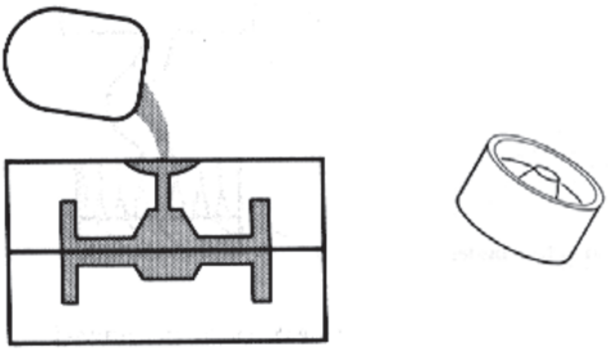

Figure 1.1. *Gravity die casting accompanied by the obtained casting*

1.2.2. *Machining*

Machining is a material removal operation making use of a cutting tool. This process allows for highly accurate complex forms and a controlled surface finishing. Different processes are identified and classified into two large categories. The first involves chip formation, which mainly includes turning, milling, grinding and drilling. The second does not involve chip formation and designates flow-turning, electrical discharge machining, shearing and waterjet cutting. From a structural point of view, machining only alters a superficial layer of the material, which therefore causes a hardening of the surface. As a result, we can observe the creation of a residual sublayer stress field, causing significant heating in the superficial layer. Ease of machining is linked to the physical contact of the tool-workpiece pair during machining. It depends not only on the mechanical behavior of the material (resistance, consolidation and malleability of the machined material) but also on its thermal behavior. A low resistance is recommended, which means a sufficient malleability, however this facilitates chip breaking. It can also be noted that a good thermal conductivity most often facilitates the machining. As a result of adding cold or hot particles, the cutting conditions can be improved (controlled inclusions of low melting point lead or even sulfides, etc.). These latter facilitate the fragmentation of the chip:

– *Chip formation*: Machining takes place following optimized cutting conditions, which consider the geometry of the cutting tool, the cutting fluid and the dimension of the non-deformed chip. It is formed following primary shearing of the metal when making contact with the cutting edge of the tool and following a secondary shear when in contact with the external edge of the tool. This effort zone undergoes superficial strain hardening and heating. In addition, the chip is subjected to the same efforts coupled to the tool on its external edge. Futhermore, the cutting speed V_c plays a paramount role and is thus expressed:

$$V_c = \frac{n.\pi.d}{1000}$$

with V_c expressed in m/min, rotational speed in rpm and tool diameter for milling.

– *The machined surface*: It is defined by a heated and hard-tempered underlying superficial area. The microstructure can therefore be modified (constituents or phase change) or even undergo local strain hardening by cold working. Often, there remains a significant local residual stress field. Moreover, microcracks can be observed.

– *The chip*: When the material is fragile, it quickly becomes fragmented into lemels (for example some smeltings). In the event that it is ductile and slightly consolidates. However, when this consolidation occurs as a result of the hardening phenomenon, it easily fragments. On the other hand, a few obstacles to chip formation may surge notably due to heating and pressure. A galling phenomenon can be observed between tool and chip forming a build-up edge. It is defined by lemel stuck to the tool. Thus, the maximal temperature is variable according to the cutting speed and the hardness of the tool. The stress and strain field induced by the cutting enforces an increase in the temperature of the metal.

As a result to the cutting conditions, the tool is subjected to the following observations:

– adhesive wear;

– abrasive wear;

– damage due to atomic diffusion or to oxidation;

– damage due to thermal fatigue;

– irreversible deformation (creeping).

1.2.3. *Powder metallurgy*

This process consists of obtaining a final piece adapted to special needs by means of compression and sintering. From the agglomeration of very fine powders, a compacted object is produced with a form very close to that desired. Then, we control the cohesion of the powder with a thermal sintering process. Different applications can be identified, used in specific categories of workpieces:

– in cases where the production of controlled fine-porosity metal products with complicated forms is sought after;

– in pieces composed of refractory metals presenting a good resistance to heat;

– in alloys that cannot be obtained by smelting, notably tungsten or some magnetic materials such as soft magnetic metal ferrite composites. As an example, we can therefore cite cermets composed of "coarse" ceramics particles distributed in a metal matrix. In the field of cutting tools, we come accross cobalt matrix-based indexable lathe tools;

– in friction materials of which brake pads or clutch discs are made of;

– in electrical contact materials of which we can cite as an example silver- or copper-based contacts.

This technique is often used when some materials are hardly fusible or seldom deformable by plastic deformation. We then obtain products with improved microstructure, finer and more homogeneous than that observed by smelting as some nickel-based superalloys. It is also popular as an alternative with other forming processes to reduce production costs. As a matter of fact, metal losses and machining operations can be significantly optimized because it allows engineers to manufacture complexly shaped pieces with precise dimensions using a single method. The latter is a very common method in the development of multiple products in mineral materials such as oxides, carbides and refractory products. It mainly enables the control of the porosity of the developed products. Two categories can be contrasted:

– weak microporous parts;

– massive parts with almost no porosity providing good mechanical properties as well as good ductility.

The process is defined as follows:

– *Powder production*: The shape and the grain size can vary between 1 and $1,000$ μm and are obtained by means of mechanical techniques involving the grinding of hard metals such as molybdenum (Mo) and chromium (Cr). The production can originate from a liquid phase by atomization of aluminum or copper. In addition, the process of atomization is defined by a drying operation that consists of transforming a liquid pulverized in the form of droplets in reaction with a hot gas into powder. It is operational in all processing industries of the material, particularly in the agrifood and the chemistry sectors. Its design is dependent on the properties of the product to be obtained and the characteristics of the drying gas as well as on the specifications of the powder.

– *Powder compaction*: This operation is compulsory to reduce the porosity. The latter is measured by the ratio $\delta = \frac{(V_a - V_r)}{V_a}$ where V_a is the apparent volume of the powder and V_r its actual material volume. The compaction is given by the following relation $\gamma = \frac{V_r}{V_a}$ and the expansion is $\frac{1}{\gamma}$. Powder forming is achieved by cold, hot and isostatic compression.

– *Powder sintering*: This step consists of forming while respecting the continuity of the solid. It is a process activated by solid-state atomic diffusion at a temperature ranging from 60 to 80% of that of fusion for a variable period according to the material under study. This energy is activated between the contact surfaces of the grains of powder and the shape of the pores is deformed until it is completely reduced.

As a whole, the process must be highly controlled due to the permanent risk of oxidation.

1.3. Hot and cold forming

Liquid casting, hot open-die forging and cold sheet metal forming have been documented as early as $5,000$ B.C. These are often relatively simple methods based on the use of molds, a hammering tool and a base. During the first centuries of the Christian era, wire drawing by means of perforated plates and primitive machining using chisels were discovered. During the Renaissance, rolling dominated the industry because of its high productivity and its great versatility. Over the last century, the sector has been in full expansion, with an acceleration in the development of processes since 1940. As a matter of fact, the Germans invented cold forging (extrusion) of steels for the manufacture of weapons. Since 1945, machining has improved considerably and other processes such as electrical discharge machining or waterjet cutting have been invented. We would like to point out the discovery of hot melt spinning of copper alloys by the Frenchman Séjournet.

Forming ability is intrinsically linked to structural evolution, whether under the effect of thermomechanical processing or not, according to its three-dimensional plastic behavior. The latter is subjected to deformation speeds and imposed temperatures. It can be observed that compression efforts associated with the reduction of gradients of strain rate facilitate deformation without necking nor rupture. The literature discusses three major phenomena that have to be avoided:

– ductility generalized to fracture in mismatch with the targeted deformation amplitude. Deformation involving several steps separated by annealing is thus advocated;

– incompatible necking ductility with respect to localized deformation;

– sensitivity to strain rate inconsistent with the field of practiced speeds. Under optimal forming conditions, it is possible to take action on this field by decreasing the average rate or by lubricating the solicited surfaces with the aim to reduce the rate gradients between the edges and the center of the desired shape. Among these methods, we cite the following:

- *forming by plastic deformation*: this operation relies on hot or cold work in the plastic region of the metal. It allows that the product be obtained without metal loss in large productivity. There is a certain interest for very long parts or with a very small thickness. Plasticity is therefore an important property. Following a stress state, the plasticity criterion whose critical value is defined by the plastic flow constraint is verified. It is assumed at first that the volume remains invariant. It is applicable on the majority of metal alloys and implements numerous processes. In the case of massive products, the work is carried out by means of direct action of the pressure (open-die forging, discharge, stamping, forging, sheet rolling, wiring or extrusion). Through the indirect action of the pressure, we obtain traction-type processes such as wire-drawing and cold-drawing;

- *typical operational chain for the forming of steel*: it is particularly long and complex for the manufacture of steel for common use. It begins by obtaining a semifinished product by continuous casting at a relatively low speed and a relatively large section. These conditions are required by the exhaust speed of heat and the productivity rate. Then, a decrease in the transversal dimensions can be observed that is caused by rolling. It is defined as a continuous cycle of strong productivity. A first hot pass is necessary, then a cold one aiming for thinner products;

- *hot forming*: the recognized high quality of hot forming lies surely in its ability to endure very large deformations as a result of reduced efforts. On the other hand, it should be noted that the final dimensions remain inaccurate and the state of the surface is often altered (oxidation, decarburization, etc.). It is advised to carry out blasting as a finalizing solution. Overall, the metal does not present a good mechanical resistance with hot casting but this gives it a very significant malleability. We refer to hot forming when the temperature rises above 0.5 Tf (melting point). We are interested in the behavior of the material during and between the stages of plastic deformation by recrystallization or restoration. These individual or conjugate phenomena strongly decrease the hardening and the yield stress value decreasing according to the temperature. On the other hand, the yield stress becomes an increasing function with the plastic strain rate;

- *cold forming*: we refer to cold forming when the ambient working temperature is comprised between 0.15 Tf (melting temperature) and 0.3 Tf. We retain a structure that only works in the field of plastic deformation. This phenomenon is characterized by hardening by increasing the material yield stress. On the other hand, a decrease in ductility can be seen that is defined by its ability to endure plastic deformation without damage;

- *warm deformation*: an intermediate area is observable that is called warm deformation. In theory, this relates to taking advantage of hot forming (lower yield stress) and those of cold forming in order to harden the product by strain hardening. The method commonly used is by forging. This method is seldom used due to the big problems in formulating the necessary tools and lubricants, notably for all fairly ductile materials, but it is suitable for high-speed steels. It is possible to obtain forms and thicknesses for very varied products making use of forming techniques that often result in different characteristics. They differ by the tools being used and the strain and the rate fields associated with the operated directions as well as their amplitude (compression, traction, etc.). They are also limited each in their respective fields of productivity. Some examples include:

- *rolling*: this process is characterized by passing between the rolling mill cylinders in reverse rotation of the production of the flat (sheet) or long product (profiled). Rolling is qualified as discontinuous when it is effected through a single cage at a time or continuous through a number of several cages. The result is a product in the form of more or less thick sheets or of strips packaged in coils. The desired deformation is obtained after several passes and intermediate annealings (beams, rails, etc.);

- *forging*: this process is defined from a billet that is compressed by the pilon hammer or by hydraulic or mechanical presses. The forging is known as “open-die” when the deformation slopes are not subjected to any pressure. Forging can be done by dieing or stamping. A blank is compressed in a mold. In addition, die forging is recognized for the family of light alloys;

- *spinning and extrusion*: these two operating procedures, consisting of slow compression through a die, allow for reducing the cross-section of long products and giving them the desired final shape. In the case of high speeds, it is referred to as wire drawing since the aim is to obtain a calibrated wire in the coil form. This is the result of a pass through a suite of lubricated dies;

- *stamping*: it is advisable for complex workpieces with non-developable surfaces. The principle consists of a shaping punch penetrating a blank held in position, which will give the final form with the counter form called forming die. The efforts are often very important and can alter the structure; it is the reason why intermediate annealings are common practice. There are several forming areas determined by the orientation of the deformations, that is the expansion, the restraint or the extension. We can also observe the limits of the process according to the material used that can lead to necking (a phenomenon observed before the fracturing of a structure at the point where the value of the yield strength permissible by the material is reached) or fracture [CHE 08b].

1.3.1. *Influence of the static parameters*

1.3.1.1. *Stress level*

At least one stress level is imposed by the yield strength of the material under consideration. The latter evolves according to the hardening by means of work hardening directly linked with the deformation. There is a strain hardening exponent determined by tensile testing for each material. It follows a behavioral law for the generalized stress (Pa) that appears as a significant factor notably for cold forming. We thus obtain, in three-dimensional plasticity without necking nor rupture at a given temperature:

$$\bar{\sigma} = k\bar{\varepsilon}^n \bar{\dot{\varepsilon}}^m \qquad [1.1]$$

where $\bar{\varepsilon}$ is the generalized strain, $\bar{\dot{\varepsilon}}$ is the generalized strain rate (in s^{-1}), m is the strain rate sensitivity coefficient and n is the work hardening coefficient.

1.3.1.2. *Stress triaxiality*

Stress triaxiality conditions the "confinement" of the material and delays the appearance and the multiplication of internal or surface microruptures. It is identifiable by means of the ratio $\frac{\sigma_m}{\sigma_{eq}}$ of the hydrostatic component $\sigma_m = \frac{(\sigma_1+\sigma_2+\sigma_3)}{3}$ (directly interfering on the elastic change of the volume) to the equivalent Von Mises stress (σ_{eq}) responsible for the change in shape.

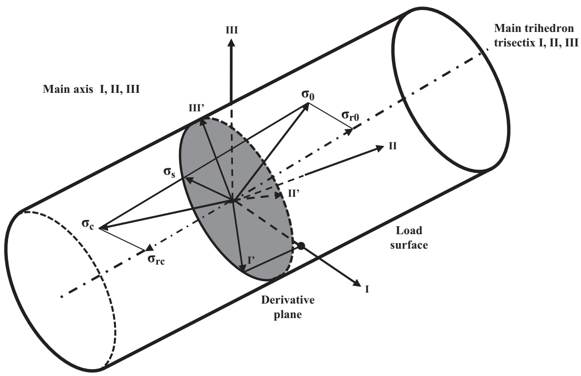

Figure 1.2. *Space of the principal stresses in the Von Mises cylinder with the state decomposition of depressive (σ_D) and compressive stress (σ_C) accompanied by its deviatoric (σ_S) and spherical components (σ_{TD} and σ_{TC})*

In the case of massive or long products, the formability limit increases with decreasing positive values as those of the uniaxial tension to the negative values of those spinning or forging. These latter, respectively, characterize the depressive mechanical state and the compressive mechanical state. Concerning the deformations, triaxiality can be estimated by a tensile test in which the two dimensions of the cross-section of a flat test piece are measured. The observed deformations are therefore inferred as well as the anisotropy coefficient $r(\varepsilon_1, \alpha) = \frac{\varepsilon_2}{\varepsilon_3}$ for a longitudinal stress ε_1 observing an angle with the rolling direction. An average anisotropy coefficient r^* is specified for the flat products containing all of the directions α. The sheets are usually anisotropic, and we thus estimate the average coefficient by:

$$r^* = \frac{r(0°) + 2r(45°) + r(90°)}{4} \qquad [1.2]$$

We obtain the following consequences:

– *consequences in rolling*: a single phase of plane strain is observed because the width of a sheet is not modified with this manufacturing process. The work hardening coefficient n plays an important role since it drives the effort of cold rolling. This may result in a deformation of the rolling mills. In contrast, in hot rolling the coefficient n is small;

– *consequences in stamping*: in this specific case, we are considering the field of planar stresses outside folding. The charges and the strains have very complex trajectories:

- it is possible to form in the region "in expansion", that is ε_2 comprised between 0 and ε_1 and σ_2 is located between σ_1 and $\frac{\sigma_1}{2}$,

- in "extension", the region spreads for ϵ_2 comprised between 0 and $-\frac{\epsilon_1}{2}$ for the strains and concerning that of the stresses, it positions itself for ϵ_2 comprised between $\sigma_1/2$ and 0,

- in the "restraint" area, ϵ_2 can be observed ranging between $-\varepsilon_1/2$ and $-\varepsilon_1$ and so as σ_2 be located between 0 and $-\sigma_1$,

- testing can be performed to determine the restraint with a limit deep-drawing ratio, increasing with n. Also, there is a biaxial test ($\varepsilon_1 = \varepsilon_2$) characterizing the expansion.

This coefficient n varies mostly according to the microstructure but little with the texture. It is observed that a high value of n improves the deformations by expansion. A high coefficient r^* depending on the texture for most metallic materials helps toward restraint deformations. Thus, when a high value of the two previous regions is combined, we can speak of optimum conditions for expansion forming.

– *consequences of strain rate*: local plastic strain rates are in direct relation to the strain modes and the usual operating parameters of machines. The strain is expressed by the following relation: $\frac{d\varepsilon}{dt}$ in s^{-1}. When the rate is high, it can be seen that the thermodynamic and the inertial efforts must be taken into account. The yield stress varies according to the plastic strain rate following a power relation:

$$\sigma = C(\frac{d\varepsilon}{dt})^m \qquad [1.3]$$

where C is the plastic flow stress (Pa.s^{-1}).

1.3.2. *Hydroforming*

The signatory countries of the Kyoto protocol for the reduction of greenhouse gas emissions and the agreements of the COP(21) in Paris in 2015 have prompted the automotive industry to review their methods and their production technologies with the objective of meeting these new environmental standards. A decrease in fuel consumption can immediately lead to a reduction in the emission of gaseous pollutants. It is estimated that there is a 15% gain in consumption when the mass of the vehicle is reduced by 25%. The appearance of these new requirements has resulted in the development of new lighter grades in motor structures. As such aluminum alloys already make up the structural parts of several vehicles. Moreover, new grades of steel with high elastic yields offer a better specific weight resistance ratio than that of conventional steel.

In the spirit of reducing weight, an idea is being developed concerning a method which consists of the reduction of the number of elementary parts. As a result, we can note a decrease in primary material being used, of welding seam, or even of blank. Concretely, deep drawing finds its limitations in the production of complex forms in one single part. As a result, the hydroforming process proves to be indispensable with regard to quality as an alternative technology. This relatively new method makes both use of diverse and varied technologies. However, these are based on the same principle, that is to say that a liquid under pressure is injected for the forming of a primary piece that can be a tube, a blank or a preform. The hydroforming process is characterized by pressurizing a liquid that pushes the material, with a homogeneous distribution, called tool or die. This equipment is mounted on a hydraulic press specifically equipped with an injection system to ensure the closing in order to avoid any risks of leakage from the liquid. The tubes or the sheets are plastically deformed until obtaining the final piece. When comparing with deep drawing or die forging processes, there is no use of punches or intermediate forms. Four main variants can be noted in the implementation:

– *fixed-die hydroforming*: in this case, the pressurization of the fluid itself enables obtaining the final form;

– *mobile-die hydroforming*: this is the most commonly employed and the most technical process. The strain is assisted by the action of cylinders at the ends of the workpiece in constant relation with the internal pressure that acts simultaneously. There is therefore interest in this process and we will describe the main stages of the full forming cycle;

– *low-pressure hydroforming*: we refer to low-pressure expansion when it does not exceed $1,000$ bars;

– *high-pressure hydroforming*: we refer to high-pressure expansion when it does exceed $1,000$ bars. A thinning phenomenon can be observed in the thickness of the wall enduring the tension. High-tonnage presses are used for shutdown forces that can reach more than $10,000$ tonnes according to the surface projected of the workpiece to obtain.

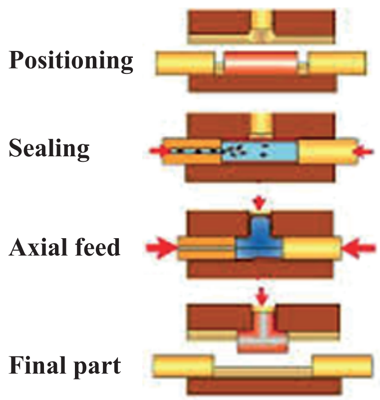

Figure 1.3. *Hydroforming principle*

1.3.3. *The limitations of the process*

We can identify two disadvantages in this process:

– *pleating effect known as "wrinkle"*: it occurs when the axial force is too high relative to the internal pressure. It can be eliminated by increasing the internal pressure;

– *buckling*: occurs when the axial force is too high for the length of the tube that is not supported or when changes in the geometry of parts are not symmetrical after the tube have reached plastic deformation or when the variations in friction states result in unbalanced deformation.

1.3.4. *Deep drawing*

Deep drawing is a sheet metal forming process in which a sheet metal blank is radially drawn in a forming mold by the mechanical action of a punch. This is therefore a form transformation process with retention material. The process is considered to be “deep” when the depth of the drawn part exceeds its diameter. This is achieved by redrawing the piece through a series of dies.

The flange region (sheet metal in the shoulder region of the die) undergoes a radial drawing stress and a tangential compression stress due to the material retention property. These compressive stresses cause flange wrinkles (first-order wrinkles). Wrinkles can be avoided by using a blank holder, whose function is to facilitate the controlled material flow within the radius of the sheet metal [MOR 10].

The total tensile load is composed of the ideal load and forming an additional component to compensate for frictions in the contact regions of the flange area and the bending forces as well as the inflexible forces at the level of the die radius. The forming load is transferred from the punch radius through the wall of the workpiece drawn in the deformation region.

In the wall of the drawn workpiece, in contact with the punch, the circumferential deformation is equal to zero by which the plane strain state is reached. In fact, most of the time the stress condition is only brought forward. Due to the tensile forces acting in the wall of the part, the thinning of the wall is important and results in an uneven thickness such that the wall thickness is the lowest where the wall of the part loses contact with the punch.

1.4. Experimental characterization

The most widespread development process of sheet metal is rolling. Due to its nature, this process provides a strong orientation according to the rolling direction to the grains constituting the material. The end results are rolled sheets characterized by fiber patterns at the microscopic scale and a texture, that is to say preferential crystallographic orientations.

The study of the behavior of these sheets is most often addressed within the context of an elastic–plastic approach for most of the processes of sheet-metal forming. The elastic–plastic theory itself comprises two different approaches describing each on a physical scale of the behavior: the first is called phenomenological approach (or macroscopic) and the second is called microscopic approach (or micro–macro model). The two approaches have the objective of describing the evolution of the stress and the strain state during a succession of deformations.

Within a phenomenological approach, the elastic–plastic behavior of the material is described by an envelope called initial charge surface. Defined in the stress space, this closed surface defines the elastic limit and the beginning of the plastic flow of the material for the different configurations of possible loading, it is a generalization of the uniaxial elastic limit. We introduce in the phenomenological approach the concept of the plasticity criterion that is nothing more than a mathematical description of the form of the initial charge surface. This criterion can be isotropic (von Mises, Tresca, Hosford criterion) or anisotropic. In addition, the Hill48 criterion [HIL 50] describes both general anisotropy and orthotropic anisotropy particular to rolled sheet metal. There are other anisotropic criteria [HOS 79, BAR 05] that contribute to the description of the orthotropic anisotropy and that differ among themselves by their form (quadratic or non-quadratic functional), the stress hypothesis in use (plane stress, 3D stress), the shear stress being taken into account or not, as well as by the number of parameters utilized in these criteria.

Once the shape of the initial charge surface is described by the plasticity criterion, the phenomenological approach introduces a work-hardening model for describing the evolution of the shape, size and position of the initial charge surface during the deformation. Although isotropic work hardening results in the expansion of the charge surface without any distortion of its form, anisotropic work hardening, such as kinematic hardening, describes the displacement of the charge surface without distortion, in the stress space [KOS 94]. Since the strain-hardening model is supposed to describe the update of the initial charge surface during charging, and that the latter is formed by a number of different stress states, this update thus has to be carried out for each of the stress states to a same value of an internal variable; this variable can be either work hardening [KOS 94], or the equivalent plastic work-hardening strain [KUR 00].

After the definition of the charge surface and the type of work hardening, the third hypothesis upon which the phenomenological approach relies is relative to the description of the plastic flow, which is the description of the relationship, on the one hand, between the strain rate tensor, the stress rate tensor and the stress tensor. This is then referred to as the associated plastic flow rule when the plasticity criterion is considered as being the plastic potential, and to the non-associated flow rule if a second function other than the plasticity criterion is considered (most often the chosen function is of the same mathematical form as the plasticity criterion).

In contrast, within a microscopic approach, the macroscopic quantities such as the stress tensor and the strain tensor are typically deducted from the numerical modeling of the behavior of the grains constituting the material. Although this approach is becoming more consistent and is getting closer to the physics of plastic strains, it has a limited utilization due to the need for storage and the significant memory size as well as a prohibitive computational time. The phenomenological approach is more widespread because of its convenience, its relative ease of implementation, its speed but also often because of the sufficient accuracy of its results. Futhermore, the two approaches can be complementary to the extent where the microscopic study enables for understanding the mechanisms of plastic deformation and validating phenomenological models.

1.5. Forming criteria

The function of these criteria is to judge the capacity of a sheet to endure the different possible strains during forming:

– *Conventional criteria*: These are the fastest and the cheapest to implement because they mainly consist of simple tests on the blank that tend to reproduce as much as possible the strains occurring in pressing. We mainly use the following tests:

– Rockwell hardness (HRB index);

– stress–strain (yield point Re);

– tensile strength Rm;

– elongation at break A (%);

– Erichsen's deep-drawing (index IE).

This type of criterion provides only a single element and therefore only provides a low accuracy in the study of the blank. Nevertheless, by only considering these tests, it is possible to bring forward a number of essential characteristics of the metal. The metal has to exhibit a very high fracture toughness in order to resist uniaxial tensile strength, a low yield point (because in the plastic field, despite being the lowest possible to avoid fractures, the exercised strains have nonetheless to be above the yield point), significant elongations and low resistance to the tangential compression in the blank holder (that is a good capacity to restraint).

– *Combined criteria*: They are not merely accepting separate parameters but make use of combinations of conventional factors. We thus find criteria such as Re/Rm, Rm-Re, (Rm-Re)*A, etc. They contribute with higher accuracy to the characterization of forming but require a larger number of experiments and materials.

– *Rational criteria*: These are the most difficult and the most expensive to determine but they are the ones that offer the best judgment to the forming of sheet metal. Two can be found: the strain-hardening n and the anisotropy r coefficients.

The strain-hardening coefficient n is linked to the consolidation of the material. Note that strain-hardening increases fracture toughness as well as the yield strength that gets closer to fracture toughness. If two sheets having the same value of n but different elasticity coefficient k are formed, they will behave in a similar manner despite of the different forming forces. Thus, this criterion can determine the capacity of a sheet to be implemented. It is obtained from the rational stress–strain curve connecting the relation $\sigma = \frac{F}{S}$ to the rational strain $\varepsilon = \ln(\frac{S}{S_0})$ (where σ is the stress, F is the applied force and S is the actual cross-section).

In the general case, it uses two successive formulas of the form:

$$\sigma = \sigma_0 + k.\varepsilon_0 \quad \text{or} \quad \sigma = k(\varepsilon_0 + \varepsilon)^n \qquad [1.4]$$

In the simplest case, the work-hardening coefficient n is also equal to the rational elongation at the end of the uniform distributed elongation ε_u at the maximum of the charge elongation curve. When $\frac{dF}{dl} = 0$, the derivation of $\sigma = k\varepsilon_0$ leads to $\varepsilon_u = n$.

It is therefore shown that this criterion is justified to characterize sheet metal forming, but it should be accompanied by a criterion characterizing the biaxial stress instability, that is to say the appearance of necking.

The plastic strain anisotropy r of sheet metal plays an important role in characterizing a sheet. The extent of this criterion has been highlighted by means of the strain analysis of the blank on the blank holder (restraint) in the walls of a cup or at the poles of the drawn (expansion).

Due to the preferential orientation of the crystals, the plate does not have the same mechanical properties according to the direction under consideration. It also results in a loss in the equilibrium of the strains between the width and the thickness during a uniaxial strain–stress test. It is on this point that we have decided to base the second deep-drawing criterion:

$$r = \frac{\ln(\omega/\omega_0)}{\ln(e/e_0)} \qquad [1.5]$$

with (ω) the width and (e) the thickness.

Figure 1.4 shows the variation of the anisotropy coefficient r in the sheet-metal blank with a value of the angle between the tensile test direction and the rolling direction. These curves represent the three possible cases in the case of low-carbon steel for forming:

– curve (1) in Figure 1.4 corresponds to the general case, that is to say, where r reaches a minimum. This is characterized by a drawn with 4 ears at $0°$ and $90°$;

– curve (2) in Figure 1.4 represents the case in which r reaches a maximum, that is to say, where the sheet presents two $45°$ ears;

– curve (3) in Figure 1.4 represents the case in which r increases between $0°$ and $90°$. In the latter case, the sheet presents two ears at $90°$.

This criterion, if high, would therefore indicate a strong resistance to thinning from the sheet metal and a large ability to deform before necking.

1.5.1. *Influence of the structure of sheet metal*

Thin sheets are polycrystalline aggregates. Their forming, as well as all of their characteristics, depends to a large extent on these aggregates:

– *Influence of the grain size*: Grain size is one of the most important parameters. Actually, it has an effect on the yield point and on the tensile strength which are (conventional) criteria of drawability. It should be added that, in the case of low-carbon steel, it is possible to relate the drawing coefficient to the size of the grains as follows and it should be recalled that if d (average grain size) increases, a change in structure occurs causing an increase in r. It is however necessary to note that if the grains are too significant, a surface defect appears. It is called “orange peel” and it is characterized rise by a blurred and undulating surface.

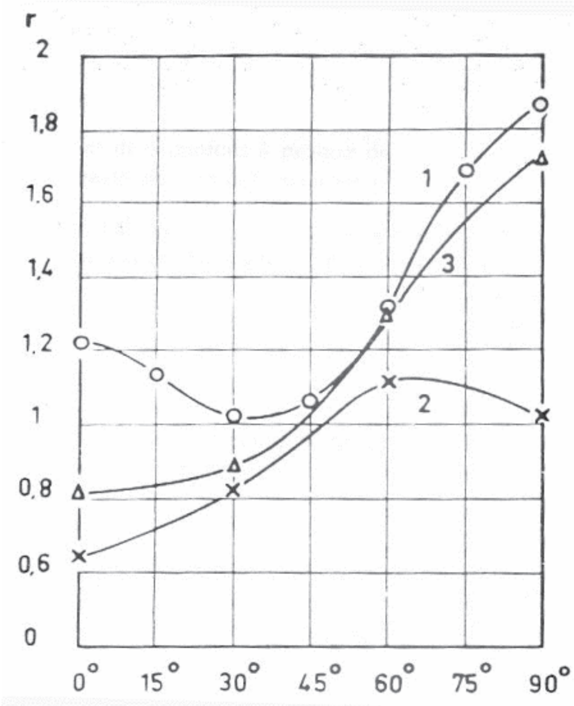

Figure 1.4. *Variation of r according to the rolling direction*

– *Influence of the crystallographic structure*: As mentioned previously, the crystallographic orientation is a non-negligible parameter. It occurs not only at the work-hardening level but also on the characteristics Re, Rm, A, etc. Work hardening of sheet metal occurring during annealing or rolling is responsible for the crystallographic direction of the grains and therefore for the preferential tensile directions or other similar tests.

– *Springback*: When the punch withdraws after forming, the piecework thus formed part is no longer subject to the retention force. A shrinkage of the material then occurs due to the elastic deformation of the primitive blank and resulting from residual stress after forming. This is then referred to as springback. It manifests itself in bent workpieces, cylindrical workpieces (inner diameter of the piece greater than the diameter of the punch) and in slightly deformed large dimension workpieces. This phenomenon is easily verifiable by means of a controlled stress–strain test. Indeed, if the test is stopped before the fracturing of the test piece and the stress is sufficient to exceed the yield point, the length of the test piece will be greater than its initial length but less than that obtained at the end of the test. The test piece undergoes a springback corresponding to the strain it suffered prior to its yield. In order to obtain a piece of dimensions corresponding to the expectations, it is thus important to take this phenomenon into consideration. To mitigate this phenomenon, it is common use to resort to some artifacts such as coining, bottom bending or extended maintaining of the punch. This phenomenon is so significant that the yield point of the material is itself increased (case of stainless steels compared to mild steels);

– *Other influential elements*: The presence of alloy elements in solid solution in ferrite increases the yield, tensile strength and reduces the elongation. These elements may have a significant indirect influence by modifying the conditions of the recrystallization and grain growth, in the texture, during annealing. Similarly, the second phase particles are of great importance in the ability of a sheet to be deep-drawn. This influence depends on their size and distribution. Thus, fine particles will likely impair the drawability (an increase in Re and Rm and a decrease in A and n) and clusters of non-negligible size may result in tearing or fractures.

1.5.2. *Physical strain mechanisms*

The observed macroscopic behavior is actually the result of local deformations on a microscopic scale. This microscopic aspect is fundamental for the physical understanding of phenomena:

– *elastic strains*: correspond to variations of interatomic spaces and reversible movements of dislocations. These strains are essentially instantly reversible; the initial configuration is recovered after discharge;

– *viscous deformations*: correspond to the undergoing deformation while the charge is constant; there is no more equilibrium. Time and strain rates play an important role in the laws of behavior of a viscous material. When this phenomenon is favored by thermal activation, it is referred to as creep flow;

– *permanent strains*: correspond to irreversible movements of dislocations. These displacements occur when the crystallographic planes slip (plane of greater atoms density). In practice, these movements do not alter the crystal structure and the volume remains unchanged; it is referred to as plastic incompressibility;

– *strain hardening*: this phenomenon corresponds to an increase in the number of bottlenecks in the dislocations motion. It counteracts the increase in the number of dislocations and modifies the threshold beyond which the deformations are no longer reversible;

– *restoration*: this phenomenon corresponds to a recrystallization by regrouping opposite sign dislocations. It occurs over time and is favored by thermal activation;

– *conventional yield strength*: unlike the yield strength Re, the conventional yield strength is defined as the yield obtained when the strain reaches 0.2% of the initial length. However, the yield strength is the stress delimiting the elastic limits of the other limit regions and defines the range of validity of Hooke's law.

1.5.3. *Different criteria*

The determination of a criterion is particularly delicate. There is unfortunately no universal criterion that integrates all the experimental results. Even if it was possible to determine such a criterion, it is feared that the cost of preparation and the utilization costs would not be admissible at the industrial level. Indeed, the determination of the various yield points associated with the different tests makes use of more or less sophisticated testing machines that can prove expensive. Moreover, it is preferable to use criteria that only involve one or two trials and that are simpler to implement. We are then fully aware that we are losing some accuracy, but this loss has to be relativized with regard to the uncertainties of the experimental measurements of the yield points, or when determining the characteristic quantities of the law of behavior:

– *Von Mises criterion*: This criterion is based on the last observation regarding the isotropic compression and the strain energy. As there is no limit, it is necessary that this criterion allows quantifying the strain energy that is not depending on the isotropic compression. Based on the results obtained by the experiment, namely that we modify the volume without modifying the form, it can be shown that the stress tensor as the strain tensor is purely spherical. The deviatoric parts are non-existing. The idea associated with the Von Mises criterion is therefore to limit the deviatoric elastic strain energy, that is to say that obtained from deviatoric tensors. According to the principal stresses, we obtain:

$$(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \leq 2\sigma_e^2 \qquad [1.6]$$

Depending of the form of the stress tensor, the Von Mises criterion will assume different notations. In the general case, it is written in the following manner:

$$\sigma_{eq} = \sqrt{\frac{1}{2}\left[(\sigma_{11}-\sigma_{22})^2+(\sigma_{22}-\sigma_{33})^2+(\sigma_{33}-\sigma_{11})^2+6\left(\sigma_{12}^2+\sigma_{13}^2+\sigma_{23}^2\right)\right]} \quad [1.7]$$

The equivalent strain must naturally be smaller than the plastic flow stress to remain in the elastic limits of the material.

– *Tresca's criterion*: This criterion is based on a limitation of shear at one point. It amounts in fact to limiting the radius of the largest of Mohr's circles and due to this fact it is particularly well suited to shear stresses such as beam torsion. Its expression is simply given in main stresses ordered by the formula:

$$\frac{\sigma_1-\sigma_3}{2} \leq \tau_e \quad [1.8]$$

Such as for the Von Mises criterion, we are confronted with a simple criterion to define and to implement but that does not consider taking into account the complexity of the different test results. In particular, as for the previous criterion, it can be observed that there is no limitation to isotropic tensile stress, which contradicts the experimental results.