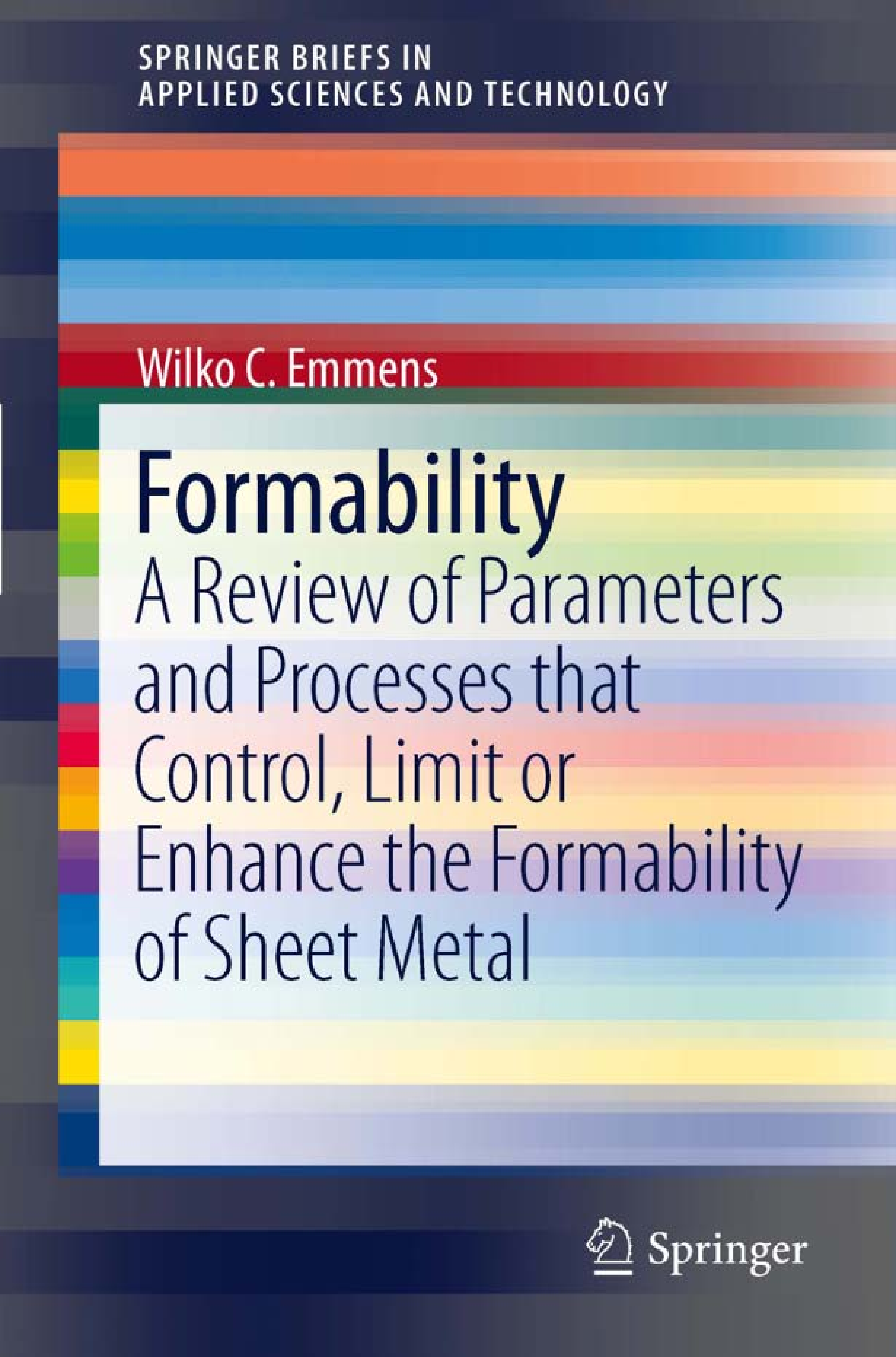

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Wilko C. Emmens

Formability

A Review of Parameters and Processes that Control, Limit or Enhance the Formability of Sheet Metal

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Foreword

The basic of investigation, Kershaw, is to keep asking: why.
Chief Inspector Morse, 1998

The idea to write this work originated a couple of years ago. The first reason was that such did not exist. During my quite long career in sheet metal forming I have encountered work on forming technology (but not that much) and on material behaviour (a little more), but nothing devoted to the interface between that: formability. So I decided to write that myself. At that time, I also had started research in ISF (Incremental Sheet Forming), and as a good researcher is supposed to do, I started a literature survey. The enhanced formability in ISF was already recognized in the early years, but I was surprised to discover that seemingly nobody had asked the question: Why are high levels of uniform straining possible in ISF? So I set myself a task to answer that question. Apparently, I was not the only one; it is a fact that in the recent years much research has been going on to get a better understanding about formability inspired by ISF, for example concerning the role of additional shear. That is also the reason why much literature that this work is referring to, is of recent date. This increased interest in the more fundamental aspects of formability was the second reason to write this work. It has evolved over the previous years until this present work that I consider as fairly complete (time will tell). I have tried to create an overview as complete as possible but without going into detail too much. That was the hardest part, I have been tempted to give much more information on various subjects. Nevertheless, in a work like this it is always a personal choice what to implement and what not. Much information that I present here comes from my own memory, but without remembrance where I heard it or read it, or sometime I did remember it but the original document is lost. Therefore, as a rule, information is given without reference. However, reference is always given in situations where I explicitly used information from the literature; I can't do everything myself. Finally, a special thanks to my dear friend Henk Vegter for proof-reading the manuscript and making some useful comments.

Hengelo, April 2011

Contents

Chapter 1
Introduction and Scope

Abstract The ever ongoing development in both sheet metal forming and in forming simulations have demanded a better understanding of sheet metal formability: the ability to be formed into a desired shape.

Keywords Sheet metal forming · Car body development · Automotive industry

This work is about formability. It is not about forming technology or forming processes, although these may be discussed briefly. It is just about formability: the ability to be formed into a desired shape.

Although many materials can be formed, this work is restricted to the forming of sheet metals. Sheet metal forming is not new, it was already practiced by the ancient Greek and has been applied through the ages by the blacksmith (Fig. 1.1).

A new driving force arrived by the upcoming of the automotive industry. The ever ongoing automation of the manufacturing process, and the ever ongoing demand for new body shapes has lead to a steady increase in the demand for understanding sheet metal formability (Fig. 1.2).

The application of numerical simulation techniques demanded a more fundamental relation between formability and material properties. But the recent developments in incremental sheet forming techniques showed that the forming limits established so far apparently can be overcome by simple techniques. This has lead to a new interest in the basics of formability, and it fact it was also the driving force to write this work.

The automotive industry has always been the driving force for new developments in sheet metal forming. As cars are (were?) traditionally made from mild steel, many aspects of sheet metal forming are derived from the experience with mild steel, often without people being aware of that. For example, the power-law strain hardening relation ($\sigma = C.\varepsilon^n$) was simply based on the experience that mild steel obeys this relation quite well. Now this relation, together with the related

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Fig. 1.1 Medieval powered hammer for metal working. From: Georgius Agricola, *De Re Metallica*, Basel 1556

Fig. 1.2 The development in car body shaping that demanded better understanding of sheet metal formability. Picture Copyright Daimler AG, courtesy Mercedes-Benz Museum GmbH

hardening coefficient *n*, is widely used despite the fact that many other materials do not follow this relation. As this work is written from a vast background in steel forming, many examples that will be presented come from that area. However, the concepts presented in this work are valid for all sheet metals. Beware that in American literature the term “sheet metal forming” is used for all processes that perform a forming operation on metal sheet, so including for example wall ironing of cans. In Europe the term is interpreted more fundamentally, and used for forming operations where the forces normal to the sheet surface are low compared to the flow stress of the material, justifying an assumption of plane stress.

The purpose of this work is to present an overview. Therefore none of the various subjects are discussed in detail. The reader is expected to have some elementary knowledge of forming technology and plasticity; a but very brief introduction to stress and strain is presented in Chap. 18, that also defines the parameters for stress and strain. Occasionally, in this work matters will be simplified deliberately ignoring second order effects to emphasise a certain major effect. However, it is never the intention to over-simplify matters leading to incorrect conclusions.

Chapter 2
Stating the Problem

Abstract Comparing forming steel to construction steel illustrates the problem that arises when discussing formability: is it a material parameter in the strict sense?

Keywords Formability versus strength · Material properties · Forming process

Until some time ago, steel grades were divided roughly into two categories: construction steel and forming steel. Construction steel was optimised for strength, and forming steel was optimised for formability, and the two categories were considered to be mutually exclusive. As an illustration: in construction steel the yield stress was made as high as possible (the higher the more expensive), and in forming steel the yield stress was made as low as possible (the lower the more expensive).

These two categories deserve some more investigation.

Construction steel is used for the manufacturing of constructions where the total strength is of importance. Consider for example a steel railway bridge. If the specifications state that the bridge must allow the passage of a 2000 ton train, then it is clear what the strength of the bridge must be. The strength of the construction as a whole is directly proportional to the strength of the material, and the latter can be measured in the laboratory easily, for example by performing a tensile test.

For forming steel the situation is not that simple. Forming steel is being used for the manufacturing of certain products, but the formability of the final product is of no importance. On the contrary, often the final product is expected not to have any (easy) formability at all. Of course there are exceptions: modern cars have crash zones that are designed to absorb energy. To do this the construction is expected to deform without fracture. Nevertheless, the formability property is related to the forming process, and not to the final formed product. This makes it more difficult to define formability as a property and to measure it in the laboratory (Chap. 13 discusses formability testing).

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This comparison illustrates that formability is not a straightforward property as for example strength is. In fact, one can ask oneself the question:

> Is formability really a material property in the strict sense?

This work tries to answer that question, and discusses many other things related to formality as well. During our journey through formability land, the findings will be presented as a number of statements or conclusions.

Chapter 3
Definition of Formability

Abstract The definition of formability depends heavily on what it is used for: the press-shop uses another definition that the scientist, but both are relevant.

Keywords Formability definition · Press-shop · Forming limits

In the press-shop (and that is were finally all the forming is being done) people have a very straightforward definition of formability:

A A material shows good formability if it passes through the forming operations without presenting any problems.

This definition however has some shortcomings. In general, the success of a forming process depends on three parts: the material being formed (the workpiece), the forming tooling, and the process conditions like lubrication, blankholder settings etc. A shortcoming in the process for example leading to fracture may have a cause in either three, and often can be solved by changing any of the three parts. This indicates that the practical definition of formability is only partially related to the material. Nevertheless, if problems arise during the manufacturing, it is a habit to blame the material supplier in advance, who then has to show that there is nothing wrong with the material.

This definition is unsuitable for the scientist, who is used to express all kinds of properties in numbers that can be measured. Therefore, from that point of view, the only acceptable definition is one that allows the formability of two materials to be simply compared by looking at their numerical values: material A has a formability 8, and material B only 6, so material A is better. Therefore a common scientific definition of formability is:

B The formability of a material is the level (read: amount of strain) to which that material can be deformed (stretched) before fracture occurs.

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For example, the uniform elongation and maximum elongation in standardized tensile tests are often used for this purpose. This may seem satisfying, but it turns out that the level of deformation depends on the strain state, so that the maximum level of strain has to be presented as a function of that strain state, generally in a strain-state diagram as for example the well known FLC = Forming Limit Curve, see Chap. 5. To make things even more complicated this limit also depends on the actual forming process, so it seems that we are back to square one.

Nevertheless, in the following we will take this definition {B} as a guide line, but at the end of this work (Chap. 15) we will look again to the practical definition of formability presented above {A} as that helps us to look at formability from a broader point of view. All the statements or conclusions as the two presented here will be resumed in Chap. 16. Noteworthy: in Chap. 12 a procedure is discussed that increases formability by both definitions.

Chapter 4
The Tensile Test

Abstract The tensile test is the most widely used material test. By looking at the tensile test as a forming operation several lessons can be learned. Basic the tensile operation is unstable, and the forming is restricted by an instability that concentrates the formation into a small zone, the neck. The formability is directly related to the amount of work hardening of the material. The forming limit depends also on how much local thinning is allowed. When the instability can be suppressed by whatever means, much higher levels of deformation can be obtained. This is discussed in detail. The chapter ends with an overview of material parameters related to formability.

Keywords Tensile test · Hardening · Necking · Stability · Considère condition · Taraldsen test

Many important aspects of formability can be discovered by looking in detail at the well-known tensile test (at least the reader is supposed to be familiar with this test).

4.1 Phenomena Occurring in the Specimen

We first take a look at the tensile test. Remember that originally the tensile test was developed as a loading test, a simple test to determine the maximum loading capacity (read: strength) of the material. Later, when it became possible to record the loading force as a function of elongation (cross-bar displacement), the tensile test became a more general test to measure material properties. Despite its limitations, it is still the most widely used material test.

Figure 4.1 shows an actually recorded force-displacement curve of mild steel that is typical. One can see that the curve has a maximum, in this case at approx. 18% elongation. Although this may seem trivial, this has some profound consequences, some of which will be discussed later (Sect. 15.1). This maximum divides the curve

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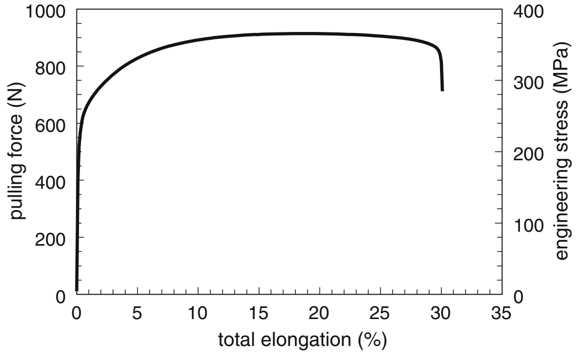

Fig. 4.1 Example of an actually recorded tensile curve for mild steel

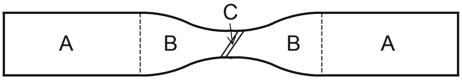

Fig. 4.2 Regions in a tensile test specimen (schematically). A = uniform elongation. B = diffuse neck. C = local neck

into two parts: a first part (uniform elongation) where the force is increasing with elongation and a second part (post-uniform elongation) where the force is decreasing with elongation. To understand this we have to look in more detail to what is actually happening in the specimen. Imagine a situation where the load is gradually increasing. An actual material is not an ideal continuum but contains imperfections.[1] This means that the properties will in general not be identical over each cross-section, and consequently, there is a weakest spot that deforms first. At that location the strip elongates, and the cross-section area reduces accordingly. But as the force remains constant, the pulling *stress* on that cross-section will increase and becomes higher than the stresses on all other cross-sections. This means that the part that deformed first will be deforming more and more, and all other parts will not deform. Consequently, the deformation becomes concentrated into a small zone and a neck will develop (the diffuse neck B in Fig. 4.2). Therefore, the plastic deformation of a tensile specimen is in fact an unstable phenomenon.

4.2 Effect of Hardening

This instability will occur in all situations where the actual pulling force is decreasing with increasing elongation. To overcome this, and create a stable (uniform) elongation, the pulling force must actually increase with increasing

---

[1] Imperfections may be either a local reduction of cross-section area, or a local reduction of yield stress by microscopic defects. The technological effect of both is the same, but in mathematical treatments often a local reduction of cross-section area is used.

elongation. The best-known mechanism that can create this is work hardening, a phenomenon that causes the strength of a material to increase with strain; all common (technical) metals show some amount of work hardening. To be more precise, necking will not occur if the material satisfies the following condition known as the Considère condition (see Chap. 19; parameters for stress and strain are defined in Chap. 18):

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\varepsilon} > \sigma \tag{4.1}$$

Let us look at this condition for certain materials.

For *perfectly plastic materials* we have $\mathrm{d}\sigma/\mathrm{d}\varepsilon = 0$, so these materials never satisfy the Considère condition and will develop a neck immediately.

For many materials and notably mild steel the relation between stress and strain can be approximated by the well known Hollomon (or: Ludwik-Nadai, or: power law) equation: $\sigma = C.\varepsilon^n$. Substituting this in Eq. 4.1 we find that necking will not occur as long as $\varepsilon < n$. This is indeed observed in many practical tensile tests where the strain at maximum force is (approx.) equal to n; the material of Fig. 4.1 had $n = 0.17$.

Materials with *proportional loading* ($\sigma = C.\varepsilon$, as in elastic loading) are basically a special case of the Hollomon equation for materials with $n = 1$, so necking will only start at $\varepsilon = 1$, a situation not lightly encountered in practice.

For *pre-strained materials* the Hollomon equation can be written as $\sigma = C.(\varepsilon + \varepsilon_0)^n$ where ε_0 is the level of pre-straining (Swift law). Necking starts when $\varepsilon = n - \varepsilon_0$ meaning that in cases of $\varepsilon_0 > n$ necking will start immediately. For many materials that are pre-strained to a significant level the stress-strain relationship can be approximated by a linear relation: $\sigma = \sigma_0 + C.\varepsilon$. Substitution in Eq. 4.1 shows that no necking will occur if $C > \sigma_0 + C.\varepsilon$. For mild steel this is the case for, say, $\sigma_{\mathrm{eff}} > 0.5$, and the constant C is in the order of 100–200 MPa. Now realize that in most cases the yield stress σ_0 will already be (much) higher than that, so it will become clear that significantly pre-strained materials will generally fracture immediately[2]; the formability of pre-strained material will be discussed further in Sect. 5.4. The Swift law is also used to artificially create a yield stress, as the Hollomon equation incorrectly states that $\sigma(0) = 0$. The value of ε_0 needed for that purpose is generally very small.

If a material does not harden if will fracture immediately. If it does harden, the right-hand part of Eq. 4.1 will increase steadily with elongation (strain). For most materials the rate of hardening will decrease with strain, or in other words: the left-hand part of Eq. 4.1 will decrease steadily with elongation. This means that eventually after some amount of elongation a situation will occur where Eq. 4.1 is

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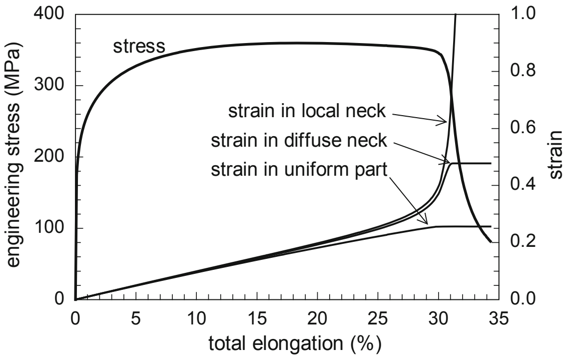
[2] In a tensile test steel does never fracture immediately in the strict manner of speaking. Test shows that even fully-hardened steel shows an amount of plastic strain of 0.5–1%, mostly due to strain-rate hardening. This means that all cases with plastic strain lower than, say, 1% will be treated as 'fractures immediately'.

Fig. 4.3 Results of a tensile test simulation for mild steel



no longer met and an instability will start to develop (the fact that for mild steel and some other materials the rate of hardening will increase again after severe deformation is not relevant here).

The above makes clear that *there is a link between formability and work hardening*. To be precise: a high *rate* of hardening ($d\sigma/d\varepsilon$) will postpone necking, but a high *level* of hardening (σ) on the contrary will accelerate the onset of necking.

4.3 The Tensile Test as a Forming Operation

What does this teach us about formability?

Let us resume the phenomena occurring in a tensile test specimen. The phenomena are controlled by two mechanisms: the tendency to become weaker by reduction of the cross-section area, and the tendency to become stronger by work hardening. For most soft materials, initially the hardening wins and the deformation is uniform, constant over the whole specimen. After some straining however the thinning wins and a neck starts to develop. This means that the deformation becomes concentrated into a small area, the neck. After more straining in the neck, a second instability occurs causing the so-called local neck (see Fig. 4.2) concentrating the deformation into an even smaller area, and eventually causing fracture. The mechanisms that eventually create the actual fracture are not relevant at this moment but will be discussed later in Chap. 14.

To understand what this has to say about formability we must change our point of view, and not look to the operation as a material test, but as a forming operation where a product is created by pulling a strip.

Figure 4.3 shows the results of a tensile test simulation where the parameters have been set to simulate the curve of Fig. 4.1 as much as possible. This figure also shows the actual strains in various parts of the specimen.

Note: this simulation and others presented in this work have been carried out with an extreme simple model; the numerical values may be slightly inaccurate, but the general trends are considered to be reliable.

Again, look at the test as a forming operation. The goal is to manufacture a product with sound properties. That means in this case that the variation in thickness over the length of the product may not be too large.

Up to the onset of necking (at the maximum of the curve, 18% elongation) the stretching and thinning will be uniform, and no (significant) variation in thickness will occur. After that, a neck starts to develop causing some part (the neck) to become thinner than the rest of the specimen. Figure 4.3 shows that the neck needs some time (read: straining) to become noticeable; this is caused by strain-rate hardening that will be discussed later in Chap. 11. Due to this retarded neck growth the specimen will be stretched somewhat further, until a final level of 0.257 (29% engineering strain) albeit with a clear neck. It is now a matter of definition (or: specification) what level of local thinning is still acceptable, and from that to what level the specimen can be stretched acceptably, and so what the formability of the material is. In any case, it must clearly be somewhere between 18% and 29%.

In this case a 5% neck, defined as decrease of cross-section area in the neck relative to the uniform part, is reached only at 28% elongation (26% strain in the uniform part), and a 10% neck at 30% elongation (29% strain in the uniform part). This indicates that:

C The formability of the material may increase considerably if some (local) thinning is allowed.

However, realise that the amount of thinning before fracture strongly depends on the strain-rate hardening of the material, see Chap. 11. Noteworthy: this aspect is a source of confusion in the measurements of FLCs, see Chap. 20.

In the neck the material will keep deforming, much more than in the uniform part. However, that is of no importance here as a severe neck will already lead to rejection of the part, even if the part is not fractured actually. Therefore, it is not important to look at the phenomena on a micro scale that will eventually cause the fracture. All this leads to a very important conclusion:

D The formability is limited by an instability that will occur and that will lead to an unacceptable uneven distribution of the properties of the part to be made (read: reduced local thickness or even fracture).

It was shown above that *hardening* can postpone necking. However, the true mechanism is that necking will be postponed if the stretching *force* will increase with elongation. This does not necessarily have to be work hardening or a related metallurgical phenomenon:

E Any mechanism that will cause the pulling force (tension) to increase with strain, will postpone necking.

An example will be presented later in Sect. 6.2.

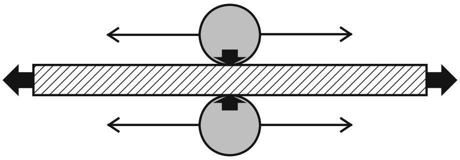


Fig. 4.4 Principle of the Taraldsen test

4.4 The Weakest Spot

It has been mentioned above that deformation always start at the *weakest spot*. Such a location always exists as technical materials have varying properties and imperfections that may act as stress concentrators. We do not know beforehand where that weakest spot will be. However, it is possible to create artificially a weakest spot, for example by making a small notch in the specimen.

Now let us expand this concept a little further. Suppose we have some means to force the deformation to start at certain location without damaging the specimen. This will then act as the weakest spot although strictly speaking the material there may be identical to the rest of the material and not weaker at all. Suppose now that we are able to move this weakest spot along the specimen by some means. In that way we are able to control the deformation of the specimen and, if we perform it correctly, without a neck to develop.

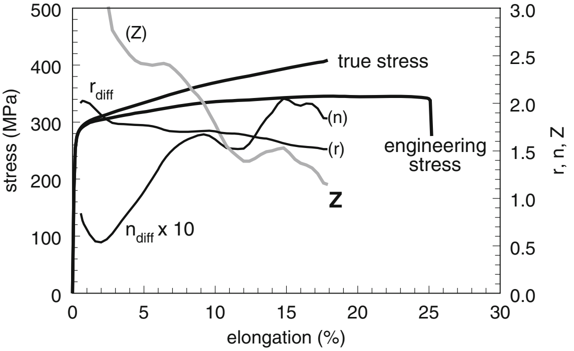
This may sound fantastic but it actually works. In 1964 Taraldsen reported results of modified tensile tests shown schematically in Fig. 4.4. His test is a slow tensile test on a long specimen, where at the same time a set of two rolls is continuously moving along that specimen. The effect of the rolls is to supply a modest normal stress at the roll contact, well below the yield stress. This changes the stress state so that a lower tension force is required for plastic elongation, and therefore a weak spot is created. In fact, he carried out tests on square and octagonal specimens using multiple sets of rolls, and achieved uniform elongations as high as 600% on OFHC copper [1]. However this test can be used on flat specimens as well with only two rolls, elongations of 100% on strip have been reported elsewhere [2]. This test is a very pure form of incremental forming that will be discussed in Chap. 10. Similar effects have been obtained by a tensile test with simultaneous repetitive bending; these are discussed in Chap. 6. Taraldsen called his test a ‘stabilized tension test’, and the discussion in his paper shows that he was well aware of the limitations of a conventional tensile test.

This leads to the following important conclusion:

F If we can suppress or postpone local necking in some way the formability will be enhanced considerably.

Although the material does not neck, it does deform and consequently hardens. This means that the driving force to generate a neck, for example expressed as $\sigma - d\sigma/d\varepsilon$, will gradually increase so that in practical tests a neck will always originate after some time, causing final failure.

Fig. 4.5 Example of an actually recorded tensile test curve of mild steel with differential values for both *r* and *n*, and the normalized strain hardening *Z*



4.5 Some Parameters Related to Formability

To close this chapter about the tensile test we will have a quick look to some parameters that are related to formability.

It has been shown above that formability is related to work-hardening, the latter generally expressed by the *hardening coefficient n*. However this coefficient is derived from the Ludwik-Nadai or Hollomon or power-law relation $\sigma = C.\varepsilon^n$, and not all materials satisfy this relation. We can expand the use of *n* by defining a *differential n* (sometimes referred to as *n**) by:

$$n_{\text{diff}} = n^* = \frac{\mathrm{d}(\log\sigma)}{\mathrm{d}(\log\varepsilon)} \tag{4.2}$$

For materials satisfying the Ludwik-Nadai / Hollomon relation the differential *n* becomes equal to the 'normal' *n*. In general *n** will depend on strain. Related to this is the so-called *normalized strain hardening parameter Z* defined as:

$$Z = \frac{1}{\sigma}.\frac{\mathrm{d}\sigma}{\mathrm{d}\varepsilon} = \frac{\mathrm{d}(\ln\sigma)}{\mathrm{d}\varepsilon} \tag{4.3}$$

This parameter expresses the sensitivity to necking in accordance to the Considère condition Eq. 4.1 and should be compared to unity. An example of the application of this parameter will be presented in Sect. 7.3. Note that this parameter is not uniquely defined, other definitions are presented in the literature as well.

Similar to *n* is defined the *strain-rate hardening coefficient m* (we will meet this parameter again in Chap. 11):

$$m = \frac{\mathrm{d}(\log\sigma)}{\mathrm{d}(\log\dot{\varepsilon})}, \quad \dot{\varepsilon} = \frac{\mathrm{d}\varepsilon}{\mathrm{d}t} \tag{4.4}$$

All flat materials fabricated by rolling have an anisotropy meaning that the properties are not the same in every direction. Important for formability is the so-called *normal anisotropy* defined by the ratio between width-strain and thickness-strain *in a tensile test*. This parameter is referred to as r (sometimes: R) or the 'Lankford parameter', see also Sect. 18.4. The relevancy to forming will be discussed in Sect. 15.2. In general r will vary with strain. In discussions about r it has to become clear if either the total or the differential value of r is meant, these are defined as:

$$r_{\text{total}} = \frac{\varepsilon_2}{\varepsilon_3}, \quad r_{\text{diff}} = \frac{d\varepsilon_2}{d\varepsilon_3} \tag{4.5}$$

Assuming that r is constant the following relations can easily be derived for the strain state in a tensile test:

$$\varepsilon_2 = -\frac{r}{1+r}\varepsilon_1, \quad \varepsilon_3 = -\frac{1}{1+r}\varepsilon_1 \tag{4.6}$$

Figure 4.5 presents an example of actually measured r and n values, both differential. In this particular example, both are far from constant. In the example we see that r_{diff} is decreasing with strain, this is a general observation for mild steel with initially $r > 1$. We also see that n_{diff} is increasing. This is not valid in general; situations where n_{diff} is decreasing with strain are encountered as well. The stable elongation ends when the engineering stress reaches a maximum. Indeed, at that point Z has a value of approx. 1.

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Chapter 5
The Forming Limit Curve

Abstract In a deforming sheet, the strain state is defined as the ratio between minor strain and major strain. The formability depends on this strain state and can be expressed as the so-called forming limit curve (FLC). In complex strain states the deformation is limited by an instability just as in a tensile test. In cases of negative minor strain this can be analyzed simply, in cases of positive major strain a more complex analysis is required. Two strain states allow high formability: deep-draw and equi-biaxial, in case of the first one the formality is infinite in theory. The FLC however is only valid under certain conditions: no bending, straight strain path, planar stress, no shear.

Keywords Strain state · Forming limit curve · Necking · Marciniak-Kuczynski analysis · FLC restrictions

In this chapter we will expand the analysis of the tensile test above to a more general analysis covering different strain states. Parameters for stress and strain are defined in Chap. 18.

5.1 Strain State and Conventions

As already mentioned before, the formability is related to the strain state. The strain state is the combination of the three principal strains ε_1, ε_2 and ε_3. As their sum is assumed to be zero, only two are required to specify the strain state and it is common to use ε_1 and ε_2 for that. The ratio between these two is conventionally expressed as β:

$$\varepsilon_2 = \beta.\varepsilon_1 \tag{5.1}$$

Note that β may be either positive or negative.[1] In practice, the expression 'strain state' is used not only for a single combination of strains, but for all

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[1] The parameter β is also used for the limit deep-draw ratio, see Sect. 15.1.

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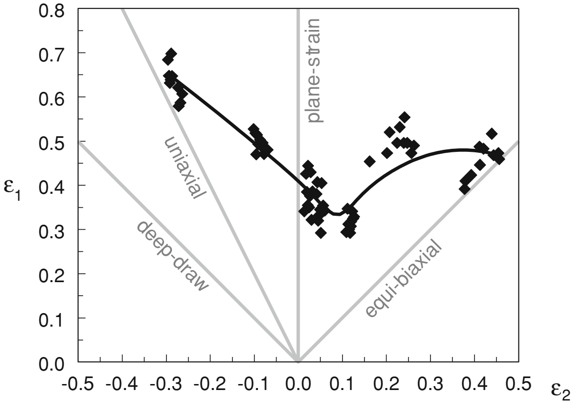


Fig. 5.1 Example of an actually recorded FLC (Forming Limit Curve) for a high grade forming steel. The *black line* is a fit through the measured data. The *grey lines* denote special situations as described in the text

situations that are characterized by a certain constant value of β, and that are graphically presented in the strain state diagram by a straight line through the origin as for example the grey lines in Fig. 5.1. The reason is that many properties mainly depend on the ratio $\varepsilon_2/\varepsilon_1$ and less on the actual values of ε_1 and ε_2. This means for example that the expression 'equi-biaxial strain state' simply refers to any situation where $\varepsilon_1 = \varepsilon_2$.

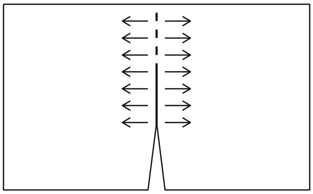
Some values of β describe situations that are of particular interest, these are shown by grey lines in Fig. 5.1:

- $\beta = 1$: in this case $\varepsilon_1 = \varepsilon_2$, the strain is constant in all directions (on the surface!); this state is referred to as *equi-biaxial*; more in general: any case with $\beta > 0$ is called *biaxial*;
- $\beta = 0$: in this case there is no strain in the second principal direction ($\varepsilon_2 = 0$), and this state is called *plane-strain*;
- $\beta = -0.5$: this is the state in a tensile test of isotropic material and this state is named to the corresponding stress-state: *uniaxial*; note that for non-isotropic materials we have in the tensile test: $\beta = -r/(1 + r)$;
- $\beta = -1$: in this case $\varepsilon_1 + \varepsilon_2 = 0$ and consequently $\varepsilon_3 = 0$, there is no change in thickness; this state is present in the flange of deep-drawn products and consequently named *deep-draw* state; note that this is also a plane-strain situation.

The situation with $\beta = -1$ can also be regarded as in-plane shear, see Chap. 9; the different naming is only determined by the choice of the co-ordinate system.

The forming limit (regardless of how that is defined) as a function of strain state can now be presented as a curve in a ε_1–ε_2 diagram. Such a diagram is called the forming limit diagram (FLD), and the curve the forming limit curve (FLC). Conventionally the FLC presents forming limits caused by fracture or necking, and unless otherwise stated those limits are presented throughout this work. Figure 5.1 presents an example of an actually measured FLC. Chap. 20 explains how strain in general, and the FLC in particular is measured. Generally, the diagram is presented as in Fig. 5.1. Note however that sometimes the diagram is plotted using engineering strains instead of true strains; examples of that will also be encountered in

Fig. 5.2 Schematically: a local neck can develop and cause a crack only if the strain state is plane strain, as no strain is occurring along the neck



this work. Also, in Japanese literature ε_1 is sometimes plotted on the horizontal axis and ε_2 on the vertical axis contrary to the practice in the Western world. There are also other types of forming limit curves, and some will be presented in Sect.15.2.

It is important to realize that the common FLC as presented in Fig. 5.1 and discussed here is only valid for forming processes under certain conditions; that will be discussed further in Sect. 5.5.

Correctly, the FLC is expressed by showing both the major and minor strain as defined in Chap. 18. It is also possible to plot the strains in fixed direction. This is for example often done for rotationally symmetric parts where both the tangential and meridian strains are presented. Plotting strains in fixed directions is also useful to clarify different situations, an example will be presented in Sect. 7.3.

5.2 Plane Strain Direction

To understand the nature of the FLC we have to look into more detail to what is happening. Realize that fracture of the material (splitting, tearing) always starts with the development of a local neck just as in the tensile test, see Fig. 4.2. Also, realize that in a local neck there is no strain along the direction of the neck: a plane strain condition. This is caused by the fact that the uniform part adjacent to the neck does not deform any longer and will prevent any elongation along the neck, see Fig. 5.2.

This leads to a very important conclusion: cracks can only arise in situations where there is plane strain deformation, or more correctly: in directions where there is no elongation. However, such directions of zero strain are only present in sheet metal forming under certain conditions.

Imagine a piece of sheet deforming with principal strains ε_1 and $\varepsilon_2 = \beta.\varepsilon_1$, and define a direction in that sheet with angle ϕ relative to the direction of major strain ($0 \le \phi \le \pi/2$), see Fig. 5.3. It will be shown in Chap. 21 that the direction will be a direction of zero strain if:

$$(\tan\phi)^2 = -\frac{1}{\beta}; \quad \beta \le 0 \tag{5.2}$$

Note that this direction of zero strain is in general not a principal strain direction! It is directly clear that directions of zero elongation only exist for $\beta \le 0$, the left hand side of the strain state diagram as presented in Fig. 5.1. The direction of zero strain will be the direction of the final crack. Let us examine some special cases.

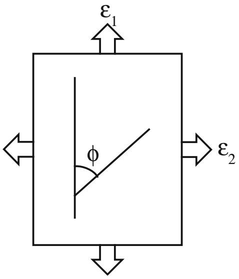


Fig. 5.3 Definition of a direction in a deforming sheet (see text)

- If $\beta = 0$ we find $\phi = \pi/2$, not surprisingly as $\beta = 0$ stands for plane-strain deformation with $\varepsilon_2 = 0$;
- In the tensile test we have $\beta = -0.5$ (for isotropic material) and the direction will be: $\phi = 54.7°$, the well known direction for fractures in a tensile test;
- If $\beta = -1$ (deep draw state) we find $\phi = \pi/4$, however this is difficult to verify as that strain state has in principle infinite formability.

The direction of the local neck in a tensile test is determined by β and thus by r. Therefore, it has been proposed by some to use this direction as a means to determine the value of r at fracture.

5.3 Necking in Complex Strain States

The phenomena causing the final fracture as expressed in the FLC are not different from the phenomena in the tensile tests that we have discussed in detail above. After some amount of straining a situation arises where an instability can occur, forcing the deformation to concentrate in a small area (the neck) and finally causing fracture (tearing). It has also been shown above that a neck requires a direction of zero elongation to develop.

It can be shown that the Considère condition (Eq. 4.1) can be expanded to a more general condition for local necking known as Hill's local necking criterion, see Sect. 19.3:

$$-\frac{d\sigma_1}{d\varepsilon_3} > \sigma_1 \tag{5.3}$$

where σ_1 is the major stress and ε_3 is the thickness strain (note: $\varepsilon_3 < 0$). It can further be shown that for materials obeying the generalized stress-strain law $\bar{\sigma} = C.\bar{\varepsilon}^n$ this yields for the onset of necking (both expressions are the same):

$$\varepsilon_1 + \varepsilon_2 = n; \quad \varepsilon_3 = -n \tag{5.4}$$

In case $\varepsilon_2 = 0$ (plane strain) we find for the onset of necking $\varepsilon_1 = n$, the same value as found before in case of the tensile test (Sect. 4.2). In all other cases we can

Fig. 5.4 Schematic representation of the FLC showing theoretical limits

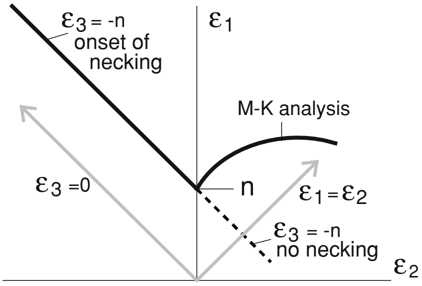
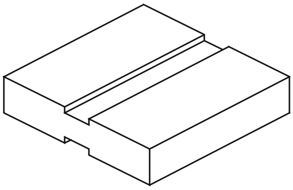


Fig. 5.5 Groove type imperfection used in M-K analysis



conclude that necking starts at that combination of ε_1 and ε_2 that causes the same reduction in thickness as in plane-strain stretching. This relation can be plotted in a strain state diagram as a straight line with slope –1 ($\varepsilon_3 = -n$), see Fig. 5.4.

Realise however that this analysis is only valid for $\varepsilon_2 < 0$ as only then there are directions of zero elongation present in the material. For situations of $\varepsilon_2 > 0$ there are no directions of zero elongation. That situation is often analysed using the so-called Marciniak-Kuczynski method (conveniently abbreviated to M-K analysis, M-K method or similar). In this type of analysis a groove type imperfection is considered as shown in Fig. 5.5. During deformation the stress state in this groove is followed, and it can be shown that after some amount of deformation the strain state in the groove becomes plane-strain. From that moment on a neck can develop, and this happens relatively fast as the material has hardened in the mean time considerably. Note however that the actual shape of the FLC predicted in this way depends heavily on the shape of the yield locus. Marciniak-Kuczynski analyses can be applied for very complex problems; examples will be presented in Sects. 7.2, 9.2 and 12.2.

We can now draw the following conclusion:

G The forming limit expressed in the conventional FLC is caused by the same basic phenomena that are encountered in the tensile test: after some straining instability occurs causing the deformation to concentrate into a small area, finally resulting in fracture.

The more perspective reader will now conclude that there is an inconsistency in the line of reasoning. After all, in Chap. 4 it was stated that in a tensile test necking starts when $\varepsilon_1 = n$, while the discussion of the FLC leads to the conclusion that necking starts only when $\varepsilon_1 = n.(1 + r)$ (combine Eqs. 4.6 and 5.4). The explanation is that in a tensile test there are in fact two instabilities, see Fig. 4.2. The second one indeed at $\varepsilon_1 = n.(1 + r)$ that is responsible for the creation of the local neck and fracture, but the first instability causing the diffuse neck is solely caused by the specific nature of the tensile test. In a complex deep-drawn part areas may exist where the strain state is uniaxial just as in a tensile test. However, the first instability might not occur when for example uniform necking of the material is restricted by the surrounding material. This leads to another important conclusion:

H The specific nature of a forming operation may create phenomena that limit the formability but that are not present in other situations with the same strain state.

5.4 Favourable Directions in the FLC

There are two specific situations (strain states) that request further examination, both are presented by the grey arrows in Fig. 5.4.

The first one is the strain state characterized by $\beta = -1$, or $\varepsilon_2 = -\varepsilon_1$, or $\varepsilon_3 = 0$ (*deep draw state*). In that case there is no reduction of thickness, and following the line of reasoning presented above, no necking should occur. This means that the material should be able to be stretched infinitely, but this is difficult to check. An indication however can be found in the forming of highly cold worked materials that effectively behave as full-hard. Such material can be found in the wall of two-piece beer and beverage cans; in a tensile test this fractures immediately. In the past tests have been carried out to form two-piece cans by blowforming (similar to tube hydroforming), see an example in Fig. 5.6. By careful adjusting the axial feed some control over the actual strain state is possible. By keeping the strain state as closely as possible to the deep-draw state an expansion of 10% could be obtained in some cases (meaning $e_1 = 10\%$). This indeed indicates that the deep-draw state allows deformations well beyond the levels expected from a tensile test, although for the readers not familiar with can shaping it will not look spectacular. On the other hand, it must be mentioned that some deviation from the ideal deep-draw state to either side is allowed before fracture actually occurs, as the process would never have been possible in practice otherwise.

Another example is the drawing of cylindrical parts with high height/diameter ratio by deep-drawing and successive redrawing, like the compressed air cylinders used by divers. These products show high levels of deformation in deep draw state without fracture.

The second specific situation is the strain state characterized by $\varepsilon_1 = \varepsilon_2$, the *equi-biaxial state*. If we realize that in that case $\varepsilon_3 = -2.\varepsilon_1$ it should be clear that this state has the highest ratio between effective strain, that determines the level of work-hardening, and major strain, of all practically possible strain states; the ratio

Fig. 5.6 Actual shaped can made by blowforming illustrating the relevance of the deep-draw state. In this example the expansion is 5%, but expansions of 10% have been obtained using a more smooth shape. Note the cross-bands in the centre of the product

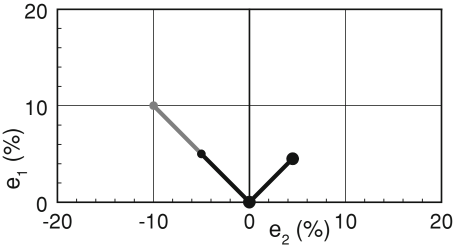
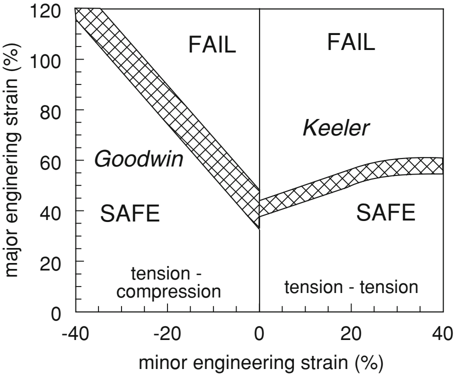


Fig. 5.7 FLC of can wall material. Data for uniaxial, plane-strain and equi-biaxial state have been obtained with Nakazima strips; the data for deep-draw state are from blowforming tests

is 2 versus 1.15 for a plane strain state and 1 for the uniaxial state. Nevertheless relatively high levels of straining are possible. This can be illustrated by looking again at the wall of two-piece cans. An FLC of such material has actually been measured using standard Nakazima strips (see Chap. 20). In plane-strain and uniaxial state the specimens fractured immediately, however in equi-biaxial state fracture occurred not until 4.5% major strain, see Fig. 5.7. This material has also been subjected to incremental forming, and the increased formability is shown in Chap. 10.

This clearly illustrates the mechanisms discussed above. The material is heavily cold worked and fractures immediately once an instability does arise; the hardening relation is something like $\sigma = 800 + 200.\varepsilon$ MPa (compare this to Eq. 4.1), the normalized strain hardening parameter is only 0.25. In plane-strain and uniaxial state directions of zero elongation are present, so an instability can arise immediately and this happens indeed. However, in equi-biaxial state such directions are not present from the beginning, but require a certain amount of straining to arise, in this case apparently 4.5% major strain.

Fig. 5.8 FLC as originally constructed by Goodwin and Keeler, see [1]



It might seem beneficial to combine these two favourable directions to create extended formability, more in detail high levels of plane-strain deformation; this will be discussed in Chap. 7.

5.5 FLC Restrictions

It is important to realize that the forming limits as expressed for example in Fig. 5.4 are no more than predictions based on a certain (material) model. Such models generally are heavily based on the hardening law of the material ($\sigma = \sigma(\varepsilon)$) and one has to start checking if the material to be studied indeed obeys that hardening law. Furthermore, these models just predict the onset of necking, which means the level of strain at which the forming operation becomes unstable. We have seen in the discussion of the tensile test that once the situation becomes unstable, fracture will not necessarily occur immediately but under certain conditions considerable more straining of the uniform part of the specimen is possible before fracture actually occurs. This again indicates that the definition of formability as a strain before fracture is far from simple. Consequently, comparative measurements of FLCs require a large amount of standardization, but that is beyond the concept of this work.

In this respect, it is also illustrative to have a quick look at the history of the FLC. The FLC was ‘discovered’ in the 1960 s and was originally named ‘Goodwin-Keeler’ diagram after the two researchers Goodwin and Keeler who carried out original work in the 1960 s, and who’s combined work created the first FLC (Fig. 5.8). This discovery was met in the world of forming technology with a lot of “hurray-hurray”, because researchers recognized this as a means to study industrial forming operations. The idea was: measure the actual strain-state in a product (for example a fender) using a circular grid and compare that to the FLC of the particular material; this tells how critical the operation in question is.

This was done enthusiastically in the late 1960 s and 1970 s and extensive research on FLCs was carried out in that period (much of which has been forgotten by now it must be feared).

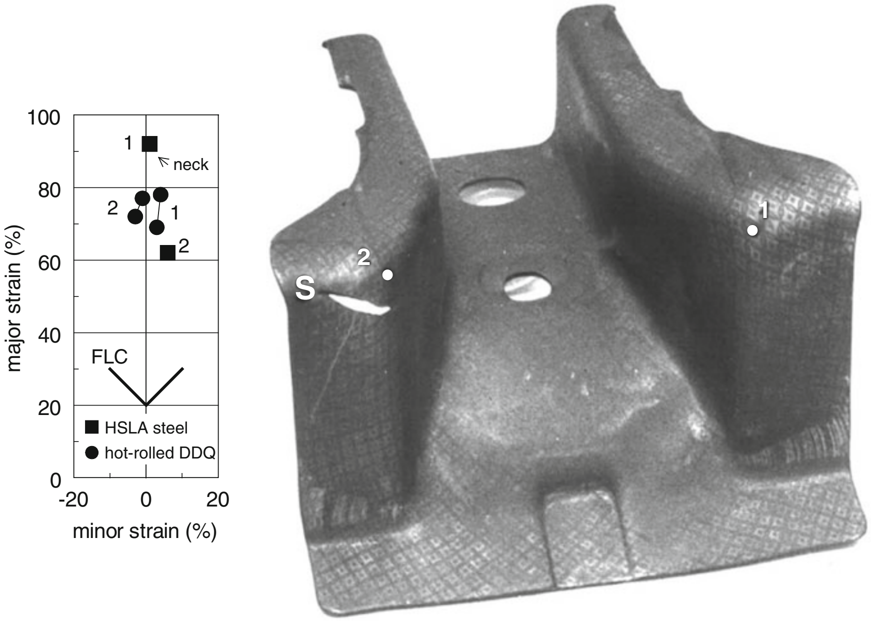


Fig. 5.9 A commercial automotive part (1984) made from 2 mm thick low-C steel in two grades, showing exceptionally high local strains and anisotropic failure. *Left*: measured strains, *right*: picture of the part (HSLA steel). Numbers 1 and 2 denote measuring position. The FLC is only indicated. Comment: no fracture occurred at S when using DDQ steel

However, during that time situations were met where apparently the FLC was incorrect: in some situations the material failed well below the FLC, while in other cases strains were measured in an actual product well above the FLC, see example in Fig. 5.9. These observations could be encountered for example in situations with bending or a non-straight strain path (see next chapters). So things turned out to be not as simple as they seemed to be in the beginning.

As a result, during the 1980 s the enthusiasm lowered, the interest declined, and it became a little quiet around the FLC.

In the 1990 s a renewed interest in the FLC was seen but from an entirely different point of view. The FLC was no longer seen as an instrument to study industrial forming operations (although it is still used in that way), but more as an instrument to develop and verify enhanced material models, notably in cases of varying strain path (the Holy Grail in forming technology). This is still going on.

The part of Fig. 5.9 shows another aspect of formability. Fracture always occurred at the position shown in the picture near point 2, but never at the other side near point 1. This may seem strange in an otherwise symmetrical product. However, the actual part was cut out of the sheet at an angle, so that the line of symmetry of the part is not at 0° or 90° relative to the rolling direction; this can be slightly noticed from the orientation of the grid. The visible crack at point S was oriented at 90° relative to the rolling direction. The mirror orientation at the right hand part of the product is at approx. 45°, and due to the anisotropy of the material no crack arose there. So:

I For technical materials the formability may depend on the orientation in the sheet.

Concluding, the FLC as presented in this chapter and shown in Fig. 5.1 is not as conclusive as it was anticipated originally and possible still regarded as such by some. The reason is that the FLC is only valid under certain conditions but this was not clear from the start. These conditions are:

- there is no bending,
- the strain path is straight (meaning that β remains constant during the process).

These restrictions may seem quite severe, but there are many processes operated on an industrial scale that satisfy these conditions sufficiently enough to justify the use of the FLC. There are two more conditions imposed to the FLC. These are not often mentioned because they are seldom met in standard sheet metal forming operations. These are:

- the stress state is plane stress,
- there is no shear.

Exceptions as shown in Fig. 5.9 simply indicate that apparently also in commercial products these conditions seem to be violated every now and then. The following chapters will investigate in detail what will happen if each one of these conditions is not met.

Reference

1. R. Pearce, *Sheet Metal Forming*, 1st edn, chapter 12. (Adam Hilger, IOP Publishing Ltd, 1991)

Chapter 6
Bending

Abstract Nearly all forming operations have some amount of bending. Bending can cause a multitude of effect, but raising the formability is the most relevant. In a situation of bending combined with tension the occurrence of compressive fibres at the concave side creates additional stability, therefore raising the formability. This also lowers the tension force. A normal stress at the tool contact has a similar effect, albeit of smaller magnitude. Bending can also create shear, or cause inter-crystalline fracture in some materials at the convex side that obviously lowers the formability.

Keywords Bending · Bending-under-tension · Stability · Tool contact stress · Shear · Bending defects

It is impossible to imagine a sheet metal forming operation without bending in some place. Therefore, it is surprising that effects of bending on formability seem to have been ignored over the years. Indications to this effect are very old, but only recently serious research in this field has started.

6.1 Introduction

Bending differs from the common forming process by the fact that the deformation is not uniform over the sheet thickness but varies: at the outer side there is elongation, at the inner side there is contraction (compression). In principle there is no change in thickness (exceptions will be discussed below), and consequently no necking. This means that bending is an operation that can create a substantial amount of deformation, but without failure.

The effect of bending can be various.

- If the strain is measured on the outer side of a bent area (convex side), the values will be higher than the mid-plane strain (mean elongation) unless corrected for

W. C. Emmens, *Formability*, SpringerBriefs in Applied Sciences and Technology,
DOI: 10.1007/978-3-642-21904-7_6,

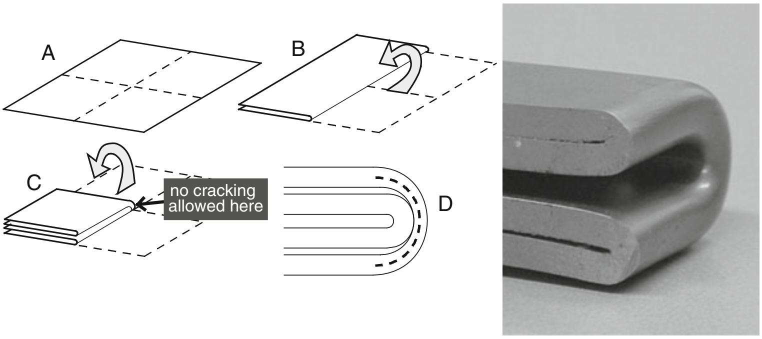


Fig. 6.1 The handkerchief-bending-test. A piece of sheet is bent twice (A-B-C); no cracking is allowed in the corner of the double bend. *Right* a picture of an actual test carried out on 6 mm thick (!) high-strength steel

the material thickness[1]; the data in Fig. 5.9 have not been corrected in such a way, although the error created by this is not dramatic.

- If there is bending and unbending, a situation of full stress-reversal will occur causing the so-called Bauschinger effect; this will be discussed in Sect. 7.3.
- There is thinning of the material caused by bending-under-tension (Sect. 6.2).
- If the bending takes place over a tool radius there is a contact stress ($\sigma_3 < 0$) that changes the strain state (Sect. 6.3).
- Bending can evoke shear (Sect. 6.4).
- There is an increase of formability, sometimes dramatically, but this mechanism is not well understood; this effect can be observed in the data of Fig. 5.9 as well, see also Sect. 6.2.

As an illustration of the latter we will now have a look at a very simple test known as the ‘handkerchief-bending-test’. This is an ancient, very straightforward bending test that however does not produce quantitative results. This test is only rarely used presently. In this test a piece of material is bend twice to 0-T as pictured in Fig. 6.1, and the material passes if no cracking occurs in the edge of the double bend (Fig. 6.1C) where obviously the deformation is quite severe.

It turned out that mild steel passes this test without any problem, probably also the reason why this test has become obsolete, although it is sometimes still used to test welds, or to illustrate the bendability of high-strength steel. If we make a cross-section right at the edge of the double bend we get the situation as shown in Fig. 6.1D. It should be clear that the part indicated by the dashed line must have elongated considerably, otherwise the geometry simply would not fit.

Surprisingly, also material taken from the wall of a two-piece steel can passes this test. This means that material hardened to such a degree that it fractures

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[1] This statement is based on the general accepted assumption that in a situation of combined bending and tension indeed the mid-plane strain describes the material behaviour, but this is doubted by some authors.

immediately in a tensile test (see the FLC in Fig. 5.7) can be subjected to a considerable elongation *if it bends at the same time*.

Already this simple observation leads to an important conclusion:

J The formability of a material can be enhanced considerably if it is subjected to simultaneous bending and stretching.

The effect of bending on formability is encountered in the measurement of FLC's. A much-used method is the use of so-called Nakazima strips where the material is stretched over a hemispherical punch, see Chap. 20. It has been noticed that the FLC rises if the ratio t/R is increasing, but also that this effect depends on the particular material being tested. Even before that, it was well known that thicker material presents higher forming limits in the so-called Erichsen stretching test, pointing in the same direction.[2]

6.2 Combined Bending and Tension

We will look now more specifically to the combination of bending and stretching (tension).

In case of pure bending, the material at the convex side will be in tension, and at the concave side in compression. If the material is stretched at the same time, there will be more extension and less compression, in an extreme case all material will be in tension. The case where the material is stretched, but at the concave side material is still in compression is of special interest. This situation is known as bending-under-tension, or stretch-bending.

This situation will now be analyzed in more detail. For the sake of simplicity, we will assume perfectly plastic (non-hardening) material with yield stress σ and neglect elastic effects.

Fig. 6.2 shows the situation schematically. Graph A shows the strain in a sheet of thickness t bent to a radius R (of the centre line); the strain at the outer fibre e_b is $e_\mathrm{b} = t/2/R$ assuming $t << R$. Graph C shows the corresponding stress distribution, the net tension is zero.

Graph B shows the situation where there is an additional straining with amount e. The neutral line shifts over a distance $z_t = t/2.\ e/e_\mathrm{b} = e.R$. Graph D shows the corresponding stress state; there is now a net tension force T per unit width equal to $T = \sigma.t.z_t/(t/2) = \sigma.2.z_t$. This leads to the following relation between T and e:

$$\begin{aligned} T &= \sigma.t.\tfrac{e}{e_\mathrm{b}} = \sigma.e.2R; \quad && e < \tfrac{t}{2R} \\ T &= \sigma.t; && e > \tfrac{t}{2R} \end{aligned} \tag{6.1}$$

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[2] The Erichsen test, dating from 1914, is probably the oldest standardized, pure formability test. It applies equi-biaxial stretching with a punch of 10 mm radius. The outcome has to be corrected for thickness, see for example DIN 1623 and similar specifications.

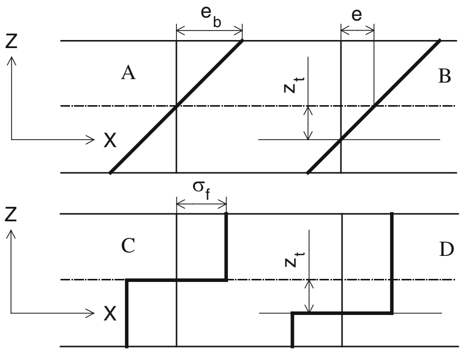

Fig. 6.2 Situation of combined tension and bending. *Top* strain, *bottom* stress

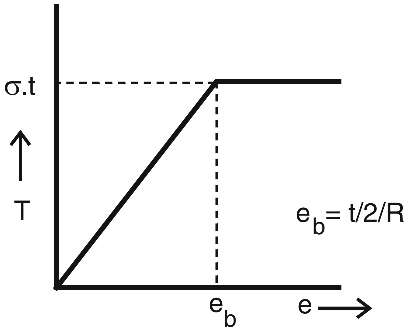

Fig. 6.3 The relation between tension per unit width and elongation in a situation of bending and stretching

It has been assumed that $t << R$ so that the level of thinning due to the strain e can be neglected. Otherwise there would be a correction to Eq. 6.1 that however does not influence the major conclusions.

Equation 6.1 is graphically presented in Fig. 6.3. That figure shows that a special situation occurs when $e < e_b$, or: as long as the neutral line stays within the sheet, or: as long as the inner fibre is still in compression. That situation creates some special effects:

- The tension is proportional to the elongation. That means that even a small tension force will create some elongation (stretching) and consequently some amount of thinning. This is applied deliberately in some forming operations where additional thinning of the material is created by pulling it over a very small die radius (stretch-redraw in can making). Consequently, multiple bending and unbending as in pulling material over draw-beads will always cause some amount of thinning of the material.
- The tension is proportional to the elongation. This means further *that we have a situation as described in statement E* (Sect. 4.3): *this will postpone necking and improve the formability*.

The fundamental stabilizing effect is based on the situation that additional elongation causes less material to be in compression, which increases the net

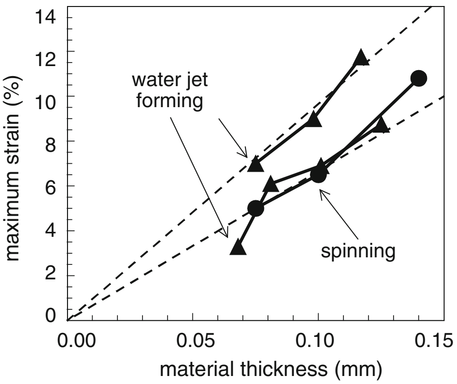

Fig. 6.4 Results from can shaping experiments showing formability being proportional to material thickness. The *dashed lines* show proportionality. See [2] for more details

tension force. In other words, the elongation is stable if $z_t = e.R$ increases with increasing e (and of course as long as $z_t < t/2$). In situations where the bending radius is constant, this will obviously be the case. Furthermore, the limit stable elongation is $e = e_b = t/2/R$ that is proportional to the sheet thickness for constant R, and this has been observed indeed (see below). In many situations however the bending radius is not constant, but is determined by an equilibrium between pulling force and bending moment. In general R will now be a function of e: $R = R(e)$. Therefore, it is not clear beforehand if $e.R$ will still be increasing with increasing e, notably when we realize that an increase of tension force (increase of e) will expectedly reduce the bending radius. A detailed analysis shows that as a first approximation one can state $R \approx C/\sqrt{e}$ [1], so that $e.R$ still increases with increasing e, and the elongation remains stable.

This stabilizing effect is not limited to non-hardening materials, and not even to 2D bending situations. It is valid in all situations where the tension force is reduced by the effect that bending causes the fibres at the concave side to be in compression. As an illustration, Fig. 6.4 shows results of three series of can shaping experiments. In these experiments heavily cold-worked material, that shows little work hardening, is formed by tests using incremental techniques where the bending radius was found to be constant in first approximation. The observed formability, defined as maximum expansion in a single operation, is roughly proportional to the wall thickness, and this hints to forming by bending-under-tension.

Direct evidence of enhanced formability by bending-under-tension can further be found in performing tensile tests with simultaneous bending, so-called CBT tests. These tests are similar to the Taraldsen tests described in Sect. 4.4, but the two rolls supplying a contact stress are replaced by a set of three rolls as in a three point bending test. These tests have been proposed originally by Benedyk [3]; recent experiments carried out at the University of Twente succeeded in obtaining 400% uniform strain in this way [1, 4].

It is not known if this effect (enhanced formability by bending under tension) is solely responsible for the observed increased formability in cases of additional

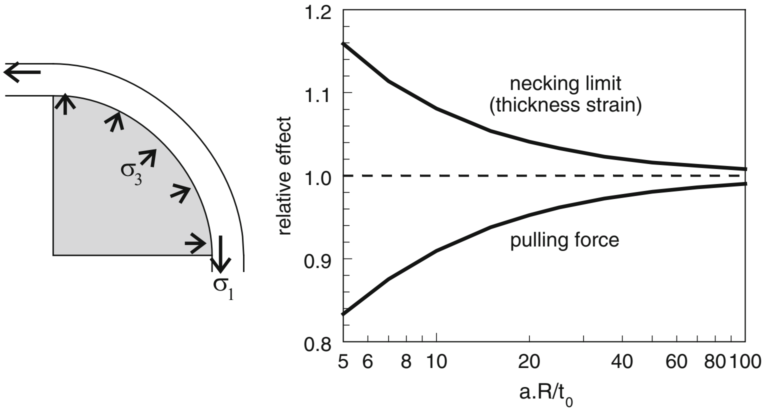

Fig. 6.5 Contact stress created by bending over a tool radius. *left* situation; *right* effect of bending on formability and pulling force

bending as described in Sect. 6.1. However, the proportionality between formability and sheet thickness that is sometimes observed suggests that at least in some cases it is.

This phenomenon hints to a very interesting property. Note that in fact the formability is only determined by t and R, and that these parameters have nothing to do with the mechanical or metallurgical properties of the material, and that after the forming operation they have not changed (forgetting a small reduction of thickness). This means that it can be expected that this specific forming operation can be repeated again, and again, and again etc. We can now formulate the following statement:

K If the formability is governed by other parameters than basic material properties, the formability can be increased by simply repeating the forming process.

This may sound as pure speculation, but the observations from the CBT tests and incremental sheet forming in general support this. This aspect is further discussed in Sect. 15.1.

6.3 Tool Effects of Bending

In many practical cases, bending is done over some tool radius. This creates a normal stress in the contact zone given by $\sigma_3 = -\sigma_1.t/R$, see Fig. 6.5, left. This changes the strain state in the material, and one effect is that the length stress for plastic deformation reduces. Consequently, in combined bending-stretching operations the deformation is concentrated in that part that is actually bending. The effect of contact stress in general will be discussed further in Chap. 8, but the

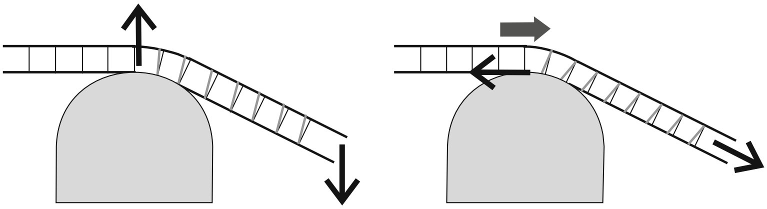

Fig. 6.6 Shear caused by bending. The thin cross-section lines are perpendicular to the surface, the thick *grey lines* indicate shear. *Left* common effect, *right* effect caused by pulling over a radius

formability for the situation of Fig. 6.5 can be analyzed relatively simple with the maximum force condition. Results are presented in Fig. 6.5, right, where the parameter a in the abscissa is defined as $\sigma_{3,\ \mathrm{mean}} = \sigma_{3,\ \mathrm{contact}} / a = -\sigma_1 . t/a/R$; for a linear stress distribution over the thickness we have $a = 2$. The upper part shows the effect on formability (necking limit), the lower part the effect on the pulling force for different situations, see [5] for more details. For many practical situations, the value of $a.R/t_0$ is not lower than, say, 10. This graph illustrates that consequently the effects are restricted, not larger than roughly 10%.

6.4 Bending and Shear

Bending can cause shear by two different effects.

In every bending operation will always be some amount of shear, for the simple reason that there must be a force acting normal to the surface, and consequently there is a shear stress acting on the original perpendicular cross-sections (Fig. 6.6, left). This means that part of the deflection is caused by shear, the other part by bending.

In many situations the material is bent due to the fact that it is pulled over a radius, implying that there is a *movement* of the material over the punch. The resulting friction force at the tool contact may also cause shear (Fig. 6.6, right). This is particular the case at small tool radii, where the contact stress may be considerable, as in incremental sheet forming. Note that both effects are opposite.

The effects of shear will be discussed further in Chap. 9.

6.5 Other Bending Defects

It should be mentioned here that bending can also be limited by fracture of the outer fibre as illustrated in Fig. 6.7, resulting in limited formability in bending. This is not caused by a macroscopic instability but by microscopic effects (intercrystalline cracking). It turned out that aluminium in general is prone to this type

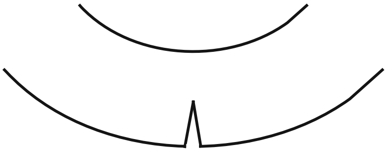

Fig. 6.7 Fracture of the outer fibre in bending (schematically)

of defect while mild steel is not, due to the differences in crystallographic structure. This was notably encountered when the automotive industry changed from steel to aluminium for body construction, and required an adaptation of the forming process.

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Chapter 7
Non-Straight Strain Path

Abstract A non-straight strain path can both raise and lower the formability, depending on the character of the strain path changes. Abrupt changes create a stress overshoot that may cause premature fracture. The transient stress effect on the other hand can create a situation of quasi-hardening that creates additional formability. Pure cyclic straining can raise the formability as well.

Keywords Non-straight strain path · Pre-straining · Transient stress effect · Bauschinger effects · Cyclic straining

A complex-shaped product may be manufactured by a series of forming operations. This means that a certain part is subjected to a succession of forming operations with possibly different strain states, like deep drawing followed by stretching. This is called a change in strain path. It has an effect on formability, and that was already recognized in the early days.

7.1 Definition

The strain state of a certain material part will be expressed as a point in the strain state diagram. The history of that part is consequently presented by some curve in that strain state diagram. This history (in fact its graphical representation) is called the strain path. The FLC as discussed in Chap. 5 was derived under conditions of a straight strain path, which means that during the forming operation the ratio $\varepsilon_1 : \varepsilon_2 : \varepsilon_3$, or better: the value of β (Eq. 6) remains constant.[1]

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[1] An additional condition is that the directions of principal strain may not rotate; this can sometimes be visualized by plotting the strains at fixed orientations (like axial and tangential in cylindrical products) and requiring that the graphical strain path indeed remains straight.

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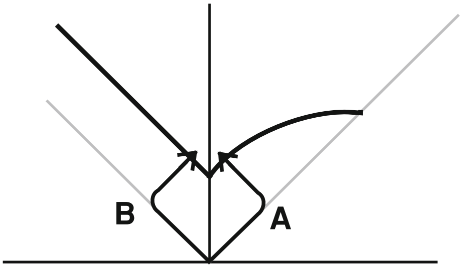


Fig. 7.1 Try to obtain large(r) plane-strain levels by combining two favourable strain states

A succession of different forming operations of different character can create a situation that this strain path, the graphical representation of the forming history, is not a straight line. The following will investigate what can happen in such a case.

7.2 Broken Strain Paths

The common FLCs as shown in Figs. 5.1, 5.4 and 5.8 show a minimum at (or: around) the plane strain situation $\varepsilon_2 = 0$. Peculiarly, this strain state often occurs in many practical forming operations, one of nature's mean tricks. It is now tempting to try to obtain a higher level of deformation at plane strain by combining the two favourable strain states equi-biaxial and deep-draw that were indicated by the grey arrows in Fig. 5.4. It is assumed that we have indeed some means to impose an arbitrarily strain state to a piece of material, which however in practice is often impossible.

The two candidates for strain path are shown in Fig. 7.1. Let us look at strain path A. The operation starts with a biaxial deformation ($\varepsilon_2 > 0$), this causes a large amount of effective strain and consequently a large amount of work hardening. When the deformation shifts to the left ($\Delta\varepsilon_2 < 0$), fracture is controlled by instabilities that will occur rapidly as the material is pre-stressed significantly. Concluding, this strain path will not allow much increased straining, certainly not in case of a work-hardened material, unless the second part of the strain path is *exactly* deep-draw.

Now look at strain path B. The operation starts with a uniaxial deformation ($\varepsilon_2 < 0$) that creates a certain amount of effective strain. However, when the deformation shifts to the right ($\Delta\varepsilon_2 > 0$) fracture will not occur immediately as the fracture mechanism is less sensitive to work hardening (see discussion in Chap. 5). This means that route B seems more successful than route A. This is the basis for a rule of thumb: *in a complex strain path never turn to the left as this causes immediate trouble, only turn to the right* (there is also some theoretical foundation for this).

Analysis of material behaviour under complex strain paths is difficult. It is possible to use a more general version of the M-K analysis, allowing more complex stress states, and variable orientation of the defect relative to the direction

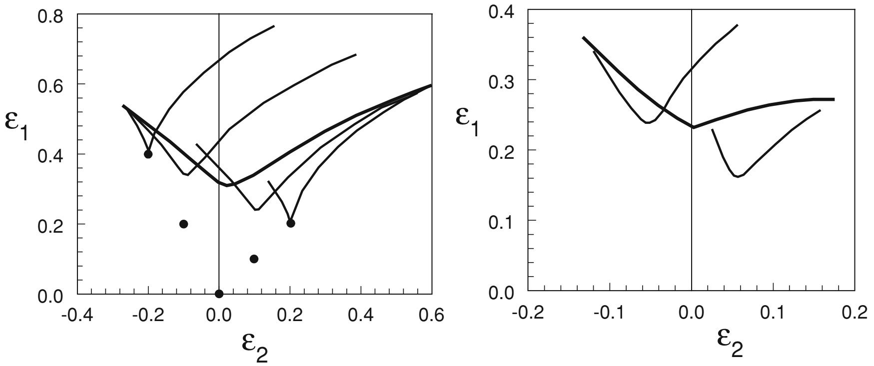


Fig. 7.2 FLCs of pre-strained material. *Left*: theoretical FLCs obtained using an M-K type analysis, data from [1]; the dots indicate the pre-strain. *Right*: Actually measured FLCs (mild steel), data from [2]

of major strain. Results of such an analysis carried out by Yoshida et al. [1] are presented in Fig. 7.2, left, where various levels of biaxial and uniaxial pre-strain have been applied. Actual measurements on mild steel have been carried out by Gronostajski [2], and some results are shown in Fig. 7.2, right. Both figures show very comparable results. All cases show that the minimum of the pre-strained FLCs are below the original curve, but that high levels of plane-strain deformation can only be obtained by first deep-draw straining following by biaxial straining. This confirms the rule of thumb mentioned above.

The conclusion is:

L

> A non-straight strain path can either lower or raise the formability. As a rule of thumb, the formability of a material is reduced in situations of changing strain state where the value of β (=$d\varepsilon_2/d\varepsilon_1$) is decreasing, and is raised where β is increasing.

7.3 Effects of Stress

One of the decisive phenomena in forming with complex strain path is the material behaviour. In general this is a very complex matter, and the determination of material behaviour under conditions of (continuously) changing strain paths is still the Holy Grail in forming technology. More in detail, this concerns the stress-strain relations of pre-strained materials.

Fig. 7.3 shows some results for pre-strained mild steel. The left-hand graph presents stress-strain curves of pre-strained material. The material was pre-strained to 9% elongation in uni-axial tension, but the uni-axial directions differs from that in the final tensile test. In fact, the pre-straining was done with a very large specimen, from which a small specimen was cut for the second tensile test in varying directions. Note that the actual change in strain path may be much more

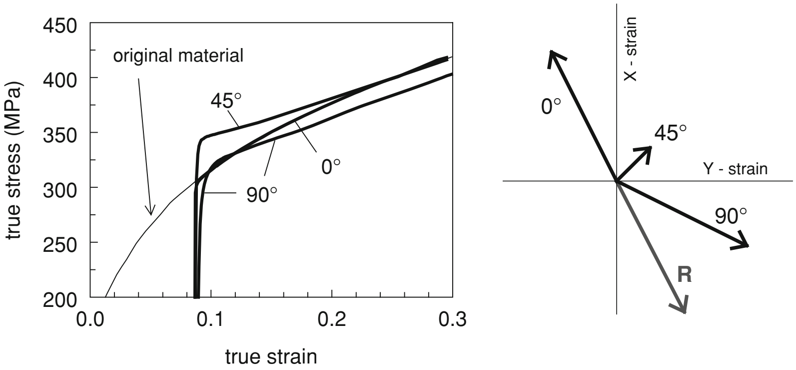
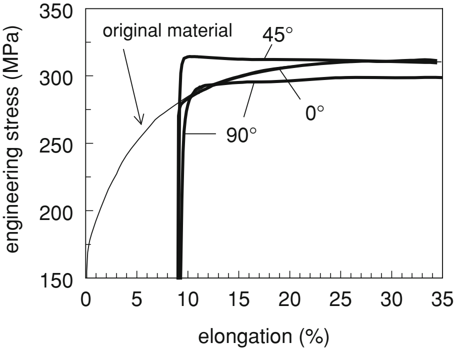


Fig. 7.3 Effect of pre-strain in a tensile test. *Left*: stress-strain curves of mild steel pre-strained in a separate tensile test; labels denote difference of uni-axial direction between first and second tensile test. *Right*: strain state in uni-axial tests plotted in a strain state diagram for an isotropic material

Fig. 7.4 Data from Fig. 7.3, left, presented as engineering tensile curves



than simple the change in uni-axial direction, see the right-hand graph. In fact, a change of 90° in uni-axial direction almost evokes strain reversal, compare this to the reverse strain direction marked R. This effect is even stronger for materials with a high *r*-value. Note also that in a diagram with fixed co-ordinates as in the right-hand graph a tensile test at 45° is a combination of some biaxial straining and pure shear.

If there is no change in direction (0°) the curve coincides with the curve of the original material (thin line), and is barely noticeable. For a change of 45° the curve shows an overshoot but later coincides with that of the original material. For a change of 90° the curve shows aspects of the Bauschinger effect (early re-yielding and softening, see below) but still also shows a slight overshoot.

The overshoots as shown in Fig. 7.3 may just look like a material effect of academic interest, however they can reduce formability. This becomes more clear in Fig. 7.4, where the same curves have now been plotted as engineering tensile

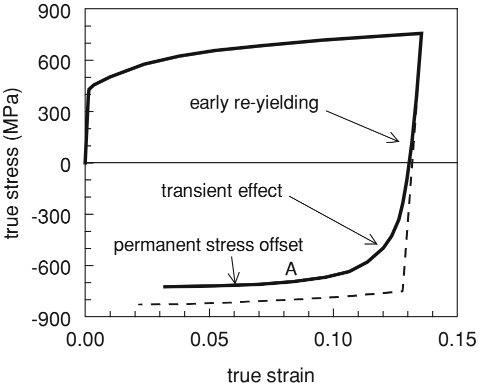


Fig. 7.5 Example of Bauschinger effect as measured on high-strength steel showing typical effects; data from [3]. The *dashed lines* shows the expected curve without Bauschinger effect

curves. The overshoot in the 45° now creates a situation where the engineering stress (read: pulling force!) actually decreases with increasing elongation, an unstable situation. In this case the reduction in force is mild, but situations have been encountered where specimens actually failed after an overshoot despite the fact that the strains were still quite low. The 90° curve does not show a decrease in engineering stress, but only barely.

The curves illustrate a well-known effect: an abrupt and significant change in forming direction creates an overshoot in the engineering tensile curve followed by some softening. However, the effect of pre-strain is only of short duration: after some time the effect is lost. If the change in forming direction is not abrupt but smooth, a more gradual transition in the stress is observed without an overshoot.

A special case arises when there is a full reversal of the strain direction as shown by the direction marked R in Fig. 7.3. In that case there is actual unloading. This happens for example in bending and unbending. This particular situation has been investigated relatively well (notably for spring-back analysis) and shows the so-called Bauschinger effect, meaning that in reversal of the strain direction the material shows a lower (absolute) flow stress.

A typical example is presented in Fig. 7.5. Now let us look in more detail to the phenomena from a formability point of view, as this is what this work is all about, and in view of the stability criterion of Eq. 4.1 (the Considère condition). The Bauschinger effect results in a lower absolute yield stress (σ) but with the same absolute rate of hardening ($d\sigma/d\varepsilon$), see point A. This is favourable for the suppression of necking, so in some cases this will improve formability.

Of more interest is the transient effect clearly visible in Fig. 7.5. This transient effect creates a situation where, over a certain level of straining, there is in fact work hardening, probably sufficient to postpone necking in agreement with statement E (Sect. 4.3). This is analysed in more detail in Fig. 7.6 that shows the stress/strain relation after the onset of strain reversal plotted in a more conventional way. This graph also presents the normalized strain hardening parameter Z that was defined in Sect. 4.5 by the grey line. Elongation is stable as long as Z is

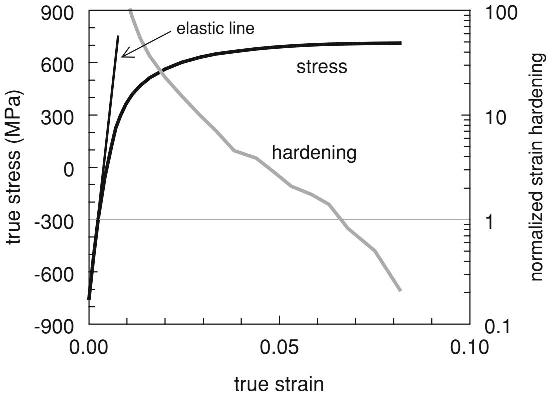


Fig. 7.6 Transient effect of Fig. 7.5 analysed in detail

larger than 1, and this is the case up to strains of approx. 0.065. This is considerably larger than the elastic strain that is approx. 0.0075, see the elastic line.

This example illustrates that transient effects can create formability. Note that this is the case for all transient effects, so also in the cases shown by the 90° curves in Figs. 7.3 and 7.4. The increased formability by transient effects as shown here are in general not spectacular, but repetitive stress transients might create a noticeable effect. There is also experimental evidence. Tensile tests carried out on material taken from necked can walls that shows little formability, indicate that indeed the Bauschinger transient effect can enhance the formability of hard-to-form materials, see [4].

This leads to the following conclusion:

M The transient stress effects occurring during strain path changes create a situation of (quasi) work hardening that may cause (additional) formability.

7.4 Cyclic Straining

A special case of non-straight strain path is cyclic straining.

The effect of cyclic straining on for example changes in the microstructure of the material has been studied in detail by several authors, but effects on formability are still obscure. Pure cyclic straining as in repetitive bending is of little interest, but the combination with stretching is more important. This subject has gained recent interest inspired by incremental sheet forming (see Chap. 10), where high levels of deformation can be obtained, and the material is subjected to cyclic straining. Cyclic straining in pure tension and compression is difficult to perform, but allowing some bending makes it much easier. Recent studies by Yagami et al. applying that method [5] indicate that indeed cyclic straining can raise the formability (see Fig. 7.7), but this strongly depends on the specific conditions. A general understanding is still lacking, but it might simply be caused by the stress

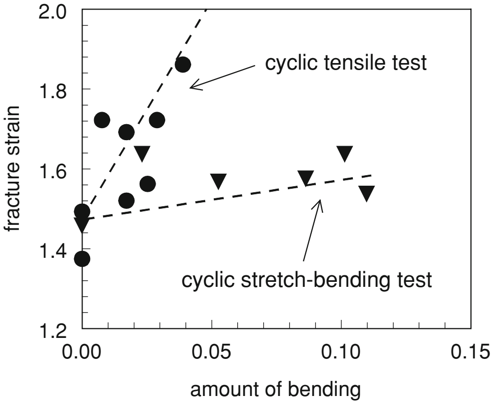


Fig. 7.7 Experimental results showing increase of formability in cyclic straining, data from [5]

transient effects created by the repetitive strain reversals. A special case of cyclic straining occurs in so-called ultrasonic forming, this is discussed in Chap. 12.

Another effect of cyclic straining related to formability is the occurrence of fatigue, more in particular low-cycle fatigue. Some materials are quite sensitive to low-cycle fatigue, and that may limit the formability in situations of cyclic straining. Fatigue however falls outside the scope of this work, and the reader is referred to dedicated literature.

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Chapter 8
Non-Planar Stress

Abstract In all situations of contact between tool and sheet there is some contact stress (negative normal stress). This will raise the formability, but the effects are limited.

Keywords Contact stress · Stress state · Thickness stress

In sheet metal forming the dimensions of the material in one direction (thickness) is much smaller than the dimensions in the other two directions. As there can be no normal force on a free surface, stresses normal to the surfaces are often low and therefore ignored: a situation of plane stress. Strictly speaking, a situation of plane stress means that there is neither a thickness stress, nor shear. The effects of shear will be discussed in Chap. 9; this chapter discusses effects of thickness stress (normal stress, contact stress).

8.1 Effects of Contact Stress

In every situation where there is contact between workpiece and tool, there is a surface stress: a contact stress normal to the sheet surface. This violates the condition for plane stress ($\sigma_3 = 0$) that underlies the FLC.

One has to distinguish between single sided contacts and double sided contacts, as shown in Fig. 8.1. A single sided contact (left) occurs for example when the material is pulled or stretched over a tool radius. In extreme cases the contact stress can be very high, comparable to the yield stress of the material! There is a negative contact stress at the contact side, but at the other side the normal stress is zero. This means that the normal stress inside the sheet will vary, and the mean normal stress is lower than the actual stress at the surface. Only in a double sided contact (right) where also the length of contact is (much) larger than the thickness

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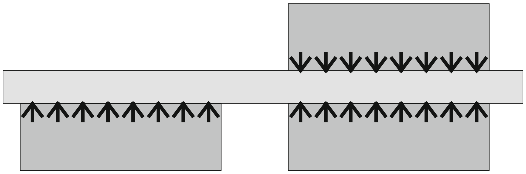

Fig. 8.1 Situation of contact stress; *left*: single sided contact, *right*: double sided contact

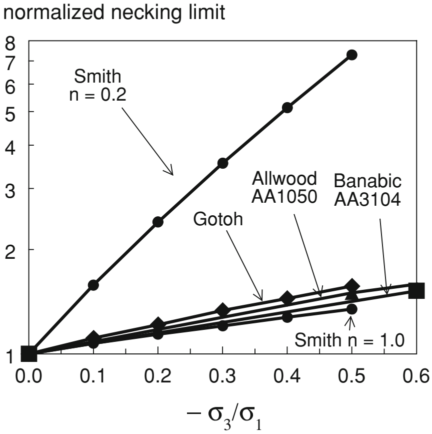

Fig. 8.2 Effect of thickness stress on necking limit under conditions of plane strain. Data from [1–4]

of the sheet, a proper through-thickness normal stress can be created that is (more or less) constant over the thickness of the sheet: thickness stress. This however can only occur if the material is actually clamped between two tool parts.

The presence of a contact stress changes the stress state of the material, which has two effects. The most obvious one is that it reduces the yield stress in tension, meaning that a lower tension stress is required for plastic deformation. This follows directly from the well known yield functions. The Tresca yield function (Chap. 18) for example, simply states; $\sigma_1 - \sigma_3 = \sigma_{f,}$ and as σ_3 is negative, this lowers the yield stress in tension $\sigma_{1.}$

A lesser-known effect is that it does raise the formability, meaning it increases the length strain at which an instability starts. Several researchers have investigated this analytically, but they do not always find the same result. A compilation of results is presented in Fig. 8.2. This figure presents the effect on the necking limit at plane-strain conditions, but note that a proper, through-thickness, constant σ_3 is assumed. The predictions of the Smith model for low values of n are unrealistically large, and can be regarded as erroneous. The other models agree satisfactorily but indicate that the effect is restricted, a rough estimate would be:

$$\frac{\varepsilon_0(\sigma_3)}{\varepsilon_0(0)} \approx 1 + \frac{-\sigma_3}{\sigma_1} \tag{8.1}$$

where ε_0 is the necking limit at plane strain conditions. This relation shows that a considerable level of thickness stress is required for a significant raise of the

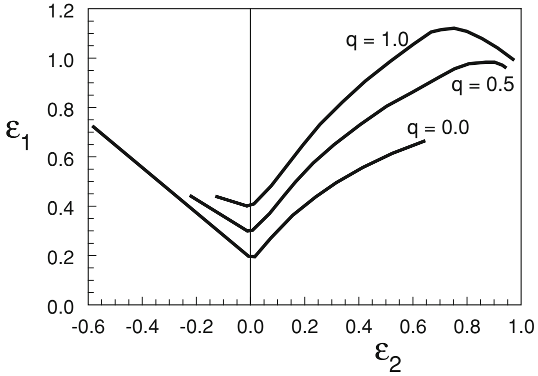

Fig. 8.3 Effect of thickness stress on the FLC, data from [4]. Parameter q $= -\sigma_3/\sigma_1$

formability, this will be difficult to achieve with single-sided contacts. The contact stress created by bending has already been analyzed in Sect. 6.3, and that analysis also showed that the effect is restricted. Note that relation Eq. 8.1 can also be derived using the Considère condition under some general assumptions, see Sect. 19.5

Allwood and Shouler have carried out a detailed investigation of the effects of both thickness stress and shear on the FLC using an M-K analysis with application of a six-component stress tensor [4]. The results presented in Fig. 8.2 have been obtained in this way, but Fig. 8.3 presents a more detailed image; their results on shear will be discussed in Sect. 9.2. Figure 8.3 suggests that the effect of thickness stress is stronger in the right-hand part of the graph ($\beta > 0$) than in the left-hand part ($\beta < 0$). This is not surprising. The more the thickness changes during a forming operation (more to the right in the graph), the more a normal stress at the surface is likely to have an effect.

A conclusion now is:

N The presence of contact stress (negative thickness stress) raises the formability.

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Chapter 9
Shear

Abstract There are three kinds of shear: in-plane shear, through-thickness shear, and out-of-plane shear, although fundamentally there is no difference. Forming by pure shear can in principle create infinite formability as there is not reduction in sheet thickness. The situation of shear combined with stretch is more complex, but several analyses have showed that it can raise the formability significantly.

Keywords Shear · In-plane shear · Through thickness shear · Out-of-plane shear · Shear and stretch

The forming operations discussed above have all one thing in common: a cross-section line perpendicular to the surface remains perpendicular to the surface (at least in first approximation). This is called forming by stretch. If the cross-section lines do not remain perpendicular to the surface the process is called forming by shear, see Fig. 9.1. Section 9.1 discusses forming by shear alone; Sect. 9.2 discusses shear combined with stretching.

Note: in (translated) Japanese literature the term "shearing" is used for cutting or similar operations (like punching).

9.1 Forming by Shear Alone

Forming by shear requires some further attention. Note however that the following only applies to the macroscopic situation, notably the way the forming force is applied to the material. On a microscopic scale shear is just the result of the choice of the coordinate system, and has strictly speaking nothing to do with macroscopic forming by shear.

In the following we will assume a plane-strain situation, meaning that in one of the principal directions the strain is zero. One can however raise the question if in these situations the assumption of plane stress is still valid, but that is a beyond the concept of this work.

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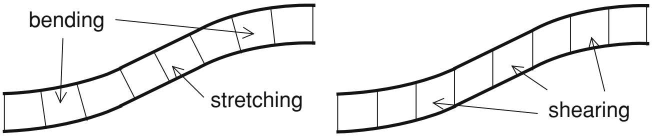

Fig. 9.1 S-shaped part showing the difference between stretch and shear

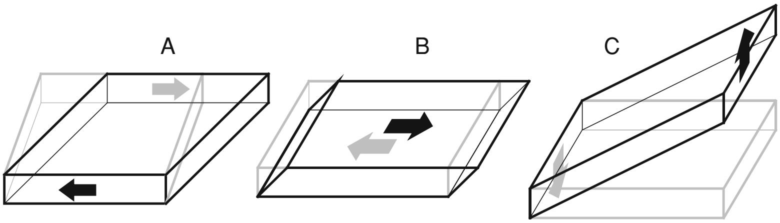

Fig. 9.2 Three situations of sheet forming by shear (macroscopic). The undeformed state is pictured in *grey*, the deformed state in *black*. The arrows indicate the process forces

Shear takes place when the forming force is acting parallel to a surface of the material. If a rectangular block is deformed by shear it transfers into a parallelepiped, one pair of faces remains unchanged, one pair of faces transfers into parallelograms, and one pair of faces is lengthening by $1/\cos(\alpha)$, α being the technical shear angle. In sheet metal forming we can now distinguish three different situations depending on which pair of faces forms the sheet surface and these are shown in Fig. 9.2, note the orientation of the forming forces. Again, fundamentally all three situations are the same, only the macroscopic appearance differs and, more important, also the technological behaviour. Note that the areas (faces) that the forces are action on do not change.

Situation A (*in-plane shear*) is the best known. This situation occurs in many shear tests and also in simple torsion (either of tube or bar). In this case the direction of zero strain is normal to the sheet surface, there is no change in thickness. Note that the strain state is identical to a deep-draw state as discussed in Chap. 5, and consequently we expect infinite formability. However, there is compression in one direction parallel to the surface causing possible buckling or wrinkling, see Fig. 9.3. The latter limits the practical level of deformation. If however this phenomenon can be suppressed by some means, large deformations are possible. As the deformation is uniform over the specimen, contrary to that in the flange of a deep drawn part, this technique is often used in studies on the effect of changing strain path. A practical means to study this type of shear is torsion of thin-walled tubes. In in-plane shear the cross-section lines remain perpendicular to the surface, so this is in fact not different from forming by stretch. It is just a matter of definition of the co-ordinate system, see Fig. 9.3.[1]

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[1] The representation of shear as in Fig. 9.3 is the fundamentally correct definition: pure shear. The variants of technological shear as shown in Fig. 9.2 are in fact a combination of pure shear and some rotation: simple shear.

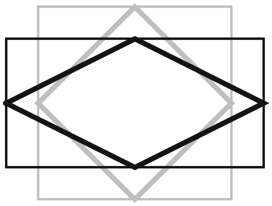


Fig. 9.3 Equivalence of in-plane shear (*thick lines*) and stretch (*thin lines*). *Grey*: original situation, *black*: new situation. Note the compression in vertical direction

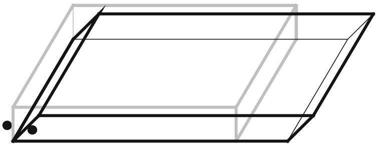


Fig. 9.4 Situation C of Fig. 9.2 presented in a different way

Situation B (*through-thickness shear*) can arise in cases of high shear stresses on the surface, for example in cases where the material is clamped between two mutually moving tool faces (as in wall ironing, be it that that process is bulk forming, not sheet metal forming). In situation B there is also no change in thickness so large levels of strain can be expected. However, as all macroscopic dimensions remain unchanged (assuming the thickness is small compared to the other dimensions) this is hardly a practical forming operation.

Situation C (*out-of-plane shear*) is more difficult to obtain, as the forming forces preferably will simply rotate the specimen instead of shear it. One of the very few mechanisms that possibly can create this situation is bending. Also, out-of-plane shear is assumed to occur in shear spinning, see Chap. 10. It has been proposed in the past that this mechanism also occurs in incremental sheet forming (see Chap. 10), but that has not been confirmed by direct observations. At first sight situation C may just look like a tilted version of situation B. However this is not the case, which becomes clear if we rotate the formed part back so that the sheet surface coincides with the original sheet surface, see Fig. 9.4 (in sheet metal forming the sheet surface is almost always the plane of reference). The edge with the dot keeps its original length. The relation to formability becomes also more clear in this way. We can now see that the length increases and the thickness decreases, but this is not done by simply pulling at the specimen as in plane-strain stretching. Realise that from a fundamental point of view all three situations in Fig. 9.2 are identical, and that material thinning in situation C is just an *apparent* effect caused by our choice of reference system. Therefore, one might assume that necking at least will start at larger strains than in simple stretching, if at all, indicating that this mode of deformation will lift the formability above the FLC.

The overall conclusion:

O Forming by shear is expected to create larger formability than forming by stretch.

Fig. 9.5 Effect of combined shear and stretch. Data from [1]

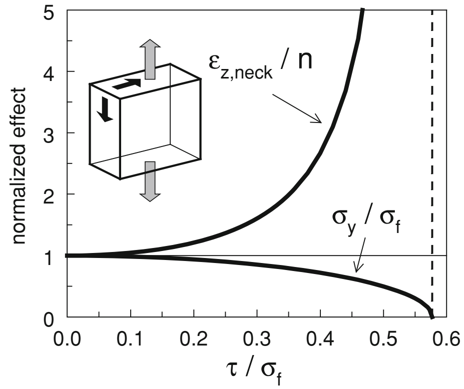
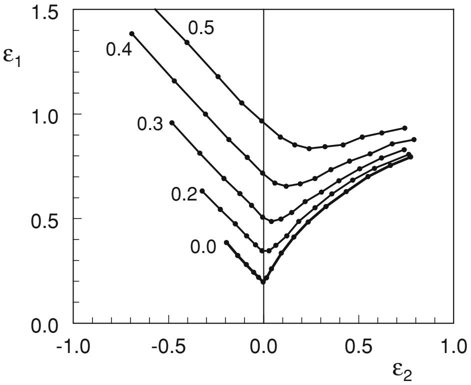


Fig. 9.6 Some effects of additional shear on the FLC. The parameter indicates the severity of shear. Data from [2]



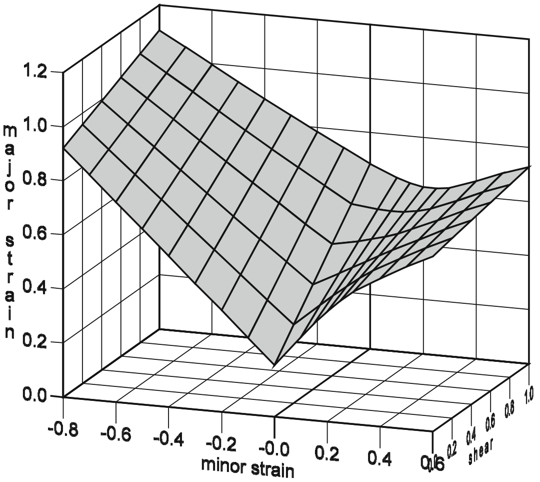
9.2 Shear Combined with Stretch

Forming by shear alone as discussed in the previous section occurs seldomly, although it has been proposed to occur during shear spinning. More often there is a combination of shear and stretch.

The occurrence of additional shear in a stretching operation changes the stress-state of the material. Its effect is twofold: it reduces the yield stresses in tension, and it increases the formability. The first effect follows directly from the well-known yield functions and will not be discussed here. The second effect can be studied analytically and some results for a simple situation are presented in Fig. 9.5. This graph shows the effect of a combined shear stress and normal stress on both the necking limit (top line) and the yield stress in tension (bottom line).

To study the effects of additional shear in a general way is very complicated, but much work has been done by Eyckens et al. They used an M-K analysis to study the effects on the FLC, some results are presented in Fig. 9.6 that clearly show that additional shear can raise the formability. Their results however indicate

Fig. 9.7 3D FLC showing the combined effects of stretch and through-thickness shear. Data from [3]



that the effect of shear depends on the relative orientation of shear and the major strain in stretch, Fig. 9.6 shows the situation with the largest effects. Allwood and Shouler have carried out a similar approach that has already been mentioned in Chap. 8. They have expanded the FLC by adding a third axis presenting the shear strain. In this way the FLC becomes a ‘forming limit surface’. Results obtained for AA1050 are presented in Fig. 9.7. Both figures show that additional shear shifts the minimum in the FLC towards biaxial.

Note that the effects of additional shear on formability are (much) larger than the effects of contact stress, another phenomenon that changes the stress state of the material (Chap. 8).

Forming by shear in practice is difficult to obtain. Nevertheless, Allwood and Shouler have proposed a new class of forming operation called ‘paddle forming’ where additional shear is created. A dedicated test with a straight specimen showed that indeed large levels of uniform deformation can be obtained, up to 300% elongation [3].

We can now expand statement N although still somewhat speculative:

N′ Any external effect that changes the strain state resulting in a reduction of the yield stress in tension, will raise the formability.

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Chapter 10
Incremental Forming

Abstract In incremental forming operations high levels of deformation are easily obtained. In shear spinning these are obtained by out-of-pale shear. In Incremental Sheet Forming (ISF) high levels of deformation are obtained by a combination of effects mentioned above: bending, cyclic straining, non-planar stress and shear.

Keywords Spinning · Shear spinning · Incremental sheet forming · Taraldsen test · Shear · Bending

Incremental forming is the name of a variety of processes characterised by the fact that at any moment only a small part of the workpiece is actually being deformed; a very effective designation is: “a progression of localised deformation”. Incremental forming of sheet is very old, and it allows large levels of deformation.

10.1 Spinning

Traditional spinning is very old, apart from hammering the oldest sheet metal forming technique in the world. In *spinning* a round blank is clamp unto a rotating mandrel, and the sheet is formed by a moving roller or rod. In traditional spinning this is done by successive roll passes, as shown schematically in Fig. 10.1, left. There is a large similarity with conventional deep drawing. In first approximation the thickness of the sheet does not change, and the outer diameter gradually reduces. This similarity can also be noticed in the fact that earing shows up in the spinning of cups (see Sect. 18.4). Spinning is widely used for the manufacturing of rotational symmetrical parts in small-series production. It allows a large flexibility in shapes. Recent developments show that also non-rotational symmetrical products can be made by spinning within certain limitations on automated devices.

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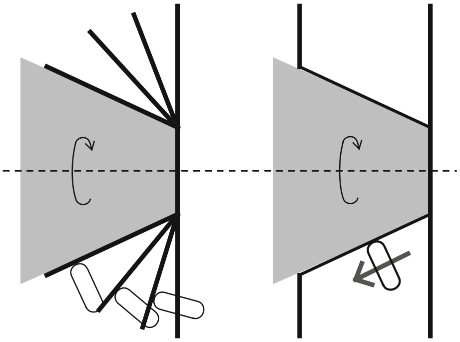

Fig. 10.1 Principle of spinning. *Left*: traditional spinning, *right*: shear spinning

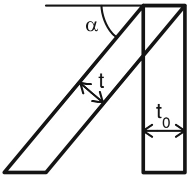

Fig. 10.2 Thickness in shear spinning illustrating the sine rule

Of special interest is what is called *shear spinning*. In shear spinning a conical product is made in a *single pass*, and the outer diameter does not change, see Fig. 10.1, right. There is a considerable reduction of thickness. It is generally assumed that forming is done by out-of-plane shear as defined in Sect. 9.1 [1], see Fig. 10.2, although it is not clear if this is based on hard experimental evidence. The final thickness follows the so-called sine rule:

$$t = t_0 \cdot \sin(\alpha) \tag{10.1}$$

where t_0 is the original thickness, t the final thickness, and α the semi cone angle.

Shear spinning is only successful if the final thickness is carefully controlled by the clearance between roller and mandrel, and in fact is forced to follow the sine rule. If this is done indeed, “any dimensions of the blank can be spun without failure or defects” [1]. This obviously creates high levels of formability, but only if this refers to the strains on the sheet surface.

10.2 Incremental Sheet Forming

The remainder of this chapter will focus on what is generally referred to as ‘Incremental Sheet Forming’ (ISF), also known as SPIF (Single Point Incremental Forming) and TPIF (Two Point Incremental forming). Generally, in ISF a part is made by having a small punch with hemispherical tip draw consecutive contours (trajectories) of increasing depth as schematically presented in Fig. 10.3. The final geometry is not determined by a mould or die (although one may be used), but by the

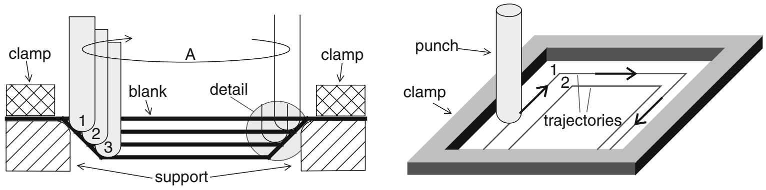

Fig. 10.3 Schematic presentation of Incremental Sheet Forming (SPIF). Detail: see Fig. 10.5

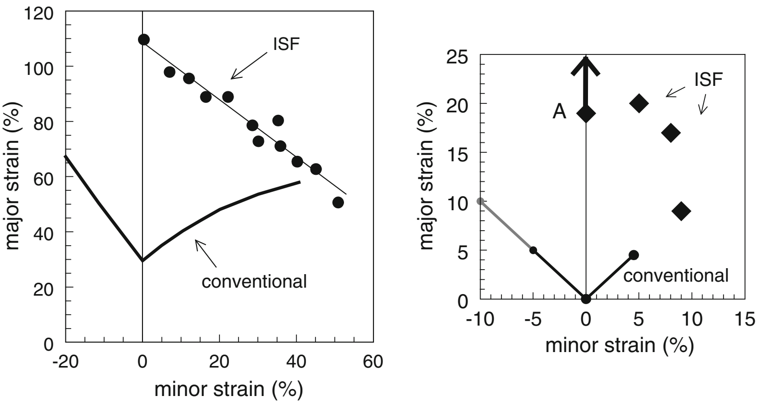

Fig. 10.4 Increased formability in incremental forming. FLC in ISF compared to conventional FLC. *Left*: material with good formability (aluminium, data from [3]). *Right*: material with poor formability, compare to Fig. 5.7, see [4]. Point A only shows a lower limit

envelop of all XYZ positions of the punch. Contrary to (shear) spinning no mandrel or similar is required, and this is the reason that in early literature this process was called 'Dieless Forming'. In ISF the final thickness also follows the sine-rule, certainly in first approximation. This is the reason that originally it has been suggested that also ISF is done by out-of-plane shear, simply in parallel with shear spinning. However, a fundamental difference with shear spinning is that the thickness does not have to be controlled carefully, but simply results from the basics of the process itself. This suggests that shear spinning and ISF are performed by different forming mechanisms. Detailed examination by Jackson and Allwood has revealed that ISF is not done by shear [2], this is discussed in more detail below.

ISF has gained worldwide interest because it enables material to be deformed well above the conventional FLC (see examples in Fig. 10.4) hence creating enhanced formability.

The increased formability can have two causes:

- The incremental character of the process;
- Special conditions in the forming zone.

Both find their cause in the fact that the deformation is concentrated in a very small zone around the punch contact. This localization is partly caused by pure

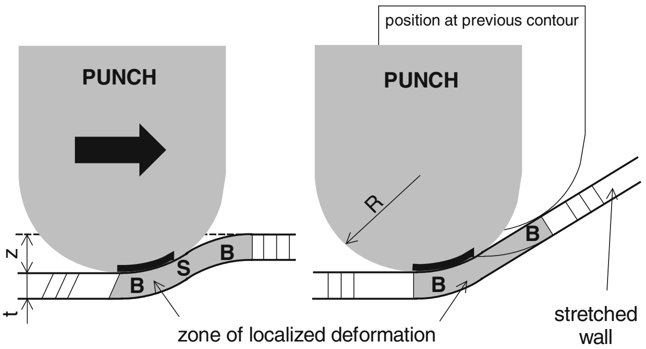

Fig. 10.5 Situation around the punch contact in incremental sheet forming. The *thick line* denotes high contact stress, *B* denotes bending, *S* denotes shear. The arrow indicates the direction of punch movement

geometrical effects, partly by the fact that several mechanisms that are mentioned below lower the yield force in tension and so create a 'weakest spot' just as in the tensile test (Sect. 4.4).

We have already encountered an example of incremental character in Sect. 4.4. The Taraldsen test as described there is in fact an incremental forming operation. In the contact zone between the rolls the yield force is reduced by contact stress (as described in Chap. 8) and the formability there is increased, but only slightly. It is the movement of the zone of concentrated deformation that is responsible for the large levels of uniform deformation that can be obtained. Speaking in a popular way: a neck that originates does not have time to develop, as the zone of deformation quickly moves to another spot.

The ISF forming limit presented in Fig. 10.4, left, is typical: a line of negative slope in the right-hand part of the FLC. Little data is available of the left-hand part, strain states with negative minor strain are more difficult to obtain with ISF. The graph illustrates that ISF favours plane strain.

Originally, some authors have proposed that incremental forming is done by out-of-plane shear (Sect. 9.1). This was not based on actual observations, but by drawing a parallel to shear spinning. More recent, detailed investigation however revealed that this is not the case [2]. The actual forming is very complex by a combination of shear, bending and stretching, combined with a high contact stress; the situation around the punch contact is schematically pictured in Fig. 10.5. The occurrence of shear in the direction of punch movement has been observed by direct experimental observations, the bending is obvious, and the high levels of contact stress have been indicated by FEM simulations. In this figure the stretched wall is indicated without shear. Recent investigations however indicate that some shear might occur there, but not in such a way that it points to forming by out-of plane shear. Some in-plane shear might occur as well, but that is not indicated in the figure.

In Fig. 10.5 the vertical step increment z is shown large for reasons of clarity. However in an actual operation it is small, often (much) smaller than the sheet thickness. This means that the punch passes a certain spot several times, up to a few dozen, and it is clear that the material is subjected to cyclic straining as well.

Concluding, in incremental sheet forming conditions are encountered that have been discussed in Chaps. 6, 7, 8, 9, and from which it is known that they can raise the formability of a material. In fact, ISF is the living proof of that. At the moment, it is not clear how much each condition contributes to the enhanced formability, and if that is the same in all situations. Nevertheless, the facts are clear, and it is a fact that the occurrence of enhanced formability in ISF has created a renewed interest in factors governing formability in general.

A detailed discussion of these aspects and their particular relation to ISF can be found in [5].

The data in Fig. 10.4, right, have been obtained by ISF with a high-pressure water jet instead of a metal punch, on the same material as presented in Fig. 5.7. Point A is only a lower limit, as larger strains were prevented by the tooling, not by fracture; see [4] for more details. The absence of a punch eliminates friction forces at the tool contact, and presumably also shear in the direction of punch movement. The contact stress at the impact position of the water jet is comparable to the water pressure (350 bar = 35 MPa) and low compared to the material flow stress (800 MPa). Also, the number of passes of the jet over a certain point was low, three at most. This indicates that in this situation bending is probably the most important formability raising effect.

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Chapter 11
Speed Effects

Abstract The forming speed affects the forming operation by (in order of increasing magnitude): inertia effects, metallurgical effects, and tribological effects. Metallurgical effects (strain-rate hardening) can lower the uniform strain in a tensile test but slow down the development of necks. Enhanced formability in true high-speed forming operations however are not caused by strain-rate hardening, but by secondary inertia effects. At extreme speeds the formability can also be increased by viscous drag.

Keywords Speed effects · Inertia effects · Strain-rate hardening · Post-uniform elongation · Secondary inertia effects · Viscous drag

Every forming process depends on the forming speed to some extent. However, it is known that forming at extreme speeds may enhance the formability of the material considerably. That is the final subject of this chapter.

11.1 Speed Effects in General

In forming operations the forming speed may affect the operation by three causes:

- Inertia effects
- Metallurgical effects
- Tribological effects

Inertia effects are caused by the acceleration of parts by the forming tool, that creates internal stresses. An estimation of the severity of these effects can be done by estimating the level of acceleration that can be created by the material's flow stress. Applying Newton's first law yields:

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$$a_{\max} = \frac{\sigma_{\max}}{l.\rho} \tag{11.1}$$

where ρ is the material's density, and l the specimen 'length', or better: the dimension of the part in the direction of acceleration (it can be just the thickness!). Some quick calculations show that the maximum acceleration is in the order of 10^4–10^7 m/s^2. These levels of acceleration are not encountered in normal stamping operations, meaning that inertia effects can be ignored. However, they can occur in true high-speed operations like electro-magnetic forming or explosive forming, and in crash-tests. In general, inertia effects cause additional stresses in the material that may reduce the formability. But secondary inertia effects may occur that can raise the formability significantly, that will be discussed in Sect. 11.4.

Metallurgical effects are for example effects of strain-rate hardening, these are discussed in detail in Sects. 11.2 and 11.3.

Tribological effects notably occur when a viscous lubricant is used. Relative movement of tool and workpiece creates hydrodynamic effects in the lubricant. This reduces the level of friction between workpiece and tool, and generally this reduces the load on the workpiece during the forming operation, and will increase the formability. The effect is counter intuitive: the operation performs better when the press-speed is increased! The effect of lubrication is further discussed in Sect. 14.1 and Chap. 22.

In conventional stamping operations the tribological effects are by far the largest. Metallurgical effects come second, and inertia effects can be ignored completely.

The remainder of this chapter will focus on the effects in high-speed forming operations where it has been observed that strains can occur well above the FLC, and look for the origin of that effect.

11.2 Metallurgical Effects: Strain Rate Hardening

Strain rate hardening is a phenomenon that the strength of a material (or in this case better: the resistance against forming) increases when the forming speed increases. Note that this is not a permanent effect: as soon as the forming speed decreases again the hardening effect decreases also. A direct consequence of this is that tensile tests have to be carried out at prescribed speeds.

For many materials the effect of work hardening and strain-rate hardening can be separated. Two classes of material are generally distinguished: materials where the both effects are multiplicative, expressed as:

$$\sigma(\varepsilon, \dot{\varepsilon}) = \sigma_1(\varepsilon) \cdot \sigma_2(\dot{\varepsilon}), \quad \dot{\varepsilon} = \frac{\mathrm{d}\varepsilon}{\mathrm{d}t} \tag{11.2}$$

and materials where the effects are additive, expressed as:

$$\sigma(\varepsilon, \dot{\varepsilon}) = \sigma_1(\varepsilon) + \sigma_2(\dot{\varepsilon}) \tag{11.3}$$

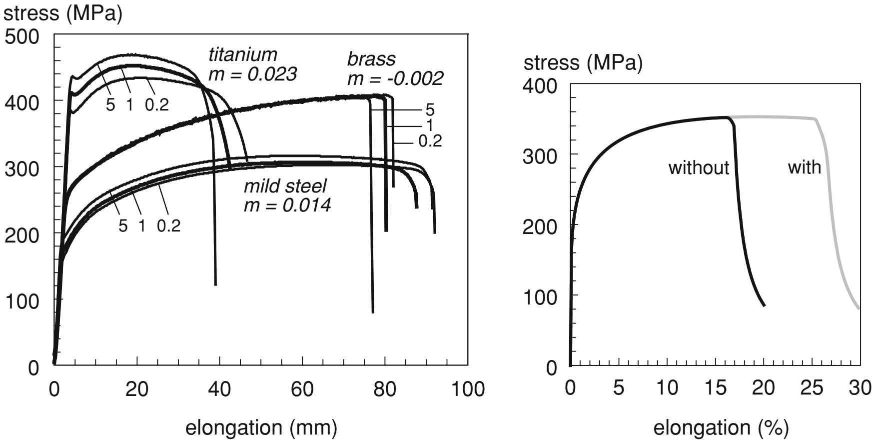


Fig. 11.1 Effect of strain-rate on tensile test. *Left*: examples of actually recorded stress-strain curves carried out at different speeds, legend: testing speed in mm/s. *Right*: simulated curves for mild steel, with and without strain-rate hardening

Many fcc materials fall in the first group, and relation Eq. 11.2 is often further refined to:

$$\sigma(\varepsilon, \dot{\varepsilon}) = C.\dot{\varepsilon}^m.\varepsilon^n \tag{11.4}$$

This relation also defines the strain-rate hardening parameter *m*. By redefining *m* as done in Eq. 4.4:

$$m = \frac{\mathrm{d}(\log \sigma)}{\mathrm{d}(\log \dot{\varepsilon})} \tag{4.4a}$$

the parameter *m* can also be used for materials that do not obey relation Eq. 11.4, but in general *m* will depend on the actual strain. Note that *m* can be negative as well as positive; for most materials *m* is in the range $-0.01/+0.02$. Mild steel is the best known example of materials hat obey relation Eq. 11.3, a typical value for *m* as defined in Eq. 4.4a is 0.012.

Strain rate hardening has a profound effect on stress-strain curves that can be noticed in the examples shown in Fig. 11.1, left. An obvious effect is the influence of speed on the height of the curve. It can further be noticed for titanium that the maximum of the curve (uniform elongation) shifts to lower strains when the testing speed increases. This effect depends on the nature of the strain-rate hardening:

- If the strain-rate hardening is multiplicative as in relations Eqs. 11.2 and 11.4 the uniform elongation is not affected by the testing speed;
- If the strain-rate hardening is additive as in relation Eq. 11.3 the uniform elongation decreases with increasing speed, assuming positive strain-rate hardening.

These effects follow directly from the Considère condition Eq. 4.1, see Sect. 19.4. Both mild steel and titanium show an additive effect, brass shows a multiplicative effect but this is too small to be noticed in Fig. 11.1.

Very relevant is the effect on the post-uniform elongation (the elongation from the maximum of the curve until actual failure). A high level of strain-rate hardening significantly increases the amount of post-uniform elongation, which is clearly visible in Fig. 11.1, left. This is further illustrated in Fig. 11.1, right, where a simulated tensile test curve (the same as in Fig. 4.3) is plotted both without and with strain-rate hardening as for mild steel. This effect can be easily understood. Suppose a neck is developing in the specimen. That means that the deformation becomes concentrated into a small part, and, as the pulling speed remains constant, consequently the strain rate in that part increases, causing additional hardening. This hardening effect will slow down the development of that neck, and a larger total elongation is obtained before fracture. Note that there is a clear difference between the effects of work hardening and strain-rate hardening:

- work hardening will postpone or suppress the onset of necking
- strain-rate hardening will only slow down the development of the neck once it has originated

Strain rate hardening therefore will not prevent necking, it only slows it down. Nevertheless, the following statement can be made (as an extension to statement {C}):

C′ Strain rate hardening will increase formability if some (local) thinning is allowed.

Please realise that in a practical situation some thinning is ALWAYS allowed.

11.3 Strain Rate Hardening and Formability

Compared to other technical materials, mild steel shows a high level of strain-rate hardening, and this section will focus on that material as an example, to see if strain-rate hardening can create enhanced formability in high-speed operations.

The strain-rate hardening of mild steel is investigated extensively, and the complete hardening can be expressed by the so-called Bergström relation that is based on physical phenomena:

$$\sigma = \sigma_0 + \Delta\sigma_m . \left(\beta.(\varepsilon + \varepsilon_0) + \left[1 - e^{-\Omega.(\varepsilon+\varepsilon_0)} \right]^{n'} \right) + \sigma_0^* . \left(1 + \frac{kT}{\Delta G_0} . \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right)^{m'} \tag{11.5}$$

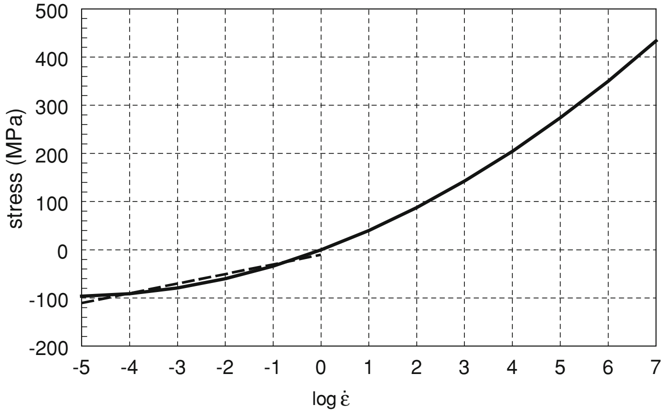


Fig. 11.2 Strain-rate effect on strength of mild steel, according to Eq. 11.5 (*solid line*). *Dashed line*: linear approximation for low strain rates

Note that the strain-rate term also contains the temperature as a parameter. This relation looks a nightmare due to the large number of parameters but in fact, many parameters are (more or less) constant.

The second term describes the work hardening and is in fact just a linear relation with a transient function for low strains. This part does not include the increased hardening rate expected to take place for mild steel at very high strains, say $\varepsilon > 5$. The third term describes the strain-rate hardening and, although probably not immediate visible, tells us that the effects of high strain rate can also be studied by performing tests at low temperature. This is done indeed, as actual tensile tests at high speeds are very difficult to perform.

Extensive tests on mild steel show that indeed the strain-rate hardening is an additive term, highly independent of the pre-strain of the material (if at all) and the material grade, satisfying Eq. 11.5. Fitting Eq. 11.5 through measured data shows a satisfactory fit with the following parameters: $m' = 2$ and $\sigma_0^* = 620\text{MPa}(\Delta G_0 = 0.8\text{eV}, \dot{\varepsilon}_0 = 10^8\,\text{s}^{-1}$, and room temperature), this relation is presented in Fig. 11.2 as the solid line, where the stress is normalized to 0 at $\log(\dot{\varepsilon}) = 0$. The line was fitted through actually measured data with effective strain rates ranging form 10^{-4} to $10^7\ \text{s}^{-1}$. For high-strain rate data tests where actually carried out a low temperature, and using Eq. 11.5 the effective strain-rate at room temperature was determined, that is plotted in the figure. For low strain rates below, say, 1 s^{-1} the relation $\sigma - \log(\dot{\varepsilon})$ can also be approximated by a linear relation with a slope of approx. 20 MPa that is also shown in Fig. 11.2; this is sufficient for nearly all practical situations.

We can study the effect of high strain rates by carrying out simulated tensile tests and use the data from Fig. 11.2 to describe the strain-rate hardening. Results are presented in Fig. 11.3 by the black lines (the grey curves with inertia will be discussed in the next section). Note: the simulation starts with the final velocity

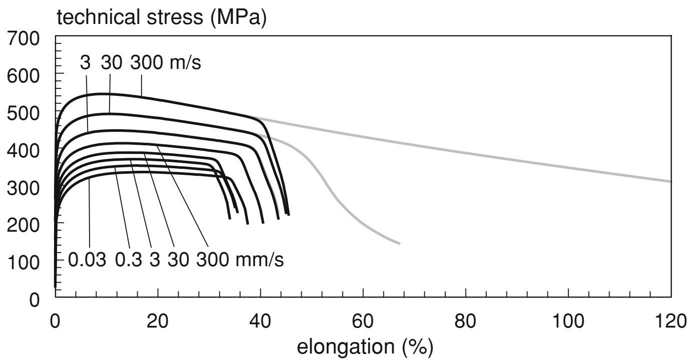


Fig. 11.3 Simulated tensile tests at different pulling speeds (specimen length = 100 mm). *Black lines*: without inertia, *grey lines*: with inertia

Table 11.1 Some examples of actual strain rates occurring in forming processes

Forming process	Typical strainrate (1/s)
Tensile test	0.001–0.01
Deep drawing	0.1–10
Incremental Sheet Forming	1–10
Rolling	10–100
Can wall ironing	1000
Electro magnetic forming	10000

field already present, therefore there are no acceleration effects that often cause oscillations.

Figure 11.3 shows some interesting features, several of which we have already encountered in Fig. 11.1; the inertia effects will be discussed in the next section. We see that speed has an effect on the amount of post-uniform elongation, but this effect is limited, even in case of mild steel that shows relatively large levels of strain-rate hardening. This indicates (but still somewhat speculative) that: *strain-rate hardening by itself cannot be responsible for the large straining observed at high-speed forming operations*. The next section will discuss what can cause extended formability at high forming speeds.

Table 11.1 lists some values for the strain rate in a number of forming operations. This presents the reader with some idea of actual values (order of magnitude).

11.4 Secondary Inertia Effects

It has been claimed in literature that the excessive straining in high-speed forming may be caused by inertia effects, at least partially, but these effects are of a different nature than the effects discussed in Sect. 11.1. This needs some explanation.

Fig. 11.4 Speed in a tensile test specimen, schematically. The *grey line* represents the situation at uniform strain, the *black line* the situation when a local neck is developing

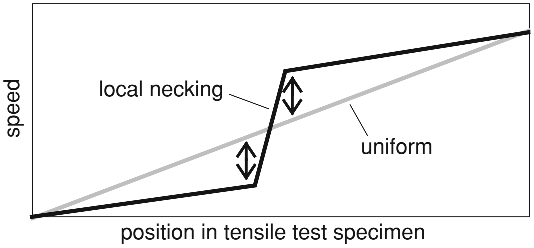
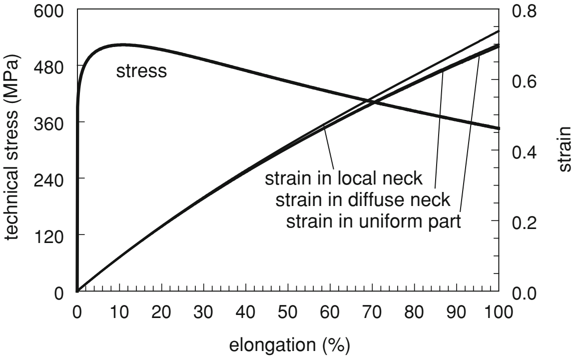


Fig. 11.5 Simulated tensile test at extreme speed (300 m/s) including inertia effects. Compare to Fig. 4.3



If a material is being stretched, each part of that material has a certain speed as obviously there can be no elongation otherwise. When a neck develops, the speed will change as the deformation becomes concentrated in the neck; this is illustrated in Fig. 11.4 that shows schematically the speed in a tensile test specimen. A change in speed however is limited by inertia effects as described by Newton's first law. In normal situations these effects are negligible, but at very high speeds they may become noticeable.

The effect of inertia (for steel specimens) has been studied by simulating tensile tests and the results have been plotted in Fig. 11.3 as well by the grey lines. The effect is overwhelming, albeit only at very high forming speeds. Please realise that inertia effects are *a linear function of speed*, *not strain-rate*, so that if the forming speed is high enough to make inertia effects noticeable, a relatively small increase in speed (generally interpreted on a logarithmic scale) will increase the inertia effects significantly.

Note that the effect of inertia is the same as the effect of strain-rate hardening, in such a way that it will not suppress or postpone necking, but strictly speaking only slows down the necking once it has started. Nevertheless, it can postpone necking from a practical point of view as illustrated in Fig. 11.5. This figure shows the same 300 m/s test as in Fig. 11.3, but also shows the strains in the various parts, just as in Fig. 4.3. Although indeed a neck is starting to develop at approx. 10%

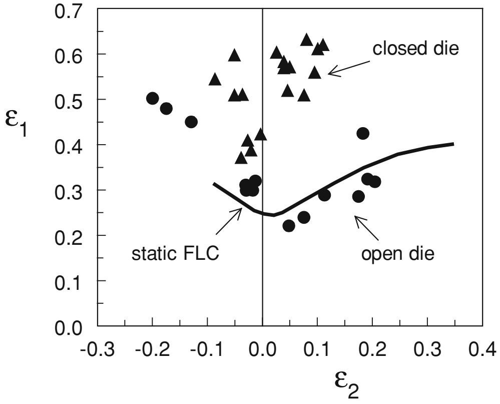


Fig. 11.6 Some results obtained with EM-forming, data from [1]

strain, the development of that neck goes so terribly slow that in practice the specimen can be elongated 100% without too much problems. However, realise that this is a very extreme situation. So:

P The formability can be increased considerably by inertia effects occurring at extreme forming speeds.

11.5 Other High Speed Effects

There is another speed effect that has to be mentioned here.

A plastic material deforms by moving dislocations. The speed at which dislocations move increases with strain, initially very rapidly. However the speed is limited by lattice friction and drag effects and cannot become infinite. Now imagine a piece of material that is forced to deform at a certain prescribed forming speed. If the maximum dislocation speed is reached, the material cannot deform faster by increasing the speed of the moving dislocations, but only by creating more dislocations. In that case the yield stress increases rapidly with forming speed and eventually becomes proportional to the strain rate: $\sigma(\dot{\varepsilon}) = C.\dot{\varepsilon}$. This is the same situation that happens in a viscous liquid $(\tau = \eta.\mathrm{d}v/\mathrm{d}t)$ and hence it is called '*viscous drag'*.

If the material behaves indeed like a liquid there will be no necking any more. This can be illustrated referring to molten glass, a liquid with very high viscosity: people who visit demonstrations in glass factories can often see that a piece of molten glass can be stretched enormously (by orders of magnitude) into a thin wire without fracture. Tensile test simulations support this.

Nevertheless, so far this mechanism is still speculative. It is based on theoretical considerations but has not (yet) been observed directly as the predicted strain rate at which this might occur is larger than, say, $10^4\ \mathrm{s}^{-1}$. This rate is almost impossible to check in the laboratory but it will occur in true high speed forming operations.

This effect resembles that of *superplasticity*. Superplasticity is a phenomenon occurring in certain alloys at high temperatures, say above 0.5 T_m, (T_m = melting point) and *low strain rates*, where the yield stress drops to low values and becomes related to the strain rate by $\sigma \approx k.\dot{\varepsilon}^m$, with $0.5 < m < 1$. Superplasticity will not be discussed here further.

11.6 Some Practical Consequences

Figure 11.6 shows some results obtained with Electro-Magnetic forming, illustrating that indeed lager strains can be obtained [1]. Noteworthy is that free forming (open die) does not show much increased formability, this in contrast to forming with a die where the test piece hits the die at high speed (closed die). This may seem weird but it is a direct consequence of high speed effects.

High speed effects are effects affecting formability, that only take place at extreme forming speeds. This means that there is a minimum forming speed (by any definition) only above which extended formability occurs. In a practical forming operation however the forming speed always starts at zero, but obviously also ends at zero. That means that in a forming operation the material has to pass through two potentially dangerous zones were the formability is low, one at the start and one at the end of the operation.

The first one is at the very start of the forming process. Here the material still has its original formability, and at extreme accelerations the material can pass through this zone while still deforming elastically. At the end however the situation is more dangerous. The material is deformed and has hardened considerably. This means that if the formability is no longer enhanced by the high speed, it reduces to that of simply hardened material, causing immediate fracture. So in fact the formability is still limited by low-speed effects: the common FLC. Only when the deceleration can be done so quickly that the material does not elongate any further, full advantage can be made from the high-speed effects. This is achieved by hitting the material at high speed against the tool.

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Chapter 12
Ultrasonic Forming

Abstract The application of vibrating tools can enhance the formability significantly. A major cause is the decrease of friction between workpiece and tool, but also the formability in the strict sense can be increased.

Keywords Ultrasonic forming · Vibrating tools · Friction · Superposition principle

Ultrasonic forming does not mean that the material is formed at excessive speeds, that is called supersonic. It means that the tool or part of it is vibrating during the forming operation. This can increase formability. All tests that are reported have been carried out in some laboratory; it is not known if ultrasonic forming is actually carried out in large scale production.

12.1 Ultrasonic Deep Drawing

The application of a vibrating tool has been applied on several types of forming operations, and the benefits of vibrating tools have been demonstrated for deep drawing, wire drawing and wall ironing. Of these, most research has been carried out on ultrasonic deep drawing. Here either the blankholder ring, or the punch-head, or both are vibrating. As vibrating tool parts can make quite a lot of noise, most applications use ultrasonic frequencies of over 10 kHz (hence the name), although low frequency (1–50 Hz) or ultra-high frequency (1 MHz) have been applied as well. The forced vibration of a large tool part requires a fair amount of energy. Therefore many applications uses tools that are designed to have a resonant mode in the required frequency range, notably in case of radially vibrating rings, see below. This restricts actual application. The use of vibrating tools in deep drawing has been tested extensively, and without exception an increase in formability is reported. An outstanding example is presented in Fig. 12.1.

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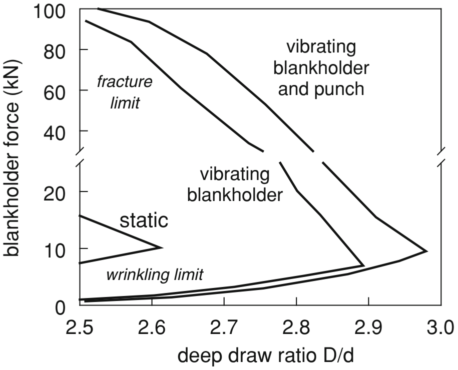

Fig. 12.1 Effect of vibrating tools on the process window in cup deep drawing; material: SS304. Deep draw ratio = blank diameter / punch diameter. Data from [1]

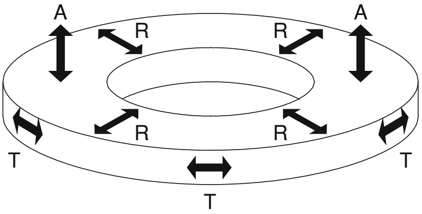

Fig. 12.2 Possible vibration modes in a blankholder ring: axially (A), radially (R) and tangentially (T)

This figure presents a typical example of a process window in deep drawing: the range in blank holder force (plotted vertically) to make a sound product between wrinkling limit and fracture limit.

A generally accepted explanation is that vibration of the bankholder ring reduces friction in the blankholder area. Several mechanisms have been proposed, depending on the vibrating mode of the blankholder (see Fig. 12.2):

- With a tangentially vibrating blankholder the effect may be similar to that of a rotating blankholder;
- With a radially vibrating ring the direction of friction changes repetitively, the material maybe pushed inwards periodically.
- With a axially vibrating ring contact may be lost repetitively.

These proposed mechanisms assume simple Coulomb friction.

12.2 Material Formability

The reduction of friction is not the only (possible) mechanism. Several authors have reported effects of vibration on material formability in a more fundamental way.

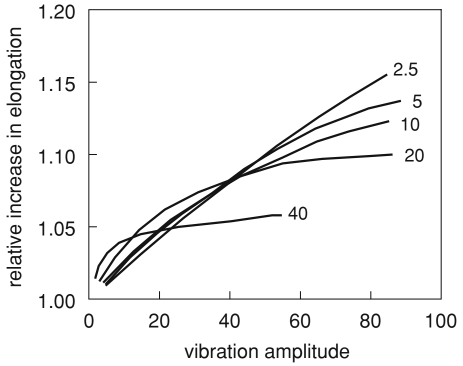

Fig. 12.3 Effect of vibration on total elongation in a tensile test for mild steel. Legend indicates vibration frequency in Hz. Data from [2]

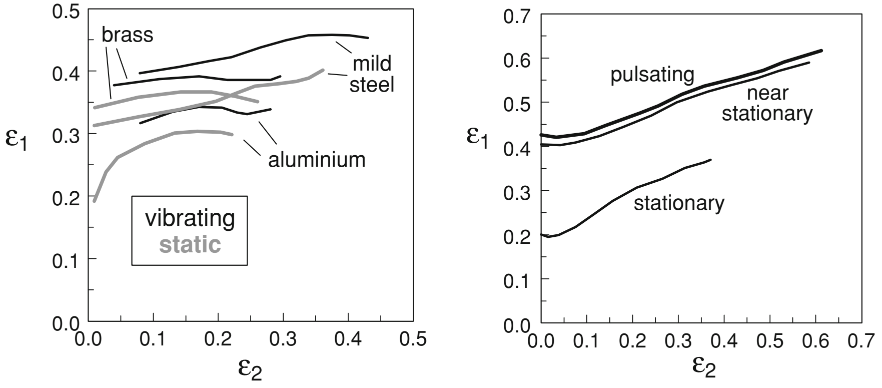

Fig. 12.4 Effect on vibration on the FLC. *Left*: experimental results for three materials, *right*; theoretical results of an M-K analysis. Data from [3]

Breun et al. have carried out tensile tests with a vibrating clamp on various materials, and under various conditions [2]. Figure 12.3 presents the effect of vibration in the total elongation in the tensile test for mild steel (St 14) This shows that vibration can indeed increase the total elongation. Similar tests on 5000 Aluminium (AlMg5) however showed a much smaller effect, while tests on 6000 Aluminium (AlMgSi1) showed a negative effect: vibration lowers the formability. The vibration also affects the yield force. As a general rule of thumb, an increase in elongation is accompanied by a decrease in strength, but this is not fully decisive.

Banabic and co-workers have carried out an extensive research on the effect of vibration on the FLC, both experimentally and theoretically using an M-K analysis. Some results are presented in Fig. 12.4. The M-K analysis focused on strain-rate effects and showed that vibration increased the plane-strain limit by a few percent compared to tests with a constant strain rate of the same mean value. Their theoretical results also show that a higher frequency shows a stronger effect.

The theoretical results do not agree completely with the experimental results, but both indicate an increase in formability, although only biaxial straining has been tested.

Several authors have proposed mechanisms to explain this effect:

- Periodic variation of the strain rate; this approach was used in the M-K analysis by Banabic et al. (Fig. 12.3). This is expected to affect strain-rate sensitive materials mainly.
- Heating by dissipation of mechanical work.
- Periodic unloading; this was notably observed by Breun et al. (Fig. 12.2). This is known as the *superposition principle* and is accepted by many authors.
- Creation of mobile dislocation during stress peaks.
- Micro deformations in the workpiece.

The superposition principle is in fact the same phenomenon as cyclic straining that was discussed in Sect. 7.4, although it is assumed than in this case unloading is only elastically, so that no actual stress reversal takes place.

We can now conclude that the application of a vibrating blankholder in deep drawing increases the material formability, or more precise: enlarge the process window (Fig. 12.1); this is further discussed in Sect. 15.1. There is also evidence that vibrations can raise the formability of the material in a more strict sense, but it is unclear if this is just caused by phenomena that have already been discussed in the previous chapters, or that an new phenomenon appears.

In any way, also supported by Sect. 7.4:

Q The formability can be increased by oscillating tools that cause periodic unloading of the material.

A final note: this is an outstanding example where the formability is increased by both the definitions stated in Chap. 3.

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Chapter 13
Testing of Formability

Abstract There are three types of formability testing: direct testing, simulative testing, and indirect testing. All are relevant for the classification of material formability.

Keywords Formability testing · Direct testing · Simulative testing · Indirect testing

There are numerous formability tests: tensile test, plane-strain test, shear test, bulge test, hole-expansion test, Erichsen test, limiting dome height test, Swift cup test, etc. However, it is not the intention of this chapter to present an overview of these tests, but only to discuss formability testing from a more fundamental point of view.

The aim of formability testing is to be able, by means of a limited number of tests, to judge if a certain material will pass a certain forming operation or not. In general this requires a thorough understanding of the relation between press performance of a material at large, and its basic properties (like the traditional mechanical properties).

Three types of testing can be distinguished:

- direct testing
- simulative testing
- indirect testing

Direct testing means the making of the full-size part in question, either in the press shop or in the laboratory. The latter is only possible if the laboratory has a suitable press on hand, and can use the press-shops tooling, or has a sufficiently identical tooling. This type of testing presents the most direct relation between material parameters and press performance. However, it is expensive. It requires much material (large blanks), large investments (press and tooling) and, if the tests

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are carried out in the press-shop, loss of production time. More important: it is in general very difficult to translate the findings to other parts/geometries.

Simulative testing means carrying out the basic forming operation, but on a smaller product often of simple type. The idea is to exclude some effects that do occur in a complex product so to be able to focus on a limited number of aspects. This type of testing allows the study of the influence of several parameters relatively quick and cheap. In deep drawing this could be the drawing of a small cylindrical product (the well-known Swift-cup). This is used in general to study effects of material parameters like anisotropy, thickness, frictional effects, but also tool parameters like die radius, punch radius, roughness, and process settings like blankholder force, lubrication etc. The translation to a full-size complex product is in general not too difficult, but requires understanding of the actual forming process. Simulative tests come and go. Many tests that have been developed in the past (see for example [1]) have become obsolete, for example because it turned out that the results were very strongly correlated to parameters that can be measured with indirect testing; a good example of this is the Yoshida buckling test. That does not mean that these tests have been a waste of time, on the contrary: they have helped us to gain a better understanding of the relation between material parameters and press-behaviour.

As new processes do originate from time to time (like incremental forming), new simulative tests are required as well.

Indirect testing means determining some parameter that is known to have an effect on the press behaviour in a test that strictly is not a forming operation. The best-known examples are the determination of n and r in a tensile test, but for example, friction tests also fall into this category (but that is open for discussion). These tests are generally simple and require little material. However, translating the results into the press behaviour of the material when forming a complex part is far from easy and requires a thorough understanding of the forming process. For simple parts it is simpler: pure deep-drawing depends mainly on r, while pure stretching depends mainly on n.

Over the years, a gradual shift can be noticed from simulative testing to indirect testing. This is not only caused by a better insight in the mechanisms of forming processes, but also by an increasing need for material models that can describe the fundamental forming parameters of the material into much more detail than the tensile test. These for example include the determination of the yield locus, the work-hardening law for large strains, and also the behaviour under varying strain paths. The main driving force for this is the development of FEM simulations that requires this knowledge (the discussion of FEM techniques falls beyond the concept of this work), but also analytical work like the prediction of behaviour under non-straight strain paths using M-K type techniques. This has caused the development of new tests or revival of old tests, like plane-strain tensile tests or shear tests.

However, all three types of tests will be required always, simply because the step from indirect testing directly to the full-size product is often too large (or too expensive!), and an intermediate step is required, for example to verify relations that are predicted by models. Two examples will try to clarify this.

Example 1. The production of 2-piece beer-and-beverage cans includes deep-drawing/redrawing, wall ironing, stretching (the bottom), necking and flanging. All processes however are carried out on a single material. To optimise that material for the production process a deep understanding is required about which material properties are actually governing the individual production steps (and how these properties change during the process, but that is another story). This will request the development of simulative tests that focus on an individual aspect of the entire process. These tests will deliver insight in the relation between material parameters and press behaviour, and once it is known which parameter is important specifically, indirect tests can be selected (or: developed!) that will produce this parameter.

Example 2. When some time ago the automotive industry started to use aluminium for body panels instead of steel, it was noticed that frequently cracks occurred during the hemming process, as pictured in Fig. 6.7. This means that the manufacturing process had to be changed. To do this, simulative tests were developed in the laboratory to study this specific phenomenon and to establish the forming limits of the material. However, the proof of the pudding is still in the eating, and finally full-scale tests (direct testing) were carried out in the press-shop.

Reference

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Chapter 14
Instabilities Again and Not

Abstract The absence if instabilities, if possible, does not create infinite formability, the material will always fail finally by damage development. In sheet metal forming this forming limit is called fracture limit, contrary to the necking limit that is caused by instability.

Keywords Instabilities · Considère condition · Fracture limit

We have seen in the previous chapters that formability is often limited by the occurrence of an instability that causes the deformation to concentrate in a restricted area. In general we can state, as a variation to statement {E}:

The terms forming force and forming strain should be interpreted here widely:

E′ Instabilities will arise in situations where the forming force decreases with increasing forming strain.

- in a tensile test the forming force is the tensile force, and the forming elongation is the cross-bar displacement;
- in a torsion test the forming force is the forming torque, and the forming strain is the angle of rotation (better: the tangent of that angle);
- in a bending test the forming force is the bending moment, and the forming strain is the strain of the outer fibre, or: the curvature of the bend (= 1/R).

Now in technical metals the stress will increase with strain (rare cases of work softening will be ignored). How can the deformation force then decrease with strain?

The forming force can only decrease if during the forming operation the area that it is acting on is decreasing.

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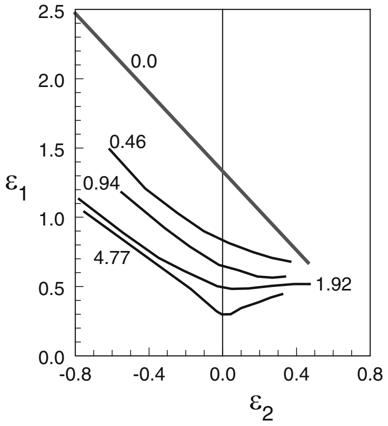
Fig. 14.1 Effect of grid size on measured FLC [1]. The original paper is from 1972 (IDDRG), the golden age in FLC research



In a tensile test this is clear: the cross-section area of the specimen decreases by strain, leading to the Considère condition as only sufficient work-hardening can prevent instabilities. In a torsion test, or more general: forming by shear, the area does not decrease as will become clear if we look at Fig. 9.2. Also, in bending the cross-section area of the part will not decrease (ignoring second order effects). This indicates that *the occurrence of instabilities, that do limit formability, strongly depends on the actual type of forming operation*, but the reader will probably have realised that already by now. Furthermore, the creation of an instability may also be restricted by operation dependent constraints, like the friction against the tooling. On the other hand, in actual (technological) forming tests that are principally stable, instabilities may arise due to side-effects.

Now what happens if instabilities never occur?

Let us take a look at rolling. Rolling is a plane-strain forming operation that creates the same strain state in the material as plane-strain stretching. However, as a daily routine thickness reductions of 90% are obtained in a cold-rolling operation and obviously without causing defects into the material. This means that the material is lengthened by a factor of 10, corresponding to a (logarithmic) major strain of 2.3. This is much more than can be obtained in a plane strain stretching operation by any means. So two important conclusions are:

R In principle, materials can withstand huge levels of deformation without failure.

S The strain state by itself is not decisive for the maximum allowable level of strain.

Other examples of forming operations that create huge levels of deformation are wiredrawing and impact extrusion, and also multiple redraw operations.

An interesting question now is: is there a limit to the rolling reduction? The answer is: yes, but it is not known what that limit is. Ongoing deformation will create damage into the material by the stacking of dislocations. This damage will finally cause failure of the material. An important factor here is the stress-state. A compressive hydrostatic component as present in rolling will suppress the creation of voids and consequently slow-down failure. However, *finally all material will fail*. This causes a refinement of statement {S}:

S′ Final failure of the material is governed by both strain-state and stress-state.

An interesting feature is presented in Fig. 14.1. This figure shows what happens to the measured FLC if the grid size is getting smaller and smaller. The effect of smaller grid size means that we are measuring inside the local neck. This deviates from the discussion in Chap. 5 where the strain in the uniform part was taken as a measurement for formability. The original paper from 1972 could not be retrieved, but it is sure that the zero-size line was obtained by extrapolation. This diagram suggests that the forming limit by fracture is a straight line with negative slope ($\varepsilon_1 + \gamma.\varepsilon_2 = C; C \approx 1.3$ in this case). However, this must be interpreted with care. First we must realise that once the ‘normal’ FLC is obtained and necking starts, the strain state shifts to plane-strain, so the curves of Fig. 14.1 have not been obtained using a straight strain path. More important is that we are dealing with an *intrinsically unstable* process, while for example rolling is an *intrinsically stable* process. This means that the results cannot be compared directly. Nevertheless, this confirms what was found already before and stated in statement {F}: *if we can suppress or postpone local necking in some way the formability will be enhanced considerably*.

Failure by damage as presented by the zero-size line in Fig. 14.1 is sometimes called the *fracture limit*, contrary to the *necking limit* as presented in conventional FLCs. Some materials are more prone to failure by damage than other, and it may occur that the fracture limit is reached before the necking limit, therefore limiting the formability. This can notably occur in equi-biaxial deformation.

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Chapter 15
Back to the Press Shop

Abstract The formability may be restricted by either a strain limit, or a force limit. In case of the latter the process may be repeated for increased formability. In an actual press forming operation the product may be rejected by numerous causes, not only fracture. This illustrates that formability is a more complex concept that is not a straightforward material property in the strict sense. However for a certain prescribed process/product the formability can be related to a set of material parameters.

Keywords Process windows · Force limited process · Corrosion limits · Material properties

After having looked to formability from a scientific point of view, it is time to go back to were we started: the press shop.

15.1 Process Windows

In the press shop workers are trying to make a sound product by a forming operation. The success of the operation depends on many parameters, besides material properties also the process parameters (like machine settings). The combination of settings of all parameters that produce a sound product is called the process window or operating window, an example has been shown in Fig. 12.1. In this section we will still restrict ourselves to failing by fracture (splitting, cracking), in the next section we will expand that.

So far we have linked the occurrence of fracture to limit strains. However, that is only one part of the story. In Sect. 4.1 we have made a very elementary observation: the technical stress strain curve has a maximum. This means that the maximum load a piece of material can withstand is limited. Consequently, a material can also fail because the required load exceeds its maximum bearing capacity. This may seem trivial, but it is not.

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It is of vital importance to realise that failure can occur both by exceeding a strain limit, and by exceeding a force limit.

An example will clarify this. In deep drawing of a cylindrical cup the strain state in the flange is deep-draw ($\varepsilon_2 = -\varepsilon_1$), and the FLCs presented above indicate that there is no strain limit, so infinite straining should be possible. Nevertheless, there is a limit to the actual strain that can be created in the flange in an actual operation. In a deep-draw operation the force to form the flange and pull the flange out of the blankholder area is transported from the punch head to the flange by the wall of the already created part. If the force exceeds the load bearing capacity of that wall, the wall will simply fail. This means that the so-called deep-draw ratio (= blank diameter / punch diameter) is limited to values in the order of 2. A limiting deep draw ratio (LDR, common symbol β) of 2 means that the major strain in the flange edge is limited to 0.7. However, as the limit strain is not exceeded (this is infinite) the process may simply be repeated. This is valid in general, so we can conclude as a variation to statement {K} (Sect. 6.2):

K′ In forming processes that are limited by a maximum force the formability can be increased by repeating the forming process.

This is the basis of redrawing operations. Examples of other processes that are limited by a maximum force are wire drawing and wall ironing. Interesting: all these processes benefit from vibrating tools (Chap. 12). Processes that are limited by a maximum force are in general less dependent on material properties. Another consequence is that the formability can be increased if we are able to reduce the load on the critical part by some means, in deep drawing this is the wall. An example of this is so-called hydro-mechanical deep drawing (back-pressure drawing); examples are known where by this means the LDR could be increased from 2.0 to 3.4 [1]. Another applicable process is thermo-mechanical forming (heating the blank/dieholder area and cooling the punch).

A very elementary (and well-known) way to reduce the process forces is to apply lubrication. The application of a lubricant creates a thin boundary layer on the surface that prevents metal-to-metal contact and therefore prevents scoring / galling. It also reduces the friction forces. This not only reduces the load on the product, but it may also create a more uniform distribution of the strain over the product and so reduces local strain peaks, but too much lubrication can cause wrinkling. However for a liquid lubricant (oil) the friction strongly depends on the experimental conditions (read: machine setting) and that can make the process sensitive to small variations in material properties and/or machine settings that are always present; see Chap. 22. Consequently, some manufactures deliberately select minimal lubrication to make the process more robust, and accept a higher press force or lower formability. Note that in the deep drawing of large products friction may contribute to more than half the total punch force, so reducing friction may reduce the load on the critical part considerably. Depending on the experimental conditions, the friction can be largely affected by press speed, and

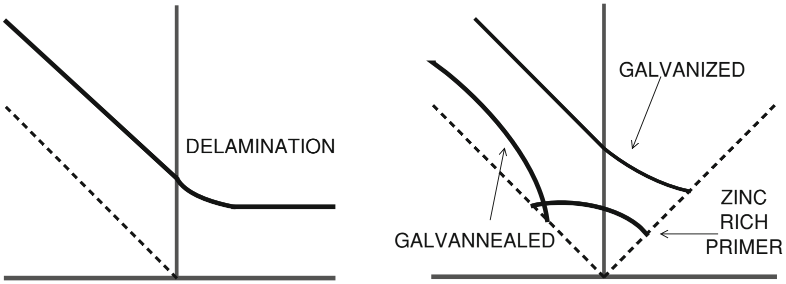

Fig. 15.1 Typical forming limits for coated materials, schematically. *Left*: coating delamination. *Right*: corrosion limits for some zinc based coatings on steel

occasionally the performance can be increased by setting the press speed to maximum, even when this contradicts common sense. Other ways to reduce friction are the application of a rotating blankholder (not discussed here), or the use of vibrating tools as discussed in Chap.12.

In processes that are truly limited by limit strains (as for example bulging) the limit is indeed a true limit: it cannot be overcome by performing the operation in a number of small steps.

Process limits can be plotted in a strain–state diagram and are often called ‘forming limits’. Although that is correct in the strict meaning of the word and some uncommon examples will de presented following, one must realise that the term ‘forming limit curve’ is derived from the concept as discussed in Chap. 5, and that the original FLC is also a strict material limit that cannot be overcome, of course within the assumptions underlying that concept. Failing to realise the difference between force-limited processes and strain-limited processes can cause an unjust interpretation of the ‘forming limits’.

In Sect. 6.2 we have met still another situation, a situation where the formability is governed by neither maximum strain or maximum force, but by characteristics of the process itself. Such situations are rare, but they deserve special attention as they allow us to form materials which are generally regarded as unformable (as full-hard steel).

The process may also be limited by aspects that strictly speaking have nothing to do with material formability. This is notably the case with coated materials. If the coating is thin its deformation simply follows the deformation of the substrate, but the coating may delaminate, or suffer damage that may reduce the expected lifetime of the product concerning corrosion. These create there own forming limits, and some typical examples are presented schematically in Fig. 15.1. The corrosion limit curve depends very much on the type of protection and the brittleness of the coating, therefore showing very distinct characteristics.

15.2 Formability in a Wider Context

In the pervious chapters, formability has been treated according to the scientific definition as in statement {B} (Chap. 3). However, this work started with the practical definition of formability as in statement {A}:

A A material shows good formability if it passes through the forming operations without presenting any problems.

This definition allows us to look at formability in a wider context. A product may for example be rejected by:

- fracture (splitting, cracking)
- too much thinning
- too much roughening
- scoring / galling
- wrinkling
- size defects by spring-back
- other causes

We have also started our tour by asking the question:

is formability really a material property in the strict sense?

We will now have a brief look to the relation between these causes of rejection and material parameters.

- fracture: this generally is a fatal defect, and may be cured by many measures, like improving the material grade (discussed in detail in the previous chapters), but also by reducing the blankholder force (beware of wrinkling), enlarging tool radii, improving lubrication etc; a possible trick is also not to avoid fracture, but to make sure that it occurs in a part of the blank that is removed anyway, like the window opening in car doors.
- thinning: this may be important for example at pressure vessels that require a minimum thickness; this may be solved by excessive lubrication, otherwise complete redesigning of the process may be necessary;
- roughening (of free surfaces): this is almost completely determined by the level of deformation and the grain size of the material;
- scoring / galling: this is caused by metal-to-metal contact that can never be eliminated completely, but can be reduced by good tool maintenance and sufficient lubrication; another cure is to increase the sheet roughness (if permissible!);
- wrinkling: in many cases a matter of good press setting, but materials with high r show a reduced tendency to wrinkling;

- spring-back: determined by yield stress and Young's modulus; in stamping operations often caused by a too low level of straining, therefore in shallow automotive parts like roofs a minimum level of straining (2–3%) is often prescribed to overcome this; in pure bending operations like the manufacturing of machine frames a control of spring-back often requires understanding of the Bauschinger effect;
- other causes may occur for example with coated material as shown in the previous section; solving these require a specific approach for each problem.

This shows that many aspects of formability are indeed governed by material parameters, but no general rule can be presented. This is also illustrated by the overview presented in Chap. 23. This overview is outdated, and some of the effects presented there are a matter of discussion, but it illustrates that different forming operations are characterized by different material properties. So the basic question must be answered in general by: **NO**.

However, for a *certain prescribed process or product* it is quite possible to determine a set of material parameters (values) that must be met to make a sound product, and in that sense the answer is simply: **YES**.

Luckily there are some general rules. In general, a forming process will benefit from a high level of *hardening rate* ($d\sigma/d\varepsilon$), for example as expressed by n (see Sect. 4.2). Materials with high levels of n (stainless steel, brass) generally show excellent formability, as can be seen in the manufacturing of double kitchen sinks (sometimes even triple) from a single sheet of stainless steel; such a product simply cannot be made from low-carbon steel. However also to this rule there are exceptions. In complex products with varying levels of forming a high hardening rate will increase the difference in strength (yield stress) between heavily formed parts an lesser formed parts, and situations have been encountered where this causes premature failure, notably if the forming process is limited by the maximum load of the lesser formed parts.

Also a high value of the *normal anisotropy* r will generally increase formability although the effect is limited. The limiting draw ratio (LDR) is one of a few forming parameters that benefit from a high value of r. Also, a high level of r will reduce local thinning in deep drawing. However one should not overdo: materials with a hexagonal structure (hcp) like Titanium or Zinc generally show poor formability and at the same time excessive values of r.

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Chapter 16
Summary

There is a general rule of thumb (but only that): if a mechanism makes it easier for a material to be stretched, meaning by a lower force, than that material can be stretched further. Keeping this in mind we can make the following categories for formability enhancing mechanisms. This may help the reader for further research.

- Mechanisms that lower the process force without changing the flow force of the material. The most clear example is reduction of friction.
- Mechanisms that lower the flow force of the material without changing the flow stress. This is typical the case in bending.
- Mechanisms that lower the flow stress of the material. Clear examples are shear and contact stress, that change the stress state in the material.
- Mechanisms that do not affect force or stress, but suppress instabilities. Examples are pure incremental forming (the Taraldsen test!), and high-speed forming. Changing stain paths in general and transient stress effects in particular can also be placed in this category, but that may be a matter of discussion.

The summarize this work all the statements about formability that have been derived in this work are repeated here, also referring to the chapter / section where it was discussed.

- A - A material shows good formability if it passes through the forming operations without presenting any problems. (Chap. 3, Sect. 15.2)
- B - The formability of a material is the level (read: amount of strain) to which that material can be deformed (stretched) before fracture occurs. (Chap. 3)
- C - The formability of the material may increase considerably if some (local) thinning is allowed. (Sect. 4.3)
- C′ - Strain rate hardening will increase formability if some (local) thinning is al-lowed. (Sect. 11.2)
- D - The formability is limited by an instability that will occur and that will lead to an unacceptable uneven distribution of the properties of the part to be made. (Sect. 4.3)

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- E - Any mechanism that will cause the pulling force (tension) to increase with strain, will postpone necking. (Sect. 4.3)
- E′ - Instabilities will arise in situations where the forming force decreases with increasing forming strain. (Chap. 14)
- F - If we can suppress or postpone local necking in some way the formability will be enhanced considerably. (Sect. 4.4)
- G - The forming limit expressed in the conventional FLC is caused by the same basic phenomena that are encountered in the tensile test: after some straining instability occurs causing the deformation to concentrate into a small area, finally resulting in fracture. (Sect. 5.3)
- H - The specific nature of a forming operation may create phenomena that limit the formability but that are not present in other situations with the same strain state. (Sect. 5.3)
- I - For technical materials the formability may depend on the orientation in the sheet. (Sect. 5.5)
- J - The formability of a material can be enhanced considerably if it is subjected to simultaneous bending and stretching. (Sect. 6.1)
- K - If the formability is governed by other parameters than basic material properties, the formability can be increased by simply repeating the forming process. (Sect. 6.2)
- K′ - In forming processes that are limited by a maximum force the formability can be increased by repeating the forming process. (Sect. 15.1)
- L - A non-straight strain path can either lower or raise the formability. As a rule of thumb, the formability of a material is reduced in situations of changing strain state where the value of β (= $d\varepsilon_2/d\varepsilon_1$) is decreasing, and is enlarged where β is increasing. (Sect. 7.2)
- M - The transient stress effects occurring during strain path changes create a situation of (quasi) work hardening that may cause (additional) formability. (Sect. 7.3)
- N - The presence of contact stress (negative thickness stress) raises the formability. (Sect. 8.1)
- N′ - Any external effect that changes the strain state resulting in a reduction of the yield stress in tension, will raise the formability. (Sect. 9.2)
- O - Forming by shear is expected to create larger formability than forming by stretch. (Sect. 9.1)
- P - The formability can be increased considerably by inertia effects occurring at extreme forming speeds. (Sect. 11.4)
- Q - The formability can be increased by oscillating tools that cause periodic unloading of the material. (Sect. 12.2)
- R - In principle, materials can withstand huge levels of deformation without failure. (Chap. 14)
- S - The strain state by itself is not decisive for the maximum allowable level of strain. (Chap. 14)
- S′ - Final failure of the material is governed by both strain-state and stress-state. (Chap. 14)

Chapter 17
Closure

This work was about formability. It was not about forming technology, but just about formability: the ability to be formed into a desired shape.

We have learned a lot about the different aspects of formability, and which properties control formability. One thing is still missing: a proper definition of formability. The practical definition as stated in {A} is still the best we can find, but unsatisfactory for the researcher. However, that is the situation, and it has to be accepted just like that. Formability cannot be treated as a simple material property, and hence not determined by a simple test. This makes things complicated, the formability as defined in {B} depends heavily on the actual forming process. Luckily, there is another side. Because formability is such a complex phenomenon there is room for improvement. As formability depends heavily on the process there is a possibility that the formability of the material can be increased by proper process settings. An extreme example of this has been met in Sect. 6.2 where a situation was encountered where the formability was controlled by the material thickness only, and not by any other material parameter. This particular situation enables the forming of materials that are generally regarded as unformable, like heavily cold worked material (double reduced steel), or materials with an unfavourable crystal structure. This further enables special applications for these materials. For example: materials that harden only little cannot be formed in a classic operation. But if they are formed by some fancy operation, they will produce products where the difference in material properties between more and less strained areas is low, creating possible new applications. The 'discovery' of incremental forming in the early 1990 s illustrates this, and shows that the world of forming technology is far from closed. This also creates a challenge for the researcher to stretch the possibilities of a certain material as far as possible, and to seek new possibilities in formability.

The basic question: *is formability really a material property in the strict sense?* has been answered by both YES and NO. The fact that it is sometimes to be answered by NO means that apparently formability is but little determined by the material properties. The best example is pure deep-drawing that can be applied to almost all metals. This allows even materials to be formed that are generally

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regarded as ‘unformable’ like laminated wood [1] and paper [2]. On the other hand, the fact that it is sometimes to be answered by YES means that there is room for the development of advanced materials like TRIP steel. So maybe it is not bad at all that the matter is undecided.

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Chapter 18
Appendix: Some Basic Concepts of Stress and Strain

This Appendix presents only a very brief introduction to plasticity. The reader is referred to text books for a more detailed treatment. Note that most expressions presented here are only valid for isotropic materials, materials of which the properties are the same in every direction. Anisotropy is discussed in Sect. 18.4.

18.1 Stress

When an object is subjected to some external force, stresses are created, not only on the outside surfaces, but through the whole object. Figure 18.1 presents a force F that is acting on some surface. This force can be divided into a component F_N acting normal to the surface (normal force), and a component F_S acting parallel to the surface (shear force). This is the case not only for the outer surfaces, but also for any imaginary surface inside the material, as if a cross-section has been made there. The stress now is defined as the force acting on a surface of unit area: $\sigma = F/A$; conventionally normal stresses are denoted by σ, shear stresses by τ.

It can be shown mathematically that it is always possible at any given location in the material, to define a set of three mutually perpendicular surfaces (as the faces of a cube) so that there are no shear stresses acting on these surfaces. The directions normal to these surfaces are called principal directions, and the normal stresses there the principal stresses. These stresses are conventionally labelled σ_1, σ_2 and σ_3 ($\sigma_1 \geq \sigma_2 \geq \sigma_3$). As a result many analyses consider only these principal stresses, ignoring shear stresses.

When the stresses are getting too high failure of the material may occur. Failure can mean fracture as for brittle materials, or the start of plastic deformation for ductile materials. In the past several criteria for failure have been proposed and these are mentioned following. σ_f means the flow stress (or fail stress) of the material, that however in general depends on the level of strain.

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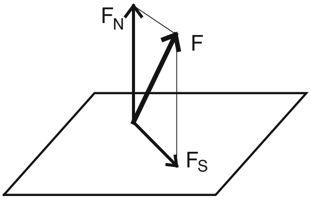

Fig. 18.1 Forces acting on a surface

1: a material fails when the highest normal force exceeds a certain limit (Lamé criterion), in formula:

$$\max(|\sigma_1|, |\sigma_2|, |\sigma_3|) > \sigma_\mathrm{f} \tag{18.1}$$

This criterion finds no use for metals, but it can be used for brittle materials like concrete and stone.

2: a material fails when the highest linear strain exceeds a certain limit (Poncelet criterion). No materials have been found that actually satisfies this criterion.

3: a material fails when the highest shear stress exceeds a certain limit (Coulomb criterion, later: Tresca criterion), in formula, translated to normal stresses:

$$\max(|\sigma_1 - \sigma_2|, |\sigma_2 - \sigma_3|, |\sigma_3 - \sigma_1|) > \sigma_\mathrm{f} \tag{18.2}$$

This criterion can be used successfully for metals.

4: a material fails when the total stored elastic energy exceeds a certain limit (Huber-Hencky criterion), in formula:

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 > 2\sigma_\mathrm{f}^2 \tag{18.3}$$

There are two more criteria of more complex character (Mohr and Haigh) that need not be discussed.

Criterion 4 has found application as the so-called von Mises criterion. Originally the von Mises criterion was proposed as a mathematically more elegant version of the Tresca criterion, but it can also be derived more fundamentally based on the so-called octahedral shear stresses. This criterion is widely used for metals.

These criteria have raised the question if it is possible to define a single parameter that characterises failure. For the von Mises criterion this is simple, and this has lead to the definition of the so-called effective stress or equivalent stress defined as:

$$\sigma_{eff} = \overline{\sigma} = \sqrt{\frac{1}{2}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]} \tag{18.4}$$

The factor ½ ensures that for a tensile test the effective stress is just the normal pulling stress.

The Tresca and von Mises criteria only contain differences between principal stresses. This means that increasing all principal stresses with a certain constant value has no effect on the failing of the material. Based on this aspect the following new parameters have been defined:

- the hydrostatic stress, defined as $\sigma_h = (\sigma_1 + \sigma_2 + \sigma_3)/3$
- the deviatoric stresses, defined as $\sigma_i{}' = \sigma_i - \sigma_h \; i = 1,2,3$

Basically the deviatoric stresses define the reaction of the material, not the hydrostatic stress.

In studies on material behaviour another parameter is often used, the triaxialty ratio defined as $M = \sigma_h/\overline{\sigma}$, this can be either negative or positive. This ratio is sometimes used to characterise the stress state in general, and plays a role in damage development.

In tensile tests and steel constructions stress is frequently defined as the tension force divided by the *original* cross-section area of the specimen, this is called engineering stress or technical stress, contrary to the correct definition of stress that is called true stress: the tension force divided by the *actual* cross-section area, either apparent or real.

Most metals show the same strength (absolute) in tension and in compression. Amorphous material like stone generally do not: they are much stronger in compression than in tension. A noteworthy exception is cast-iron that shows the same asymmetry, that is the reason that early cast-iron bridges followed the same construction as stone bridges.

18.2 Strain

Strain means the change of dimension. This is not often encountered in every day life, at least not for ‘solid’ materials like metals that are regarded as very stiff, but the springs in your car’s suspension are living proof that metals can deform.

Two basic type of deformation are distinguished: shear and stretch, see Fig. 18.2, depending on whether the straining force acts either parallel or perpendicular to the surface.[1]

Similar to stress, a set of three mutually perpendicular surfaces can be defined at any location in the material where all surfaces are subjected to stretch without shear. The directions normal to these surfaces are called also principal directions, and the normal strains (length strain) there the principal strains. These strains are conventionally labelled ε_1, ε_2 and ε_3 $(\varepsilon_1 \geq \varepsilon_2 \geq \varepsilon_3)$. Realise that in complex situations the principal directions of stress need not coincide with the principal directions of strain!

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[1] In fundamental studies another definition of shear is used that is shown in Fig. 9.3. The presentation in Fig. 18.2 is an engineering approach.

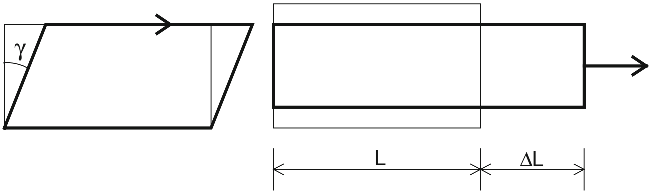

Fig. 18.2 Straining. *Left*: shear, *Right*: stretch

Shear strains are expressed by the shear angle γ (see Fig. 18.2). Traditionally length strains are defined by e = $\Delta L/L$ where ΔL is the increase in length (elongation), and L the original length. This is called technical strain or engineering stain, and it is generally expressed in %: $e = 0.05$ means 5% elongation. This definition presents problems in cases of large deformations, for example +100% elongation is possible, but -100% elongation is very much impossible. For that reason a more fundamental definition of strain has been defined, $\varepsilon = \ln(1 + \Delta L/L)$ called true strain or logarithmic strain. For small strains both definitions give the same value.

It is further assumed that the overall behaviour of the material can be expressed by what is called the effective strain. An often used definition of effective strain is the so-called von Mises effective strain, defined by:

$$\varepsilon_{eff} = \overline{\varepsilon} = \sqrt{\frac{2}{3}.(\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2)} \tag{18.5}$$

The constant 2/3 is chosen so that in a tensile test the effective strain is equal to the length strain.

Here the similarity between stress and strain ends. In plastic deformation of metals the volume remains constant in good approximation. This creates an additional condition for strain: $\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0$ (note: the sum of the deviatoric stresses is also zero). More complex however is that strain builds a history. For example it is possible to bend a strip of metal, and then reversely bend it to flat so that the original shape is resumed. At the end there is no change in dimensions, so the strains seem zero although on a micro scale considerable changes in the material have taken place. Therefore it is better to base an analysis on the momentarily change in dimensions, or strain increments $d\varepsilon_1$, $d\varepsilon_2$ and $d\varepsilon_3$. It can be shown that these strain increments are related to the deviatoric stresses defined above.

It is generally assumed that the material hardening that is observed in a tensile test, is in general also valid for effective strain and effective stress. So, if in a tensile test a hardening relation is found like $\sigma_1 = C.\varepsilon_1^n$, then it is assumed that also: $\overline{\sigma} = C.\overline{\varepsilon}^n$.

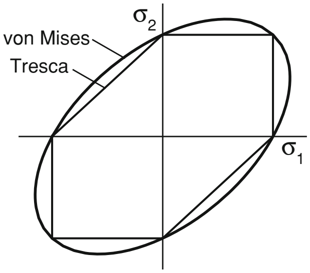

Fig. 18.3 Often used yield loci

18.3 Aspects of Sheet Metal Forming

A condition for sheet metal forming is that the normal stresses acting on the surface are small compared to the yield stress of the material, and can be neglected. Consequently, in many situations (but not all!) the principal directions of stress and strain are parallel and perpendicular to the surface. Therefore in sheet metal forming the sheet surface is generally taken as a plane of reference, and the definitions of stress and strain have been adapted accordingly.

Direction 3 is taken perpendicular to the surface (thickness direction), and directions 1 and 2 are taken parallel to the surface. This means that $\sigma_3 = 0$ (plane stress) and the effective stress is now:

$$\overline{\sigma} = \sqrt{\sigma_1^2 - \sigma_1 . \sigma_2 + \sigma_2^2} \tag{18.6}$$

For a situation of plane stress both the Tresca criterion and the von Mises criterion are visualized in Fig. 18.3. These lines define the so-called yield locus: no plastic deformation occurs when the stresses remain inside this locus, and plastic deformation starts when the stress state reaches the locus. If the material hardens the shape of the yield locus will change as a result of plastic deformation. For many practical metals the actual yield locus lies somewhere between the Tresca and the von Mises locus, and both yield criteria can be used equally well (or poorly).

18.4 Anisotropy

The situations discussed above are for isotropic materials, meaning that the material properties are the same in every direction. However, technical sheet metals are made by rolling and heating (annealing). This creates a microstructure that results in anisotropic behaviour: the properties are not the same in every direction. Most relevant is the difference in properties parallel to the surface and normal to the surface, so called *normal anisotropy*. Properties normal to the

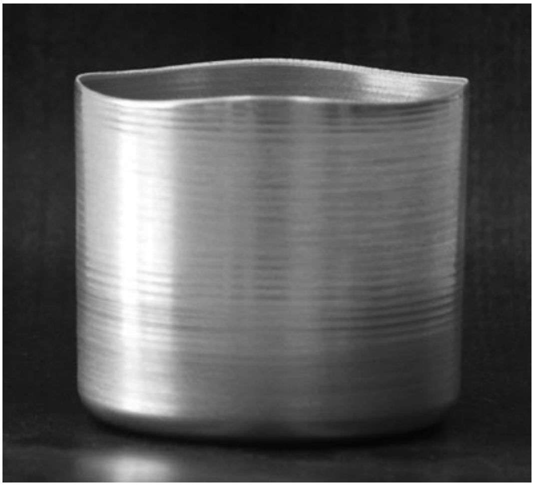

Fig. 18.4 Earing (wavy upper edge) as a result of planar anisotropy

surface are hard to measure, but the resultant amount of thinning in a forming operation can easily be obtained and is relevant in many situations. Normal anisotropy brings about that in a tensile test the relative reduction in thickness differs from the relative reduction in width. The ratio between these two is called r (or R, or: Lankford's parameter):

$$r = \frac{\text{width strain}}{\text{thickness strain}} = \frac{\varepsilon_2}{\varepsilon_3} \tag{18.7}$$

Note that r is defined by strains *in a tensile test*; in other situations the strain state is also affected by r, but in a more complex way. A high value of r is beneficial for pure deep drawing. As a rule of thumb $r = 0.7\text{–}1$ for fcc materials like aluminum and brass. Mild steel has a bcc structure, and r can be affected by careful rolling and annealing, values of 2.5 for ultra low-carbon steel are no exception. Materials with a hexagonal structure like zinc or titanium show high levels of anisotropy, r can be either very low ($\ll 1$) or very high ($\gg 1$).

The value of r also varies with the orientation in the sheet, mostly taken relative to the rolling direction. This phenomenon is called *planar anisotropy* and is responsible to the phenomenon of earing in deep-drawing and spinning, see Fig. 18.4. This has lead to the definition of the following parameters:

$$\begin{aligned} r_{\text{mean}} &= \frac{r_0 + 2.r_{45} + r_{90}}{4} \\ \Delta r &= \frac{r_0 - 2.r_{45} + r_{90}}{2} \end{aligned} \tag{18.8}$$

where r_0, r_{45} and r_{90} are the values of r measured at an orientation of 0°, 45° and 90° relative to the rolling direction. The parameter Δr is often used to quantify planar anisotropy, but the reader should be warned that these parameters date from the days of classic forming steel that showed a 4-fold symmetry in r with ears at 0° and 90°. Modern ultra low-C steels frequently show a 2-fold or 6-fold symmetry in r for which these definitions may give a very wrong impression of anisotropy and should not be used. Planar anisotropy is also the reason that for complex products success or failure may depend on the orientation of the blank relative to the rolling direction. An example is presented in Fig. 5.9.

Anisotropy affects the yield locus, but the reader is referred to text books for further information.

Chapter 19
Appendix: The Considère Condition

In Sect. 4.2 the Considère condition was presented as the basic condition that determines stability in the tensile test. This Appendix discusses that condition in detail.

19.1 The Considère Condition, 1

Consider a part of a tensile test specimen loaded with a tension force F and momentary cross-section area A, the momentary yield stress will be $\sigma = F/A$. Suppose that in that part a small section exists that has been strained additionally with a small strain $\mathrm{d}\varepsilon \ll 1$, with resulting cross-section area A' and stress σ', see Fig. 19.1. Assuming the volume to remain constant the cross-section area A' of that part has reduced: $A' = A/(1 + \mathrm{d}\varepsilon) \approx A.(1 - \mathrm{d}\varepsilon)$.

The tension force in that section has to be equal to F, so that for the actual stress in that part $\sigma'.A' = F = \sigma.A$, consequently:

$$\sigma' = \sigma.(1 + d\varepsilon) \tag{19.1}$$

The question is now if that section has actually become stronger or weaker. If the section has become stronger, meaning that a force larger than F is required to elongate it more, it will not deform any further but another part of the specimen will start to deform instead; the deformation is stable and no necking will occur. This depends on the change in yield stress, the stress required to deform that part any further. This new yield stress can be expressed as:

$$\sigma_{\text{yield, new}} = \sigma + d\sigma = \sigma + \frac{d\sigma}{d\varepsilon}.d\varepsilon = \sigma.\left(1 + \frac{1}{\sigma}.\frac{d\sigma}{d\varepsilon}.d\varepsilon\right) \tag{19.2}$$

We can now state that no instability will arise, and necking will not occur, if the new yield stress of the section expressed by Eq. 19.2 has become larger than the actual acting stress expressed by Eq. 19.1, this finally yields:

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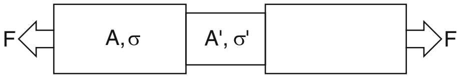

Fig. 19.1 Force and stress in a tensile test

$$\frac{1}{\sigma}.\frac{d\sigma}{d\varepsilon} > 1\,, \quad \text{or :} \quad \frac{\mathrm{d}\sigma}{\mathrm{d}\varepsilon} > \sigma \tag{19.3}$$

This is the well known Considère condition.

19.2 The Considère Condition, 2

We will now derive the Considère condition in a more fundamental way, so that it can be expanded easily.

When a strip of thickness t is pulled in tension with a force F, the operation is stable if and only if F increases with elongation. So an instability can start when F reaches a maximum or: $\mathrm{d}F = 0$. Using $F = \sigma.A$ (A = cross-section area):

$$\mathrm{d}F = 0 = \mathrm{d}(\sigma_1.A) = \mathrm{d}\sigma_1.A + \sigma_1.\mathrm{d}A, \quad \frac{\mathrm{d}\sigma_1}{\sigma_1} = -\frac{\mathrm{d}A}{A} \tag{19.4}$$

Using constancy of volume, $\mathrm{d}V = 0$:

$$\mathrm{d}V = 0 = \mathrm{d}(l.A) = \mathrm{d}l.A + l.\mathrm{d}A, \quad \frac{\mathrm{d}A}{A} = -\frac{\mathrm{d}l}{l} = -\mathrm{d}\varepsilon_1 \tag{19.5}$$

Combining both yields the Considère condition.

$$\frac{d\sigma_1}{\sigma_1} = d\varepsilon_1, \quad \frac{d\sigma_1}{d\varepsilon_1} = \sigma_1 \tag{19.6}$$

Assuming that $\sigma_1 = C.\varepsilon_1^n$:

$$\frac{\mathrm{d}\sigma_1}{\sigma_1} = C.n.\varepsilon_1^{n-1} = C.\varepsilon_1^n = C.\varepsilon_1.\varepsilon_1^{n-1}, \quad \varepsilon_1 = n \tag{19.7}$$

Note that if we would get as a condition $\mathrm{d}\sigma_1/\mathrm{d}\varepsilon_1 = p.\sigma_1$ instead:

$$\frac{\mathrm{d}\sigma_1}{\sigma_1} = C.n.\varepsilon_1^{n-1} = p.C.\varepsilon_1^n = p.C.\varepsilon_1.\varepsilon_1^{n-1}, \quad \varepsilon_1 = \frac{n}{p} \tag{19.8}$$

19.3 Hill's Local Necking Criterion

There are two instabilities in a tensile test, one creating the diffuse neck, and a second one creating the local neck and final fracture. The first one can be analysed as above. The second one is a local neck, meaning that there is no elongation along

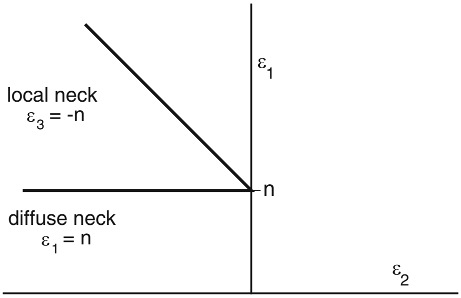

Fig. 19.2 Necking limits for diffuse neck and local neck

the neck, only across the neck (Sect. 5.2). In that case we can ignore any changes in width of the specimen, and apply the same analysis on a piece of unit width, so $A = 1.t = t$. This yields:

$$\mathrm{d}F = 0 = \mathrm{d}(\sigma_1.t) = \mathrm{d}\sigma_1.t + \sigma_1.\mathrm{d}t, \quad \frac{\mathrm{d}\sigma_1}{\sigma_1} = -\frac{\mathrm{d}t}{t} = -\mathrm{d}\varepsilon_3 \tag{19.9}$$

Or:

$$\frac{\mathrm{d}\sigma_1}{\mathrm{d}\varepsilon_3} = -\sigma_1 \tag{19.10}$$

This is known as Hill's local necking criterion. In a more general situation we have defined the strain state by a constant β defined as: $\varepsilon_2 = \beta.\varepsilon_1$ (Sect. 5.1), and consequently: $\varepsilon_3 = -(1+\beta).\varepsilon_1$ as $\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0$. We can rewrite Eq. 19.10 as:

$$\frac{\mathrm{d}\sigma_1}{\mathrm{d}\varepsilon_1} = (1+\beta).\sigma_1 \tag{19.11}$$

Which yields as an instability limit:

$$\varepsilon_1 = \frac{n}{1+\beta}, \quad \varepsilon_3 = -n \tag{19.12}$$

The limits are graphically presented in Fig. 19.2. For a situation of plane strain ($\varepsilon_2 = 0$) both limits are the same.

19.4 Strain Rate Hardening

The effect of strain-rate hardening on the necking limit can also be studied easily. For the following analysis we assume that the tensile test is carried out at a constant strain-rate, so that any strain-rate terms or factors become a constant.

Two cases are distinguished, multiplicative and additive strain-rate hardening. In the first case the total hardening is expressed in general by:

$$\sigma(\varepsilon, \dot{\varepsilon}) = \sigma_1(\varepsilon) \cdot \sigma_2(\dot{\varepsilon}), \quad \dot{\varepsilon} = \frac{d\varepsilon}{dt} \tag{19.13}$$

Or more specifically by:

$$\sigma(\varepsilon, \dot{\varepsilon}) = C.\dot{\varepsilon}^m.\varepsilon^n \tag{19.14}$$

Assuming constant strain-rate relation Eq. 19.14 becomes:

$$\sigma(\varepsilon) = C'.\varepsilon^n \tag{19.15}$$

which is the same as the relation used in Eq. 19.7. So this does not change the necking limit.

In the second case the total hardening can be expressed by:

$$\sigma(\varepsilon, \dot{\varepsilon}) = \sigma_1(\varepsilon) + \sigma_2(\dot{\varepsilon}) \tag{19.16}$$

Assuming a power-law hardening and constant strain rate we get:

$$\sigma(\varepsilon) = C.\varepsilon^n + A \tag{19.17}$$

Applying the Considère condition as in Eq. 19.7

$$\begin{aligned} \frac{\mathrm{d}\sigma_1}{\sigma_1} &= C.n.\varepsilon_1^{n-1} = C.\varepsilon_1^n + A = C.\varepsilon_1.\varepsilon_1^{n-1} + A \\ \varepsilon_1.\varepsilon_1^{n-1} &= n.\varepsilon_1^{n-1} - \frac{A}{C} \end{aligned} \tag{19.18}$$

For positive values of A this will yield a solution for ε_1 that is lower than n, indicating that a positive strain-rate hardening will lower the necking limit.

19.5 Thickness Stress

The case of a non-zero thickness stress σ_3 as discussed in Sect. 8.1 can be analysed similar to the case of additive strain-rate hardening. The Tresca criterion states: $\sigma_1 - \sigma_3 = \sigma_\mathrm{f}$. We can also regard this as a change of the flow stress: $\sigma_1 = \sigma_\mathrm{f} + \sigma_3$. Considering σ_3 to be constant, this is the same situation as analysed above with A = σ_3:

$$\begin{aligned} \varepsilon_1.\varepsilon_1^{n-1} &= n.\varepsilon_1^{n-1} - \frac{\sigma_3}{C} \\ \varepsilon_1 &= n - \frac{\sigma_3}{C} \cdot \frac{1}{\varepsilon_1^{n-1}} = n - \frac{\sigma_3.\varepsilon_1}{C.\varepsilon_1^n} \end{aligned} \tag{19.19}$$

Still assuming a simple power law hardening with $\sigma_\mathrm{f} = C.\varepsilon_1^\mathrm{n}$:

$$\begin{aligned} n &= \varepsilon_1 \cdot \left(1 + \frac{\sigma_3}{\sigma_f}\right) = \varepsilon_1 \cdot \left(1 + \frac{\sigma_3}{\sigma_1 - \sigma_3}\right) = \varepsilon_1 \cdot \frac{\sigma_1}{\sigma_1 - \sigma_3} \\ \frac{\varepsilon_1}{n} &= \frac{\sigma_1 - \sigma_3}{\sigma_1} = 1 - \frac{\sigma_3}{\sigma_1} \end{aligned} \tag{19.20}$$

This is the same relation as shown in Eq. 8.1 as $\varepsilon_0(\sigma_3) = \varepsilon_1$ in Eq. 19.20, and of course $\varepsilon_0(0) = n$. Note however that this is a first order approximation valid for low absolute values of $\sigma_{3,}$ as ε_1 is not the effective strain any more.

Chapter 20
Appendix: Measuring Strains and the FLC

This work discusses formability in terms of strain. This Appendix explains how strains are measured in practice.

20.1 Measuring Strains

To determine strains they have to be measured. This is done by marking the surface in some way, and to compare the situation after forming to that before forming. These markings can easily be made by painting, but there is a possibility that the paint wears off when the surface slides over the tool. Another way is to etch the markings chemically into the surface. This supplies very robust markings, but the procedure is tedious. Also, a deep etching may act as a stress concentrator initiating early failure.

During forming an original circle on the surface is changed into an ellipse, see Fig. 20.1. The lengths of the two axes immediately supply the major and minor strain, and the orientation of the axis supplies the principal direction of strain on the surface. So it seems appropriate to mark a set of circles on the surface, and this has long been the standard way of supplying measuring grids (Fig. 20.2, left). This type of grid is easy to measure by hand, and the product shown in Fig. 5.9 is supplied with a grid of circles similar to the right-hand top grid in Fig. 20.2.

When automatic measuring became possible, rectangular grids were used as shown in Fig. 20.2, bottom. Either the dots, or the intersections of lines are marking points. Fig. 20.2 also shows an example of an actual dot grid. The effect of grid size on the measured strain is already discussed in Chap. 14. As an indication: a grid size of 2 mm or 2.5 mm is commonly applied for automotive parts (circle diameter, or point/line distance).

These regular grids have the advantage that they can be applied in the laboratory, are not limited by sheet size, and can be measured in the laboratory after having been pressed elsewhere. A limitation is that they rely on a perfect grid.

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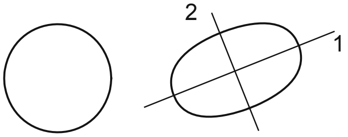

Fig. 20.1 A circle changes into an ellipse by deformation

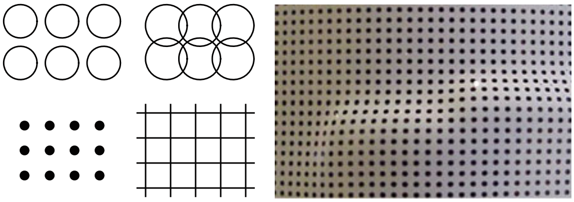

Fig. 20.2 *Left*:. types of measuring grids. *Right*: Example of an actual grid on a product

This means that any irregularities in the grid create small errors in the final result. A consequence is that the resolution is limited, and small strains are therefore difficult to measure. Another approach is to use irregular grids, but this should preferably only be used in situations where during the whole forming process the grid can be monitored by a camera. This limits the applicability, but allows very small strains to be measured, and also the progress during all intermediate stages can be studied.

These procedures supply the major and minor strain on the surface. The thickness strain can be obtained either by direct measurement of the thickness, or from the surface strain using constant volume. However these strains are only the principal strains if there is no shear, or more correctly: if both sides of the sheet have not moved relative to one another. If shear is expected, this movement must be detected and three procedures have been used by various authors.

1. Carefully mark both sides of the sheet, for example with very fine scratches, and measure the whole sheet including both sides in a 3D measuring machine.
2. Drill a small hole through the sheet and detect the orientation of that hole after forming. A complication is that such a hole may effect the straining locally. This is the simplest way.
3. Cut the sheet along a line, mark the cross-sections, solder the parts together, split the product again after forming and analyse the marks. This method can only be used with thick sheets and in situations where the direction of shear is known beforehand. It is extremely tedious, but allows also the detection of variation of shear over the thickness.

For rotational symmetric parts it is also possible to determine the strain state without a grid, by carefully measuring the thickness and shape of a cross-section, and mapping that onto the original blank.

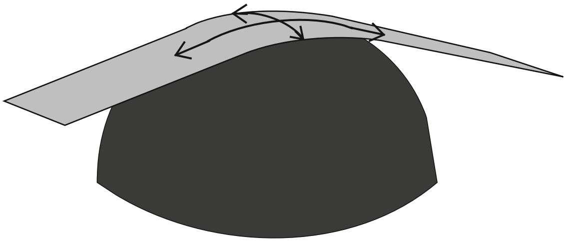

Fig. 20.3 Principle of Nakazima strips

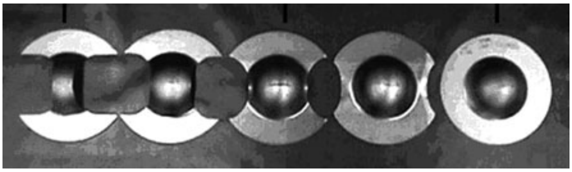

Fig. 20.4 Samples of actual products for measuring the FLC. *Left*: uniaxial, *centre*: plane-strain, *right*: equi-biaxial

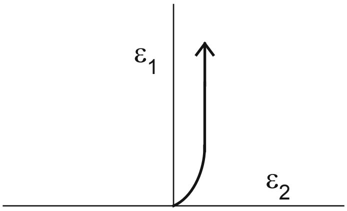

Fig. 20.5 Actual strain path in a supposedly plane-strain situation

20.2 Measuring the FLC

To measure the FLC of a material one has to be able to create various strain states in a sheet. This is mostly done by using so-called Nakazima strips. These are strips or similar shapes that are clamped and stretched over a hemispherical punch, see Fig. 20.3. The clamping ensures that there is stretching in the length direction of the strip. The dome shape creates an additional force across the strip that causes a change in width. This transverse force depends on the relative width of the specimen. For very narrow specimens it can be neglected, and the situation is as in a conventional tensile test. For very wide specimens a symmetric situation is obtained, and the situation becomes equi-biaxial. This illustrates that the strain state that is possible ranges from uni-axial to equi-biaxial, and for example a deep-draw strain state cannot be obtained. Examples of actual test samples are presented in Fig. 20.4.

The sample is expected to fail at the very top of the punch. Detecting the limit strain requires definition of that limit: at the onset of necking or at the onset of fracture. For materials that show strain rate hardening these are not the same, and this can create a lot of confusion. Even when this question has been answered, obtaining the limit strain is far from easy and still shows a lot of controversy.

The FLC is not a pure material test; the limit strain for example depends on the sheet thickness and/or the punch radius.

Measured FLCs often show a minimum just right to the plane-strain axis, see Figs. 5.1 and 11.6. This is not a material effect but it is caused by the specific test method, at least partially. At the very centre of the strip deformation starts biaxially due to the dome shape of the punch, see Fig. 20.5. This means that the strain path is not straight.

Chapter 21

Appendix: Directions of Zero Strain

In Chap. 5 it has been shown that necking needs a direction of zero strain These directions can easily be determined from the strain state.

Consider a piece of material that is being stretched, with major strain ε_1, and minor strain $\varepsilon_2 = \beta \cdot \varepsilon_1$, see Fig. 21.1. Consider further an element of unit length orientated at a direction of angle ϕ relative to the direction of major strain, $0 \leq \phi \leq \pi/2$. The projections of that element to the principal directions are $\cos\phi$ and $\sin\phi$. After stretching with an amount $\varepsilon_1 \ll 1$ the lengths of the projections have changed to $\cos\phi \cdot (1 + \varepsilon_1)$ and $\sin\phi \cdot (1 + \varepsilon_2) = \sin\phi \cdot (1 + \beta \cdot \varepsilon_1)$ respectively. If we assume that the orientation ϕ is indeed a direction of zero strain then the length of the element must remain constant. This yields:

$$(\cos\phi \cdot (1+\varepsilon_1))^2 + (\sin\phi \cdot (1+\beta\cdot\varepsilon_1))^2 = 1 \tag{21.1}$$

Assume $\varepsilon_1 < < 1$ so that $(1+\varepsilon_1)^2 \approx 1 + 2\cdot\varepsilon_1$:

$$(\cos\phi)^2(1+2\cdot\varepsilon_1) + (\sin\phi)^2(1+2\cdot\beta.\varepsilon) = 1 \tag{21.2}$$

After some reworking using $(\cos\phi)^2 + (\sin\phi)^2 = 1$

$$(\cos\phi)^2 + \beta\cdot(\sin\phi)^2 = 0 \tag{21.3}$$

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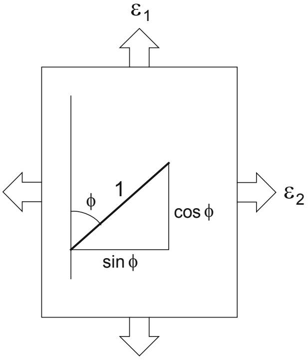

Fig. 21.1 Direction of zero strain

It is clear that this equation can only have a solution if $\beta \leq 0$! This finally yields:

$$(\tan\varphi)^2 = -\frac{1}{\beta}; \quad \beta \leq 0 \tag{21.4}$$

Chapter 22

Appendix: Speed Effects of Lubrication

If in a practical forming operation lubrication is applied (as is most often), speed affects may be created by the lubricant. This is caused by the fact that movement of the sheet over the tool can generate a pressure in the lubricant by hydrodynamic effects. As a result the pressurized lubricant carries part of the load thereby reducing the load on the roughness asperities. This will reduce friction. Under ideal conditions the influence of speed on friction may be presented by:

$$\mu = \mu_0 . \left(1 - \frac{V}{V_0}\right) \tag{22.1}$$

where μ is the coefficient of friction, V the process speed and μ_0 and V_0 constants.

For practical applications the coefficient of friction is often presented in a so-called Stribeck diagram. In such a diagram the coefficient of friction is plotted as a function of the parameter H defined as $H = \eta.V/P$ ($\eta =$ lubricant viscosity, $V =$ process speed, $P =$ external macroscopic pressure). This parameter H follows directly from lubricant hydrodynamics assuming a simple, Newtonian liquid. More important is that H can be interpreted as describing the process conditions: lubricant, process speed, press settings.

Some actual friction measurements are presented in Fig. 22.1 [1], this graph also shows the influence of surface roughness. Note that the influence of process conditions (speed) or roughness on the friction is much higher for some values of H (process settings: speed) than for other values. This illustrates the controversy that occasionally arises about the influence of lubrication, as the process conditions may vary from press-shop to press-shop.

Relation Eq. 22.1 and also the results presented in Fig. 22.1 are only valid under some conditions. Firstly, there must be enough lubricant on the sheet to fill the roughness valleys sufficiently, if there is too little lubricant the load bearing capacity of the lubricant decreases, and the reduction of friction is also lower [1]. Secondly, the surface roughness should not flatten much in the friction contact. If the surface roughness does flatten significantly a different relation arise, sometimes to such an extent that the product does not fracture at all in deep

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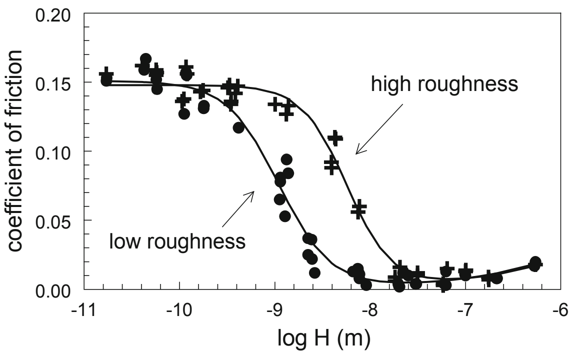

Fig. 22.1 Actual friction measurements plotted in a so-called Stribeck diagram. This diagram also illustrates the effect of sheet surface roughness (values: $R_a = 0.85$ μm and $R_a = 2.9$ μm respectively. H is defined as in the text

drawing, even when applying the maximum blankholder force [2]. Thirdly, the lubricant should be a simple (Newtonian) liquid. Wax type lubricants for example show a much lower influence of process conditions and roughness on friction.

The effect of (liquid) lubrication however always remains: if there is an influence of speed, then increased speed reduces the friction.

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Chapter 23
Appendix: Influence of Parameters on Press Behaviour

The following table presents an overview of the influence of some material parameters on press behaviour found in literature, as compiled by Alan Daglish [1].

Process	Forming Index	n	m	ε_u	ε_m	r	μ	f
Deep Drawing	D/d	o	o	o	o	+	−	o
Re-Drawing	d0/d1	−	o	+	o	+	−	o
Die Necking	d0/d1	−	o	+	o	o	−	o
Hole Expansion	d1/d0	+	+	−	o	o	o	+
Stretching	h/d	+	+	−	o	o	−	+
Bulging	h/d	+	+	−	+	o	o	+

+ = higher value is beneficial
− = lower value is beneficial
o = indifferent

Forming Index:

D = blank diameter
d = punch diameter
d0 = old diameter
d1 = new diameter
h = product height

Material parameters:

n = work hardening coefficient
m = strain-rate hardening coefficient
ε_u = uniform strain
ε_m = fracture strain
r = normal anisotropy
μ = tool/workpiece friction coefficient
f = lack of material defects

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