NEW METHODS FOR PREDICTING THE FORMABILITY OF SHEET METALS

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Abstract
Car manufacturing is one of the main target fields of sheet metal forming; thus sheet metal forming is exposed to the same challenges as the automotive industry. The continuously increasing demand on lower consumption and lower CO₂ emission means the highest challenges on materials developments besides design and construction. As a general requirement, the weight reduction and light weight construction principles should be mentioned together with the increased safety prescriptions which require the application of high strength steels. However, the application of high strength steels often leads to formability problems. Forming Limit Diagrams (FLD) are the most appropriate tools to characterize the formability of sheet metals. Theoretical and experimental investigations of forming limit diagrams are in the forefront of today’s research activities. In this paper, an up-to-date research methodology elaborated and applied at the Department of Mechanical Technology at the University of Miskolc will be shown.

Keywords: formability, Forming Limit Diagrams, optical strain measurement

1. Introduction
The first forming limit diagram was published by Keeler in 1961 [1]. But he determined the forming limit curve only in the positive range of minor strain (i.e. for $\varepsilon_2 > 0$). The left hand side (i.e. for $\varepsilon_2 < 0$) was then determined by Goodwin in 1968 [2] and since then it is called as the Keeler-Goodwin diagram. This type of forming limit diagram is shown in Figure 1. The curve connecting the fracture points of each strain paths is called forming limit curve and denoted by $FLC$. For most materials in conventional forming processes, the forming limit diagram has a typical V-shaped form as seen in Figure 1.

![Figure 1. Forming Limit Diagram for various strain paths (1-pure shear, 2-uniaxial tension; 3-plain strain, 4, 5, 6-different biaxial tension)]
2. Basic understandings concerning the forming limit diagrams

Forming Limit Diagrams represent the formability limits in the coordinate system of major \((\varepsilon_1)\) and minor \((\varepsilon_2)\) principal strains as shown in Figure 1. The formability limit is usually characterized by the failure (rupture) and this is called as formability (fracture) limit curve.

However, it is evident that in normal production conditions even the local necking cannot be permitted: neither from the point of view of aesthetic appearance nor the functional operation of the part. This is the reason that further limit curves are determined besides the rupture for the limit of necking as well. The zone between the fracture and the necking limit curve is called as the range of local necking.

At certain level of compressive stresses a local instability of sheet can also occur: this phenomenon is regarded as wrinkling. It is also evident that besides rupture and local necking, wrinkling should also be avoided. The forming limit diagram with these limit curves and zones is shown in Figure 2. Below the local necking zone, the green zone indicates the safe region of normal forming conditions in terms of major \((\varepsilon_1)\) and minor \((\varepsilon_2)\) principal strains.

![Figure 2. Characteristic limit curves and zones of Forming Limit Diagram](image)

As it can be seen from the Figure 2, there are various limit curves and also the zones denoted by different colours mean different behaviour from the point of view of formability. The Fracture Limit Curve which is more often called as Forming Limit Curve (FLC) represents those limit values of \(\varepsilon_1\) and \(\varepsilon_2\) where fracture occurs. While to observe the onset of fracture is quite easy, however to determine the principal strain values at the onset of rupture is rather complicated.

The Necking Limit Curve (NLC) represents the onset of local necking. Though the exact measurement of principal strain components at the limit state of necking is at least as difficult as it is for the onset of fracture, but this limit is more acceptable for real industrial parts, since at this stage still there is no any undesirable local necking. It can also be stated...
that due to the modern optical strain measurement facilities, continuously improved and further developed possibilities are available for both the scientific research and for the everyday industrial practice, too.

3. Experimental determination of Forming Limit Diagrams

An integrated Sheet Metal Formability Testing System (SMFTS) was installed at the Department of Mechanical Engineering at the University of Miskolc with the financial support of several national and international projects. It consists of an electro-hydraulic, computer controlled testing machine with an optical strain measurement system as shown in Figure 3. According to its nominal loadability \( F_{\text{max}} = 600 \text{kN} \), this system is suitable to perform sheet metal testing up to 3 mm thickness. The applied punch diameter is a standard \( d = 100 \text{mm} \), the velocity range is \( v = 0 \div 5 \text{mm/s} \). The computer control can provide the harmonized operation of the formability and optical strain measurement system.

![Figure 3. Universal sheet metal formability testing system with optical strain measurement](image)

For the measurement of the strain distribution over the whole part, a printed grid is applied on the surface of the part before the forming operation. In our experiments, regular, square grid is applied as the carrier of the measuring information in the AutoGrid® strain measurement system. The applied grid can influence the measuring certainty and reliability. An intact grid of high contrast is the main prerequisite for successful analyses. On the one hand, the grid has to survive the forming process without damage due to friction and plasticity and on the other hand it mustn’t have any effect on the forming behaviour of the sheet metal itself. There are number of methods for grid preparation. They differ with respect to their cost, durability, and accuracy. The most common techniques are mechanical engraving, screen printing, offset printing, photo masking, electrochemical etching, etc. In our experiments offset printing regularly applied in press shops was used.

The applied Vialux-AutoGrid optical strain measurement system \([3]\) is capable for in-process and post-process evaluation of grid deformation. In the determination of forming limit diagrams, usually the post-process evaluation is applied; however, it is often combined with the in-process capabilities of the system for more precise detection of the onset of necking or the rupture itself.
3.1. Experimental specimen

For the determination of forming limit diagrams, the specimen proposed by Nakazima [4] and Marciniak [5] are generally used. In our experiments, we applied a modified version of Nakazima specimen. These modified specimens are shown in Figure 4.

![Figure 4: Modified Nakazima specimen](image)

3.2. The experimental procedure

As it was already mentioned, before the examinations a square grid was made on the surface of the specimens applying an offset printing technique. The deformation of the square grid was measured by the Vialux optical strain measurement system. The evaluation of the deformed grid is based upon the recognition of identical grid-crosses from the different views obtained by the four CCD cameras mounted on the testing machine.

The behaviour of the material during plastic deformation can be characterized by the true strain. The components of true strain in \( x \) and \( y \) direction can be calculated by the following expressions:

\[
\varepsilon_x = \int \frac{dx}{x_0} \ln \frac{x_1}{x_0} \quad \text{and} \quad \varepsilon_y = \int \frac{dy}{y_0} \ln \frac{y_1}{y_0}.
\]

The third component – i.e. the true strain \( \varepsilon_z \) in the \( z \)-direction which corresponds to the strain perpendicular to the thickness – can be determined from the volume constancy law

\[
\varepsilon_x + \varepsilon_y + \varepsilon_z = 0.
\]

Performing the evaluation for all the applied specimens having different width various \( \varepsilon_1, \varepsilon_2 \) clouds of points can be obtained as shown in Figure 5. They represent different strain path history depending on the width of the specimen.

On this Figure, it can be also well seen, how the clouds of measured points of strain components move with the varying bridge width in the \( \varepsilon_1, \varepsilon_2 \) coordinate system of major and minor principal strains covering the whole range of both the positive and the negative sides of the Forming Limit Diagram.

When all the measurements and the evaluations are completed, they should be simultaneously loaded into \( \varepsilon_1, \varepsilon_2 \) coordinate system. To get the Forming Limit Curve (FLC) we have to connect the fracture points on each deformation path (Figure 6.)
Formability of sheet metals

bridge width $b_w = 20$ mm  
bridge width $b_w = 40$ mm  
bridge width $b_w = 80$ mm

bridge width $b_w = 125$ mm  
bridge width $b_w = 200$ mm

**Figure 5.** Results of strain measurements for various strain paths

**Figure 6.** Graphical generation of FLC from the measured strains

The AutoGrid system provides various possibilities for fitting the right curve on the measured points. Obviously, the more points we have the more precise the FLC will be.
4. Analysis of parameters affecting the Forming Limit Diagrams

As we could see from the previous points, the determination of forming limit diagrams is a quite complicated process and during their determination we have to consider many parameters that may influence it. The most important influencing parameters are:

- the strain path, i.e. the strain history applied during the investigations,
- the material quality and the various material properties (e.g. the strain hardening coefficient \(n\), the strain-rate sensitivity index \(m\), the anisotropy coefficient \(r\), the rolling direction, etc.)
- the sheet thickness \(t\),
- the shape and sizes of specimens,
- the experimental conditions (e.g. the shape and precision of applied grid, the precision of grid measurement, the temperature, the friction conditions, etc.)

From these many influencing parameters, here only some of them will be analysed.

4.1. Effect of the material quality and the material properties

Analysing the effect of material quality on the formability, it is valid as a general rule that with increasing the strength properties the formability decreases. This relationship may be well seen from the Figure 7, where the relationship between the ultimate tensile strength \(R_{um}\) and specific elongation \(A_5\) is shown.

From the material properties concerning the effect of strain hardening exponent \(n\) Keeler and Brazier [7] created a semi-empirical relationship to calculate the minimum value of major principal strain \(\varepsilon_1\) which is often denoted as \(FLD_e\):

\[
FLD_e = (23,3 + 359t) n / 0,21.
\]
If the thickness \( t \) substituted in inch into the equation (3) the value of \( FLD_0 \) is get in percentage value. (The point \( FLD_0 \) is located in the forming limit diagram where the forming limit curve crosses the \( \varepsilon_1 \)-axis, i.e. at \( \varepsilon_2 = 0 \)). The industrial significance of this relationship can be reasoned by the following experimental observation: if we have a forming limit diagram for a mild steel material grade and \( n \) for other materials is also known we can construct a simple forming limit diagram by calculating \( FLD_0 \) with the expression (3) and shifting the curves to this calculated \( FLD_0 \) value as shown in Figure 8.

![Figure 8. Effect of strain hardening exponent on the location of FLD](image)

Analysing the effect of anisotropy coefficient, it was found that higher \( r \) values have favourable effect on the limit strain values particularly in the negative range of minor principal strain (i.e. for \( \varepsilon_2 < 0 \)) as shown in Figure 9.

![Figure 9. Effect of anisotropy coefficient (r) on the forming limit curves](image)
It can be easily proved that for simple tension the slope of the strain path trajectory can be calculated by the following expression

$$\tan \alpha = -\frac{r}{r+1}. \quad (4)$$

It follows from the equation (4) that the larger the anisotropy coefficient the larger the slope of the straight strain path. Since the forming limit curve is going upwards in the directions of $-\varepsilon_2$, it means that the fracture point on the strain path can be found at higher $\varepsilon_1$ values, i.e. the limit strains are increased.

### 4.2. Effect of sheet thickness

It is also generally valid that in certain range, the formability is increasing with increasing sheet thickness. This is also valid for the forming limit diagrams, i.e.: increasing the sheet thickness the forming limit curve is shifted upwards along the $\varepsilon_1$ axis.

However, there are some contradictory results in this respect as summarised by Col [8]. Due to these contradictions, we have done a large scale investigation to study the effect of sheet thickness on the forming limit diagrams. The tests were done on different grade of steel sheets. These tests were done also on the universal sheet metal formability testing machine using the optical strain measurement technique. The next figure shows the thickness effect for DC05 material quality for the thickness gauges $t = 0.8; 1.0; 1.2$ and $1.56$ mm. The results are shown in Figure 10.

![Figure 10. Effect of sheet thickness on the forming limit diagrams for DC05 material grade](image)

Similar tests were carried out for DC04 and DD14 material grades. The thickness for DC04 was in the range of $t = 0.4+1.0$ mm, while for the DD14 material in the range of $t = 1.0+3.2$ mm. Thus for the three material grades the thickness range covered the full thickness range for fine thick gauges. The results are shown in Figure 11. for DC04, and in Figure 12. for DD14.
Analysing the results of experiments we can state that the experiments proved the favourable effect of the increase in the sheet thickness. The three diagrams had very similar character, i.e. a more significant influence of sheet thickness may be observed in the positive range of the forming limit diagrams (i.e. for $\varepsilon_2 > 0$) than in the negative range i.e. for $\varepsilon_2 < 0$).

**Figure 11. Effect of sheet thickness on the forming limit diagrams for DC04 material grade**

Comparing the effect of sheet thickness on the forming limit diagrams for the three different steel grades, it can be concluded that the forming limit curves are shifted towards higher limit strains with the increase of the sheet thickness. It is also valid for each tested material that the effect is higher in the positive range of the forming limit diagram. It can be also stated that the highest changes can be observed at the material grade DC04 compared to the two other ones.

**Figure 12. Effect of sheet thickness on the forming limit diagrams for DD14 material grade**
5. Summary

The paper deals with the theoretical and experimental investigation of forming limit diagrams as a special field of the formability of sheet metallic materials. Forming limit diagrams can be regarded as the most appropriate tools in the qualification of sheet metal formability.

In this paper various aspects of damage limitations (e.g. fracture, local necking and diffuse necking) were studied as the limits for formability. It has been pointed out that for the everyday industrial practice, even the onset of local necking is not permitted which needs a very careful determination of forming limit curves.

Among the several parameters affecting the sheet formability, the effect of material grades, the strain hardening exponent and the anisotropy coefficient were studied as material properties. Besides these material properties, the effect of sheet thickness was also investigated. It was stated that the sheet formability is increased with the increasing value of strain hardening exponent and the anisotropy coefficient. It was also proved that the increase of the sheet thickness has a favourable effect on the forming limit diagrams concerning the available strain limits.

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7. References