INTRODUCTION

Sheet Metal Formability

Formability refers to the ability of sheet metal to be formed into a desired shape without necking or cracking. Necking is localized thinning of the metal that is greater than the thinning of the surrounding metal. Necking precedes cracking. From the metallurgical perspective, the formability of a particular metal depends on the metal’s elongation, which is the total amount of strain measured during tensile testing. A metal with a large elongation has good formability because the metal is able to undergo a large amount of strain (work) hardening.

Anisotropy and the Lankford Coefficient

Anisotropy is defined as the directionality of properties and it is associated with the variance of atomic or ionic spacing within crystallographic directions (Callister, 1997). For single crystals it can be the variation of properties (like the...
electrical conductivity, the elastic modulus, the index of refraction, etc.) in different crystallographic directions. (Callister, 1997) Points that the extent and magnitude of anisotropic effects in crystalline materials are functions of the symmetry of the crystal structure. Since common engineering materials are polycrystalline, the crystallographic orientations of the individual grains are totally random, if completecrystallization has taken place. Although all grains have certain anisotropy, the overall structure will behave isotropically, since the anisotropy effect is averaged out. However if the materials are deformed for instance with no complete recovery, the crystal grains are oriented in deformation specific directions, making the material anisotropic. During deformations, the crystal lattices rotate and they affect the plastic properties (Hosford and Caddell, 2007). The anisotropy coefficient or the Lankford coefficient (Lankford, et al., 1950) is a measure of anisotropy. This parameter can be called as the 'resistance to thickness change'. This coefficient is defined as
\[
r = \frac{\varepsilon_2}{\varepsilon_3}
\]
Where \(\varepsilon_2\) and \(\varepsilon_3\) are the strains in the width and thickness directions.

For a successful sheet metal stamping, the normal anisotropy must be as large as possible whereas the planar anisotropy must be as small as possible. (Weilong and Wang, 2002) indicate when the \(r\)-value of sheet metals is greater, the thinning should be smaller and thus the formability is better. However, a greater \(r\)-value does not satisfy all sheet metal forming processes such as necking and bending, meaning that each forming process should have individual forming properties related to the anisotropy of the materials, and the different strain states would cause different forming failures (Hosford and Ducan, 1999). The Lankford anisotropy coefficient depends on the in-plane direction. In orthogonal anisotropy three \(r\)-values are determined: Along the rolling direction (RD), along 45° to RD and perpendicular to rolling direction (transverse direction, TD). These values are denoted as \(r_0\), \(r_{45}\), and \(r_{90}\) respectively. The average of these \(r\)-values in the plane of the sheet metal represents the coefficient of normal anisotropy \(r_n\). The coefficient of normal anisotropy is obtained from equation given below (Banabic, et al., 2000).
\[
r_n = \frac{r_0 + 2r_{45} + r_{90}}{4}
\]

A measure of the variation of normal anisotropy with the angle to the rolling direction is given by the quantity \(\Delta r\), known as planar anisotropy.

\[
\Delta r = \frac{r_0 + r_{90} - 2r_{45}}{2}
\]

Yield Strength

Yield strength production variation varies with the mill and processor: chemistry, mechanical processing and annealing and the range suppliers.

<table>
<thead>
<tr>
<th>Materials</th>
<th>K [MPa]</th>
<th>n</th>
<th>(R_0)</th>
<th>(R_{45})</th>
<th>(R_{90})</th>
<th>(\Delta r)</th>
<th>(r_n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6111-T4</td>
<td>538.225</td>
<td>0.2255</td>
<td>0.894</td>
<td>0.611</td>
<td>0.660</td>
<td>0.083</td>
<td>0.694</td>
</tr>
<tr>
<td>DDQ mild Steel</td>
<td>547.763</td>
<td>0.2692</td>
<td>2.160</td>
<td>1.611</td>
<td>2.665</td>
<td>0.401</td>
<td>2.012</td>
</tr>
</tbody>
</table>

Table 1. Detailed information about the material properties is given.
normal distribution or ± 20 MPa, high influence on hardening behaviour, yield surface, effectiveness of beads and pads, springback (Marciniak, et al., 2002).

**Tensile Strength**

Tensile strength variable with chemistry and mechanical processing and the range suppliers normal distribution or ± 20 MPa, influence hardening with yield (Marciniak, et al., 2002).

**Strain Hardening Exponent (N)**

The input of N value for which the production variation varies with chemistry, mechanical processing, and annealing and the range fluctuates with variation of yield and tensile strength and effect of hardening behaviour, forming limit (Marciniak, et al., 2002).

**Plastic Strain Ratio (R)**

The input of R value for which the production variation varies with hot roll vs cold roll, mechanical, coil rolling direction and the range is ± 20 (steel), ± 10 (aluminium), influence yield surface, strain/stress distribution (Marciniak, et al., 2002).

**Effect of Anisotropy in Drawing**

The plastic flow behaviors of these two materials are nearly identical as far as the flow curve is concerned; the difference in product properties arises therefore from the differences in anisotropy and elastic properties (Fig. 1).

Additionally, the anisotropy constants (strain ratios at three different angles trolling direction) of the two materials show (that their anisotropic behaviors are entirely different. This difference in anisotropy is also an important reason for differences in product shapes and qualities. The effect of anisotropy is inspected within this benchmark (Fig. 2).

**Plastic Tensile Instability and Necking**

The forming limit diagram (FLD) (also known as the forming limit curve, FLC) is another important concept utilized for the evaluation of the formability of sheet metals. By the use of these diagrams, the onset of failure due to local necking, or potential trouble areas on the deformed part under various loading types can be estimated and investigated The research in this field was pioneered by (Keeler and Backofen, 1963) based on the observations of (Gensamer, 1946). Maximum values of principal strains $\varepsilon_1$ and $\varepsilon_2$ can be determined by measuring the strains at fracture on sheet components covered 20 with grids of circles. The most widely used technique involves printing or etching a grid of small with constant diameter on the metal sheet before forming. During forming the initial circles of the grid distort and become ellipses. From the minor and minor axes of these ellipses, the principal strains on sheet specimens can be determined. Keeler plotted the maximum principal strain against the minimum principal strain obtained from such ellipses at fracture of parts after biaxial stretching. This way, a curve limiting the tolerable range is obtained (Fig. 3).

Later, (Goodwin, 1968) plotted the curve for tension/compression domain by using different mechanical tests. In this case, transverse compression allows...
for obtaining high values of tensile strains like in rolling or wire drawing. The diagrams of Keeler and Goodwin together give the values of $\varepsilon_1$ and $\varepsilon_2$ at fracture. This currently is called the forming limit diagram, sometimes also as the Keeler - Goodwin diagram (Fig. 4) indicated that from subsequent experimental and theoretical research, two more types of FLD’s have emerged (Banabic, et al., 2000): the wrinkling limit diagram and the limit stress diagram. There are various tests to determine the FLD experimentally (Banabic, et al., 2000) like the uniaxial tensile test, hydraulic bulge test, punchstretching test, Keeler test, Hecker test, Marciniak test, Nakazima test and Hasek test. From these, Marciniak test or hydraulic bulge test is utilized for eliminating friction effects; uniaxial test is preferred for its simplicity and Nakazima test is suitable since it is capable of covering a great variety of strain paths. It was stated by (Banabic, et al., 2000) that there are various models present for the calculation of FLD’s. The first ones were proposed by Swift and Hill utilizing the models of diffuse necking and localized necking respectively.

Instability

Different (Hosford and Caddell, 2007) said phenomena limit the extent to which a metal may be deformed. Buckling may occur under compressive loading if the ratio of height-to-diameter is too great. Fracture may occur under tension called plastic instability. When a structure is deformed, there is often a maximum force or maximum pressure after which deformation continues at decreasing loads or pressures. It is assumed throughout this chapter that the strain hardening is described by $\sigma = K \varepsilon^2$. If other expressions better represent the behaviour, they can be used with the same procedures. Solutions for effective strain at instability are functions of $n$.

Variation of Necking Limits with Strain Ratio

Selected theoretical results for limit strains are presented in (Fig. 5-7) (Mellor, 1956; Swift, 1952) for different material characteristics. In each case the depth of the incipient groove at instability has been assumed to be equal to the surface roughness depth $R_s$ existing at that point. The Swift instability curves are included in these Figure in order to give a feeling for the level of straining. Results are plotted for different ratios of to do and it can be noted that a ratio of about 30 is typical of many commercial sheet metals. The assumed material constants in (Fig. 5) are characteristic of an isotropic steel sheet, in (Fig. 6), of aluminium and in (Fig. 7), of 70130 brass. The results are consistent with experimental observations that the limit strains decrease as the sheet thickness decreases. It is clear from (Fig. 5-7) that the $k$-value exerts a considerable influence on the limit strains and when $k = 2$ (Fig. 7), the plotted...
limit strains are all less than the Swift instability strains. This last result might seem surprising but it is consistent with experimental.

Results reported by Azrin and Backofen. It is also interesting to note that Mellor found that a diaphragm of annealed 70/30 brass, deformed by hydrostatic pressure, fractured without exhibiting a classical instability condition. The effect of reducing the incipient groove depth from $R$ to $R/2$, where $e_v/n$ is plotted against $R$. The limit strains are, of course, increased by reducing the assumed incipient groove depth and the effect is proportionately greater as $k$ decreases. The Swift instability strain is represented on this (Fig. 7), by a value of $e_v/n$ equal to unity.

The general material characteristics that influence the outcome of a sheet metalforming process are the following (Marciniak, et al., 2002).

**Strain Hardening of the Sheet**

The greater the strain-hardening of the sheet, the better it will perform in processes where here is considerable stretching; the straining will be more uniformly distributed, and the sheet will resist tearing when strain-hardening is high. Additionally, since necking failures are associated with the strainhardening coefficient $n$, materials having higher $n$ will generally exhibit better formability (Beddoes and Bibby, 1992).

**Initial Yield Strength**

It is related to the strength of the formed part. Although for light weight materials, higher yield strengths are preferable, such materials are harder to form and combined with low elastic moduli, it induces increased springback problems (Sönmez, 2005; Sivam, et al., 2016; Sivam, et al., 2015; Sivam, et al., 2016).

**Elastic Modulus**

A higher modulus will give a stiffer component, whereas a lower modulus gives larger springback (Marciniak, et al., 2002).

**Total Elongation**

It is the amount of uniaxial strain at fracture it includes both elastic and plastic deformation and is commonly reported as percent elongation at fracture. Percent elongation = (elongation at rupture) x 100/ (initial gage length).

**Anisotropy**

If the magnitude of the planar anisotropy parameter, $R$, is large, either, positive or negative, the orientation of the sheet with respect to the die or the part to be formed will be important; in circular parts, asymmetric forming will be observed. If the normal anisotropy ratio $R$ is greater than unity it indicates that in the tensile test the widthstrain is greater than the thickness strain; this may be associated with a greater strength in the through-thickness direction and, generally, a resistance to thinning. Normal anisotropy $R$ also has more subtle effects. In drawing deep parts, a high value allows deeper parts to be drawn. In shallow, smoothly-contoured parts such as autobody outer panels, a highvalue of $R$ may reduce the chance of wrinkling or ripples in the part. Other factors such as inclusions, surface topography, or fracture properties may also vary with orientation; these would not be indicated by the $R$-value which is determined from plastic properties (Marciniak, et al., 2002).

**Fracture**

Even in ductile materials, tensile processes can be limited by sudden fracture. The fracture characteristic is not given by total elongation but is indicated by the cross-sectional area of the fracture surface after the test-piece has necked and failed. This is difficult to measure in thin sheet and consequently problems due to fracture may not be properly recognized (Marciniak, et al., 2002).

**Homogeneity**

Industrial sheet metal is never entirely homogeneous, nor free from local defects. Defects may be due to variations in composition, texture or thickness, or exist as point defects such as inclusions. These are
difficult to characterize precisely. Inhomogeneity is not indicated by a single tensile test and even with repeated tests, the actual volume of material being tested is small, and non-uniformities may not be adequately identified (Marciniak, et al., 2002).

**Surface Effects**

The roughness of sheet and its interaction with lubricants and tooling surfaces will affect performance in a forming operation but will not be measured in the tensile test. Special tests exist to explore surface properties (Marciniak, et al., 2002).

**Damage**

During tensile plastic deformation, many materials suffer damage at the microstructural level. The rate at which this damage progresses, varies greatly with different materials. It may be indicated by a diminution in strain-hardening in the tensile test, but as the rate of damage accumulation depends on the stress state in the process, tensile data may not be indicative of damage in other stress states (Marciniak, et al., 2002).

**Rate Sensitivity**

As mentioned, the rate sensitivity of most sheet is small at room temperature; for steel it is slightly positive and for aluminium, zero or slightly negative. Positive rate sensitivity usually improves forming and has an effect similar to strain-hardening. As well as being indicated by the exponent m, it is also shown by the amount of extension in the tensile test-piece after maximum load and necking and before failure, i.e. $E_{\text{Total}} - E_u$, increases with increasing rate sensitivity (Marciniak, et al., 2002).

**Sensitivity to Material Properties**

It is widely understood that wrinkling of sheet metal is strongly influenced by the material properties (Ameziane-Hassani and Neale, 1991; Havránek, 1975; Lee, 1987; Logan and Hosford, 1985; Naziri and Pearce, 1968; Ni and Jhita, 1990; Saran, et al., 1990; Wang and Lee, 1989; Yoshida, 1997). Work hardening behaviour, strength coefficient and yield stress are among those that may have significant effects on the drawing process. Yield strength, $S_y$, strength coefficient, K, and work hardening exponent, n, were varied over a reasonable range of values, one at a time, while the other parameters were kept constant. The true stress-strain curves produced based on different combinations of K and n values are shown in (Fig. 8) below.

It can be seen from (Fig. 8) that the stress-strain curve moves downward with increasing work hardening exponent, n. This corresponds to more plastic deformation at a given level of stress. In contrast, the stress-strain curve moves upward with increasing strength coefficient, K. In a drawing process, the blank has more tendency to wrinkle when the material has a greater resistance to plastic deformation. It can therefore be predicted that materials with a high K value, and low n value will wrinkle more easily than materials with a low K value and high n value.

**CONCLUSION**

The assessment of formability effect of material properties of sheet metal were made by using different material and anisotropy, strength of material, limit strain ratio were shown, material properties, and sensitivity of material were studied. The high r-value, which is effective in improving cup formability, and thanks to this, its limit-drawing ratio is higher for material formability. The strain at maximum stress and ultimate strain of the sheets increases as sheet thickness increases after which the strain values remain almost the same or slightly decrease. The yield strengths of sheets with different thicknesses to be correlated with the values of the ultimate strain and strain at maximum stress suggesting that the dependency of the strain values on sheet thickness might have to do with the rolling process used for the production of sheet metals. The minimum bending radius linearly increases as the sheet thickness increases. Unlike deep-drawing processes, the failure strain of sheets in air bending decreases as sheet thickness increases.

**REFERENCES**


Banabic, D., Bunge, H.J., Pöhlandt, K. and Tekkaya,


