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Review on Sheet Metal Formability

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Abstract: Sheet metal Forming is one of the most important and diverse manufacturing processes and has been an integral part of industries like automotive and aerospace which need high density, lightweight and high strength materials. This paper tries to encapsulate the features related to Formability and its testing. Various parameters like anisotropy and strain rates on which the formability depends are also considered and their impact on the testing. Further, the paper includes study of Formability of Tailor Welded Blanks which is an integral part of the automotive sector. At last the paper concludes with the future developments that can be made in this field along with new modelling techniques and new advancements in testing.

1. Introduction

Sheet-Metal Formability is generally defined as the ability of the material (typically called as blank) to undergo plastic deformation governed by flow rules to give the desired shape change without failure, such as wrinkling, cracking, necking, cracking, tearing, etc. Formability is not easily quantified as it depends on several factors such as material flow properties, ductility, die geometry, die material, lubrication, press speed, stress rate, strain rate, temperature roughness, springback, strain localization, etc. [1]. Further, formability of different materials also depends upon the sheet metal process that is being undertaken for the production of the part. Important processes in this field are bending, deep-drawing, stretch forming, hydroforming, incremental forming and many more. The formability of any sheet is at its minimum at plane strain conditions and so about 80-85% industrial failures occur around this state. So, an ideal test should be able to simulate these conditions efficiently and effectively. It should also be taken into consideration that no single formability test can relate the formability for all types of forming or stamping operations [2]. The basic forming characteristics of sheet metals can be obtained from simple mechanical tests such as tensile, bulge and hardness tests but these tests are too simple to relate to various parameters and phenomena such as strain-hardening. A few important parameters on which the formability of a sheet metal depends on are the strain-hardening index (n) which is usually obtained from flow curves (fig.1), strain rate and anisotropy of the material. Higher the strain hardening index and higher the strain-rate

strain before necking. Further, improvements in the drawability of the material is seen when the Anisotropy index (r) is higher. But there is a major disadvantage of these simple tests, i.e., they completely ignore the effect of variables (geometry of punch or die, lubrication, punch speed etc.) on the forming behavior of sheet metal completely. According to the power-law of strain hardening-

$$\sigma = k\varepsilon^n \qquad (1)$$

2. Formability Tests

All the sheet metal industries have been looking for an ideal formability t

splitting failure that usually occur in plane-strain condition [1]. The most accepted way to predict of as sheet metal is by plotting the Forming Limit Diagram (FLD) (fig.2). It is an experimental procedure in which a combination of two principal surface strains (major and minor) are represented. The diagram consists of Formability Limit Curve (FLC) above which localized instability is observed. The major and minor strains plotted in the FLC are obtained from these tests that are done under various train paths from uniaxial tension over plane strain tension to biaxial tension [4]. In stretching is measured and the metals are rated on the basis of them. Formability tests are mainly divided into three broad categories- intrinsic tests, simulative tests and the test that are used to plot the FLDs. The intrinsic tests consist of basically the uniaxial tension tests and are independent of the sheet metal geometry. In simulative tests, drawing and stretching conditions are simulated because these are the most common ones in the industrial applications. The different types of simulative tests are Erichsen Olsen Tests, Swift Cup test, Limit Dome Height test and OSU tests. There are two experimental methods for obtaining FLDs, one is, Out-of plane formability tests [5,6] and the second one is, In-plane formability tests [7,8]. For both the tests, a grid marking scheme is used in which the sheet metal is marked with a grid pattern and is deformed in the stretching tests [9]. After this the deformation of the grid pattern is measured where either necking has taken place or fracture has occurred, thus, giving the values of major and minor strains. Examples of these tests include Nakajima Test [10], Marciniak Test [11].

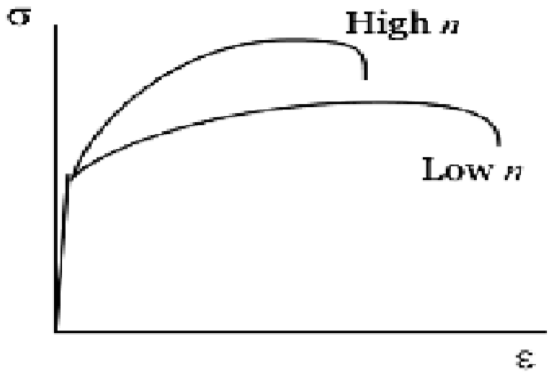

Fig.1: True stress versus True Strain Diagram [3]

Various theoretical models are also proposed to calculate forming limit diagrams of different sheet metals. These Modelling techniques are mostly based Bifurcation theory, geometrical imperfection theory and Continuum damage mechanics [4]. The modelling is also an integral part of formability analysis because during the process of sheet metal forming, the plastic deformation itself includes a lot of different phenomena like anisotropy, hardening, failure and fracture that too occurring simultaneously. Thus, modelling or numerical analysis tries to combine all these factors so that the cumulative effect on formability can be seen. Some of the important modelling

l (Maximum force criterion), Modified maximum force criterion (MMFC), Storen and Rice (S-R) theory, Marciniak and Kuczynski (M-K) model and one of the recent developments in this field is NADDRG model.

Swift cup test evaluates the drawability of a sheet metal by simulating the drawing operation, in which the sheet is held under a blank holder and is drawn into small parallel sided cup. Drawability is measured by drawing various blanks with increasing the diameter one by one and thus defines the Limit Draw Ratio (LDR) which gives an estimation of the drawability. Swift cup test is highly standardized,

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with die and punch radii as 6.35mm. But its drawback is that it is a very time-consuming process

$$LDR = \frac{Maximum\ Blank\ Diameter}{Cup\ Diameter} \qquad (2)$$

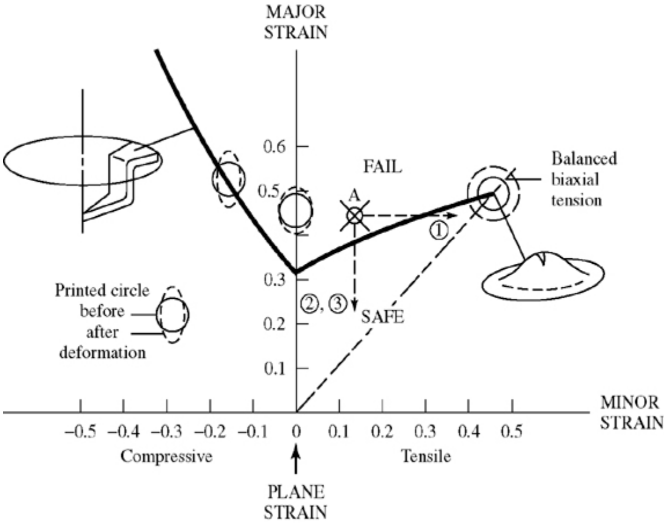

Fig.2: Forming Limit Diagram (FLD) [12]

Erichsen and Olsen are basically two tests that simulate the stretching operation conditions. In these tests, a sheet metal is clamped between two plates and a hole of diameter 25.4 mm is made into it. Now, a ball with diameter, d, is pressed into the sheet until the fracture occurs. For Olsen test, d=22.2 mm and for Erichsen test, d=20mm. Height of the cup, h at failure is used as formability index, higher this index is higher will be the formability of the material. The disadvantages of this test are first they cannot be correlated with other mechanical properties of the sheet metal and second these tests have poor data reproducibility. Limiting Dome Height Test (LDH) simulates the stamping conditions more effectively. This test includes clamping the metal sheets of varying width into a blank holder and a 102 m hemispherical punch is used to stretch the sheet over. Small diameter circles (2.5mm) are marked like a grid on the sheet and the circle closest to the fracture gives the width strain. The height at which dome fails gives us Limiting Dome Hight (LDH) near plane strain and thus is used as a formability index. The standard width used in the industry is 133mm. The disadvantages of this test are that it gives scattered results on various machines and tooling. Further, stable plane strain conditions are not achieved in this test due to the axisymmetric tooling. In OSU (Ohio State University) test there is no axisymmetric tooling of punch diameter of 25.4 mm thus giving stable plane strain conditions. In this test, 5 sheets are used of width 124mm and length 178mm and results are averaged. This test also defines formability index at the height at which failure occurs. OSU test is said to be 6 times faster than the LDH test.

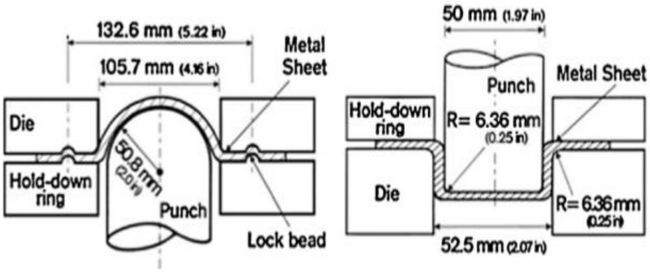

Fig.3: Sketch of the limit dome height test on the left [13], and the sketch of swift cup test on the right [14]

3. Anisotropy and Formability

Till the 1980s the yield criterion for materials did not have the required anisotropic coefficients that these criterions were not much accurate. Hills provided the useful yield criteria for anisotropic materials in 1948 and it was the only one to have some applicability in a number of stress cases.

The isotropic yield conditions for various metals were given by $_i$) and deviatoric stress (Sj) tensors.

$$\phi = |\sigma_1 - \sigma_2|^a + |\sigma_2 - \sigma_3|^a + |\sigma_3 - \sigma_1|^a = |S_1 - S_2|^a + |S_2 - S_3|^a + |S_3 - S_1|^a = 2\underline{\sigma}^2 \qquad (3)$$

$_1$, $_2$, $_3$ are the principal stresses, $\underline{\sigma}$ is the effective stress.

For a=2 and a=4 the equation becomes the Von mises criterion for a=1 and for the limiting case of $a \to \infty$ the equation becomes

For isotropic materials the yield criterions are independent of the reference frames. But for anisotropic materials yield properties are directional and thus the yielding criterion is independent on the reference frame. Thus, Hill extended the Von Mises criteria [16] to orthotropic materials (which exhibit orthotropic symmetry) $\phi = F\left(\sigma_{yy} - \sigma_{zz}\right)^2 + G\left(\sigma_{zz} - \sigma_{xx}\right)^2 + H\left(\sigma_{xx} - \sigma_{yy}\right)^2 + 2\left(L\sigma^2{}_{yz} + M\sigma^2{}_{zx} + N\sigma^2{}_{xy}\right) = \underline{\sigma}^2$ (4)

Here, F, L, G, H, M, N are material-based constants. This yield criteria provided accounts for planar anisotropy which is obtained from the equation (5)

$$r_0 = \frac{r_0 + 2.r_{45} + r_{90}}{4} \qquad (5)$$

These values of r are determined by uniaxial tension tests and then cutting the sheet metal along three directions in the plane of the sheet at 0°, 45° and 90°.

Lankford et. Al [17] introduced the term strain ratio, or as it is commonly called as the plastic anisotropy r-value and used this to represent the drawability of different sheet metals.it is also seen in some researches that the limiting draw ratio in simulative tests is quite closely related to the average r-value. Thus r-value of anisotropy has been quite extensively used as a parameter for the drawability of sheet metals [17].

4. Formability and Strain Rates

Hecker [18] proposed that strain-hardening index (eqn. 6) was not alone responsible for the prediction of fracture height in Olsen test and thus strain-rate sensitivity index also has to be taken into consideration. Thus, it was seen that for a given strain-hardening index (n), higher the strain-rate sensitivity index (m), the material will yield a larger cup height, therefore, indicating an increase in formability of the sheet metal [19]. Hence, for a given value of n steel has more formability than aluminum since it has higher strain-rate sensitivity index

$$m = \frac{\partial ln ln\, \sigma}{\partial \dot{\varepsilon}} \qquad (6)$$

It is seen that formability increases with high speed due to the reasons such as constitutive behavior, inertial effect and die impact effect. Also, some materials show increase in ductility and low stress too. Strain rate effects also play a role in increased formability due to high-velocity [20]. Due to inertial aid, there is a change observed in the necking region which causes the increase in formability of sheet metal [21]. Dariani et al. [20] conducted a study on FLDs of Al 6066-76 & AISI 1045 sheets at various deformation velocities int the explosive forming process and found that formability increased by 53.8% by impact and 146.1% by explosive forming. Gerdooei & Dariani [22] analyzed the formability of metal sheet at varying strains (from 0.001 to 100/s) and their effects were shown on the critical plane strain (FLD$_0$).

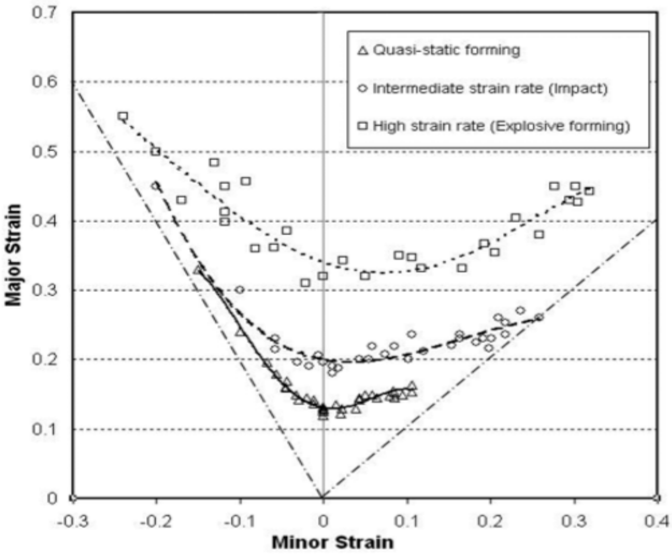

Fig. 4: FLDs of Al 6061-T6 sheet under various strain rates

5. Formability in Tailor Welded Blanks

As we are seeing, there is a worldwide trend of trying and achieving low weight, high density, high strength materials with high formability in industries such as automotive and electrical applications. Therefore, the use of Tailor Welded Blanks (TWBs) have increased tremendously as this process allows materials of varying thickness, properties or surface conditions in a single pressed or stamped part [23]. The parts produced by this process have joints of high strength and high reliability. In making Tailor Welded Blanks, 99.9% of the times either CO_2 or Nd: YAG laser welding is used [24]. But theses welding processes affect the formability of the sheet metal or the end product too. Mustafa A. Ahmetoglu et. Al [25] concluded in their study that in case of TWBs failure in deep drawing usually occurs at the flat bottom of the punch parallel to the weld line and this happens due to the non-uniform distribution of the deformation. According to Hisashi Kusuda et. al. [26], in automotive sector, TWBs are used in making three different parts- 1. Side panel, outer 2. Door, inner 3. Front side inner and the formability problems seen in these three respectively are split in stretch flanging, stress concentration in thin plate and insufficient ductility of weld bead. Thus, by considering these 2 studies, a point is very clear that there is a constant need of new formability data for the TWBs to control the failure of the formed parts. Saunders et. al. [27] conducted four different formability tests on the Tailor Welded Blanks by using two base materials, first, 1.8 mm Aluminum- Killed Drawing Quality (ASDQ) steel and second, 2.1 mm High Strength Low Alloy Steel (HSLA) and concluded that two modes of failures were occurring. Type 1 failure occurred when the principal stretch axis lied parallel to the weld and fracture depended on the ductility. Type 2 failure was the dominant forming failure which was not affected by welding operations. Their study further concluded that weld-line displacement is also an important parameter of formability in TWBs.

6. Future scope in formability analysis of sheet metal forming

At the present stage, different FLC models have different advantages to offer and at the same time their inherent limitations also. So, the future of FLCs would be to develop new models that can increase their advantages and at the same time suppressing their limitations. As seen in the discussion of strain rates it is evident that formability of metals improves with high velocities to a great extent. This has led to researchers focus on techniques of high velocity forming as seen in processes like Explosive forming, Electromagnetic Forming, etc. Some non-conventional testing methods are also emerging nowadays such as Continuous Bending under Tension (CBT) test which generates cyclic stretch bending [28]. Tube Extension tests are also been put to use for the study of formability of sheet metals. Also tube forming is nowadays used in automotive radiator closure also and the advantage lies in the fact that this process has fewer components than the conventional process and stiffness of the parts are also significantly increased. Hydroforming is also one of the new techniques used for tubular products and enables testing under bi-axial stress state. Further techniques such as Incremental Forming are also gaining momentum because this process uses universal tooling and thus increases the flexibility of the forming method. Further, materials at very high temperatures are also formed by various sheet metal processes and the formability calculated under such circumstances is of utmost importance. So, formability analysis of such new techniques is also needed to ensure that there is reduction in costs and low scrap is generated and the forming methods could be used to different set of materials. So, at present the main focus of researchers and engineers should be on developing a more sophisticated testing equipment so that a single test ensures procurement of maximum possible information of formability of the sheet metal. Also, new modelling techniques and numerical analyses should also be developed which strengthen the theoretical concept of FLDs and can confine a lot more forming parameters and their consequent effects. Further, advancements in the field of new materials should also be looked forward to, as the new materials open new horizons of high strength and lightweight application and thus can be beneficial to the industry. And this can further increase the profits of the organizations.

7. Conclusions

This paper tries to give an insight to the reader about the importance of sheet metal forming methods and how formability analysis is an integral aspect of it. The paper gives a brief overview of the various tests involved in getting quantifiable data on formability and to get the forming limits above which the failure occurs. There has been a lot of advancements in formability over the past four decades and still the research continues in search of new materials, comprehensive testing methods & equipment and mathematical analyses of the yielding criterion considering a lot more parameter and their effects on formability. So, this paper has been an attempt to study the basic nature of formability and its importance in the industry of today.

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