Mini Review

A Short Review on Forming Limit Curve

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Abstract

In sheet metal forming process the sheet metal is characterized such that it provides the deformation limit in a variety of deformation mode. The line joining those limits at various deformation modes is called as forming limit curve. This curve is considered as a tool to design or modify dies so that the material should not reach the failure and a safe product can be created. In this short review, the forming limit curves, and some basics are covered. In addition, different common forming methods, typical material used, methods to obtain forming limit curve, dependence of strain path and remedy, and pressurization effect.

1.Introduction

1.1. Sheet metal forming processes

The forming of metal is a very useful process that allows for creation of different parts or useful shapes of metals through various processes. The first of these processes is Bending. Bending is when a force is applied to a sheet of metal to bend it at an angle along a line [1,2]. This is typically used if the metal needs to be formed at an angle to meet a certain design. The second process is Roll forming. This forming process progressivly shapes the metal by putting it through several roll stations to gradually shape the metal as it goes through each roll station. These stations may have a unique combination of rollers and dies or they may have several different forms. This is typically used to form channels or beams that need the metal in a shape that is consistent along the length [3-5]. The third process is spin forming. This process is achieved by spinning a piece of sheet metal while applying force with a roller tool to have the metal take the form of a mandrel that is the base. And is used for shapes that are typically uniform around an axis [6]. The fourth process is Deep drawing. This process is achieved by putting the metal between a die and a blank holder. Both parts have a hole in them to allow for a punch to be pushed through and force the metal to take the shape of the die. This process is typically used to form shapes such as cans or other shapes where a hollow inside is needed [7]. The last common forming process is stretch forming. This forming process is achieved by attaching a piece of metal in two gripping jaws. A die is then positioned beneath the sheet metal and is then pushed up as the gripping jaws are pulled down in order to form the sheet metal. This is used for process that need to have a specific form or design on them [8,9].

1.2. Typical metals

The metals that these processes typically use are all types of steels including stainless steels and advanced high strength steels, all types of aluminum alloy, magnesium alloy, copper, brass, and titanium. These metals are typically used due to their ductility and allow for better formability. Some common applications made from these metals are pans, cups, cans, oil tanks, car body-in-white parts, etc.

2.Forming Limit Diagram

While the sheet metal forming processes are very useful there are many challenges that can occur. One of these challenges is the material failure or fracture. This happens if the material is subjected to a lot of strain that will cause necking. Once the material starts to neck it no longer holds any value as what it was formed into as it now has a much thinner area that may have already fractured from the strain that it has received. To counteract this, a tool called a Forming Limit Curve (FLC) is used to identify the amount of strain that will cause the material to fail [10,11]. This is done by where the strain has occurred. This graph has two axes, the horizontal axis is the minor strain the material receives, and the vertical axis is the major strain the axis has received. When the amount of major strain crosses the FLC the material has failed, however if the strain doesn't cross the FLC then the part is safe. Figure 1 shows the forming limit curve.
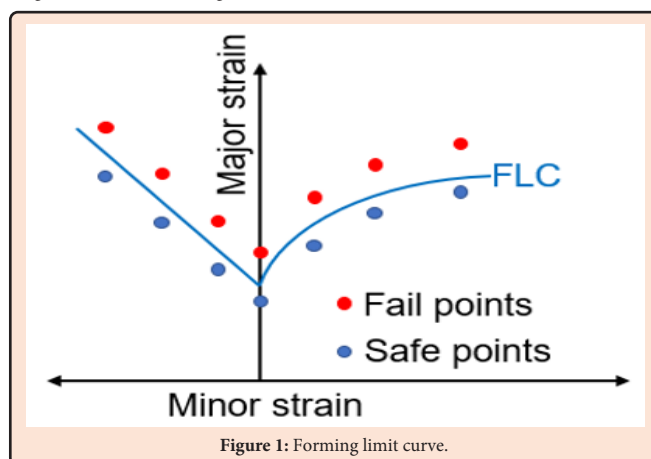

Figure 1: Forming limit curve.

3. Tests to Determine Forming Limit Curve

To determine the forming limit curves there are several tests that can be performed in order to find the forming limit curve of any metal. The first test is the Nakazima test. This test is the standard test used by most journals and in professional settings. This test involves the etching of small circles onto the metal and then inserting it into a punch die. The punch die is then activated and stretches the metal until it fractures to determine the fail point of the metal. This is done with several stretch tests until the entire diagram is formed. Figure 2 shows the sheet metal specimen geometries to capture the limits from uniaxial to equi-biaxial strain modes and Nakazima test set-up [12,13]. The next test is the biaxial test. This test uses a biaxial testing sample as a cruciform shape that has also has circle, square or diamond center. The advantage of this testing is that a single specimen geometry can be used to capture the range of limit strain, and it doesn't have any friction from the rigid surface where the limit strains are measure (i.e., at the specimen center). The sample is then mounted on horizontal and vertical axis and these axes can pull the specimen at different rates. This test while less common as it is newer, however it is more accurate due to absence of friction [12,13]. Figure 3 shows the cruciform specimen with diamond center and biaxial machine at Penn State Behrend funded by National Science Foundation.
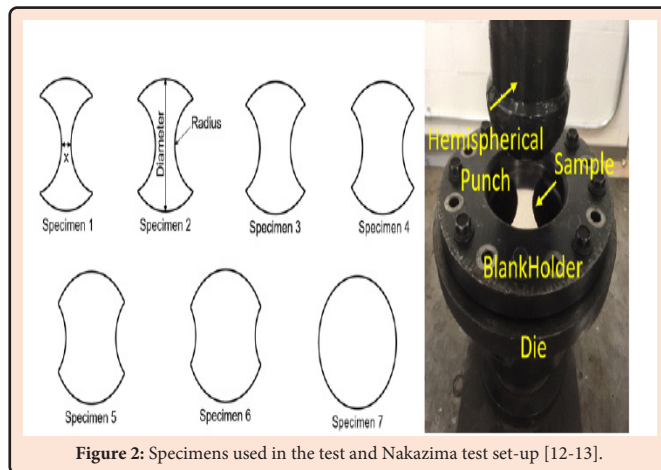

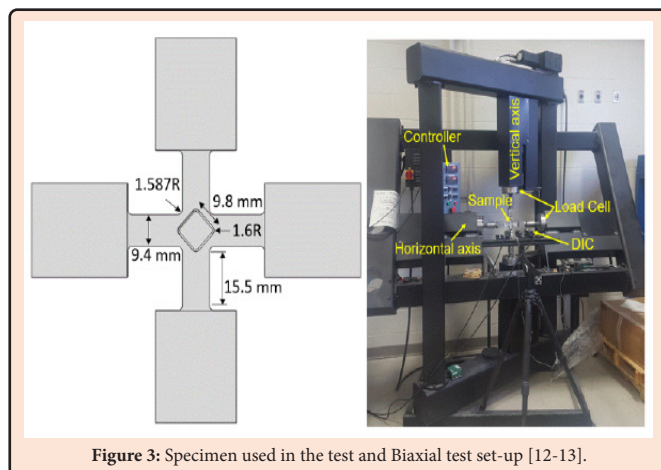**Figure 2:** Specimens used in the test and Nakazima test set-up [12-13].

Figure 3: Specimen used in the test and Biaxial test set-up [12-13].

3.1 Strain based FLC

The strain path effect on FLCs is typically seen when the material must go through multiple runs through the forming methods as a single run to the final shape may cause the failure. However, for each pre-strain a new FLC is required to generate, as the FLC shift after pre-strain Figure 4a. If the pre-strain is towards uniaxial strain the pre-strain FLC rises and if the pre-strain is towards equi-biaxial the FLC drops. This is called pre-strain effect on FLC. The strain based FLC depends on the pre-strain and thus large resource is needed to generate each individual pre-strain FLCs [14].

3.2 Stress based FLC

While FLC is useful in the previous form shown they do have the major downside that it largely depends on the pre-strain value. To counter this effect the stress based FLC was adapted. This is the plot between major and minor stress of a critical region in various deformation modes as shown in Figure 4b. When no pre-strain and pre-strain strain based FLCs converted in stress space, the all curves coincide to each other and proved that the stress based FLC ignores the pre-strain deformation mode. The same failure criteria are apparent in the original FLC with the area below the line being the area where it is safe and above the line being where failure will occur [15].
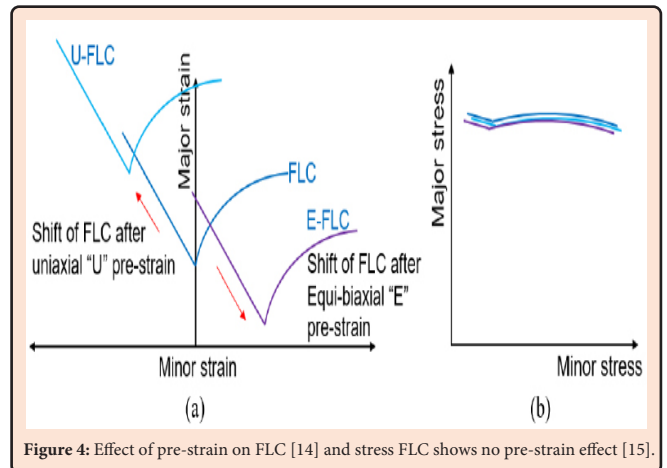

Figure 4: Effect of pre-strain on FLC [14] and stress FLC shows no pre-strain effect [15].

3.3 Pressurization effect

Pressurization effect occurs when the rigid tool pushes or applies a pressure on a certain region of a material to deform it. In the Nakazima test, the hemispherical punch presses the sheet metal to deform to a geometry which does have a similarity with the processes happens during stamping process in the sheet metal industry, the punch presses the sheet metal towards the die. Due to the similarity in the testing method to obtain FLC and the stamping method, the FLC was never questioned as it always matched the testing. However, when the FLC created from the newly developed biaxial method, the FLC is lower than the Nakajima test as shown in (Figure 5). If this FLC would have been used to design the process, the sheet metal would not have been used to its optimal forming and thus safety factor would be higher than required and it would increase the weight of the same part as compared to part deformed by considering FLC generated by Nakazima test. Due to the differences in the limits from Nakazima test and biaxial test, it can be noted that the Nakazima test FLC does have the pressurization effect where the materials failure is delayed by suppressing the voids. Whereas the FLC by biaxial test can be considered as pure material limits [12,13].
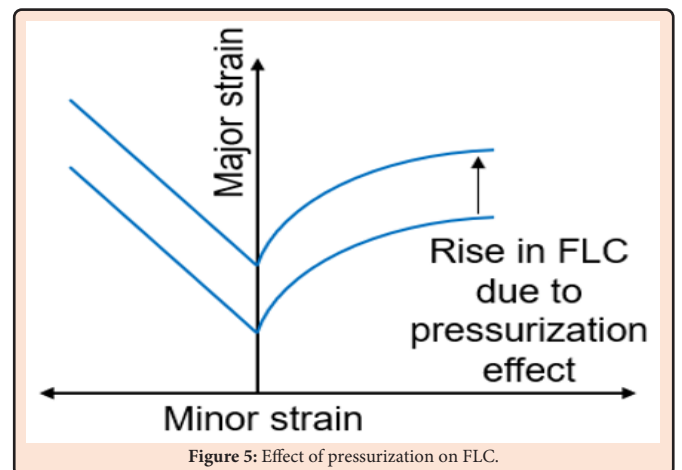

Figure 5: Effect of pressurization on FLC.

4.Conclusion

The Forming Limit Curve is an important tool in sheet metal forming processes. This provides the capability to access the safe strains and a limit during a forming process. The common forming processes and material used in sheet metal forming are discussed. To characterize the material limit strain, the Nakazima and Biaxial tests were discussed. The conventional method i.e., Nakazima provided a strain based forming limit curve which is a plot between major and minor strain. It was noted that the strain based forming limit curve depends on the strain or deformation path and changing the deformation path changes the forming limit curve for the next forming stage i.e., FLC depends on pre-strain and deformation path. To reduce the tardiness on generating strain based FLC at different pre-strain values, the stress based FLC was proposed which found independent of strain path and a single curve can be used to predict the failure. On comparing the forming limit curve from Nakazima test and biaxial test, it was concluded that the pressurization effect occurs in Nakazima test and delays the failure which shows higher limits as compared to the biaxial tests. This effect was not realized as the conventional stamping was replica of Nakazima test i.e., solid punch pushes the sheet metal. Thus, the forming limit curve from biaxial test can be considered as pure material limit curve.

Acknowledgement

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