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***Research Article***

# ALTERNATIVE NUMERICAL SIMULATION APPROACH FOR OBTAINING FLC/FLD

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## ABSTRACT

To be able to predict the forming behavior of sheet metal parts by simulation, it is necessary to determine the FLD[1] (Forming Limit Diagram) curves of the sheet material that is subjected to bending, hemming, deep drawing, progressive forming, embossing, hydro-forming processes. To determine such curves, the usual practice is to carry out a series of experiments that need to be repeated many times, and therefore it takes a long time to finalize them [1], [2], [3], [4], [5], [6]. Not to mention undertaken experiments are very detailed and need tedious and careful work has to be done such as screen printing on the material and doing simultaneous optical measurements during the experiments. Indeed, a fully equipped laboratory and qualified lab personnel are required for such experiments which may not be easily found. When it's found, there is usually six months to a year, queue to conduct such experiments.

Because of these difficulties, many academic institutions and manufacturing sites develop their in-house test equipment if funding is available. If not, it is dependent on research whether it comes to an end or whether it can continue without it.

An alternative method developed for extracting FLD/FLC curves is using today's state-of-the-art simulation technology. This method requires two main inputs;

a) Tensile test of the material
b) An explicit solver

The scope of this paper is to detail this method such that the findings in this document can be reproduced when the mentioned requirements are satisfied. Therefore, all data used in charts, a high-resolution image, and a sample Abaqus input file are provided as supplemental data [7].

The results from the simulations of FLD/FLC were compared to published literature [13] [14] to confirm their compliance with experiments. The comparison showed good results and demonstrates that expensive and time-consuming FLD/FLC experiments are not necessary when the mentioned requirements are met.

**Keywords:** FLD, FLC, Sheet Metal, Forming, Bending, Hemming, Forming Limit Diagram, Forming Limit Curve

## 1. INTRODUCTION

FLD/FLC curves of the sheet metal that will be subjected to any forming process should be determined for the necking and/or cracks that may occur during the forming process in numerical analysis/simulations. To do that, it is necessary to carry out a series of experiments those need to be repeated many times and take a long time. Detailed and very careful work should be carried out, which includes screen printing on the material and using optical measuring devices during the experiment [1]. It may be because this should have been done in the Covid-19 pandemic timeline; there was no single laboratory that can perform this experiment in Turkey. To find the FLD curves of the materials, there were three options;

a) Developing the necessary experimental equipment in-house.
b) Because of the force major (Pandemic), this requirement will be ignored and surpassed.
c) Some other practical and versatile alternatives should be developed.

Fortunately, as a result of a long investigation, research, [8]-[11] and trial and error, it is discovered that extracting the FLD curve of materials is possible with a quasi-static explicit solver and tensile test results of the material.

This paper details how these curves were obtained in such a way that the reader should need no other than the requirements, references, and method stated in this paper. Also, since it took one and a half months man-hour time to find the right method for a similar need, using the information and data provided in this article can at least save that much research time for the reader.

[1] Also known as FLC (Forming Limit Curve)

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## 2. STRESS-STRAIN CURVE

The stress-strain curve obtained as a result of the tensile tests performed on the material (according to [8]) in determining the basic mechanical elastic-plastic material model properties gives us the most basic information at room temperature. All the tensile test specimens are prepared 90º in Rolling Direction, which is known to be the weakest material direction for tensile tests.

**Ramberg-Osgood Equation**

The stress-strain curve of the material can be obtained as a result of multiple tensile tests. As an alternative method, if the elasticity (Young) modulus, stress, and strain values at the yield and ultimate points of the material are known, the stress-strain curve of the material can be established with the “Ramberg-Osgood” relation [9]. The “Ramberg-Osgood” relation tries to simulate the behavior of the material in both the elastic and plastic regions. The total strain relation on both regions as a function of stress can be expressed as;

$$\varepsilon = \frac{\sigma}{E} + 0.002\left(\frac{\sigma}{\sigma_y}\right)^{1/n} \tag{1}$$

Where, ε strain, σ stress, E elasticity modulus, $\sigma_y$ tensile yield stress and n known as strain hardening exponent of material which can be obtained from;

$$n = \frac{\log\left(\sigma_u/\sigma_y\right)}{\log\left(\varepsilon_f/0.002\right)} \tag{2}$$

Where, $\sigma_u$is the ultimate stress value of the material and $\varepsilon_f$ is known as plastic strain and can be calculated from;

$$\varepsilon_f = \varepsilon_u - \frac{\sigma_u}{E} \tag{3}$$

Where, $\varepsilon_u$ is the ultimate strain value of the material.

All the above-mentioned values ($\sigma_u$, $\sigma_y$, E and $\varepsilon_u$) can be either obtained from material tables or derived from material tensile test results. As an example for Aluminum 6061-T6 material, the convergence of “Ramberg-Osgood” & tensile test results can be compared as follows;

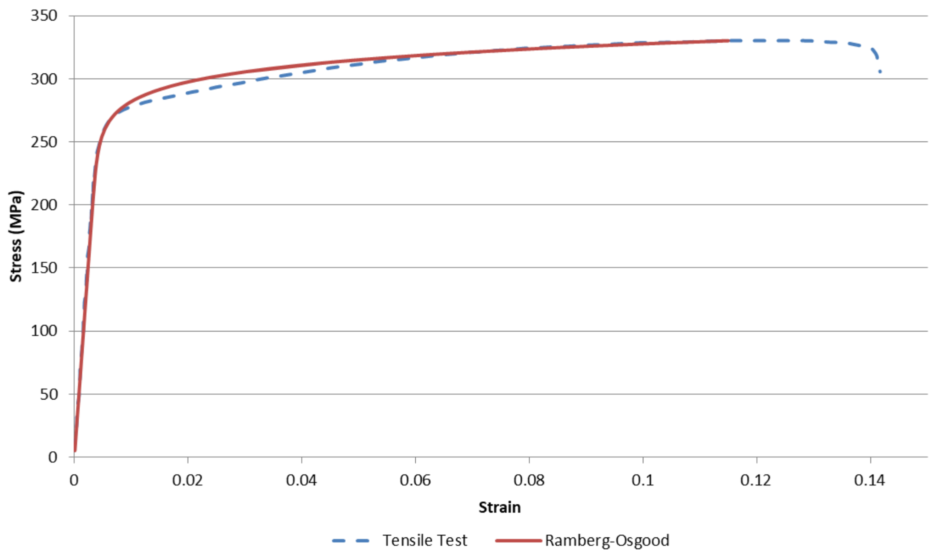


**Figure 1.** Comparison of Ramberg-Osgood Equation and tensile test results

As can be seen from

Figure **1**, although the Ramberg-Osgood relation converges quite well to the tensile test in the elastic and near-tensile plastic region, it can produce results that diverge significantly, at least for aluminum material, right after the elastic region. Therefore, directly using tensile test results for the simulation will produce more reliable and realistic results.

## 3. TRUE STRESS – STRAIN CURVE

The stress-strain curve obtained as a result of the tensile tests is called the engineering stress-strain curve. However, simulation software such as Finite Elements uses the "True" stress-strain curve, which takes into account the change in the cross-sectional area of the specimen during the tensile test.

The relationship between the Engineering and True Stress-Strain curve is defined [10] by the following formulas;

$$\sigma_t = \sigma_e(1 + \varepsilon) \tag{4}$$

$$\epsilon = \ln(1 + \varepsilon) \tag{5}$$

Where, $\sigma_t$ and $\epsilon$ are true stress and strain, and $\sigma_e$ and $\varepsilon$ are engineering stress and strain values.

Accordingly, the engineering and true stress-strain curves of an experiment performed on Aluminum 6061-T6 material are as follows;

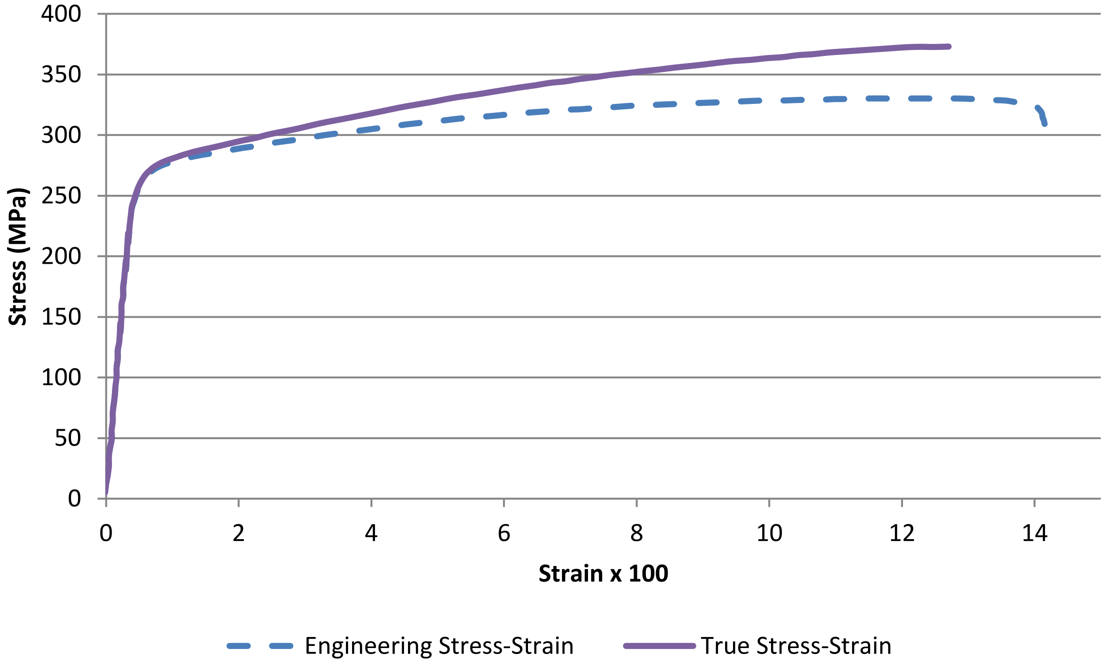


**Figure 2.** Comparison of engineering and true stress-strain curves of AL6061-T6

Engineering curves obtained as a result of tensile tests were converted into true curves which are used in all simulation studies.

## 4. OBTAINING FLD/FLC CURVE OF A MATERIAL

There are many sources, such as reference [1], describing how the Forming Limit Diagram (FLD) is experimentally derived. There are [2], [3], [4], [5] and [6] standards related to the derivation of this curve, and among these standards, the "Nakajima" test defined in the standard [3] was used as the base reference in finding the FLD curves in this document. The mold geometry definition for the Nakajima test is as shown in the following Figure 3;

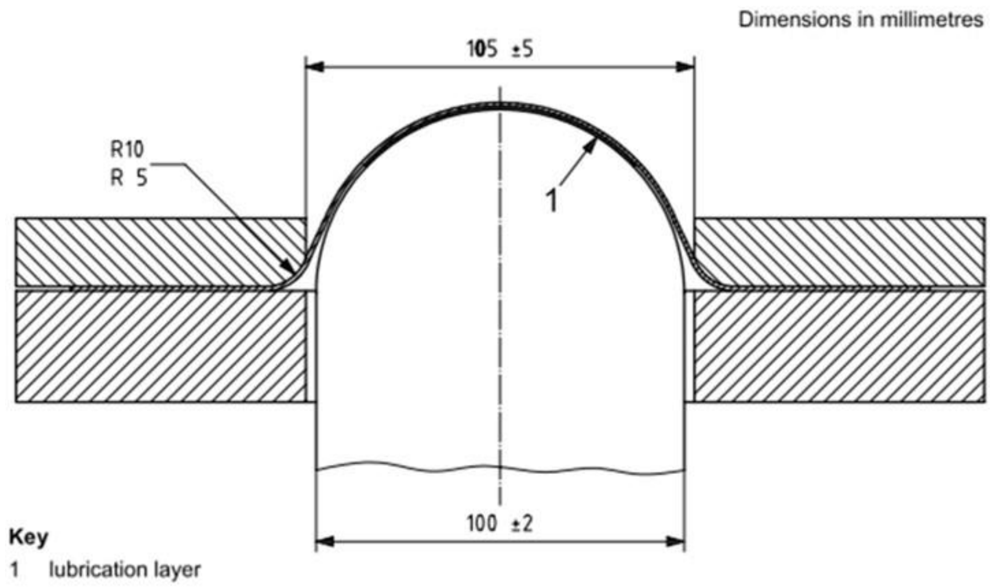


**Figure 3.** Die cross-section used in Nakajima Test

In standard [3], PTFE material is used as the sliding surface, and therefore, the dynamic friction coefficient is assumed to be 0.15 for both aluminum and steel parts. It is also one of the conclusions of reference [11] that such an assumption will produce correct results.

According to the standard, the speed of the punch should be 1.5 mm/s. The friction coefficients were accepted as shown in the following Table 1;

**Table 1.** Friction coefficients

| | Steel-Steel | Steel-Aluminum | Aluminum-Aluminum |
|---|---|---|---|
| **Static** | 0.8 | 0.45 | 1.35 |
| **Dynamic** | 0.42 | 0.47 | 1.4 |

To achieve different stress-strain states, separate geometries are used to find each point on the FLD curve. The sample sheet metal part geometries that can be selected by the Nakajima test are as Shown in the following Figure 4;

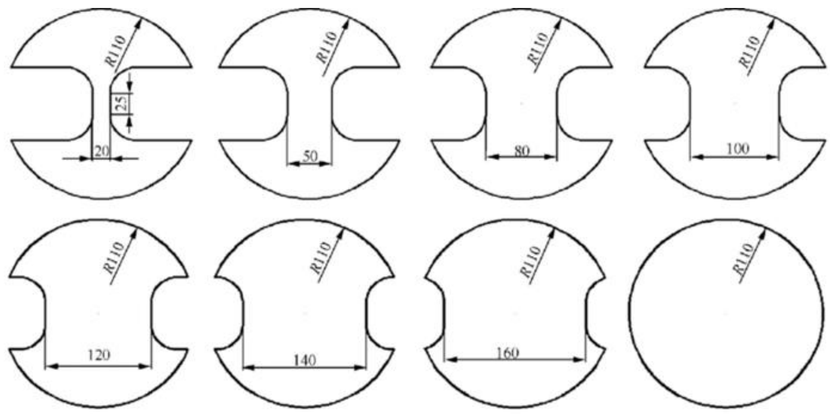


**Figure 4.** Part geometries

The properties of the following materials were used in the simulation studies to create FLD curves for three different materials are shown in the following Table 2;

**Table 2.** Main material properties

| | AL 6061-T6 | AL 6016-T4 | CR180BH |
|---|---|---|---|
| **Density (g/cm3)** | 2.70 | 2.70 | 7.00 |
| **Elasticity Modulus (GPa)** | 62.50 | 66.00 | 209.70 |
| **Poisson's Ratio** | 0.33 | 0.33 | 0.30 |

Above in

Figure **2**, the true stress-strain curve of AL6061-T6 material is given. Likewise, the true stress-strain curve for both AL6016-T4 and CR180BH materials is given below in the following Figure 5 and Figure 6. In simulation studies, the true stress-strain values used in the plastic region with a negative offset in strain such that strain at the yield point is accepted as its 0 (zero) value.

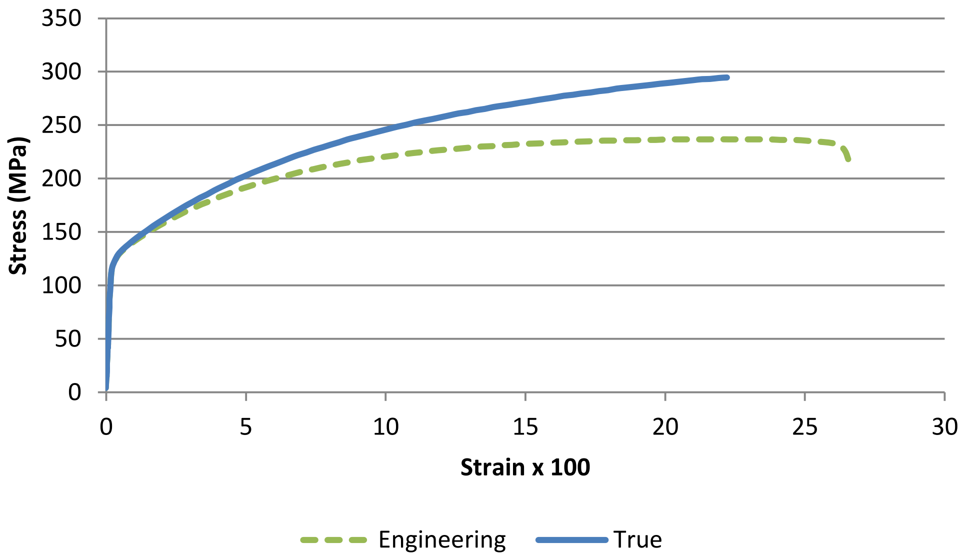


**Figure 5.** Comparison of engineering and true stress-strain curves of AL6016-T4

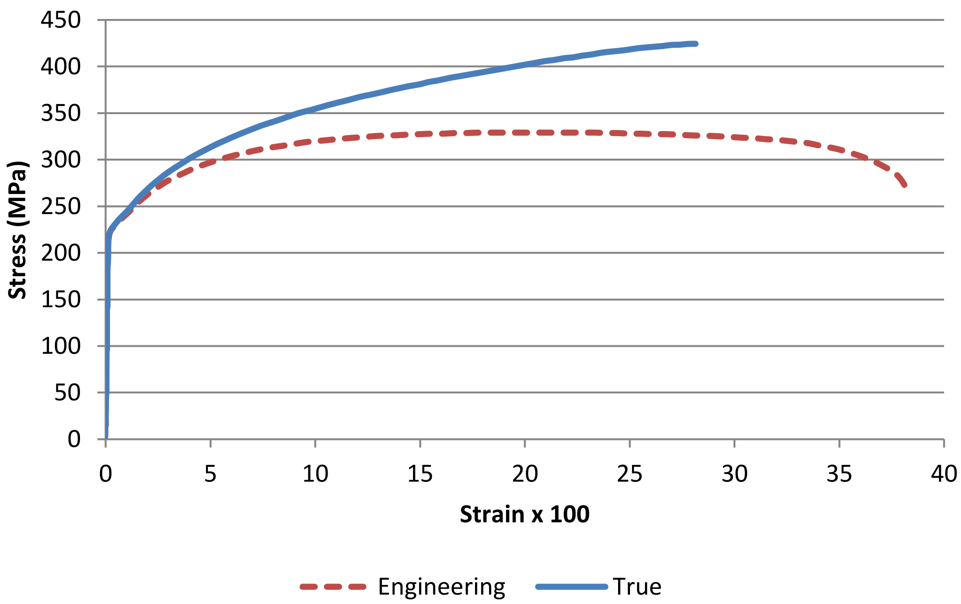


**Figure 6.** Comparison of engineering and true stress-strain curves of CR180BH

## 5. DETERMINATION OF MINOR AND MAJOR STRAINS

In physical tests, major and minor strains occurring immediately at the crack initiation are taken into account. Only a single major and a single minor strain point can be extracted from each test done on different geometry. It is known that the minor and major strains at the crack initiation are the ones that we are seeking after.

To detect the crack initiation, the reaction force graph in real experiments was examined in finding the FLD curve. The point where the counter force applied to the system by the geometry (reaction force) peaks and starts to decrease is accepted as the beginning of crack initiation and the plastic major and minor strains at this point are determined [11]. By using this method, it was observed that the obtained minor-major strain curve did not produce realistic results, especially for the positive minor strain values which are near 0 (zero).

Instead, it has been discovered that realistic results could be achieved in the FLD inference made by considering the starting points of the sudden change in the major-minor strain values on the FEM element that has the utmost deformation (
Figure **7**).

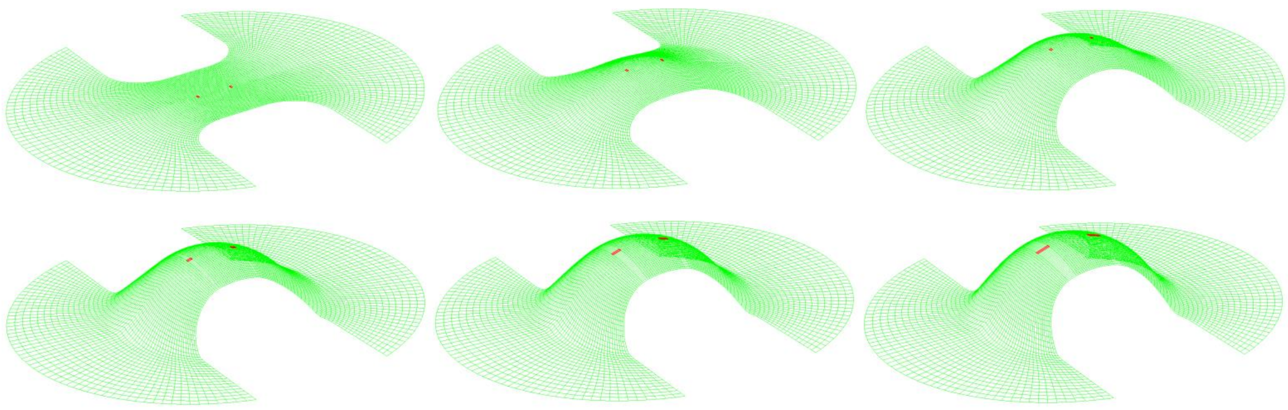

**Figure 7.** FEM element shown as red is subject to the utmost deformation on the Nakajima FEM test simulation

On above mentioned the most deformed FEM element of the test specimen, major & minor strain values are obtained, and their change is plotted as shown in Figure 8. Below, it has been tried to show where these crucial sudden changes or also known as fracture points are in the graph;

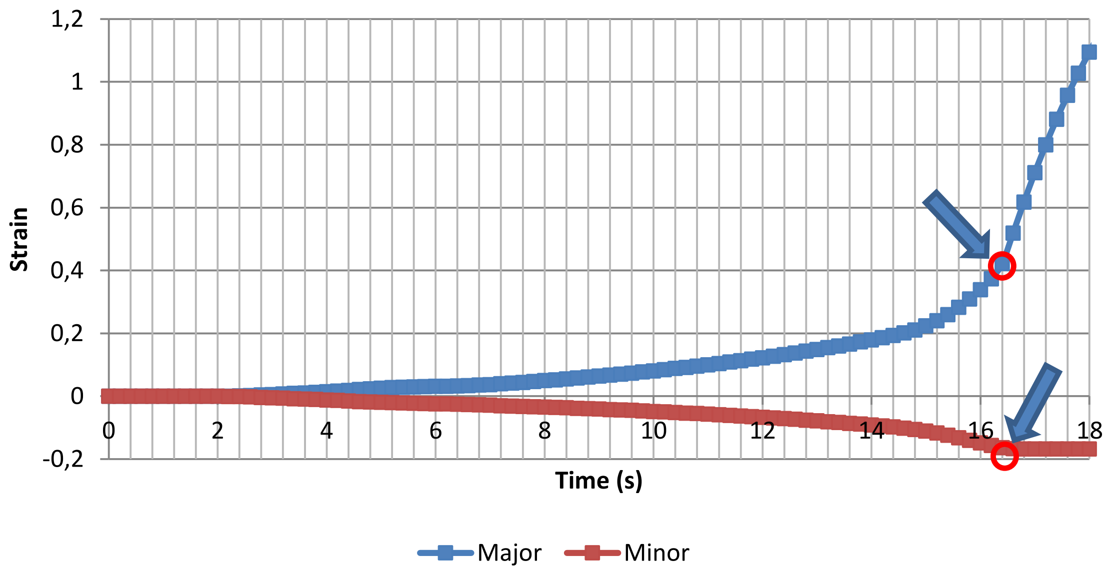


**Figure 8.** Major-minor plastic strain change graph at the integration point of the finite element exposed to the maximum deformation and the points where the values taken for the FLD curve are shown in this graph.

The points found in the above approach can also be perceived as values that occur at the beginning of the maximum tangent on the major strain curve and the beginning of the minimum tangent on the minor strain curve.

It is later found that the method introduced in this paper is almost identical to [12] which proposes the maximum strain acceleration at the most strained locations as the fracture indicator.

## 6. FLD/FLC CURVES

In a nutshell, the forming limit curves are determined through applying strains to metal samples in tests until a crack appears. Samples are marked with a grid pattern and the strains are calculated based on the measurement of the grid before and after deformation. The FLD is generated from the calculated major and minor strains for different strain states.

Tensile test and FLD/FLC simulation studies are conveyed on three different sheet metal materials in the scope of this report. These are;

- Aluminum 6061-T6
- Aluminum 6016-T4
- CR180BH

Their corresponding simulation results shown in the following Figure 9, Figure 10, and Figure 11 respectively;

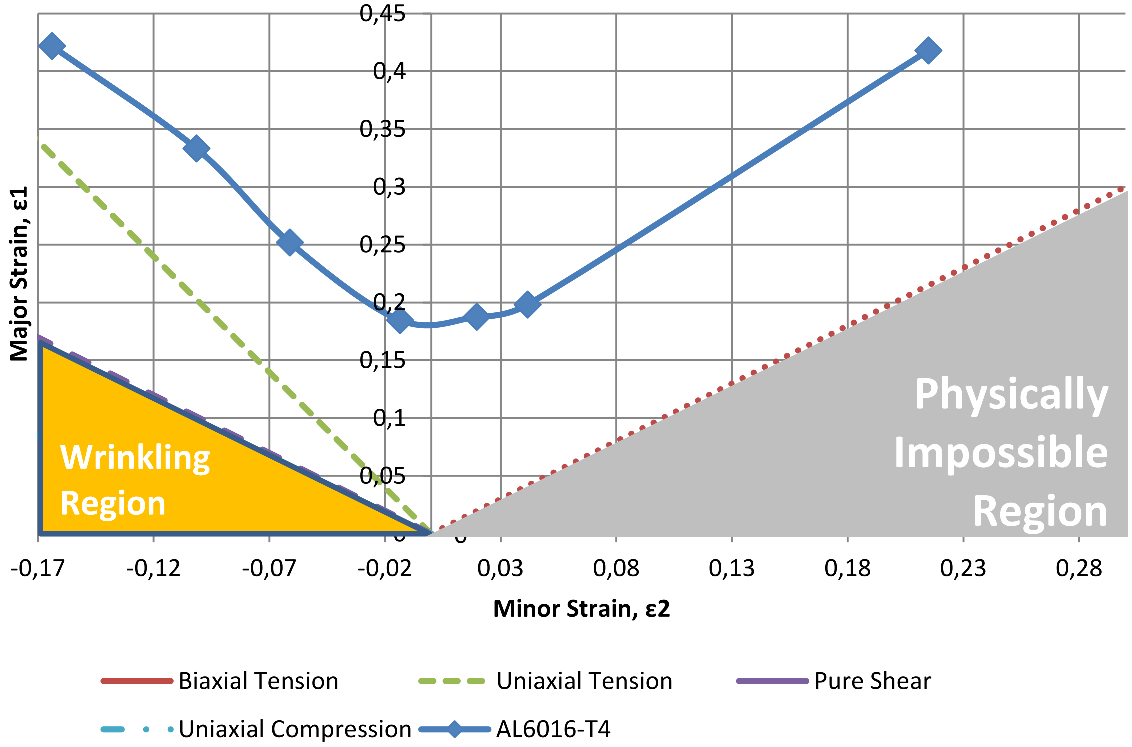


**Figure 9.** FLD Curve of AL6016-T4 sheet-metal material as a result of numerical simulations

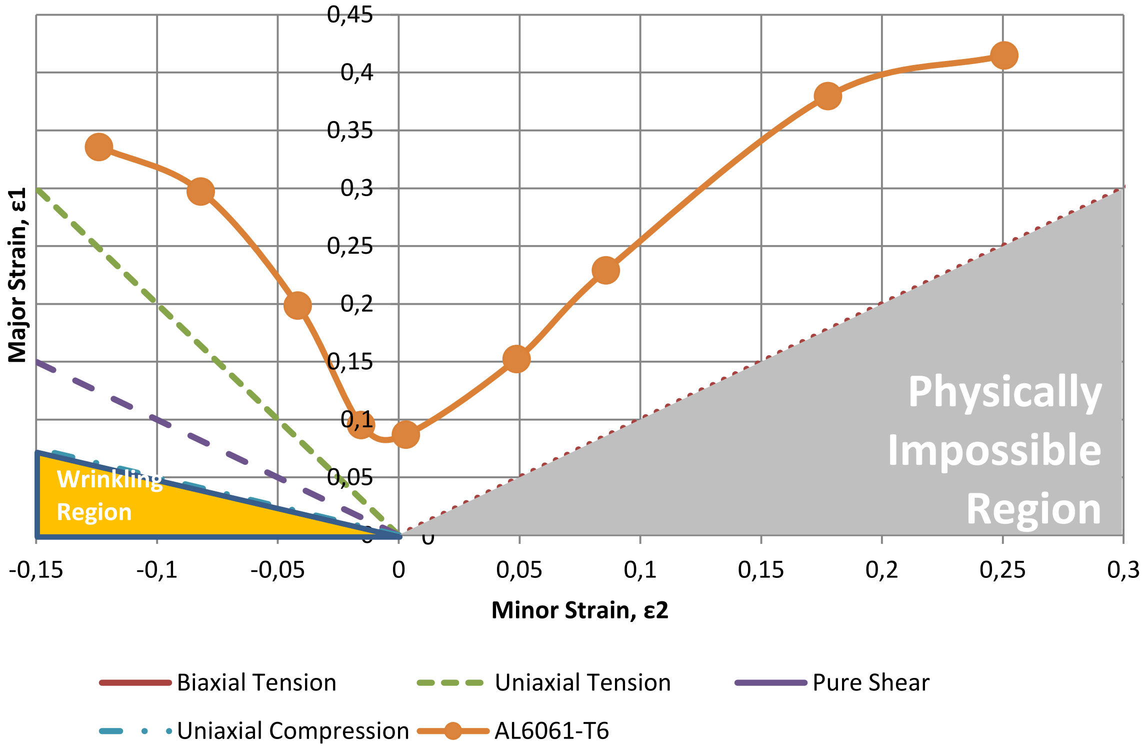


**Figure 10.** FLD Curve of AL6061-T6 sheet-metal material as a result of numerical simulations

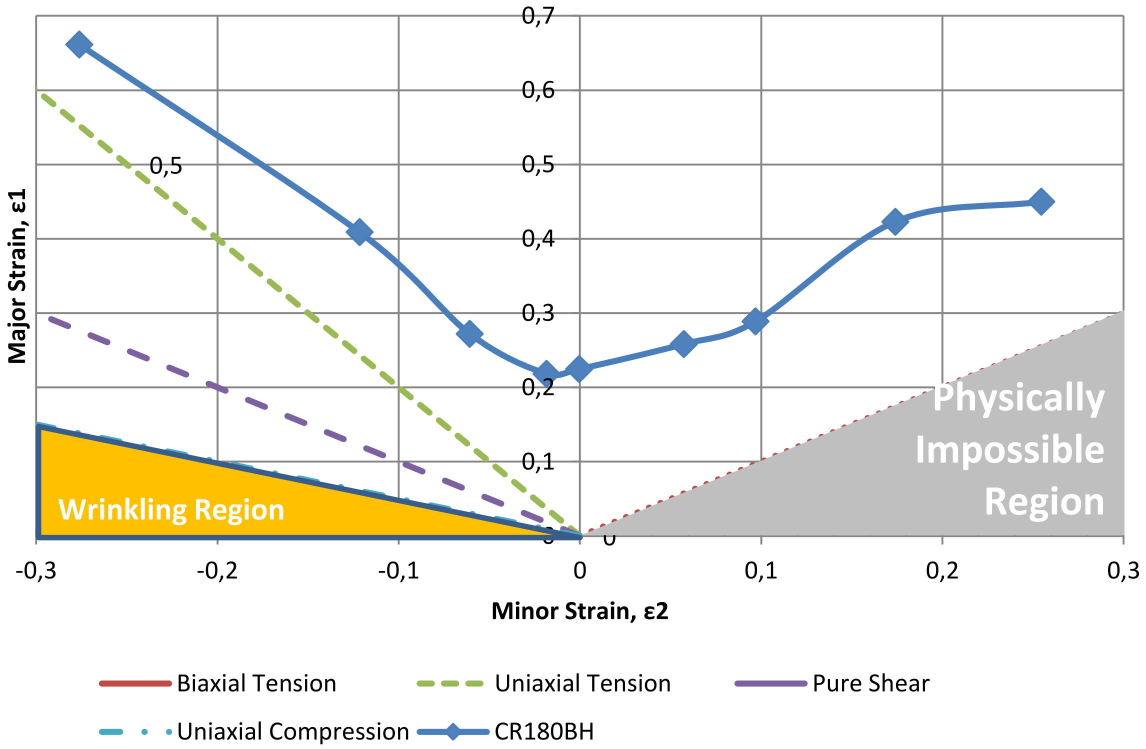


**Figure 11.** FLD Curve of CR180BH sheet-metal material as a result of numerical simulations

## 7. CONCLUSION

The FLD curve results obtained are quite satisfactory as they are similar to the results found in internet resources for the materials CR180BH [13] and AL6061-T6 [14].

The curves found for the detection and comparison of crack regions during sheet-metal forming processes can be used in physical testing, in comparison of simulation studies, and, if necessary, in simulation convergence studies with the test results.

The outcome of this study should not be considered as the total replacement of the very tedious and expensive physical test method of finding FLD/FLC curves but can be considered as the economical alternative method instead. This outcome is an important achievement by itself, not to mention alternative physical methods may be out of the scope of most SMEs world-wide if such input curves are required for the extended studies.

## SIMILARTY RATE: 2 %

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