Design of A Specific MatLab Code for Processing of Standard Tensile Test Data for Sheet Metal Forming Simulations

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ABSTRACT

In order to obtain proper and sufficiently precise results from metal forming simulations, accurate material data should be input to the simulation software. One of the most important input for the simulation software is the flow curve (yield curve) of the material. Although there are many tests which could be performed in order to construct the flow curve such as standard tensile test, hydraulic bulge test, frictionless dome test, etc., standard tensile test is the simplest and cheapest technique despite of its technical restrictions.

In this article, the studies regarding to the creation of a specific MatLab code for processing of tensile test data are presented. This specific MatLab code is capable of determining the constants of Hollomon's, Ludwig's, Swift's and Voce's hardening equations with their regression results, as well. By means of this code, the proper flow curve of any material and also the Lankford parameters could be obtained and the hardening equations which fits best to the experimental data could be determined.

Key Words:
Tensile Test; Flow Curve; Hardening Equation; Sheet Metal Forming Simulation.

INTRODUCTION

In sheet metal forming operations the mechanical properties of the sheet material (i.e. flow stress or stress–strain curve) greatly influence metal flow and product quality. Therefore, accurate determination of the flow stress is of paramount importance in process simulation via finite element method (FEM) [1]. There are several possible methods or test options for determining the flow curve of the materials. It could be stated that apart from standard tensile test, the other methods necessitates some more complicated set-ups and computations. Even some digital image correlation (DIC) applications may also be compulsory for some cases which dominantly affects the cost of the experiment. Conventionally, tensile test is used to determine flow stress curves. However, tensile test data is limited to small amount of strain, due to uniaxial instability (necking) [2]. Despite of its limitation on maximum obtainable strain values, standard tensile test is commonly used because of its low cost and ease of accessibility. For instance a standard tensile test machine may be found in any mechanical characterization lab in Turkey, but the total quantity of hydraulic bulge test machine is less

than five all around the country. There is another important point that well-defined testing standards and technical recommendations exist for many years for standard tensile test such as EN ISO 6892-1 [3]. However it is not valid for bulge test. Although the hydraulic bulge test was used for a long time, especially in sheet metal forming, the standard ISO 16808:2014 is recently published for determination of biaxial stress-strain curve by means of bulge test with optical measuring system [4].

By means of proper data processing and curve-fitting techniques, it is possible to obtain the flow curves with a reasonable amount of uncertainty. In other words, the amount of precision could be sufficient enough for most cases under the condition that standard tensile test data is processed by convenient techniques.

LIMITATIONS of STANDARD TENSILE TEST

Generally in industrial solutions, a standard tensile test machine (Zwick Roell, Instron, MTS, etc.) is used

for mechanical testing with their specific software. The embedded software usually is capable of computing the ultimate tensile strength (UTS), yield strength ($R_{p0,2}$), the Young's modulus (E), the maximum percent elongation, and Lankford parameter (r). In some applications they may also determine the strength coefficient (K) and exponent of strain hardening (n). A sample test result is illustrated in Figure 1.

However standard tensile test has limitations for sheet metals because it only provides the stress–strain behavior of the sheet material under uniaxial deformation conditions. In contrast, during stamping operations the material deforms under biaxial conditions of deformation. Under the biaxial tensile this state of stress, the true strain level may reach a magnitude of about 0.7 or more. With the standard tensile test, however, the true strain level can hardly reach 0.3 [1]. The basic reason of that limited max. true strain value is the instability in the form of early necking encountered during the tension test. This phenomenon hinders the post-diffuse-necking computation of stresses and strains based on the elementary measurements of force and extension in the axial direction [5]. Therefore, in process simulations via

Series graph:

Nr	L0 mm	S0 mm²	Rp 0.2 N/mm²	E-Modulus kN/mm²	ReH N/mm²	Tensile strength N/mm²	ε Fmax. %	Elongation %
1	110,00	130,1	925,84	34,36	-	1108,11	4,95	4,95
2	110,00	131,3	916,58	33,71	-	1007,68	3,71	3,71

Figure 1. A standard tensile test result obtained from Zwick-Roell machine.

Figure 2. A comparison of standard tensile test and hydraulic bulge test for DP 600 steel [2].

finite element method (FEM), the flow curve obtained from tensile test must be extrapolated. This may cause significant errors in process simulations using FE codes [1]. The result of a case study on determination of the uncertainty introduced by the extrapolation of tensile test data is shown in Figure 2.

ADVANTAGES of DATA PROCESSING

In scientific research studies, the obtained force-displacement data from tensile test machine is processed separately by special techniques. The embedded software makes the computation with some basic assumptions. However by means of a special MatLab code which is dedicated to this task, more realistic and precise results could be obtained. In this article created new MatLab code is used for processing of tensile test data of TBF-1050 (TRIP Aided Bainitic Ferrite) steel [6]. The tensile test is performed at Zwick/Roell Z300 machine. The software is Text Expert which is embedded to the tensile test machine. The details of special data processing is explained in coming sections.

Pre-Load Correction in Data Processing

In tensile testing in order to eliminate the slip/stick affect at the beginning of the test, a pre-load is generally applied. As a common application, the extensometers are clamped (prepared for the data record) after the application of pre-load to the tensile specimen. Therefore there is an elastic elongation at the beginning of the tensile test and generally this elongation is neglected by the embedded software. However by means of data processing with MatLab, a pre-load correction can be easily applied to the experimental data. For the pre-load correction, it is sufficient to modify the formulations of true strain and true stress values as below:

$$\Delta = \frac{P*G}{P + A_0 * E} \tag{1}$$

$$\sigma_{true} = \left(\frac{F}{A_0}\right)\left(\frac{G + \Delta L}{G - \Delta}\right) \tag{2}$$

$$\varepsilon_{true\ plastic} = \ln\left(\frac{G + \Delta L}{G - \Delta}\right) - \left(\frac{\sigma_{true}}{E}\right) \tag{3}$$
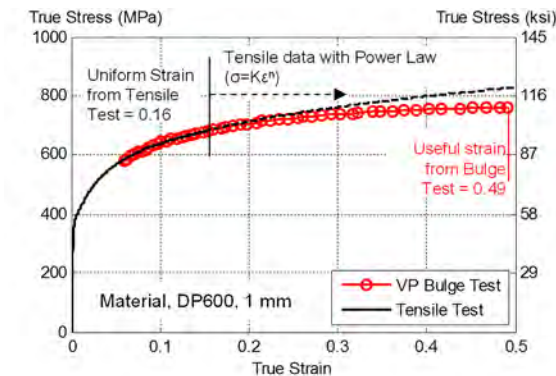
where Δ is the elongation that corresponds to the pre-load, P is the pre-load, G is the initial gage length which is a default value of extensometer, F is the force, A_0 is the initial cross-sectional area, E is the Young's modulus and ΔL is the longitudinal elongation recorded by the extensometer [7].

This pre-load correction may also be done to calculate Lankford parameters which is also neglected by the
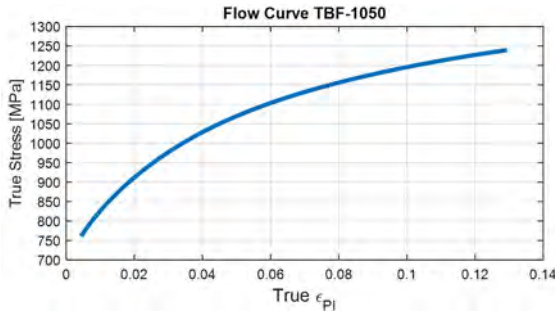
Figure 3. Flow Curve of TBF-1050 Steel.

embedded software of tensile test machine.

$$r = \frac{-\ln\left(\dfrac{w_0 - \Delta w}{w_0}\right)}{\ln\left(\dfrac{G + \Delta L}{G - \Delta}\right) + \ln\left(\dfrac{w_0 - \Delta w}{w_0}\right)} \qquad (4)$$

where w_0 is the initial width, and Δw is the change in width recorded by the extensometer. If the pre-load is omitted then it is possible to use the conventional true stress, true strain formulations as specified in standards [8]. Contrast to this fact, in created MatLab code, these proposed calculations (Eq. 1-4) are engaged related to pre-load correction. The flow curve obtained from created MatLab code with preload correction is shown in Figure 3.

Furthermore, the specimens should be controlled visually after the test for their clamping marks. In some of the tests, slippage may observed as shown in Figure 4.b even if a pre-load is applied. For these specific cases, the tensile tests have to be re-done until proper results were obtained as in Figure 4.a [7].

Computation of Yield Strength by Extrapolation of Flow Curve

Determination of yield strength (or yield stress) is not an easy task. There is always some ambiguity in computing the yield strength.

As it is stated in the literature, the yield strength is not unique in recognition that the plastic deformation in metals due to dislocation flow is not a singular event but a diffuse process [9]. In order to avoid ambiguities in determination of the yield strength, the most commonly used convention is to define the yield strength as the stress required to produce a small previously specified amount of permanent strain or plastic deformation. For most metallic materials, the commonly specified offset strain is 0.002 (or 0.2%) [10]. The embedded software of tensile test machines generally uses $R_{p0.2}$ method. However in this $R_{p0.2}$ approach, the calculated stress is the engineering stress which does not actually a physical meaning in continuum mechanics point of view and also discontinues yielding phenomena is commonly faced with in sheet metals. Thus some more sophisticated and precise approaches exist in sheet metal forming applications in determination of the yield strength. For instance, yield strengths of the tensile specimens could be calculated from the extrapolation of the flow curve (true plastic strain vs. true stress curve) to the zero true plastic strain value. For this extrapolation, high order polynomial curve-fitting might be applied to the flow curve. In this study, 4th order polynomial fit is used because it is observed that this fit operation has sufficient amount of success ($R^2 > 0.99$). This more scientific and precise method is used in the created MatLab code. MatLab code is capable of performing the curve-fitting coefficients and store the last term which is actually the yield strength and display it in the command window. An example of the extrapolation operation is illustrated in Figure 5. An example of command window representation is also shown in Figure 6.

Determination of the Hardening Equations Coefficients

There are several possible hardening equations which could be used to describe the flow curve. Generally four of them is most commonly treated. These are Hollomon's, Swift's, Ludwig's and Voce's hardening equations which are illustrated below:

$$\sigma = K * \varepsilon^n \qquad \text{(Hollomon)}$$

Figure 4. a) Clamping marks, no slippage observed.

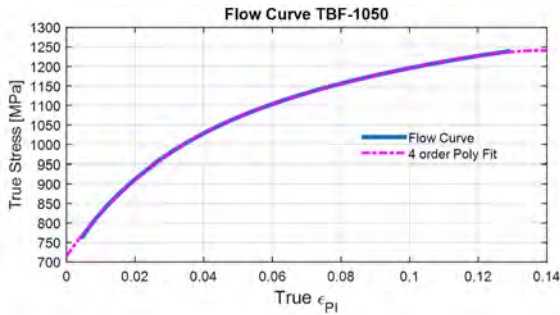**Figure 4.** b) Clamping marks, slippage observed.

Figure 5. Determination of yield strength by extrapolation of flow curve.

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The coefficients and fit performance data of Poly fit to flow curve of TBF 1050 are as below:
    Linear model Poly4:
    fitresult(x) = p1*x^4 + p2*x^3 + p3*x^2 + p4*x + p5
    Coefficients (with 95% confidence bounds):
      p1 =  -2.647e+06  (-2.689e+06, -2.605e+06)
      p2 =   9.853e+05  (9.741e+05, 9.965e+05)
      p3 =  -1.473e+05  (-1.483e+05, -1.463e+05)
      p4 =   1.233e+04  (1.229e+04, 1.236e+04)
      p5 =      715.7   (715.4, 716.1)
        sse: 1.4170e+03
    rsquare: 0.9999
        dfe: 1537
  adjrsquare: 0.9999
       rmse: 0.9602

The Yield Strength of TBF 1050 is below:
  715.7264
  MPa
```

Figure 6. Command window representation of the created MatLab code.

$$\sigma = K * (\varepsilon_0 + \varepsilon)^n \qquad \text{(Swift)}$$

$$\sigma = \sigma_0 + K * \varepsilon^n \qquad \text{(Ludwig)}$$

$$\sigma = B - (B - A) * \exp(-n * \varepsilon) \qquad \text{(Voce)}$$

where σ is the true stress, ε is the true plastic strain and the others are equation constants [11]. The most basic hardening equation is the Hollomon's which is named as *"Power Law"* in some scientific papers. Because of that fact, some embedded software of tensile test

Figure 7. Curve fitting results of four hardening equations for TBF-1050 steel.

machines give only the K and the n values. In contrast, the created MatLab code is capable of performing curve fitting operation with respect to all four basic hardening equations. The regression analysis is also written in the command window by means of which the user could select the most convenient hardening equation for the tested material, i.e. the fit result which has the biggest R^2 value. After selecting the best-fitted hardening equation it can easily be imported to the metal forming simulation software like Ls Dyna, PamStamp and etc. The results of curve fitting operations performed by the MatLab code for TBF-1050 steel is shown in Figure 7.
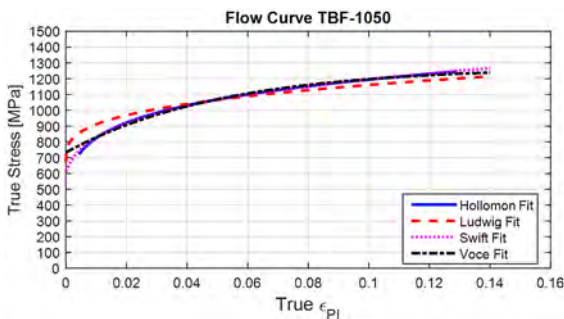
Determination of the Lankford Parameter

In microstructural scale, the mechanical properties of all single crystals differ with respect to the orientation. In other words, it could easily be stated that single crystals are anisotropic. On the other hand, the polycrystalline structures, under the condition that there is sufficient amount of grains that are randomly oriented exhibit isotropic behavior. However it is not the case for sheet metals. Since they are always processed by rolling operations, they usually gain a textured microstructure which leads to anisotropy [12]. In other words the cold or hot deformation history of sheet metals in production chain causes anisotropy. Therefore it is a well-accepted assumption that sheet metals are anisotropic.

The variation of plastic behavior of sheet metals with direction is assessed by a quantity called Lankford parameter or anisotropy coefficient. The anisotropy coefficient *"r"* is defined by:

$$r = \frac{\varepsilon_2}{\varepsilon_3} \qquad (5)$$

where ε_2 and ε_3 are the strains in the width and the thickness directions respectively [13]. By using the

```
for i=1:length(TPStrain)
        R0(i) = -log((W-TD1.data(i,3))/W)/(log((G+TD1.data(i,1))/(G-D))+ log((W-TD1.data(i,3))/W));
end;
FigH = figure('Units','Inches','Position', [1, 1, 6, 3],'PaperPositionMode','Auto');
plot(TPStrain,R0,'LineWidth',2);

[x4,button]=ginput(1);
[x5,button]=ginput(1);

% R0Av and TStrainAv are the averaging values

TPStrainAv = TPStrain;
R0Av = R0;

% This loop deletes the data which are out of avareging range ,i.e. out of
% user cursor click

for i=length(TPStrain):-1:1
    if TPStrain(i)<x4 || TPStrain(i)>x5
        TPStrainAv(:,i) = [];
        R0Av(:,i) = [];
    end;
end;
```

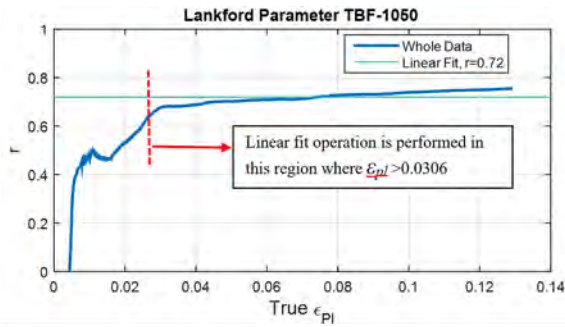**Figure 8.** An example MatLab code for deleting the unstable regions of "r vs. ε_{pl}" curve.

Figure 9. Computation of the Lankford parameter by linear fit to stable region of "r vs. ε_{pl}" curve.
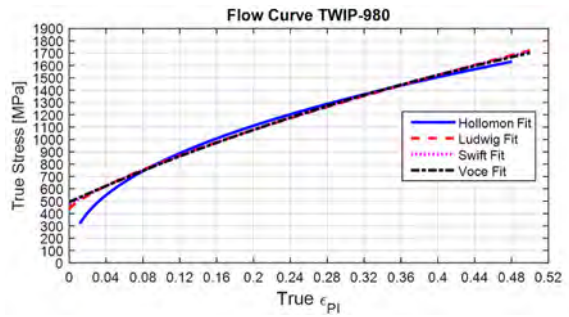

Figure 10. Curve fitting results of four hardening equations for TWIP-980 steel.

volume constancy (Eq. 6) the Lankford parameter can also be calculated as:

$$\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0 \qquad (6)$$

$$r = \frac{-\varepsilon_2}{\varepsilon_1 + \varepsilon_2} \qquad (7)$$

In tensile test, the elongations from longitudinal and transversal extensometers are recorded instantaneously. By

Table 1. Comparison of the MatLab code and the embedded software computations.

	Yield Strength (MPa)	Lankford Parameter
Embedded Software	722.50	0.77
MatLab Code	715.70	0.72

Table 2. Analysis of Curve Fits for Four Hardening Equations (TBF-1050)

Equations	K(MPa)	n	σ_o(MPa)	ε_o	B (MPa)	A (MPa)	R²
Hollomon	1733	0.1615					0.9979
Ludwig	1000	0.3105	671.6				0.9002
Swift	1768	0.1712		0.001889			0.9986
Voce		19.4			1275	733.4	0.9990

Table 3. Analysis of Curve Fits for Four Hardening Equations (TWIP-980)

Equations	K(MPa)	n	σ_o(MPa)	ε_o	B (MPa)	A (MPa)	R²
Hollomon	2249	0.4379					0.9835
Ludwig	2178	0.7564	433				0.9987
Swift	2432	0.6305		0.07532			0.9991
Voce		1.389			2908	493.2	0.9996

means of this fact, the Lankford parameter might also be computed in each time step. Therefore it is possible to plot "*r vs. ε_{pl}*" curve and perform a linear fit operation by a created MatLab code. When this curve is plotted some unstable regions could be detected which are caused by yield drop, discontinuous yielding, elastic effects and etc. Therefore it is a general application to compute the Lankford parameter by making a line fit to the stable region after deleting the unstable portion. For this purpose *"ginput"* function can be used in MatLab. By using this command the user may enter the strain values between which the Lankford parameter is wanted to be calculated. And a simple *"for loop"* can be engaged in order to eliminate the unstable region in linear fitting operation. The command lines of the MatLab code which is used for this computation approach is shown in Figure 8.

With using the MatLab code, this sophisticated computation approach for Lankford parameter is possible whereas embedded software generally use overall averaging approach which creates significant amount of deviations between computed values. The result of MatLab computation is shown in Figure 9.

RESULTS AND DISCUSSION

The expressed computation methods are applied to the tensile test data of TBF-1050 steel by created MatLab code. The comparison of the results from MatLab and embedded software and the analysis of four different hardening equation fits are shown in Table 1 and Table 2.

As could be seen in Table 2, the most appropriate hardening equation is Voce's equation for the processed data (TBF-1050 steel in rolling direction). On the other hand, it should not be neglected that this result may likely alter material to material. This is actually the powerful point of the code that users could easily detect the best hardening equation which will be used for sheet metal simulations regarding to the regression analysis. In Table.3, the results of the TWIP-980 steel is illustrated as a second example.

Lastly, as it is discussed previously, yield strength and Lankford parameter of any material could easily be computed by means of the created MatLab code. If the tensile specimens are prepared with respect to the rolling direction and 90 degree direction, then Hill-48 Yield Criterion parameters could automatically be determined. Hill-48 model is not highly complex yield surface definition compared to Hill-89, Barlat-2000 or Karafillis-Boyce and etc.; however, it is widely-used in sheet metal simulations due to its simplicity. It exhibits sufficiently well performance especially in monotonic loading cases. With a simple supplementary study on the MatLab code, Hill-48 yield surface could be obtained for TBF-1050 as illustrated in
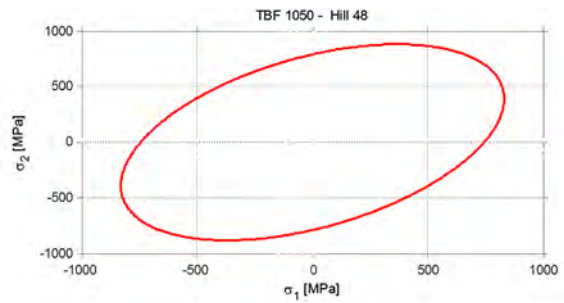

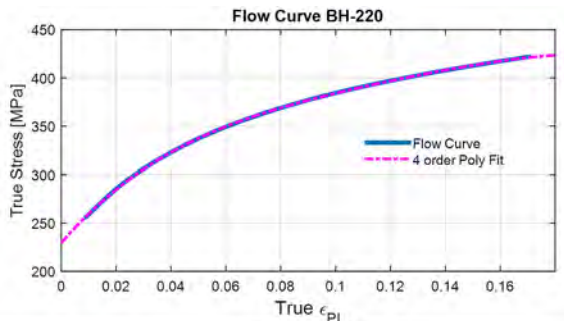**Figure 11.** Hill-48 Yield Surface of TBF-1050

Figure 12. Determination of yield strength by extrapolation of flow curve for BH-220 steel.

Figure.11 if the rolling direction and 90 degree direction tensile tests are performed.

Hill-48 yield surface definition can be expressed as follows:

$$\sigma_1^2 - \left(\frac{2*r_0}{1+r_0}\right)\sigma_1\sigma_2 + \frac{r_0(1+r_{90})}{r_{90}(1+r_0)}\sigma_2^2 = \sigma_0^2 \tag{8}$$

where r_0 and r_9 are the Lankford parameters in rolling and 90 degree direction respectively, σ_0 is the yield strength in rolling direction and σ_1, σ_2 are the principal stresses [13].

CONCLUSIONS

In this study, a specific MatLab code which is consists of approximately three hundred command lines is designed in order to process the force and displacement data obtained by a standard tensile test. This MatLab code is capable of performing some corrections and more complex computations compared to the embedded software of the tensile test machine. Therefore, there are some differences between the two computations. By means of this specific MatLab code, more realistic and precise values could be obtained which increases the precision of the sheet metal forming simulations. Furthermore it is possible to determine the most realistic best hardening behavior of the material by comparing the

regression analysis. For instancte, in this specific case of TBF-1050 steel, Voce's hardening equations exhibits the best regression result.

Moreover, the MatLab code is designed flexibly, so that it can be used for any other material than TBF-1050 steel by just modifying the imported force-displacement data. This data can be imported in *.txt, *.tra or *.csv formats. Then, it takes just few seconds for MatLab code to make the whole computation.

One of the other advantage of this specific MatLab code is that it enables a standardization of material characterization by tensile test at FNSS Defense Systems Co. Inc. It is used for various other materials so far. An example which is the outcome of processing of BH-220 steel data with the MatLab code is illustrated in Figure 10.

As future work, new MatLab codes are being designed for processing of hydraulic bulge test data and also the high temperature, high strain rate characterization of metals at FNSS Defense Systems Co. Inc.

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