THE METHODS TO DETERMINE THE STRAIN RATE OF THE STEEL SHEETS USED IN THE PRODUCTION PROCESS

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The paper deals with observation and description of the influence of strain rate on true stress - true strain. It compares various material models that consist strain rate for deep-drawing sheets in order to work out the most accurate material models. The more accurate input to the simulation program, give the more exact output. These simulation programs introduce higher accuracy into development and production of the pressed material and reduce production costs. Computer simulation using the software programs (e.g. PAM-STAMP, ABAQUS – Explicit, DYNA 3D etc.) also presents replacement of financially expensive experiment, utilization of potential properties of materials and error detection in the production process.

KEYWORDS

strain rate, material constants, steel sheets, Matlab, Curve Fitting Toolbox

1 INTRODUCTION

The influence of strain rate on dependence true stress – true strain can be described by the relation that is analogous with Hollomon strain-hardening equation. If φ strain is replaced by $\dot{\varphi}$, then standard Hollomon equation can be also written for the strain rate:

$$\sigma = C \cdot \varphi^n \cdot \dot{\varphi}^m \tag{1}$$

where σ – true stress, C - material constant, n – strain hardening exponent, m – parameter expressing strain rate sensitivity index, φ - true strain, $\dot{\varphi}$ - strain rate.

To describe sensitivity of the curves of natural strain resistance on the strain rate the following models are used [Mielnik 1991], [Hrivnak 2004]:

– Cowper-Symonds

$$\sigma(\varphi,\dot{\varphi}) = \sigma_0(\varphi)\cdot[1+(\dot{\varphi}/D)^{1/p}] \tag{2}$$

where D and p are material parameters obtained by fitting

- Johnson-Cook

$$\sigma(\varphi,\dot{\varphi}) = \sigma_0(\varphi)\cdot[1+(1/p)\cdot\ln(\max(\dot{\varphi}/D,1)] \tag{3}$$

- modified Jones law, which presents generalization of Cowper-Symonds law

$$\sigma(\varphi,\dot{\varphi}) = \sigma_0(\varphi)\cdot\left[1+\left(\frac{(\varphi_u+\varphi_y)\cdot\dot{\varphi}}{D_u\cdot(\varphi-\varphi_y)+D_y\cdot(\varphi_u-\varphi)}\right)^{\frac{1}{A\varepsilon+B}}\right] \tag{4}$$

where φ_u and φ_y are strain at ultimate and yield strength, *A*, *B* - material parameters, *ε* - proportional strain.

Above mentioned models use stress strain curves that are defined point to point by $\sigma_0(\varphi)$ or strain hardening function according to Krupkowsky

$$\sigma_0(\varphi) = k_{ref}(\varphi+\varphi_{0ref})^{n_{ref}} \tag{5}$$

φ_{0ref} - reference strain at the quasi static strain, k_{ref} - material constant at reference strain.

2 MATERIAL AND SOFTWARE USED FOR THE EXPERIMENT

2.1 Experimental materials

The following steel sheets were used for an experimental research:

- DC 04 – extra deep-drawing sheet suitable for demanding outside and inside parts of car bodies and other stampings (further indicated as a B material)
- DC 05 - extra deep-drawing sheet suitable for complex large size stampings of car bodies and other stampings (further indicated as an A material)
- DX 54D – heat galvanized sheet, extra deep-drawing sheet suitable for complex large size stampings of car bodies and other stampings (further indicated as an E material)
- DC 04 EK – drawing steel sheet metal designed for conventional annealing (further indicated as a C material)
- DIN 1.4301 – chrome-nickel corrosion-resistant steel suitable for cold forming ([STN 17 241] - further indicated as a D material).

2.2 Curve fitting toolbox

The toolbox extends Matlab environment and access to the toolbox is possible through intuitive visual interface or command line. The functions of the toolbox are implemented in open language of Matlab. That allows an access to the source code, which enables to study algorithms or development of its own algorithms. Matlab allows to import into its environment standard data files, where Curve Fitting Toolbox is applied to process them fast and use standard or own models. It is possible to compare the results either visually or through statistics. Curve Fitting Toolbox provides the library of standard linear, nonlinear and nonparametric models: polynomial, exponential, rational, power etc.

Curve Fitting Toolbox also uses the non-linear method of least squares for a non-linear model. The non-linear model is defined as an equation that is non-linear in coefficients or a combination of linear and non-linear equations in coefficients. It is more difficult to approximate non-linear models than linear models because coefficients cannot be determined by utilization of simple non-linear techniques.

3 METHODS TO DETERMINE THE STRAIN RATE

To calculate the proportional strain rate the following (3) equation is used:

$$\dot{\varepsilon} = \frac{v}{L_0\cdot C_{str}} \tag{6}$$

v is velocity of the traverse in mm·min^{-1}, L_0 - gauge length of a sample, C_{str} – constant $(C_{str} = 1.25 \pm 0.05)$, $\dot{\varepsilon}$ - proportional strain rate $\dot{\varepsilon} = \frac{1}{dt}\left(\frac{dL}{L_0}\right) = \frac{d\varepsilon}{dt}$.

Strain rates from 0.01 to 25 s^{-1} are characteristic at production on hydraulic and crank presses. Based on the results [Labellarte 2000] it is possible to assume that the influence of proportional strain rate is not markedly evident for quasi static proportional strain rates (up to $\dot{\varepsilon} = 1$ s^{-1}).

According to STN EN 6892-1 [STN EN 6892-1] norm the following velocities were selected to analyze the influence of strain rate on the values of yield strength, ultimate tensile strength, ductility, strain hardening exponent etc.:

v_1 = 5 mm·min^{-1} $\Rightarrow$ $\dot{\varepsilon}$ = 0.0007 s^{-1}

v_2 = 10 mm·min^{-1} $\Rightarrow$ $\dot{\varepsilon}$ = 0.0014 s^{-1}

v_3 = 20 mm·min^{-1} $\Rightarrow$ $\dot{\varepsilon}$ = 0.0028 s^{-1}

v_4 = 40 mm·min^{-1} $\Rightarrow$ $\dot{\varepsilon}$ = 0.0056 s^{-1}

v_5 = 60 mm·min^{-1} $\Rightarrow$ $\dot{\varepsilon}$ = 0.0083 s^{-1}

In general it is possible to state that the higher the strain rate, the higher the resistance of metal against the plastic strain. The influence of strain rate on natural strain resistance can be expressed by the following equation:

$$\sigma = A \cdot (\dot{\varphi})^m \qquad (7)$$

The equation (7) is analogous with Hollomon equation to determine the curve of natural strain resistance at reference strain rate, only φ strain is replaced by $\dot{\varphi}$. If the equation (7) is written for two various strain rates, then we get [Mielnik 1991]:

$$\sigma_0(v_{0\mathrm{ref}}) = A \cdot (\dot{\varphi}_{0\mathrm{ref}})^m \qquad (8)$$

$$\sigma_1(v_1) = A \cdot (\dot{\varphi}_1)^m \qquad (9)$$

If we divide equation (8) by the equation (9) we have

$$\frac{\sigma_1}{\sigma_0} = \left(\frac{\dot{\varphi}_1}{\dot{\varphi}_{0\mathrm{ref}}}\right)^m \qquad (10)$$

thereafter

$$m = \frac{\ln\left(\frac{\sigma_1}{\sigma_0}\right)}{\ln\left(\frac{\dot{\varphi}_1}{\dot{\varphi}_{0\mathrm{ref}}}\right)} \qquad (11)$$

If it is assumed that $\dot{\varphi}_1 / \dot{\varphi}_{0\mathrm{ref}} = v_1 / v_{0\mathrm{ref}}$ and $\sigma_1 / \sigma_0 = F_1 / F_0$, then strain rate sensitivity index can be expressed as

$$m = \frac{\ln\left(\frac{\sigma_1}{\sigma_0}\right)}{\ln\left(\frac{\dot{\varphi}_1}{\dot{\varphi}_{0\mathrm{ref}}}\right)} = \frac{\ln\left(\frac{F_1}{F_0}\right)}{\ln\left(\frac{v_1}{v_{0\mathrm{ref}}}\right)} \qquad (12)$$

If the standard Hollomon equation is derived, we get

$$\sigma = C \cdot \varphi^n \frac{\dot{\varphi}_1^{\,m}}{\dot{\varphi}_{0\mathrm{ref}}^{\,m}} \qquad (13)$$

4 OBTAIN RESULTS AND THEIR ANALYSIS

Values of natural strain resistance and sensitivity index dependent on velocity of transverse motion can be found in Table 1 (only for A material). Experiment was carried out on all above mentioned samples.

Taking into consideration that n strain hardening exponent is not constant with increasing true strain, Krupkowski model was completed by the influence of strain rate

$$\sigma = C \cdot (\varphi + \varphi_0)^{(n + b\varphi)} \cdot \left(\frac{\dot{\varphi}_1}{\dot{\varphi}_{0\mathrm{ref}}}\right)^m \qquad (14)$$

C, b, n, φ_0 calculated values determined by non-linear methods of least squares from experimentally obtained data can be found in Tab. 2.

Table 1. Evaluation of *m* sensitivity index on velocity of transverse motion at *A* material.

Initial interval value in the area of uniform deformation [%]	Natural strain resistance [MPa]	Reference velocity of transverse motion $v_{0\mathrm{ref}}$ [mm·min^{-1}]	Comparative velocity of transverse motion v_1 [mm·min^{-1}]	Sensitivity index on strain rate m
0.2	167	10	20	0.034
	172		40	0.040
	172		60	0.029
5	243	10	20	0.018
	246		40	0.015
	247		60	0.015
10	275	10	20	0.022
	278		40	0.019
	279		60	0.017
Ag	294	10	20	0.018
	296		40	0.015
	298		60	0.016

Table 2. Results obtained by non-linear approximation of least squares by means of the model at reference velocity.

Material	Thickness [mm]	*C* [MPa]	φ_0	*n*	*b*	Correlation coefficient
A	0.7	520	0.0047	0.232	0.0373	0.99995
B	0.81	565	0.005	0.205	0.01485	0.9999
C	0.81	540	0.009	0.225	0.000575	0.9999
E	0.78	520	0.0034	0.235	0.009937	1
D	0.79	1421	0.0201	0.441	0.007059	0.9998

Coefficients are calculated at velocity of transverse motion of 10 mm·min^{-1}. Algorithm Trust-Region was used at the calculation. n strain hardening exponent influences the stress-strain curve in the area of uniform plastic strain and m sensitivity index on strain rate influences the curve of natural strain resistance in the area of post-uniform strain. If n and m increase, strain outgrows into disorder, and therefore it can be expected that the higher n and m values, the better formability of material.

Comparison of interval change in the area of uniform deformation on values of strain hardening exponent and material constant can be found in Tab. 3.

Table 3. Comparison of strain hardening exponent for the material constant *C* in the studied material in the direction of 90° using power and logarithmic regression models.

Regression model	*v* [mm·min^{-1}]	$n_{0,002}$	$C_{0,002}$ [MPa]	$n_{0,05}$	$C_{0,05}$ [MPa]	$n_{0,1}$	$C_{0,1}$ [MPa]
A MATERIAL							
Power	5	0.238	521	0237	520	0230	514
Logarithmic	5	0.233	516	0237	521	0.229	514
B MATERIAL							
Power	5	0.196	553	0.201	561	0.201	559
Logarithmic	5	0.191	546	0.201	563	0.201	559
C MATERIAL							
Power	5	0.221	535	0.224	539	0.220	535
Logarithmic	5	0.214	525	0.224	538	0.220	535
E MATERIAL							
Power	5	0225	545	0.228	550	0.222	544
Logarithmic	5	0214	538	0.226	550	0.225	544
D MATERIAL							
Power	5	0433	1420	0.496	1464	0.5	1492
Logarithmic	5	0435	1421	0.474	1420	0.474	1452

It results from Tab. 3 that at A, B, C, E materials higher values of *n* were measured when the power regression model was used and lower values were measured at linearization of dependence true stress – true strain. To describe the curves of natural strain resistance for individual materials the following models were tested:

– linear (logarithmic) - $\ln(\sigma) = \ln(C) + n \cdot \ln(\varphi_i)$

– power (Hollomon) - $\sigma = C \cdot \varphi_i^n$,

– Krupkowsky - $\sigma = K \cdot (\varphi + \varphi_0)^{(n+\varphi b)}$.

Based on obtained results it can be concluded that it is possible to use all three models to determine the curves of natural strain resistance for materials at which linear dependence is presented in a certain interval of uniform deformation. Dependencies of true stress on strain by means of linear, power or $\sigma = C \cdot (\varphi + \varphi_0)^{(n+\varphi b)}$ models are comparable at all materials (A, B, C, D, E materials – correlation coefficient was not lower than 0.999 in any case). As for D material, where dependence of strain hardening exponent is non-linear, it is preferable to use $\sigma = K \cdot (\varphi + \varphi_0)^{(n+\varphi b)}$ model.

Hollomon and Krupkowsky equations were extended by influence of strain rate [Michel 1995] on dependence of true stress and true strain ($\sigma = C \cdot \varphi_i^n \cdot \dot{\varphi}^m$, $\sigma = C \cdot (\varphi + \varphi_0)^{(n+\varphi b)} \cdot \dot{\varphi}^m$) within the interval of strain rate from 0.0014 s^{-1} to 0.0083 s^{-1} [Fechova 2014].

m strain rate sensitivity index was used to describe the influence of strain rate. For instance it results from measured values in Tab. 1, personal knowledge of the first author of the article that there are not any significant changes of sensitivity index on strain rate at A, B, C and E materials at strain rates from 0.0028 s^{-1} to 0.0083 s^{-1} [Evin 1996], [Geoffroy 1998]. Similarly the influence of strain at these materials on *m* value is not significant at strains higher than 5 % (*m* values range from 0.015 to 0.019 at A material; from 0.008 to 0.015 at B material; from 0.013 to 0,019 at C material; from 0.007 to 0.016 at E material and from 0.04 to -0.021 at D material).

In further research it is necessary to examine the influence of strain rate up to the maximum strain rate that can be set up on the shredder (approximately 0.08 s^{-1}). As measured results indicate, it is necessary to describe the sensitivity index as a function of strain and strain rate at materials with multiphase structure (D material). One constant value of *m* is apparently sufficient at classic materials.

5 CONCLUSION

a) The program was proposed in Matlab, which allows to evaluate the curve of natural strain resistance from the record of force and elongation of the shredder (dependence of true stress – true strain) for any interval in the area of uniform plastic deformation for the linear regression model - $\ln(\sigma) = \ln(C) + n \cdot \ln(\varphi_i)$, power (Hollomon) model - $\sigma = C \cdot \varphi_i^n$ and Krupkowsky model - $\sigma = K \cdot (\varphi + \varphi_0)^{(n+\varphi b)}$. The proposed program also enables to determine yield strength, ultimate tensile strength, strain hardening coefficient and normal anisotropy coefficient.

b) It accrues from measured results that if strain rate was increasing within the interval recommended by the STN EN 6892-1 from 0.0007 s^{-1} to 0.0083 s^{-1}, the values of yield strength at A, B, C, E and D materials slightly increased from 9 MPa to 15 MPa, ultimate tensile strength at A, B, C, E materials went up approximately by 6 MPa. At austenitic steel sheet metal at stated strain rate decrease of tensile strength by 19 MPa occurred. At A, B, C and E materials slight decrease of ductility by 2 – 5% occurred. Within the interval of strain rate from 0.0007 s^{-1} to 0.0083 s^{-1} at A, B, C and E materials no changes of coefficient of normal anisotropy were recorded, however, slightly decreasing tendency was presented. The influence of strain rate more markedly occurred at D material, at which decrease of ductility by 9.5% and strain hardening exponent approximately by 0.07 occurred.

c) To determine the curve of natural strain resistance three regression models were verified:

   - linear model - $\ln(\sigma) = \ln(C) + n \cdot \ln(\varphi_i)$
   - power (Hollomon) model - $\sigma = C \cdot \varphi_i^n$
   - Krupkowsky model - $\sigma = K \cdot (\varphi + \varphi_0)^{(n+\varphi b)}$.

   In cases where the dependence of strain hardening exponent is linear, all three models are suitable in the interval of uniform deformation. In cases where the dependence of strain hardening exponent in the uniform deformation is not linear, Krupkowsky model has to be preferred from the analysed models.

d) Hollomon and Krupkowsky models were extended by the influence of strain rate. The influence of strain rate was in $\sigma = C \cdot \varphi_i^n \cdot \dot{\varphi}^m$ and $\sigma = C \cdot (\varphi + \varphi_0)^{(n+\varphi b)} \cdot \dot{\varphi}^m$ models expressed by *m* sensitivity index on strain rate, which values at individual materials were:

   A material – $m \in (0.015 \div 0.022)$
   B material – $m \in (0.008 \div 0.015)$
   C material – $m \in (0.013 \div 0.019)$
   D material – $m \in (0.04 \div -0.021)$
   E material – $m \in (0.007 \div 0.016)$.

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