Measurement and evaluation of forming limit curves from digital image of deformation network

J. Kmec, E. Fechová, S. Hrehová

Abstract — Efficient computer technology connected with program files of simulation of technological processes provides invaluable information. The program files of simulation bring elements of accuracy, reduction of work expenditure and total cost into the phase of development and preparation of material production. Computer simulation presents significant shortening of the phase of production preparation from drawing to tools production, reduction of costs for production preparation, better utilization of potential material properties, replacement of expensive experiment, detection of errors at designing production processes. It is possible to eliminate inaccuracies at determining sizes from deformation network at the crack area of the steel sheet by suitable choice of the procedure of measurement and evaluation of forming limit curves (FLC). The procedure for removing inaccuracies at determining forming limit curves from digital picture of deformation network by means of computer technology is proposed in the paper. Software program Matlab and its Image Processing Toolbox is used for direct measurement and evaluation of forming limit curves.

***Keywords*—** Camera system, forming limit curves, forming limit diagrams, Matlab.

I. Introduction

RAISING requirements for manufacture qualities of cars heighten requirements for development of new material types, lubricants, new technologies of preparation and realization of sheet metal pressed parts production. One of the possibilities how to increase technical and economical levels of products is an application of steel sheets and steel sections with special properties. Technological processing of those materials causes problems too, because in most cases the change of stampability parameters occurs in consequence of higher strength and special properties.

It is not possible to imagine to predict stampability of these materials for particular stamping conditions without computing simulation. Reliability and accuracy of numeric simulation results depends on accuracy of the used model and completeness of input data. It results from analyses that apart from the tool model and kinematics of stamping the following material data are necessary to predict stampability of steel sheets by means of computing simulation: ν - Poisson number, E – modulus of elasticity, the curves of natural deformation resistances, r– normal anisotropy coefficient, FLC – forming limit curves, f - friction factor [1], [2], [3].

II. Experimental

A. Material and software used

The following steel sheets were used for an experimental research:

- DX 54D – a hot-dip zinc coated extra deep-drawing sheet, suitable for complex large sheet pressings of automobile bodies and other pressed parts (described further as an E material)
- DIN 1.4301 – chrome and nickel anti-corrosion steel suitable for cold forming (STN 17 241 – described further as a D material).

Matlab is an integrated environment for scientific and technical calculation, modelling, simulation, presentation and data analysis. It is a tool for both comfortable interactive work and development of wide spectrum of applications. Open architecture called into existence the libraries of functions that are called toolboxes, which spread the use of the program in particular scientific and technical areas [4], [5].

These proposed libraries written in Matlab by world experts offer pre-processed specialized functions that can be extended, modified or only information from well-arranged documented algorithms can be utilized.

The family of Matlab toolboxes is formed by:

- Matlab compiler
- Signal Processing

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- Control Systém
- Optimalization
- System Identification
- Wavelet
- Communications
- Statistics
- Splines
- Partial differential Equation
- Real time
- Image Processing
- Curve Fitting
- and many others

For example, Real time toolbox connects Matlab with the surrounding world. It enables an immediate access to external analog and digital signals. Matlab allows to use either command line or graphics interface or efficient library of Simulink. External signals can be experimented directly from Matlab. It is not necessary to transfer data from specialized programs for data acquisition.

Image Processing Toolbox is efficient, flexible and easily manageable tool for processing and analysis of the picture. Based on the massive potential of Matlab, extensions for filter proposals, reconstruction and picture analysis as well as extensions for manipulation with colors, geometry and picture structure including 2-D transformations are built.

The methods of medical and industrial diagnostics, data analysis and automation are based on technology of picture processing. Picture analysis is indispensable in astronomy, geophysics, but also in ecology and other areas such as communication, military and consumer electronics.

Matlab with Image Processing Toolbox is an optimal tool in such an area as a digital processing of picture because of its computing power, directness and unique structure of application libraries. A new version of this toolbox mainly introduces back-up of 8-bit data format of picture, significant acceleration of all operations and radical memory savings compared to the previous version. Significant acceleration of execution of individual functions is achieved by interconnection of innovative approaches in Matlab core.

B. Methodology of measurement and evaluation of forming limit curves

The network deposition technique is used to determine deformation distribution at the plane of steel sheet dependant on deformation history.

Objective definition of limiting state is difficult, because in the crack area it is necessary at evaluation of changes of deformation network measurements to eliminate uncertainty of reading measurements of deformation network at the place where the crack arose. Deficiencies of above mentioned way can be eliminated by the use of digital recording by means of the camera system (Fig. 1).

Fig. 1 Camera system

Recordings of camera systems enable to sort and choose any arbitrary moment of deformation history of a selected element (deformations right before a crack arose) [6] – Fig. 2 and Fig. 3.

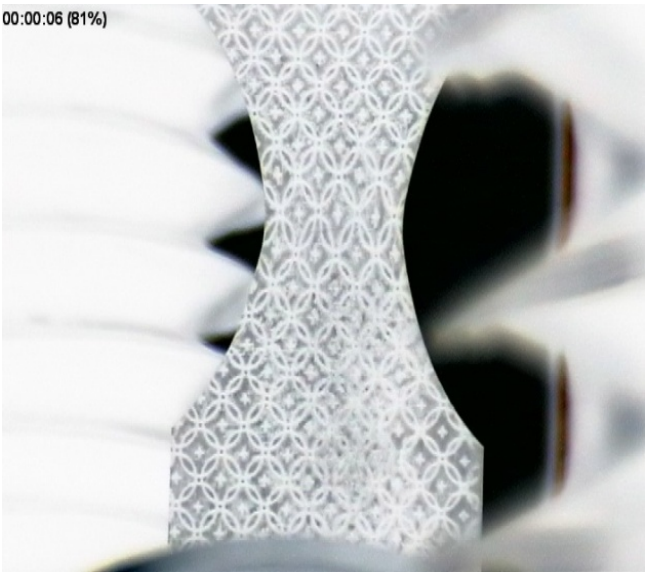

Fig. 2 Sample before breakdown

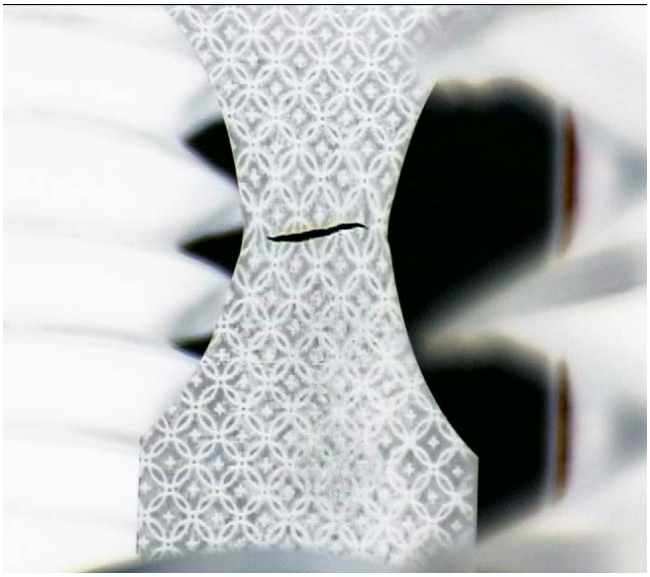

Fig. 3 Sample after breakdown

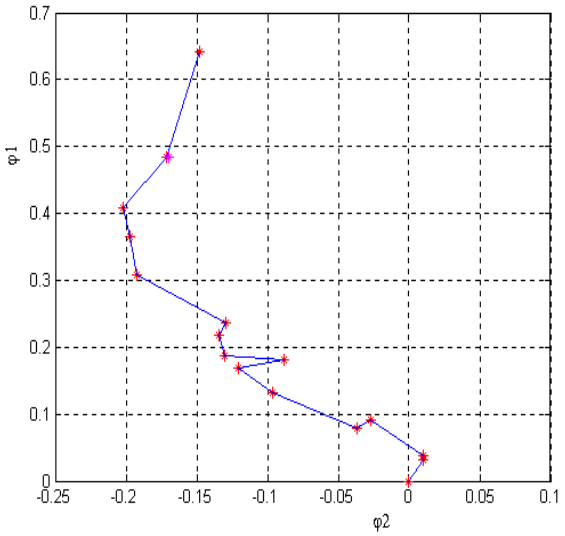

Fig. 4 Deformation history of D material for Tab. 1

Digital Video Camera NV-GS15EG was used to record deformation history at tensile test on the samples with a notch. Deformation networks with diameter of 5 mm were installed on the sample with notches of 5 mm, 10 mm, 17,5 mm and 25 mm. The samples underwent plastic deformation in the TIRATEST 2300 machine at punch velocities v_1 = 5 mm/min and v_2 = 60 mm/min. Deformation history of D material at reference velocities $v_{ref} = v_1$ can be found in Tab. 1, Fig. 4.

Tab. 1 The values of minor and major strain for D material with the notch r = 5 mm and v_{ref}

Minor Strain φ_2	Major Strain φ_1
0.0000000e+000	0.0000000e+000
1.0617321e-002	3.6019612e-003
1.3293315e-002	-2.2213363e-004
2.9560547e-002	1.8823796e-002
2.1595751e-002	1.5487847e-002
3.0152404e-002	4.5067917e-002
5.5442176e-003	4.8669053e-002
-2.4332430e-003	8.8418198e-002
-4.6820371e-003	1.0574542e-001
2.1226278e-002	1.2651370e-001
-1.0293546e-002	1.3634217e-001
-4.5402219e-002	1.9172641e-001
-2.6907409e-002	2.1706102e-001
-6.1200724e-002	2.6819554e-001
-5.6683789e-002	3.1721589e-001
-8.6400720e-002	**4.4498079e-001**
-6.3844365e-002	4.4381798e-001
-9.7180155e-002	5.1010730e-001
-1.0332852e-001	5.1278406e-001

1 ... n images are recorded at proper measurement of deformations during material test. Ten images at an interval from the beginning of deformation to the sample breakdown are selected to describe deformation history (Fig. 3).

The diameter of deformation network on the samples with a notch was measured by means of Abbe linear meter and Image Processing Toolbox. 41.6 pixels conforms to the diameter of deformation network [7] before deformation of 4.98 mm.

Corresponding measurement sizes of deformation network for selected images, which are specific to deformation history, are written interactively into the created matrix (e.g. Tab. 1).

The images from an industrial camera were put into the Matlab environment in BMP (bitmap) format. Circular deformation network, from which starting position (L_0 diameter before deformation) and final position (L_1 and L_2 lengths of main and secondary axes after deformation) are read by means of Matlab instruction ginput, is deposited on the sample. The distance between two points is determined several times and arithmetic average is calculated. φ_1 and φ_2 deformations are calculated by means of relations $\varphi_1 = \ln(L_1/L_0)$ and $\varphi_2 = \ln(L_2/L_0)$. After that the dependence of major strain on minor strain is recorded in the graph (Fig. 4). φ_{1K} and φ_{2K} deformations are evaluated from the images for defined limiting state. The second degree curve is formed by given points (bold numbers in Tab.1) and recorded in the graph (one point in the graph represents one notch and one velocity).

It results from Fig. 5 and Fig. 6 that deformation history is not linear. Therefore it is necessary to count with this fact at defining relations for prediction. Moreover it is necessary to remark that position of the forming limit curves is sensitive to the defect density (impurities, cavities and so on), change of steel sheet thickness, change of tool geometry, change of

diameter size of the used strain net and so on.

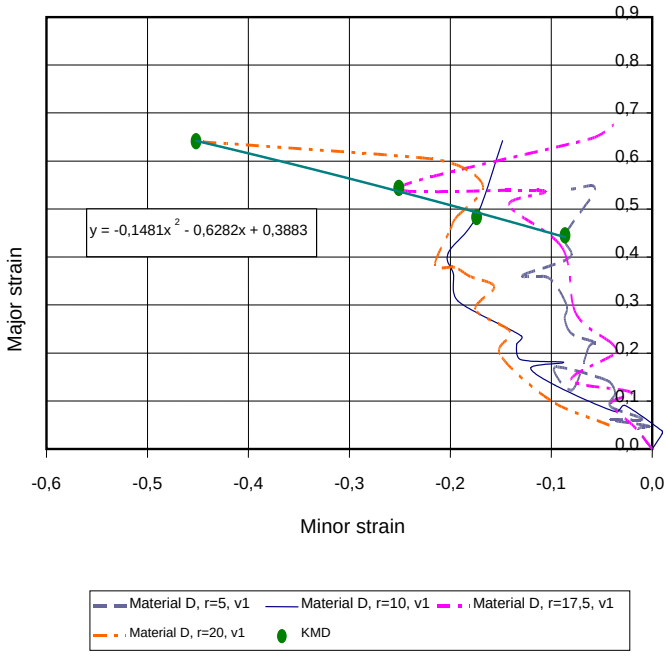

Fig. 5 Deformation history process at D material and punch velocity of 5 mm.min^{-1}

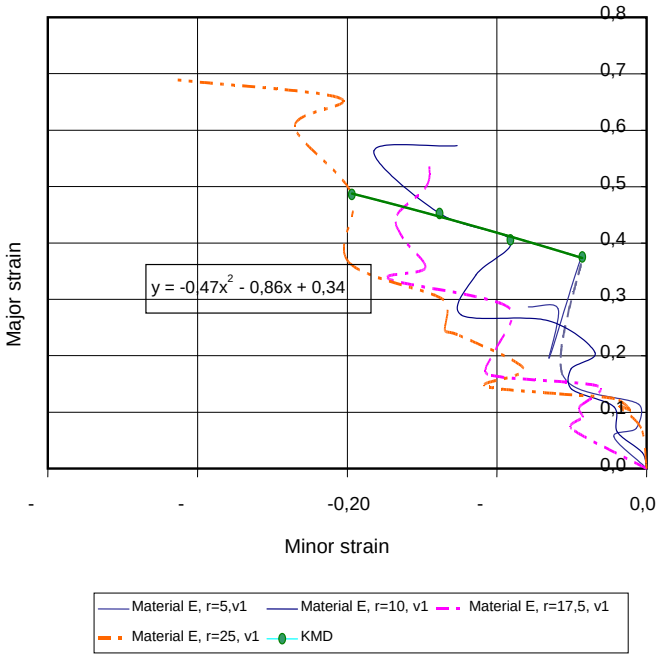

Fig. 6 Deformation history process at E material and punch velocity of 5 mm.min^{-1}

It is possible to determine the left side of the forming limit curve on the samples with a notch by means of the tensile test. The left and right sides of the forming limit curve can be determined by Nakazima and Marciniak methods.

The designed tool (Fig. 7) is a part of the TIRATEST 2300 machine in order to study the influence of deformation velocity on the position of the forming limit curves.

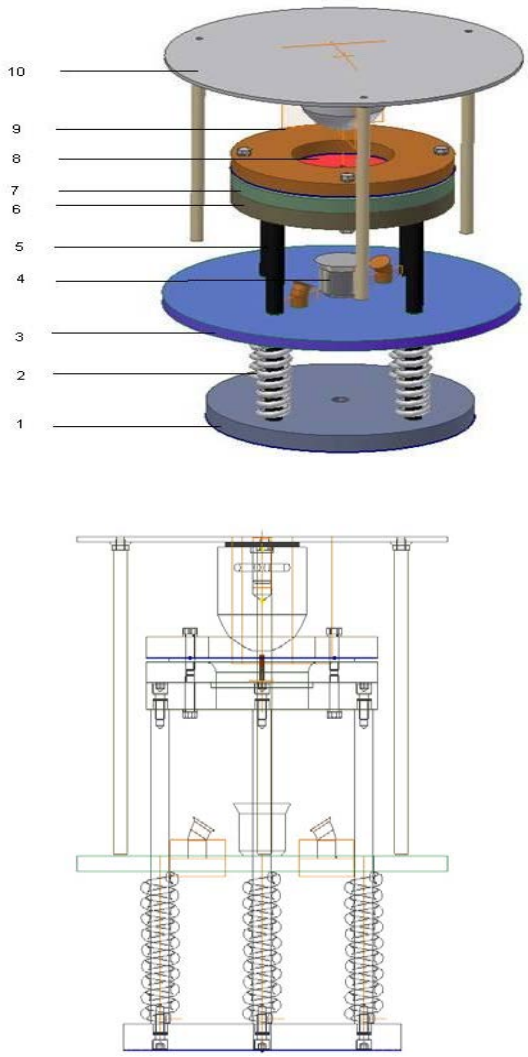

Fig. 7 Dispositional solution of the tool (1 – base plate; 2 - springs; 3 – camera system board; 4 – camera system; 5 – carrier bar; 6 – steel sheet mounting plate; 7 - die; 8 - sample; 9 – blank holder; 10 – punch)

The tool is tightly fixed into the lower shredder cross beam by means of the base plate. The base plate is firmly connected with a die. There is a mobile plate with a camera and lighting between the base plate and die (Fig. 7). The upper part of the tool is formed by the upper plate in which the punch is fixed. The upper part is fixed into the mobile cross beam of the shredder by means of the plate. To keep the constant distance of the camera from the sample the bars, which affect the middle plate with a camera system, are fixed in the upper plate. The camera system board (Fig. 7) is placed on the springs. The camera system board also moves at the motion of the upper cross beam with the punch. The punch penetrates into the die, at which the sample that is tightly fixed between

the blank holder and die is pulled out.

III. OBTAINED RESULTS

Stress on material by uniaxial and biaxial tension occurs at stretching and bending. Deformations at the plane of steel sheet for these deformation states can be described by forming limit diagrams - *FLD*. It results from the measured results of deformation distribution on the samples with notches at the tensile test that deformation path is not linear (Fig. 8 and Fig. 9). Limiting values of deformations at the plane of steel sheet (deformations right before a crack arose) are more significant to define limiting conditions of stampability. It means that if a curve is transferred through critical values of deformations, the left side of *FLD* is obtained.

It results from the comparison of the forming limit curves determined at the austenitic steel sheet (D material–Fig. 8) and ferritic steel sheet (E material–Fig. 9) that the higher material values of A_{80} ductility and n strain hardening exponent, the higher is the position of the forming limit curve. The values of those material characteristics are higher at austenitic steel sheets than at low carbon steel sheets – E material. The position of the curves is not significantly influenced by the normal anisotropy coefficient ($r = 1$ at austenitic steel and $r = 1.8$ at low carbon steel - E material).

Obtained forming limit curves are in accordance with current knowledge [1], [8]. The statement that position of the forming limit curves depends mainly on ductility and strain hardening exponent is proved by the results obtained at deformation velocity $\dot{\varphi} = 0{,}0083 s^{-1}$. There was a shift (decrease) of the forming limit curve at D material as well as low carbon steel E material at change of deformation velocities from 0,0007 s^{-1} to 0,0083 s^{-1}.

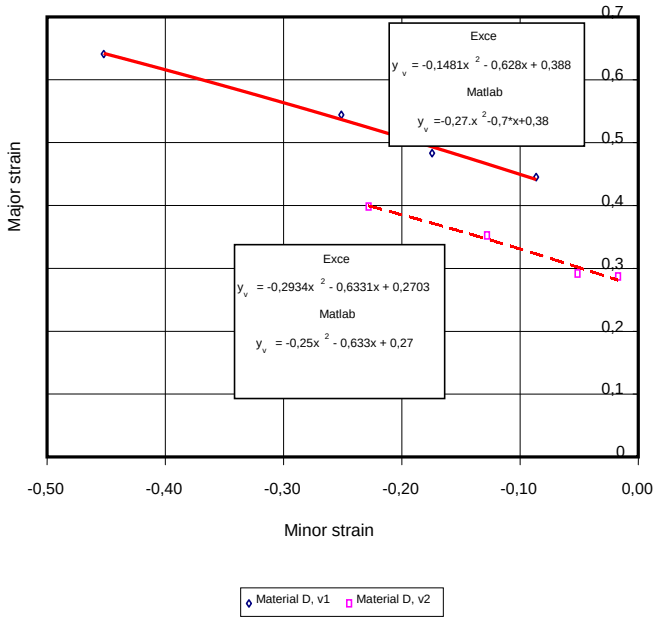

Fig. 8 Forming limit curves determined at D material

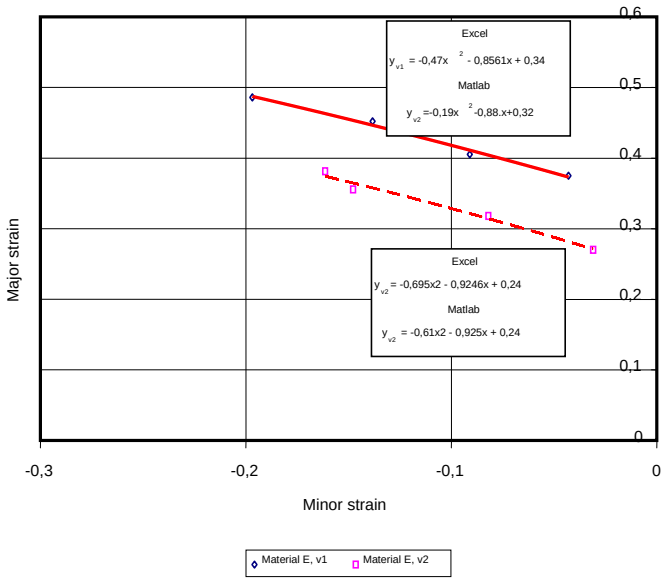

Fig. 9 Forming limit curves determined at E material

Relations to predict $FLD0$ $(\varphi_{1K})_{\varphi_2=0}$ by means of ductility and strain hardening exponent were derived in the paper [9], [8] based on extensive research of various material types:

$$FLD0 = (\varphi_{1K})_{\varphi_2=0} = (2{,}78 + 3{,}244 \cdot a_0 + 0{,}892 \cdot A_{80}) \quad (1)$$

$$FLD0 = \varphi_{1K} = (23{,}3 + 14{,}3 \cdot a_0) \cdot \frac{n}{0{,}21} \quad (2)$$

The values calculated according to the relation (1) (Bethlehem relation) are at about 3 % higher than in the relation (2) (Keller relation). The difference between measured values of $FLD0$ $(\varphi_{1K})_{\varphi_2=0}$ and values calculated by means of above mentioned relations was in the interval from $+0{,}25\%$ to -5%. As mentioned before, if deformation velocity increases, there is a slight decrease of ductility and strain hardening exponent [10], [11]. If changes of ductility dependant on deformation velocity are inducted into the relation (1), it is proved that there is a decrease of position of $FLD0$ at about $\Delta FLD0 = 0{,}09$ and at low carbon steel there is a decrease of $FLD0$ at about $\Delta FLD = 0{,}023$. Similarly, if the change of the strain hardening exponent dependant on deformation velocity is inducted into the relation (2), it is proved that at austenitic steel sheets there is a change of $FLD0$ at about $\Delta FLD0 = 0{,}12$ to $0{,}132$ and at E material there is a change at about $\Delta FLD0 = 0{,}003$ to $0{,}02$. The differences between measured and calculated values are lower at D material in comparison to E material.

IV. CONCLUSION

Obtained results can be summarized as follows:

1) The camera system for measurement and evaluation of the forming limit curves, which enables to record entire deformation history, was proposed and verified in the paper. The system was verified on the samples with notches of $r = 5mm$, $r = 10mm$, $r = 17{,}5mm$, $r = 25mm$ by means of the tensile test.

2) To evaluate the changes of measurements of deformation network, the program, which enables to evaluate deformation size, write them into the table and process them graphically, was prepared in Matlab. The advantage of this system in comparison to formerly used system is in the fact that it enables to record entire deformation history, define limiting deformation state and evaluate major and minor critical strain at the plane of the steel sheet (right before the crack arose).

3) With regard to the fact that influence of deformation velocity in the examined area became evident in ductility, position of the curve in *FLD*, strain hardening exponent at D material and did not become evident in the change of normal anisotropy coefficient, it is possible to assume that the higher values of ductility and strain hardening exponent, the higher is the position of the curve in *FLD*. The curve in *FLD* slightly decreases at increasing deformation velocity [12]. For velocities of movement of the shredder traverse v_1 = 5 mm/min and v_2 = 60 mm/min equations for prediction of the left *FLD* were inducted from measured critical values of deformations at the plane of steel sheet

- D material

  v_1 velocity: $\varphi_{1K,v1} = -0{,}27 \cdot \varphi_2^2 - 0{,}7 \cdot \varphi_2 + 0{,}388$

  v_2 velocity: $\varphi_{1K,v2} = -0{,}25 \cdot \varphi_2^2 - 0{,}633 \cdot \varphi_2 + 0{,}27$

- E material

  v_1 velocity: $\varphi_{1K,v1} = -0{,}19 \cdot \varphi_2^2 - 0{,}88 \cdot \varphi_2 + 0{,}32$

  v_2 velocity: $\varphi_{1K,v2} = -0{,}61 \cdot \varphi_2^2 - 0{,}91 \cdot \varphi_2 + 0{,}24$.

The influence of the normal anisotropy coefficient did not become evident in the position of the curve in *FLD*. The curve in *FLD* was positioned higher at austenitic steel with $r \cong 1$ than at E material with $r \cong 2$.

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