NEW MATERIALS CHARACTERIZATION APPROACHES IN COMPUTER AIDED DESIGN

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Improvements in computer simulation, materials characterization and lowering of design safety margins leads to significant decrease of components mass. In order to maintain functions and increase components service reliability while reducing their mass, new approaches describing closer material behaviour and in service component properties are applied. The current paper is shoving recent trends contributing to improvement of the forming technology and components design thanks to improved material models and local properties measurements for flat and bulk components. Complex material models taking into account multiaxial loading conditions together with approaches considering load path history influence on material deformation behaviour are presented here. Additionally, local properties measurement with the use of miniaturized tensile specimens is presented here that provides data for anisotropy and local properties assessment that are applied to models tuning and verification.

KEYWORDS

ductile damage, strain path influence, small size testing, triaxiality

1 INTRODUCTION

Increasing demands on components reliability, durability, light but robust structures lead to the materials utilization to the edge of its performance under considered service conditions. Computer design is crucial part of any single part development nowadays and this fact increases pressure on more accurate material behaviour description from material models point of view as well as from the experimental characterization of stress-strain behaviour of the materials investigated under complex loading conditions. Stress-strain curves under uniaxial loading conditions are standard material models inputs. However, in the most cases real structures are loaded under multiaxial conditions and thus more advanced models considering multiaxial loading shall be applied. In order to utilize full material potential not only plasticity under multiaxial loading should be followed, but also damage of the material. In the case of flat products properties anisotropy is strongly pronounced due to production technology and non-linear loading path can severely influence the resulting component mechanical behaviour. Further issue of components behaviour description is related to material properties heterogeneity either due to thermo-mechanical treatment, local heat treatment e.g. by inductive heating, or due to component construction where welds can be applied. In these cases, local properties have to be assessed for the complex material model determination, in order to describe real components behaviour and thus small sized specimens have to be employed to describe real local properties. The paper presented here is going to show some recently used material models and appropriate experimental programs for determination of complex models describing the traxiliaty influence on plasticity and damage, load path history on stress-strain behaviour and determination of local material properties with the use of small sized specimens.

2 COMPLEX MATERIAL MODELS

Standard tensile test is traditional source of design input data that is based on uniaxial sample loading. The tensile test results are useful for elastic solutions or elastic-plastic solution for a small plastic strains. However, if states near to fracture are to be considered, more complex material description taking into account multiaxial loading conditions is necessary, [Bai 2010, Bai 2008, Wierzbicki 2005, Bao 2004, Li 2009]. Example of material behaviour expression under multiaxial loading can be found in Fig. 1. Usual stress-strain description is replaced by fracture locus defined by fracture strain, Von Mises stress q, stress triaxiality η and Lode parameter ξ (or normalized Lode parameter θ) for plasticity and damage description. These quantities are defined using second J_2 and third J_3 invariant of deviatoric stress, as it is shown in **Eqs. (1-7).** Experiments with samples of various geometries tested under several loading modes have to be used for these material models fitting, Fig. 2. Butterfly specimens can be successfully used here for wider loading conditions coverage. Based on these tests a complex material model covering elastic, plastic material behaviour as well as damage for various triaxiality states can be obtained. This kind of the material behaviour description allows a wide range of application from calculation of component limit loading conditions to material properties conversion for samples of different sizes e.g. [Dzugan 2015a, Spaniel 2014, Kubik 2013].

Ductile damage describes properties deterioration due to monotonic loading here. Phenomenological material models describing ductile damage in continuum mechanics mostly introduce extension of plasticity models. From the coupling plasticity and failure description point of view two types of material models can be distinguished. Uncoupled models separate plastic response from influence of ductile damage and failure. Coupled models modify plastic response in dependence on damage evolution. The coupled models have huge potential, but calibration costs results in small application. Easier calibration process where plasticity and damage can be separated is an essential advantage of uncoupled material models. Recently there are also research activities dealing with miniaturized specimens' application to ductile damage parameters determination in cases when e.g. local properties are being assessed as it was demonstrated by Ribadas [Ribadas 2015].

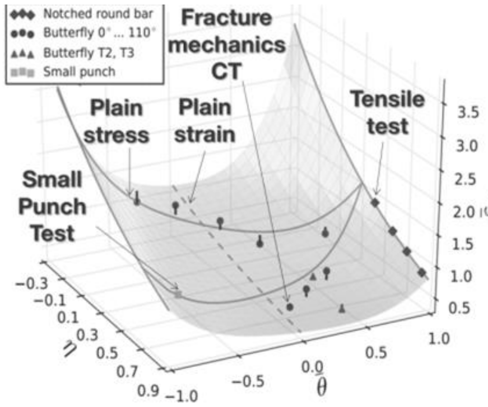


Figure 1. Fracture locus

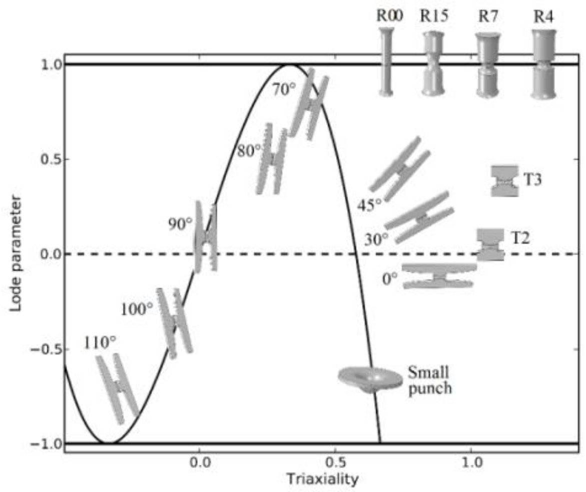


Figure 2. Calibration specimens portfolio

Material models shown here are based on both classical incremental model of plastic response with isotropic hardening and phenomenological concept of damage in continuum mechanic. Two example of complex material models are shown here, well known Johnson-Cook [Johnson 1985] and more recent Xue-Wierzbicki [Xue 2007, Wierzbicki 2005] that is being widely used recently. Johnson-Cook model in general form is given in **Eq. (1).** This model is taking into account mainly triaxiality, but can also consider temperature, plastic strain or strain rate by adding more terms.

$$\overline{\varepsilon_f}(\eta,\dot{\overline{\varepsilon_{pl}}},\hat{T}) = [d_1 + d_2 e^{-d_3\eta}]\left[1 + d_4 \ln\left(\frac{\dot{\overline{\varepsilon_{pl}}}}{\dot{\varepsilon_0}}\right)\right](1 + d_5\hat{T}) \quad (1)$$

In [Wierzbicki 2005] was introduced extended dependence of the fracture strain on triaxiality by a third invariant of the stress deviator – the Lode parameter, **Eq. (2)**.

$$\bar{\varepsilon}_f(\eta,\bar{\theta}) = \frac{1}{2}[(D_1 e^{-D_2\eta} + D_5 e^{-D_6\eta}) - D_3 e^{-D_4\eta}]\bar{\theta}^2 + \frac{1}{2}(D_1 e^{-D_2\eta} - D_5 e^{-D_6\eta})\bar{\theta} + D_3 e^{-D_4\eta} \quad (2)$$

The artificial degradation function described by parameter of degradation D is implemented in order to guarantee sufficient smoothness of fracture process simulation. It is based on gradual loss of stiffness in the material point. The stress triaxiality η can be expressed by **Eq. (3).**

$$\eta = -\frac{p}{q} \quad (3)$$

where p is hydrostatic stress and q is Von Mises stress defined by **Eqs. (4)**

$$p = -\frac{1}{3}tr(\sigma) \qquad q = \sqrt{3J_2} \quad (4)$$

Lode parameter ξ, or normalized Lode parameter can be expressed by **Eqs. (5).**

$$\xi = \frac{27}{2}\frac{J_3}{q} \qquad \bar{\theta} = \frac{6\theta}{\pi} = 1 - \frac{2}{\pi}\arccos\xi \quad (5)$$

Failure criterion for described models is based on phenomenological quantity damage ω that is defined as non-decreasing scalar parameter, **Eq. (6).**

$$\omega = \int_0^t \frac{\dot{\overline{\varepsilon_{pl}}}}{\overline{\varepsilon_f}(\eta,\xi)}dt \quad (6)$$

it depends on loading history and can be understood as linear accumulation of incremental damage in process of monotonic loading. Ductile failure initiation of material point occurs as soon as critical damage value ω_{crit} is reached. Usually fracture locus is calibrated to reach material failure when damage equals unity, so $\omega_{crit} = 1$. In this case fracture locus has physical meaning of accumulated plastic strain at the instant of material point failure initiation.

The accumulated intensity of plastic strain, resp. accumulated plastic strain, **Eq. (7).**

$$\overline{\varepsilon_{pl}} = \int_0^t \dot{\overline{\varepsilon_{pl}}}dt \qquad \text{where} \quad \dot{\overline{\varepsilon_{pl}}} = \sqrt{\frac{2}{3}\dot{\varepsilon_{pl}}:\dot{\varepsilon_{pl}}} \quad (7)$$

3 STRESS STRAIN BEHAVIOUR DESCRIPTION OF SHEETS

The material behaviour description in the case of metal sheets for forming is based on the concept of the flow limit curve (FLC) diagram introduced by Keeler and Goodwin [Goodwin 1968, Keeler 1975]. It is a criterion of sheets formability in terms of safety for deep drawing operation. The diagram determination is given by the standard ISO 12004 [EN ISO12004-2] including evaluation with regards to modern methods of digital image correlation (DIC). The vertical axis in the diagram represents major strains of tensile deformation φ1, while the horizontal axis represents minor strain values ± φ2. The advantage of this procedure is fairly easy interpretation of the ultimate strain diagram which could be used for post-processing for deep drawing simulation FEM programs. The result and goal of this procedure is the critical areas identification, i.e. those which are located in the area of thinning or even fracture.

Based on a deeper analysis of explanatory power of FLC diagram, one can see that it more represents the deformability from a practical-technical point of view rather than from the perspective of ductile damage. Another disadvantage is that it only represents linear loading path regardless of whether it is created on the basis of Nakazima or Marciniak approach [Nakazima 1968, Marziniak 1973]. The actual deformation at a certain point of the stamped sheet metal part surface may be achieved through linear and nonlinear strain path depending on the shape and number of operations. Therefore, assessment of the load path impact is crucial. This impact increases in the case of high-strength steel, when the transition between the formation of plastic instability ("neck") and the fracture is in very narrow range.

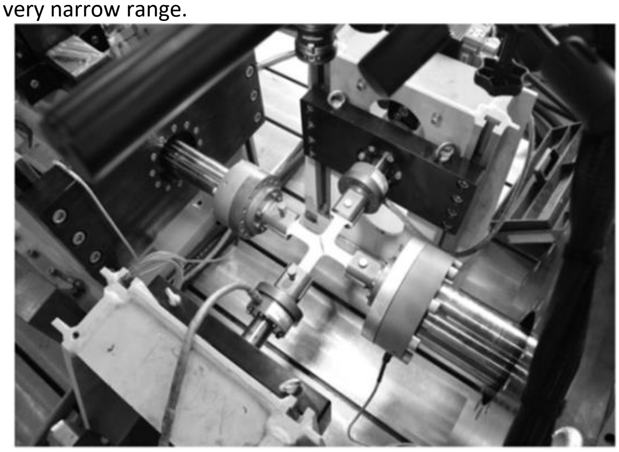
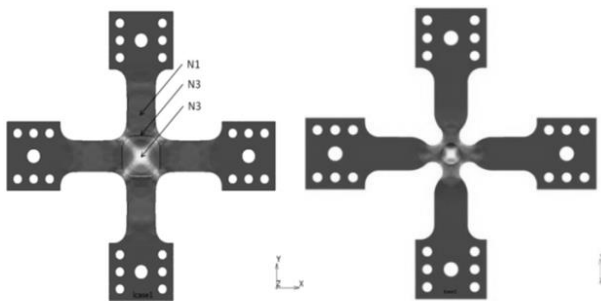


Figure 3. Four pistons testing device with cruciform specimen



a) b)

Figure 4. Specimen design for various sheet thicknesses: a) Thickness > 1mm, b) - Thickness < 1mm

There are different procedures for the load paths impact assessment. In the literature there are mentioned procedures where tests based on Nakazima are performed for each samples geometry up to a certain degree of deformation and consequently a deformed shape is cut to get a new specimen to complete the test. In this way, the deformation path variations are taken into consideration. It is apparent from the description, that there are certain inaccuracies and uncertainty. Another possible approach is using biaxial test. The biaxial test was normalized in order to obtain the yield surface based on the work of Kuwabara [Kuwabara 2002] standardised in [ISO 16842]. The limit strain diagram measurement through biaxial tests with cross-shaped samples is summarized in [Zidane 2010, Tasan 2008]. Basically what is necessary is appropriate testing system and specimen geometry. Testing system should have four independent actuators with suitable force, displacement and velocity ranges, Fig. 3. Moreover, digital image correlation system for strain measurement in the course of the test is necessary. Concerning the appropriate specimen geometry, specimen assuring fracture at desired region under the considered multiaxial loading conditions has to be defined for the material of interest. Examples of successful specimen geometries are shown in Fig. 4. An interesting cross shape was designed in [Mitukiewicz 2016], using the ribs increasing strength in the arms without affecting the centre of the cross. The identification of the ultimate strain diagram (FLD) can be performed with the use of several methods. The most up to dated one is deformation time change according to Hora [Hora 2009]. It was applied for evaluation in **Fig 5**. The figure shows significant influence of the loading path on the material strain behaviour that is crucial for the forming processes optimization.

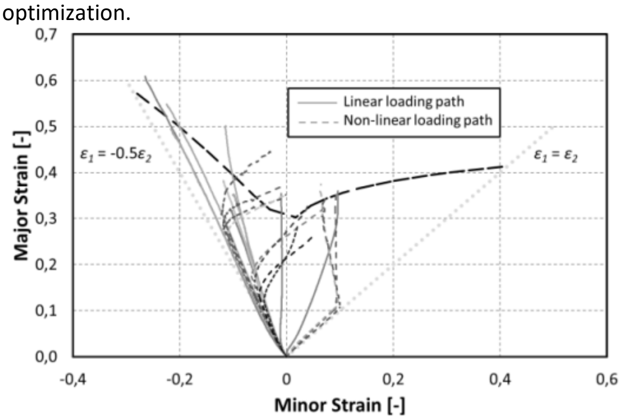
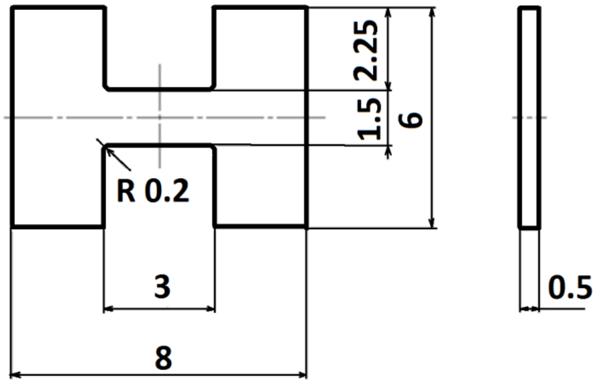


Figure 5. Comparison of FLC and cruciform tests with linear and nonlinear loading path.

4 MINI TENSILE SPECIMENS

There are many cases when shortage of the experimental material prevents mechanical properties characterization with the use of standard sized specimens. Therefore increasing demand on materials characterization together with improvements in testing apparatus lead to development of new testing procedures such as sub-size specimens testing. Miniaturized specimens allow reliable properties determination while using very small material amount. The application of these methods is especially for new materials development, evaluation of residual service life, developments of a new thermal and thermo-mechanical procedures or evaluation of local properties evaluation or anisotropy.



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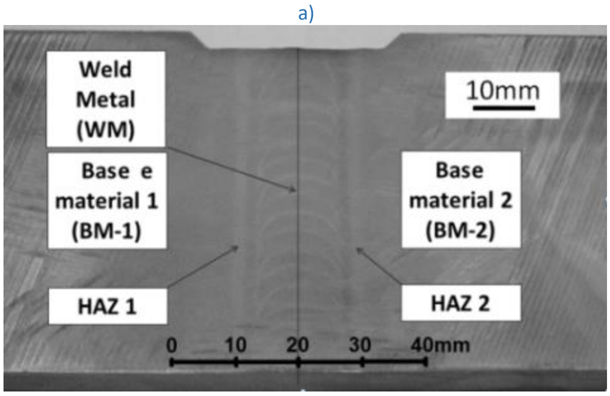


b)

Figure 6. a) Flat micro-tensile test specimen, b) Macro of the investigated heterogeneous weld

The sub-sized tensile testing was verified in [Dzugan 2014] and applied in [Dzugan 2015b , Prochazka 2015, Rund 2015, Konopik 2014, Konopik 2013, Konopik 2015]. The specimen geometry is shown in Fig. 6a). It is applied here to heterogeneous weld characterisation under quasi-static loading conditions at room temperature. Sampling was performed across the weld from one basic material to the other one with step of 1mm, Fig. 6b). Obtained values of tensile tests characteristics across the weld are summarized in Fig. 7. The advantage of local properties measurement is demonstrated on three point bending of weld, where model with local properties is confronted with usually used global properties of base materials and weld metal only, without consideration of gradual properties change. FEM model with local properties is depicted in Fig. 8a). Comparing obtained force-displacement response with experimental results, clearly confirms excellent agreement between real experiment and FEM simulation when local properties are considered, Fig. 8b). More details about these investigations can be found in [Konopik 2017].

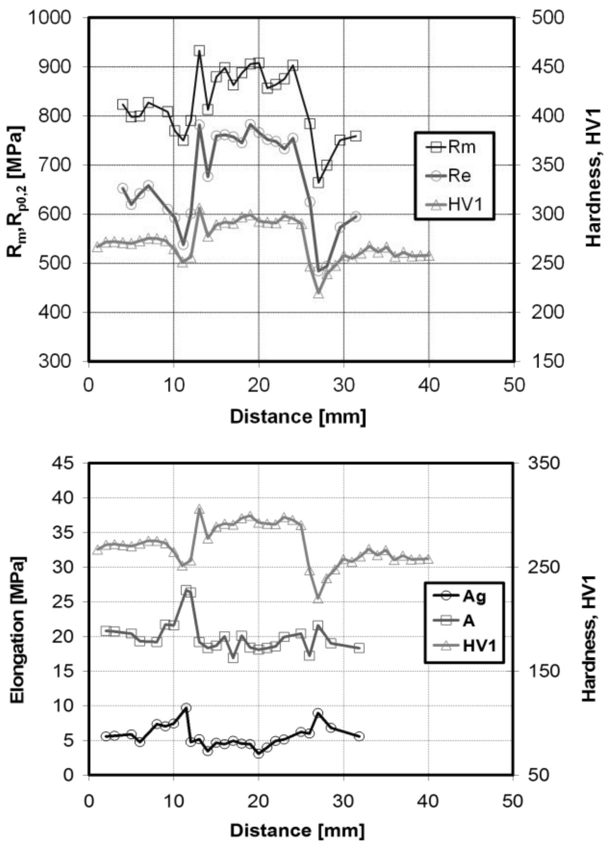
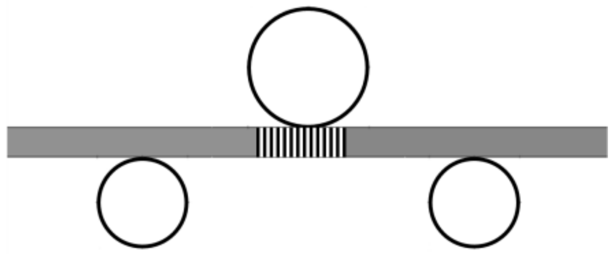


Figure 7. Results of M-TT and hardness measurement across weld for strength and plastic behavior characteristics



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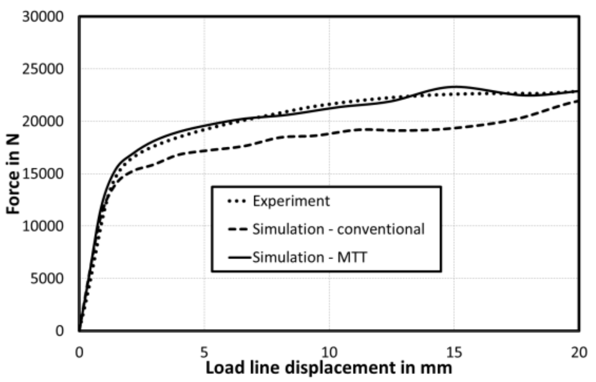

b)

Figure 8. a) FEM model with depicted local zones with assigned specific properties b) Comparison of results obtained from FEM simulations and experimental tests

5 CONCLUSION

The paper gives brief overview of advanced material models and material characterization possibilities for progressive design. Complex material models considering plasticity and damage are shown in the first part together with possible experiential procedures for their fitting. Following part is dealing with advanced sheet characterization based on multiaxial loaded cruciform specimens that can be applied to linear as well as nonlinear loading path influence on plastic behaviour. There is also shown successful testing set up and test piece geometries for these investigations. The last part presents micro tensile test technique used for determination of local properties. This is very powerful tool for materials and components characterization under various loading conditions (temperatures, rates, orientations) that can be effectively used without any significant cost requirements. More details about topics presented here can be found in the references provided.

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REFERENCES

[Bai 2008] Bai, Y., Wierzbicki, T.: A new model of metal plasticity and fracture with pressure and Lode dependence, Int. Journal of Plasticity 2008, vol. 24, pp.1071–1096, ISSN: 07496419.

[Bai 2010] Bai, Y., Wierzbicki, T.:Application of extended Mohr–Coulomb criterion to ductile fracture, Int J Fract, 2010, Vol. 161, pp. 1–20, ISSN: 03769429.

[Bao 2004] Bao, Y., Wierzbicki, T.: A Comparative Study on Various Ductile Crack Formation Criteria, in Transactions of the ASME, 2004, Vol. 126, pp.314-324, ISSN: 00944289.

[Goodwin 1968] Goodwin, G.: Application of strain analysis to sheet metal forming problems in the press shop, Society of Automotive Engineers, 1968, No. 680093,pp. 380-387.

[Johnson 1985] Johnson, G.R., Cook, W.H.: Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures, Engineering Fracture Mechanics, 1985, 21(1), pp. 31-48, ISSN: 00137944.

[Dzugan 2014] Dzugan, J., Prochazka, R., Konopik, P.: Micro-Tensile Test Technique Development and Application to Mechanical Property Determination, Small Specimen Test Techniques, 2014, ASTM STP 1576, 6th Volume, pp. 12-29, doi:10.1520/STP157620140022.

[Dzugan 2015a] Dzugan, J., et al.: Identification of ductile damage parameters for pressure vessel steel. Nucl. Eng. Des., 2015, http://dx.doi.org/10.1016/j.nucengdes.2015.12.014

[Dzugan 2015b] Dzugan, J., et al.: Determination of Local Tensile and Fatigue Properties With the Use of Sub-Sized Specimens, in ASME 2015 PVP Conference Volume 1A: Codes and Standards, Boston, Massachusetts, USA, July 19–23, 2015, ISBN: 978-0-7918-5692-5, Paper No. PVP2015-45958, pp. V01AT01A066; 8 pages, doi:10.1115/PVP2015-45958"

[Hora 2009] Hora, P., Eberle, B. Volk, W.: Numerical method for a robust user-independent evaluation of Nakajima tests for the FLC determination, In IDDRG International Conf., 2009, Golden CO, USA

[Keeler 1975] Keeler, S. P., Brazier, W. G.: Relationship between laboratory material characterization and press-shop formability, Micro Alloying, 1975, pp. 21-32.

[Konopik 2013] Konopik, P., Dzugan, J., Prochazka, R.: Determination of fracture toughness and tensile properties of structural steels by small punch test and micro-tensile test, in Metal 2013, 2013, Brno, Czech R., ISBN: 978-808729441-3.

[Konopik 2014] Konopik, P., Dzugan, J., Prochazka,R. Evaluation of local mechanical properties of steel weld by miniature testing technique, in Materials Science and Technology Conf. and Exh. 2013, MS and T 2013; Montreal, QC; Canada; 2014, Vol. 4, pp. 2404-2411, ISBN: 978-162993309-2.

[Konopik 2017] Konopik el al. : Use of micro-tensile tests results for improvement of FEM simulation of steel weld, in Metal 2017, May 2017, Brno, Czech Republic.

[Kubik 2013] Kubik, P., el al.: Calibration of Selected Ductile Fracture Criteria Using Two Types of Specimens, Key Engin. Materials, 2013, Vol. 592-593, pp.258-261, ISSN: 1662-9795,

[Mitukiewicz 2016] Mitukiewicz, G., Glokowski, M. : Cruciform specimen to obtain higher plastic deformation in a gauge region, Journal of Materials Processing Technology, 2016, 227, pp. 11-15, ISSN: 09240136.

[Kuwabara 2002] Kuwabara, T., Van Bael, A., Iizuka, E. Measurement and analysis of yield locus and work hardening characteristics of steel sheets wtih different r-values, Acta Materialia, 16 Aug. 2002, Volume 50, Issue 14, pp 3717-3729, ISSN: 13596454.

[Li 2009] Li, Y., Wierzbicki, T. Mesh-size Effect Study of Ductile Fracture by Non-local Approach, In Proceedings of the SEM Annual Conference June 1-4, Albuquerque New Mexico USA, SBN: 978-161567189-2;978-161567189-2.

[Marziniak 1973] Marciniak, Z., Kuczynski, K., Pokora, T. Influence of the plastic properties of a material on the forming limit diagram for sheet metal in tension, International Journal of Mechanical Sciences, October 1973, Volume 15, Issue 10, Pages 789-800, ISSN: 00207403.

[Nakazima 1968] Nakazima K, Kikuma T, Hasuka K. Study on the formability of steel sheets, Yawata Tech Report, September 1968, Issue 264, pp. 8414-8442.

[Prochazka 2015] Prochazka, R., Dzugan, J., Kover, M. Miniature specimen tensile testing of AZ31 alloy processed by ECAP, Archives of Materials Science and Engineering, December 2015, Volume 76, Issue 2, pp. 134-139, ISSN: 18972764.

[Ribadas 2015] Ribadas, H.F., Rund, M.: Evaluation of Ductile Fracture Using Micro-samples, Procedia Engineering, 2015, Volume 114, pp. 377-384, ISSN: 18777058.

[Rund 2015] Rund, M., et al : Investigation of Sample-size Influence on Tensile Test Results at Different Strain Rates, Procedia Eng., 2015,Vol. 114, pp. 410-415, doi:10.1016/j.proeng.2015.08.086.

[Tasan 2008] Tasan, C.C., Hoefnagels, J.P.M., Quaak, G., Geers M.G.D. In-Plane Biaxial Loading of Sheet Metal until Fracture, in Proc. of the XI Int. Cong. and Exp., Orlando, USA, 2008,June 2-5, ISBN: 978-160560415-2.

[Spaniel 2014] Spaniel, M. et al. Calibration of fracture locus in scope of uncoupled elastic–plastic-ductile fracture material models, Advances in Engineering Software, June 2014, Vol. 72, pp.95-108, ISSN: 09659978.

[Wierzbicki 2005] Wierzbicki ,T. et al. Calibration and evaluation of seven fracture models, International Journal of Mechanical Sciences, 2005, 47, pp. 719–743, ISSN: 00207403.

[Xue 2007] Xue, L.: Damage accumulation and fracture initiation in uncracked ductile solids subject to triaxial loading, International Journal of Solids and Structures, August 2007, Volume 44, Issue 16, pp. 5163-5181, ISSN: 00207683.

[Zidane 2010] Zidane, I., Guines, D., Leotoing, L. Ragneau, E. Development of an in-plane biaxial test for forming limit curve (FLC) characterization of metallic sheets, Measurement Science and Technology, 2010, 21, pp.1-11.

[EN ISO12004-2] EN ISO12004-2: Metallic materials -- Sheet and strip -- Determination of forming-limit curves -- Part 2: Determination of forming-limit curves in the laboratory

[ISO 16842] ISO 16842 Metallic materials -- Sheet and strip -- Biaxial tensile testing method using a cruciform test piece

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