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Identification of Ductile Damage Parameters for Austenitic Steel

J. Dzugan, M. Spaniel, P. Konopík, J. Ruzicka, J. Kuzelka

Abstract—The modeling of inelastic behavior of plastic materials requires measurements providing information on material response to different multiaxial loading conditions. Different triaxiality conditions and values of Lode parameters have to be covered for complex description of the material plastic behavior. Samples geometries providing material plastic behavoiur over the range of interest are proposed with the use of FEM analysis. Round samples with 3 different notches and smooth surface are used together with butterfly type of samples tested at angle ranging for 0 to 90°. Identification of ductile damage parameters is carried out on the basis of obtained experimental data for austenitic stainless steel. The obtained material plastic damage parameters are subsequently applied to FEM simulation of notched CT normally samples used for fracture mechanics testing and results from the simulation are compared with real tests.

Keywords—baqus, austenitic steel, computer simulation, ductile damage, triaxiality.

I. Introduction

THE computer simulations in the field of design and safety assessment represent very powerful tools, but are strongly limited by available material models and material input data. Most of the current calculations are performed on the basis of standard tensile tests, if not only on database data or data from literature. Such a material description is not sufficient for accurate design assessment. Standard tensile test is mainly based on uniaxial sample loading and more complex loading appears after material necking, in case of ductile materials. However, the state after necking is not properly evaluated by standard testing procedure using mechanical extensometer for strain measurement. The standard tensile test results are useful for elastic solutions or elastic-plastic solution for small plastic strains. If states near to fracture are to be considered, more complex material description is necessary, taking into account multiaxial loading conditions [1]-[5]. Thus samples of various geometries and tested under various loading modes has to be used. On the basis of these tests a complex material behavior model covering elastic and plastic material behavior for various triaxiality states can be obtained.

J. Dzugan is with the COMTES FHT Inc., Dobrany, 334 41, The Czech Republic (phone: +420-775-201-421; fax: +420-377-197-310; e-mail: jan.dzugan@comtesfht.cz).
M. Spaniel is with Czech Technical University, Prague, The Czech Republic. (e-mail: miroslav.spaniel@fs.cvut.cz).
P. Konopík is with the COMTES FHT Inc., Dobrany, 334 41, The Czech Republic (e-mail: pavel.konopik@comtesfht.cz).
J. Ruzicka is with Czech Technical University, Prague, The Czech Republic. (e-mail: jan.ruzicka@fs.cvut.cz)
J. Kuzelka is with Czech Technical University, Prague, The Czech Republic. (e-mail: jiri.kuzelka@fs.cvut.cz)

This would allow a wide range of application from calculation of component limit loading conditions, over calculation of the properties, that could not be directly measured on available amount of the experimental material in cases when restricted amount of the materials is available, to material properties conversion for samples of different sizes.

Current paper is dealing with ductile damage parameters determination for austenitic steel. There will be chosen appropriate samples geometries based on the FEM stress state analyses of samples at first. Subsequently testing of proposed samples is performed and material parameters are evaluated. The obtained material plastic damage parameters are subsequently applied to FEM simulation of notched CT samples used for fracture mechanics testing and results from the simulation are compared with real tests of the sample simulated.

II. Experimental samples proposal

The modeling of inelastic behavior of plastic materials requires measurements providing information on material response to different multiaxial loading conditions. This can be obtained by various samples geometries and loading modes resulting in different stress triaxialities and values of Lode parameter. On the basis of literature survey [1]-[9] there were proposed samples geometries that were subsequently analyzed with the use of FEM and triaxiality and Lode parameter were identified for these samples. Finally, following set of samples was proposed for ductile damage material parameters description: smooth tensile samples, notched tensile samples with notch radius 1, 2 and 4mm and butterfly type of specimens used in [7]. Tensile samples were in all cases of minimal diameter 12mm. Butterfly samples were proposed to be used at angles 0, 30, 45, 70, 80 and 90° in tension. This set of samples was supposed to cover necessary range of triaxialities and values of Lode parameter. Samples geometries are shown in Figs. 1 – 2.

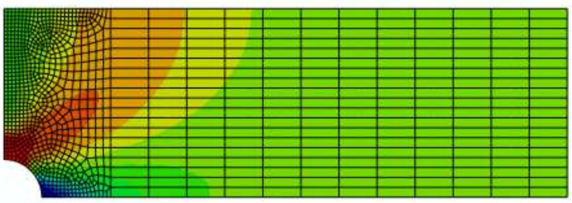

Fig. 1 Quarter of notched tensile sample – 1mm notch radius

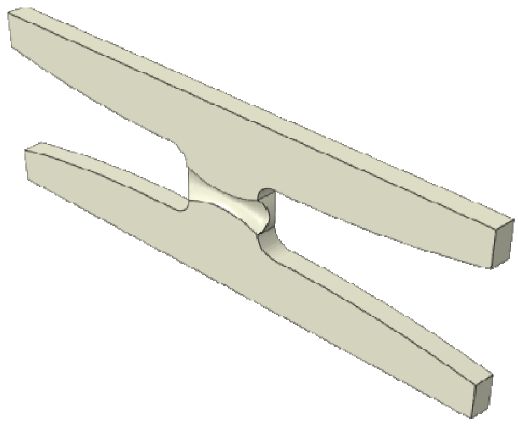

Fig. 2 Butterfly sample

III. Testing

There are tensile tests and tests of butterfly type of samples to be executed. In the case of tensile samples, standard procedure and fixtures can be employed. While in the case of butterfly type of samples, testing fixture had to be designed at first and subsequently manufactured prior to tests execution. The fixture preparation was successfully completed and fixture was successfully tested in the testing system. All current tests were done under quasi-static loading conditions at room temperature on servohydraulic testing system MTS 810.

In order to obtain maximum information from the tests, next to standard mechanical extensometer also high speed camera was used for all tests. The recordings enable later evaluation of strains at certain points and evaluation of necking during tensile tests. In the case of butterfly samples displacements at six points directly on the sample were determined. Testing set up for butterfly samples is shown in Fig. 3.

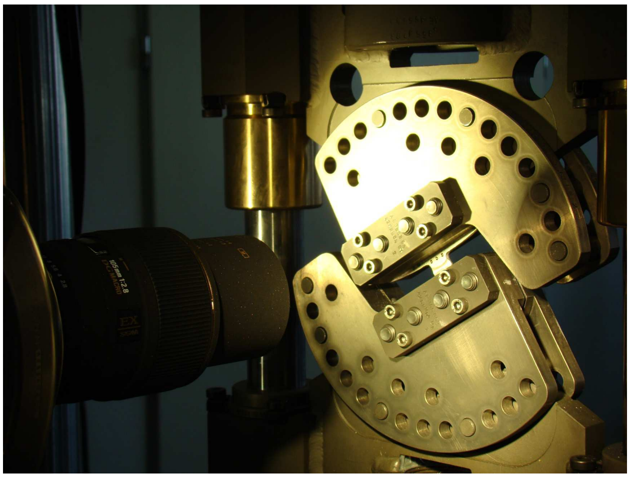

Fig. 3 Testing set up for butterfly samples

Records obtained for round samples and butterfly type of samples is shown in Figs. 4 and 5.

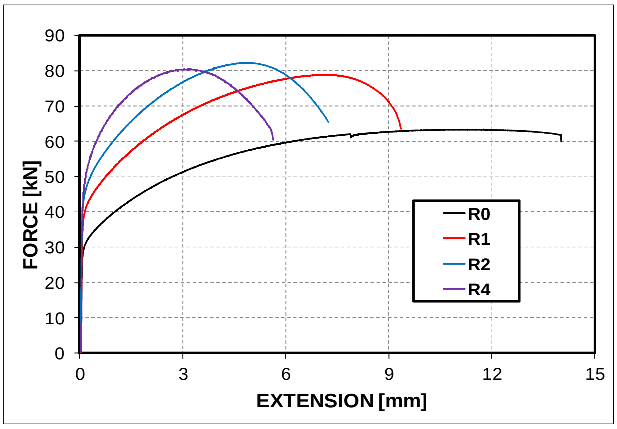

Fig. 4 Records of tensile tests

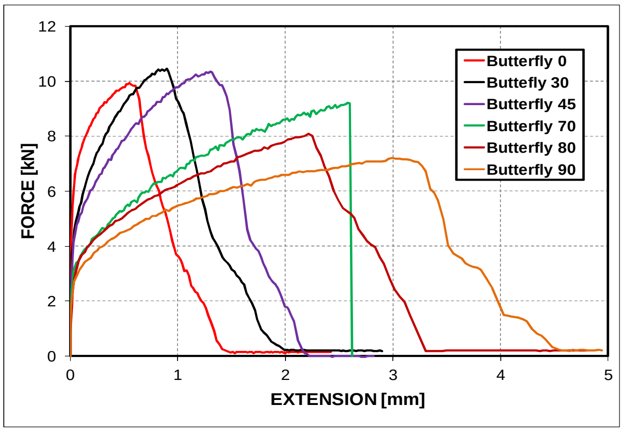

Fig. 5 Records of tests of Butterfly type of samples tested at different angles

It appears to be useful to have for the first guess of the plasticity curve determination a true stress - true strain diagram, thus there was additionally measured smooth tensile sample with video recording for this purposes. This test was executed with partial unloadings that were aimed to be used for damage evaluation, but this evaluation was not performed so far. Evaluated true stress-true strain diagram is shown in Fig. 6.

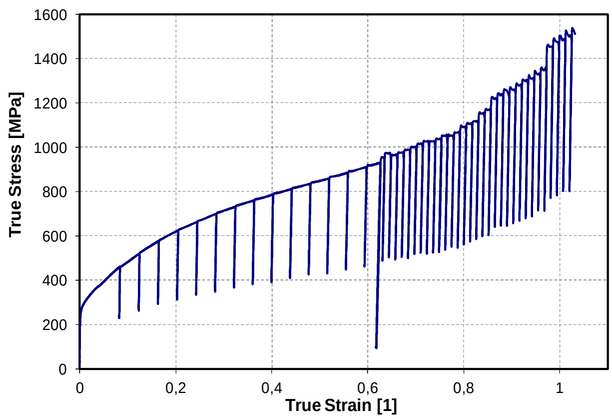

Fig. 6 Measured True stress true strain diagram

IV. Ductile Damage Parameters Identification

In the current investigations standard simplified model of metal plasticity is used, based on the second deviatoric stress invariant. The model is using von Misses plasticity plane with associated law of plastic flow with isotropic hardening. This simplified model shall yield satisfactory results for considered monotonic loading. The simulations are done in ABAQUS.

Continuum damage concept is assuming that response of damaged material is based on the response of the original material. Geometric and physical damage parameters are not described on the micro scale, but are using a fictive scalar damage parameter ω, that can be expressed by accumulation of plastic deformation, Eq. 1.

$$\omega = \int_0^{\varepsilon_c} f\left(p, q, \xi, T, \varepsilon, \dot{\varepsilon}\right) \mathrm{d}\varepsilon^{pl} \tag{1}$$

where is:

- $\boldsymbol{p}$ hydrostatic pressure
- $\boldsymbol{q}$ Von Misses stress invariant
- $\boldsymbol{\xi}$ Lode parameter
- T temperature
- $\boldsymbol{\varepsilon}$ strain
- $\dot{\varepsilon}$ strain rate

Failure criterion is usually expressed in normalized form ω =1. In the cases where damage had feedback to material elastic-plastic behavior, coupled model is considered for continuum damage, otherwise there is uncoupled model.

The experimental findings in the field of metals ductile damage have shown that the second deviatoric stress invariant has influence on the failure as well as hydrostatic pressure and Lode parameter [1]-[5], [7]. The hydrostatic pressure is covered by triaxiality which is expressed in following form:

$$\eta = \frac{-p}{q} \tag{2}$$

Thus the Eq. 1 can be rewritten into:

$$\omega = \int_0^{\varepsilon_c} f\left(\eta, \xi, T, \varepsilon, \dot{\varepsilon}\right) \mathrm{d}\varepsilon^{pl} \tag{3}$$

If damage process in the course of deformation is evenly distributed, the function $\boldsymbol{f}$ is independent of strain level $\boldsymbol{\varepsilon}$, it is possible to describe damage by:

$$\omega = \int_0^{\varepsilon_c} \frac{\mathrm{d}\varepsilon^{pl}}{\varepsilon_D^{pl}\left(\eta, \xi, T, \dot{\varepsilon}\right)} \tag{4}$$

where ε_D^{pl} is accumulated plastic deformation intensity at which failure takes place if constant values of η, ξ, T and $\boldsymbol{\varepsilon}$ are used for hypothetical calibration experiment.

Calibration parameters of plasticity and damage are searched on the basis of real tests results and their FEM simulations. The aim of the calibration is to find material parameters that, if used for FEM simulation, provide as close results to real tests as possible. The measure of calibration accuracy is area between measured and calculated curve force versus displacement as shown in **Fig. 7**. The smaller area, the better is the calibration.

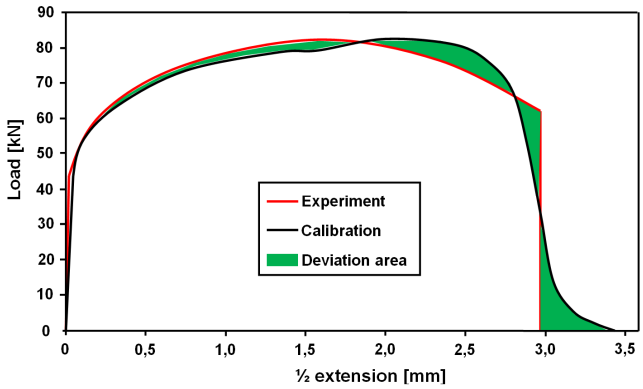

Fig. 7 Area between experimental and FEM curve

Plasticity and ductile damage calibration is done with the use of open optimization scripts in Python, that can minimize the function by change of the variables. The calibration scripts are based on simplex algorithm of local optimization. This algorithm allows simultaneous multiple parameters optimization. The optimization uncertainty and demand on computing capacity is strongly increasing with increasing number of variable parameters. Therefore, there is always a tendency to use model with minimum of parameters for optimization. Disadvantage of the local optimization is a high demand on the accuracy of the initial estimate of parameters. Simplex algorithm assures local minimum of target function only.

The investigations here are performed with the use of ABAQUS FEM package. It has implemented fenomenologic model of continuum damage as an add-in to classic metal plasticity models. These models are not coupled, thus there are higher requirements on the plasticity models, but in the current case of the monotonic loading, this obstacle doesn´t play a significant role. The main problem is that there is not implemented Lode-parameter. In the current work Von Misses plasticity model with isotropic hardening is used together with uncoupled ductile damage model. Taking into account slow monotonic loading at room temperature, one can rewrite ***Eq. 4*** into following form:

$$\omega = \int_0^{\varepsilon_c} \frac{\mathrm{d}\varepsilon^{pl}}{\varepsilon_D^{pl}\left(\eta, T = 20^{\circ}C, \dot{\varepsilon} \to 0\right)} \tag{5}$$

The above mentioned plasticity model requires calibration of the actual yield stress in relation to accumulated plastic energy intensity, which can be expressed as:

$$\sigma_Y^{True} = \sigma_Y^{True}(\varepsilon_{\ln}^{pl}) \tag{6}$$

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As an initial estimate of the relation of the actual yield stress on accumulated plastic deformation, the true stress-true strain tensile curve of the smooth tensile sample was used. There were applied two parametrization techniques:

1. The curve is described by analytical function with parameters *A*, *B* and *n*.

$$\sigma_Y^{True} = A + B(\varepsilon_{\ln}^{pl})^n \tag{7}$$

2. The curve is described by initial sequence of points $(\sigma_Y^{*True}, \varepsilon_{\ln}^{*pl})_i$ with variable parameters A_0, A_1, B:

$$\sigma_{Y,i}^{True} = A_0 + A_1\sigma_{Y,i}^{*True}, \quad \varepsilon_{\ln,i}^{pl} = B\varepsilon_{\ln,i}^{*pl} \tag{8}$$

Considering dependency of material damage on triaxiality and Lode parameter, it is necessary to perform calibration experiments on samples with various pre-mentioned parameters. Plasticity parameters identification is done on the same samples population in order to assure the best average agreement of the plastic response for varying material loading conditions.

The calibration procedure is schematically described in Fig. 8.

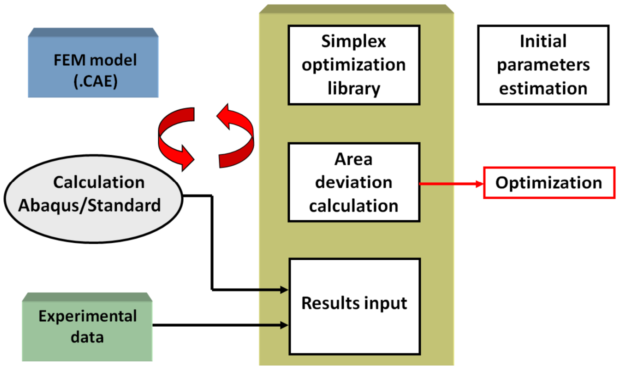

Fig. 8 Calibration procedure

It is clear from the Eq. 5, that failure description has to be done on the basis of calibration of the accumulated intensity of the plastic deformation in relation to triaxiality $\varepsilon_D^{pl} = \varepsilon_D^{pl}(\eta)$. Parametrization of this relation can be done for example according to Johnson-Cook model in following form:

$$\varepsilon_D^{pl} = D_1 + D_2 e^{D_3\eta} \tag{9}$$

Parameters D_1, D_2 and D_3 can be calibrated by target function minimization.

$$F = \sum_i |1-\omega_i|, \quad \omega_i = \max_j \left[\int_0^{\varepsilon_i^{pl*}} \frac{d\varepsilon_{i,j}^{pl}}{\varepsilon_D^{pl}(\eta_{i,j})}\right]_j \tag{10}$$

where index ***i*** represents types of the experimental samples and ***j*** finite elements in target area of samples.

With the use of above mentioned procedure ductile damage parameters were determined. A comparison of curves for selected samples obtained with optimized set of parameters based on whole population of the experimental samples with experimental curves can be found in Figs. 9 to 15.

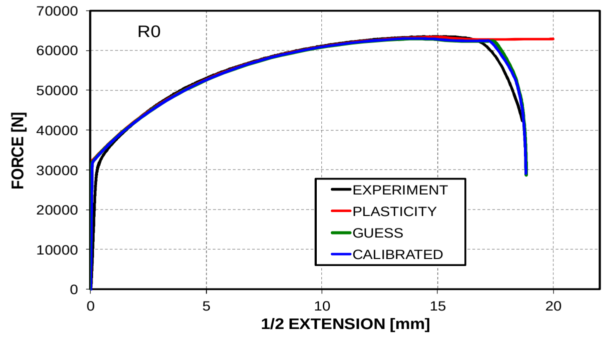

Fig. 9 Comparison of the experimental curve with calibrated curve – smooth sample

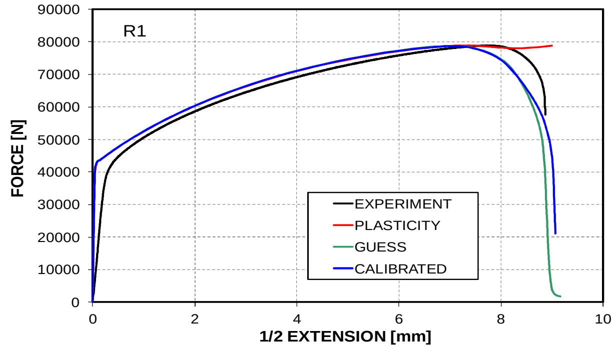

Fig. 10 Comparison of the experimental curve with calibrated curve – R1

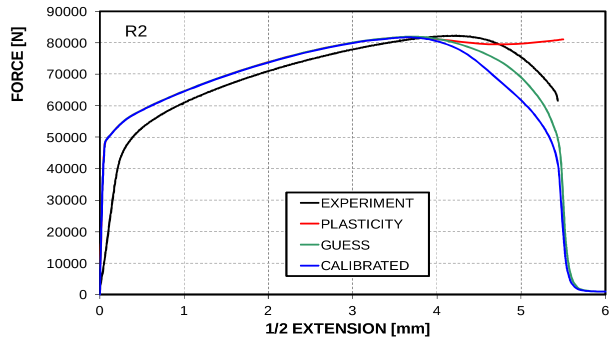

Fig. 11Comparison of the experimental curve with calibrated curve – R2

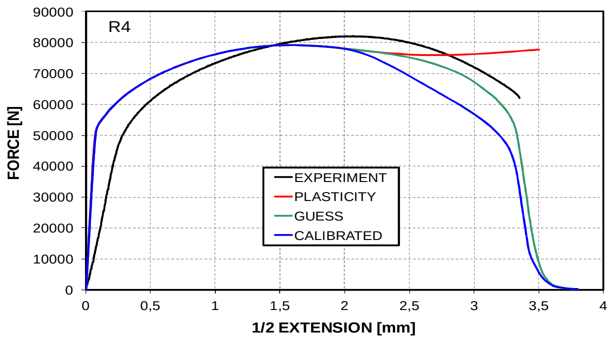

Fig. 12 Comparison of the experimental curve with calibrated curve – R4

Comparison of the experimental and the calculated curves shows difference in displacement. This difference is originating from the fact that measured extension is taken from the crosshead and thus the whole testing system compliances are included in the record. The optimization itself was done for plastic part of the curve in coordinates force versus plastic deformation and there can be found significantly better agreement.

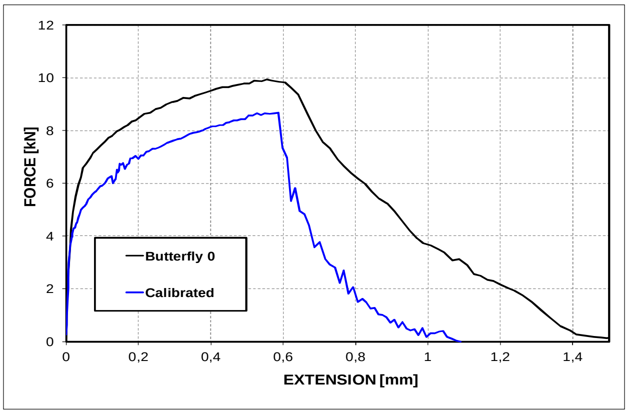

Fig. 13 Comparison of the experimental curve with calibrated curve – Butterfly 0°

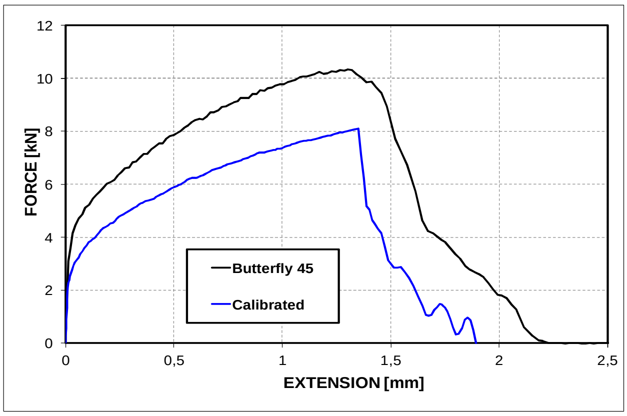

Fig. 14 Comparison of the experimental curve with calibrated curve – Butterfly 45°

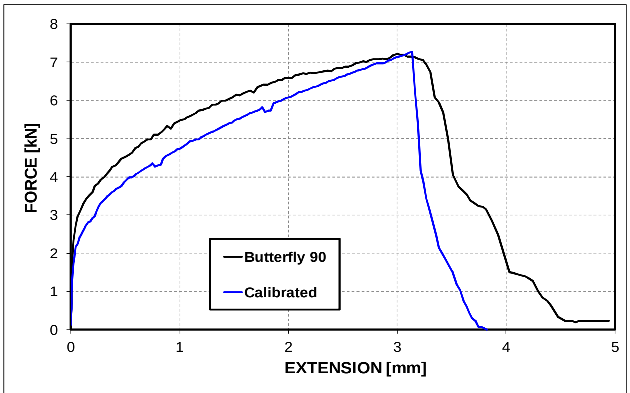

Fig. 15 Comparison of the experimental curve with calibrated curve – Butterfly 90°

A curve describing plasticity in relation to triaxiality was constructed on the basis of the experimental tests and computer simulation. The obtained curve is shown in Fig. 16.

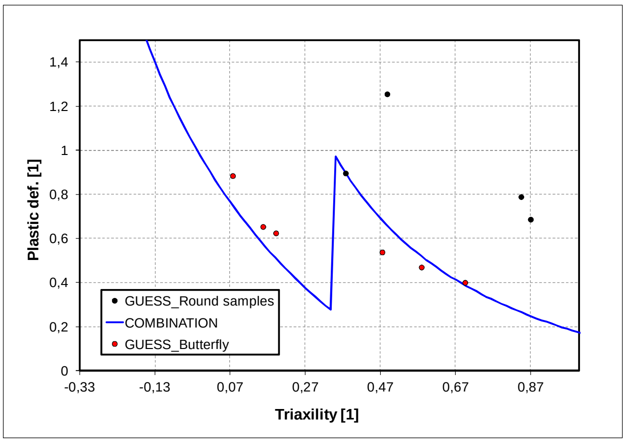

Fig. 16 Relation of plastic deformation to triaxiality

V. Verification

The verification of the applicability of the identified ductile damage parameters for the investigated steel was done by comparison of experimental test of complex sample with FEM simulation of the same sample. As a verification sample, Central Tension (CT) fracture mechanics sample of thickness 25,4mm was used. The CT samples for the current purposes were notched only without pre-crack. In this way large plastic deformation at the notch tip were attained. Testing was performed with the application of the unloading compliance technique enabling crack length monitoring in the course of stable crack growth during the test. Record of the test is shown in Fig. 17 together with results of FEM simulation. FEM calculation of the CT sample was executed with identified ductile damage parameters. There can be seen very good agreement between measured and simulated curves. In the course of the test although large plastic deformation, crack tip blunting appeared only. CT sample after test together with FEM model at the same state are displayed in Fig. 18. CT sample broken after test at liquid nitrogen temperature can be seen in Fig. 19. There is not visible any stable crack extension.

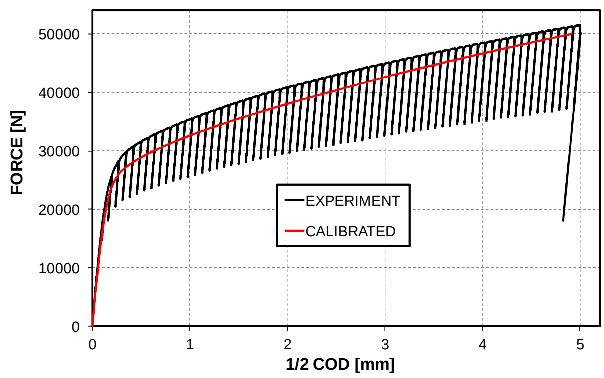

Fig. 17 Comparison experimental test of CT sample and FEM simulation

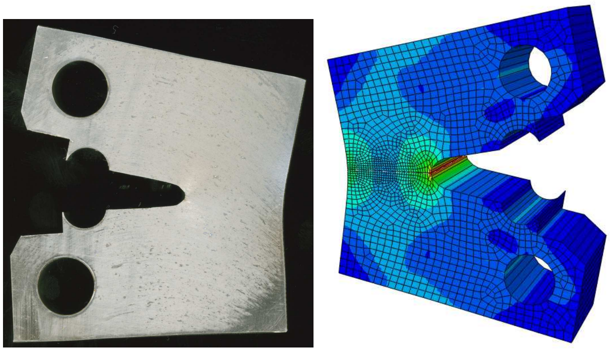

Fig. 18 Real sample and FEM model at the end of test

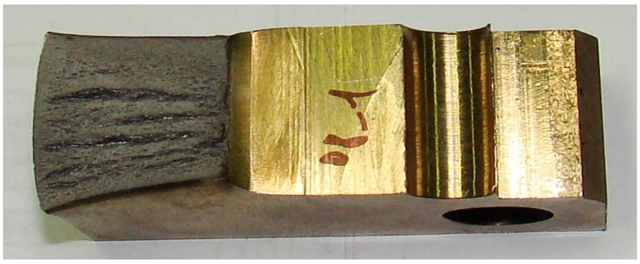

Fig. 19 CT sample after test without stable crack growth

VI. Conclusion

The paper deals with ductile damage parameters determination for austenitic steel. There were proposed samples geometries with various states of stress triaxialities and values of Lode parameter at first. These various conditions are necessary if a broad range of plastic behavior is to be covered. Round samples with notches of radius 1, 2 and 4 mm and smooth ones were tested together with butterfly type of samples tested at 6 different angles.

The experimental results served as a input data for ductile damage parameters identification. Plasticity and ductile damage parameters identification was done with the use of open optimization scripts in Python, that can minimize the function by change of the variables. A simplex based algorithm was used for local optimization. The optimization was done on the basis of minimization of the area between measured and calculated curves that was carried out for whole sets of the samples investigated simultaneously.

The identified ductile damage parameters were subsequently applied to simulation of 1in thick CT fracture mechanics sample. There were performed also experimental tests on CT samples. Very good agreement between experimentally measured curve and simulated one was found.

Current results are one of the first steps of the project. Further investigations will be carried out on material exhibiting stable crack growth at considered conditions. Also investigation of the materials ductile behavior will be carried out at increased temperature and dynamic loading conditions. A challenge is procedures development for ductile damage parameters identification based on measurements on miniature samples available in cases e.g. when remnant service evaluation of in service structures can be established is established.

Acknowledgment

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