Available online at https://journal.rescollacomm.com/index.php/ijqrm/index

International Journal of Quantitative Research and Modeling

e-ISSN 2721-477X
p-ISSN 2722-5046

Vol. 1, No. 2, pp. 59-66, 2020

A New Way to Identify Thin Sheet Behaviour: Micro-InDef

Pierrick Malécot, Gemala Hapsari, Sébastien Thibaud, Fabrice Richard

Univ. Bourgogne Franche-Comté, FEMTO-ST Institute, CNRS/UFC/ENSMM/UTBM, France
E-mail: pierrick.malecot@ens2m.fr, gemala.hapsari@femto-st.fr, sebastien.thibaud@ens2m.fr, fabrice.richard@univ-fcomte.fr

Abstract

Incremental forming is a rapid prototyping process which uses a forming tool to form a sheet metal according to a predetermined trajectory. In this work, a micro incremental deformation test (Micro InDef test) derived from the principle of single point incremental sheet forming is developed and proposed. A complex mechanical loading is applied and has a strong potential for the identification of inelastic behavior using inverse method. In the first part, this work addresses the parameters identification and validation procedures of ductile damage behavior of ultra-thin sheet metal under very large strain during this instrumented Micro InDef test. An inverse finite element method based on the comparison between numerical and experimental axial forming forces of the micro incremental deformation test is employed to extract a coupled ductile damaged plastic model. In the second part, the objective is to prove the reliability of ductile damage parameters identification using forming force. The richness of data contained in forming force is quantified and compared to the one from tensile test. Firstly, the verification of the estimated parameter's reliability is done via a simple analysis based on the forming force sensitivity to material parameters and secondly by calculating elastoplastic and elastoplastic with ductile damage.

Keywords: Incremental forming, Micro InDef test, complex mechanical, finite element method.

1. Introduction

The mastery of numerical modeling is a preliminary step in processes optimizations and in understanding complex phenomena. However, the quality of the numerical simulations depends on the accuracy of the input data. Regarding thin sheet metal, the identification of constitutive law is often performed by using classical characterization tests, i.e., tensile, bending, and shear tests. The strain level reached by these tests is limited and does not represent the complex and large deformations that occur during metal forming operations. The developed Micro Incremental Deformation (Micro InDef) test consists of locally deformed a clamped blank using a hemispherical tool. The advantages of this test are, the magnitude of deformation achieved is considerably large and it can be performed on a CNC milling machine, where the deformation path can be varied easily. Several studies have shown that the force predictions made from finite element (FE) simulations of incremental sheet deformation are sensitive to material parameters, for example Henrard et al. [1] and Duflou et al. [2] found that axial forming force is the dominant force and is close to the total force. For these reasons we decided to use the axial force as data for inverse problem approach using the finite element model updating (FEMU)

Table 1. Material parameters

Parameters	Definition	Mechanisms
$\boldsymbol{E}$	Young's Modulus	Elasticity
ν	Poisson's ratio	Elasticity
σ_Y	Initial yield stress	Plasticity
$\boldsymbol{Q}$	Saturation value (Voce hardening law)	Plasticity
$\boldsymbol{b}$	Hardening exponent (Voce hardening law)	Plasticity
$p_{\boldsymbol{D}}$	Accumulated plastic strain threshold	Damage
$\boldsymbol{S}$	Damage strength (Lemaitre denominator parameter)	Damage
$\boldsymbol{s}_0$	Damaged material constant (Lemaitre exponent parameter)	Damage
$\boldsymbol{D}_C$	Critical damage	Fracture

method. The objective is to minimize the gap between a result response of a finite element simulation and the measured quantity. Several authors have applied this method using global measurements response, for example Gelin and Ghouati for an elastic plastic constitutive law parameters using a deep-drawing test [3]. In this paper, the identification of a ductile damage model is carried out (hereto a Lemaitre type behavior). A calibration procedure is proposed to estimate the associated material parameters using the FEMU method. Then some tests are presented to validate the inelastic behavior. Finally, a practical identifiability analysis is performed to quantify the information richness of forming forces measurement.

2. Material and methods

The selected material for this study is a single-phase copper foil with an initial thickness of 210 μm. The material is annealed at $400°C$ for 30 min to eliminate the effects of rolling texture and to refine the structure by making it homogeneous. The average grain size after annealing is equal to 30 μm. The elastic parameters are obtained from ultrasonic characterization . Uniaxial tensile tests were conducted on flat specimens in three directions: 0°, 45° and 90° with respect to the rolling direction. The specimen was elongated up to fracture, and the true stress-strain curve was obtained for the three orientations (0°, 45° and 90°). The calculated normal anisotropy R_N and the planar anisotropy are R_N=0.955 and ΔR=-0.12, respectively. These results demonstrate that the material can be considered isotropic. Due to experimental results, the sensitivity to the strain rate is not considered.

2.1. Material and considered behavior law

The continuum damage mechanics concepts developed by Lemaitre and Desmorat [4] in the context of thermodynamics with internal variables are considered. 9 parameters should be identified, as listed in Table 1. These parameters are divided into four categories: characterizing the elasticity, plasticity, damage and fracture mechanisms.

2.2. Calibration methods of the coupled damage-plasticity model

The idea is to compare an experimental Micro InDef test and a numerical version (FEM) of the same test. More precisely we compare the experimental and numerical forming forces on Z axis. The material parameters are estimated in order to minimize the difference between these two forces. The procedure is divided in 2 steps. First step (initialization) is the identification of elastic and plastic parameters by comparing results between tensile testing and modeling. The result of first step is then used as input data for the second step (estimation), which is identification of plastic and damage parameters by comparing forming forces between Micro InDef testing and modeling.

2.3. Tensile test (Step 1)

The first step is dedicated to determinate the initial hardening parameters set (σ_{y0},Q_0,b_0) by using tensile test. This step is necessary to start the identification (step 2) from a physically solution and to reduce the computation time. The first step comprise of experimental and numerical procedure. Experimental quasi-static tensile tests are performed. A finite element parametric model is then used to simulate tensile test. Initial hardening parameters determination for the tensile test is realized using the FEMU method. Then, the numerical reaction force is compared to the experimental measurement and the hardening parameters are adjusted iteratively using an optimization algorithm. In order to avoid the necking phenomenon, only the experimental data until 23% of deformation are considered. A constrained optimization algorithm based on the Levenberg-Marquardt method is used to solve the problem in the MIC2M software. More details are given in [5].

2.4. Micro Incremental Deformation (Micro InDef) test (Step 2)

The Micro InDef testing device, illustrated in Figure 1.a., is composed of a fixed die support, a modular die, a fixed blank holder clamped to the die using screws and a forming tool with a radius of 1 mm (hemispherical end tool). The lubrication of the sheet/tool interface (water/oil mixture) is used to improve the sheet formability and to minimize frictions effects. The tool moves with a constant feed rate of 500 mm/min and rotates with a constant speed rate of 1000 rpm to ensure the spindle integrity and reduce the effects of friction. A 3-axis micro-milling CNC Machine (KERN) is used and the forming forces F_{exp} are acquired by using a 4-axis dynamometer (Kistler 9272), as represented in Figure 1.b.

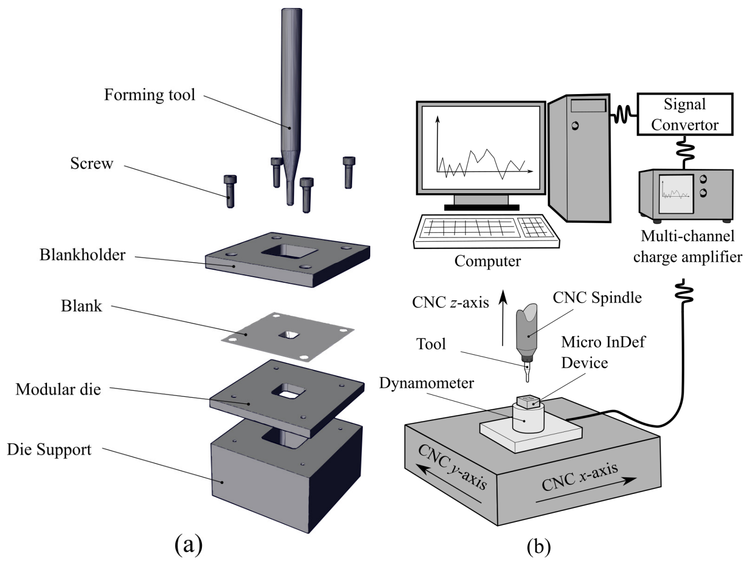

Figure 1. Testing device: (a) Micro InDef testing device, (b) forces acquisition principle(F_{exp})

As for the tensile ones, each test is repeated three times to ensure that the test is reliable. Pyramidal shape, with a draft angle α, is used to perform the Micro InDef test. The geometrical definition of this shape is given in Figure2.

A fully parametric toolbox, programmed in MATLAB language, has been developed to prepare the input files necessary for Micro InDef test's simulation (mesh, boundary, load and

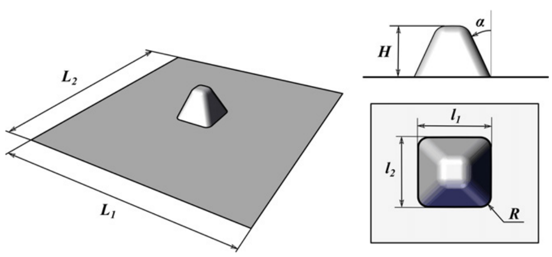

Figure 2. Definition of the pyramidal part shape.$L_1 = L_2 = 30mm$, $l_1 = l_2 = 6mm$, $H = 4mm$, $R = 1mm$, $\alpha = 2°$

initial conditions, material behavior). This numerical toolbox was completely detailed and validated in the study proposed by [6]. Considering the numerical approach, the blank is meshed with 8-nodes fully integrated solid elements and tools with 4-nodes rigid shell elements. Three elements are used in the blank thickness (6 integration points through the thickness). 120 elements are imposed upon the length and width to discretize the blank with a total of 43200 solid elements. The tool and the blank are modeled with the same geometrical parameters as in the experimental test. During simulation tests, the sheet is clamped along its edges. The LS-DYNA software with an explicit integration method is used to simulate the Micro InDef test. The coupled damage-plasticity model used for this simulation represents the main mechanisms of inelastic behavior, including plastic deformation, the change of elastic response and the localized failure.The friction law chosen to simulate the tribological behavior at the interfaces between tools and the blank is a Coulomb's friction law, with a friction coefficient equal to 0.2. This choice derives from studies proposed by [6] on the influence of friction on forming forces level. To summarize : this step consists of simulating a Micro InDef test, whose results (forming force) are sensitive to material parameters. These material parameters are the ones to adjust. The test is first simulated with a set of initial parameters identified from tensile test, considered to be physically acceptable. Then, numerical results are compared to experimental measurements and the material parameters are adjusted iteratively using the same optimization algorithm as on tensile test. The initial values of the accumulated plastic strain threshold p$_(D_0)$, the damage strength s_0 and the damaged material constant t_0 are introduced from the literature. Here, the cost function $\omega_2(\boldsymbol{\theta}_2)$ is defined as the gap between the axial forming forces obtained through the experiments F_{ZE}(t) and those obtained through the simulation, $F_{ZN}(\boldsymbol{\theta}_2$,t) of Micro InDef test with the helical strategy.

$$\omega_2(\boldsymbol{\theta}_2) = \frac{1}{N_2} \sum_{i=1}^{N_2} \left[F_{ZE}(t_i) - F_{ZN}(\boldsymbol{\theta}_2, t_i)\right]^2 \tag{1}$$

Where N_2=1000 is the number of experimental points, which is equally distributed over the time interval$[t_1, t_{N_2}]$, and θ_2 is the vector of material parameters. Six parameters associated with plasticity and damage mechanisms $\hat{\theta}_2 =^T (\hat{\sigma}_y, \hat{Q}, \hat{b}, \hat{p}_D, \hat{S}, \hat{s}_0)$ which minimize this cost function, are thus estimated. The critical damage parameter D_c is estimated after the minimization procedure by detecting the moment of the experimental fracture. For each iteration of the calibration procedure, if n represents the number of parameters to identify, it should be performed at least n+1 simulations. This is necessary to fulfill the optimization algorithm requirements. Due to the significant size of the problem and the stability condition associated with the explicit algorithm, simulation time holds an important role, for this study one simulation requires approximately 8 hours. The massively parallel processing (MPP) version of LS-DYNA is used with 16 processors to decrease the computational time.

2.5. Validation tests

A validation procedure is carried out to verify the quality of the calibrated model. Firstly, the experimental part geometry is compared with the one obtained with the finite element simulation. The experimental part is digitalized using a non-contact high resolutin 3D laser scanning system. The experimental data are then compared with the mesh using inspection software (Geomagic Qualify). Secondly, validation tests are done. The coupled damage-plasticity model identified with the helical strategy and pyramidal geometry with the procedure defined previously is for example used to simulate:

- pyramidal-shaped part using a Z-level strategy.
- conical shaped part using both forming strategies (helical and Z-level strategies).
- FLD are simulate and compared to experimental ones

3. Quantification of information richness from forming force

An identifiability analysis is conducted to ensure the parametric identification problem is well-posed, FEMU method robustness and physical significance of the parameters. This analysis uses a scalar criterion, based on the forming force sensitivity vectors' collinearity and norm. It allows to quantify information richness and all parameters' subset identifiability. This type of analysis has already been applied in other disciplines that develop over-parameterized models, e.g., [7] and [8] for the environmental simulation models and econometrics, respectively. Recently, [9] employed this technique to ensure the identifiability of viscoelastic behavior from instrumented spherical indentation test.

A criterion based on axial forming force sensitivity, is used to measure the parameter identifiability of the coupled damage-plasticity constitutive law. The purpose is to determine the sensitivity of axial forming force numerical simulation during Micro InDef test for various input material parameters. The parameter sensitivities are computed using the backward finite difference method. The components of the dimensionless sensitivity matrix **S** are mathematically defined by:

$$S_{ij} = \frac{\theta_{2j}}{F_{ZN,max}} \frac{\partial F_{ZN}}{\partial \theta_{2j}} \tag{2}$$

For computing this matrix, the optimization software MIC2M is used and a sensitivity ranking is performed by means of the following relation:

$$\delta_j = \frac{1}{N} \sum_{i=1}^{N} |S_{ij}| \tag{3}$$

where N is the number of measurement points. The sensitivity ranking measures the mean sensitivity of the simulated z-axis forming force to a variation of the parameter value θ_{2j}. A high δ_j means that the value of the parameter θ_{2j} has an important influence on the simulation result, while a value of zero indicates that the simulation result does not depend on the parameter θ_{2j}.

A local identifiability index I_K of parameter subset K can be written as follows [10]:

$$I_K = log_{10}\left(\frac{\lambda_{max}}{\lambda_{min}}\right) \tag{4}$$

λ_{max} and λ_{min} are the largest and the smallest eigenvalue of the dimensionless pseudo-hessian matrix **H**, respectively. The **H** matrix is estimated from a dimensionless sensitivity matrix (defined for a subset K of parameters) by the following relation:

$$\boldsymbol{H} = \boldsymbol{S^T S} \tag{5}$$

I_K smaller than 2 are considered as having high identifiability, while a value above 3 indicates a low identifiability. The I_K index is computed for all the subsets of the parameter space and reveals all the identifiable sets of parameters ($I_K < 3$) by quantifying the richness of the used data.

4. Results and discussion

4.1. From Step 2 (Micro InDef Test)

By using the parameters estimation from Micro InDef test, the parameters are obtained in eight iterations. The set of calibration parameters is summarized in Table 2.

Table 2. Material parameters calibrated by using Micro InDef test with helical strategy and pyramidal geometry.

Hardening			Damage			Fracture
$\hat{\sigma_y}$	$\hat{Q}$	$\hat{b}$	$\hat{p}_D$	$\hat{S}$	$\hat{s}_0$	$\hat{D}_c$
67.97 MPa	189.60 MPa	16.00	0.35	1.31 MPa	1.01	0.68

The comparison between the numerical axial forming F_Z and the experimental one is presented in Figure 3

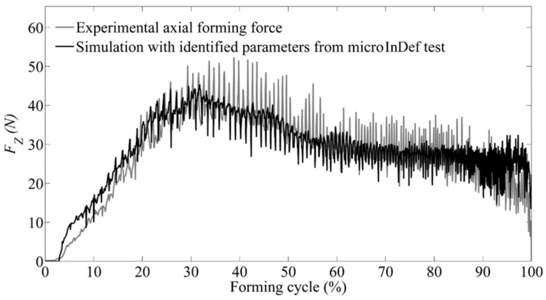

Figure 3. Evolutions of numerical and experimental axial forming forces.

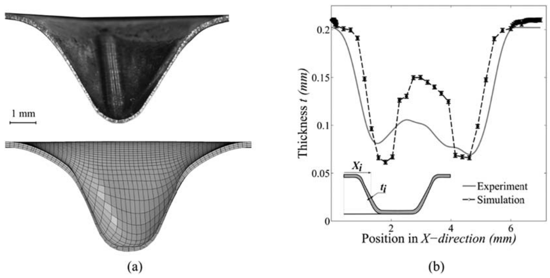

Figure 4. Numerical and experimental comparisons: (a) section, (b) thickness evolution.

4.2. validation tests

To validate the ductile damage model, a comparison between the final numerical geometry and the experimental one is carried out. The pyramidal shape obtained via simulation is close to the experimental part. The differences between the edges of workpiece (±0.15 mm) and the base of pyramid (±0.06 mm). The value of die radius and its position strongly influence the final shape. The actual die radius is not strictly identical to that used for the simulations. Moreover, this area is highly dependent on the springback effect, which is a difficult parameter to control. The comparison between the numerical model section and the experimental one is given in Figure 4a, and the thickness evolution is plotted in Figure 4b. A good correlation between experiments and simulations can be noticed. The minimum thickness value is approximately 0.07 mm, which corresponds to a thinning of 66%.

The parameters presented in Table 2, are used to simulate different tests. For the forming of a conical geometry with helical strategy, a good agreement between the numerical prediction and the experimental measurements in terms of forming forces (level and tendency) geometric accuracy and fracture prediction is noted (an example is given Figure 5).

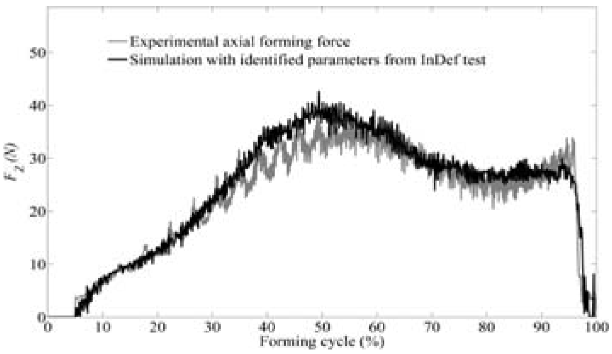

Figure 5. Evolutions of numerical and experimental axial forming forces using the helical strategy and conical geometry.

Other validation tests are presented in Hapsari [5].

4.3. Forming force information richness

Figure 6 compares tensile force and axial forming force sensitivity δ_j to the plastic damage parameters. The sensitivity is defined by Equation 3. It can be seen that tensile force is sensitive to plastic parameter variations, but is very insensitive to damage parameters. Concerning the axial forming force, it is important to note that all sensitivities are approximately of the same order of magnitude. This is a necessary condition (but not sufficient) for good conditioning of the parametric identification problem.

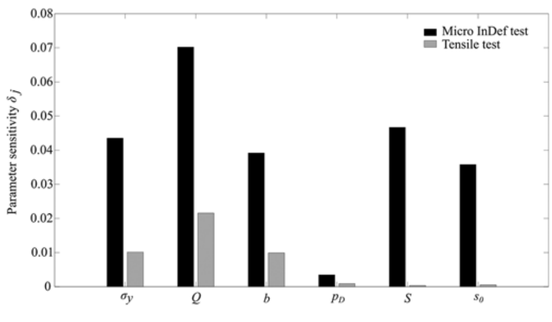

Figure 6. Average sensitivities of the tensile force and the forming force to the plastic damage parameters using tensile and Micro InDef test.

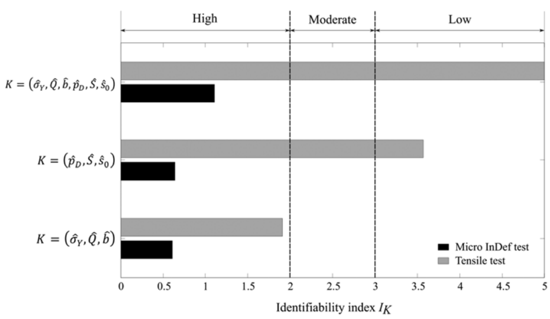

Figure 7. Identifiability index using tensile test and Micro InDef test for different parameters subsets K.

Figure 7 shows the measurement of identifiability index (Equation 4 for three sets of parameters K: plastic ($\hat{\sigma}_y$; $\hat{Q}$; $\hat{b}$), damage ($\hat{p}_D$; $\hat{S}$;$\hat{S}_0$) and plastic with damage ($\hat{\sigma}_y$; $\hat{Q}$; $\hat{b}$;$\hat{p}_D$; $\hat{S}$;$\hat{S}_0$) for tensile and Micro InDef. In the case of tensile test, the K values show that plastic sets are identifiable ($K < 2$) and the damage parameters are weakly identifiable ($K > 3$). These results show the poorness of experimental data obtained by tensile test when identifying the damage parameters. On the contrary, for Micro InDef test with helical strategy, all the parameter sets lead to low values ($K < 2$). It can be then considered as a promising technique to accurately identify material in very large deformations.

5. Conclusions

This work is dedicated to the complete definition of the identification and identifiability of the ductile damage behavior of ultra-thin sheet metal under notably large strain via the Micro InDef test.

The following conclusions can be drawn from the present work:

- The initial plastic material parameters obtained from the tensile tests are close to the final calibration. It is impossible to identify the damage law from only tensile test results because the failure is due to both mechanisms: damage growth and necking.
- The results of the validation tests, using the parameters estimated via FEMU method, showed good agreement compared with the experimental measurements.
- The identifiability analysis demonstrates the advantage of using instrumented deformation process for determining the meaningful mechanical properties of thin sheets under very large strain (in regards to the material in this study, approximately 240

Future studies will focus on the application of the proposed test as a characterization method with more complex models. typically, the effect of anisotropy, kinematic hardening or multiple hardening and more complex damage laws will be considered.

References

[1] Henrard C, Bouffioux C, Eyckens P, Sol H, Duflou J R, Houtte P V, Bael A V, Duchêne L and Habraken A M 2011 *Computational Mechanics* **47** 573–590 ISSN 0178-7675, 1432-0924 URL `https://link.springer.com/article/10.1007/s00466-010-0563-4`

[2] Duflou J, Tunçkol Y, Szekeres A and Vanherck P 2007 *Journal of Materials Processing Technology* **189** 65–72 ISSN 0924-0136 URL `http://www.sciencedirect.com/science/article/pii/S0924013607000192`

[3] Ghouati O and Gelin J 1998 *Journal of Materials Processing Technology* **80-81** 560 – 564 ISSN 0924-0136 URL `http://www.sciencedirect.com/science/article/pii/S0924013698001599`

[4] Lemaitre J and Desmorat R 2005 *Engineering Damage Mechanics: Ductile, Creep, Fatigue and Brittle Failures* (Berlin Heidelberg: Springer-Verlag) ISBN 978-3-540-21503-5 URL `//www.springer.com/gp/book/9783540215035`

[5] Hapsari G, Richard F, BenHmida R, Malécot P and Thibaud S 2018 *Material and Design* **140** 317–331

[6] Thibaud S, Ben Hmida R, Richard F and Malecot P 2012 *Simulation Modelling Practice and Theory* **29** 32–43 ISSN 1569-190X URL `http://www.sciencedirect.com/science/article/pii/S1569190X12001001`

[7] Brun R, Reichert P and Künsch H R 2001 *Water Resources Research* **37** 1015–1030 ISSN 1944-7973 URL `http://onlinelibrary.wiley.com/doi/10.1029/2000WR900350/abstract`

[8] Gujarati D N 2004 *Basic Econometrics, 4th Edition* 4th ed (New Delhi; London: Tata McGraw Hill) ISBN 978-0-07-059793-8

[9] Richard F, Villars M and Thibaud S 2013 *Journal of the Mechanical Behavior of Biomedical Materials* **24** 41–52 ISSN 1878-0180

[10] Pac M J, Giljean S, Rousselot C, Richard F and Delobelle P 2014 *Thin Solid Films* **569** 81 – 92 URL `https://hal.archives-ouvertes.fr/hal-01073849`