



An Inverse Calculation of Local Elastoplastic Parameters from Instrumented Indentation Test

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Abstract. The aim of this work is to identify the local behavior of a mechanical sample's surface layers from the instrumented indentation test and through optimization techniques. These tools are used to automate the search of the parameters of the mechanical constitutive law used in a finite element (FE) calculation and to reduce the number of calculations necessary to solve the problem of calibration. The experimental database includes mechanical responses of instrumented indentation performed on aluminum Alloy AA2017 and AISI 316L austenitic stainless steel samples. The Hooke and Jeeves iterative optimization method is used due to its efficiency, cost of calculation and precision. The procedure predictive aptitude is validated by determining correctly the behavior law of the aluminum alloy sample. The modification of the local material behavior induced by electrical discharge machining to the AISI 3016L sample is highlighted by identifying the tensile curves of different surface layers using the proposed procedure.

Keywords: Optimization techniques · Finite element method · Inverse analysis · Instrumented indentation · Mechanical behavior of materials

1 Introduction

The control and prediction of the physical mechanisms associated with the different deformation modes are often carried out through monotonic or cyclic tests according to different load paths (tensile, compression, shear). These tests, commonly performed on standardized specimens, are destructive and practically unusable for the characterization of mechanical parts having complex geometries and dimensions ranging from the micron scale to the metric scale. In addition, the prediction of fatigue life of mechanical component requires the determination of the local material behavior of layers affected by processes or treatments which is not possible using classical characterization tests (Zouhayar et al. 2013; Yahyaoui et al. 2015; Sidhom et al. 2014a, b; Ben Moussa et al. 2014a, b). Instrumented indentation, which appeared in the 1980s, is an interesting alternative for characterizing the mechanical and tribological behavior of parts and coatings. The analysis of the load-displacement curve resulting from the test allows,

using analytical models such as Oliver and Pharr model (Oliver and Pharr 1992), the most conventionally used, to determine the average modulus of elasticity and the average hardness of the material. Nevertheless, it remains difficult to exploit instrumented indentation results to identify the coefficients of models like Chaboche, Ludwig, Hollomon, Voce, etc. commonly used to describe the material behavior law. Several studies have been conducted to identify the behavior of the material from the indentation test. Most of the proposed methods are limited to the case of spherical indenters and are based on the estimation of the indentation representative strain and the ratio of plastic and total energies (Dao et al. 2001). Beghini et al. (Beghini et al. 2006) determined the constitutive law parameters by the inversion of the $P(h)$ curve resulting from a spherical indentation test. Authors assumed that the elastic properties of the material are known and their method led to a good approximation of some metallic materials parameters. Concerning the problem of the solution uniqueness in indentation test, Cheng and Cheng (Cheng and Cheng 2004) proposed a very complete study of the indentation and more particularly the possibility of determining a material's behavior law from an indentation test. Bucaille et al. (Bucaille et al. 2003) proposed a method to determine the tensile curve parameters by using two different conical indenters. In this context Nakamura et al. (Nakamura and Gu 2007) used an inverse analysis based on the Kalman filter technique and two indenters tips in order to obtain as much information about an anisotropic material's response. Although the robustness of their method, the error on the estimation of the hardening coefficient and their hypothesis of its compensation with the yield stress value, presents a limitation of their work. In the current study, a new procedure for identifying an elastoplastic constitutive law's parameters from the instrumented indentation test was established. This procedure is based on a numerical simulation of the instrumented indentation test and Hooke-Jeeves pattern search technique. The procedure ability to predict the local material behavior is validated using an aluminum alloy sample then it was applied to the case of a stainless steel sample machined by electrical discharge.

2 Numerical Study

The determination of the constitutive law coefficients using inverse methods requires performing a large number of indentation simulations before finding the correct values minimizing the differences between the experimental and the simulation results. This requires a significantly reduce of computing time significantly without affecting results quality. One of the alternatives commonly used in numerical simulation based on finite element method, is to take advantage of the problem symmetries to switch from the three-dimensional model to a bi-dimensional configuration. For indentation simulation, Vickers and Berkovich indenter can be assimilated to a conical geometry to make the problem axisymmetric (Fig. 1). The determination of the equivalent conical indenter and more particularly the semi-apex angle was carried out in this work by conducting several simulations with a semi-apex angle variation in 2D models until the results were consistent with those of the 3D models. Since both indenters have similar projected surfaces and generate the same representative strain, an equivalent semi-apex angle of 70.32° is retained.

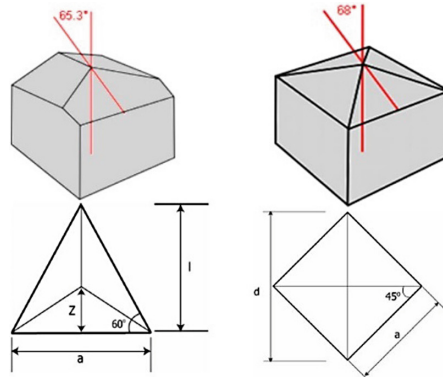


Fig. 1. Berkovich and Vickers indenters

The indenters used are generally made of diamond or sapphire having high mechanical characteristics ($E_i = 1140$ GPa and $\nu_i = 0.07$) compared to the sample material, which justifies the definition of the indenter as a rigid solid. This avoids unnecessary calculations of deformations in the indenter. The specimen behavior law was described in this work by Ludwig’s isotropic elastoplastic model linking true stress σ to true strain ϵ by the relation:

$$\sigma = \sigma_y + k.\epsilon^n \tag{1}$$

The determination of the elements’ mesh size is a crucial step in order to compromise speed and calculation precision. Within this framework we chose a structured quadratic mesh refined of $0.1 \mu\text{m}$ in the contact zone (under the indenter) and a mesh with quadratic elements dominant in the rest of the geometry (Fig. 2a).

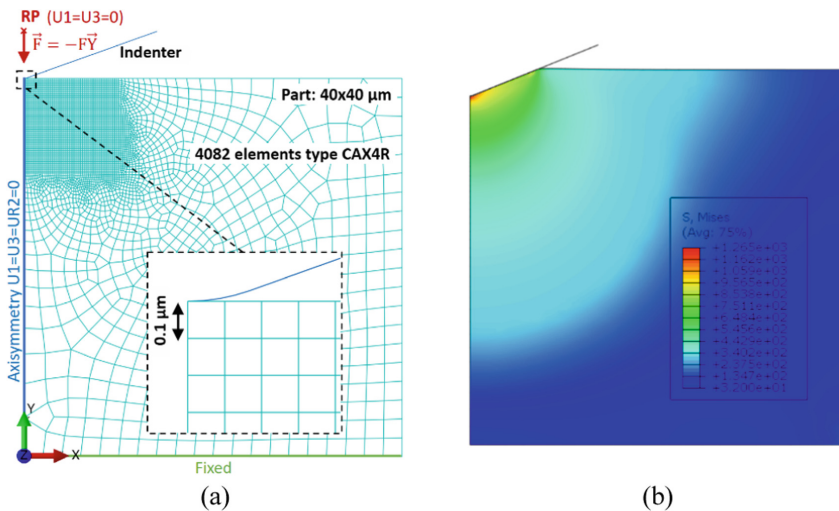


Fig. 2. Instrumented indentation simulation, a: model details, b: Indentation von Mises stress

3 Parameters Identification Procedure

3.1 Inverse Analysis Technique

An inverse analysis procedure is proposed in this work to identify the material's parameters from the load-displacement curve (P-h) obtained during the loading and unloading phases of an instrumented indentation test (Fig. 3). This procedure consists in conducting a first simulation of instrumented indentation with an initial combination of material parameters saved in an ".inp" data file. The calculated load displacement curve of the node located at the indenter tip is written in an ".odb" file. This curve is read by an optimizer tool and compared to the experimental load displacement curve. Based on the differences between the experimental and calculated curves and according to Hooke and Jeeves pattern search technique (Hooke and Jeeves 1961), the optimizer tool tries a new combination of material parameters by updating the input data file and executes a new instrumented indentation simulation.

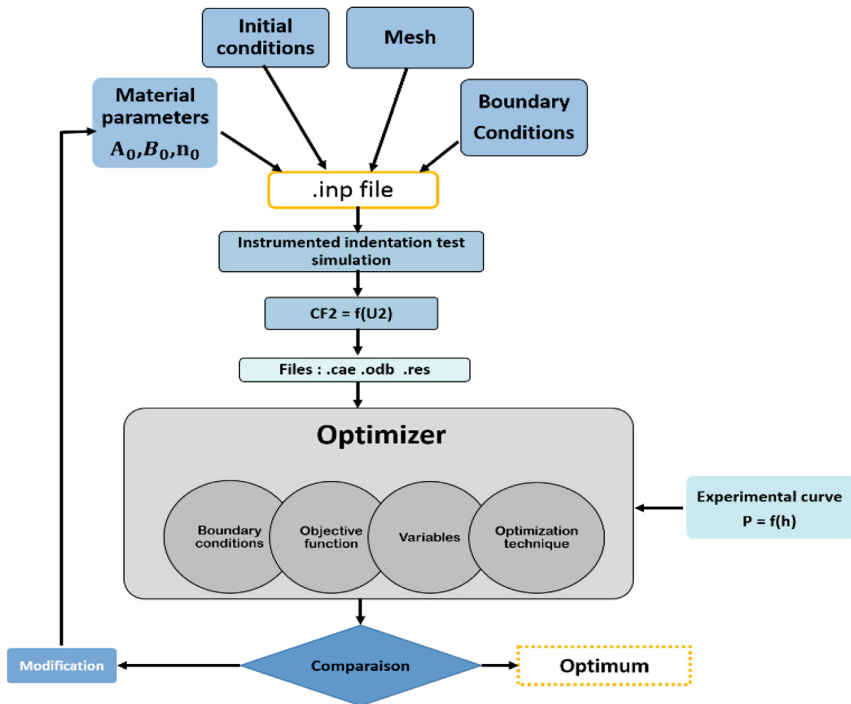


Fig. 3. Material parameters identification procedure

The procedure is repeated automatically until reaching the optimal material coefficients, minimizing the differences between the numerical and experimental results.

3.2 Validation of the Proposed Procedure

The evaluation of the proposed methodology ability to predict correctly the material's behavior from instrumented indentation test, is performed by trying to find out the parameters A, B and n of an aluminum alloy. An AA2017 aluminum prismatic sample with dimensions 20×20 mm was mechanically polished with emery papers grad 600, 1000, 2400 and 4000 to remove the layers affected by anterior machining and retrieve the bulk material. Subsequently, an instrumented indentation test with an imposed load of 100 mN using a Berkovich indenter was performed on the sample (Fig. 4a). The numerical simulation of the indentation test was performed with an initial combination of the coefficients ($A = 623$, $B = 1436$ and $n = 0.66$). After a series of simulations performed automatically using the proposed procedure and during which the differences between the calculated and experimental load-displacement curves have been minimized, the values of the behavior model's parameters found to be close to those obtained by tensile test. The optimality criterion chosen is the sum of the squared differences defined as follow:

$$f = \sum_{i=1}^n (P_{i_simulation} - P_{i_experimental})^2 \quad (1)$$

The AA2017 parameters found at the end of the identification procedure are: $A = 605$ MPa, $B = 1452$ MPa and $n = 0.62$ corresponding to a deviation of $1E-6$. The identified stress-strain curve of the aluminum alloy AA 2017 has been represented and compared to the experimental tensile curve in Fig. 4b.

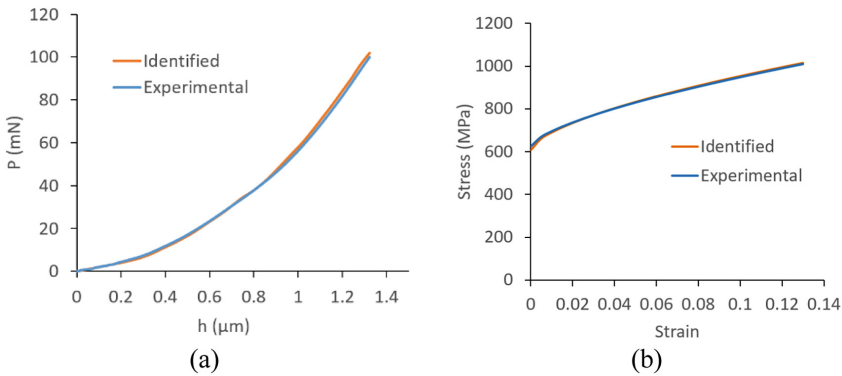


Fig. 4. Validation of the procedure for the case of aluminum alloy AA2017

4 Application

After the validation of the aptitude of the proposed procedure to predict the mechanical behavior law of aluminum sample, the same procedure is used to identify the effect of residual stress and hardening induced by electrical discharge machining (EDM). An AISI 316L stainless steel prismatic sample was machined by EDM sinking using a

graphite tool. The intensity, pulse duration and pulse-off time duration of discharge are 5A, 26 μs and 5 μs , respectively. The chemical composition and the mechanical properties of the AISI 316L stainless steel are presented in Table 1.

Table 1. Chemical composition and mechanical properties of the AISI 316L stainless steel.

C	N	Cr	Ni	Mo	Mn	Si	Cu	Co	S	P	Fe
0.018	0.078	16.6	10.2	2.02	1.84	0.38	0.36	0.18	0.029	0.035	Balance
Elastic modulus		Ultimate strength			Yield stress		Elongation		Hardness		
E=210.3 GPa		R _m = 578 MPa			R _{p0.2} =302 MPa		A=63%		HV _{0.05} =232		

In order to characterize the local behavior of the surface layers affected by the EDM process, instrumented indentation tests were carried out at different depths over a thickness of 200 μm . The load-displacement curves $P = f(h)$ for seven depths acquired at a frequency of 10 Hz are presented in Fig. 5a. The differences between the load-displacement curves reveal the modification of the material local behavior resulting from the residual stress and hardening distributions induced by the EDM process. The local material behavior law for each layer is identified by the determination of Ludwig model coefficients using the proposed methodology from the indentation curves and plotted in Fig. 5b. It has been demonstrated that EDM process leads to a hardening resulting in an increase of yield stress with a maximum value at the surface. This effect decreases in deeper layers until reaching the bulk material. The tensile residual stresses induced by EDM process act in the same direction since the material is subject to compressive stress during instrumented indentation.

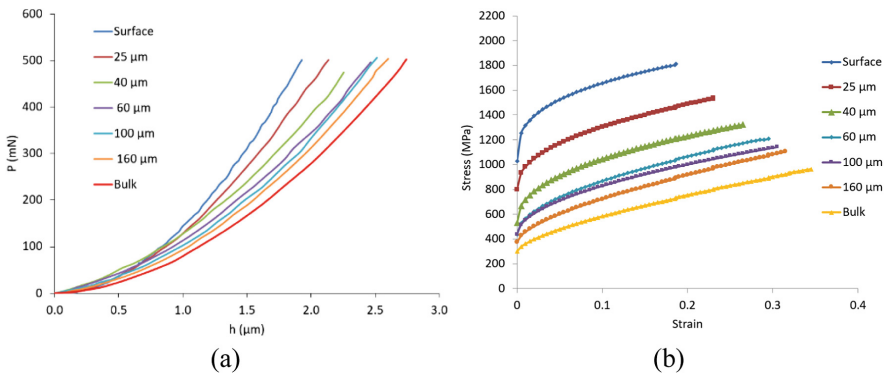


Fig. 5. Application to electro eroded sample, a: experimental indentation curves, b: identified tensile curves

5 Conclusion

In this work, a methodology of identification of local material behavior from instrumented indentation test is proposed. This methodology is based on a numerical simulation of the indentation test coupled to Hooke and Jeeves iterative optimization method. The numerical simulation of the instrumented test was optimized by determining the semi-apex angle of equivalent conical indenter making the problem axisymmetric and by testing several configurations and mesh sizes in order to reduce computation times while improving results precision.

The validation of the methodology accuracy is performed by identifying the tensile curve of aluminum alloy AA2017 from an instrumented indentation test. For the case on AISI 316L sample, the identification of the local material behavior of different surface layers highlighted the effects of hardening and residual stress distribution induced by the EDM process.

The identification of the local material behavior of each affected layers is very useful to enhance the predictive aptitude of fatigue life models by considering the correct behavior resulting from process and surface treatment.

References

- Beghini, M., Bertini, L., Fontanari, V.: Evaluation of the stress–strain curve of metallic materials by spherical indentation. *Int. J. Solids Struct.* **43**(7), 2441–2459 (2006). <https://doi.org/10.1016/j.ijsolstr.2005.06.068>
- Ben Moussa, N., Al-Adel, Z., Sidhom, H., Braham, C.: Numerical assessment of residual stress induced by machining of aluminum alloy. *Adv. Mater. Res.* **996**, 628–633 (2014a). <https://doi.org/10.4028/www.scientific.net/AMR.996.628>
- Ben Moussa, N., Sidhom, N., Sidhom, H., Braham, C.: Prediction of cyclic residual stress relaxation by modeling approach. *Adv. Mater. Res.* **996**, 743–748 (2014b). <https://doi.org/10.4028/www.scientific.net/AMR.996.743>
- Bucaille, J.L., Stauss, S., Felder, E., Michler, J.: Determination of plastic properties of metals by instrumented indentation using different sharp indenters. *Acta Mater.* **51**(6), 1663–1678 (2003). [https://doi.org/10.1016/S1359-6454\(02\)00568-2](https://doi.org/10.1016/S1359-6454(02)00568-2)
- Cheng, Y.-T., Cheng, C.-M.: Scaling, dimensional analysis, and indentation measurements. *Mater. Sci. Eng. R Rep.* **44**(4), 91–149 (2004). <https://doi.org/10.1016/j.mser.2004.05.001>
- Dao, M., Chollacoop, N., Van Vliet, K.J., Venkatesh, T.A., Suresh, S.: Computational modeling of the forward and reverse problems in instrumented sharp indentation. *Acta Mater.* **49**(19), 3899–3918 (2001). [https://doi.org/10.1016/S1359-6454\(01\)00295-6](https://doi.org/10.1016/S1359-6454(01)00295-6)
- Hooke, R., Jeeves, T.A.: “Direct Search” solution of numerical and statistical problems. *J. ACM* **8**(2), 212–229 (1961). <https://doi.org/10.1145/321062.321069>
- Nakamura, T., Gu, Y.: Identification of elastic–plastic anisotropic parameters using instrumented indentation and inverse analysis. *Mech. Mater.* **39**(4), 340–356 (2007). <https://doi.org/10.1016/j.mechmat.2006.06.004>
- Oliver, W.C., Pharr, G.M.: An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments, vol. 7 (1992). <https://doi.org/10.1557/jmr.1992.1564>
- Sidhom, H., Ben Moussa, N., Ben Fathallah, B., Sidhom, N., Braham, C.: Effect of surface properties on the fatigue life of manufactured parts: experimental analysis and multi-axial

- criteria. *Adv. Mater. Res.* **996**, 715–721 (2014a). <https://doi.org/10.4028/www.scientific.net/AMR.996.715>
- Sidhom, N., Moussa, N.B., Janeb, S., Braham, C., Sidhom, H.: Potential fatigue strength improvement of AA 5083-H111 notched parts by wire brush hammering: experimental analysis and numerical simulation. *Mater. Des.* **64**, 503–519 (2014b). <https://doi.org/10.1016/j.matdes.2014.08.002>
- Yahyaoui, H., Ben Moussa, N., Braham, C., Ben Fredj, N., Sidhom, H.: Role of machining defects and residual stress on the AISI 304 fatigue crack nucleation. *Fatigue Fract. Eng. Mater. Struct.* **38**(4), 420–433 (2015). <https://doi.org/10.1111/ffe.12243>
- Zouhayar, A.-A., Naoufel, B.M., Houda, Y., Habib, S.: Surface integrity after orthogonal cutting of aeronautical aluminum alloy 7075-T651. In: *Design and Modeling of Mechanical Systems*, pp. 485–492. Springer, Heidelberg (2013)