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Parameter identification of a mechanical ductile damage using Artificial Neural Networks in sheet metal forming

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ABSTRACT

In this paper, we report on the developed and used of finite element methods, have been developed and used for sheet forming simulations since the 1970s, and have immensely contributed to ensure the success of concurrent design in the manufacturing process of sheets metal. During the forming operation, the Gurson–Tvergaard–Needleman (GTN) model was often employed to evaluate the ductile damage and fracture phenomena. GTN represents one of the most widely used ductile damage model. In this investigation, many experimental tests and finite element model computation are performed to predict the damage evolution in notched tensile specimen of sheet metal using the GTN model. The parameters in the GTN model are calibrated using an Artificial Neural Networks system and the results of the tensile test. In the experimental part, we used an optical measurement instruments in two phases: firstly during the tensile test, a digital image correlation method is applied to determinate the full-field displacements in the specimen surface. Secondly a profile projector is employed to evaluate the localization of deformation (formation of shear band) just before the specimen's fracture. In the validation parts of this investigation, the experimental results of hydroforming part and Erichsen test are compared with their numerical finite element model taking into account the GTN model. A good correlation was observed between the two approaches.

1. Introduction

Recently, virtual tools, such as numerical simulation using finite element methods (FEMs), is a useful tool to optimize the sheet metal forming process (hydro-forming, deep drawing, thermoforming, etc.) and to reduce the cost of final products. For the engineering community, an accurate estimation of the material parameters for constitutive models is often indispensable. The numerical simulation, taking into account damage in constitutive behavior of metallic materials, is necessary to develop a virtual model for various engineering problems involved in forming processes (necking, macroscopic cracks, fracture, etc.).

In recent decades, the attention of many researchers has been focused on understanding and modeling the basic mechanisms of ductile failure in metal forming process, Mediavilla et al. [1] developed a model to describe the complete evolution, from the initiation of damage to crack propagation during forming processes. Among many authors, Brünig and Ricci [2] and Badreddine et al. [3] proposed respectively an anisotropic and isotropic damage model to predict the instability phenomena appear in the different mechanical loading states during metal forming. Also the importance of the coupling between the damage and plasticity in numerical simulation has proved by Guo et al. [4]. In same context, Lin et al. [5] proposed an improvement in the Gurson model in order to will allow investigating in future other mechanical structures made up of ductile porous media. The pioneering work elaborated by Kachanov in 1958 [6], started the subject that is now known as Continuum Damage Mechanics (CDM).

From industrial point of view, the results obtained in this field are now very helpful in the preliminary design stage, particularly are widely used to avoid the failure during the forming process. Accordingly, many authors proposed constitutive equations of ductile damage. The most widely used approaches are based on the Gurson type modeling of ductile damage [7]. Inter alia, Tvergaard study the localization of deformation using Gurson model [8], the influence of voids on shear band instability [9] and the analysis of ductile failure by the voids evolution up to coalescence [10].

Experimental methods do not provide a complete stress analysis solution without additional processing of the data and/or assumptions about the structural system [11]. Also, it is obvious that in metal forming process, the results of numerical simulation depend strongly on the ability of the used constitutive equations to describe the physical phenomena accurately but the parameters values of the behavior law are also very important. For that, it is recommended to use a good technique in the evaluation of mate-

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Nomenclature

ANNGTN	Artificial Neural Networks model of GTN
TMSE	training mean square error
X	term of input
F_t	training function
P	pressure
H	dome height
E	Young's modulus (MPa)
ν	Poisson's ratio
n	hardening coefficient
K	strength coefficient
$\bar{\varepsilon}$	equivalent true strain
ε_0	pre-strain
ϕ	plastic potential
f	void volume fraction
f_c	critical volume fraction
f_f	void volume fraction
f^*	modified void volume fraction
f_c	critical volume fraction
f_u^*	ultimate value of f^*
ε_{kk}^p	plastic hydrostatic strain
ε_n	mean effective plastic strain
S_n	standard deviation
f_n	nucleation micro-void volume fraction
(q_1, q_2, q_3)	fitting parameters
V_M	volume of the material without defects
V	volume of material
σ_m	hydrostatic stress (MPa)
σ_y	yield stress of matrix material (MPa)
$\bar{\sigma}$	von Mises equivalent stress (MPa)
$v(x, y)$ $u(x, y)$	homogenous displacement field for one pattern
a_1, b_1, a_2, b_2	elongation terms
a_3 and b_3	shearing terms

rial properties. Generally the parameter fits are processed by optimization methods. Exceptionally, the inverse methods offer a powerful tool for the identification of the parameters of the behavior law and the material properties of metals. The Principle of inverse identification method, that identifies a set of material parameters in a constitutive model, describes the complicated stress–strain responses by minimizing the difference between the test results and the results of the corresponding numerical simulation using an advanced optimization technique, but the inverse methods require prohibitive computing time because they usually use finite element computation coupled with an optimization procedure.

In order to resolve the problem of computing time in inverse identification process, this investigation presents a new ANNGTN Approach based on the Artificial Neural Network Method for the identification of GTN model parameters. A Design of Experience (DOE) method is used to select the suitable and the correct training base.

The remainder of this paper is structured as follows: the first paragraph will explain the principle of GTN ductile damage mainly the origin and the physical aspect that describe the micro-growth nucleation and mechanical effects of damage in ductile metals. The GTN model is also presented as it is one of the most widely employed models to evaluate the ductile damage and fracture. The second section gives an experimental investigation based on tensile test with notched specimen to determinate the evolution of the damage process in a ductile metal related to the macroscopic loading evolution using Digital Image Correlation (DIC). As used in this article, the term digital image correlation refers to the class of non-contacting methods that acquire images of an object, store images in digital form, and perform image analysis to extract full-field shape and deformation measurements in the specimen surface. After the fracture of specimen, the fracture topographies are analyzed by SEM in order to prove the use of GTN model. The third section is devoted to the identification programming procedure of ANNGTN model and the benefits of this technique in terms of computing time and reliable results. In the next section we will present two case studies: the hydroforming (bulge test) and the Erichsen test. Finally, conclusions are drawn in section five.

2. Modeling of ductile damage

2.1. Physical aspect of ductile damage

Damage phenomena of materials are generally investigated by means of a damage model, which can represent variations of material properties and processes of material failure due to damage initiation, growth, propagation and crack nucleation within the material [12]. Especially, in sheet metal forming industry, the localized necking failure is recognized as important limitation on metal formability. Two stages diffuse and local necking visually precedes the failure of ductile metals. The last one represents the result of damage evolution cited previously (Fig. 1). This phenomenon reacts inside material called ductile damage. During the analysis of the defect present in the forming process, especially the progress of failure in materials, many physical observation and micromechanical analysis have led to the development of a number of phenomenological or micro mechanical ductile fracture criteria [13,14] for the prediction of the rupture of metals in service. Principally, the damage criteria are classified into two approaches (i) uncoupled: which neglect the effects of damage on the yield surface of materials, and (ii) coupled: which incorporate damage accumulation into the constitutive equations.

2.2. GTN ductile damage model

The main purpose of the present work is to use ductile damage model to predict a sheet metal failure. In 1977, Gurson [15] developed a constitutive model to describe the micro-growth nucleation

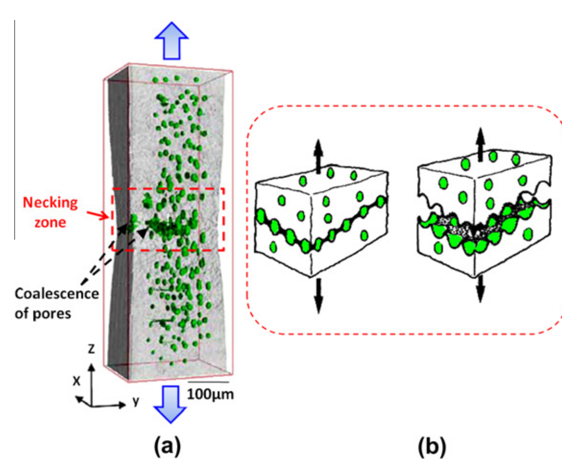

Fig. 1. Physical aspect of ductile damage (a): A reconstructed 3D image acquired during the loading process representing inner pore [13], (b): damage evolution in the necked region.