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Experimental study with a Digital Image Correlation (DIC) method and numerical simulation of an anisotropic elastic-plastic commercially pure titanium

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In this paper, the tensile behaviour of a commercially pure titanium is studied using a full-field strain measurement. A fine analysis of the measured strain fields is carried out in order to determine the intrinsic behaviour of the material. An elastic-plastic model taking material anisotropy into account is proposed. On the basis of experimental results, the parameters of this model are identified then introduced into a FEM code in order to simulate the behaviour of titanium. To assess the performance of the approach, the numerical results are finally analysed and compared with measurements coming from image processing. A quite satisfactory agreement between simulation and experiment is obtained.

Keywords: *mechanical testing, full-field measurement, anisotropic material, finite elements, titanium*

1. Introduction

Commercially pure (CP) titanium is a metal having several interesting physical properties: its density (ρ = 4.5 kg/m3) is 40% lower than that of carbon steels, it is non-magnetic, its aptitude to be passivated by the formation of a protective oxide film confers to it an exceptional resistance to corrosion, its biocompatibility is markedly higher than that of other metals (e.g. stainless steels). Because of all these characteristics, commercially pure titanium finds many applications and more specifically in the medical sector, in particular in orthodontic and orthopaedic appliances.

So far, research has been devoted to improve the mechanical properties of the material [1, 2], study the material behaviour in corrosion [3–5], analyse its friction resistance [6, 7]. In contrast with the significant number of studies concerned with the intrinsic properties of the material, the literature relating to the rheological properties and the numerical simulation of CP titanium forming operations is much scarce and incomplete [8–13]. However, a better knowledge of the stress-strain relation of CP titanium could contribute to improve rheological models integrated in the finite element code, the results of simulations being helpful in the optimisation of the manufacturing process of a new prosthesis, for example.

Among these former studies, Salem et al. [8] propose an interesting model of crystalline plasticity. This model is suitable to predict the anisotropic behaviour in terms of stress-strain relations as well as evolution of texture of commercially pure titanium. While this kind of modelling has significantly improved the understanding of material deformation, computation is time- consuming for industrial forming operations such as deep-drawing for example.

The recent work of Fuh-Kuo and Kuan-Hua [13] dedicates to stamping formability of commercially pure titanium sheet metal is also very interesting from an experimental point of view. The mechanical behaviour of CP titanium sheets is studied from a significant number of tensile tests carried out at various temperatures ranging from ambient to 300 ºC and at various strain rates from 0.1 to 0.0001 s^{-1}. Tests are carried out on samples cut out in a 0.5 mm thick sheet along three different directions (0º, 45º and 90º) following the rolling direction. An anisotropic behaviour is highlighted and a behaviour independent to the strain rate is observed when $\dot{\varepsilon}$ is lower than 0.001 s^{-1}. However, in spite of the precious information underlined by this work, no rheological model is proposed to describe the behaviour of commercially pure titanium.

It appears from the previous discussion that a finer experimental analysis is needed to model and simulate the behaviour of commercially pure titanium. This point constitutes the main objective of this contribution. The behaviour of commercially pure titanium is studied from various tensile tests. The deformations of the sample are measured with a Digital Image Correlation (DIC) method presented in Section 2. A fine analysis of the results is carried out in Section 3 in order to determine the intrinsic behaviour of the material. The anisotropy resulting from the operation of rolling performed on the sheets during their industrial elaboration and from the crystallographic structure of the material is also highlighted. In Section 4, the constitutive equations of an elastic-plastic model taking this anisotropy into account are proposed. The material parameters of the model are determined from experimental data then introduced into a commercial finite element code. The numerical simulation results of CP titanium deformation under tensile loading are finally analysed and discussed in Section 5.

2. Experimental procedure

2.1. Material

Provided by ACNIS International (France), the studied material is a Commercially Pure (CP) titanium grade 2 (of French denomination T40). The limits of the chemical composition of the material are described in Table 1.

Table 1. Chemical composition limits of commercially pure titanium grade 2

Element	Ti	C	Fe	N	O	H
Weight (%)	bal.	0.10	0.30	0.03	0.25	0.015

As the material has been rolled during its industrial elaboration, we note by DL the rolling direction and DT the transverse direction. The samples tested are cut out using a wire cutting machine in a 0.5 mm thick sheet following three different directions (0º, 45º and 90º) from the rolling direction DL (Figure 1).

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