International Journal of Non-Linear Mechanics 46 (2011) 519–531

Contents lists available at ScienceDirect

International Journal of Non-Linear Mechanics

journal homepage: www.elsevier.com/locate/nlm

A generic stress–strain model for metallic materials with two-stage strain hardening behaviour

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ARTICLE INFO

Article history:
Received 26 December 2009
Received in revised form
23 November 2010
Accepted 4 December 2010
Available online 13 December 2010

Keywords:
Constitutive law
Strain hardening
Metallic materials

ABSTRACT

Constitutive equations are often used to describe the stress–strain behaviour of metallic materials. This allows the execution of parametric studies for various purposes. Despite the large number of developed stress–strain equations, all frequently applied ones fail to accurately describe a strain hardening behaviour in two distinct stages, which many metallic materials tend to show. For this purpose, the authors developed a new stress–strain model, based on the well-known Ramberg–Osgood equation, which focuses on this two-stage strain hardening behaviour. This article describes the model and its analytical background, along with a graphical method to derive suited model parameters. To validate the proposed methodology, it is applied on stress–strain curves of two high-strength steels, an aluminium alloy and a duplex stainless-steel alloy. Whereas a good correspondence for the stainless-steel alloy is confined to limited plastic strains, excellent agreements are observed for the steels and the aluminium alloy. Following the proposed method, it was possible to obtain model parameter values that give a good correspondence within a detectable strain range.

1. Introduction

The stress–strain curve of metallic materials is often described by means of a simple mathematical expression. This approach allows the post-yield behaviour to be treated by a set of parameters, thus enabling a more systematic material characterisation and the execution of parametric studies through finite element modelling. Most of the widely used stress–strain equations have a limited number of model parameters, because of simplicity reasons. However, this restricts the possibility of accurately representing complex strain hardening curve shapes. A high level of accuracy may be required in some applications, two examples of which are the calculation of sheet metal forming processes [1] and integrity assessment of pipelines subjected to plastic deformation (earthquakes, permafrost, …) [2].

There is an abundance of literature concerning metals which have two distinct stages of strain hardening behaviour. Due to their inherent simplicity, most frequently used stress–strain formulae do not succeed in describing this phenomenon, or at least show limitations in trying to. To address this issue, the present work elaborates the development of a new full-range stress–strain model (named the 'UGent' model in what follows), which can be applied to metals that exhibit two-stage strain hardening. It is based on the Ramberg–Osgood equation, thus representing elastic–plastic deformation with a continuous yielding behaviour.

Despite many attempts, a unified theory on the relationship between strain and microstructural behaviour of polycrystalline materials has not yet been found [3]. It is, however, known that the strain hardening behaviour is the result of a complex interaction between a series of factors. Noteworthy to illustrate this complexity are the occurrence of transitions from planar to cross dislocation slip, solid-solution alloying effects, precipitation effects, and strain-induced phase transformations [4]. Given the lack of fundamental knowledge regarding the interactions between all microstructural mechanisms, no attempts are made to explain the introduced model parameters by means of physical considerations, and the UGent model should hence be considered as purely empirical.

The article is organised in different sections. Section 2 presents a study of existing constitutive laws and how to analyse them, along with a survey on materials which show two distinct strain hardening stages. Section 3 provides the mathematical background for the development of the UGent model. In Section 4, the interpretation and analysis of the proposed relation is discussed. Next, Sections 5–7 focus on an experimental validation (material, method, and results, respectively). Principal conclusions are finally drawn in Section 8.

2. Background

2.1. Stress–strain models and methods to analyse them

Table 1 summarises the most frequently applied constitutive laws. Every model is briefly discussed below.

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doi:10.1016/j.ijnonlinmec.2010.12.004