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Modeling of strain hardening and creep behaviour of 2024T3 aluminium alloy at room and high temperatures

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ABSTRACT

In this paper constitutive models of 2024-T3 aluminium alloy have been developed at room and high temperatures in order to be used in finite element simulations of cold hole working process. The material behaviour in the plastic field has been described by the non-linear kinematic hardening on the basis of uniaxial tensile test (half cycle) at 8 different temperatures in the range between 25 °C and 200 °C. The dependence of the yield stress at zero plastic strain and the kinematic hardening modulus C on the temperature have been established when the material parameter γ is equal to 10. The latter determines the rate at which C decreases with increasing plastic deformation. The constitutive model authenticity has been proved by finite element simulations of the uniaxial tensile tests. The creep behaviour of the 2024-T3 aluminium alloy at high temperatures (150–200 °C) has been described by the power-law model. The model material parameters A, n and m have been determined as functions of the temperature on the basis of uniaxial creep test. The constitutive model authenticity has been proved experimentally and by finite element simulations of the creep test. The obtained constitutive models have been used in finite element simulations of residual stress relaxation around cold worked open holes due to thermal overloading.

1. Introduction

The aluminium alloys have enough strength at relatively low weight, big corrosion resistance and good workability. Because of that, they are widely used in responsible structures, due to their optimum combination of physical and mechanical properties [1]. The 2024-T3 aluminium alloy in sheet metal form has a wide application in the airspace industry for various structural elements, and more specifically for wing and fuselage structures, characterized by multitude fastener holes. The latter, as is well known, are natural stress concentrators and potentially critical spots for initiation and growth of fatigue cracks. The introduction of beneficial residual compressive stresses around these holes through cold working [2–12] is an effective prevention for enhancement of fatigue life of the corresponding structural component. An efficient means for studying the process of introducing the beneficial residual stresses and their redistribution under the influence of an external load, are the numerical simulations [13–22] through the finite element method. To build a reliable finite element model, it is of significant importance the building (or presence) of adequate constitutive model of the material. The mathematical model, defining in qualitative and quantitative aspect the dependence between the measures of the stressed and strained states (stress and strain tensors) of given structural material, is called constitutive model of this material. Without this model, the corresponding equations could not be defined in closed form and be used to determine the quantities, which characterize the mechanical and thermo-mechanical processes in the deformable solids. Apart from the physical nature of the material and the deformation history, the constitutive model also depends on the loading law. The constitutive model is built on the basis of mechanical and mathematical model, which represents an idealization of the actual material's behaviour, subjected to external influence. The mechanical and mathematical model is most frequently built on the basis of the phenomenological approach. The constants in the constitutive model equation are determined on the basis of a natural experiment. In spite of the wide variety of experiment types with phenomenological meaning (according to the type of the stressed state, the velocity and duration, temperature field in the specimen, etc.), the one-dimensional tests are most frequently used, due to their relatively easy implementation [23,24]. In the case of one-dimensional tension, an increase is observed in the material resistance against the plastic deformation after the yield limit, known as strain hardening [25]. On a micro-level the latter is explained with retention of the dislocations propagation in some points, and in order for them to be continued, an increase of the external

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load is necessary. If the applied external load causes monotonous increase of deformations and presence only of active such, the hardening could be modeled as isotropic – the yield surface in the stress space expands without moving as a "rigid body" in this space [23–25]. In counterbalance, the cyclic external load causes change in the structure of the material on a micro-level, which reflects in the alteration of the material's behaviour in an aspect of strain hardening. As a result, a correction in the material's constitutive model is necessary, aiming an adequate prediction of the material behaviour in cyclic load conditions [26,27]. In the vicinity of each point of the material arises cyclic loading [28], due to which, a deformation anisotropy is obtained. The strain hardening could be modeled as kinematic – characterized by shifting of the yield surface into the stress space. Through an empirical way the following phenomena [23,24] have been established, which are a manifestation of the deformation anisotropy, provoked by the cyclic loading: Bauschinger's effect, shake down, ratcheting, middle stress relaxation.

In most cases of FE simulations of cold hole working process [13–22], in spite the fact the material constitutive models account the above phenomena, they are accepted to be independent from the deformation velocity. They are well-known as "rate independent models" [24]. Methods for modeling the behaviour of carbon steel in the plastic field in the cases of cold hole working are developed in [26,27] and could also be applied for the 2024-T3 aluminium alloy.

In fact, a constant deformation connected to a certain stress does not exist, i.e. the deformation changes in the course of time [29]. The cause is in the physicochemical changes, which arise in the metals and alloys with the increase of the deformation duration. At continuous constant loading, inflicting stresses smaller than the material's yield limit, at certain temperature conditions, the metals and alloys gain increasing in time deformations. This phenomenon is called creep [29]. It is believed that the creep is caused by diffusion phenomena. At room temperature, the diffusion processes are inflicted by macro- and micro-scopic stress gradients in the crystals of metals and alloys.

The creep phenomenon is most highly expressed in the non-ferrous metals and alloys, including the 2024-T3 aluminium alloy. In order to build an adequate constitutive model of this material, it is mandatory to take into account the creep phenomenon. Modeling of 2024-T3 creep has been made in [1], using the "θ-projection" method (developed by Evans and Wilshire [30]) for three temperatures – 200 °C, 175 °C and 150 °C, and on the specimens of each constant tensile stresses under the yield limit have been applied, 185 MPa, 205 MPa and 225 MPa respectively. The "θ-projection" method has been used to describe the creep of other aluminium alloys: Lin et al. [31] have obtained a creep model of the 2124-T851 aluminium alloy at high temperatures. However, for FE simulations it is advisable for the creep process to be described through the so-called power-law model [24]. Detailed information for the power-law creep depending on the applied stress is shown in [32]. This model at moderate stresses is used by Garsia-Granada et al. [33] for describing the creep of 2650 aluminium alloy with an increased creep resistance, at temperature of 150 °C. The power-law model has been applied in [34] in a FE model for determining the residual stress relaxation around cold worked holes in 7050 aluminium alloy at room temperature. However, information for the material constants in power-law model for 2024-T3 aluminium alloy is missing.

Main objective of the present study is to obtain an adequate constitutive model of 2024-T3 aluminium alloy at room and high temperatures with the purpose of applying it for numerical simulations of the behaviour of objects, subjected to a cyclic load, and in particular, of the cold hole working process.

For achieving the main goal, the following tasks have been solved:

- On the basis of experimental results, obtained through one-dimensional tests, known in literature [1,35], a constitutive model of 2024-T3 aluminium alloy has been developed. The model accounts the deformation anisotropy, caused by a cyclic load in conditions of room and high temperatures, as well as the creep at the same temperatures through power-law model.
- The obtained constitutive models have been used for FE simulations of the residual stress relaxation around cold expanded holes.

2. Theoretical background

2.1. Kinematic strain hardening

According to this theory, the deformation anisotropy is a result from arising stresses from type-II (microstresses) due to change of the material structure, caused by plastic deformation of a cyclic load. The microstresses are described in view of the macro approach with symmetric tensor (back stress tensor), which components are α_{ij}. It is accepted that the actually operative stresses are σ^a_{ij}, called active and defined by [23]:

$$\sigma^a_{ij} = \sigma_{ij} - \alpha_{ij}, \tag{1}$$

where σ_{ij} is the stress tensor.

The yield surface is defined by the function [23]

$$F = f(\sigma^a_{ij}) - \sigma^0 = 0, \tag{2}$$

where $f(\sigma^a_{ij})$ is the equivalent stress; σ^0 is the equivalent stress defining the size of the yield surface, whose initial value is $\sigma|_0$ - equivalent stress defining the size of the yield surface at zero plastic strain; σ^0 is determined through a one-dimensional test and is assumed valid for all possible stressed states and loading paths. For plastic materials an equivalent stress is usually used according to Von Mises:

$$f(\sigma^a_{ij}) = \sqrt{-3I_2(s^a_{ij})}, \tag{3}$$

where the components of the second invariant I_2 of the deviatoric stress tensor are defined by:

$$s^a_{ij} = \sigma^a_{ij} - \frac{1}{3}\delta_{ij}\sigma^a_{kk}. \tag{4}$$

These models are used to describe the behaviour of the metals, subjected to cyclic loading and independent from the middle normal stress $\frac{1}{3}\delta_{ij}\sigma_{kk}$.

On the basis of the kinematic hardening theory are developed the following models [23]:

- *Linear kinematic hardening.* This model describes the displacement of the yield surface into the stress space through the back stress tensor α_{ij}.

When the problem is independent from the temperature, that shift is described by the linear Ziegler hardening law:

$$\dot{\alpha}_{ij} = \frac{C}{\sigma^0}\sigma^a_{ij} \cdot \dot{\bar{\varepsilon}}^{Pl}, \tag{5}$$

where C is kinematic hardening modulus and $\bar{\varepsilon}^{Pl}$ is equivalent plastic strain. In this model the equivalent stress, defining the size of the yield surface (or the yield stress), remains constant: $\sigma^0 = \sigma|_0$.

The Ziegler model describes the shift of the yield surface from the centre of the surface towards the observed point of that sur-