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Johnson-Cook based criterion incorporating stress triaxiality and deviatoric effect for predicting elevated temperature ductility of titanium alloy sheets

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ABSTRACT

In this paper, a new model based on the Johnson-Cook fracture criterion is proposed to predict the ductility of Ti6Al4V titanium alloy sheets deformed at wide range of temperatures (25–900 °C) and stress states. Experiments were carried out and strain at fracture recorded on samples of different shapes to cover various loading conditions: uniaxial tensile, shear and equi-biaxial plane stress tension. The stress triaxiality and the deviatoric effect were evaluated through numerical simulations of these experiments. The original Johnson-Cook (J-C) fracture strain criterion was modified to incorporate a quadratic function of the stress triaxiality and a deviatoric parameter to represent different stress states. In the new formulation of the J-C criterion, a quadratic function of the temperature was also introduced to represent the transformation related ductility inherent in the two phase (α/β phases) titanium alloy Ti6Al4V at elevated temperatures. The model was calibrated using as reference state the strain rate of 1 s^{-1} and temperature of 600 °C. The choice of 600 °C as reference was based on the rapid increase in the β phase and ductility above this temperature. The new ductile fracture criterion for elevated temperature sheet forming was finally validated using testing conditions different from those used in its derivation.

1. Introduction

In the past, sheet forming was primarily carried out at room temperature. Therefore, most of the design criteria for sheet forming are based on the room temperature yield, and the post yield plastic behaviour, of the sheet material. More recently, elevated temperature ductility of sheet material is being exploited to generate geometries that are difficult to form at room temperatures, leading to processes such as hot stamping [1,2] and electrically-assisted incremental sheet forming process [3,4]. To successfully design and implement sheet forming processes for elevated temperatures, besides the investigation of the material rheological behaviour [5], the failure prediction, which defines the upper limit to the forming process, has increasingly become a primary focus of the metal forming community [6,7]. When simulating sheet forming operations, at both academic and industrial level, the failure is commonly predicted using the method of the Forming Limit Diagram (FLD) [8], which was proposed by Keeler and Backofen [9], and then extended by Goodwin [10]. However, the use of this method to predict sheet formability for a wide range of process conditions, typical of sheet forming processes, requires great experimental efforts as the FLDs depend on different factors, namely the sheet thickness, lubrication strategy, temperature and strain rate. To overcome this disadvantage, researchers have looked at alternative methods, based on fracture criteria [11], using either coupled or uncoupled approaches [12]. While the coupled approaches are based on the link between the material progressive damage and the flow stress, the uncoupled approaches neglect the yield surface sensitivity to the damage evolution. The coupled criteria consider the physical phenomena at the basis of the ductile fracture, but the complexity and difficulty in calibration limit their use, especially in case of industrial applications [13]. On the other hand, the simple formulation and the user-friendly calibration of the uncoupled criteria contribute to their wide spread use [12].

Among the uncoupled approaches, the most widely used models are those of Cockcroft and Latham [14], Brozzo [15], Oyane [16] and Johnson and Cook (J-C) [17]. These models are generally characterized by a formulation that predicts the onset of fracture when a damage parameter reaches a critical value. This damage variable is a function of different material related factors, such as the equivalent plastic strain, tensile stress and hydrostatic stress [12]. Because the hydrostatic stress was found to influence the nucleation and growth of the voids [18–20] that control the material ductility [12], it was introduced in the damage function through the stress triaxiality, η, which is the ratio between the

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hydrostatic stress and the Von Mises equivalent stress. The stress triaxiality was shown to influence also the onset of fracture [21,22] and was included in fracture criteria by Oyane [16] and Johnson-Cook [17].

When the forming processes are carried out at elevated temperatures, where the material is strongly influenced by both the temperature and strain rate, the fracture occurrence depends also on these rheological parameters, besides stress triaxiality. In this context, the Oyane criterion [16] was recently modified by introducing a function of the temperature and strain rate and applied to hot rolling conditions [23], where the influence of the stress triaxiality was proved to be high [24]. The Johnson-Cook criterion [17] includes temperature and strain rate effects through the introduction of two separate terms in its formulation. It was found to have good prediction capabilities over the positive range of the stress triaxiality values [13], which can be advantageous in predicting the fracture occurrence in sheet forming processes where the complementary effects of tensile and in-plane stresses lead to fracture [25]. However, the Johnson-Cook criterion does not consider the deviatoric effect, expressed in terms of Lode angle, which was recently recognized to play a significant role in the description of the ductile failure behaviour [13]. Therefore, the Lode angle together with the stress triaxiality allows predicting the fracture occurrence in more complex stress states [26].

Wilkins et al. [27] was the first to propose the fracture occurrence at room temperature as a function of both the stress triaxiality and Lode angle, assuming a separable dependency of the fracture locus on these two parameters [28]. The same approach was used in later applications [29,30], until Wierzbicki and Xue [31] proposed a new model, as an extension of the Wilkins' one, which considered a non-separable form but symmetric 3D fracture locus as a function of the stress triaxiality and Lode angle, still at room temperature. Because both the separable form and the symmetry of the fracture locus were considered too restrictive assumptions, Bai and Wierzbicki [28] postulated a non-separable and asymmetric form of the fracture locus, where the effect of the Lode angle parameter (namely, the normalized Lode angle) was represented as a parabolic function. The coupled effect of the stress triaxiality and Lode angle was first studied in case of bulk materials [29,32], but, more recently, the interest has been shifted to the analysis of their influence in sheet metal forming [13,26,33].

Over the last decade, the elevated corrosion resistance, high strength-to-weight ratio and good biocompatibility of Ti6Al4V prompted aerospace and biomedical industries to use this lightweight alloy for different technological applications [34–36]. Despite the wide use of Ti6Al4V, only few papers are devoted to the characterization of its fracture behaviour, either in bulk [20,37] or sheet [38,39] as-received conditions, at room temperature. On the contrary, a comprehensive evaluation of the influence of the stress triaxiality and deviatoric effect on the material ductility in a wide range of temperatures, relevant for sheet forming operations carried out at elevated temperatures, is still missing.

Therefore, the aim of this research is to present a new model that can accurately predict the ductility in Ti6Al4V sheets deformed at different temperatures and strain rates, and incorporating the effect of the stress state by including both the stress triaxiality and the deviatoric effect. Based on J-C fracture criterion [17] that was chosen since it takes into account the temperature and strain rate effects and it predicts fracture under tensile and in-plane stresses typical of sheet forming processes, the proposed new model introduces the Lode effect and a polynomial dependency of the material ductility on the temperature, as a consequence of the experimental evidences. In our formulation, we consider that the temperature dependent phase transformations significantly affect the ductility of the dual phase (α/β) titanium alloy. This strong dependence on temperature is incorporated in the new formulation of the J-C model using higher order polynomial of temperature. The model is applied to 1 mm-thick Ti6Al4V sheets deformed in a wide range of temperatures, spanning from room temperature to 900 °C, at different strain rates.

In the paper, the theoretical background and the approach used to develop the new model are first described in Section 2, followed by the description of the experimental tests and related numerical modelling in Section 3 and Section 4, respectively. Finally, Section 5 focuses on results and discussion, presenting the calibration of the proposed model and its validation.

2. Development of the J-C based model

It has been shown that the fracture strain is strongly influenced by stress triaxiality and Lode parameter during plastic deformation. The stress triaxiality is defined in terms of a dimensionless pressure as:

$$\eta = \frac{-p}{\bar{\sigma}} = \frac{\sigma_m}{\bar{\sigma}}, \tag{1}$$

where σ_m is the hydrostatic stress and $\bar{\sigma}$ the Von Mises equivalent stress, which are represented in terms of the three principal stresses σ_i:

$$p = -\sigma_m = -\frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) \quad , \tag{2}$$

$$\bar{\sigma} = \sqrt{3J_2} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \quad . \tag{3}$$

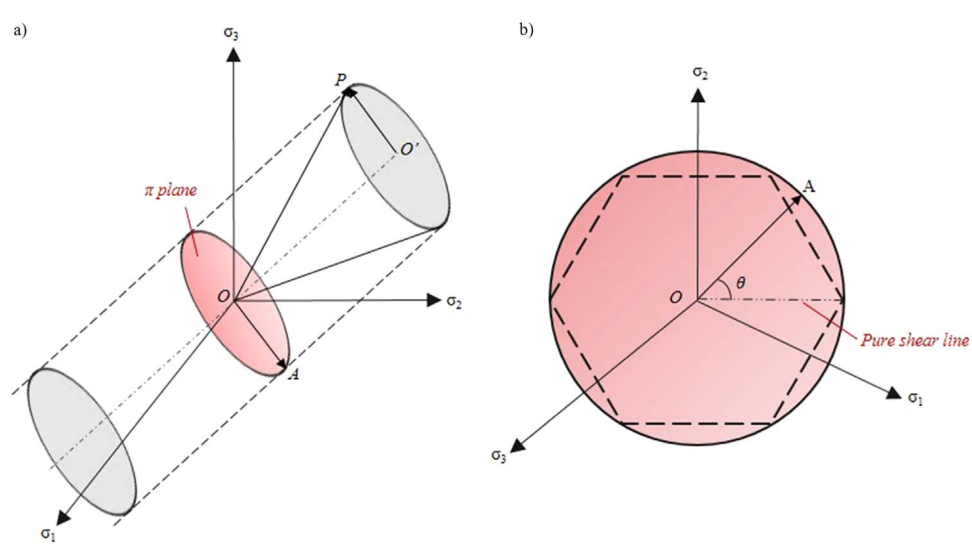

Fig. 1. a) Stress state in the space of the principal stresses; b) geometrical representation of the Lode angle on the π plane.