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Prediction of limit strains in hot forming of aluminium alloy sheets

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ABSTRACT

Theoretical analysis for the prediction of the limit strains of AA5083 aluminium alloy sheets deformed at room and elevated temperatures are presented and discussed in relation to experimental limit strains. The AA5083 forming limit strain curves, FLC, were predicted by employing D-Bressan and Marciniak–Kuczynski macroscopic concept models and were compared with the experimental FLC from Nakazima tests performed at room and high temperatures. In order to calibrate the models, tensile tests on specimens cut at 0°, 45° and 90° with respect to the rolling direction were carried out in a wide rage of temperatures and strain rates in order to obtain the coefficients of plastic anisotropy as well as material strain and strain rate hardening behaviour at different temperatures. The applied critical shear stress rupture criterion and strain gradient evolution models showed to give a satisfactory agreement with the forming limit strain curves of AA5083 aluminium sheet, proving the suitability of a novel concept of shear stress rupture and local necking evolution in sheet metals deformed at room and elevated temperatures. The correlation of M–K predicted FLC-N curve with the experimental points for room and high temperatures was also fairly good.

1. Introduction

Sheet metal forming processes are among the main manufacturing processes devoted to the production of components for the aerospace, automotive, household electric products, kitchen artefacts and packing industries. The drivers of success of sheet metal forming processes, which make them attractive and competitive, are numerous: among them, the possibility of producing net-shape complex-geometry parts, using metal sheets of good mechanical and surface properties and their low cost that makes them suitable for mass production.

The increasing request of lightweight products especially in the aerospace and automotive industries for saving energy and to decrease CO_2 gas emissions, thus, to respect the more and more stringent environmental regulations, has recently stressed the attention in using metal sheets of enhanced mechanical properties for producing parts of car body and body-in-white. However, these sheet metals are usually characterized by reduced formability at room temperature, which requires carrying out the sheet forming processes at elevated temperature. This is the case of hot stamping of high strength steel sheets, already industrialized for the production of anti-intrusion parts of the car body-in-white. In the aerospace industries, high strength aluminium alloys are employed in the fuselage and wings of modern aircrafts, despite its reduced formability. It is well known that aluminium alloys can exhibit superplastic behaviour at high temperatures, such as Supral [1], AA7475 [1,2] and AA5083 [1,3]. The strain rate sensitivity, *M*-value parameter, is the main mechanical property to control superplastic behaviour which depends on temperature and strain rate. In general, superplasticity is attained for low strain rate of 10^{-2}/s to 10^{-1}/s [4].

Furthermore, recent studies [5] have drawn the attention to the hot stamping of aluminium alloy sheets, in particular sheets of 5xxx and 6xxx series. The published experimental results proved a significant enhancement of the sheet metal formability when the blanks are formed in hot temperature range, using strain rates much higher than the case of superplastic forming. In the case of cold forming, formability at room temperature of AA6014 aluminium sheet has been also recently investigated by Weber et al. [6], which is mainly applied in the automotive outer skin.

The correct design and optimization of sheet forming processes at elevated temperature requires the use of numerical simulation tools that help reducing the time needed in the process development stage and, therefore, optimising the time for producing the first new stamped part in the production line. Being the fracture occurrence one of the major limitations in sheet forming, these numerical tools require the implementation of accurate material formability data. However, the approach conventionally used at industrial level, based on Forming Limit Curves (FLCs), implies a costly and time-consuming experimental campaign, particularly in

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case of forming processes conducted at elevated temperatures, since a set of FLCs at various increasing temperatures and strain rate has to be implemented. To overcome these difficulties, alternative analytical approaches, based on both phenomenological and physical modelling, have been proposed by many authors [7,8], with good predictive capabilities of FLCs from material tensile test properties, but mainly applied to sheet forming processes conducted at room temperature.

The AA5083 aluminium sheet is commonly selected for structural components and panels in the automotive and aerospace industries, owing to its good corrosion resistance, moderate weldability, high Ultimate Tensile Strength (UTS) up to 275 MPa strength and low density [9], thus, representing a lightweight material with a high ratio between the strength and density. Whereas the AA5083 sheet formability at room temperature is moderate, it increases significantly at high temperature [3], making possible to manufacture complex geometry parts. AA5083 can be supplied with both a conventional and a superplastic microstructure: in this study, the 1.5 mm thick sheets were provided in the annealed state, which was proved to have forming properties at elevated temperature and high strain rate compared to those of the superplastic alloy AA5083 [3].

Within this context, present paper examines an innovative approach in modelling the forming limit strains of AA5083 sheets deformed at both room and elevated temperature, taking into account the different rupture mechanisms leading to sheet failure as a function of the testing temperature. Two different D-Bressan models [10,11] were employed, which provide a satisfactory agreement with the experimental results presented by Bruschi at al. [3].

2. Background

2.1. Formability map of metal sheets

Aiming at reducing the development cost and optimising the first part production, numerical simulation tools have been successfully implemented in many engineering departments of companies, working in the field of sheet forming. These tools usually employ the Map of Principal Surface Limit Strains (MPLS) [12,13] to check critical points of maximum limit strains in the part surface, therefore giving the chance to lately redesign the part or the forming dies and/or select a sheet material with improved formability. With this methodology of systematic modelling the process, using numerical simulation and MPLS map, it is possible to increase the quality of final product and decrease the time for product development.

Formability of sheet metals, from the point of view of material mechanics, can be defined as the material capability to withstand large strains in any sheet metal forming process or testing without occurrence of local necking, rupture by shear or wrinkling in the specimen or part. In addition, adequate low surface roughness or waviness, non-geometrical distortion due to spring back and free of blister defects in the surface are also required. Thus, in general, sheet metal formability is a complex technological attribute and almost impossible to be fully evaluated by a single parameter or test, as it depends on several variables, including material properties, process parameters, microstructure features, phase transformation, friction and surface finish.

Usually in practice, sheet metal formability or the limit strains are experimentally assessed by using the Forming Limit Curves (FLC), plotted in the MPLS for linear strain paths, see Fig. 1. The FLC curve is the average curve drawn through the measured points of principal true strain on the sheet surface, ε_1 and ε_2, nearest to the region of local necking, rupture by shear stress [11] or wrinkling

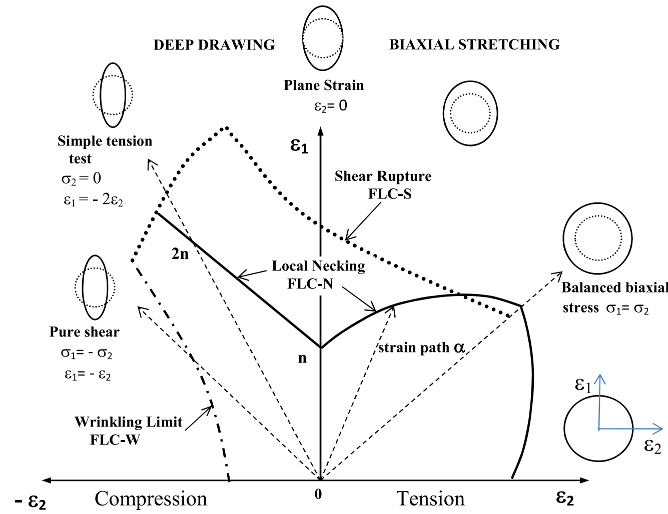

Fig. 1. Sketch of Map of Principal Surface Limit Strains (MPLS) for linear strain paths: local necking limit curve, FLC-N, shear stress rupture limit strain curve, FLC-S, and wrinkling limit strain curve, FLC-W of metal sheets.

limit strains, obtained by experimental laboratory tests. The principal true strains on the sheet surface are measured by means of a printed grid of squares [13] or circles of small diameters.

The MPLS map can be divided in two main regions: the positive quadrant or tension region or stretching region, when the minor true strain $\varepsilon_2 > 0$, and the negative quadrant or compression region for $\varepsilon_2 < 0$. In the positive quadrant, sheet metal deformation process is due to biaxial stretching or positive plastic strain path $\boldsymbol{\alpha}$ $(= d\varepsilon_2/d\varepsilon_1) > 0$. For an isotropic material and linear plastic strain path, the $\boldsymbol{\alpha}$-values are in the range of equal principal strains, $\boldsymbol{\alpha} = 1$, or the balanced biaxial stress state and the plane strain state condition, $\boldsymbol{\alpha} = 0$. In the negative quadrant, the strain path $\boldsymbol{\alpha}$ varies from zero (plane strain) up to uniaxial tension ($\boldsymbol{\alpha} = -0.5$) and pure shear strain, $\boldsymbol{\alpha} = -1$. However, for non-linear strain path, the FLC curve varies substantially [6]. Also, the limit strain at plane strain condition is a critical minimum point of FLC and is named FLC_o .

Extensive experimental investigations and metallographic observations have shown that the rupture of a metal sheet during forming is generally either preceded by visible local necking or is due to shear stress fracture without localized necking. Consequently, two kinds of localized failure mechanisms can occur in deforming metal sheets: visible local necking or groove and through-thickness shear stress fracture without onset of localized necking. In addition, the wrinkling limit strains curve is also important and should be plotted in the MPLS map.

Hence, three types of FLC curves should be plotted in the MPLS map: the limit strain curve for visible local necking, FLC-N, the limit strain curve for fracture by shear stress, FLC-S [10,11], and the wrinkling limit strain curve, FLC-W, see sketch of Fig. 1 for linear strain paths. Inside the region defined by these curve, deformation is safe and outside is failure.

The prediction of occurrence of visible local necking and through-thickness shear stress fracture mechanisms in sheet metals requires two different mathematical models that are briefly recalled in the next section, and will be later on applied to the present specific case study of aluminium alloy sheet forming at elevated temperature.

2.2. Theoretical analysis of limit strains

Many mathematical models to predict the onset of visible local necking curve, FLC-N, and rupture limit strain curve by ductile rupture in sheet metal forming, from material and forming process