Numerical simulation and experimental validation of a ductile damage model for DIN 1623 St14 steel

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Abstract St14 steel (DIN 1623) is widely used in sheet metal forming industries because of its remarkable formability and also its low price. In this paper, damage behaviour of St14 steel is studied in order to be used in complex forming conditions with the goal of reducing the number of costly trials. Damage parameters of St14 steel have been determined by using standard tensile and Vickers micro-hardness tests. A fully coupled elastic-plastic-damage model has been developed and implemented into an explicit code. With this model, damage propagation and crack initiation, and ductile fracture behaviour of drilled and notched specimens are predicted. The model can quickly predict both deformation and damage behaviour of the part because of using plane stress algorithm, which is valid for thin sheet metals. Experiments are also carried out to validate the results. It is concluded that finite element analysis (FEA) in conjunction with continuum damage mechanics (CDM) can be used as a reliable tool to predict ductile damage and fracture of St14 steel.

Keywords Ductile damage · Vickers micro-hardness · Rupture mode · St14 steel

1 Introduction

Various thin-walled parts with fairly complex shapes are produced from sheet metals such as automotive panels and other structural parts. The main emphasis is to make these parts in fewer forming operations. Hence, prediction of the forming limits has always been one of the most important challenges confronting design engineers. Damage mechanics has played a significant role in meeting this need. Damage of materials means the progressive or sudden deterioration of their mechanical strength due to loading, thermal or chemical effects. Damage to the micro-structure of an alloy under loading ultimately results in the failure of the component. Improvements to continuum-based material models have focused on quantifying the affects of statistical distributions of micro-structural features that are a result of processing. Both the alloying and the processing are responsible for the final micro-structural features that include inclusions, voids, grain size, surface inhomogeneties, and texture. Damage in cast metals has been correlated with the size and distribution of macro-voids while damage in wrought metals has been correlated with the size and distribution of micrometre-sized inclusions and second-phase particles. It has been repeatedly reported that during a forming process, mechanical properties of the material change, which causes a decrease in its strength due to micro-structural changes [1]. Young’s modulus and also micro-hardness are among these mechanical properties. Hence, studying the variations of Young’s modulus and micro-hardness are two of the proposed indirect methods that can be used to measure the damage parameters in ductile metals [2, 3]. The two indirect methods mentioned above have been compared by Mkaddem et al. [4]. They concluded that from a practical point of view, micro-hardness procedure is much easier, cheaper and less time consuming than successive loading–unloading tensile tests. Over many years, measurement of damage parameters by micro-hardness technique has been applied, and its reliability in the analysis of damage behaviour of materials has been proved [5–7]. A reliable prediction of the material damage behaviour in a forming process crucially depends on the appropriate
identification of damage parameters, which are used in simulations. Mkaddem et al. have proposed a new procedure of damage characterization, which is used in this paper [8]. The technique is based on a series of micro-hardness measurements that are performed along the axis of a tensile test specimen loaded up to failure. This method is practically easier to be used.

In the present work, damage behaviour of St14 steel (DIN 1623) is investigated because of its vast applications in complex sheet metal forming processes. Mechanical properties of the material St14 steel such as Young’s modulus, Poisson’s ratio, initial yield stress and flow stress are determined by using the standard tensile test. Then, Vickers micro-hardness tests are performed on the ruptured specimens to calculate its damage parameters which appear in the Lemaitre’s continuum damage model. The Lemaitre’s damage model is developed for plane stress cases. A fully coupled elastic-plastic-damage subroutine is developed and implemented into an explicit code. Since plane stress model is developed and plane stress elements are used, computational time is reduced drastically and there is no need to use a time-consuming three-dimensional algorithm for thin sheet metals. Hence, the model can quickly predict both damage behaviour and deformation of the thin parts. Also, it will be shown that the model can predict damage propagation and crack initiation, and ductile fracture of St14 steel sheet metal under various loading conditions. For validation of the model and the identified damage parameters, a number of examples such as standard tensile test, drilled and also notched samples under tensile stresses are investigated both numerically and experimentally. The reaction forces and the critical force required for crack initiation of sheet metal for the above-mentioned loading conditions are also predicted and compared with experimental observations. Comparison of these results reveals that the damage behaviour of St14 steel can be reliably predicted by the proposed model. Therefore, it is concluded that the Lemaitre’s damage model in the plane stress case can quickly and accurately estimate the crack initiation and rupture of thin sheet metals. Also, it is shown that Vickers micro-hardness test is a sufficient method for extracting the ductile damage parameters of the Lemaitre’s model.

2 Continuum damage mechanics model

According to Lemaitre’s damage model and strain equivalence principle, any constitutive equation for a damaged material may be derived in the same way as for a virgin material except that the stress tensor is replaced by the effective stress tensor [9]. The effective stress tensor $\bar{\sigma}$ can be represented as:

$$\bar{\sigma} = \frac{\sigma}{1 - D}$$

where $\sigma$ is the stress tensor for the virgin material. The damage variable, $D$, is between 0 and 1 for an undamaged to ruptured material, respectively. The evolution law for the internal variables can be derived from a potential dissipation function which is decomposed into plastic, $\psi_p$, and damage, $\psi_d$, components as:

$$\psi = \psi_p + \psi_d = \Phi + \frac{r}{(1 - D)(s + 1)} \left( \frac{-Y}{r} \right)^{s+1}$$

for an isotropic hardening and isotropic damage model. In the above equation, $r$ and $s$ are damage parameters of

![Fig. 1 Flow chart of numerical integration algorithm for the elastic-plastic-damage model](image-url)