Computational Materials Science 84 (2014) 1–12

Contents lists available at ScienceDirect

Computational Materials Science

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

Determination of bulk flow properties of a material from the flow properties of its constituent phases

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ARTICLE INFO

Article history:
Received 21 August 2013
Received in revised form 6 November 2013
Accepted 21 November 2013
Available online 14 December 2013

Keywords:
Empirical rule of mixture
Iso-stress, iso-strain, iso-energy condition
Representation volume element
Dual phase steel

ABSTRACT

The aim of the present work is to determine the bulk flow properties of a material from the flow properties of its constituent phases using simple empirical relationships. The materials chosen for this investigation are DP 780 and DP 590 steels. It is well known that the linear rule of mixtures is not generally able to predict the flow behaviour of DP steels using conditions of iso-stress, iso-strain and iso-energy. Therefore, a weighted energy condition has been proposed which is found to predict the flow properties reasonably well except in the elasto-plastic transition zone (initial 2–4% strain). Using FE simulation based micromechanics modelling, it has been shown that the iso-stress, iso-strain and iso-energy conditions are not valid for DP steels. In order to be able to use the linear rule of mixtures, it has been shown that the different steps of the deformation process needs to be considered. It has also been shown that the variation in degree of strain partitioning with deformation has to be accounted for, to be able to predict the flow behaviour. The flow curves calculated with the proposed methodology has been found to have very good agreement with the FE simulation results as well as the experimental data.

1. Introduction

The demand for high strength steels is ever-increasing particularly in the automotive industry, for bringing about weight reduction without sacrificing passenger safety. Reduced vehicle weight leads to decrease in fuel consumption which in turn limits greenhouse gas emissions and also reduces raw material costs. In the last few decades this has led to the development of various advanced high strength steels or AHSS, like Transformation Induced Plasticity or TRIP steels, Dual Phase or DP steels and Complex Phase or CP steels, which provide an enhanced combination of high strength and ductility compared to conventional steels such as High-Strength Low Alloy or HSLA steels. Among all AHSS, DP steels have found maximum use in the automotive industry, mainly due to their superior strength, formability and relative ease of production.

DP steels are essentially multiphase steels consisting of a soft ferrite matrix and 0.10–0.5 volume fraction of hard martensite as second phase. This coexistence of microstructural components of widely different plastic behaviour leads to a composite like strengthening effect. And like in any composite material, the mechanical properties of these steels strongly depend on the size, volume fraction and spatial distribution of the second phase with respect to the matrix. In addition, other common strengthening mechanisms such as solid solution strengthening, grain refinement and precipitation hardening also contribute to the exceptional properties of these steels. Considering the strong influence of the microstructure on the mechanical properties, there is a strong need for the development of constitutive models to predict flow behaviour, which will not only help in minimizing costly trial and error methods to achieve optimum phase combinations, but it will also help in the design of adequate forming operations for these steels.

Modelling the deformation behaviour of multi phase steels is one of the most challenging fields in material mechanics and extensive research has been carried out to predict the bulk flow properties of DP steels. Principally two approaches have been used in these studies and they are: (i) empirical rule of mixtures and (ii) finite element (FE) analysis. Among these, empirical rule of mixtures is the simpler method and hence is most widely used. However, due to its unrealistic assumptions, it is not able to predict the flow behaviour accurately. Therefore, in order to overcome the inherent problems with this method, a number of researchers have adopted FE analysis to describe the flow behaviour of DP steels.

In the FE based models developed, flow properties of the constituent phases (i.e. ferrite and martensite) have been used as inputs for predicting the bulk flow behaviour. For example, Al-Abbasi and Nemes [1] used a cell model to predict the tensile behaviour of DP steels with different volume fractions of martensite. The model was able to predict the experimentally observed variation in tensile strength and uniform elongation with change in volume fraction of martensite with reasonable accuracy. Further,

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http://dx.doi.org/10.1016/j.commatsci.2013.11.039

a microstructure based FE modelling procedure was developed by Sun et al. [2] in which the failure mode and ultimate ductility of DP steels were predicted under tensile loading conditions using the plastic strain localization theory. Marvi-Mashhadi et al. [3] were also successful in predicting full flow curves for DP steels containing 0.18 and 0.44 volume fraction of martensite using a continuum finite element model based on actual microstructure. In still other works, it was shown in the case of various DP steels [2,4–8] that microstructural inhomogeneity can serve as the initial imperfection that triggers the instability which induces plastic strain localization during the deformation process.

Apart from the modelling work, a large number of experimental studies have also been undertaken to understand the deformation behaviour of DP steels at the microstructural level. Sodjit and Uthaisangsuk [9] observed that under tensile deformation several short interrupted shear bands developed in DP structure with low martensite contents, but when the martensite content increased, long continuously pronounced localizing bands appeared. In situ Scanning Electron Microscopy and Digital Image Correlation analysis of DP steels by Kang et al. [10] and Ghadbeigi et al. [11], revealed inhomogeneous deformation at the microstructural level. These studies also showed that deformation is mainly concentrated in the ferrite phase.

From the above discussion it is clear that microstructure based FE modelling is a far more appropriate technique than the empirical rule of mixtures, for predicting the flow behaviour of DP steels. However, compared to empirical rule of mixtures the FE technique is a very resource intensive and time consuming approach. Therefore, in order to simplify the methodology of predicting flow behaviour of DP steels, and at the same time maintain the accuracy of prediction, a modified empirical model has been proposed in this work. For this, at the outset, FE simulation using Representative Volume Elements (RVE) has been used to understand the deformation behaviour of a cold rolled DP steel at the microstructural level and determine the stress and strain partitioning between its constituent phases. Using this analysis, the shortcomings of the empirical rule of mixtures have been addressed and a modified empirical model has been proposed. The modified empirical model has been tested on two different DP steels.

2. Finite element simulation

A cold rolled dual phase steel with 780 MPa tensile strength (DP 780) was used for the FE simulation. The composition and microstructural details of the steel are published elsewhere [7,8]. The microstructure of the steel was found to consist of 0.77 volume fraction of ferrite and 0.23 volume fraction of martensite. The flow properties of the individual phases were calculated using the procedure described in the literatures [6–8] and are depicted in Fig. 1. These were used as an input for the FE simulation.

In order to account for the influence of the different microstructural constituents on the flow behaviour, a three dimensional Representative Volume Element (RVE) was used for the FE simulation. The RVE was defined as a cube as in literatures [7,8,12]. The RVE was described by taking into account the experimentally measured phase fractions and using a statistical algorithm for the phase distribution. Fig. 2 shows the RVE of the microstructure of DP 780 steel with its constituent phase fractions. The FE simulation was carried out using ABAQUS. Three dimensional eight node brick elements were used for the simulation. Uniaxial tensile deformation was applied to the top surface of the RVE in the *z*-direction while its bottom surface was kept fixed.

The flow curve determined from FE simulation using 3-d RVE compares well with the experimental flow curve, as shown in Fig. 3. Fig. 4 shows the equivalent plastic strain distribution

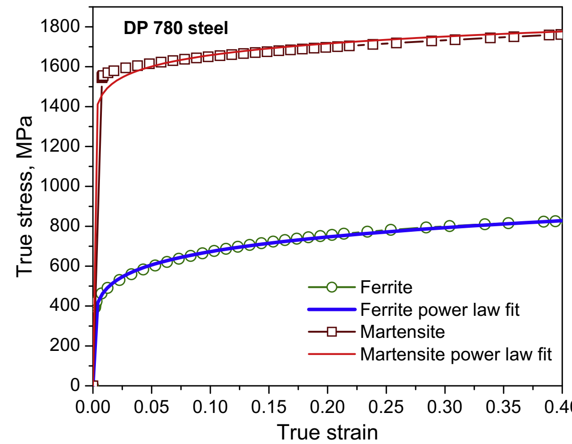

Fig. 1. Stress–strain curve of ferrite and martensite phases in DP 780 steel.

between ferrite and martensite phases after the RVE is subjected to an overall engineering strain of 10%. As is evident from the figure, ferrite undergoes much larger deformation than martensite. In order to quantify the strain partitioning between the phases, the mean values of the equivalent plastic strain and equivalent stress in ferrite and martensite were also calculated for overall engineering strains of 0.4%, 1.0%, 3.0%, 5.0%, 7.0%, 10.0% and 12% of the RVE. The same is depicted in Fig. 5a and b. The error bars shown in the figures represent the standard deviation of the calculated values. From this analysis, it is clear that the stress is high in the martensite phase whereas strain (i.e. deformation) is high in the ferrite phase. Further, in Fig. 5c, for each overall engineering strain value, the mean von Mises equivalent stress is plotted against the mean equivalent plastic strain for both the ferrite and martensite phases. The overall von Mises equivalent stress versus equivalent plastic strain curve for the RVE is also included in the figure. Clear partitioning of stress and strain between the phases is revealed through this micromechanics based FE analysis.

Further, in order to have a more comprehensive understanding of the deformation behaviour of each phase, the von Mises equivalent stress and equivalent plastic strain distributions within each phase were computed for various deformation levels of the RVE and the same are depicted in Figs. 6 and 7 for ferrite and martensite respectively. In the case of ferrite, (Fig. 6) it is observed that with increasing overall deformation, the distributions become wider and the peaks of the distributions shift towards higher values of equivalent stress/plastic strain. On the other hand in the case of martensite, for overall engineering strains of up to 1% until which it remains elastic (yield strength of martensite is computed to be 1544.5 MPa), the von Mises equivalent stress shows a normal distribution (Fig. 7a), whereas the equivalent plastic strain remains zero (Fig. 7b). As the overall deformation increases, plastic deformation initiates in martensite and the distribution of the equivalent strain becomes wider. However, very little change in the von Mises equivalent stress distribution is noticed which can be attributed to the negligible strain hardening of martensite.

The overall distribution of von Mises equivalent stress and equivalent plastic strain of the RVE for an engineering strain of 5% is shown in Fig. 8. Two clearly distinct peaks are observed, both in the case of von Mises equivalent stress, (Fig. 8a) as well as equivalent plastic strain (Fig. 8b). This is due to the huge difference in the stress and strain levels in ferrite and martensite. In the von Mises equivalent stress distribution plot, the peak at the lower stress value corresponds to ferrite whereas that at the higher stress level corresponds to martensite. In the equivalent plastic strain distribution plot on the other hand, the peak at the higher strain