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ScienceDirect
Computational Materials Science 43 (2008) 27–35
COMPUTATIONAL MATERIALS SCIENCE
www.elsevier.com/locate/commatsci

Micromechanical modelling of damage behaviour of multiphase steels

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Available online 12 September 2007

Abstract

Multiphase steels offer very attractive combinations between strength and formability, due to the coexistence of different microstructural components and their interactions. The advantages of multiphase steels can be utilised by adjusting the type, the amount and the spatial distribution of the different phases, which are ferrite, martensite, bainite, and retained austenite. Understanding damage initiation and evolution are important to successfully process the material with only small scatter band of the formability properties. In the investigations two failure modes were simultaneously observed on a micro-scale, cleavage and dimple fractures. The model presented here attempts to describe the influence of the multiphase microstructure on the complex failure mechanism as well as mechanical properties by approaching the problem using representative volume elements (RVE) within the framework of continuum damage mechanics. Simulations for the dimple failure of TRIP steels, using the Gurson–Tvergaard–Needleman (GTN) model with two void nucleation mechanisms, will be presented. The cohesive zone model, based on the traction-separation law, is applied to the cleavage failure modelling.

Keywords: Multiphase steel; Finite element modelling; Representative volume elements; Ductile and cleavage fracture; Gurson–Tvergaard–Needleman; Cohesive zone model

1. Introduction

The demand on multiphase steels, such as DP (Dual Phase), TRIP (Transformation Induced Plasticity), PM (Partly Martensitic), and TWIP (Twinning Induced Plasticity) steels with excellent strength and ductility, has increased in the automotive industry due to development aims, weight reduction, improved passive safety features, energy saving considerations and environmental protection [1,2]. In spite of their higher specific weight, compared to other materials like aluminium, magnesium, composites and plastics, multiphase steels give steel a highly competitive edge in car body construction applications [3]. The increased strength and formability of multiphase steels is not only the result of solid solution hardening, grain refinement and precipitation hardening, but also due to the coexistence of softer and harder phases and different grain sizes [4,5]. Their useful properties are controlled by adjusting the type, size, fraction and spatial distribution of the different phases, which also play a significant role in the complex damage mechanism and failure behaviour of these steels.

Two failure modes were observed locally in parallel on the micro-scale: cleavage and dimple fracturing. The relative contribution of each fracture mode depends on the stress state (in particular on the triaxiality), the internal cleanness, the volume fraction of the retained austenite and the conditions of neighbouring austenite and martensite grains [6]. In the current study, different multiphase microstructures were developed by means of various heat treatments based on one chemical composition, in order to clarify the influence of microstructure on the damage evolution. Mechanical testing of various specimens was performed for material characterisation, followed by a fractographic analysis of the fractured surface with the

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doi:10.1016/j.commatsci.2007.07.035

aid of a scanning electron microscope and light optical microscope for damage investigations.

In order to consider the influence of the multiphase microstructure, a FE (Finite Element) approach has been applied using RVEs (Representative Volume Elements) within the framework of continuum mechanics [7,8]. In general a RVE-model represents a periodic repeating cell, which describes a cut-out of the whole microstructure. The RVE-model makes it possible to identify the influences of each modelled phase on the overall strength of material. Additionally, microstructural characteristics, like morphology or different failure behaviours, for each individual phase can be described.

In this work a model describing the mechanical properties of each phase was used based on carbon partitioning [12]. Thus, the complex microstructure can be correlated with the local loading characteristics, which makes it possible to explain the complex fracture mechanisms. For the numerical simulation of damage and crack propagation with the FE-method, there are several possibilities, which differ regarding their physical background. Micromechanical based damage models represent the fracture formation (void initiation, void growth and void coalescence) within an extended material model [9]. The micromechanical damage models are mostly restricted to ductile fracturing, which is associated with high plastic deformations. The micromechanical processes during ductile damage are induced by inclusions and precipitations in material. Simulations on the dimple failure mechanisms of TRIP steels using the GTN approach (Gurson–Tvergaard–Needleman) [11] were carried out. In contrast, phenomenological models describe fracturing as material separation due to an achieved critical condition. These models were often applied to brittle fracture simulations [10]. Here, the cohesive zone model based on the separation law was used to describe the cleavage failure mechanism. The parameter identification for both models will be presented. The results show that the introduced approach enables a practical concept for failure assessment in multiphase steels.

2. Experimental procedure

2.1. Materials and mechanical properties

First, the microstructural design for the investigated materials by thermal heat treatment will be illustrated. The chemical composition can be found in Table 1. A common TRIP concept combines Si and Al in order to control the phase transformation, to suppress cementite precipitation, and to increase the solid solution strengthening. By means of different heat treatments, different multiphase microstructures were developed. Dilatometry experiments were conducted to determine the thermal cycles, which give rise to the desired microstructures. A combination of light optical metallography and magnetic measurements was used to quantify microstructures and their corresponding phase volume fractions. In Fig. 1, five time–temperature cycles are outlined, that were used for the microstructural design. An overview of the resulting phase fractions can be found in Table 2. Additionally, the mechanical stability of retained austenite and an approximation of the carbon partitioning in different phases is given. The austenite stability is specified by the austenite amount that transforms to martensite during tensile tests and was determined using magnetic measurements. Whereas the carbon partitioning was calculated using a simplified approach. More details for this approach can be found in [12,13]. Within the investigations two intercritical holding temperatures were used: 785 °C leading to 55% ferrite, and 825 °C leading to 30% ferrite. In this manner, two ferrite martensite dual phase structures A and D (directly quenched), two TRIP microstructures B and C (holding in the bainitic range) with different amounts of retained austenite and different carbon contents, as well as a ferrite bainite dual phase structure E were generated.

Table 1
Investigated TRIP steel composition

C	Mn	Si	P	Al	N
0.19	1.50	0.26	0.086	0.52	0.004

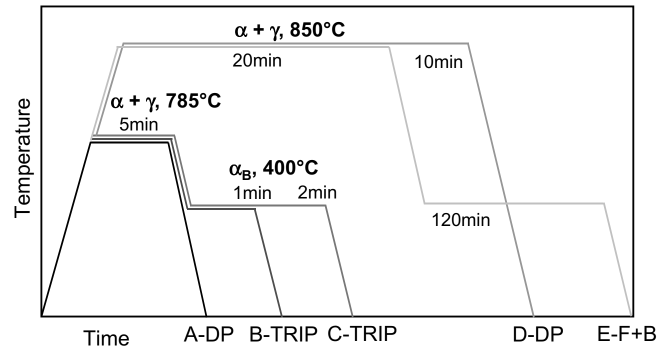

Fig. 1. Time–temperature cycles for microstructural design.

Tensile tests were carried out at room temperature according to DIN EN 10 002. The engineering stress–strain curves and the associated flow curves were determined using unnotched round tensile bars B3X15. The determined flow behaviour, in terms of true stress–strain curve, is shown in Fig. 2 for the different microstructure variants. In this case, the examination of deformed specimen after necking is allowed through image analysis. The five multiphase microstructures differ noticeably in their mechanical properties. The dual phase steel A achieves high stresses at very low strains. Microstructure B also reaches high stresses and good elongation values. Its initial higher strain hardening level is due to the presence of martensite in the microstructure. TRIP Steel C shows the highest formability values with 28% strain and high stress levels. Dual phase steel D achieves the highest stress levels but the lower strain levels due to the high martensite amount. Steel E exhibits comparable stress levels with steel B, but with a low strain hardening.