Physically based modeling of the mechanical behavior of TRIP steels

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ABSTRACT: Multiphase TRIP steels offer excellent mechanical properties that result from the composite behaviour of the different phases and the transformation of the austenite phase to martensite. For the development of a physically based micromechanical model, it is of considerable importance to evaluate the contribution of the different phases separately. For this purpose, the different constituent phases were prepared separately, and the stress-strain relationships of the different single phases were simulated taking into account their physical and microstructural properties such as the chemical composition and dislocation density. The static stress-strain properties of multiphase steels were modelled by the successive application of a mixture law. The model also allowed to integrate the strain rate and temperature dependence.

Key words: TRIP steels, modelling, strain-induced martensite, Mecking-Kocks

1 INTRODUCTION

The requirements for an increased formability and a weight reduction, especially for the automotive industry, have largely contributed to the development of new low alloy TRansformation Induced Plasticity (TRIP)-aided ferrous alloys [1]. These steels have a fine microstructure consisting of ferrite, bainite and a martensite/austenite (M/A) constituent, which is obtained by a two step annealing treatment. The particular feature of this microstructure is the presence of retained austenite, which transforms to martensite during straining. Recently, different models for the stress-strain behaviour for various types of steels (ferritic, martensitic, pearlitic, dual phase) have been proposed. However, few models consider a physically-based approach for TRIP steels [2,3].

The optimization of the mechanical properties of such complex multiphase steels requires a detailed understanding and physically-based modelling of the deformation behaviour and possible transformation that may occur during mechanical testing. The aim of the present study is to predict the macroscopic mechanical behaviour of TRIP steels using a physically based model, taking into account the composition, morphology and the behaviour of each constituent.

The presented model for multiphase high strength low alloy TRIP steels has two major characteristics: the model parameters are physically meaningful and their values are determined by fitting to experimentally determined properties of the different phases. The transformation kinetics for retained austenite are determined experimentally, taking the temperature and the composition into account and integrated in the Olson–Cohen [4] equation. The properties of the TRIP steel were predicted by combining the features of the different constituents by successively applying mixture laws for two-phase steels. This model allows for a detailed description of the behaviour of each phase separately within the multiphase microstructure during a tensile test.

2 EXPERIMENTAL PROCEDURES

2.1. *Materials preparation*

TRIP steels with various chemical compositions

(CMnSi, CMnAl, CMnSiAl, and micro-alloyed Ti TRIP) were laboratory processed. Moreover, because of the multiphase aspect of the material (ferrite, bainite and retained austenite) the different constituents were studied separately. This was done by preparing the different bulk alloys were prepared by varying the carbon content in order to obtain compositions corresponding to those of the constituents of the TRIP steel.

2.2. *Microstructure characterisation*

The resulting microstructures of the non-strained materials were observed with Light Optical Microscopy (LOM) using Lepera etching [5]. Fig.1 shows the micrographs of the ferrite and bainite phase, and of the TRIP steel for the *CMnAl* composition. Using Scanning Electron Microscopy observations, the grain size of the different phases was determined experimentally.

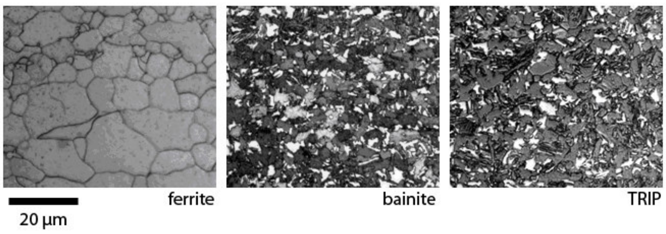

Fig. 1 - Microstructures of the different CMnAl alloys

Complementary, a study of the amount of retained austenite was performed using X-Ray diffraction (XRD) analyses. The measured values were used as input for the Olson – Cohen description of the martensite strain induced transformation kinetics. [7]

The alloys for the separate austenite constituent were not used, because athermal martensite was observed in the as-casted materials.

2.3. *Mechanical properties*

The static mechanical properties were determined by tensile tests on an Instron 5569 tensile testing machine on temper rolled samples. The specimen geometry, with 80mm of gauge length, was according to the European Standard EN 10002-1 specification. The initial crosshead speed of 10^{-4} s^{-1} was increased to 10^{-3} s^{-1} at a strain of 3.38%.

Dynamic tests were performed, at strain rates between 635 and 1500 s^{-1}, on a split Hopkinson tensile bar apparatus (Fig.2), available at Ghent University. Details of the set-up of this machine are given in [6]. The high strain rate tensile loading of the specimen is obtained by interaction of an incident tensile wave with the specimen, generating a reflected wave and a transmitted wave. The strain histories ε_i, ε_r and ε_t, corresponding to the incident, reflected and transmitted waves, are measured by means of strain gauges. From these signals the stress, strain and strain rate in the specimen are calculated.

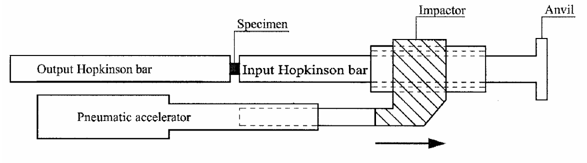

Fig. 2 - Principle of the split Hopkinson tensile bar

3 MODELLING OF THE STEELS BEHAVIOUR

On a macroscopic level, TRIP steels are treated as composite materials and their behaviour is well understood when this composite behaviour is taken into account. On a microscopic level, the deformation of these steels is the result of several interacting processes: i.e. a complex synergy between phases, the influence of a transformation and its kinetics and work hardening.

The proposed model was first developed for static purposes and afterwards extended to dynamic.

3.1. *Static loading*

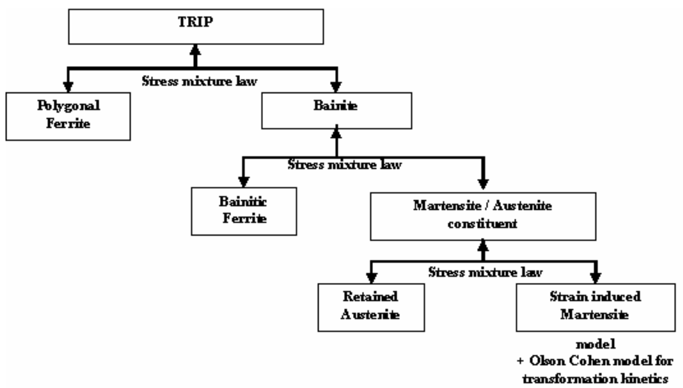

Fig. 3 - Principle of the model based of the complex TRIP microstructure decomposed into its various constituents

Fig.3 schematically describes how the stress – strain curve of a TRIP steel is simulated [7]. The TRIP steel contains two main constituents: polygonal ferrite and bainite. The bainite can, in turn, be decomposed into bainitic ferrite and a two-phase mixture of retained austenite and martensite. The stress-strain is modelled and correlated with experimental results for each constituent and the TRIP steel behaviour is simulated by combining the modelled behaviour of its constituents making use of a successive application of a Gladman mixture law.

The strength of each single constituent results from different contributions, which can be added to determine the final material strength. Eq.1 illustrates the different strengthening effects for a single phase material:

$$\sigma = \sigma_P + \sigma_{SS} + \sigma_{dis} + \sigma_{HP,d} + \sigma_{ppt} \quad (1)$$

- σ_P is the intrinsic strength of the material due to the Peierls or lattice friction the dislocations experience when moving on their glide plane; literature data [8] showed that σ_P has a value of 75 MPa for iron based alloys.
- σ_{SS} is the stress resulting of the solid solution hardening. For TRIP steels Si, Al, Mn and P solid solutions result in a permanent increase in yield, flow and tensile stress. This is due to the continuous interaction between dislocations that glide and the solutes present on the glide plane. The effects of the different alloying elements on the yield, flow and tensile stress are generally expressed as:

$$\sigma_{SS} = \sum_{P,Al,Si,Mn,C_{ss},N_{ss}} (wt\%\ element) * YS_{increase/wt\%} \quad (2)$$

The strengthening effect of the solid solution hardening is mainly considered as a constant term, but to be accurate, this effect presents a slight temperature dependence, as it has been shown in [9].

- σ_{dis} represents the accumulated strengthening effects of the grain size and the dislocation-dislocation interactions when the dislocation density is increased.
The grain size and dislocation interaction effect have been considered in detail in previous work [7]. In order to model the resulting stresses, the Mecking-Kocks theory (Eq.3) is associated with a Taylor law (Eq.4).

$$\frac{d\rho}{M.d\varepsilon} = \frac{1}{\lambda b} + \frac{k}{b}\sqrt{\rho} - f\rho \quad (3)$$

$$\sigma_{g,d} = \alpha M G b \sqrt{\rho} \quad (4)$$

In those equations, ρ is the dislocation density, b is the burgers vector, M is the Taylor factor, G is the shear modulus, α is a numerical factor that characterizes the dislocation-dislocation interaction, k and f are fitting parameters. λ, the mean free path for dislocations is assumed to be equal to the grain size, d, for the polygonal bainitic ferrite, and determined by $\lambda = d_\gamma \sqrt[3]{1 - f_{\alpha'}}$ for the M/A constituent [7], where $f_{\alpha'}$ is the martensitic volume fraction, determined by an Olson-Cohen law.

- The specific grain size effect, taken into account via the Hall-Petch term, considers the grain size contribution of the grain size refinement to the yield strength: $\sigma_{HP,d} = f_{ppt}\, k' d^{-1/2}$, where the value k' has been calculated from literature [10]
- σ_{ppt} corresponds to the precipitate contribution to the yield strength. For the studied Ti TRIP steels, the corresponding contributions are expressed in equations 5 and 6, considering the size (D_S) and the volume fraction (f_{ppt}) of the corresponding precipitates.

$$\sigma_{ppt}^{\alpha} = 10x \frac{\sqrt{f_{ppt}}}{D_{S_\alpha}} \ln\left(\frac{D_{S_\alpha}}{5x10^{-4}}\right) \quad (5)$$

$$\sigma_{ppt}^{\gamma} = 0.538x \frac{MGb\sqrt{f_{ppt}}}{D_{S_\gamma}} \ln\left(\frac{D_{S_\gamma}}{2b}\right) \quad (6)$$

3.2. *Dynamic loading*

Under dynamic solicitation, a modified work hardening process and a temperature related softening effect, which results from adiabatic heating, are also interacting. The Eq.1 becomes:

$$\sigma = \sigma_P + \sigma_{SS} + \sigma_{dis}(\dot{\varepsilon}, T) + \sigma_{HP,d} + \sigma_{ppt} + \sigma_{th} \quad (7)$$

Here, the thermally activated component of the flow stress, σ_{th}, is determined by the Seeger-Kocks approach [12] (cf. Eq.8).

$$\tau_{th} = \begin{cases} \hat{\tau}\left\{1 - \left(-\frac{kT}{G_0}\ln\frac{\dot{\gamma}}{\dot{\gamma}_r}\right)^{1/q}\right\}^{1/p} & for \quad T \le T_c \\ 0 & for \quad T > T_c \end{cases} \quad (8)$$

Here, G_0 represents the energy of the Peierls barrier; k is the Boltzman constant, T is the temperature, $\dot{\gamma}$ is the slip rate, $\hat{\tau}$ is the threshold stress, i.e. the mechanical stress required to cross the barrier without any thermal activation, p and q are two parameters that represent the geometry of the Peierls barrier and T_c is the critical temperature that separates short range to long range interactions. The temperature T can also be related to the adiabatic heating, which occurs during high strain rate deformation, can be calculated from [13]:

$$T = T_{room} + \frac{\beta}{\rho c} \int \sigma . d\varepsilon \qquad (8)$$

4 DISCUSSION

The proposed model was validated by the monotone static behaviour of CMnAl and CMnSi TRIP steels [7] as well as by the dynamic behaviour of CMnAl Ferrite [9]. As shown in Fig.4, the model is easily extended to micro-alloyed TRIP steels.

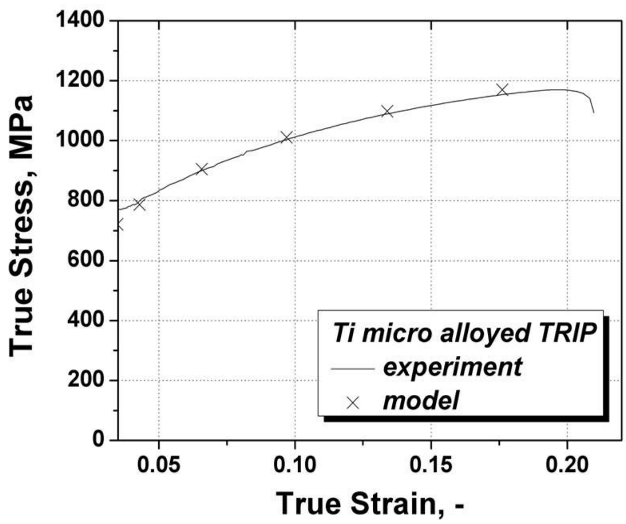

Fig.4 - Simulated stress - strain curves for Ti-TRIP and CMnSiAlP TRIP

Recently, the temperature and strain rate dependence of the fitting parameters of Eq.4. have been discussed elsewhere [13]. Furthermore, the Olson – Cohen law is presenting the same dependency [4]. Combining both factors and the proposed model could lead to a description of the TRIP steel mechanical behaviour under dynamic solicitation.

5 CONCLUSION

The current model proposes a physically based description for the stress-strain curve of a complex multiphase microstructure and has been validated by making comparison with experimental results of several TRIP steels and separately made alloys.

On a second level, the model successfully integrates the specific effect of the alloying elements and precipitates. The influences of temperature and strain rate were introduced by a contribution term to the flow stress and a variation of the parameters in the strain hardening and transformation kinetics laws.

Good agreement with experimental data was observed for a mono-phase material. Further work will consist in correlating simulations and experiments for TRIP steels under dynamic solicitation.

REFERENCES

1. M. De Meyer, D. Vanderschueren, B.C. De Cooman: The influence of the substitution of Si by Al on the properties of cold rolled C-Mn-Si TRIP steels. ISIJ Int., Vol 39 (1999), p.813
2. A. Perlade, O. Bouaziz, Q. Furnémont: A physically based model for TRIP-aided carbon steels behaviourMater. Sci. Eng, Vol A356 (2003), p.145
3. N. Tsuchida, Y. Tomota, H. Moriya, O. Umezawa, K. Nagai: Application of the Kocks–Mecking model to tensile deformation of an austenitic 25Cr–19Ni steel Acta Mat. Vol49 (2000), p.3029
4. L. Samek, E. De Moor, J. Penning, B.C. De Cooman: Influence of alloying elements on the kinetics of strain-induced martensitic nucleation in low-alloy, multiphase high-strength steels. Met. Trans. A, Vol 36A (2006), pp.109-124
5. F.S. Lepera: Improved etching technique for the determination of percent martensite in high-strength dual-phase steels J. Metal. (1980), pp.38-39
6. J. Van Slycken, P. Verleysen, J. Degrieck, J. Bouquerel: Dynamic response of aluminium containg TRIP steels and its different constituents B.C. De Cooman: Mater. Sci. Eng. A, 460–461 (2007) 516–524
7. J. Bouquerel, K. Verbeken and B.C. De Cooman: microstructure based model for the static mechanical behaviour of multiphase steels. Acta Mat, Vol.54 (2006) 1443–1456
8. S. Takeuchi, E. Furubayashi and T.Taoka: Act. Met., Vol 15/7 (1967), pp.1179-1191
9. J. Bouquerel, K. Verbeken, B.C. De Cooman, Y. Houbaert, J. Van Slycken, P. Verleysen: Physical based model static and dynamic behaviour of TRIP steel. Adv. mater. res. 15-17 (2007) pp.744-749
10. J.Bouquerel, K. Verbeken, D. Krizan, L. Barbé, P.Verleysen, Y. Houbaert: Evaluation of the static stress-strain behaviour of phosphorus alloyed and titanium micro-alloyed TRIP steels. *Submitted to Steel Res.*
11. S. Nemat-Nasser: Plasticity A Treatise of Finite Deformation of Heterogeneous Inelastic Materials, Cambridge University Press. ISBN 0-521-83979-3
12. L.P. Xu, L. Li, X.C. Wei, R.Y. Fu, B.C. De Cooman, P.Wollants, L. Wang and X.D. Zhu: Int. Conf. On TRIP-Aided High Strength Fer. All.. GRIPS (2000), pp. 367-371. ISBN 3-86130-240-3
13. B.Reichert, Y. Estrin: Modular Modelling of Stress-Strain Behaviour of Ferritic Steel Grades in Strain Rate Ranges Relevant for Automotive Crash Situations. Steel Res. 10-11 (2007) pp.791-793