IMPACT-DYNAMIC BEHAVIOUR OF AL-TRIP STEEL

P. Verleysen[1], J. Van Slycken[1], J. Degrieck[1], B.C. De Cooman[2] and L. Samek[2]
[1] Mechanics of Materials and Structures,
Department of Mechanical Construction and Production,
Ghent University (UGent)
E-mail: Patricia.Verleysen@UGent.be
[2] Laboratory of Iron and Steelmaking,
Department of Metallurgy and Materials Science,
Ghent University (UGent)

ABSTRACT

In recent years TRIP-steels (TRansformation Induced Plasticity-steels) have been developed. TRIP-steels are composite steels composed of ferrite, bainite and retained austenite. During plastic deformation, the austenite phase transforms to martensite, and this gives rise to an exceptional mechanical behaviour of the material: high strength levels (yield strength, tensile strength, …) are combined with an excellent ductility. The resulting high energy dissipation makes TRIP-steels extremely suitable for energy-absorbing devices such as the bars used in the crumpling zone of a car. To guarantee a controlled dissipation of the energy released during a crash, knowledge and understanding of the impact-dynamic material properties is essential. In this contribution results of an extensive experimental program to investigate the strain rate dependent mechanical properties of a TRIP-Al-steel are presented. A split Hopkinson tensile bar set-up was used for the experiments. Next to the TRIP-material, also the three constituent phases of the TRIP-steel were produced and subjected to high strain rate loading. From the results it is clear that TRIP steels, also in dynamic circumstances, show excellent mechanical properties.

1 INTRODUCTION

Due to increased passenger safety and comfort, the weight of passenger cars has continuously increased in recent years. Since an increased weight leads to higher fuel consumption and greenhouse gas emissions, car manufacturers try to reduce the weight of the car structure, which led to an increased use of high strength steel grades. Low alloy TRIP-aided steels (Transformation Induced Plasticity) constitute a new category of steels with high tensile strengths and a high uniform elongation. The high strain rate performance of TRIP steels makes them ideally suited for safety-related structural automotive applications. During automobile collisions, these steels offer large dynamic energy absorption. This is due to a high strain rate composite effect, i.e. the complex synergy of the high strain rate behaviour of the ferrite, bainite and meta-stable austenite within the TRIP-aided steel microstructure. During a crash, the material is strained very rapidly at strain rates which may reach 1500/s. When the strain rate is high like this, the thermal conductivity of the material is not sufficient for the heat generated within the specimen to be dissipated to the environment. The temperature rises due to the quasi-adiabatic deformation. The specimen temperature can reach 100 to 120°C during dynamic loading (Samek [1]). Therefore in dynamic conditions, the strain rate and quasi-adiabatic effects play a major role during straining. Because the austenite stability varies with the temperature, next to the chemical composition, the size of the phases, the stress state and the strain rate, the effect of the temperature has to be taken into account. An eventual rapid austenite transformation to martensite in the early stages of deformation can be detrimental to ductility. In the context of TRIP-aided alloys developed for the automotive industry for increased safety requirements during crashes, the prediction of the temperature and strain rate dependent mechanical behaviour is of considerable importance.

TRIP steels have a microstructure composed of ±50% ferrite (α), ±40% bainite (α_b) and ±10% meta-stable austenite (γ). The interaction of the high strain rate behaviour of the ferrite (α), bainite (α_b) and the meta-stable austenite (γ) phase within the TRIP-microstructure causes its typical high energy absorption potential. The meta-stable austenite phase transforms during deformation into martensite (α') causing the enhancement of ductility in high strength steels, the so-called TRIP-effect (Bleck [2], Samek [3]). The most critical parameter for controlling this effect is the stability of the austenitic phase. This stability is dependent on the chemical composition, the grain size, the temperature, …

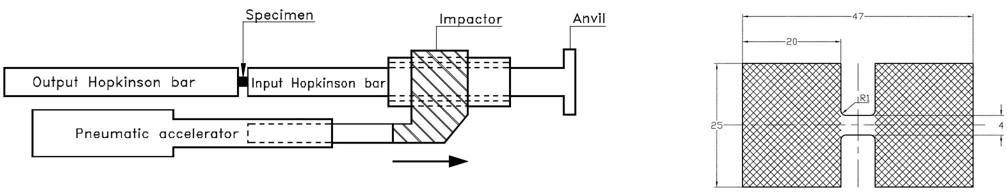
2 EXPERIMENTS

2.1 High strain rate test facility

The high strain rate experiments were conducted on a Split Hopkinson tensile bar (SHTB) apparatus, available at Ghent University. A schematic representation of a typical SHTB setup is given in figure 1a. The setup consists of two long bars, an input bar and an output bar, between which a specimen is sandwiched. For tensile tests most often a tube-like impactor is put around the input bar and is accelerated towards an anvil at the outer end of the input bar. Thus a tensile wave, the so-called incident wave, is generated and it propagates along the input bar towards the specimen. The incident wave interacts with the specimen, generating a reflected wave and a transmitted wave. The strain histories $\varepsilon_i(t)$, $\varepsilon_r(t)$ and $\varepsilon_t(t)$ corresponding with respectively the incident, reflected and transmitted wave are usually measured by means of strain gages at well chosen points on the Hopkinson bars. From those measured waves, the history of the stress, the strain and the strain rate can be derived using the following expressions (Kolsky [4]):

$$s(t) = \frac{A_b E_b}{A_s} e_t(t), \quad e(t) = \frac{U_{ob} - U_{ib}}{L_s} = -\frac{2C_b}{L_s}\int_0^t e_r(t)\,dt, \quad \dot{e}(t) = \frac{V_{ob} - V_{ib}}{L_s} = -\frac{2C_b}{L_s} e_r(t) \qquad (1)$$

with E_b the modulus of elasticity of the Hopkinson bars, A_s and A_b the cross section area of the specimen and of the Hopkinson bars respectively, C_b the velocity of propagation of longitudinal waves in the Hopkinson bars and L_s the gage length of the specimen. U_{ib} and U_{ob} are the displacements of the interface between the specimen and, respectively, the input bar and the output bar. V_{ib} and V_{ob} are the corresponding velocities.



(a) (b)

Figure 1 Principle of the split Hopkinson tensile bar setup (a) and specimen geometry (b)

Since the strain rate is obtained by an interaction of the incident wave with the specimen, the strain rate is dependent on the mechanical and geometrical characteristics of the specimen. For the TRIP steels and geometry considered here strain rates varying from 500 to 2000 s^{-1} could be reached.

Currently, no clear standard test procedures are available to test steels dynamically. So, in preparation to the tests, the influence of the specimen geometry on the obtained stress-strain curves was studied (Verleysen [5]) using a purpose-developed technique to measure the strain distribution along the length of the specimen during the high strain rate experiment (Verleysen [6]). On the basis of the results, finally, one geometry was chosen and used for the experiments. This geometry is represented in figure 1b. The shaded zones are used to glue the specimen between the Hopkinson bars.

2.2 Experimental program

TRIP steels have a microstructure composed of ±50% ferrite, ±40% bainite and ±10% retained austenite. The chemical composition of the CMnAl-TRIP-steel and its constituent phases is given in table 1. All materials, the TRIP steel and the bainite, ferrite and austenite phase, are made in the Laboratory for Iron and Steelmaking of the Ghent University.

	C	Mn	Al	Si
CMnAl-TRIP	0.18	1.56	1.73	0.02
Ferrite-phase	0.025	1.78	1.63	0.071
Bainite-phase	0.37	1.5	1.49	0.025
Austenite-phase	1.6	1.64	1.57	0.021

Table 1: Chemical composition (in wt%) of the CMnAl-TRIP-steel and its constituent phases

3 EXPERIMENTAL RESULTS

3.1 CMnAl-TRIP

In figure 2 static and dynamic stress-strain curves are given for the CMnAl-TRIP steel. From figure 2 it is clear that the TRIP-steel considered here exhibits a limited, though noticeable, strain rate dependence: stress and deformation levels rise as the strain rate increases.

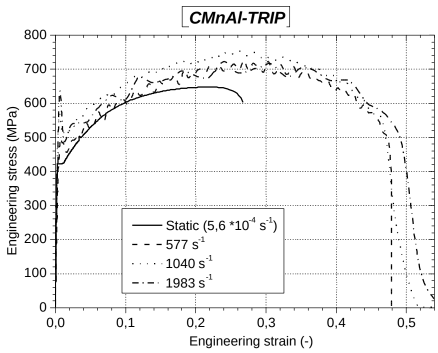
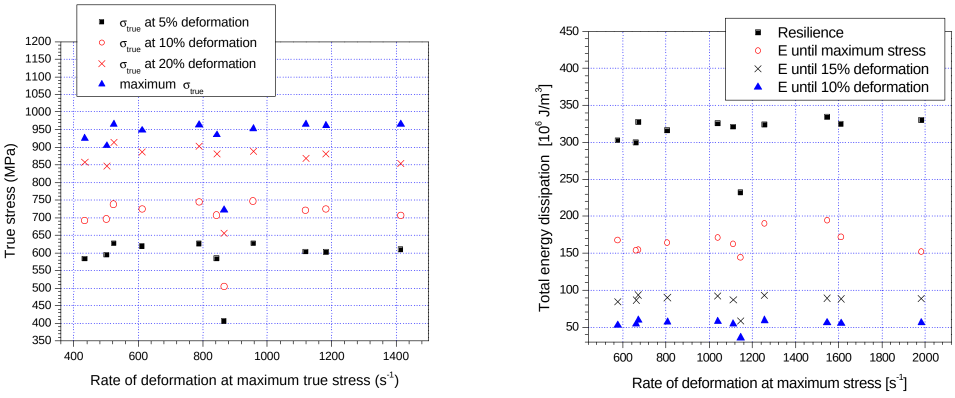


Figure 2: Representative, static and dynamic stress strain curves for the CMnAl-TRIP steel. The indicated strain rate is the value reached at maximum stress.

In figure 3a yield stresses corresponding with strain values of 5%, 10% and 20% and the maximum stress are given, again as a function of the strain rate, for the CMnAl-TRIP steel. From this figure it is clear that (1) the yield stress increases with the strain rate, and that (2) the strain rate dependency increases with the strain. In figure 3b the energy dissipated by the material at 10%, 15% strain and at maximum stress and the resilience (energy absorption at failure) is given. As could be expected, mainly the last value is affected by the strain rate.



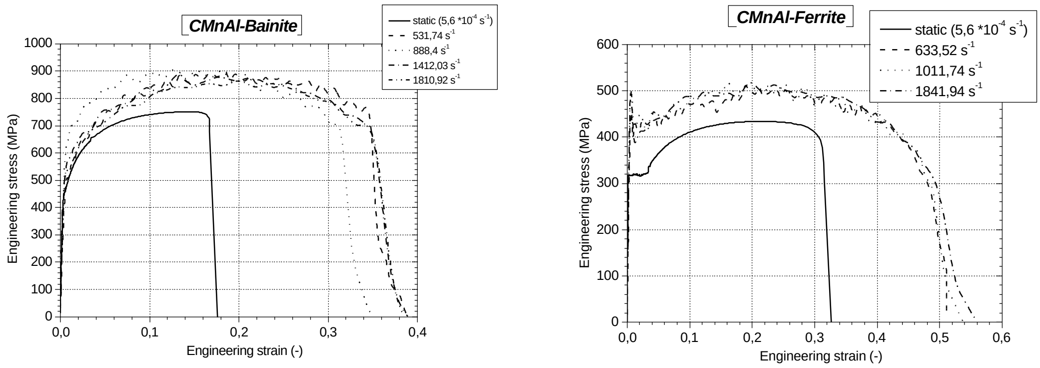
(a) (b)

Figure 3: Yield stress (a) and dissipated energy (b) at different strain levels as a function of strain rate for the CMnAl-TRIP steel

3.2 Constituent phases

In figure 4a static and dynamic stress-strain curves are given for the *bainite* phase. Comparing the static curve with the dynamic curves, the strain rate dependency is clear. However, if the dynamic stress-strain curves are compared with each other the strain rate effect is less pronounced. Indepent of the strain rate two types of behaviour can be distinguished: one exhibiting strong hardening in the beginning of the plastic deformation, and one with lower hardening at low strain levels, but with a higher ultimate deformation. These differences can probably be attributed to the presence of a minor fraction of retained austenite in the bainite phase.

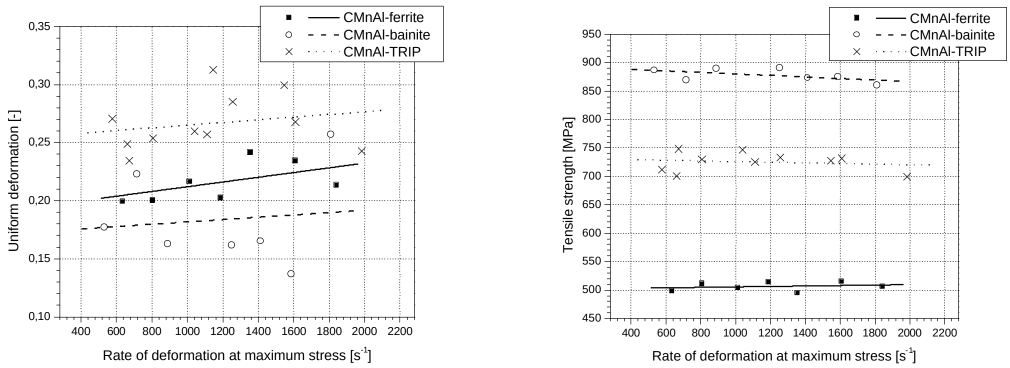
For the *ferrite* more consistent stress-strain curves are found, as can be seen in figure 4b. For the range of strain rates considered here the strain rate dependence is limited; between the dynamic stress-strain curves only minor differences exist.



(a) (b)

Figure 4: Stress strain curves for the (a) bainite phase and (b) ferrite phase

In figure 5a and 5b uniform deformations and tensile stresses are given as a function of the strain rate for the TRIP steel, and the ferrite and bainite phase.



(a) (b)

Figure 5: Uniform deformation and tensile stress as a function of the strain rate for the TRIP steel, and the ferrite and bainite phase.

4 CONCLUSIONS

It is known that TRIP-aided steels combine high strength levels with an excellent (de)formability. In this contribution results of a series of high strain rate experiments on an Al-TRIP steel are given. From these results it is clear that the excellent properties are not only preserved at higher strain rates, but still improve. Indeed, as the strain rate increases, higher yield stresses and higher energy absorbing properties are found.

In this contribution high strain rate properties of the constituent phases are also given. These properties provide data indispensable for the fundamental understanding of composite TRIP-steels.

5 ACKNOWLEDGMENT

The authors want to thank the Fund for Scientific Research - Flanders – Belgium (Fond voor Wetenschappelijk Onderzoek - Vlaanderen) for their support.

6 REFERENCES

1. L. Samek ; B. De Cooman ; J. Van Slycken ; P. Verleysen ; J. Degrieck, “Quasi-adiabatic effects during the high strain rate deformation of dispersed-phase systems with strain-induced martensitic transformation”, *Canadian Metallurgical Quarterly*, Vol 43, No 1, 2004
2. W. Bleck, “Using the TRIP effect – the dawn of a promising group of cold formable steels”, *International Conference on TRIP-Aided High Strength Ferrous Alloys,* Ghent, June 19-21, 2002.
3. B. De Cooman ; L. Samek ; J. Mahieu ; J. Van Slycken ; P. Verleysen ; J. Degrieck ; L. Lin ; L. Wang ; X. Cheng Wei ; S. Peng, “Quasi-adiabatic effects during the high strain rate deformation of dispersed-phase systems with strain-induced martensitic transformation”, *2003 Fall Meeting of TMS and 45th ISS Mechanical Working and Steel Processing Conference,* Chicago, Nov.9-12, 2003.
4. H. Kolsky, “An investigation of the mechanical properties of materials at very high rates of loading”, *Proc. Phys. Soc.*, 1949, Sec.B.62, pp. 676-700.
5. P. Verleysen ; J. Degrieck ; J. Van Slycken ; B. De Cooman ; L. Samek, “The influence of specimen geometry on the observed mechanical behaviour during Hopkinson experiments”, *9th International Conference on the mechanical behaviour of materials*, Geneve, Suisse, May 25-29, 2003.
6. P. Verleysen ; J. Degrieck, “Experimental investigation of the deformation of Hopkinson bar specimens”, *International Journal of Impact Engineering,* Vol.30, Issue 3, March 2004, pp. 239-254.