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HIGH STRAIN RATE BEHAVIOUR OF HIGH STRENGTH STEELS FOR AUTOMOTIVE APPLICATIONS

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ABSTRACT

The continuous requirement of the automotive industry for increased safety and weight savings related to the reduction of the fuel consumption, results in an increasing application of High Strength Steels (HSS). Currently also austenitic stainless steels are under investigation for structural and safety relevant parts due to their high potential in energy absorption and their high strength. In order to achieve a better performance and accuracy of crash test finite element simulations, the mechanical characteristics at high strain rates of these different steel grades are of great importance. Therefore, the strain rate sensitivity of steel grades like dual phase, micro-alloyed and 301LN stainless steel, produced in the ARBED group, is investigated in a range of strain rates between $10^{-2}s^{-1}$ and $1000s^{-1}$ using a hydraulic tensile machine and a recently developed impact test-bench based on the split Hopkinson bar method.
Special emphasis is addressed to the austenitic stainless steel, which shows a relative low ductility loss at high strain rates and is characterised by a change in strain hardening confirmed by the measurements of the martensite volume fraction. The interaction between strain rate, temperature and strain is discussed in terms of $\gamma \rightarrow \alpha'$ transformation and strengthening behaviour.

KEYWORDS

Strain rate sensitivity, Hopkinson bar, high strength steels, austenitic stainless steels

INTRODUCTION

Since weight reduction has become more and more a hot topic in the automotive industry, industrial developments of new steel qualities with excellent deformability at high strength levels are a major concern in most steel industries. Although currently the automotive industry uses stainless steels only in small amounts for applications where corrosion resistance is an issue, austenitic stainless steel grades could challenge low-alloyed HSS grades for car body applications, due to their excellent mechanical properties. First assessments [1-4] have shown that the combination of high strength and good formability of austenitic stainless steels offers a high freedom in design. Due to their high impact energy absorption austenitic stainless steels are very well suited for e.g. safety relevant parts. However, it is essential to make the most efficient use of the available various steel grades in automotive applications to meet the competitive threat from alternative materials.

Currently, there are discussions going on concerning high strain rate testing methods and data needed to be optimised for the use of steel in Finite Elements Analysis (FEA) models. Crash models results show strain rates of up to 1000s^{-1} and therefore material data up to this strain rate level is needed. Not only the strain rate but also the temperature has an influence on the mechanical properties. Therefore, the combination of strain rate and temperature effects is of great interest. Indeed, it is well known that high temperature leads to a decrease of the mechanical characteristics, while high stain rate leads to an increase. A balance of the latter effects is important since the location of some crash relevant parts close to the engine leads to temperatures close to 80°C. With regard to the steel grades produced in the ARBED group and used for car body applications, in this study the strain rate sensitivity is investigated in the temperature range from –40°C to +80°C for different steel grades: Interstitial Free High Strength Steel IFHSS260, micro-alloyed steel ZStE420, galvanized Dual Phase steel DP500G and austenitic stainless steel 301LN.

MATERIALS AND TESTING PROCEDURE

Investigated materials

The mechanical properties were measured in rolling direction (RD) according to the standard EN10002 on a common tensile test-bench at room temperature with a strain rate of $5\cdot10^{-3}s^{-1}$ (see Table 1).

TABLE 1
MECHANICAL PROPERTIES OF THE INVESTIGATED STEEL GRADES IN ROLLING DIRECTION

Grade	Thickness mm	YS MPa	TS MPa	A80 %	n_0	r_0
IF HSS 260	1.20	260	394	36.6	0.201	1.37
ZStE 420	1.13	431	495	26.0	0.166	0.65
DP500G	1.15	368	558	25.0	0.151	0.84
301LN annealed condition	1.20	378	752	50.8	0.35-0.6	0.92

Dynamic tensile testing facilities

The dynamic tensile tests were performed in RD on a servo hydraulic high-speed tensile machine up to a strain rate of 10s^{-1} for 3 temperatures based on the automotive standards, i.e. -40°C, 20°C and 80°C. Flat tensile specimens with a 40mm gauge length were used at ram speeds up to 400mm/s. In order to complete the strain rate range up to $\dot{\varepsilon}$ = 1000s^{-1}, tensile tests were performed on a split Hopkinson tensile bar set-up developed at the University of Ghent but only at room temperature. The experimental test facility consists of a 6m long input bar and a 3.15m long output bar, between which the test specimen is fixed, as schematically presented in Figure 1.

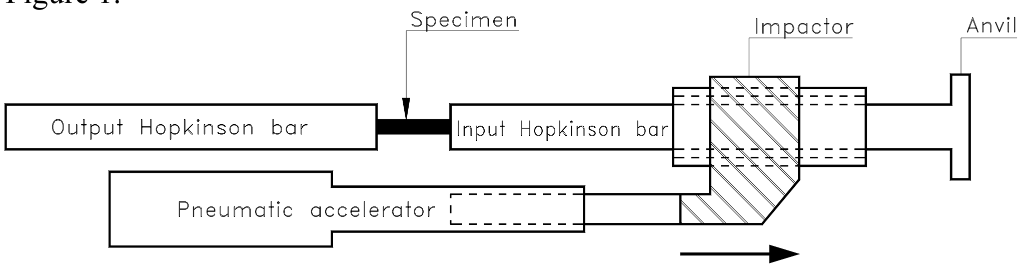

Figure 1: Schematic representation of a split Hopkinson tensile bar setup

Both the aluminium input bar and output bar have a diameter of 25 mm. The 5mm wide, flat steel sheet specimen has a gauge length of 10 mm. The anvil at the outer end of the input bar is hit by an impactor, which is pneumatically accelerated. The pneumatic accelerator has a capacity of 5kJ. A tensile wave with a duration of 1.2 msec is generated by the impact and propagates along the input bar towards the specimen.

Upon reaching the specimen the wave is partly reflected back into the input bar to form the reflected wave, and is partly transmitted to the output bar to form the transmitted wave.

The strain histories ε_i, ε_r and ε_t, respectively corresponding with the incident wave, the reflected wave and the transmitted wave, are measured by means of strain gauges. These strain gauges are located at well-known points on the input and the output bar, away from the specimen. The recorded signals are subsequently shifted, forward or backward, towards the interface planes with the specimen, in order to obtain forces and displacements at both ends of the specimen. The specimen dimensions given above were optimised using numerical simulations in order to have a uniaxial, homogeneous stress and deformation state in the specimen. With these assumptions the time histories of strain, strain rate and stress in the specimen can be obtained from the following expressions in Eqn. 1 [5]:

$$\varepsilon(t) = -\frac{2\,C_b}{L_s}\int_0^t \varepsilon_r(\tau)\,d\tau\,, \qquad \dot{\varepsilon}(t) = -\frac{2\,C_b}{L_s}\,\varepsilon_r(t)\,, \qquad \sigma(t) = \frac{A_b\,E_b}{A_s}\,\varepsilon_t(t) \tag{1}$$

with E_b the elasticity modulus 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 specimen length. The main advantage of the Hopkinson test is that strain, strain rate and stress in the specimen are obtained without measurements on the specimen.

TEMPERATURE AND STRAIN RATE SENSITIVITY RESULTS

Strain rate sensitivity at room temperature

As expected, the IFHSS260 shows the highest ratio between dynamic ($\dot{\varepsilon} \approx 1000\text{s}^{-1}$) and quasi-static lower yield strength (YS_{dyn}/YS_{st}) close to 1.8 (Figure 2a) but also a reduction of 34% in uniform elongation (Figure 4). The micro-alloyed steel ZStE420 is characterised by a low YS_{dyn}/YS_{st} of 1.3 and also by a reduction of 46% in uniform elongation. The dual phase grade and the austenitic stainless steel have nearly the same ratio YS_{dyn}/YS_{st} close to 1.7 but do not show the same strain rate sensitivity of the yield point. Indeed, 301LN shows a continuous increase of the yield stress over the range of strain rates, while the yield strength of DP500G increases more slowly up to strain rates around 300s^{-1} and shows a higher strain rate sensitivity above $\dot{\varepsilon} = 300\text{s}^{-1}$. This latter observation is also valid for the other ferritic steels but in a less pronounced manner. Plotting the logarithm of the yield strength versus the logarithm of strain rate has validated the strain rate dependency of strain rate sensitivity on the yield strength for IFHSS260, ZStE420 and DP500G and the almost constant strain rate sensitivity of 301LN, as illustrated in Figure 2b.

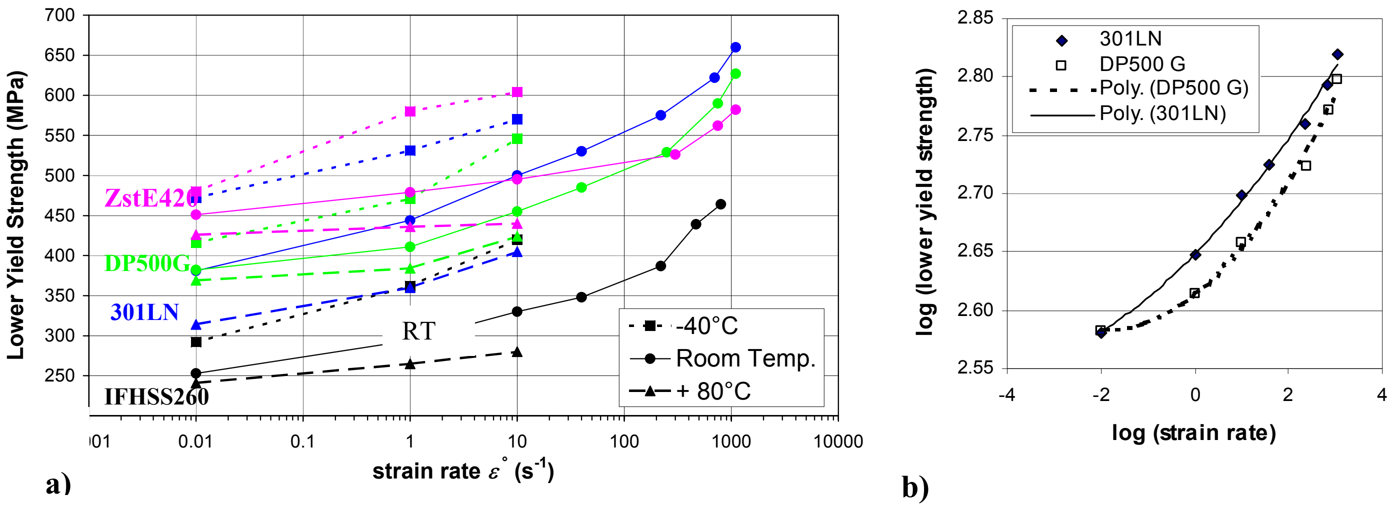

Figure 2: a) Influence of strain rate and temperature on the lower yield strength of the steel grades b) Strain rate dependency of the strain rate sensitivity on lower yield strength at room temperature

Concerning tensile strength, strain rate sensitivity is quite similar for each steel grade with a ratio between dynamic ($\dot{\varepsilon}$ = 1100s^{-1}) and quasi-static tensile strength comprised between 1.10 and 1.24 (Figure 3). The strain rate dependency of the uniform elongation shown in Figure 4 underlines the high ductility of the austenitic stainless steel 301LN compared to the other steel grades. Even at $\dot{\varepsilon}$ = 1100s^{-1} the uniform elongation of 301LN is close to 50% and the tensile curve still presents a pronounced strain hardening.

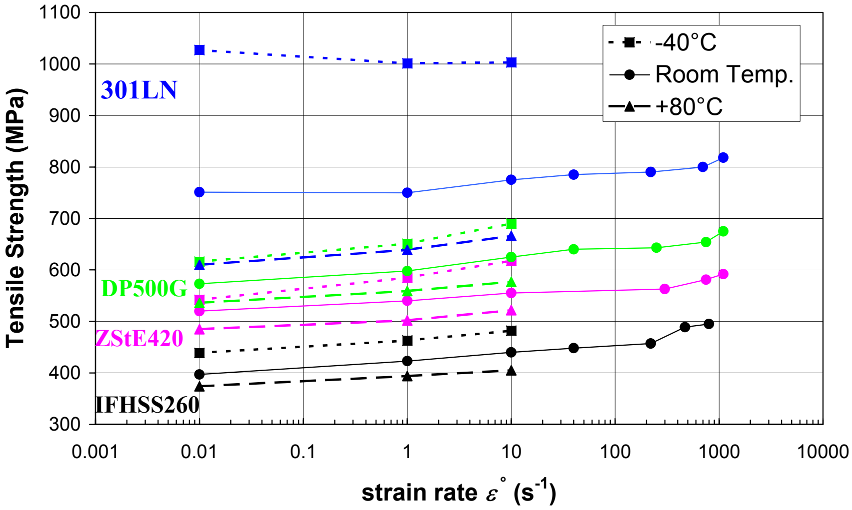

Figure 3: Influence of strain rate and temperature on the tensile strength of investigated steel grades

Influence of strain rate and temperature

The influence of strain rate and temperature in the range -40°C to +80°C defines stress domains in function of strain rate with an upper limit for -40°C describing a combined effect of strain rate and low temperature and a lower limit expressing the strain rate effect balanced by the higher temperature. Over the investigated range of strain rates the ferritic steels and DP500G are characterised by a maximum decrease of 50MPa for the lower yield strength or tensile strength at +80°C compared to room temperature. The increase of the lower yield strength noted at -40°C shows higher strain rate sensitivity due to a combined effect of temperature and strain rate (Figures 3, 4). The strain rate dependency of the uniform elongation, shown on Figure 4, is quite similar for ZStE420 and IFHSS260 with a higher reduction at -40°C compared to room temperature and a nearly constant value at 80°C. It must be noted that the dual phase steel DP500G did not show any increase or reduction in uniform elongation within the investigated temperature range, at least up to $\dot{\varepsilon}$ = 10s^{-1}. So, only the results at room temperature are presented in Figure 4.

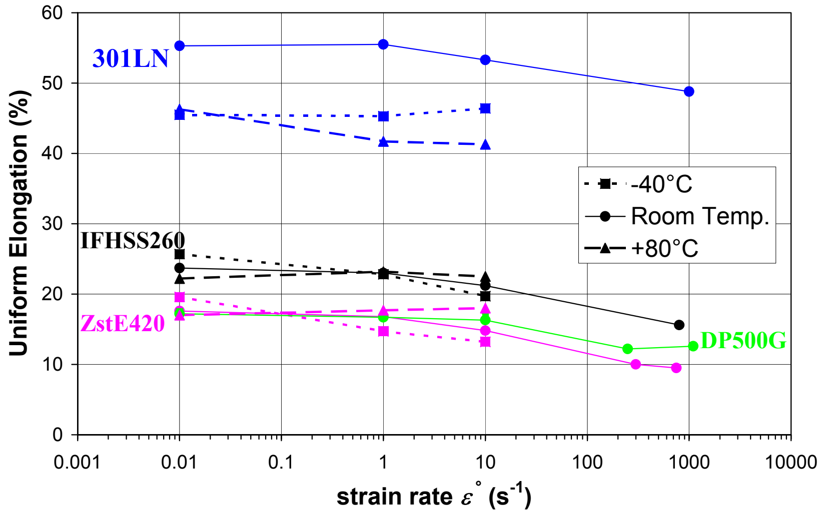

Figure 4: Influence of strain rate and temperature on the uniform elongation of investigated steel grades

The influence of strain rate and temperature on 301LN stainless steel is quite different due to the strain induced austenite to martensite (γ→α') transformation. The austenitic steel is very sensitive to temperature changes, which leads to a broader band for the yield strength and tensile strength curves than for the other steel grades. Compared to room temperature a decrease of 100 MPa in yield and tensile strength can generally be observed at 80°C for strain rates up to $10s^{-1}$. However, Figure 2 indicates that the high strain rate sensitivity is similar for each temperature, i.e. the curves related to the lower yield strength at different strength levels have the same slope. This high strain rate sensitivity allows 301LN to catch up with DP500G in yield strength at low strain rates after $\dot{\varepsilon}$ = $10s^{-1}$. At lower temperature the $\gamma \rightarrow \alpha'$ transformation increases the strain hardening rate leading to a typical discontinuous tensile curve and very high values for the tensile strength accompanied by a decrease of the uniform elongation as shown on Figures 3 and 4. The influence of strain rate is related to adiabatic heating during the deformation, which restricts the $\gamma \rightarrow \alpha'$ transformation. Hecker et al. have also observed the latter on austenitic stainless steel 304 [6]. Currently running volume fraction measurements, performed on the specimens tested at $\dot{\varepsilon}$ = $10^{-2}s^{-1}$ and $\dot{\varepsilon}$ = $10s^{-1}$ at increasing deformation levels, are confirming lower martensite volume fraction at high strain levels for high strain rate conditions. However, martensite is formed more readily at low strain levels during high strain rate testing than during quasi-static loading.

Energy absorption

The strain rate dependency at room temperature of the energy absorption of the different steels is indicated in Figure 5. The energy absorption is calculated at 10% true strain taking into account that in a crash situation automotive parts will hardly deform until fracture. On this figure the ratio of the dynamic over static absorbed energy is also plotted showing the higher ratio for the austenitic stainless steel and the ferritic steel IFHSS260 but naturally at lower energy levels. The evolution of energy absorption over the whole range of strain rate illustrates the need to characterise materials dynamically. Indeed ZStE420 and DP500G show the higher energy absorption under quasi-static testing conditions but the absorbed energy of 301LN increases stronger with the strain rate and finally, at $\dot{\varepsilon}$ = $1100s^{-1}$, reaches a value 6% higher than DP500G.

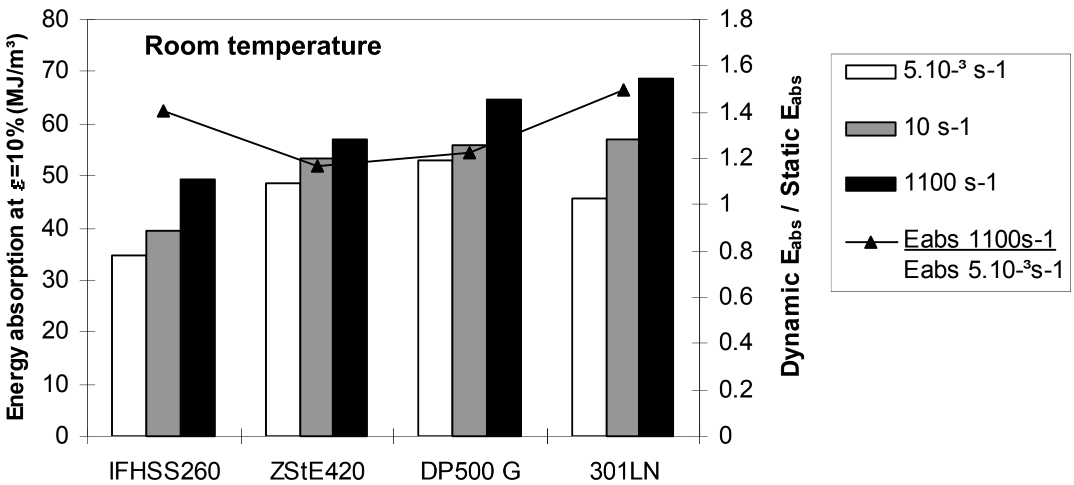

Figure 5: Energy absorption at 10% true strain (columns) and dynamic over static absorbed energy ratio (line) for the investigated steel grades at room temperature

The same behaviour is expected at 80°C with a more pronounced difference between dynamic and static conditions due to the lower yield strength of 301LN under quasi-static testing conditions. This great potential of dynamic energy absorption of 301LN is due to its higher strain hardening well described in Figure 6 showing the evolution of the dynamic strain hardening coefficient with strain at 80°C. Consequently, the difference in dynamic energy absorption between 301LN and the other steel grades like DP500G becomes larger when considering a higher true strain value than 10%.

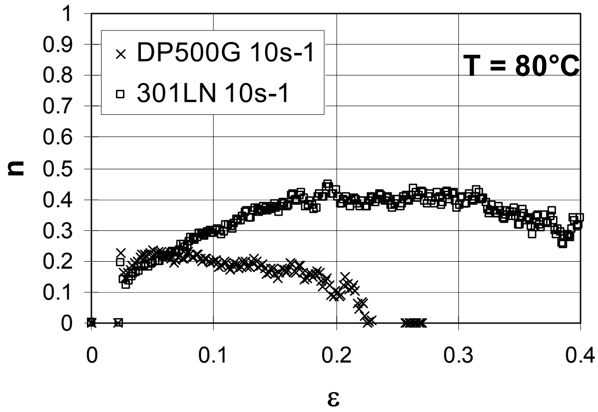

Figure 6: Dynamic strain hardening coefficient versus true strain for 301LN and DP500G at 80°C

CONCLUSION

The split Hopkinson bar testing facility developed at the University of Ghent has proven to be a very valuable technique for the determination of the dynamic mechanical properties of a wide range of steel grades. This technique is complementary to hydraulic test-benches by enabling reliable results at $\dot{\varepsilon} \geq 1000s^{-1}$. Even the austenitic stainless steel, which has a dynamic elongation higher than 50%, can be tested to rupture.

The analysis of the tensile tests performed at room temperature and up to $\dot{\varepsilon} = 1100s^{-1}$ shows that strain rate sensitivity of the lower yield strength is strain rate dependent only for IFHSS260, ZStE420 and DP500G. A low temperature of –40°C leads to higher strength values but also to higher strain rate sensitivity due to a combined effect of temperature and strain rate. In contrast, the austenitic stainless steel 301LN shows a constant strain rate sensitivity of the yield strength over the whole range of strain rates.

It has been shown that the study of combined temperature and strain rate effects is of great importance especially at 80°C where a decrease of the mechanical properties is observed. The austenitic steel is very sensitive to temperature changes and its mechanical properties are governed by the strain induced austenite to martensite transformation. The influence of strain rate is related to adiabatic heating during the deformation, which restricts the $\gamma \rightarrow \alpha$' transformation. However, martensite forms more readily at low strain levels during high strain rate testing, which allows 301LN to absorb more energy in dynamic testing conditions. The need to characterise materials dynamically is well illustrated by the strain rate dependency of a crash relevant parameter like the energy absorption, which shows that austenitic stainless steel 301LN is more sensitive to strain rate than other steel grades, especially at 80°C despite a reduction of the transformed martensite volume fraction. The already high sensitivity to temperature of austenitic stainless steels could be even improved when considering it in a pre-hardened state. This will be an issue in the course of the European project "LIGHT&SAFE" coordinated by OCAS leading to broaden know-how on manufacturing techniques and durability of austenitic stainless steels for automotive applications.

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