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THE EFFECT OF STRAIN RATE ON THE MECHANICAL PROPERTIES OF AUTOMOTIVE STEEL SHEETS

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Abstract. The automotive industry is currently seeking detailed information about various types of materials and their behavior under dynamic loading. Dynamic tensile testing of sheet steels is growing in importance. The experimental dynamic tensile technique depends on the strain rate. Each type of test serves for a specific range of strain rates, and provides specific types of information. This work deals with the influence of the strain rate on the mechanical properties of automotive steel sheets. Three different types of steel: IF steel, DP steel, and micro-alloyed steel (S 460) were used to compare static and dynamic properties.

Keywords: dynamic tensile test, automotive steel sheets, rotation wheel.

1. Introduction

An improved understanding of the behaviour of automotive materials at high velocity is driven by the challenges of various types of crash legislation and by competition among car manufacturers. The strength of a sheet steel product is dependent on the speed at which it is deformed. It is well known that the yield strength and the ultimate tensile strength of materials are determined by the behavior of dislocations, and these depend on the pre-history of the loading and on the strain rate. For FCC metals, at low strain rates, the true stress increases linearly with the logarithm of the strain rate. At high strain rates exceeding $10^3\,\mathrm{s}^{-1}$, the true stress increases approximately linearly with the strain rate [1, 2]. The mechanical behavior of materials under dynamic or impact loading is different from that under static loading. When a structure deforms in the dynamic state, the inertia effect and the propagation of stress waves are so great that the material properties are influenced by the strain rate [3]. Tensile testing of metallic sheet materials at high strain rates is important for making a reliable analysis of vehicle crashworthiness. During a crash event, the maximum strain rate often reaches $10^3\,\mathrm{s}^{-1}$, at which the strength of the material can be significantly higher than under quasi-static loading conditions. Thus, the reliability of crash simulation depends on the accuracy of the input data specifying the strain – rate sensitivity of the materials [4]. On the basis of experimental and numerical calculations, the strain – rate range between 10^{-3} and $10^3\,\mathrm{s}^{-1}1$ is considered to be the most relevant to vehicle crash events. In order to evaluate the crashworthiness of a vehicle with accuracy, reliable stress-strain characterization of metallic materials at strain rates higher than $10^{-3}\,\mathrm{s}^{-1}$ is essential [5].

2. Automotive steel sheets

An important and challenging issue in the automotive industry is lightweight, safe design and enhancement of the crash response of auto-body structures. The most widely-used automotive steels are IF steel, DP steel and microalloyed steel [6, 7]. IF steels have ultra-low carbon levels designed for low yield strengths and high work hardening exponents. These steels are designed to have more stretchability than mild steels. Some grades of IF steels are strengthened by a combination of elements for solid solution, precipitation of carbides and/or nitrides, and by grain refinement. Another common element added to increase the strength is phosphorus. The higher strength grades of the IF steel type are widely used for structural applications and also for closure applications [8]. Dual-phase steels have a microstructure which contains predominately martensite (there can be small amounts of retained austenite, bainite or pearlite) in a ferrite matrix, and these steels exhibit characteristic mechanical properties, i.e. continuous yielding, a high tensile strength to yield strength ratio, and very high initial work hardening rates. The combination of high strength and high ductility has made DP steels very attractive to industry, particularly to the automobile sector. The mechanical properties of DP steels depend on a number of parameters, including the strength, morphology and volume fraction of the constituent phases. The strength of ferrite is controlled by the steel chemistry and by its grain size, while the properties of martensite depend on its carbon concentration and on its scale. These groups of steels are strengthened primarily by micro-alloying elements contributing to fine carbide precipitation and grain-size refinement. High-strength low-alloy (HSLA) steels, or micro-alloyed steels, are de-

Material	C	S	N	Mn	P	Si	Al	Nb	V	Ti
IF	0.0013	0.0105	0.0017	0.082	0.011	0.006	0.055	0.001	0.002	0.04
S 460	0.040	0.002	–	0.44	0.009	0.05	0.046	0.035	0.2	0.016
DP 600	0.072	0.006	0.005	1.18	0.017	0.01	0.057	0.002	0.003	0.001

TABLE 1. Chemical composition of the steels.

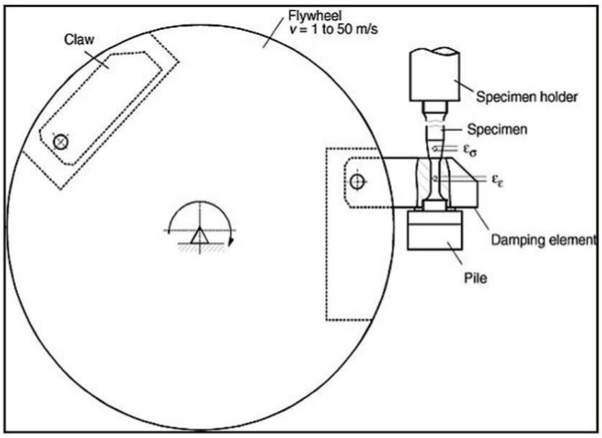

FIGURE 1. The RSO Rotation wheel.

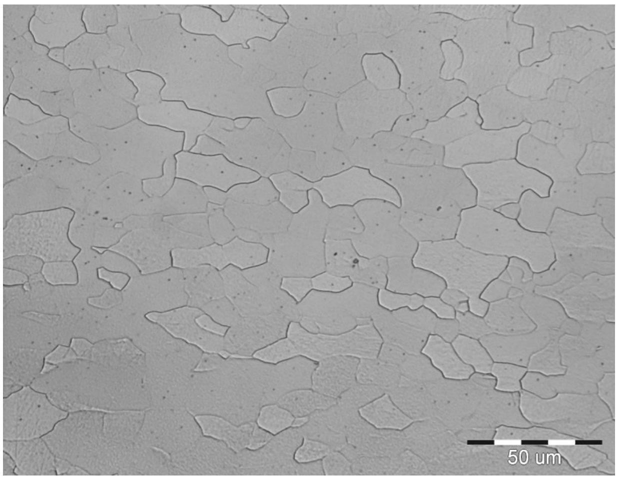

FIGURE 2. Microstructure of IF steel.

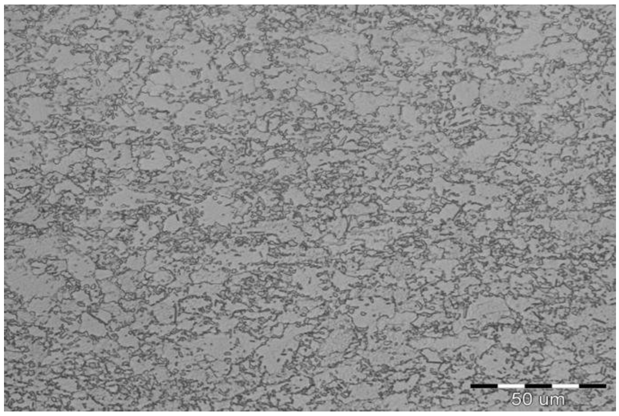

FIGURE 3. Microstructure of DP steel.

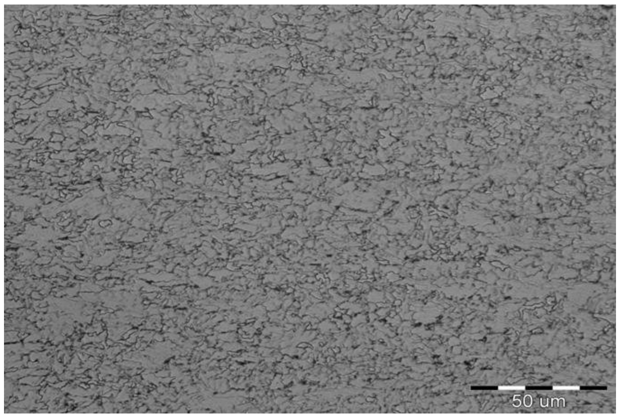

FIGURE 4. Microstructure of HSLA steel.

signed to provide better mechanical properties and/or greater resistance to atmospheric corrosion than conventional carbon steels. They are not considered to be alloy steels in the normal sense, because they are designed to meet specific mechanical properties rather than a chemical composition. The chemical composition of a specific HSLA steel may vary for different product thicknesses to meet mechanical property requirements. [9].

3. Experimental method

Three automotive steel sheets were used for a static and dynamic tensile test: IF steel 1.5 mm in thickness, DP steel 1.6 mm in thickness, and micro-alloyed steel 1.5 mm in thickness. A static test was performed according to the EN ISO 6892-1 standard. The dynamic tensile test according the ČSN EN ISO 26203-1 standard used test equipment that can reach speeds greater than $10^{-3}\,\mathrm{s}^{-1}$ of strain. A flywheel machine was used for the dynamic tensile tests. A scheme of the rotating flywheel machine and the stand set is shown in Fig. 1. The basic element, a wheel disc 600 mm in diameter and 100 mm in width, is equipped with a self-aligning forked hammer. The hammer is normally kept in a wheel pocket, and is blocked in this position by a slidable pin. The wheel is accelerated by an electric motor to the selected speed, which is measured by a rotary encoder. When the selected speed is achieved, the slidable pin is moved by an electromagnet, unlocking the hammer that rotates to working positions, striking an anvil connected to the sample. The velocity of the hammer ranges from 5 to $50\,\mathrm{m\,s^{-1}}$, yielding available impact energy from 1.4 to 140 kJ. Because the work needed to sample defor-

Material	Mechanical properties	Loading rate [m s^{-1}] $1.6 \cdot 10^{-4}$	$1.6 \cdot 10^{-3}$	$6.6 \cdot 10^{-3}$
IF	F [N]	10195	10465	10750
	R_e [MPa]	169	180	197
	R_m [MPa]	282	291	300
	A_{80} [%]	34.5	35	39.5
DP 600	F [N]	18242	18512	18622
	R_e [MPa]	346	363	365
	R_m [MPa]	561	574	570
	A_{80} [%]	23.4	21	24.2
S 460	F [N]	21611	21722	22022
	R_e [MPa]	427	457	464
	R_m [MPa]	509	538	536
	A_{80} [%]	18.8	20.9	21.3

Table 2. Mechanical properties of steels under a static loading rate.

Material	Mechanical properties	Loading rate [m s^{-1}] $1.6 \cdot 10^{-4}$	$1.6 \cdot 10^{-3}$	$6.6 \cdot 10^{-3}$
IF	F [N]	7158	7587	7961
	R_m [MPa]	502	532	559
DP 600	F [N]	10723	12517	13581
	R_m [MPa]	705	824	894
S 460	F [N]	9944	11321	11602
	R_m [MPa]	698	794	814

Table 3. Mechanical properties of steels under a dynamic loading rate.

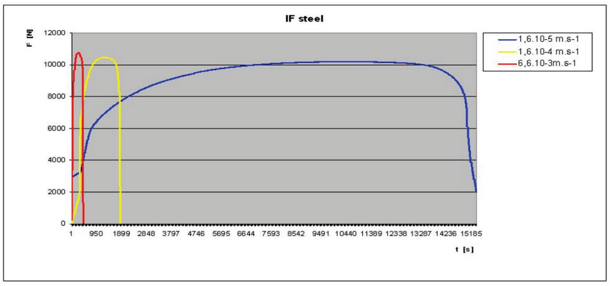

Figure 5. Static tensile curves of IF steel.

mation up to fracture is less than 60 J, the impact velocity is almost constant during the test [10].

4. Result and discussion

The chemical composition of the steels investigated here in mass [%] is presented in Tab. 1. The microstructures of the steels are presented in Figs. 2–4.

Static tensile tests were performed for a three-speed load. The tensile curves of samples deformed with strain rate $1.6 \cdot 10^{-5}$ m s^{-1}, $1.6 \cdot 10^{-4}$ m s^{-1} and $6.6 \cdot 10^{-3}$ m s^{-1} for IF steel are shown in Fig. 5, for DP steel in Fig. 6, and for microalloyed steel in Fig 7. Tab. 2 shows the results of the static tests.

For the dynamic tensile tests, an RSO rotating flywheel machine was used at three-speed load 6 m s^{-1}, 12 m s^{-1}, 20 m s^{-1}. The tensile curves of samples deformed with strain rate 6, 12 and 20 m s^{-1} for IF steel is shown in Fig. 8, for DP steel in Fig. 9, and for micro-alloyed steel in Fig. 10. Tab. 3 shows the results of the dynamic tests. Tab. 4 compares the

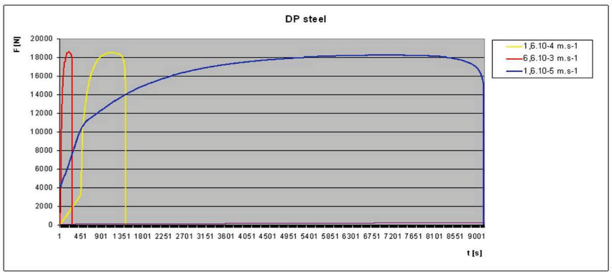

Figure 6. Static tensile curves of DP steel.

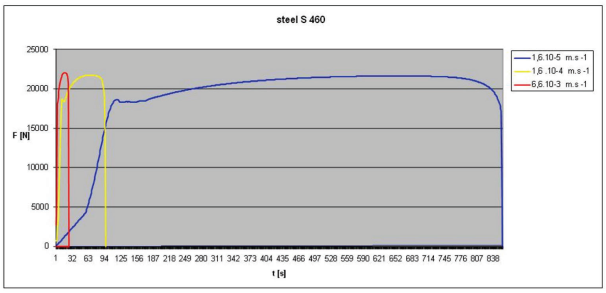

Figure 7. Static tensile curves of S 460 steel.

static and dynamic yield strength of the tested steels.

Three different types of steel were used: IF steel, DP steel, and microalloyed steel (S 460) to compare the static and dynamic properties. The samples for tensile testing were prepared according to the EN ISO 6892-1 norm. An RSO-type rotary hammer was used for the dynamic tensile test. The yield strength of the IF steel increased from 282 MPa ($1.6 \cdot 10^{-4}$ m s^{-1}) to 558 MPa (20 m s^{-1}). The yield strength of the DP 600 steel

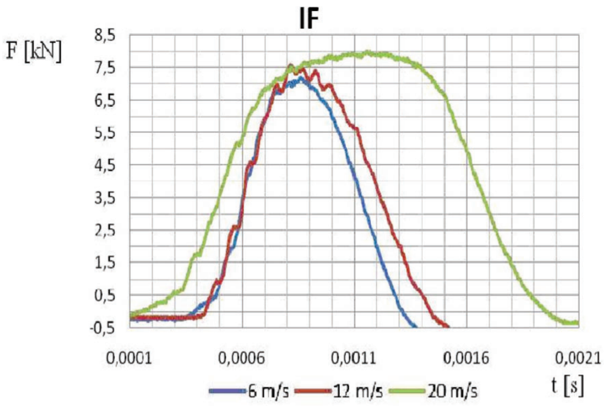

Figure 8. Dynamic tensile curves of IF steel.

Material	Static R_m	Dynamic R_m	ΔR_m
IF	282	559	276
DP600	561	894	332
S 460	509	814	305

Table 4. Comparison between the static and dynamic yield strength of the tested steels [MPa].

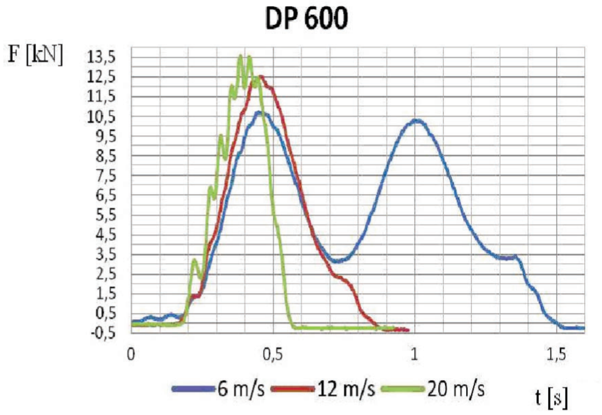

Figure 9. Dynamic tensile curves of DP steel.

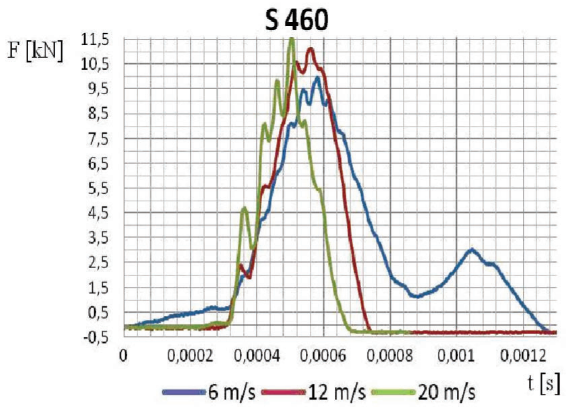

Figure 10. Dynamic tensile curves of S 460 steel.

increased from 561 MPa ($1.6{\cdot}10^{-4}\,\mathrm{m\,s^{-1}}$) to 894 MPa ($20\,\mathrm{m\,s^{-1}}$). The yield strength of the micro-alloyed S 460 steel increased from 509 MPa ($1.6{\cdot}10^{-4}\,\mathrm{m\,s^{-1}}$) to 814 MPa ($20\,\mathrm{m\,s^{-1}}$). The dislocation density increased under dynamic conditions, and this influenced the increased yield strength in all the investigated steels.

We conclude that with increasing strain rate in all three steels, there is an increase in the strength properties and a change in the plastic properties.

Acknowledgements

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