DYNAMIC TENSILE TESTING OF MODERN CAR BODY STEELS

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ABSTRACT

Crash behavior and light weight have become the major design criteria for car bodies. Modern high strength steels offer appropriate solutions for these demands.

The prediction of the crash behavior in simulation programs requires the information on materials behavior during dynamic testing. The reduction of the signal waviness and the inertia effects at strain rates above $50s^{-1}$ are major issues in dynamic tensile tests. Different techniques for load and strain measurement are compared and evaluated with regard to accuracy and testing effort. Advantages and drawbacks of those various measurement techniques are presented and recommendations for different test purposes are provided.

Various modern steels for car body applications have been intensively investigated by high strain rate tensile tests with strain rates between $0.005s^{-1}$ and $500s^{-1}$ at temperatures between -40°C and 100°C. Significant differences in the materials behavior could be detected between mild steels and other HSS steel grades like dual phase steels, TRIP, CP and martensitic steels with regard to their strain rate and temperature sensitivity. Possible explanations based on microstructural features are discussed.

Keywords: -dynamic tensile tests – high strain rate - car body steels – high strength steels

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1 INTRODUCTION

The main design criteria for modern car bodies are safety and light-weight. Modern steels, like cold formable high-strength steels, can contribute significantly to these objectives.

It is essential for steel producers and steel users to have a deep quantitative knowledge on materials behavior in order to supply reliable input data for computer aided design and manufacturing. In a joint project between the German automotive and the German steel industry the mechanical properties and flow curves for the most relevant car body steels have been measured and collected in a data base [1)]. In this paper the strain rate and temperature dependency of the mechanical properties of various steels are discussed, with a special emphasis on modern car body steels and the influence of microstructure.

In general, an increase of the yield strength and the ultimate tensile strength is expected with increasing strain rate. This behavior of body-centered and face-centered steels is known from many publications [2-3, 7-13)].

1.1 Crash tests in the automotive industry

Several tests have been developed by the industry in order to predict the real life crash behavior of a passenger car. A multitude of loading cases have therefore to be considered for the development of the car body structure with respect to the passive safety of the vehicle. Figure 1 shows the estimated maximum strain rates occurring for different parts of a car during a frontal crash test on a deformable barrier with 40% offset and 64 kmh^{-1} initial speed as prescribed in the standard EuroNCAP crash tests. High strain rates up to 200 s^{-1} can be observed in the region of the crash boxes, the strain rate level is reduced in the longitudinal rails area to $100s^{-1}$ and reaches $70s^{-1}$ on the A-pillar base. In case of a side impact test with a deformable barrier, strain rates up to $30s^{-1}$ are observed in the A- and B-pillar regions near the door [4)].

Stiff passenger area, stability of door sill and A-pillar, low door opening forces after crash and a high floor stability, these are a few criterions to be fulfilled in order to meet the passenger safety requirement in the automotive industry. The strain rate dependency of the materials has to be considered in order to save costs and weight by the design of the car body structure.

Without taking into account the increase of strength level at high strain rate, simulations would lead to higher deformations in comparison to experimental results [4)]. This leads to an underachieving of the light-weight potential of the newly developed modern car body steels.

1.2 Strain rate ranges and corresponding applications

Depending on the range of strain rate considered, different physical mechanisms have to be taken into account. For very low strain rates up to $10^{-4}s^{-1}$ diffusion controlled creep of the material may take place, especially at elevated temperatures. Higher strain rates up to $10^{-2}\,s^{-1}$ are used to determine the mechanical properties; the behavior in this strain rate range is dominated by dislocations and their interaction. Strain rates from $10^{-2}\,s^{-1}$ to $10^{4}\,s^{-1}$ characterize the dynamic properties of the materials, this is also the typical strain rate range for automotive applications. Higher strain rates up to $10^{6}\,s^{-1}$ are of importance for ballistic applications and are essentially elastic wave controlled, figure 2.

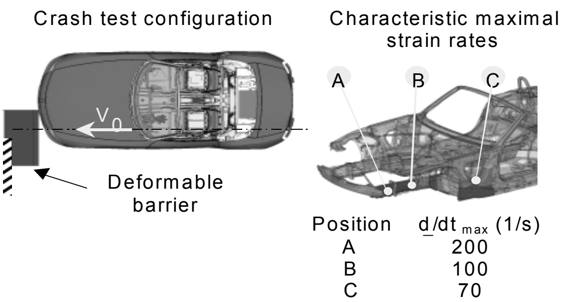

Fig.1. EuroNCAP front offset crash test and relevant strain rates [4].

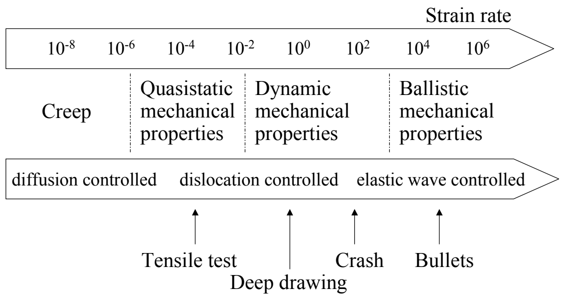

Fig.2. Strain rate ranges for different properties and applications.

2 EXPERIMENTAL LAYOUT

2.1 High speed tensile testing

High speed tensile tests at the Department of Ferrous Metallurgy (IEHK) of RWTH Aachen are performed on two servo-hydraulic testing machines, figure 3. The servohydraulic 100kN Schenck high speed tensile testing machine allows ram speeds from 0.01 to 4 000mms^{-1}. A temperature chamber enables tensile tests within a temperature range from -180°C up to 180°C. The 20kN servohydraulic Roell-Amsler tensile testing machine is used for higher ram speeds up to 12 000 mms^{-1}, but tensile tests can only be performed at room temperature with this machine.
Currently, there is no national or international standard neither for the dynamic tensile test machines nor for the testing itself; thus, it is very difficult to compare results obtained from different sources. First approaches for a specification of this tensile test procedure are prepared by The International Iron and Steel Institute [5] (IISI), the European Structural Integrity Society [6] (ESIS) and by the German Iron and Steel Institute (VDEh).
The International Iron and Steel Institute IISI already finished their paper (Recommendations for Dynamic Tensile Testing of Sheet Steels) as well as their is a German document available from the German Iron and Steel Institute VDEh (PuD) which describes in a brief way the procedures for dynamic tensile testing of sheet steel. Until the end of 2005 from the same organization their will be a more detailed document available which is right now being worked out in collaboration of the German institutes dealing with High Speed Tensile Testing. On European level their is a document planned for tensile sheet samples but so far their is no defined date of issue.

2.2 Testing configuration of the servohydraulic high-speed tensile testing machines

For reaching the required high and ideally constant piston speeds during the test, most high speed tensile testing machines are servohydraulic systems.

Fig.3. Servohydraulic high speed tensile test machines at IEHK;
left: Zwick/Roell HTM2012, right: Schenck S56.

Figure 4 shows a schematic sketch of a servohydraulic tensile testing machine. The design allows an acceleration of the piston with the lower clamping in form of a hollow cylinder. After the acceleration distance the test starts with an impact which evokes an oscillation of the whole machine. These oscillations are especially high in the force signal. So at high strain rates, wave propagation, inertial effects and frequency response of the transducers have to be monitored accurately in order to minimize the signal waviness.
During the test the force is measured continuously by strain gauges fixed on the titanium load cell (F2) and by the piezoelectric load cell (F1). A third possibility to measure the force is to attach a strain gage to the dynamometer section of the sample (F3), figure 5. Furthermore bending oscillations can be reduced by applying strain gages in the dynamometer section on both sides of the sample (F4).

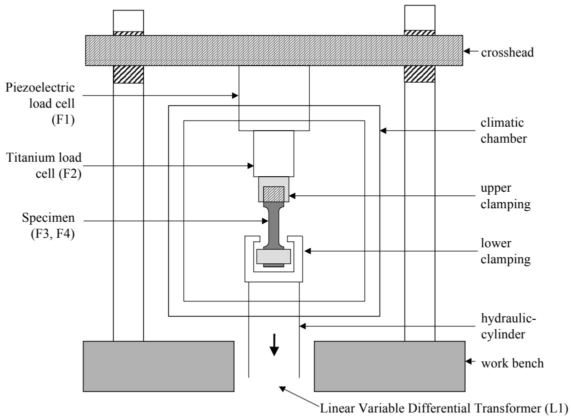

Fig.4. Sketch of the high speed tensile test experimental set up of Schenck

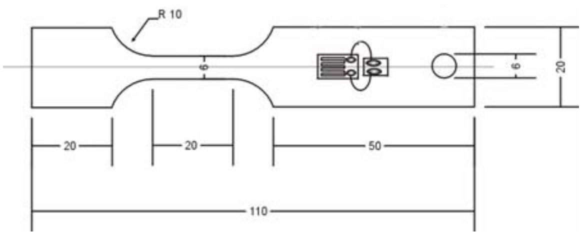

Fig.5. Example of sample geometry. The elongated sample shoulder on the right hand side includes the dynamometer section for the strain gage for force measurement.

The quality of the signals according to oscillations improves from the first to the last named possibility. Nevertheless, the operating expense is increasing as well, as the strain gages attached to the sample have to be calibrated in advance of each test.
So usually the measuring technique is varied with the nominal value of the strain rate. At piston velocities below 100 mms^{-1} the piezoelectric load cell is used to

receive the stress signal, whereas the strain gauge on the clamping system is used at piston velocities higher than 100 mms^{-1}, and a less disturbed signal is achieved. The strain gauge is quasistatically calibrated as a force transducer. At piston velocities higher than 1 000 mms^{-1} the oscillations of these load cells are too high. To use this measuring technique there is the possibility to reduce the ringing by rubber damping which is placed between the sample and the clamping where the impact happens. A disadvantage of this method is that because of the damping the strain rate at the beginning of the test might be reduced. So nowadays most experiments at high strain rates are carried out with strain gages attached to the dynamometer section of the sample itself.

For the recording of the strain there are several possibilities as well. The easiest way is to calculate the strain from the piston displacement recorded via Linear Variable Differential Transformator (LVDT) (L1). If this is done it has to be taken care that the machine rigidity is not influencing the strain data.

Therefore, it is possible to record the low strains with a strain gage attached to the gage length of the sample and then add the higher strains from LVDT (L3) [8,11]. Another possibility is to measure the strain with optoelectronical (L2) or laser extensometers directly on the sample. With this techniques it is possible to record the strain on the sample throughout the test until sample fracture. Here as well the experimental effort differs for the different possibilities. Tables 1 and 2 give a summary about the different possibilities and an estimation on the effort versus accuracy.

Force measurement		
Strain rate	Test set-up force	
$< 50s^{-1}$	F1	Force measured by PQ without damping
	F2	Force measured by calibrated strain gage on the clamping without damping
$> 50s^{-1}$	F1D	Force measured by PQ with damping
	F2D	Force measured by calibrated strain gage on the clamping with damping
	F3	Force measured by calibrated strain gage on the specimen without damping
	F4	Force measured by calibrated strain gage on both sides of the specimen without damping
Strain measurement		
Test set-up strain		
L1		Piston displacement
L2		Gauge length elongation optical extensometer
L3		Strain gage in gage length for small strains + piston displacement for higher strains

Table 1. Different measurement techniques.

Test set-up	Relative testing time	Yield stress accuracy	Tensile stress accuracy	Elongation values accuracy	Strain rate accuracy
F3+L3	x8	++	+	+	+
F3+L2	x 8	+	+	++	++
F4+L1	x 6	++	++	+	+
F3+L1	x 4	+	+	+	+
F1D/F2D+L1	x 1 (x2 with non ambient temperature)	-	+	+	- -
F1/F2+L1	x 1 (x2 with non ambient temperature)	+++	+++	+	-

+++ excellent ++ very good + good – poor – unsatisfactory

Table 2. Different testing methods with comparison of time and accuracy for some possible combinations of force and strain measurement technique.

2.3 Materials characterization

With the development of light weight steels the steel industry meets the requirements of passive safety, weight reduction, energy saving as well as economic mass production which means good formability. To characterize steels according to their light-weight potential there is often used a diagram like in figure 6. Total elongation as a measure for formability is plotted against ultimate tensile strength as a measure for high strength. The optimum material from the automotive point of view would be a material placed in the upper right edge of the diagram.

As representatives of modern light-weight steels in this investigation there have been selected a TRIP and a DP grade, a complex phase steel grade and a martensitic grade. For comparison the Low Carbon DDQ grade DC04 is investigated as well. Tables 3 and 4 show the material properties determined in quasistatic tensile testing and the chemical composition of the materials.

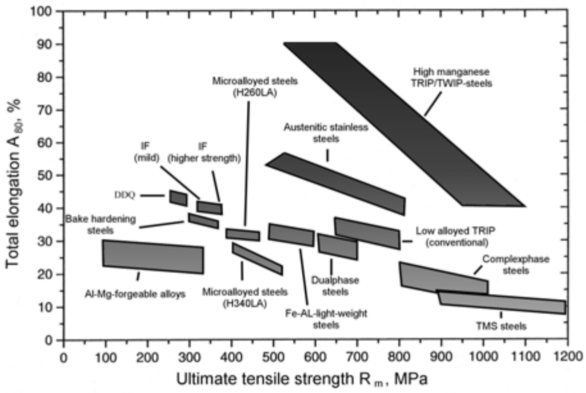

Fig.6. Characterization of modern light weight steels according to formability and strength values.

Steel	Type	Material condition	Thickness mm	YS (0.2%) MPa	UTS MPa	TE (A_{80}) %
DC04	HDDQ	cold rolled	1.0	185	299	41
HT500X	DP	cold rolled	1.0	349	540	25
HT700T	TRIP	cold rolled	1.0	411	717	26
CP900	CP	hot rolled	1.6	892	964	12
MS1200	Martensitic	hot rolled	1.5	976	1224	5

Table 3. Mechanical Properties of quasistatic tensile testing of investigated materials

Steel	Type	C	Si	Mn	P	Cr	Ni	Al	Cu	Mo	N	Ti
DC04	LC	0.025	0.01	0.19	0.008	0.02	0.03	0.054	0.013	0.003	0.005	0.002
DC06	IF	0.002	0.01	0.10	0.009	0.02	0.03	0.036	0.009	0.002	0.003	0.056
HT500X	DP	0.082	0.07	1.48	0.017	0.46	0.04	0.059	0.040	-	0.004	0.026
HT700T	TRIP	0.202	0.05	1.53	0.010	0.02	0.02	1.970	0.026	-	0.003	0.003
CP900	CP	0.121	0.46	1.93	0.013	0.31	0.03	0.043	0.460	-	0.004	0.160
MS1200	Martensitic	0.142	0.12	1.71	0.011	0.55	0.06	0.023	0.070	0.015	n.d	0.002

Table 4. Chemical Composition of investigated materials

The selected steels all represent different material concepts. Dual phase steels have a fine-grained ferrite matrix with up to 20 % hard particles of martensite islands. TRIP steels are based on a ferritic-bainitic matrix with components of retained austenite. During deformation the transformation of this retained austenite leads to a further improvement of strength and formability. Complexphase steels mark the transition to ultra-high strength steels with very high strength levels above 800 MPa. The fine-grained microstructure contains a homogeneous distribution of nanometre scale precipitates. The martensitic steels offer the possibility to reach even higher strength with reduced formability. The DC04 which has a comparing function in this paper has a single phase ferritic microstructure.

3 DISCUSSION OF RESULTS

3.1 Yield and ultimate tensile strength

The effects of strain rates between $0.005s^{-1}$ and $500s^{-1}$ and test temperatures between 233K and 373K on the yield strength and the tensile strength of some cold formable mild and high strength steels are shown in figures 7 to 9. In general, yield and tensile strength increase when the strain rate increases and the temperature decreases [7-13].

The results show remarkable strain rate dependencies for the ferritic steel DC04, figure 7. This low carbon deep drawing quality steel grade is characterized by a more pronounced strain rate dependent increase of the yield strength compared with the tensile strength. At the elevated temperature of 373K the strain rate dependency of the yield strength is not so strong compared to the lower test temperatures while there is no significant difference in the strain rate dependency of the ultimate tensile strength at the different temperatures, figure 7.

There are some characteristic differences for the high strength steels investigated. For these high strength steels a smaller strain rate dependency both for yield and for tensile strength is observed. Contrary to the ferritic steel grade the investigated dual phase and TRIP steels show a larger difference between yield stress and ultimate tensile strength, indicating a pronounced strain hardening, figures 8 and 9. Yield stress and ultimate tensile strength increase for high strength steels continuously as seen for the ferritic steel, but showing a smaller slope.

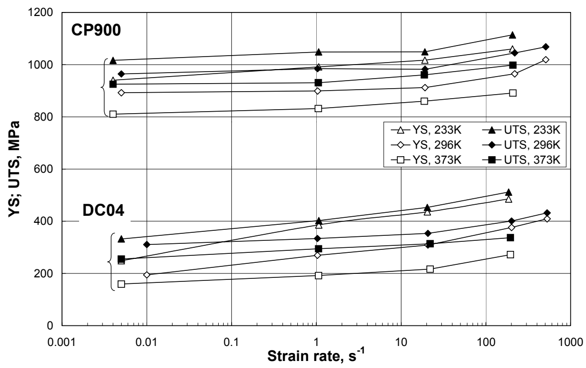

Fig.7. Yield and tensile strength vs. strain rate and temperature for DC04 and CP900 steels.

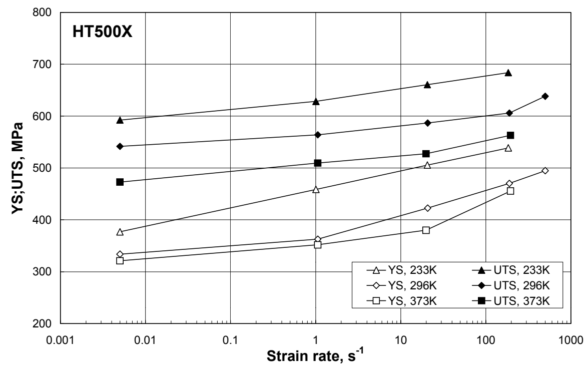

Fig.8. Yield and tensile strength vs. strain rate and temperature for HT500X steel.

There is some evidence that dual phase and especially TRIP steels have a higher temperature related increase of the tensile strength than that of the yield strength.

The high strength CP900 and MS1200 steel grades shows the same behavior with the lowest strain rate dependency for the yield and tensile strength values, figures 7 and 9.

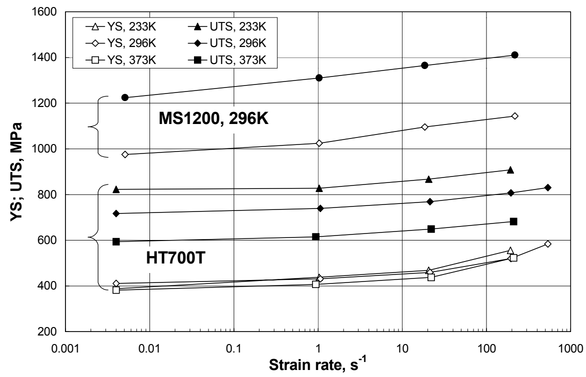

Fig.9. Yield and tensile strength vs. strain rate and temperature for HT700T and MS1200 steels.

3.2 Flow curves

The flow curves at strain rates of $0.005s^{-1}$ and $200s^{-1}$ are compared at 296K for all steel grades investigated, figure 10. The flow curves are presented for the quasistatic and high strain rate tests all smoothed with a third degree polynom (spline); all flow curves are plotted up to the uniform elongation. Compared to the mild DDQ steel DC04 the more pronounced strain hardening is obvious for the dual phase and especially for the TRIP steel. High strength values, poor ductility and low strain hardening are characteristic for martensitic MS1200 and CP900 steel grades. Several times it could be observed that the uniform elongation is larger when the strain rate is higher. This might be attributed to the behavior of relatively high amounts of solid solution elements in these particular steels [14)].

3.3 Strain rate sensitivity

Figure 11 shows the influence of temperature and quasistatic tensile strength values on the strain rate sensitivity. The m-values based on the extended Hollomon equation have been determined by plotting the logarithm of the yield stress versus the logarithm of strain rate and taking the slope of the linear regression other the whole strain rate range as m-value.

$$\sigma = k \cdot \varepsilon^{n} \cdot \dot{\varepsilon}^{m} \qquad (1)$$

The lower the temperature the higher the strain rate sensitivity for each steel grade. Strain rate sensitivity values decrease sharply with increasing tensile strength levels. High strength steels are therefore less strain rate sensitive than mild steels. The mild steel DC04 shows the highest strain rate sensitivity values among all investigated steels. CP and martensitic steel grades show the lowest strain rate sensitivity, up to one third of the DC04 value. The TRIP steel shows a lower strain rate sensitivity than the dual phase steel.

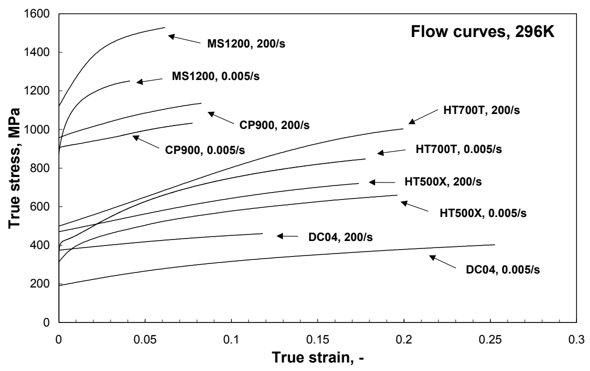

Fig.10. Influence of strain rate on the flow curves at 296K for all investigated steel grades.

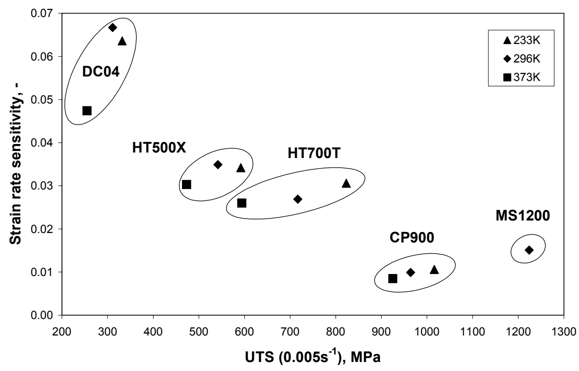

Fig.11. Strain rate sensitivity vs. quasistatic tensile strength and temperature for all investigated materials.

3.4 Microstructure

According to the experimental results, it is necessary to distinguish different steel groups with specific features in their strain rate and temperature dependency:

Mild DDQ steels are typically characterized by a very clean ferritic matrix; the mean free dislocation path is limited only by grain boundaries. As the alloying content is usually very low and the grain size is rather large we can assume a long free dislocation path with intensive dislocation interaction. The high strain rate sensitivity for the DC04 steel can be explained by a weaker initial obstacle structure (low yield strength) and a more thermally dependent character of the dislocation motion [11)].

Dual phase steels are characterized by a fine structured two phase microstructure of a ferritic matrix with martensite islands. The ferritic grain size is very small, thus the free dislocation path will be small as well; furthermore, due to the hard martensitic phase, there will be a locally high stress triaxiality just from the start of a tensile test. Dual phase steel show a stronger strain rate dependency and an increased dynamic absorbed energy when the volumetric fraction of martensite or the aera of ferrite-martensite interface is increased[8)]. With materials of the same strength, the dynamic energy absorbed at strains up to 30% has been reported to be higher for the dual phase as for the TRIP steel [8)]. The energy absorption up to 10% of HT700T is in the present investigation indeed only slightly higher than the one of the dual phase steel HT500X with a much lower UTS level. It has been also reported that the martensite phase increases strain hardening during high speed deformation. For dual phase steels, strain hardening during high speed deformation increases therefore in proportion to the difference in strength between the ferrite phase and the secondary hard phase [8,10)].

Multiphase TRIP steels show with increasing retained austenite volume fraction an increase of UTS, uniform and total elongation as well as total absorbed energy but a decrease in the yield strength and absorbed energy below 10% engineering strain [9)]. It has also been reported that increasing strain rate has little effect on strain hardening behavior for TRIP steels with 11% or less retained austenite. Similar conclusion can be drawn with the present investigated TRIP steel HT700T with about 5% retained austenite.

CP and martensitic steels show the lowest strain hardening capabilities. In ferritic-bainitic CP900 steel the ferritic volume fraction is reduced to 35%. The ferrite fraction is even lower for the martensitic steel MS1200. Increasing the volume fraction of hard phase on the expense of ferrite phase enhances therefore the strength properties but reduces in the same time the strain rate sensitivity of yield and tensile strength. Bainite or martensite phase build a network around ferrite grains and are no more finely dispersed in the ferrite matrix as for dual phase steels. This leads to a stronger initial obstacle structure (higher yield strength) and a more athermal character of the dislocation motion.

4 CONCLUSIONS

Different cold formable steels for car body applications show significant differences in their temperature and strain rate dependency of the mechanical properties:

In general, yield and ultimate tensile strength increase with increasing strain rate.

Low carbon mild steel are characterized by a strong increase in yield strength when the temperature decreases and the strain rate increases; this results in reduced strain hardening and finally in less uniform elongation. Thus, in case of crash deformation strain localization has to be considered.

The strain rate sensitivity decreases sharply with increasing static tensile strength. CP and martensitic steel grades show the lowest and DC04 the highest strain rate sensitivity. The TRIP steel show a lower strain rate sensitivity than the dual phase steel.

Comparisons of the specific mass energy absorption depend on the specific strain limit chosen. Energy absorption values determined at a fixed elongation value, in this work 10%, show the superior energy absorption of the martensitic steel MS1200. When considering the total energy absorption until fracture, the TRIP steel shows the best results due to its combination of high strength and high ductility.

Increasing fraction of hard phases in the material (martensite, bainite) results in less temperature and strain rate dependency of the mechanical behavior, because of less importance of the thermally activated term of the flow stress. Thus their behavior at high strain rates or at lower temperatures is more similar to the room temperature behavior. A significant amount of strain hardening can be expected even at low temperatures and high strain rates.

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