DETERMINATION OF INPUT DATA FOR NUMERICAL DESIGN OF SHEET STEELS A COMMON RESEARCH PROJECT OF THE STEEL AND AUTOMOTIVE INDUSTRIES

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Abstract

With 20 steel grades serving as a basis, elastic, plastic and fatigue characteristic values were determined for FE simulation in a joint project between the steel and automotive industries. The steels were tested both in the as-delivered conditions and in defined pre-deformation and heat-treatment conditions. The requirements relating to the production of these conditions and the detailed test specifications were fixed in the so-called "Prüf- und Dokumentationsrichtlinie" (testing and documentation guideline), with the aid of which it was possible to determine standardised characteristic values going beyond the test standards, and to edit data for a materials database realised by the automotive industry. It was found that groups of materials with almost identical strain-hardening characteristics exist, such that a numerical estimation of characteristic values and flow curves for generically related steels appears possible.

KEYWORDS

Sheet steels, characteristic values for FE simulation, elastic, plastic, fatigue, numerical estimation of characteristic values

INTRODUCTION

In the product design process in the automotive industry, the properties of products and the manufacturability of motor vehicles are verified by means of various calculation methods before the prototypes are fabricated [1]. Some calculation methods work with linear-elastic-plastic material behaviour and, as a result, are not very demanding in terms of the required material characteristic data. But especially the non-linear methods, such as those used for crash, fatigue strength or springback simulation, still display an unsatisfactory prognostic capability when the behaviour of components or joints is to be predicted. This is frequently explained by the lack of material characteristic data and the greatly simplistic material models [2].

1 PROJECT SCHEDULE

Steel sheet producers in Germany and Austria, automobile manufacturers and test institutes have agreed to work together to determine material- and processing-relevant characteristic values for steel sheet materials produced from mild, high-strength and stainless steels.

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The research activities were coordinated by a working group made up of the German Group of the International Deep Drawing Research Group (GDDRG) and the Materials Committee of the Steel Institute VDEh. The activities to determine the characteristic values were sub-divided into the following research domains: elastic (determination of the modulus of elasticity, Young´s modulus), plastic (including determination of flow curves and forming limit diagrams) and fatigue (determination of S/N diagrams and cyclic stress-strain curves).

A total amount of 20 steel grades were selected, on the one hand, to include representatives of the most important steel groups where steel sheet materials are concerned and, on the other hand, to cover the entire strength and formability spectrum. Fifteen steels were cold-rolled sheet grades in a thickness of 1.0 mm (DC04, DC06, H260YD, H180B, H260B, H260P, H250G1, H320LA, H340LAD, H300X, TRIP700+Z, X5CrNi18-10 and X8CrNiMnNi19-6-3). The two bake-hardening steels H180B and H260B were made available both as continuous-annealed and batch-annealed variants. The five hot rolled strips (DD13, S380MC, DD33X, CP900 and X5CrNi18-10) had thicknesses ranging from 1.5 to 3.0 mm. The steel sheet to be tested were taken from a delivered batch typical of each steel and characterised by values for the yield strength, tensile strength and elongation, which had to lie in a range of +/- 1σ relative to the mean value for standard production.

An initial testing of the materials to be tested was carried out. To rule out any confusion in identifying the batches, a chemical analysis was performed and compared with the composition serving as the basis for the steel makers. In addition, the microstructure, grain size and phase fractions were determined for each steel metallographically on longitudinal microsections. The last step of the initial testing involved determining the mechanical properties R_e, $R_{p0,2}$, R_m, A_{80}, r and n in quasi-static tensile tests at room temperature, for which purpose three parallel tests were performed longitudinally, diagonally and transversely in relation to the rolling direction in each case.

The elongation values A_{80} determined for the steels are plotted in Fig. 1 as a function of the 0.2% yield strength $R_{p0.2}$ [3]. The grey-shaded rhombs denote the tested hot strips, and the white-coloured ones the corresponding cold strips.

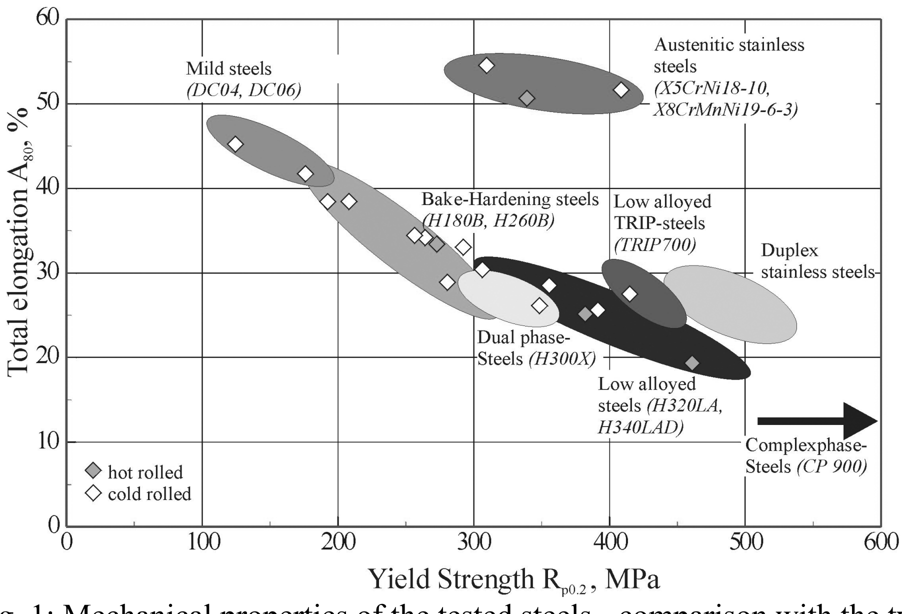

Fig. 1: Mechanical properties of the tested steels - comparison with the typical property fields taken from literature

The elliptical areas plotted in the figure roughly indicate the property spectrum known from literature for the various materials. The already familiar relationship of the elongation properties decreasing with increasing strength can be seen. The austenitic stainless steels X5CrNi18-10 and X8CrMnNi19-6-3 are an exception in this respect. Because of their face-centred cubic crystal structure and, as a result, their different kind of strain-hardening behaviour with additional austenite-martensite transformation during deformation, they attain very high strength levels and, at the same time, high elongation values.

2 TESTING AND DOCUMENTATION GUIDELINE

The project partners drew up a test and documentation guideline [3] to create a basis for harmonised determination of the material characteristic values, thereby making it possible to standardise the exchange of data between test institutes, as well as between steel and automobile manufacturers, and to integrate the data without any problems in the FE simulation programmes. In some instances the requirements in the guideline well exceeded the existing test standards in regard to scope and accuracy.

3 PLASTIC PROPERTIES

Flow curves were determined in quasi-static tensile testing at temperatures of -40°C, 23°C and 100°C in the as-delivered condition and in various pre-deformation and heat treatment conditions. The forming limit diagrams, deep-drawing working ranges and drawing limit ratios were also determined on the basis of the test sheet materials [4].

The flow curves compiled from the quasi-static tensile testing, shown in Fig 2, illustrate the spectrum of properties offered by the sheet materials currently available. It was not until the development of the multi-phase steels, though, that the realised strength increase was no longer accompanied by a decrease in elongation. Because of the face-centred cubic crystal structure and the partial transformation from austenite into martensite occurring during the deformation, much higher elongation values and, at the same time, very high tensile strength levels emerge for the austenitic stainless steels (X5CrNi18-10 and X8CrMnNi19-6-3) compared with the single- and multi-phase ferritic steels.

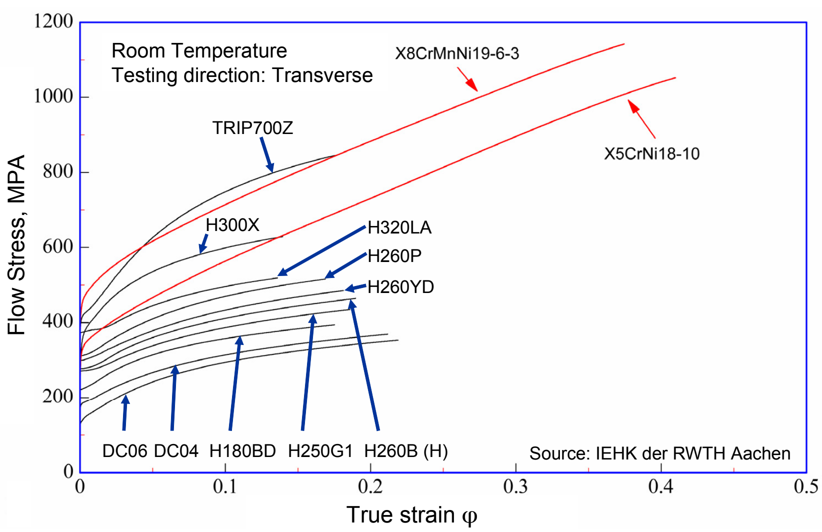

Fig. 2: Compilation of flow curves of the tested steels [4]

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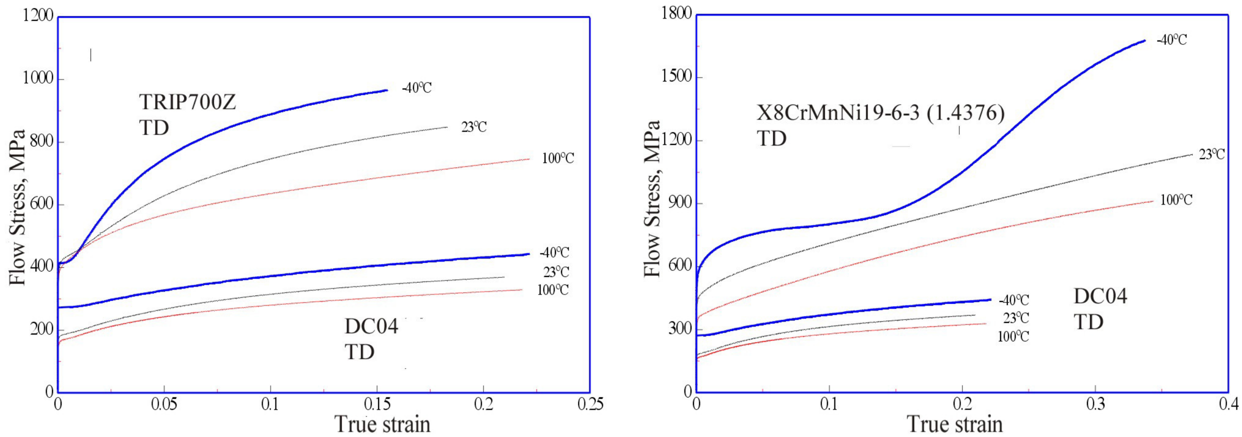
Fig. 3a and 3b show, as examples, the results of the quasi-static tensile testing at different temperatures for selected steels. The steel DC04 displays higher flow stress values as the temperature decreases and slightly lower uniform elongation at room temperature than at -40°C and 100°C. Where the low-alloy TRIP steel (Fig. 3a) and the austenitic stainless steel X8CrMnNi19-6-3 (Fig.3 b) are concerned, the TRIP (TRansformation Induced Plasticity) effect also comes into play, leading, through a deformation-induced transformation of austenite into martensite, to increased strain-hardening and, consequently, to increased elongation.



a) DC04 and HXT700T+Z (TRIP700+Z); b) DC04 and X8CrNi19-6-3

Fig. 3: Flow curves of selected steels [4]

Taking the example of bake-hardening steels H180B and H260B and of deep-drawing steel DC04, Fig. 4 demontrates that an interpolation and, within boundaries, also an extrapolation of the flow behaviour appear quite feasible for steels with a single-phase ferritic structure yet differing strength. According to the results accumulated so far, however, modelling the flow curves of generically related steels is possible only at room temperature or at temperatures that are slightly higher. At a test temperature of -40°C, on the other hand, the flow curve and the strain-hardening behaviour change significantly and non-uniformly for the various steel grades. Modelling the multi-phase steels, which are conspicuous because their strain-hardening behaviour is considerably dependent on the temperature, is even more difficult. The steel HXT700T+Z and the austenitic stainless steel grades have already served as examples in this respect

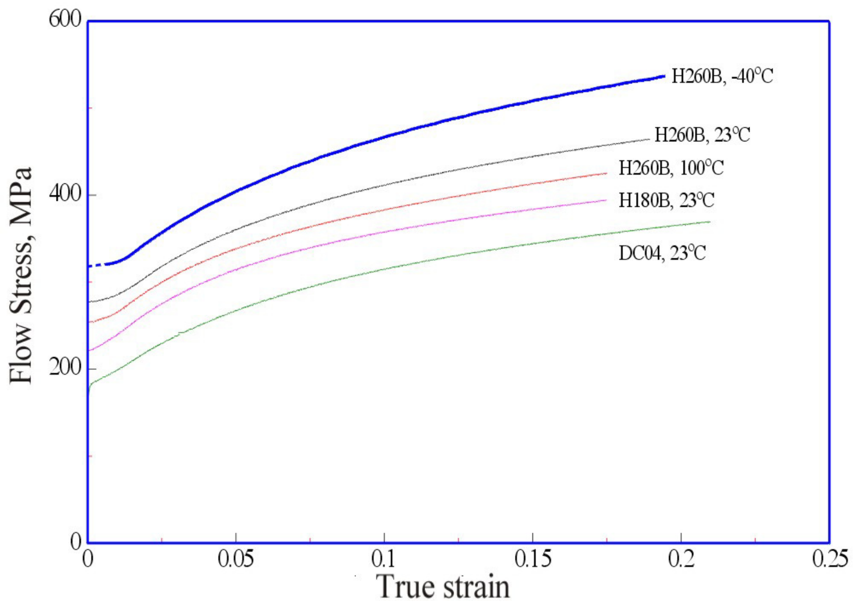


Fig.4: Comparison of flow curves of generically related steels [4]

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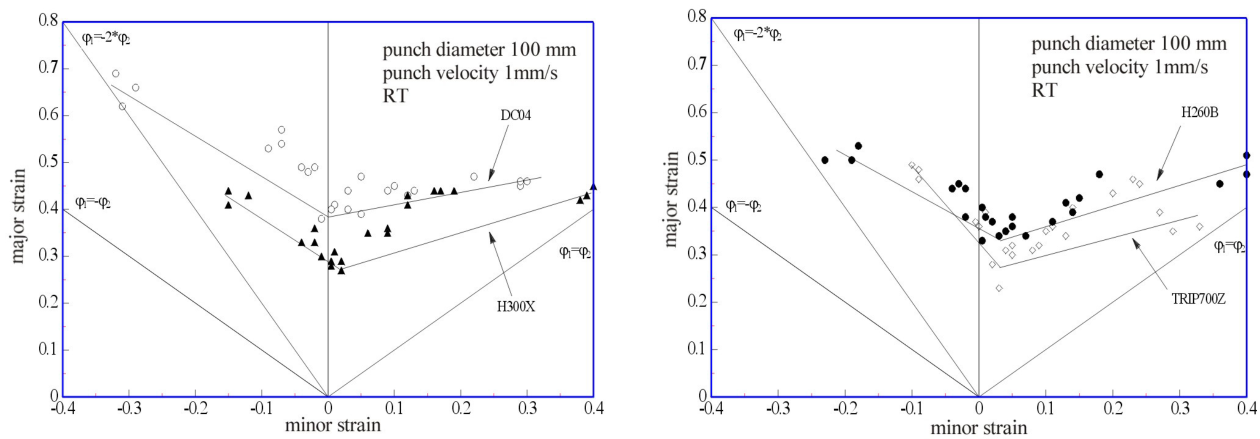
The bake-hardening potential and the effect on the flow curve was examined for several steels by applying a heat treatment of 20 minutes at 170°C prior to the testing. No influence of the applied heat treatment on the course of the flow curve at elevated strain rates could be detected. Although there was a shift in the start of the flow curve because of the pretreatment, this did not however change the characteristic course of the flow curve, such that, if the yield strength increase and the Lüders strain are known, it does appear possible to use the flow curve of the non-heat-treated material in mathematical simulations.

The comparison of the forming limit diagrams of various steels in Fig. 5a and 5b shows that these react in different ways to the diverse states of strain when the diagrams are determined. The mild deep-drawing steel displays higher forming limits than the dual-phase steel for all the strain combinations. The TRIP steel, in spite of its high tensile strength, achieves higher values than the bake-hardening steel in the left-hand part of the forming limit diagram. The H260B steel, by comparison, displays better formability in the stretch-forming range.



a) DC04 and H300X b) H260B and HXT700T+Z (TRIP700+Z)

Fig. 5: Representation of the forming limit diagrams at room temperature [4]

4 DYNAMIC TENSILE TESTING

Dynamic tensile testing at high strain rates was carried out to simulate crash behaviour. Temperatures of -40°C, 23°C and 100°C and strain rates of 1, 20, 250 and 500 s^{-1} were selected as the test parameters [5].

The testing revealed characteristic differences between the individual groups of steels. Mild steels such as DC04, DC06 or H180B, for example, exhibited a strong increase in the yield-to-tensile ratios R_e / R_m at high strain rates and low test temperatures. This resulted in a reduced strain-hardening potential for these steels and much lower uniform elongation values at high test rates and low test temperatures. The higher-strength phosphorus- and micro-alloyed steels, all the multi-phase steels and the austenitic stainless steels, by comparison, showed that their mechanical properties, particularly the yield strength, are less dependent on temperature.

The influence of the strain rate and the temperature on yield and tensile strength for the steel grades DC04 and HXT700T+Z is shown in Fig. 6.

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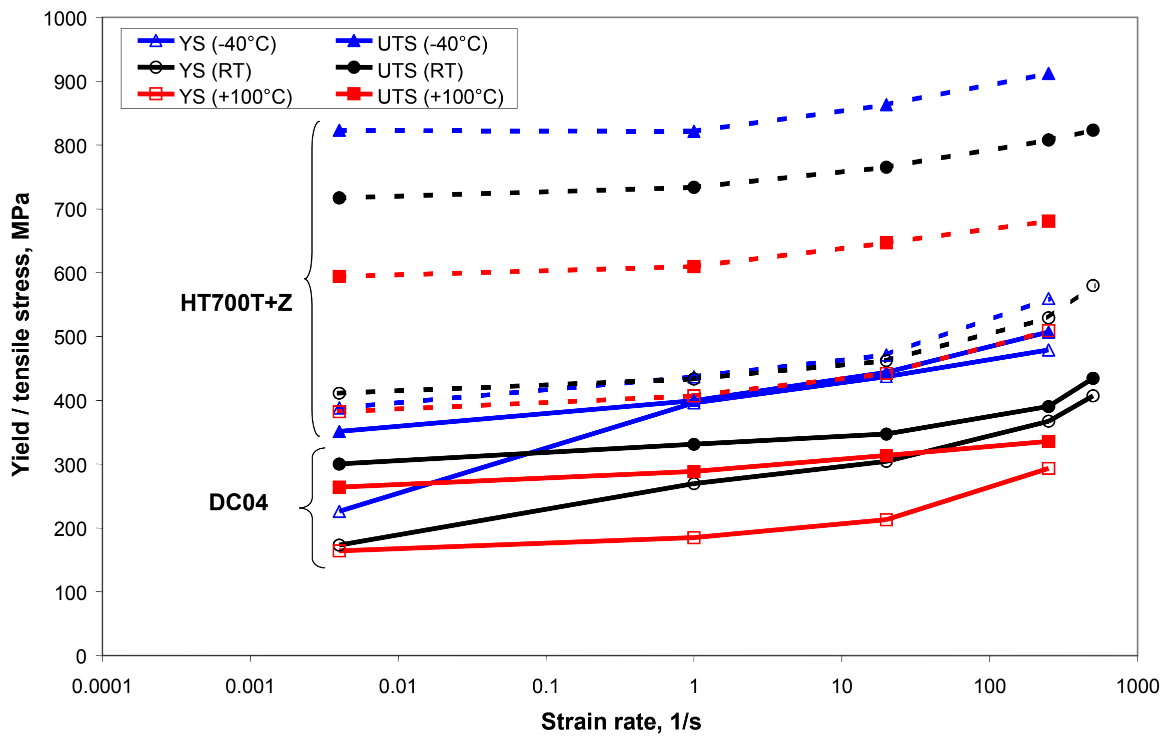

Fig. 6: Influence of the strain rate and the temperature on yield and tensile strength for the steel grades DC04 and HXT700T+Z

The testing has shown how important experimentally determined data are for FE crash simulation. It remains indispensable to determine the data through dynamic tensile testing in the relevant temperature and strain rate range, since an interpolation of the data solely from quasi-static tensile testing can lead to appreciable misinterpretations of the material behaviour.

5 ELASTIC PROPERTIES

The temperature-dependent and anisotropic modulus of elasticity plays an important role in automotive engineering as a determinant of springback in sheet metal pressing operations and general automotive component stiffness. The modulus of elasticity was determined by tensile testing in the as-delivered condition, after pre-deformation and, partly, after heat treatment, at room temperature as well as at -40°C and at +100°C [6].

The modulus of elasticity is directly dependent on the test temperature (Fig. 7). A steel-grade-specific difference ranging from around 7 GPa to 24 GPa was determined for the test temperature interval from -40 °C to +100 °C. The modulus of elasticity is found to decrease by 0.1 GPa/K on average, for all steel grades, as the temperature increases.

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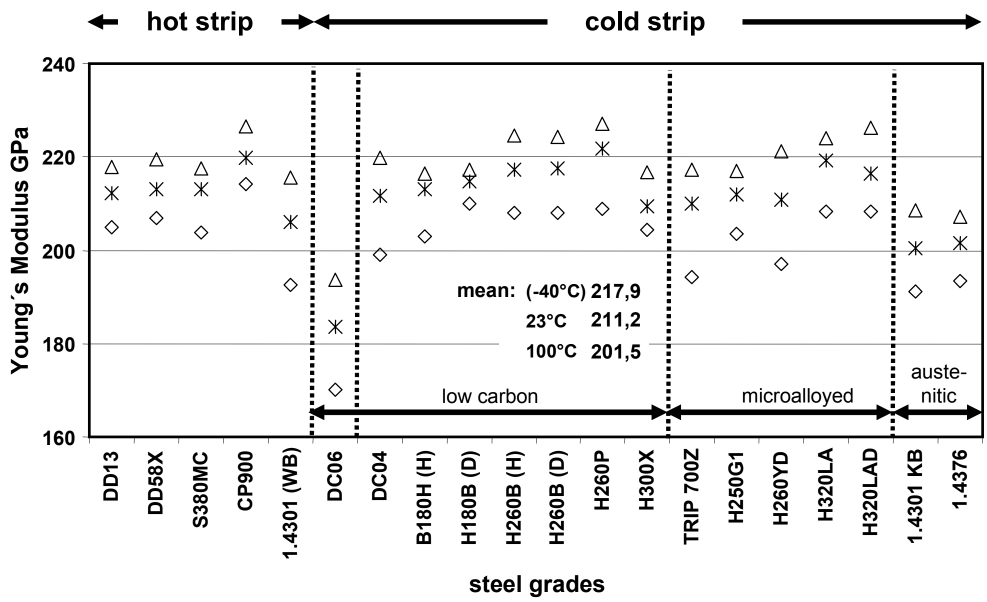

Fig. 7: Temperature dependence of the modulus of elasticity (transverse specimens – W 170); KB=cold rolled strip, WB=hot rolled strip, 1.4301=X5CrNi18-10, 1.4376=X8CrMnNi19-6-3 [6]

The modulus of elasticity in the as-delivered condition depends, because of the texture, on the position relative to the rolling direction, as a function of the production process and steel grade (Fig. 8).

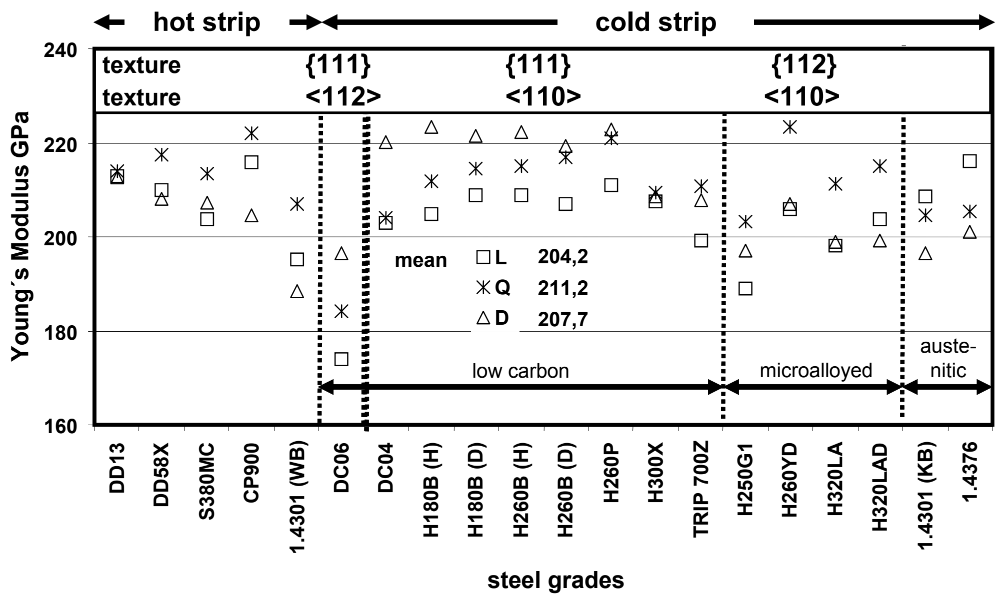

Fig. 8: Modulus of elasticity of all the tested steels in the as-delivered condition; specimen position: parallel (L), transverse (Q) and diagonal (D) relative to the rolling direction, KB=cold rolled strip, WB=hot rolled strip, 1.4301=X5CrNi18-10, 1.4346=X8CrMnNi19-6-3 [6]

The tensile testing, therefore, was conducted for specimens in longitudinal, diagonal and transverse direction, in each case relative to the rolling direction. The mean value determined for the modulus of elasticity for 20 steel grades in the as-delivered condition is around 207.9 GPa. Tensile specimens taken from sheet materials in the as-delivered condition transverse to the rolling direction were subjected to a heat treatment (20 minutes at 170°C (W170)). The modulus of elasticity decreases significantly beyond the scatter of the individual values only for steel grade

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H260YD. Otherwise, no or only a small increase in the modulus of elasticity was detected as a result of the heat treatment.

It was found that pre-deformation by as little as 2% significantly reduces the modulus of elasticity for selected ferritic steel grades, whereas pre-deformation has only little effect on the modulus of elasticity of hot strip and the tested austenitic stainless steels. Skin-pass rolling is also to be understood as pre-deformation. Heat treatment of pre-deformed specimens restores the modulus of elasticity, mainly to the value of the as-delivered condition.

6 FATIGUE PROPERTIES

The Local Strain Concept is applied ever more frequently when estimating the fatigue life, relying among other things on cyclic stress-strain curves recorded under strain control and on crack initiation S/N diagrams of the material in use to calculate local elasto-plastic deformation and, ultimately, to estimate the component lifetime.

The cyclic material behavior is described by the Coffin-Manson equation (eq. (1), taken up strain-controlled with constant amplitude until incipient crack) and by the Ramberg Osgood equation (eq. (2), cyclic stress-strain curve). The constants of the Ramberg Osgood equation are derived by compatibility conditions (eq. (3) and (4)).

$$\varepsilon_{a,t} = \varepsilon_{a,e} + \varepsilon_{a,p} = \frac{\sigma_f'}{E}\left(2N_i\right)^b + \varepsilon_f'\left(2N_i\right)^c \tag{1}$$

$$\varepsilon_{a,t} = \varepsilon_{a,e} + \varepsilon_{a,p} = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{1/n'} \tag{2}$$

$$K' = \frac{\sigma_f'}{{\varepsilon_f'}^{\,n'}} \tag{3}$$

$$n' = \frac{b}{c} \tag{4}$$

These characteristic values were determined for 17 steel grades for thin sheets in various as-delivered and deformation states at -40°C, room temperature and +100°C, with 37 series of tests, as well as crack initiation S/N diagrams and monotonic or cyclic stress-strain curves [7]. All the test points, hysteresis data and determined fatigue characteristic values have been collected in a database.

Fig. 9 shows the influence of prestraining on the cyclic stress-strain-curve (a) and on the strain-life-curve (b) of steel H320LA. The level of the cyclic stress strain curve is raised due to the prestraining. Whether the direction of loading is parallel or transverse to the direction of prestrain is of circumstantial evidence. The run of the strain-life-curve is slightly influenced by the plastic deformation. In the range of higher cycles there is a tendency of increased allowable strain amplitudes.

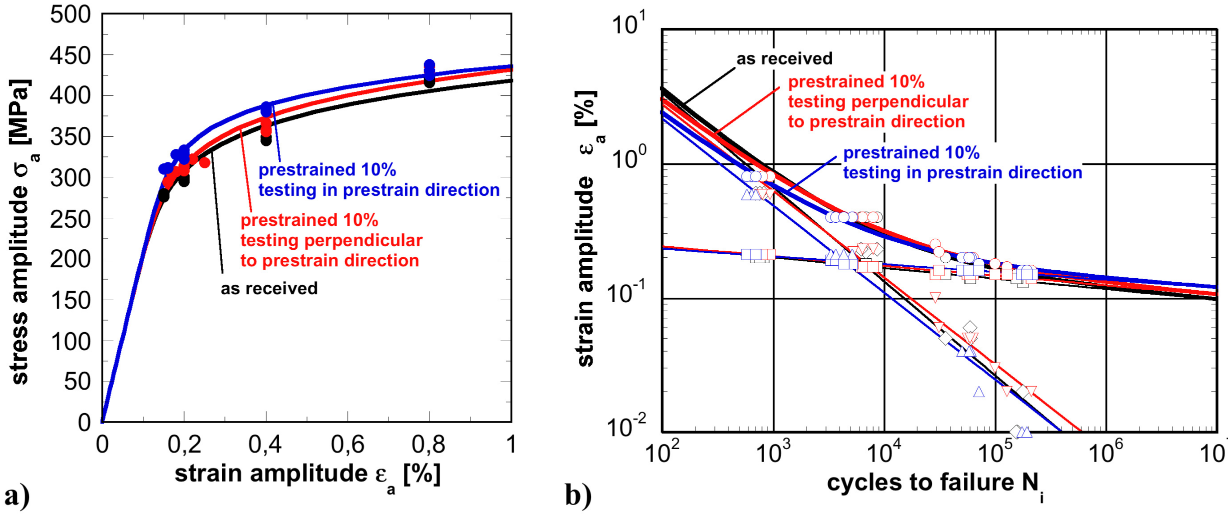

Fig. 9: Influence of prestraining on the cyclic behaviour of steel H320LAD. a) Cyclic stress-strain-curve b) Strain-life-curve

The location of the rolling direction with respect to the loading direction has only little influence as well on the cyclic stress-strain-curve as on the strain-life curve (Fig. 10).

The investigations of the influence of testing temperature consider as example of steel H250G1 (Fig. 11) and HXT700T+z (Fig. 12) at -40 °C (Fig. 11) that the cyclic stress-strain-curve is raised significantly. The run of the stress-life-curve is not influenced by an ambient temperature of -40°C. Unlike at an ambient temperature of +100 °C the course of the strain-life-curve is raised at higher cycles. The cyclic stress–strain-curve is only slightly influenced by a temperature of +100 °C. The influence of temperature was examined by five steel grades. In all of these cases life was raised at lower temperatures and decreased at elevated temperatures.

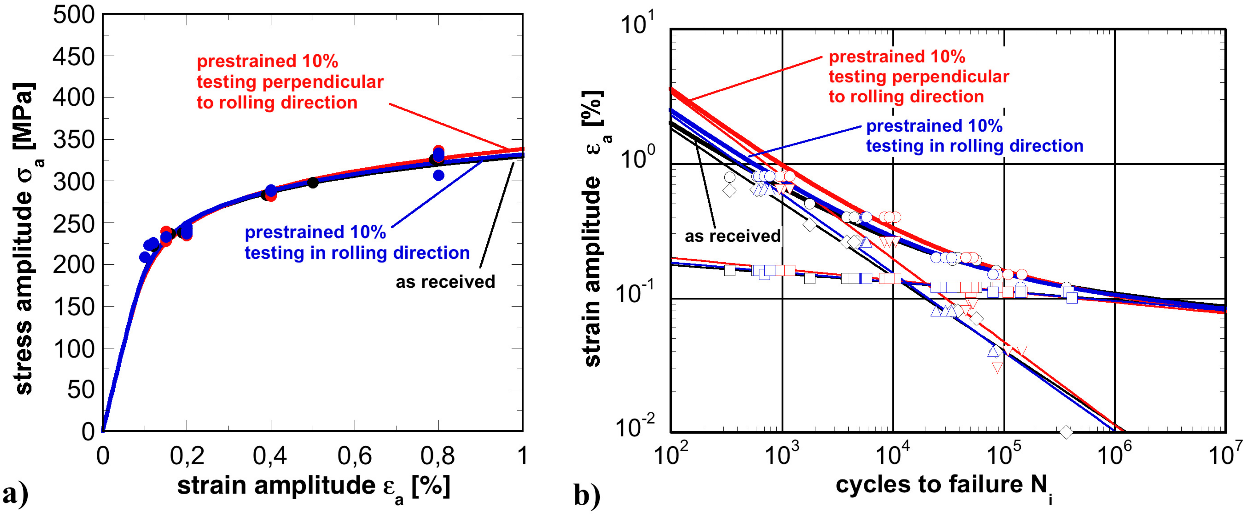

Fig. 10: Influence of direction of test specimens on the cyclic material behaviour of steel H260B. a) Cyclic stress-strain-curve b) Strain-life-curve

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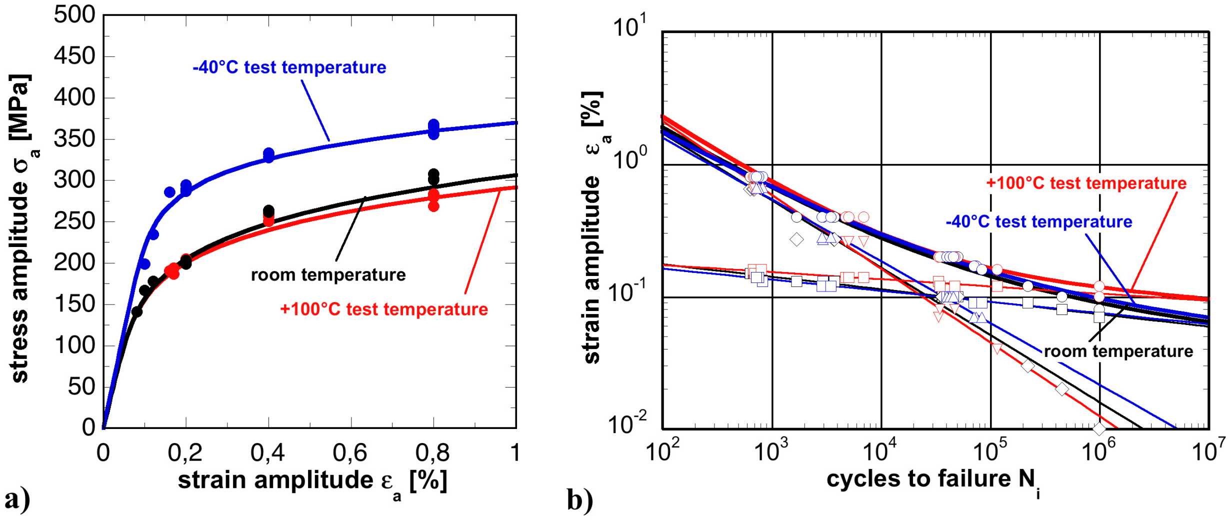

Fig. 11: Influence of testing temperature of steel H250G1. a) Cyclic stress-strain-curve b) Strain-life-curve

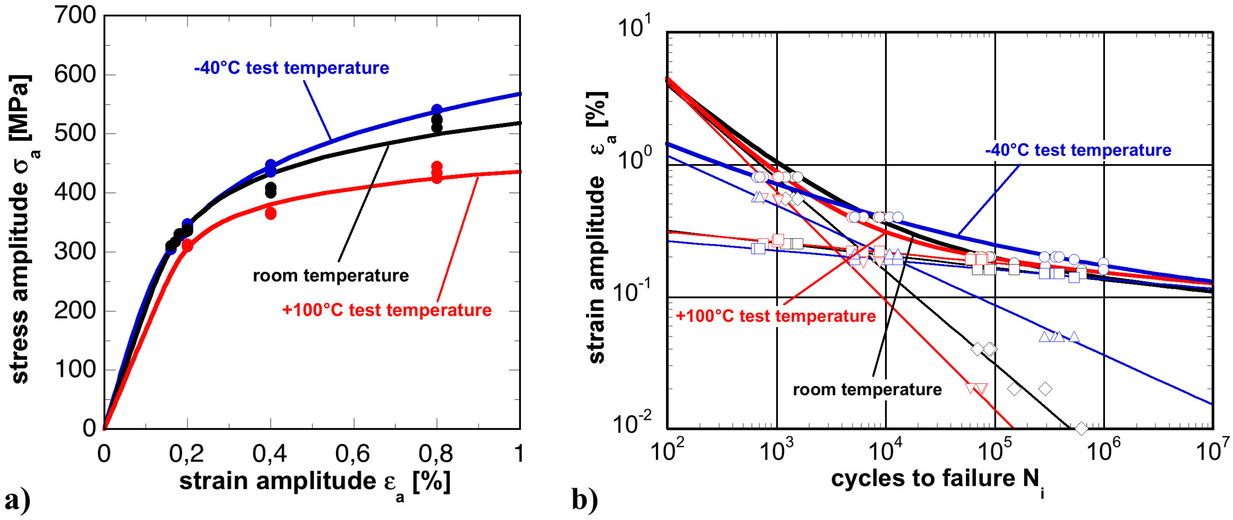

Fig. 12: Influence of testing temperature of steel HXT700T+Z. a) Cyclic stress-strain-curve b) Strain-life-curve

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All the fatigue characteristic values determined for the tested steel grades including the cyclic yield strength $R'_{p0,2}$ and monotonic stress-strain curve are compiled in Table 1. These data are mean values (survival probability $P_{ü}$ = 50%) originating from regression calculations

Table 1: Determined fatigue characteristic values

			Constants of the Coffin-Manson equation				Cyclic data from compatibility relationship		
Test serie	Steel gradesl	Young's modulus [GPa] E	Fatigue strength coefficient [MPa] σ'_f	Fatigue strength exponent b	Ductility coefficient [m/m] ε'_f	Ductility exponent c	Yield strength [MPa] $R'_{p0,2}$	$K' = \frac{\sigma'_f}{(\varepsilon'_f)^{n'}}$	$n' = \frac{b}{c}$
1	H260B	206	510,8	-0,0654	0,3298	-0,5479	274	583	0,1190
2	DC06	206	502	-0,0986	0,1083	-0,4144	194	852	0,2380
3	H260YD	206	553	-0,0662	0,5528	-0,5920	294	591	0,1118
4	H250G1	206	605,3	-0,09548	0,2668	-0,5106	242	775	0,1870
5	H260P	206	625	-0,0732	0,8542	-0,6417	310	636	0,1141
6	DC04	206	507,3	-0,09655	0,1245	0,4245	198	815	0,2274
7	H320LA	206	743,6	-0,0782	1,4598	-0,7068	358	713	0,1110
8	H340LAD	206	699	-0,0885	0,7224	-0,6140	300	733	0,1442
9	H300X	206	692,2	-0,08233	0,2318	-0,4854	309	887	0,1696
10	TRIP700	206	1066	-0,0938	1,5807	-0,6977	430	1002	0,1344
11	X5CrNi18-10	206	1291	-0,1308	0,0782	-0,3310	305	3533	0,3950
12	X8CrMnNi19-6-3	206	1154	-0,0928	0,1225	-0,3689	405	1957	0,2516
13	DD13	206	912,9	-0,1363	0,3962	-0,5179	229	1165	0,2630
14	DD58X	206	816,8	-0,09433	0,6869	-0,6007	327	866	0,1570
15	S380MC	206	833	-0,0836	2,4051	-0,7236	365	753	0,1160
16	CP900	206	1874	-0,1144	0,3577	-0,7378	839	2198	0,1551
17	X5CrNi18-10	195	866,9	-0,1051	0,0790	-0,3532	291	1845	0,2980
18	H180B	206	605	-0,0996	0,5483	-0,5785	230	671	0,1722
19	TRIP700	206	1150	-0,1013	1,9175	-0,7278	445	1051	0,1392
20	H300X	206	938	-0,1071	0,7059	-0,5948	325	998	0,1801
21	H250G1 -40°C	235	543	-0,05433	0,4077	-0,5575	323	593	0,09745
22	H260YD -40°C	235	606,6	-0,06673	0,2595	-0,4943	315	728	0,1350
23	H260B -40°C	235	592,8	-0,06773	0,2438	-0,4679	296	727	0,1448
24	TRIP700 -40°C	235	895,3	-0,07101	0,08186	-0,3713	440	1445	0,1912
25	H250G1 +100°C	206	522,8	-0,0840	0,1875	-0,4656	230	707	0,1800
26	H260YD +100°C	206	484,8	-0,0620	0,5554	-0,6003	271	515	0,1030
27	H260B +100°C	206	552,1	-0,0786	1,0170	-0,6417	257	552	0,1220
28	TRIP700 +100°C	167	781,6	-0,0787	3,1758	-0,8199	385	700	0,0960
29	H180B	206	742	-0,1242	0,3610	-0,5093	210	952	0,2439
30	H260B	206	708,7	-0,1061	1,2496	-0,6777	259	684	0,1570
31	H260B 10%längs	206	514,3	-0,05489	0,6865	-0,6197	307	532	0,08858
32	H320LA -40°C	235	709,8	-0,06579	0,1844	-0,4531	368	907	0,1452
33	H320LA +100°C	206	600,8	-0,0682	0,3449	-0,5351	312	688	0,1270
34	H320LA 10%quer	206	730	-0,0726	0,8472	-0,6450	375	744	0,1125
35	H320LA 10%längs	206	649	-0,0579	0,6661	-0,6463	385	673	0,0896
36	H260B 0°	206	633,5	-0,0829	0,8961	-0,6180	278	643	0,1340
37	H260B 45°	206	551,5	-0,07199	0,5180	-0,5873	279	598	0,1226

7 OUTLOOK

The complete characterisation of 20 steel grades produced as sheet materials, with the aim of obtaining input characteristic values for FE calculations, yielded a considerable increase in information with regard to measuring and testing methods and the collection and further processing of data.

As the results show, groups of materials exist within which the strain-hardening characteristic values appear almost identical. This presents possibilities for predicting characteristic values and flow curves of generically related steels with the aid of material models. The aim of this, not least of all, is to significantly reduce the amount of testing required to characterise materials. This topic is

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the focus of a follow-up research project funded by the Research Association for Steel Application (Forschungsvereinigung Stahlanwendung e.V.).

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