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FATIGUE BEHAVIOUR OF MULTIPHASE STEELS FOR AUTOMOTIVE APPLICATIONS

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ABSTRACT

High strength steels are becoming more and more interesting for the automotive industry as they allow car weight reduction due to lower thickness ensuring the same performance and improved safety by higher energy absorption. A known way of improving the strength, ductility and formability of steels is to make use of additional strengthening and deformation mechanisms by introducing supplementary phases. It is evident that the fatigue behaviour of the materials used for automotive applications is a major point to be taken into account in design and material selection. In this paper the fatigue behaviour of different newly developed high strength multiphase steels (TS>600MPa) including ferritic-bainitic, ferritic-martensitic and TRIP steels is compared with the fatigue behaviour of the commercially available microalloyed steels used at the moment by the automotive producers. Results from laboratory research of pre-strained specimens, which were supposed to be representative for the preceding forming process, will be shown together with results of real components, e.g. wheel disks. Finally, the effect of paint baking on cyclic loading will be evaluated.

KEYWORDS

Fatigue behaviour, multiphase steels, microalloyed steels

INTRODUCTION

Car weight reduction has recently become a very important topic for the automotive industry due to the increasing requirements on fuel consumption efficiency that are related to energy savings and environmental restrictions. In this context, a great effort is being done in order to develop new high strength steels that combine both a good formability and a high strength, with the aim of reducing the material thickness of the different automotive parts without resulting in a loss of performance, especially passenger safety.

In this paper the fatigue behaviour of some newly developed high strength hot rolled multiphase steels to be used in the automotive sector for, e.g., wheel applications will be presented and compared with the fatigue behaviour of a microalloyed grade that is currently used by the wheel producers. Recently, first industrial wheel production trials have been carried out using those multiphase steels. E.g., it was possible to reduce thickness and thus weight by using a dual-phase grade, which led to a wheel lighter than one made of aluminium [1].

The product of tensile strength (TS) and rupture strain (A) is directly linked with the minimum sheet/wall thickness ensuring safety demands, i.e. the higher the TSxA value, the smaller the sheet thickness can be chosen [2] resulting in weight and cost reductions. The (TSxA)-value thus describes the materials formability, toughness and energy absorption capacity. Figure 1 shows the comparison of the TS and A value ranges of various hot rolled steel grades such as C-Mn steels and microalloyed steels as well as the new multiphase steels, like Dual-Phase (DP), Ferritic Bainitic (FB) or Complex Phase (CP) and Transformation Induced Plasticity (TRIP) steels. From Figure 1 it becomes evident that combining different constituents in the final microstructure of the steel, normally with a ferrite matrix, together with a certain fraction of bainite, martensite and/or retained austenite, strength levels up to 1000MPa can be reached without losing too much formability. The (TSxA)-value of a TRIP steel amounts about 22000 while the actual microalloyed grades are limited to 16000-17000.

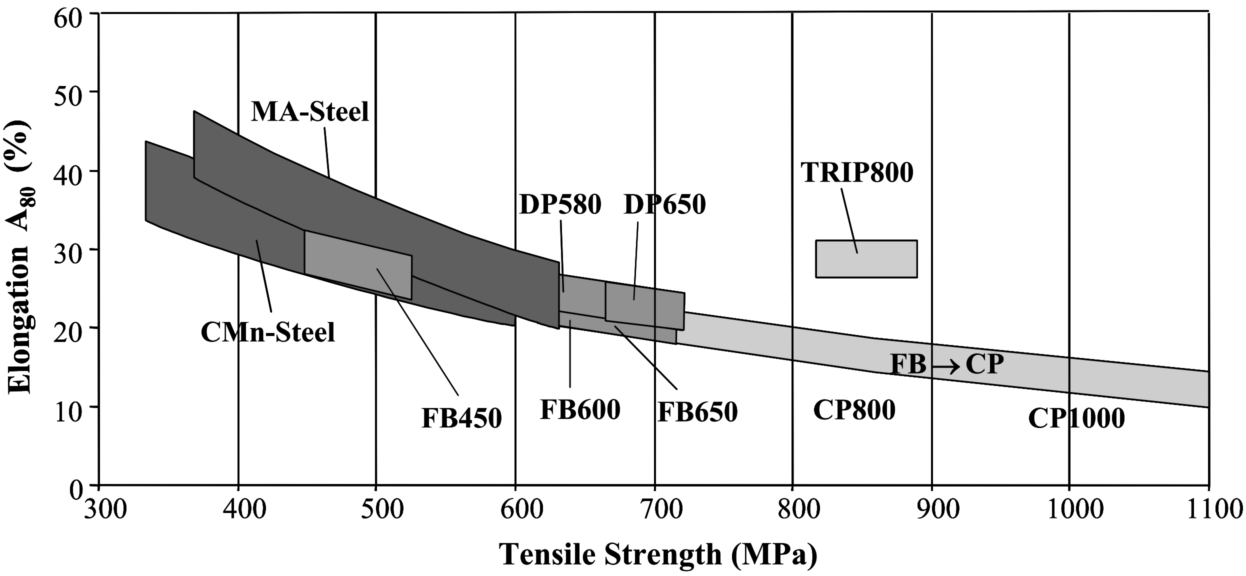

Figure 1: Schematic overview of TS and A80 of hot rolled carbon steel products

However, not only the formability and the energy absorption capability of these steels are important when it comes to applications. Especially in wheel applications fatigue resistance is a major characteristic due to the applied cyclic load. Therefore, in this paper the fatigue behaviour of the above mentioned multiphase steels will be presented, laboratory results under uni-axial loading and industrial fatigue results on wheels tested using an ex-centric rotating load will be shown.

MATERIALS AND EXPERIMENTAL PROCEDURE

The chemical composition of the industrially produced steels used for this study is shown in Table 1. Two ferritic-bainitic grades (FB600 and FB650) with different microalloying additions have been selected together with one ferritic-martensitic dual-phase steel (DP650) and a TRIP steel whose microstructure consists of ferrite, bainite and retained austenite. For comparison purposes the commercially available microalloyed grade S355MC (EN Standard 10149/2) was chosen.

TABLE 1
CHEMICAL COMPOSITION OF THE STEELS IN WEIGHT PERCENT

Grade	FB600	FB650	DP650	TRIP800	S355MC
C	0.08	0.07	0.08	0.2	<0.11
Mn	1.45	0.95	1.45	1.5	<0.8
other	Nb	Nb, Ti	Nb	Si, Nb	Nb

The microstructures of the multiphase grades in transverse direction are shown in Figure 2. Using LePera etching [3] in all steels the ferrite matrix is accompanied by bainite (black) in FB 600, FB 650 and TRIP, martensite (white) in DP 650 and retained austenite and/or martensite (white) in TRIP 800 while the Nital-etched single phased S355MC contains cementite (black) within the ferritic matrix.

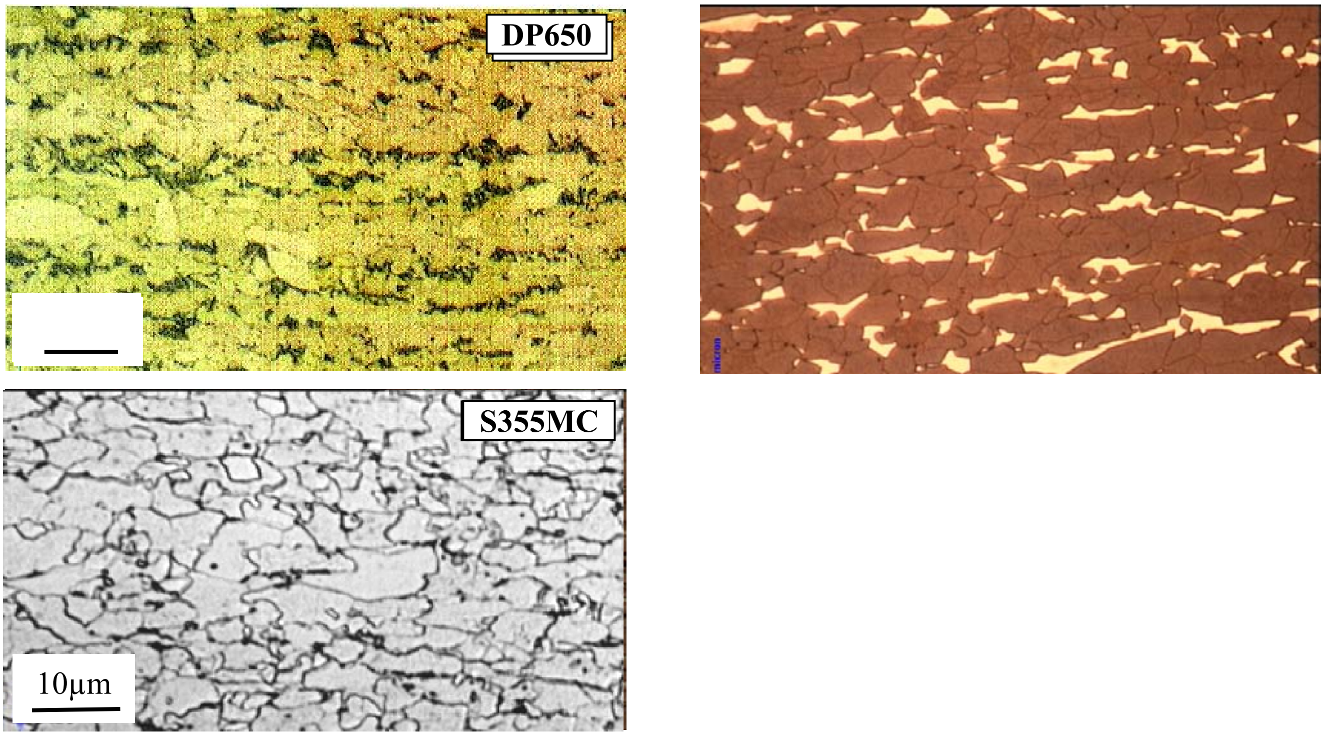

Figure 2: Longitudinal section of the investigated hot rolled grades (→ rolling direction)

The typical mechanical properties of those materials in rolling direction are given in Table 2. Here, the name of the new steel grades contains a number representing the minimum level of TS to be guaranteed.

TABLE 2
MECHANICAL PROPERTIES IN ROLLING DIRECTION OF THE DIFFERENT STEEL GRADES

Grade	YS in MPa	TS in MPa	A_{80} in %	YS in MPa after 10% pre-straining
FB600	520	620	24	572
FB650	610	670	20	660
DP650	520	695	21	692
TRIP800	617	840	28	790
QStE420 (S355MC)	400-470	480-550	22-29	469

For the fatigue tests, specimens were cut with their fatigue axis parallel to the rolling direction of the steel sheets using spark erosion. The laboratory fatigue tests were carried out on pre-strained material, which was used to represent a preceding forming process. The pre-strain of 10% was applied in rolling direction by means of an electro-mechanical closed-loop testing machine (INSTRON 4505) on non-proportional A_{80} tensile test specimens according to the EN10002 standard. The strengthening of the steels is represented by the yield strength (YS) after 10% pre-straining, see Table 2. The axial loading fatigue tests were carried out using a uni-axial closed-loop controlled servohydraulic test machine (MTS 810). All tests were performed at room temperature with a stress ratio $R=\sigma_{min}/\sigma_{max}=0$ and a load frequency f≈10Hz (sine wave) up to fracture. In the case of the Dual Phase steel, additional fatigue tests were carried out on baked material (DP650+BH) in order to simulate the effect of the paint baking after the forming process. The specimens were baked after the pre-straining at 170°C for 20 minutes and were tested afterwards following the same procedure described above.

In Figure 3 a wheel made of FB600 is shown together with a schematic outline of the test method. In order to simulate the effect of the cars weight on the wheel disk, a whole wheel is clamped to the test equipment and subjected to fatigue by means of a rotating ex-centric load applied at the end of the axis. The test is carried out until the first crack appears.

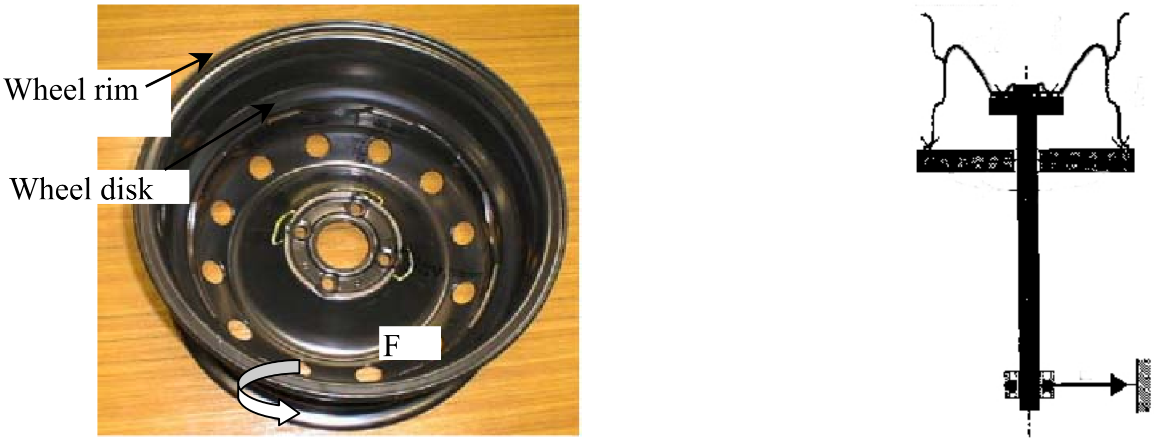

Figure 3: FB600 wheel and outline of the fatigue method

RESULTS AND DISCUSSION

The S-N curves (Wöhler diagram) of the different materials tested are shown in Figure 4, where σ stands for the maximum of the pure pulsating tensile stress (R=0) and N is the number of cycles at which the specimen fails. All curves corresponding to multiphase steels are shifted to clearly higher stress levels compared to the microalloyed S355MC, which is currently commercially used. That means, that for a given stress level the fatigue resistance of the multiphase steels is higher and, correspondingly, their fatigue limit also lies at higher stress values.

Generally, the tensile strength and the fatigue resistance are connected in such a way that with increasing tensile strength also the fatigue resistance increases [4]. This apparently is also valid for the ferritic-bainitic steels as can be deducted from Figure 4. Here, the curve of FB650 (TS=670MPa) is clearly placed above the one corresponding to FB600 (TS=620MPa). A different precipitation state due to a slightly different chemical composition is responsible for this strength increase and can explain also the increase in fatigue life. Comparing the yield strengths of FB600 and FB650 one can expect that the fatigue limit of FB650 will also be higher than the one of FB600. It must be noted that the presented results are part of an ongoing research and that the fatigue limits of the FB steels and of the S355MC grade are not yet determined. Contrary to the said above, the curves corresponding to DP650 (TS=695MPa) and TRIP800 (TS=840MPa) are placed slightly below the curve of FB650 (TS=670 MPa) despite the fact that both steels have a higher tensile strength, see Figure 4 and Table 2.

It can be assumed that the presence of a hard phase such as martensite will affect the fatigue performance of DP600 and TRIP800. Most probably, the effect of martensite is related to incompatibilities at the phase boundaries between martensite and ferrite [5]. These incompatibilities may lead to stress concentrations at the phase boundaries and thus to crack nucleation [5, 6]. Comparable effects were reported in ferritic-austenitic duplex stainless steels [6]. Since the incompatibilities and especially the difference in strength between ferrite and bainite are less pronounced than between ferrite and martensite in DP600 and TRIP800, the load transfer between ferrite and bainite can be expected to be less difficult [5].

Furthermore, while DP600 contains about 15% martensite from the beginning, in TRIP800 martensite only forms after strain induced transformation of the retained austenite during (pre-)deformation. Despite its high tensile strength the fatigue resistance of the TRIP grade at higher stresses is lower than expected. This might be due to the fact that its hardening mechanism, namely the austenitic-martensitic phase transformation, is strain dependent while the precipitation hardening of FB600, FB650 and DP650 is fully active from the beginning. One also might argue with residual stresses stemming from the austenitic-martensitic phase transformation and the corresponding volume increase of 4%.

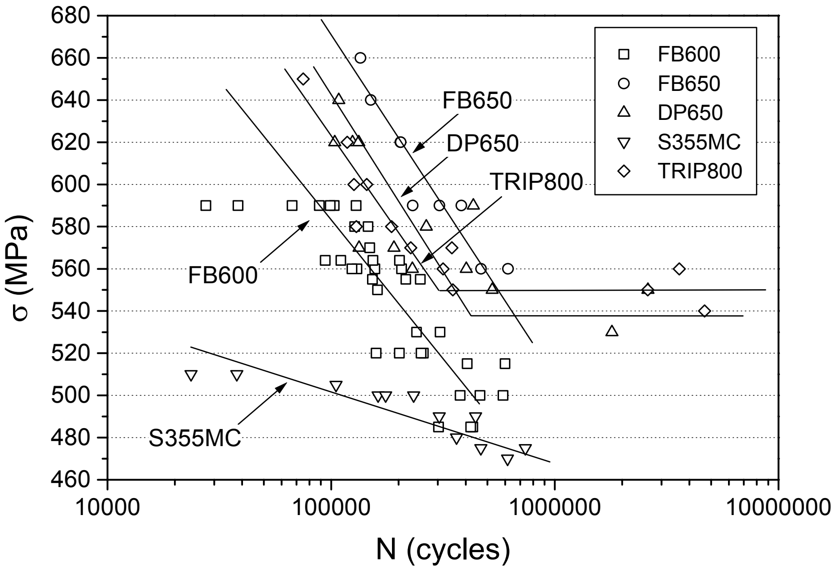

Figure 4: S-N curves of the different steels after 10% pre-straining

However, despite the assumed effect of martensite in the finite life range it is remarkable that the fatigue limit seems to correspond to the "high-strength – high-fatigue resistance" relation mentioned above. Since TRIP has the highest yield strength (Table 2) it also shows the highest fatigue limit, see Figure 4. In agreement with the literature [6, 7] the morphology of multiphase steels is responsible for retarding the crack nucleation and thus increasing the fatigue limit. The finer the microstructure the higher is the fatigue limit.

The results obtained by the industrially tested wheels according the earlier given procedure until the first crack appears are shown in Table 3. The average fatigue life of the microalloyed grade is about 100.000 cycles. It is evident that for the applied multiaxial state of strain all tested multiphase steels show a clearly better performance, i.e. an up to a twice as high fatigue life.

TABLE 3
FATIGUE LIFE OF WHEELS (AVERAGE CYCLES BEFORE CRACK INITIATION)

Steel Grade	FB650	DP650	TRIP800	S355MC
Fatigue Life in Cycles	192.700	176.000	205.050	100.000

It is important to point out that the fatigue tests were carried out using paint-baked wheels. The influence of such a paint baking on the fatigue life can exemplarily be seen for DP650 in Figure 5. The whole curve of the bake hardened steel DP650+BH shows higher values for the finite life range as well as for the fatigue limit, which increased about 60MPa compared to its non-baked state. The improvement of the fatigue performance through bake hardening (20 min. at 170°C) is caused by the diffusion of the C atoms to the dislocations created during the (pre-)deformation, resulting in an additional increase of YS, see Table 4. Simultaneously, the tensile strength increases. While the pre-straining accounts for a YS increase of 172MPa, after bake hardening the YS increased another 144MPa (=316-172), see Table 4. This extremely high value might be due to additional precipitation hardening of the ferritic phase by carbides with C stemming from the "C-saturated" brittle martensite before baking. An as such softened martensitic phase could improve the load transfer between the phases and thus contribute to the fatigue resistance increase. To clarify these assumptions, further research is needed. However, it should be paid special attention to the low cycle fatigue behaviour of multiphase steels, which show a large scattering of the results. This scattering is according to Vogt et al. [5] and Akdut [6] related to the phase morphology. Here parameters like grain size, phase size, phase volume fractions, orientation relationships between the phases, local stresses and the orientation of the phases with respect to the macroscopic sample directions play an important role. As said earlier, crack nucleation is generally retarded, but crack propagation might occasionally be enhanced leading to scattering.

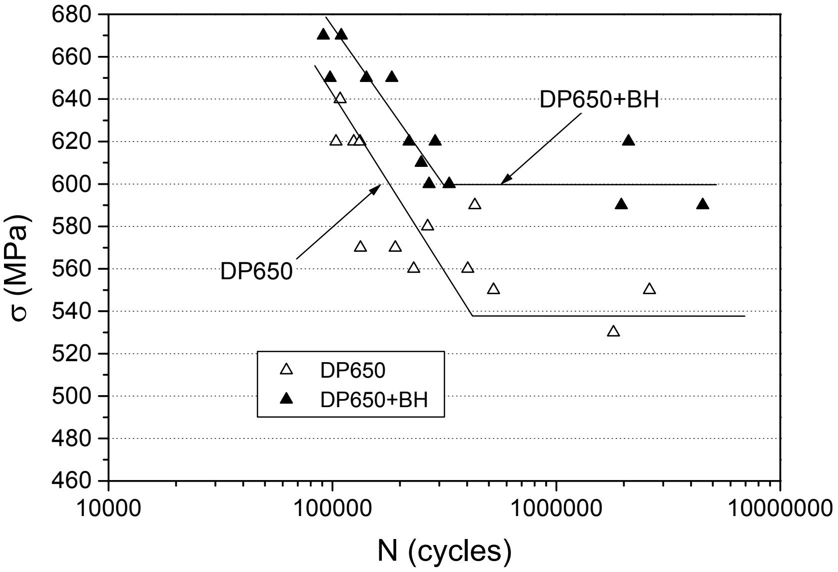

Figure 5: S-N curves of 10% pre-strained DP650 with and without paint baking simulation

TABLE 4
MECHANICAL PROPERTIES OF DP650 AND DP650+BH AFTER 10% PRE-STRAINING

	YS in MPa	TS in MPa	A_{80} in %	ΔYS in MPa
DP650	520	695	21	after pre-straining: 692-520=172
DP650+BH	836	837	6	after pre-straining and baking: 836-520=316

SUMMARY

The investigated multiphase high strength steels show qualitatively better fatigue properties than the commercially used microalloyed grade. Their higher finite life range and especially their higher fatigue limit allow a lightweight design for many automotive applications as shown here for wheels, which are subjected to high fatigue requirements.

The made assumptions concerning the effect of martensite and other phases as well as the effect of bake hardening on the fatigue behaviour of multiphase steels are still subject of investigation. Furthermore, the non-homogeneous loading sequences occurring in automotive structures during production and service have to be taken into account.

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