New Bainitic Steel for cyclic loaded safety parts with improved cyclic material behaviour

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Abstract

A bainitic forging steel, which enables the TRIP-effect, has been developed and can be used for lightweight-construction for forged components under cyclic loading. The high potential under cyclic loading conditions of the new generation of TRIP forging steels is shown and also the improved results under service loads, especially under overloads and misuse. A comparison of linear damage accumulations by Palmgren-Miner will depict the differences in characteristic damage sums between quenched and tempered and the new bainitic steel. For TRIP steels properties the process parameters are very important. Hence, the influence of the cooling conditions of TRIP will be discussed.

Keywords: lightweight, bainitic forging steel, TRIP-effect, overloads

1. Introduction

Lightweight design is often a question of new materials. In the past more and more components were developed with alternative materials like composites. But also steels have still a huge capability to compete with alternative materials. Hence the steel industry is challenged to develop high strength steels with advanced material properties,
exactly for the use in lightweight design structures. The fact that quasi-static material properties cannot represent the material strength behaviour especially under cyclic loading and environmental conditions is important considering for the car's whole lifetime. In the development of high strength steels for lightweight design, the cyclic loading behaviour has to be taken into account, to ensure the fatigue life under service conditions.

Looking at forging parts, classic quenched and tempered (Q&T) steels and newer precipitation hardening ferritic-pearlitic (PHFP) steels are often used. They compete with modern casting parts made out of austenite ductile iron (ADI). ADI-materials have improved fatigue strength under service loads [1], because of the high amount of retained austenite, which can transform into martensitic islands. This effect appears in high loaded areas and creates residual stresses, which lead to an improved fatigue strength under cyclic loading [2, 3]. On the basis of current requirements of the automotive industry and the competition of casting materials, a new bainitic steel has been recently developed. Its cyclic material behaviour will be discussed, especially under variable amplitude loading.

2. Material

2.1. Traditional forging steels

Traditional forging steels are mainly precipitation hardening ferritic-pearlitic steels and martensitic quenched and tempered steels. Both steels have good static properties and an equal cyclic strength. They differ in respect to their heat treatment after the forging process. Q&T steels are forging steels, which get a heat treatment after forging that leads to its very high static mechanical properties and allows a defined adjustment of the local material properties. PHFP steels are micro alloyed by elements like V, Nb and Ti and provide the opportunity for an advanced heat treatment. The material can be directly cooled down from the forging temperature in a controlled process without needing an additional heat treatment [4]. The cooling route between 800°C and 500°C here has a high influence towards the resulting microstructure and the strengths properties. This ensures reaching high strength values at sufficient ductility with a short process chain. The high values of yield strength and toughness in comparison to Q&T steels cannot be reached [5]. In this paper the Q&T steels will be represented by the commonly used 42CrMo4 quenched and tempered steel which contains a Mo content of 0.188 mass % and Cr content of 1.15 mass%. The whole chemical composition of the 42CrMo4 and the developed TRIP is shown in table 1.

| Table 1. Chemical composition of the developed material TRIP and the reference steel 42CrMo4 |
|-----------------|-----------------|------------------|
| mass-%          | TRIP            | 42CrMo4          |
| C               | 0.183           | 0.440            |
| Si              | 0.97            | 0.30             |
| Mn              | 2.39            | 0.80             |
| P               | 0.012           | 0.015            |
| S               | 0.018           | 0.022            |
| Cr              | 0.25            | 1.15             |
| Mo              | 0.090           | 0.188            |
| Ni              | 0.019           | 0.080            |
| Al              | 0.02            | -                |
| B               | 0.0018          | -                |
| Cu              | 0.21            | 0.20             |
| N               | 0.0084          | -                |
| Ti              | 0.033           |                  |
| V               | -               | 0.006            |
2.2. TRIP Material

The TRIP steel has in comparison to the 42CrMo4 reference steel a higher Si content (0.97%) to suppress the formation of carbides and to form retained austenite alongside the bainite. The content of the austenite stabiliser Mn (2.39%) forms more retained austenite. Al and N are alloyed to get a grain refinement effect. In comparison to the Q&T reference steel, the C content is reduced to 0.183% and B as well as Ti are added. In order to retard the ferrite and pearlite transformation during cooling and to allow a complete transformation into bainite, B is alloyed. Ti is alloyed to guard the B against the precipitation of BN by forming TiN. This bainitic steel is industrial forged and controlled cooled with an isotherm holding time of 15 minutes at 375°C.

3. Cyclic Material Behaviour

To investigate the cyclic material behaviour of 42CrMo4 and TRIP load controlled tests with constant and variable amplitude loadings with notched specimen as well as strain controlled tests with unnotched specimen are carried out. Outcome of this investigations is the fatigue life under alternating (R=−1) and pulsating load (R=0) and the cyclic stress-strain behaviour.

In order to derive the cyclic material behaviour, strain controlled Incremental Step Tests (IST) [6] are carried out. The used load sequence contains decreasing and increasing amplitudes. The test starts with the maximum strain and the strain will be reduced by a defined increment from turning point to turning point and increasing increments afterwards. An advantage of the Incremental Step Test is the possibility to derive the cyclic stress-strain curve by testing only a single specimen. With these tests the local material behaviour under variable strain amplitude loadings can be derived [7] by using only one single specimen.

3.1. Incremental Step Test results

In comparison of 42CrMo4 static and cyclic stress-strain behaviour a cyclic softening takes place. Hence, under cyclic loading conditions the same load leads to grater deformations. A reduction of 42% between R_{p_{0.2}} and R'_{p_{0.2}} can be determined, figure 1. Cyclic softening behaviour under cyclic loading is typical for all quenched and tempered steels.

The stabilised cyclic stress-strain-curve for the TRIP steel reaches approximately the same level as the static stress-strain-curve. Comparing the static stress-strain-curve with the stabilized cyclic stress-strain-curve a strength increase of 8% between R_{p_{0.2}} and R'_{p_{0.2}} can be determined. Even though 42CrMo4 static material properties are higher than TRIPs material properties, the cyclic properties are significant lower. This underlines the advantages of the TRIP steel in comparison to the basic Q&T-steel especially under cyclic loading. The static and cyclic relevant characteristic values are shown in Table 2.

| Material | R_{p_{0.2}} | R_{m} | R'_{p_{0.2}} | n' | K' |
|----------|-------------|-------|--------------|----|----|
| 42CrMo4  | 954         | 1090  | 557          | 0.166 | 1563 |
| TRIP     | 734         | 1062  | 682          | 0.179 | 2079 |
Due to the initial loading, a hardening of the TRIP material occurs. This is caused by the austenite-martensite transformation and the creation of residual stresses. This is illustrated by a comparison of the first five stress-strain hysteresis loops of the Incremental Step Tests with the initial loading, figure 2. The initial loading offers a lower stress at the maximum strain than the following loadings. Although the maximum strain decreases turning point to turning point, the achieved stress decreases at the beginning. This effect is illustrated by an Incremental Step Test with the maximum strain amplitude of \( \varepsilon_a = 0.8\% \), but can also be observed at Incremental Step Tests with minor maximum strain amplitudes.

After the hardening caused by the austenite-martensite transformation a cyclic softening take place during the fatigue life. This is illustrated by the constant amplitude test in figure 3 and is normal for martensite microstructures. In summary, the TRIP shows a hardening right at the beginning of the test, following by a cyclic softening. This leads to equal stress-strain behaviour for the initial loading and the cyclic stabilised loading.
The cyclic material behaviour of the quenched and tempered 42CrMo4 is contrary to the TRIP. The cyclic softening starts right from the beginning of the tests, figure 3. As a result the 42CrMo4 cyclic stabilised stress-strain-curve is below the static curve.

3.2. Influence of service loads

For force controlled tests under constant alternating or pulsating loads and service loads specimens with a stress concentration factor of $K_t=2$ are used. A concentration factor of $K_t=2$ is common for many products in the automotive industry. For the service load tests two load spectrums are used. A basic sequence, $H_{LS}=5\times10^4$ cycles, with a Gaussian distribution and a Gaussian distribution expanded with ten 140%-overload cycles are employed. Figure 4 shows the results for the 42CrMo4 under pulsating load ($R=0$). A decreasing fatigue life under the influence of cyclic service loads with overloads comparing to the basic test without overloads can be determined. The Gassner curve with overloads has a decreased cyclic fatigue strength of about 31MPa (11 %) at $N_f=10^7$ cycles compared to the Gassner curve without overloads.

![Figure 2. First 5 IST hysteresis loops for TRIP material](image)

![Figure 3. Softening behaviour of 42CrMo4 and TRIP in comparison to the first hysteresis](image)

![Figure 4. Influence of service loads on 42CrMo4 and TRIP](image)
The influence of overloads on the cyclic fatigue life of the TRIP material is less compared to the 42CrMo4, figure 4b. The results of both test sequences, the basic Gaussian sequence without overloads and the sequence with additional overloads, lie within one scatter band of $T_s=1:1.31$. A fatigue strengths decrease of 16MPa (5\%) can be determined at $N_f=10^7$ cycles.

For the fatigue life approach with the usage of the linear damage accumulation of Palmgren-Miner [8, 9, 10] in form of the Haibach modification [11] the knowledge of the characteristic damage sum is necessary. The characteristic damage sum $D_C$ describes the relation between the experimental and the numerical approached fatigue life using the theoretic damage sum $D_{th}=1$. Inputdata for the fatigue life approach are the Wöhler curve and the load spectrum. The formula for $D_C$ is shown below, formula 1.

$$D_C = \frac{N_{\text{experiment}}}{N_{\text{numerical}}}$$

Based on these fatigue tests the damage sums for the 42CrMo4 is constant over the load level but depends on the load sequence and occurring mean stress. A result of these damage sums are Wöhler- and Gaßner-curves with equal slopes. In contrast, for the TRIP material the characteristic damage sums depend on the load sequence, mean stresses and load level. For this reason the slope of the Gaßner-curve is steeper as of the Wöhler-curve, hence the characteristic damage sum increases with rising nominal stresses.

The linear damage accumulation evaluates the fatigue of the 42CrMo4 for Gaßner tests with overloads higher than the experimental test delivers. This leads to a decreasing damage sum for tests with overloads compared to the tests without overloads. In contrast, the characteristic damage sum for TRIP tests with overloads is above the damage sum for tests without overloads. This means that the linear damage accumulation assumes a higher damage because of overloads than in reality occurs. An increasing characteristic damage sum for high amplitudes shows the TRIPs minor sensibility against high stresses like overloads and misusages. The trend of characteristic damage sums for alternating and pulsating Gaßner tests is shown in figure 5. There is evidence that the TRIP effect, austenite-martensite-transformation, is the reason, why the characteristic damage sum for tests under variable amplitudes with overloads are higher than the comparable tests without overloads and why the damage sum increases with rising maximum stresses. At lower stresses, the transformation does not occur. This leads to damage sums $D_C<1$ for low stresses and $D_C>1$ for high stresses.
4. Cooling process TRIP

The microstructure of bainitic steels depends on the cooling strategy from the forging temperature down to room temperature. Different static and cyclic material properties are the result. To quantify the influence of the cooling strategy the cyclic stress-strain-curves for two material states are derived by Incremental Step Tests. On the one hand an industrial forged specimen is cooled at air, which is called TRIP IA, on the other hand a laboratory forged specimen is controlled cooled down with an isothermal holding time of 15 minutes at 375°C in salt baths, which is named TRIP LI, figure 6a. Both specimens are descended from the same basic material, table 1. At a total strain of \(e_{a,max}=0.8\%\) the cyclic fatigue of the isothermal cooled, TRIP LI, specimen is about 30% higher than the air cooled specimen, TRIP IA. The cyclic and static material properties are shown in Table 3.

| Material       | \(R_{p0.2}\) | \(R_m\) | \(R'_{p0.2}\) | \(n'\) | \(K'\) |
|----------------|-------------|--------|-------------|-------|------|
| TRIP LI (isothermal) | 948       | 1280   | 904         | 0.198 | 3092 |
| TRIP IA (air cooled) | 638       | 1141   | 653         | 0.186 | 2078 |

Figure 7b shows static and cyclic stabilised curves for the isothermal holding times 15min, 60min and 240min. It can be observed that the static properties decrease with increasing isothermal holding time. The cyclic material properties are less sensitive to the isothermal holding time. At maximum strain of \(e_{max}=0.8\%\) the static stress-strain-curve curves for 15min and 240min holding time differs by 60MPa. The cyclic stress-strain-curves of 15min and 240min isothermal holding time differs only by 15MPa.

5. Conclusions

With the new carbide free bainitic steel, a forging-steel is developed, which enables the TRIP effect because of the transformation of metastable austenite in the secondary phase of the microstructure to martensite under cyclic loading. The lightweight potential can strengthened though a controlled cooling after forging by avoiding a coarse grained microstructure in the forging part. A controlled cooling route with an isothermal holding time at martensite temperature is preferred. The isothermal holding time should not last too long to set up good static and cyclic properties.
Once the TRIP effect is initiated by high local stresses caused by an overload or misuse, residual stresses are formed and the cyclic strength increases. Hence overloads have only a light effect on the fatigue life of TRIP under service loads. This is demonstrated by the tie rods material behaviour under variable amplitudes as well. To consider the TRIP effect during the numerical fatigue approach a load depending damage sum can be used, for quenched and tempered steels a constant damage sum depending of alternating or pulsation load should be used.

Carbide free bainite forging steels have the advantage of a short production line in contrast to the 42CrMo4 Q&T steel, because an additional heat treatment after forging can be left out.

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