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Fatigue behavior of bainitic and martensitic super clean Cr–Si high strength steels

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ABSTRACT

This study compares the fatigue behavior of quenched/tempered and austempered super clean Cr–Si high strength steels (HSS). The microstructure of the quenched and tempered steel consisted of tempered martensite and that of the austempered steel, predominantly lower bainite. Steel samples that were given the two types of heat treatments were fatigue tested in the high cycle fatigue (HCF) regime ($10^5 < N_f < 10^7$) and just entering the very high cycle fatigue (VHCF) regime ($N_f > 10^7$). Fatigue crack initiation and propagation modes in samples given the two types of heat treatments were similar. However, those with the lower bainite structure performed better at the highest stress amplitude (500 MPa) used in the study and this was measured in terms of total fatigue life. At lower stress levels (475 MPa and 450 MPa) the total fatigue life of both samples tended to be similar.

1. Introduction

Increasing demand for quality automobile components has resulted in increased life expectancy of certain components that undergo fatigue processes, and these include engine and suspension springs, besides other automotive components. This in turn has led to studies conducted in very long life cycle regimes, beyond 10^7 cycles, where the classic fatigue limit in metallic materials is defined, known as very-high cycle fatigue (VHCF) regime [1], as enshrined in the Second International Conference on VHCF, held in Vienna in 2001.

The lifetime or durability of a component is of great importance in any project. The current rate of incidence of mechanical fatigue gives this study considerable importance; however, in most cases, despite of the serious work from OEM's, their quality indicators are not disclosed for reasons of confidentiality and eventual negative marketing. Thus, forecasting a minimum number of cycles before failure or fracture is required during the development of new products. Several techniques have been used to predict with relative accuracy the fatigue life of components subjected to VHCF regimes of fatigue, most of them being based on empirical methods. Consequently, fatigue tests need to be carried out in laboratories despite the high cost of testing.

The number of published papers dealing with fatigue mechanisms in mechanical components in the VHCF regime is sparse and inconclusive, probably because most of the studies were performed by industrial laboratories that restrict disclosure for strategic reasons. Difficulties with respect to detection and measurement of crack growth rates at the early stages, a critical factor for this class of products, as well as the long test durations (literally years in some cases) may have further contributed towards the limited information being available. To reduce test duration new methods have been developed and these use high frequency ultrasonic testing equipment.

Although many published papers report better performance of austempered steels with lower bainite microstructures compared to quenched and tempered steels, with the same hardness [2–4] there are no published papers studying the mechanical behavior of austempered valve springs made of "*super clean*" Cr–Si high strength steels with bainitic microstructures.

In this context, the goal of this study is to try to understand the reasons for the different fatigue behavior observed in "*super clean*" Cr–Si HSS valve spring samples that were quenched and tempered versus those that were austempered.

2. Materials and methods

2.1. Characterization of samples

The material chosen for our studies was a Cr–Si spring steel, as per *DIN EN 54SiCr6* and similar to *ASTM A877* grade, in the form of a wire 3.70 mm in diameter (trade name *OTEVA 70 SC RD40S*). The

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Nomenclature

HSS	high strength steel
E	elongation at break
AT	austempering
HCF	high cycle fatigue
γ_R	retained austenite
N_f	total fatigue life
A	ratio of stress amplitude and stress magnitude
*Rp*0.2	conventional yield limit
Rm	ultimate tensile strength
QT	quenching and tempering
VHCF	very high cycle fatigue
τ_{kH}	corrected shear stress amplitude
τ_{kM}	corrected shear stress magnitude
R	ratio of minimum and maximum stress amplitudes

grain size was *ASTM G7.5* and purity degree considered "super clean", i.e., very low non-metallic inclusion content.

A number of samples were used to enable statistical treatment of the experimental results and were as per specific recommendations for experiments involving fatigue processes [5]. The samples were manufactured in the form of helical springs with flat and parallel ends. Fig. 1 shows the samples (valve springs) and respective drawing.

The spring design [6] was according to a specific standard for spring construction, *DIN EN 13906-1*. The spring was "cold" wound from a hardened wire. The initial heat treatment of both samples involved austenitizing at 850 °C. One of the samples was quenched and tempered (referred to as "*QT*") and this was achieved through continuous cooling in oil to 50 °C, followed by tempering in air at 400 °C for 30 min. The other sample was austempered (referred to as "*AT*") and this was carried out by continuous cooling in a salt bath followed by holding at 290 °C for 25 min and then air cooling to room temperature. Both the samples were then double shot peened (with 0.6 and 0.5 mm steel grit) followed by hot pre-setting for 20 min at 130 °C under shear stress of 1100 MPa.

2.1.1. Chemical composition

Chemical analysis of the steel was carried out as per *ASTM E1019-08* and *DIN 51008-1:2004* and the composition is shown in Table 1. The results indicate that the chemical composition fulfills the specification for *54SiCr6* steel according *DIN EN 10089:2003*.

2.1.2. Tensile strength

The results of tensile tests performed as per *DIN EN ISO 6892-1:2009* on the wire that was given the same heat treatments as the springs are presented in Table 2. The values are quite similar for both samples, except for the yield strength, which differed by about 8%. The average values met the standard for manufacturing oil-quenched and tempered springs (*EN 10270 FD SiCr*).

2.1.3. Hardness

The Vickers hardness (HV_{10}) was determined according to *DIN EN ISO 6507-1:2006* and Table 3 shows that the hardness of both samples is similar. Even the deviation was small, indicating that the material was homogeneous.

2.1.4. Microstructure

The microstructures of the *QT* and *AT* samples are shown in Figs. 2–5. The *QT* samples revealed homogeneous tempered martensite while the *AT* samples, a predominantly lower bainite microstructure. The two samples presented heavy plastic deformation on the shot peened surfaces.

2.1.5. Residual stress

Residual stress in the samples was determined from X-ray diffraction measurements and by applying the elastic theory for an isotropic material. The measurements were carried out using the multiple exposures method: sen$^2\Psi$ with Cr Kα; filtered Kβ radiation with Cr Kα anode and a parallel beam in accordance with the *Measurement Good Practice Guide* [7]. The stress magnitudes are nearly the same at the surface as shown in Fig. 5, but the profiles show light differences in the depth at which the compressive stress is maximum.

2.1.6. Retained austenite

The amount of retained austenite, determined from X-ray diffraction measurements, is shown in Table 4. While the quenched and tempered microstructure shows 1.4% of retained austenite, the austempered microstructure shows around 7.2% of retained austenite.

2.2. Experimental procedure

The fatigue tests were performed using a bench test for springs that was driven by an electric motor as shown in Fig. 6. Twelve samples can be tested simultaneously. Frequency sensors were used to detect the occurrence of fracture. Stress amplitudes were changed by mechanically adjusting an eccentric shaft.

The total fatigue life (N_f) was determined by finding the number of cycles required for fracture to occur in 48 samples, divided into 3 groups of 6 coils for each heat treated condition. The corrected stress amplitudes τ_{kh} were approximately 450, 475 and 500 MPa. The terminology and the stress calculations follow the conventions used for specific fatigue tests with helical springs [4,5].

3. Results and discussion

3.1. Crack initiation

The cracks started sub superficially in all samples at an average depth of approximately 130 μm from the inner face of the coil in a plane at 45° with the longitudinal axis. Fig. 7 shows typical fractures and the arrow indicates the crack's origin. In all samples, crack initiation was non-inclusion induced, typical of high purity steels.

3.2. Total fatigue life

The average values of the number of cycles required for fracture or total fatigue life (N_f), the corrected shear stress amplitude (τ_{kH}), the corrected shear stress magnitude (τ_{kM}) and related test parameters (A) the ratio of stress amplitude to stress magnitude and (R) the ratio of minimum and maximum stress amplitudes, are shown in Tables 5 and 6.

The τ_{kH} and N_f were analyzed in Fig. 8. Regression analysis was applied to both samples with a coefficient of determination (R^2), which shows that the most appropriate correlation model is logarithmic.