FATIGUE DAMAGE IN AISI/SAE 8620 STEEL

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Abstract. Step-stress experiments are described in which the fatigue damage of an AISI/SAE 8620 steel is found to vary with stress sequence application. The fatigue behavior is studied by using experimental results of Fatigue Limit Resistance before and after imposing damage on several specimens. The influence of the order of application of various stress levels was investigated. For this purpose, increasing and decreasing stress sequences with four steps were applied on the specimens. Besides, damage evaluation was also performed using Barkhausen effect.

Keywords: Fatigue damage, cumulative damage, step-stress tests, fatigue failure, Barkhausen noise.

1. Introduction

Fatigue failure can take place abruptly and cause serious damages. Therefore, a method to forecast or to follow the fatigue damage plays an important role in the design of components and machines. In many engineering applications, the service fatigue load amplitudes imposed on these components may be expected to vary in some way during the service life. Such variations prevent the direct use of S-N-Curves, which are developed for constant stress amplitudes. Thus, it becomes important to have available a theory (or theories) validated by experiments, that allow to determine the fatigue life and/or fatigue resistance for components under conditions of varying load amplitudes.

It has been known (Collins, 1993, Fatemi and Yang, 1998) that the fatigue lives for specimens and components subjected to variable amplitude loads are bellow the fatigue life predicted using constant amplitude test results. One of the reasons for this fact is that operation at any stress causes fatigue damage, that is, leads to a reduction of the strength due to the creation and propagation of discontinuities in the material. The need of damage evaluation has been an important task in fatigue analysis (Lemaitre and Dufailly, 1987 and Lemaitre, 1984). The extension of this damage depends on the number of cycles (n) under a stress (σ_1) and on the total number of cycles (N) required to produce failure of an undamaged specimen, at the same stress (σ_1). Several different cumulative damage theories have been proposed for assessing fatigue lives under variable amplitude loads. Among these, the linear damage theory (Palmgren-Miner) is the most used. Fatigue damage (D_i) can be calculated from Miner's linear damage rule by using the Eq. (1). At failure, the total damage for service history should equal to 1, or

$$D = \sum_{i=1}^{N} D_i = 1 \qquad (1)$$

The advantage of Miner's rule (Eq. (1)) is due to its simplicity. The relationship n/N is a measure of damage, which is linear with N. Other theories have been proposed to approximate the nonlinear relationship between damage D and cycle ratio (n/N) (Collins, 19935 and Fatemi, 1998) and to estimate the value of damage but, often without practical application (Rice, 1997 and Yang et al, 1997).

Among other methods, Barkhausen noise measurements can also be utilized to perform fatigue damage evaluation (Tomita et al, 1994, Yuan et al, 1996 Furuya et al, 1992). Barkhausen noise measurement is a non-destructive method for stress or micro-structural analysis (Sipahi et al, 1993). A magnetic material, like ferric steels, consists of magnetic domains, in which the magnetization is saturated and directed parallel to a certain crystallographic direction. The easy direction of magnetization in bcc-metal is <100> (Sipahi et al, 1993). Domains are separated from one another by boundaries, across which the direction of magnetization changes from 180^0 or from 90^0.

In demagnetized condition the magnetic moments of the domains average to zero. Under an applied magnetic field the domains with their direction of magnetization parallel to (or near) the direction of external magnetic field become preferred and they grow at the expenses of the other domains, which takes place by the movement of 180^0 walls. Consequently, the induction of a material increases. This movement is not, however, continuous due to several obstacles (dislocations, inclusions, cracks, etc) in lattice. These abrupt changes in induction induce voltage pulses, a noise like signal, in a coil places on or near the surface of a dynamically magnetized material. This signal is called Barkhausen noise, and the amplified voltage pulses can be recorded and analyzed.

Cyclic loading causes the development of special dislocation structures and cyclic softening or hardening, depending on a material and loading level, before crack initiation and propagation take place. These changes in microstructure cause changes in Barkhausen noise during the fatigue life, which is expected to be proportional to fatigue damage (Tomita et al, 1994, Yuan et al, 1996 and Furuya et al, 1992).

The increased importance of economic considerations in structural part design necessitates a critical evaluation and selection of competing materials by design engineers. The AISI/SAE 8620 steel is very used in mobile and nuclear industries. It is used to manufacture several components as gear shafts, camshafts and crossheads. Thus, it is important to have a deeper comprehension of the mechanical behavior of this steel, when subjected to fatigue. Several step stress rotating-bend type fatigue tests (with variable loading amplitudes) have been conducted on smooth specimens of this steel AISI/SAE 8620 with the purpose of determining the fatigue damage of this material. Different cumulative damage theories and experimental methodologies were used for assessing fatigue damage. These results will be the basis for future studies of continuum damage mechanisms on this steel.

2. Experimental Methodology

2.1 Materials

Fatigue specimens of normalized AISI/SAE 8620 steel were made according to ASTM E 466-96, as shown in Fig. 1. Finish grinding was carried out to achieve a surface finish $R_A = 0.020 \pm 0.005$ μm in the gauge length.

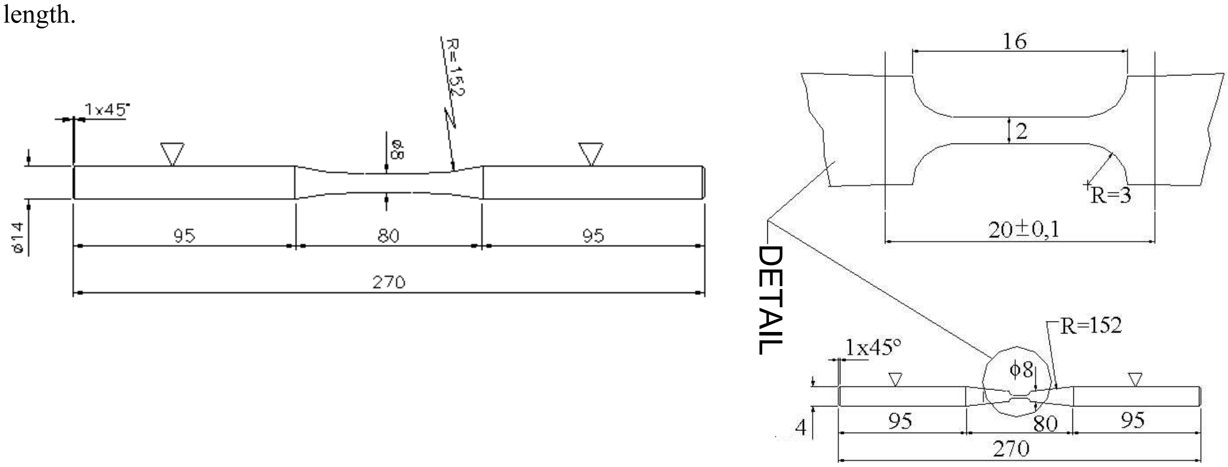

Figure1. Fatigue Specimen (Dimensions in mm) – Rotating-bending for step-stress fatigue test (left); Axial for Barkhausen measurements (right)

The microstructure of the experimental material is shown in Fig. 2. The material is characterized by a microstructure comprising ferritic and pearlit.

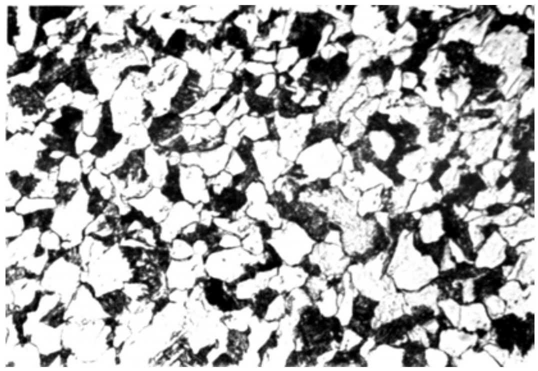

Figure 2. Microstructure of normalised AISI/SAE 8620 steel (500X)

2.2 Mechanical Testing

Tensile tests were performed on a tensile testing machine (INSTRON) with head speed of 0.002m/min, at room temperature (22 ^{o}C) according to ASTM E-23.

Vickers hardness tests were performed according to ASTM E-92 on a testing machine Wolpert using a square-base diamond pyramid indenter with angle equal to 136^{0},and applied load of 196 N. Microhardness tests were performed on a Leitz-Wetzlar machine, model Durimet, using load equal to 1.96 N. All specimens were carefully polished.

Fatigue Tests

Step-stress fatigue experiments were carried out at room temperature, applying a cyclical frequency of 58Hz, with mean stress equal to zero (R=-1), on a rotating-bending fatigue testing machine of the constant bending moment type. The specimens are subjected to a constant bending moment all along its gauge length (80 mm according to Fig. 1a) between the inboard bearings. The specimens were refrigerated to maintain the temperature constant equal to 23±2 ^{o}C during the test.

Barkhausen fatigue damage measurements were performed on an Instron servo-hydraulic test system at room temperature (23±4 ^{o}C), using the specimens showed in Fig. 1b. Sinusoidal load cycling at a stress ratio of R = 0 and a frequency of 40Hz was used for these tests.

Four different step-stress fatigue test types were performed: Increasing stresses, decreasing stresses increasing and decreasing stresses -Type 1, and increasing and decreasing stresses -Type 2.

Four Steps Test – Increasing Stresses: The first specimen is mounted on the machine and the refrigeration system is turned on. The machine runs until the intended cycles number n_1, related to the first stress σ_1, is reached. The machine is turned off, another stress value (σ_2) is applied and the machine runs again, until the cycle number (n_2) is reached. The test continues until the last step (last stress value) is reached. This procedure is shown in Table 1.

Table1 - Four steps test – Increasing stresses

Sequence	Stress (MPa)	Cycles Number (n)
1	198	195,983
2	217	100,512
3	236	51,548
4	259	22,970

Four Steps Test – Decreasing Stresses: The procedure is identical to the preceding test. However, the sequence of application of the stresses is according to Table 2.

Table 2 - Four steps test – Decreasing stresses

Sequence	Stress (MPa)	Cycles Number (n)
1	259	22,970
2	236	51,548
3	217	100,512
4	198	195,983

Four steps test - Increasing and Decreasing stresses test - Type 1: The procedure is identical to the preceding tests, with the sequence of application of the stresses according to Table 3. In these tests, the operation at the fourth (and last step) has been continued until failure occurred.

Table 3 - Increasing and Decreasing stresses test - Type 1

Sequence	Stress (MPa)	Cycles Number (n)
1	259	25,000
2	198	200,000
3	236	60,000
4	217	failure

Four steps test - Increasing and Decreasing stresses test - Type 2: These tests are similar to the above described tests type 1. However, the sequence of applying stresses is according to Table 4. Also in these tests, the operation at the fourth (and last step) has been continued until failure occurred.

Table 4 - Increasing and Decreasing stresses test - Type 2

Sequence	Stress (MPa)	Cycles Number (n)
1	198	200,000
2	236	60,000
3	217	100,000
4	259	Failure

S-N-P-Curves: Fatigue curves were determined by testing several undamaged specimens at different cyclic stress amplitudes. Stress-life (S-N) curves for 1% failure probability (or 99% reliability) were drawn.

Fatigue Resistance Limit: It was used the staircase or up-and-down method to determine the fatigue limit of the specimens (Collins, 1993). 15 specimens were used for each experiment. The first specimen is tested at a stress level higher than the estimated fatigue limit until it either was failed or was ran out. As run out criterium, it was chosen $2X10^6$ cycles. If the specimen failed before reaching $2X10^6$ cycles, the stress level is decreased by a pre-selected increment and the second specimen is tested at this new lower stress level. If the first specimen ran out, the stress level is increased by the pre-selected increment and the second specimen is tested at this new higher stress level. The test is continued in these sequences, with each succeeding specimen being tested at a stress level that is above or below its predecessor. The obtained data are statistically analyzed according to Collins (Collins, 1993).

Barkhausen evaluation: The device used for Barkhausen Noise (BN) measurement was the Stresstest 2004, Metalelektro® (Metalelektro, Budapest, Hungary). This device consisted of a magnetizing unit, a sensor, a signal conditioner unit (amplifier, hi-pass filter) and a recording unit (A/D converter, Computer). Test specimens are magnetized by an amplified alternating current (sinusoidal wave, 0.6 A, 1 Hz) through the wire wound directly on the specimen. A special clamping fixture was built to clamp the specimen during the BN measurement, as shown in Fig. 3.

Among the parameters of Barkhausen noise (BN) pulse, the Barkhausen noise RMS values were chosen as parameter for evaluating the damage during fatigue loading. The Barkhausen Noise RMS voltage was measured at virgin material and during various cycle numbers (n), under three stress levels (217, 259 e 427 MPa). For each stress level, the number of cycles (n) was divided by the life correspondent to this stress (N), according to the S-N-P curve for 99% reliability.

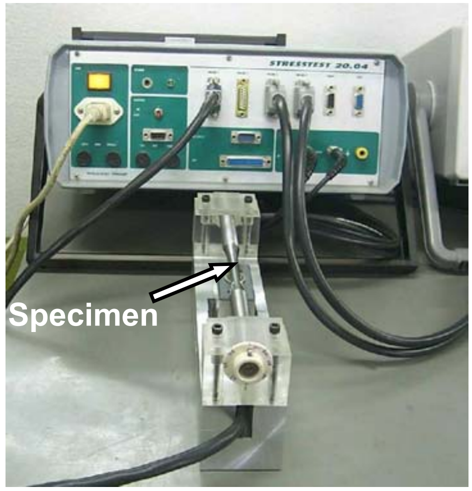

Figure 3. Barkhausen device and clamping fixture for measuring BN

3. Experimental Results

3.1 Preliminary Results

The mechanical properties of SAE 8620 steel are summarized in Table 5.

Table 5: Mechanical properties of SAE 8620 steel

Ultimate Tensile Strength - σ_{UTS} (MPa)	0,2 Yield Strength $\sigma_{0.2}$ (MPa)	Hardness (HV)	Reduction in Area (%)
602 ± 24	370 ± 10	185 ± 10	39 ± 1

The fatigue limit of undamaged specimens was determined by using the up-and-down method, as shown in Fig. 4. It was obtained a fatigue limit Se = 194± 5 MPa, at $2x10^6$ cycles, to reliability equal to 99%.

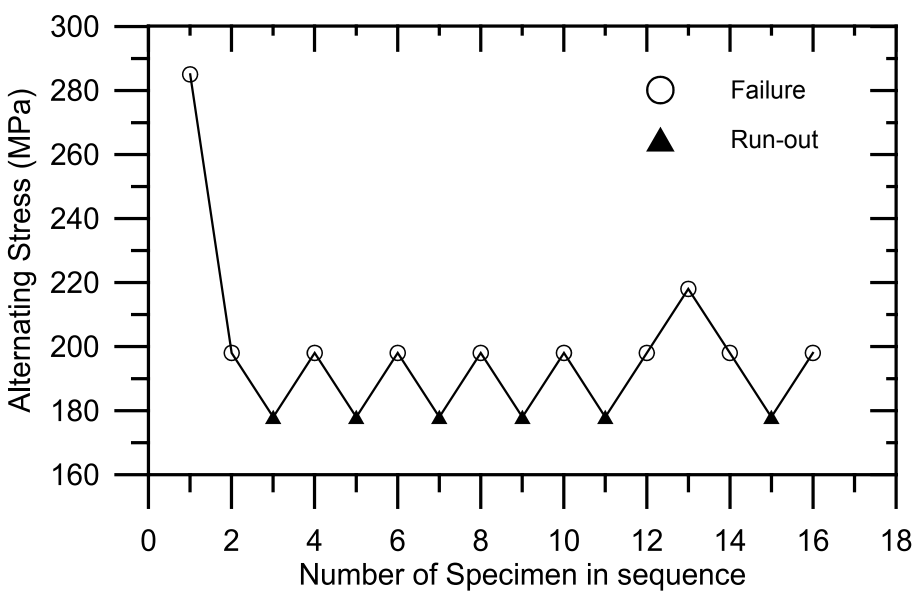

Figure. 4. Up-and-Down Fatigue test of undamaged specimens

The S-N-Curve for undamaged specimens with failure probability equal to 1% (P = 1%), or reliability R = 99% is shown in Fig. 5. The fatigue limit, calculated above, is added to the curve correspondent to P = 1%.

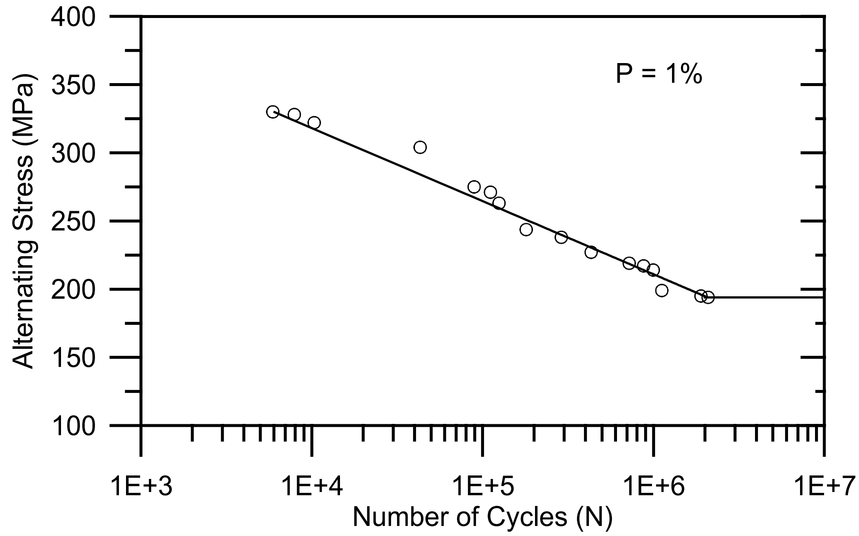

Figure 5. S-N-Fatigue curve of undamaged specimens with failure probability P = 1% or reliability R = 99%

3.2 Damage Accumulation – Step-stress

Eleven undamaged specimens were subjected to increasing stresses according to Table 1. For each stress level, each specimen was subjected to n cycles, which was equivalent to 30% of the total expected life N, according to S-N curve. Thus, the test began with σ_a = 198 MPa. The specimen was subjected to this stress value during n=195,983 cycles, which corresponds to 30% of life N. Then, another stress value (σ_a = 217 MPa) was applied and the machine ran again, until the cycles number n_2 = 100,512 cycles is reached. The test has been continued until the last step (last stress value) is reached.

Another eleven undamaged specimens were subjected to decreasing stresses according to Table 2. This test is similar to the preceding test with increasing stresses.

The fatigue limit resistance of damaged specimens was determined by using the up-and-down method. It was used the specimens of the above experiments, and the influence of damage on fatigue limit (S_e) of the material is shown in Fig. 6. It was observed a large reduction of fatigue limit for both experiment types. The effect of increasing stresses was to decrease the fatigue limit (S_e) by 15%, while decreasing stress tests have caused 25% reduction of fatigue limit (S_e).

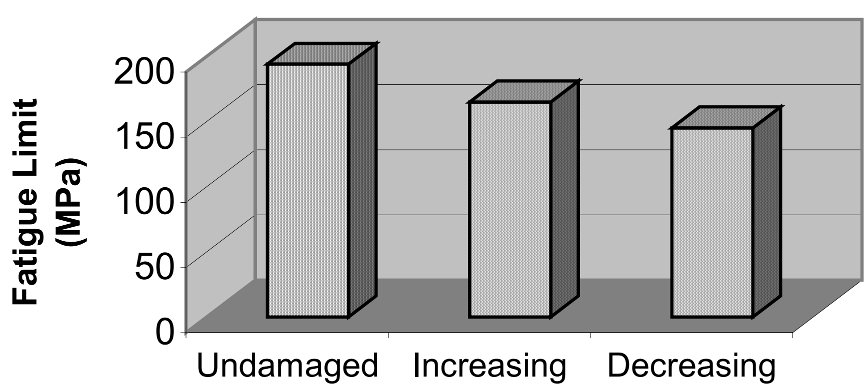

Figure 6. Influence of Fatigue Damage on Fatigue Limit S_e

The influence of fatigue damage on Vickers Hardness for four steps experiments with increasing and decreasing stresses is shown in in Fig. 7. Fatigue damage leads to a decreasing for hardness of the material.

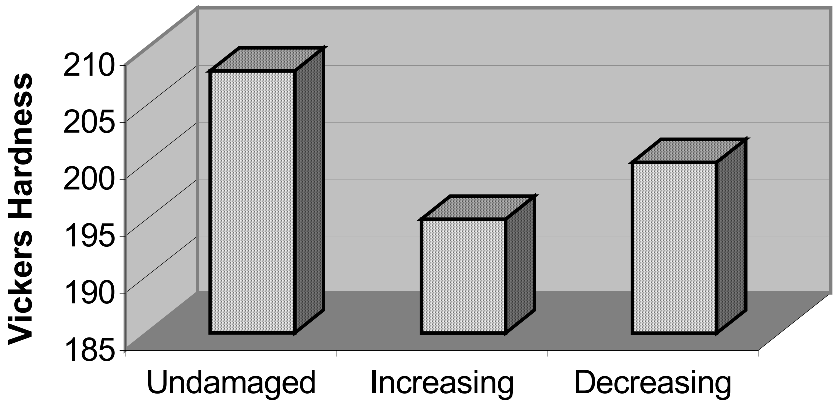

Figure 7. Influence of fatigue damage on Vickers Hardness

For the four steps test - Increasing and Decreasing stresses test - Type 1, it was used six undamaged specimens, according to Table 3. In these tests the operation at the fourth (and last step) has been continued until failure have been occurred. The specimens have been failed with average life equal to (627 ± 159) x 10^3 cycles.

For the four steps test - Increasing and Decreasing stresses test - Type 2, it was also used six undamaged specimens, according to Table 4. In these tests, the operation at the fourth (and last step) has been continued until failure has been occurred. The specimens have been failed with average life equal to (523 ± 269) x 10^3 cycles.

For each experiment, the total damage was calculated according to Miner's Rule (Eq. (1) and Eq. (2)), and the results are shown in Fig. 8. The total damages are similar for both experiment with only increasing or only decreasing stresses. The difference between both experiments is approximately 3%, with increasing stress tests showing greater values. The damages caused by the experiment types with increasing and decreasing stresses in the same test are quite different, as shown in Fig. 8. The damage caused by experiment - type 2 is 60% greater than experiment type 1. The test with increasing and decreasing stresses - Type 1differs from the test wit increasing and decreasing - Type 2 by the position of the greatest stress value σ = 259 MPa. Thus, the test type 2 is similar to test with increasing stresses, which explains the damage value for this experiment type.

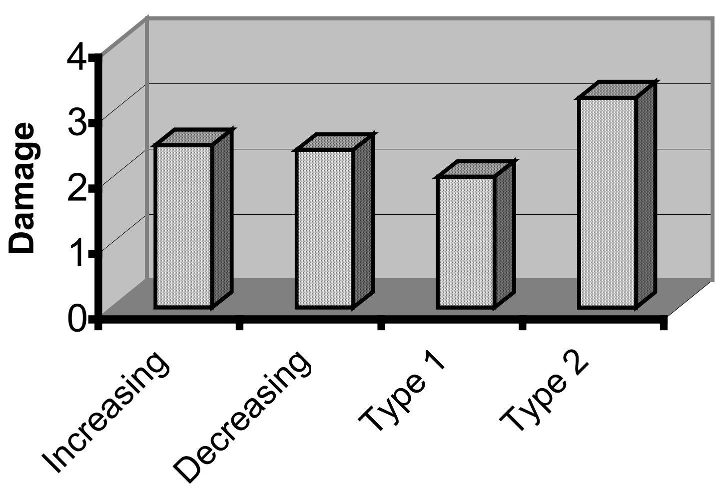

Figure 8. Total damage: Four steps tests

3.3 Damage Accumulation – Barkhausen Measurements

Fatigue damage was also determined using the Barkhausen effect. Experiments have been carried out in which the BN noise is measured as a function of number of cycles, as typically shown in Fig. 9 for alternating stress σ_a = 217 MPa. The Barkhausen noise increases rapidly at begin of test, in the early stage of fatigue life, and then decreases rapidly. With further fatigue cycles, the BN values kept nearly constant.

Besides, the BN measured values resulted in a pronounced scatter in noise values measured. Even in the same specimen a wide scatter was always observed. Thus, the results of all experiments are an arithmetic average of 15 to 20 measurements.

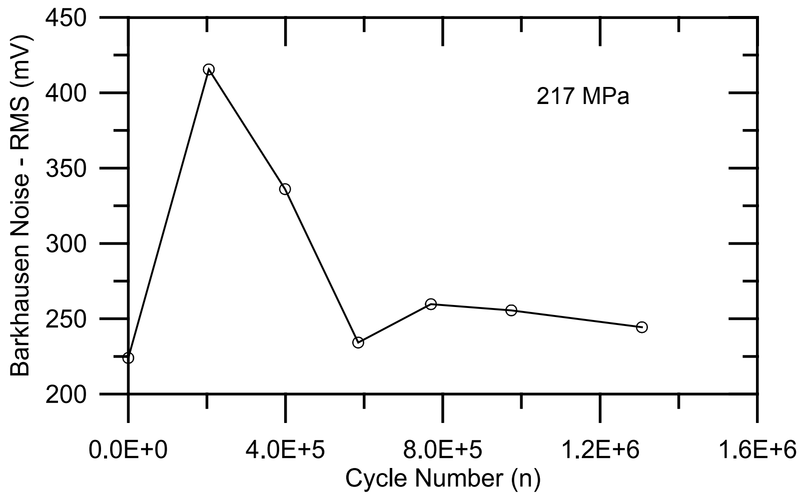

Figure 9. Changes in Barkhausen noise RMS values with number of fatigue cycles

To compare the influence of fatigue cycles under different stress values on Barkhausen noise, the changes of damage with loading cycles were examined by using the ratio of the Barkhausen noise RMS voltage of stressed specimen at the nth cycle number (Vn) to that of virgin material (V_O), that is, it was used the normalized parameter (V_n/V_O). The number of cycles (n) was also normalized dividing it to the total number of cycles that would produce failure at that stress level (n/N). The expected lives (N) were determined from Fig. 6. Typically, the influence of relative cycle number on normalized Barkhausen noise for alternating stress σ_a = 217 MPa is shown in Fig. 12. As expected, the same behavior observed in Fig. 10 is seen again in this figure.

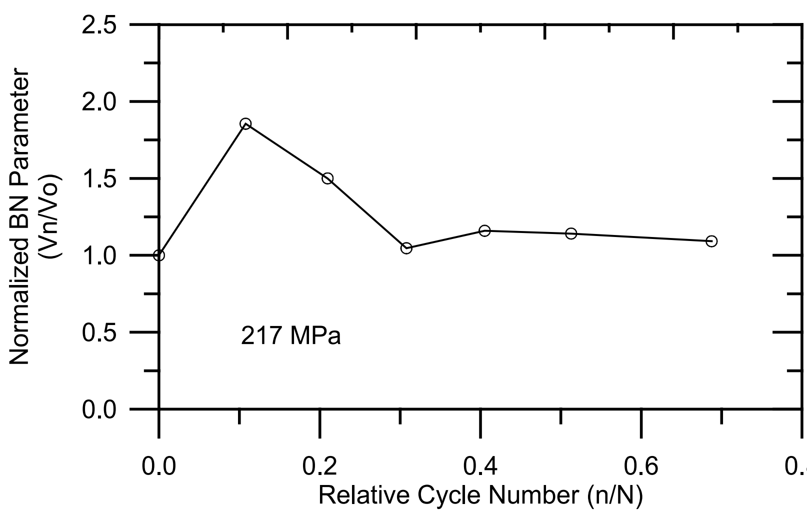

Figure 10. Influence of relative fatigue cycle on normalized Barkhausen noise RMS values

For each stress level, the normalized BN parameters (V_n/V_O) were summed, obtaining the cumulative BN parameter (BN_{SUM}), according to Eq. (24):

$$BN_{SUM} = \sum_{n=0}^{n=n} \left(1 - \frac{V_n}{V_O} \right) \qquad (2)$$

The influence of relative cycle number on cumulative BN parameter, for three stress levels is shown in Fig. 11. The cumulative BN parameter increases with increasing the number of cycles and with stress. As the alternating stress σ_a = 217 MPa is very close to fatigue limit (Se = 194± 5 MPa) of the material, internal microstructures are not expected to change very much. In consequence, the BN values are considered to keep almost constant or to vary just a little with fatigue cycles. Increasing alternating stress values lead to increase the changes in microstructure of the material, and in consequence to increase the Barkhausen noise.

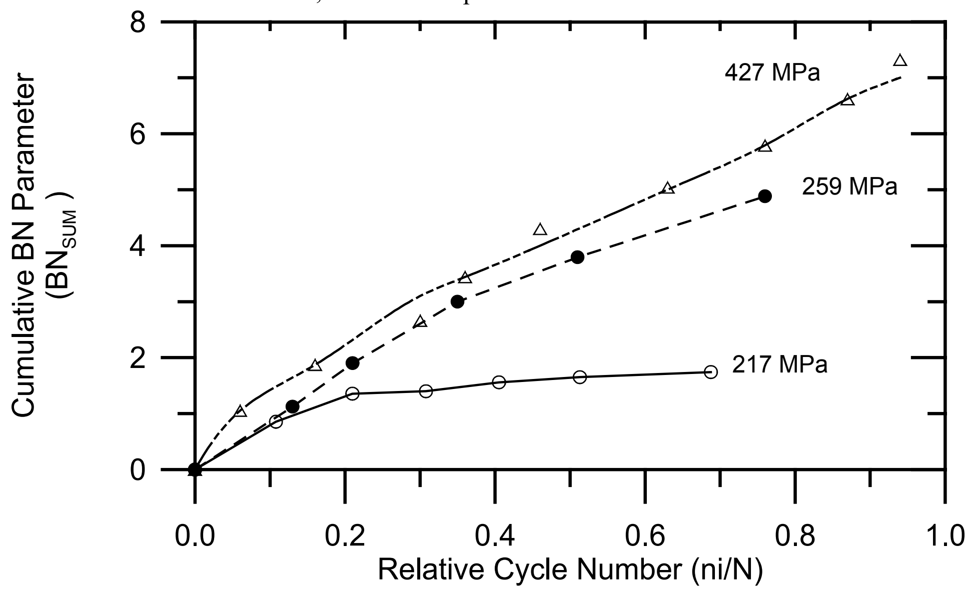

Figure 11. Influence of relative fatigue cycle on cumulative BN parameter

The Barkhausen noise is a magnetic noise signal that is very sensitive to changes of microstructures and to local stress state of the material (Yan and Longxiu, 1996, and Sipahi et al, 1993). Fatigue cause changes in microstructure and leads to a nucleation of cracks in the material. Both changes cause damage in the material. Thus, the variation of Barkhausen noise can be considered a measure of this damage, specially the cumulative BN parameter (V_n/V_O). It is seen from Fig. 11 that for both alternating stress values well above the fatigue limit (σ_a = 259 and 427 MPa), the cumulative BN noise values increase at begin of test non-linearly with fatigue cycles, and then almost linear. This rate decrease of BN voltage with fatigue cycling can be explained by the suppression of the domain wall movements based on the change of internal microstructures. By beginning the test, obstacles in material grow up rapidly with increasing cycle number. With further fatigue cycles there is a tendency of saturation, and in consequence the magnetized domain walls hardly move. As a result, the BN signals decrease with fatigue cycling.

4. Conclusions

From the results and discussions presented above, it can be concluded that:

- Fatigue damage caused a decreasing of fatigue limit, UTS and Hardness for increasing and decreasing four steps experiments.
- The damage values are greater for experiment with increasing stresses. The difference between all values is not large.
- Damage was also evaluated by using Barkhausen noise. Barkhausen noise RMS values increase with number of cycles and with stress.

- Change in BN values were smaller to specimens tester under alternating stress σ_a = 217 MPa, since it is very close to fatigue limit.

5. Acknowledgements

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