FATIGUE RESIDUAL LIFE ASSESSMENT OF IACS W22/2004 GRADE R4 STEEL USED IN THE MANUFACTURING OF MOORING CHAINS

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Abstract. *Classification societies state that the mooring lines shall be periodically inspected, but the only way to assess its residual fatigue life is through mooring chains full scale tests, simulating the service life until the fatigue failure. This full scale test requires specific test facilities involving high costs and a very long period of time to complete a testing program. This work was based in high cycle fatigue testing using the rotating bending technique to the assessment of the material's fatigue life considering four different levels of fully reversed stress ranges. Test samples of an IACS W22/2004 grade R4 steel were taken from a new mooring chain and were cyclically loaded until 20, 40, 60 e 80% of its fatigue life is reached for each one of the studied stress ranges. Tensile tests and hardness tests were performed after the cyclic loading of the fatigue damaged test samples aiming to verify a relationship between fatigue accumulated damage and mechanical properties. With a data base obtained from this relationship it will be possible to implement a new methodology for inspecting the mooring chains with a lower cost and in a shorter period of time improving the reliability of the mooring lines. The mechanical tests performed in the fatigue damaged test specimens demonstrated a poor relationship between the fatigue damage and the modification of the monotonic mechanical properties, however the Vickers microhardness measurements presented some variation with the accumulated damage in the specimen.*

Keywords*: Fatigue, Mooring, Residual life, Damage*

1. INTRODUCTION

Due to geological characteristics the major part of the Brazilian oil reserves are located offshore. This scenario has stimulated the Brazilian industry to develop its own technology to make possible the exploration of the oil and gas reservoirs that are located in regions that can reach up to 2000m water depth.

The Brazilian oil and gas production is mainly based on the semi-submersible platforms and FPSO (Floating Production Storage and Offloading) and the safety of these kinds of exploration units are related to the reliability of the mooring lines. According to Medeiros (2003), the critical component in a mooring line is the mooring chain that needs to be periodically inspected to prevent failures that may compromise the safety of the platforms and avoid the risk to the environment and mainly to the people involved in the operation of these facilities.

In order to provide an adequate safety level to the offshore operations, the classification societies establish a maximum interval of 5 years of operation to the removal and subsequent inspection of the mooring chains. Nowadays the only way to assess the residual life of a mooring chain uses full scale fatigue tests, simulating the service up to its failure. This full scale tests require specific test facilities involving high costs and a very long period of time to complete a testing program and sometimes become unfeasible due to the non availability of test rigs or limited to the loading capacity of the existing ones.

The research programs being conducted comprehend only mooring chains without accumulated fatigue damage (Medeiros, 2003; Barbosa, 2004). Therefore it was decided to startup a research program that aim to establish a criteria to assess the residual life of mooring chains that are in service. As discussed early in this section, the critical factors for the research using full scale tests are related to the test rig availability and the long time required to collect data from a reasonable number of tests to provide statistical reliable results.

Several authors have already established relations between fatigue life for different materials and non-direct measurements such as the measurement of the variations of the elasticity modulus, of the ultrasonic waves propagation and the variation of the microhardness (Lemaitre and Dufailly, J. 1987; Chen and Zhao, 2004). These results indicate that it is possible to predict the fatigue residual life of a mooring chain by performing small scale tests using test specimens from a chain that was previously fatigue damaged during its service life. The development of an experimental program with small scale tests will reduce considerably the costs and the time required to assemble a comprehensive data base that will contribute to increase the reliability of the mooring lines.

This paper focus the development of a methodology capable to provide the prediction of the residual fatigue life of an IACS W22/2004 grade R4 steel used in the mooring chain manufacturing. The work was conducted by performing rotating bending fatigue tests using specimens taken from an integral chain in order to assess it fatigue life. Additional specimens were fatigue damaged up to damage levels of 20, 40, 60 and 80% of its fatigue life and then tensile tested in order to assess for changes on its monotonic mechanical properties and hardness tested using the Vickers microhardness method to evaluate the hardness changes in its external surface.

2. FATIGUE BACKGROUND

It is well known that the fatigue is characterized by the abrupt and unexpected failure of structures and mechanical parts that suffer cyclic loading and may occur even in loading levels bellow to the ones predicted by static loading design criteria (Forrest, 1962).

According to Buch (1988), the fatigue phenomenon may be divided in two different stages governed by distinct mechanisms. The first stage is associated to the nucleation of a fatigue crack and the second one is associated to the propagation of this crack in each loading cycle up to the component's final failure.

The first stage of the fatigue phenomenon is associated to plastic strains, even if these strains are limited to a restrict portion of material and its magnitude is small (Buch, 1988)

According to Rosa (2004), in materials that presents crystalline structure, the plastic strain process is given by the movement of dislocations when the material is submitted to shear stresses. With the movement of the dislocations along the plane with highest shear stress, the condition to the displacement of two atomic planes is created. As the material is cyclically loaded the displacement of atomic plans happen in order to accommodate the plastic strains generated by this loading and the density of these plans increase along the loading generating intrusions and extrusions that will modify the topography of the materials surface (Forrest,1962).

Once the materials surface topography is modified by an intrusion or an extrusion, the presence of this occurrence will promote a local microscopic stress riser making easier to develop further plastic strains in that region (Suresh, 1998).

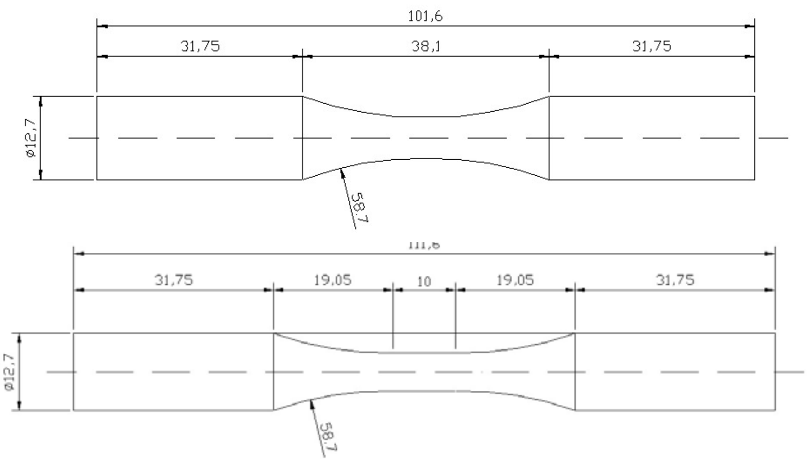
As long as the cyclic load acts in the material a larger number of intrusions and extrusions takes place and start to group forming a feature denominated protrusion that will act as a preferential site for a crack nucleation (Suresh,1998).

From the moment that the crack reaches a critical size the crack propagation stage begins and it will be governed by another phenomenon until the final rupture of the part. The time required for the nucleation of a crack is expected to vary between 70 to 80% of the total fatigue life of a material (Rosa, 2004).

This work will focus on the evaluation of the influence of the modification of the materials' surface topography due to the intrusions and extrusions generated by the movement of the dislocations caused by the cyclic loading and its effects on mechanical properties. The crack propagation stage is not considered in this work.

3. EXPERIMENTAL PROGRAM

The tests were carried out using the rotating bending method adopting a mean stress equal to zero. The selected stress ranges adopted for the test program were 600 MPa, 500 MPa, 400MPa and 300 MPa in order to provide a wide range of stress levels and allow the evaluation of different alternated stress ranges associated to different levels of accumulated fatigue damage. Figure 1 presents the test specimen geometry adopted. It should be noted that the test specimen geometry was adapted from the ASTM-E466-96 standard (ASTM, 2002). Figure 1 shows the adopted geometry with a "gage length" of 10 mm in the center of the test specimen instead of a concordance radius, in order to make possible the measurements of ductility and microhardness. All the specimens were removed from a new chain link.



(a)

(b)

Figure 1 – Fatigue test specimen. (a) ASTM E466-96; (b) Modified for tests. Dimension in mm.

Once the fatigue crack nucleation is intimately linked to the surface roughness of the test surface, all of the test specimens were polished with 1μm diamond paste in order to provide a sound surface roughness.

The S-N curve for the studied material was assessed and is presented in Fig. 2. The assessment of this curve was performed using 5 different test specimens at each stress range in order to provide statistical reliability and allow the definition of the 0.2. 0.4, 0.6 and 0.8 damage levels (associated to 20, 40, 60 and 80% of its fatigue life, respectively) to be considered in this test program.

Figure 3 presents the criteria selected to populate the target damage in each one of the selected stress ranges in order to design the number of cycles that each one of the test specimens was submitted, based on the generated S-N curve calculated as per ASTM E739 standard (ASTM, 2004). Five different test specimens were cycled to each target damage in each once of the test stress range. The test program was composed of a total of 100 test specimens.

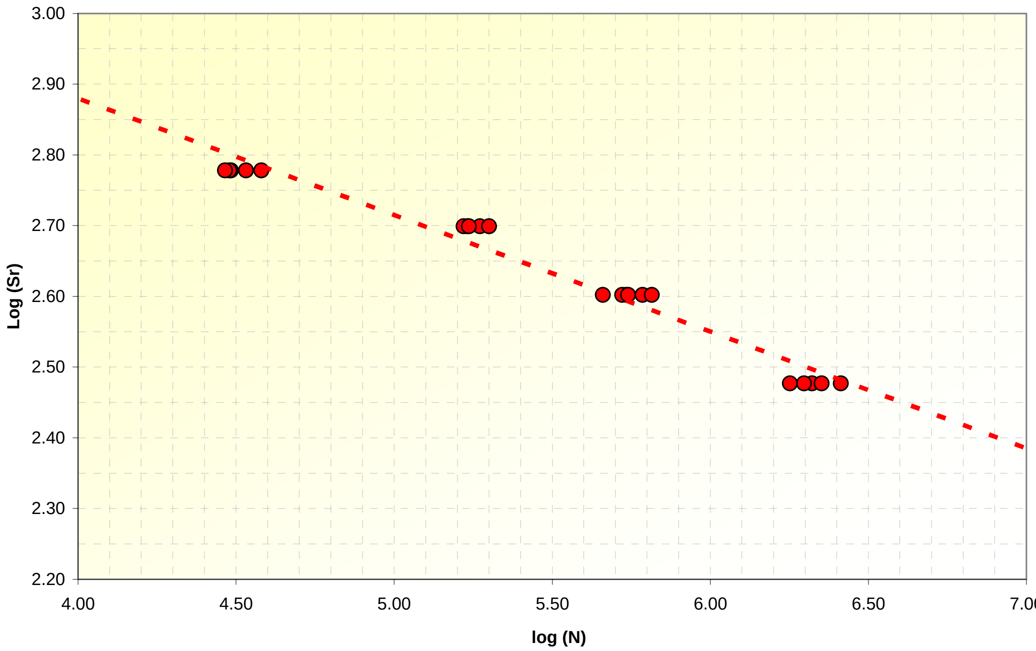


Figure 2 – IACS W22/2004 GRADE R4 SN curve

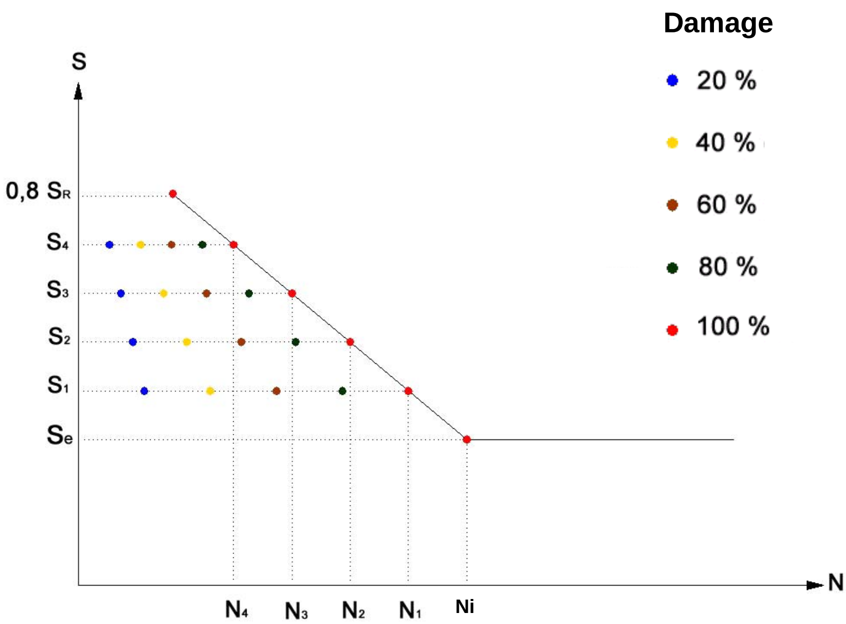


Figure 3 – Fatigue damage design based on the generated S-N curve

3.1 Tensile Tests

From the five test specimens cycled up to the desired damage level in each once of the alternating stress ranges, four specimens were tensile tested in order to evaluate the modification of the monotonic mechanical properties caused by the cyclic loading when compared to the test of the undamaged test specimens. Table 1 presents the mechanical properties of the material that has not experienced cyclic loading and Tables 2 to 4 present the tensile test results for the damaged test specimens.

Table 1 – Tensile Test Results for Undamaged Material

Yield Strength (MPa)	Ultimate strength (MPa)	Reduction of area (%)
816	990	65.6

Table 2 – Tensile Test Results - Yield Strength

Yield Strength (MPa)				
Damage	Reversed Stress Level			
	600 MPa	500 MPa	400 MPa	300 MPa
0.0	816	816	816	816
0.2	832	937	957	966
0.4	771	917	909	970
0.6	911	904	926	958
0.8	893	919	925	941

Table 3 – Tensile Test Results - Ultimate Strength

Ultimate Strength (MPa)				
Damage	Reversed Stress Level			
	600 MPa	500 MPa	400 MPa	300 MPa
0.0	990	990	990	990
0.2	970	987	1020	1014
0.4	990	982	970	1015
0.6	958	984	1007	1022
0.8	887	987	980	998

Table 4 – Tensile Test Results – Reduction of Area

Reduction of Area (%)				
Damage	Reversed Stress Level			
	600 MPa	500 MPa	400 MPa	300 MPa
0.0	65.6	65.6	65.6	65.6
0.2	64.5	68.1	66.0	68.1
0.4	64.3	65.8	66.5	65.6
0.6	65.8	66.3	68.0	68.4
0.8	66.3	66.8	67.7	68.8

The graphic representation of the tensile test results is presented in Figs. 4 to 6 to clearly demonstrate the behavior of the mechanical properties for the fatigue damaged test specimens.

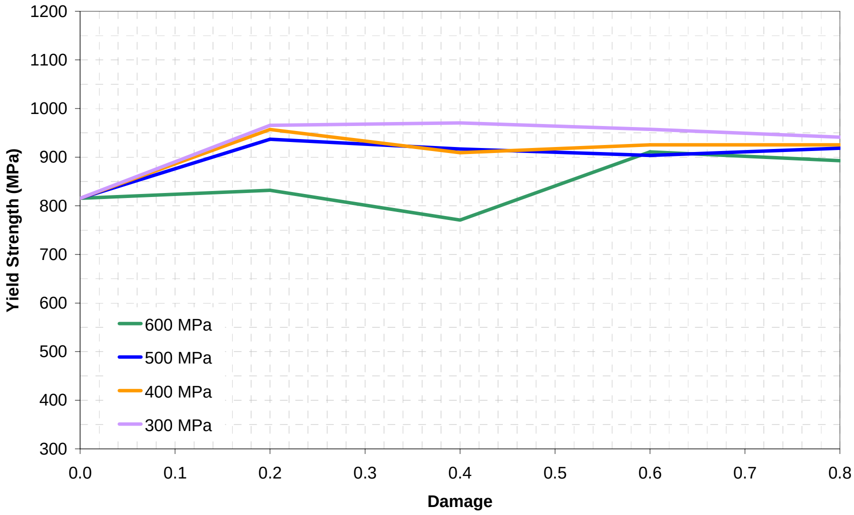


Figure 4 – Tensile test results – Yield Strength

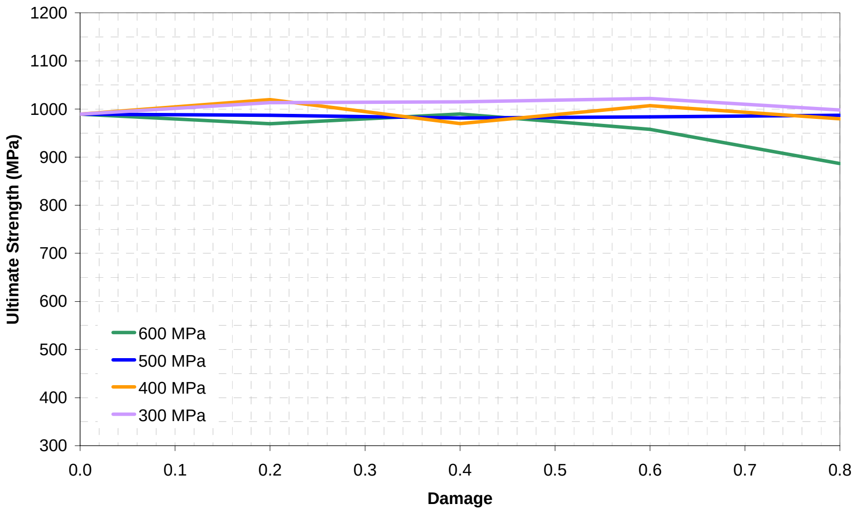


Figure 5 – Tensile test results –Ultimate Strength

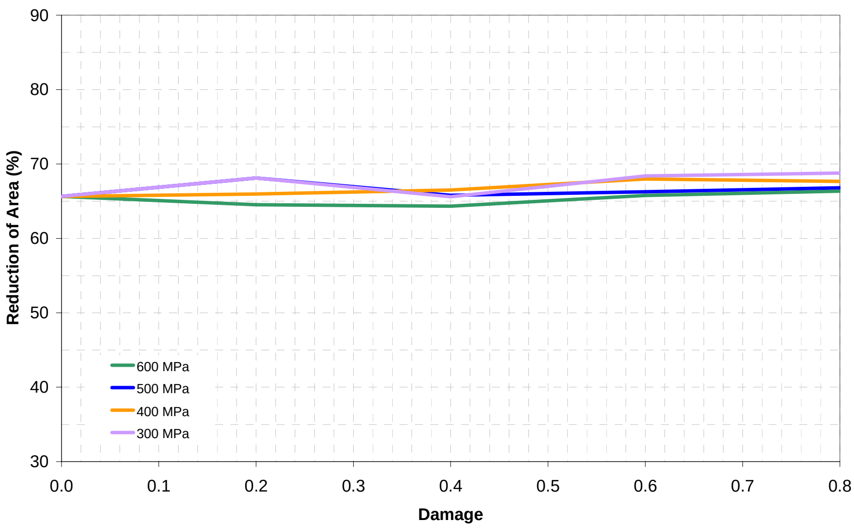


Figure 6 – Tensile test results – Reduction of Area

3.2 Vickers Microhardness Test Results

One test specimen cycled up to the target damage level in each once of the alternating stress ranges had the gage length's external surface hardness tested. The tests were carried out using the Vickers microhardness method with test load of 0.98 N and 30 measurements were performed in each one of the specimens in order to assess a representative average value and the standard deviation of the measurements in each one of the test specimens.

The hardness average values and the standard deviation of the measurements are presented in Tab. 5 and Tab. 6, respectively. The graphic representation of the assessed data is presented in Fig.7 and Fig. 8.

Table 5 – Hardness average value assessed for the fatigue damaged specimens

Vickers Microhardness				
Damage	Reversed Stress Level			
	600 MPa	500 MPa	400 MPa	300 MPa
0.0	324	324	324	324
0.2	322	324	324	324
0.4	320	324	323	324
0.6	317	321	322	322
0.8	313	318	320	321

Table 6 – Standard deviation of the measurements assessed for the fatigue damaged specimens

Standard Deviation				
Damage	Reversed Stress Level			
	600 MPa	500 MPa	400 MPa	300 MPa
0.0	5.18	5.18	5.18	5.18
0.2	4.34	5.30	4.23	4.38
0.4	5.41	5.85	5.44	5.06
0.6	7.43	6.34	7.92	6.17
0.8	7.23	7.42	7.42	6.99

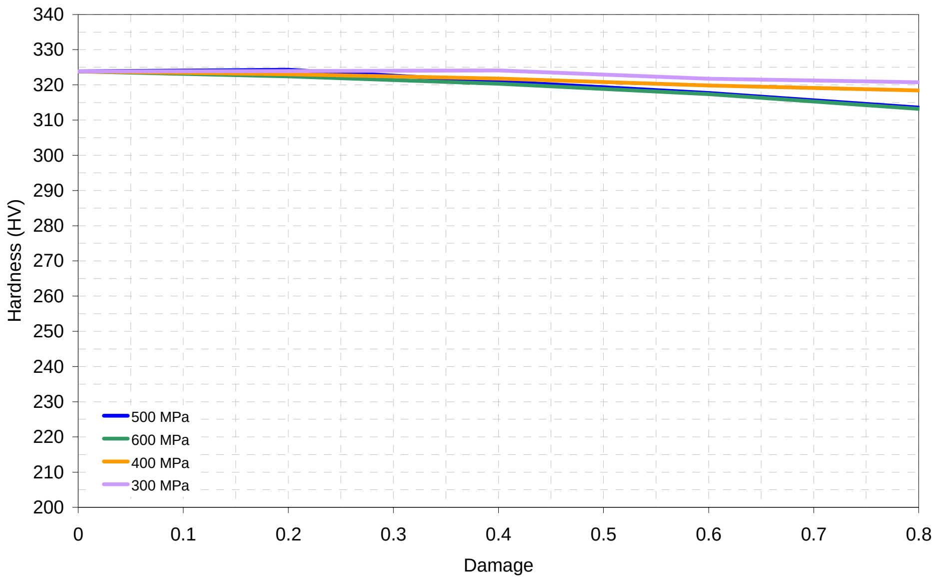


Figure 7 – Hardness average values for the fatigue damaged specimens

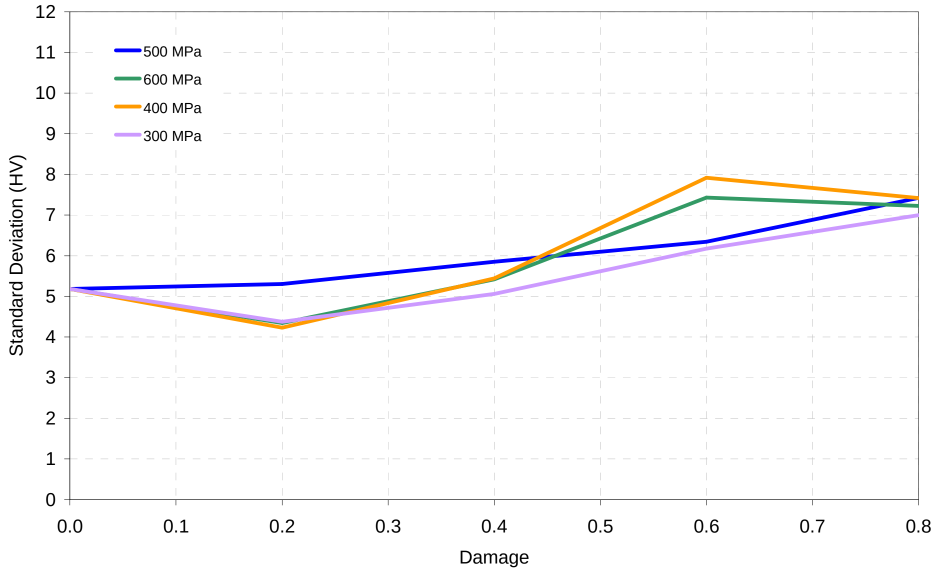


Figure 8 – Hardness standard deviation for the fatigue damaged specimens

4. DISCUSSION

The monotonic tensile tests performed on the fatigue damaged test specimens haven't presented any consistent evidence of the modification in the mechanical properties of the material related to the increase of the damage level experienced by the material. The only significant modification was found for the yield strength that presented a slight modification that can be associated to the inherent variation to the test method.

The tensile test may not present the required sensibility to detect or evaluate the modification of the mechanical properties once it represents the average value of the tested material and the stress level varies along the specimen diameter during the rotating bending tests.

However the hardness tests presented a tendency in the reduction of the materials superficial hardness and an increase in the hardness measurement standard deviation. This is due to the fact that the Vickers microhardness tests using a test load of 0.98 N provided a better evaluation of the microscopic plastic strains which develops during the cyclic loading and were able to detect the change of the material's surface topography generated by the creation of the intrusions and extrusions associated to the crack nucleation process.

5. CONCLUSION

A methodology capable to provide the prediction of the residual fatigue life of mooring chains based on small scale tests is proposed. Rotating bending fatigue tests using specimens taken from a new IACS W22/2004 grade R4 steel integral chain were developed to prescribe fatigue damage levels of 20, 40, 60 and 80%. In order to assess changes on monotonic mechanical properties and external surface hardness, tensile tests and Vickers microhardness test were developed.

Despite that the amount of specimens used in this study is not sufficient to elaborate or propose any kind of clear mathematical relation between the accumulate damage and the modification in the material hardness, the results indicate that the Vickers microhardness technique is able to capture the variation of the mooring chain fatigue residual life. A more comprehensive test program with a larger number of test specimens to be hardness tested shall be carried out to allow the definition of a relationship between the residual fatigue life and the hardness characteristics modifications for the studied material.

6. ACKNOWLEDGEMENTS

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