INVESTIGATION OF FATIGUE PROPERTIES THROUGH MINIATURE SPECIMEN TEST TECHNIQUES

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Abstract

One method for evaluating the mechanical properties of components in operation is the use of methods that focus on the use of miniaturized test specimens. Basic properties used mostly for the service life evaluation are tensile strength, impact notch toughness or impact notch toughness transition curve, fracture toughness, creep and high cycle fatigue. This research explores high cycle fatigue and tensile tests with the use of on standard test bars and sub sized samples obtained by semi destructive sampling. The first part of the testing was focused on the micro-tensile tests. The tensile tests were carried out to find out the initial stress level. In this research were studied the mechanical properties on steel X1CrNiMoAlTi 12-11-2 and 16 343. The results from micro-tensile tests and high cycle properties show excellent agreement with each other. Therefore, this fact leads us to conclusion that the miniature specimen tests can replace the fatigue testing under certain circumstances. The use of miniature specimen brings many advantages such as cost reduction, non-invasive affection of the material, time saving.

Keywords: High cycle fatigue, tensile test, small size samples techniques, Digital Image Correlation (DIC)

1. INTRODUCTION

The Residual lifetime estimation and early detection of possible risks of mechanical equipment failure and structure is a key question for reliable operation of industrial plants. Currently, this issue is particularly critical for the power stations and petrochemical plants that are approaching their designed end of life. The remaining service life can be evaluated using standard tests, but also by using semi-destructive techniques using mini samples. One method for evaluating the mechanical properties of components in operation is the use of methods that focus on the use of miniaturized test specimens These methods maintain minimal material demands without requiring previously established correlations or at least they use a much more reliable type of correlation (without necessity to measure wide range materials). The above mentioned miniaturized testing techniques have been verified. These testing methods using miniaturized specimens maintaining testing loading mode are being developed and successfully applied and this paper shows results of miniaturized standard specimens testing in the field of micro tensile test and high fatigue test. Using advantage of application of the newest measurement equipment and techniques, miniaturized samples can be successfully used providing much more reliable data than presently used methods using correlation approach. Furthermore, such a data can be used as an input data influence on FEM simulation or for calibration of fracture locus. The experimental program here is performed on X1CrNiMoAlTi 12-11-2 steel and 34CrNiMo6 steel. There are performed standard tensile tests and high cycle fatigue tests as well as small size tests. Small size samples are machined from the experimental material extracted by portable sampling device. The device is used for material extraction from real in service components in order to simulate real component service life assessment, where material has to be extracted without the component destruction. Results obtained are very positive, very good agreement between standard size and small size specimens is found for the material investigated introduction should provide a clear statement of the study, the relevant literature on the study subject and the proposed approach or solution.

2. EXPERIMENTAL MATERIAL

It Stainless steel X1CrNiMoAlTi 12-11-2 and 34CrNiMo6 (or 16 343 or 1.6582) were selected for the experiment. X1CrNiMoAlTi 12-11-2 stainless steel is precipitation hardened stainless steel of very high purity. It exhibits excellent mechanical properties in the longitudinal and transverse directions and also excellent balance between strength and toughness properties, and very high fatigue resistance, too. 34CrNiMo6 is high-strength steel for highly stressed machine parts. In a refined state, the ratio of strength to yield strength is very favourable high toughness High toughness prevents the spread of fatigue cracks.

3. STANDARD TENSILE AND HCF TESTS

As a verification of sub-size specimens test results, the standard tensile and high cycle fatigue tests were carried out on the material investigated. All tests were carried out at room temperature. Tests were conducted on servo-hydraulic testing system Inova with a load capacity of 200kN. Tensile test strain rate of $0.0004s^{-1}$ was applied. High Cycle Fatigue (HCF) tests were conducted on the magneto-resonant fatigue testing machine Vibrophore Rumul for loads up to 250 kN in tension-compression mode with load ratio of R=-1. Batch of 10 test-pieces with diameter of 8 mm loaded at various stress levels was tested. Tests were carried out in load control mode at frequency of about 120 Hz. Each test was terminated at specimen failure or after reaching 10^7 cycles. The Wöhler curve was compiled on the basis of measured values. The fatigue limit σ_C was evaluated as the highest value at which the sample didn't crack even after 10^7 cycles.

4. MATERIAL SAMPLING AND SUB-SIZE SPECIMENS

In the case of sub-size specimens testing, a special procedure was applied to the experimental material extraction, simulating a real process of the material extraction from in service components. All sub-size specimens were subsequently machined out of such an extracted material. The size of specimens was adjusted to fit into the available volume of the experimental material that is possible to extract in semi-destructive manner. Tensile tests and mainly high cycle fatigue tests were carried out on these test-pieces. A portable electric discharge sampling equipment (EDSE) features easy handling, low-pressure coolant circuit (minimize spatter), quick electrode release and replace and a possibility to design own geometry and last but not least high sampling efficiency. Due to this fact the device is suitable for an in situ sampling out of in-service components, **Figure 1**. The influence of electro-erosive machining on the work piece is demonstrated in the **Figure 2**. The depth of the affected layer appeared to be slightly less than 10 μm thick.

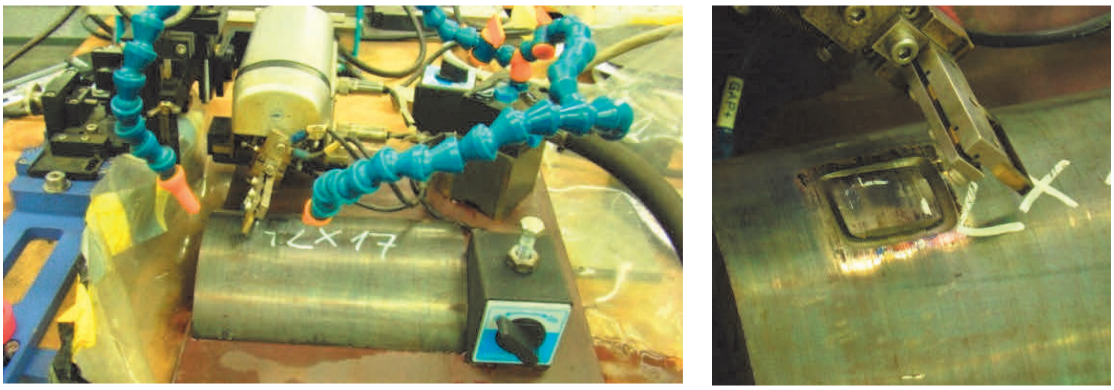


Figure 1 The set-up of EDSE; whole device set up on the left and extracted piece detail on the right

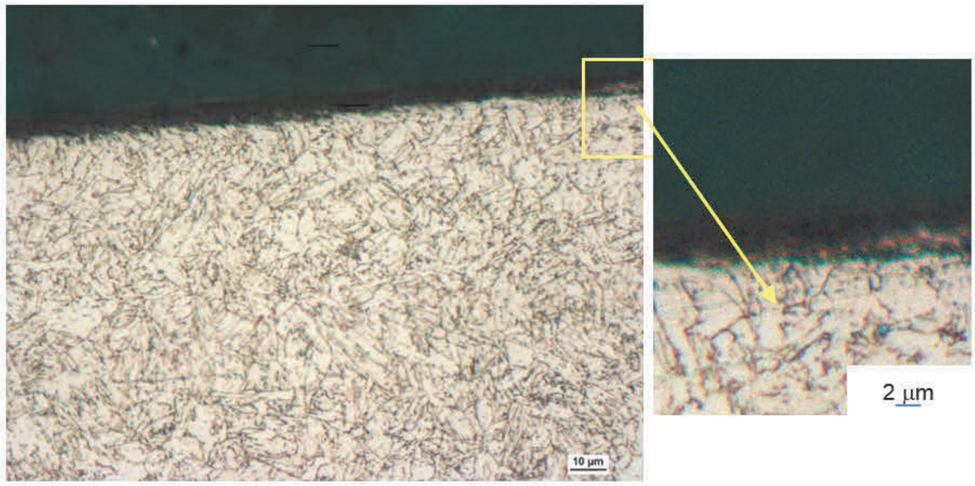
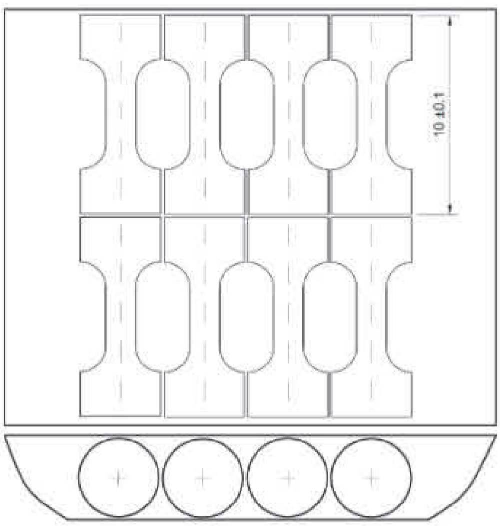


Figure 2 Influence of EDS machining on microstructure - affected depth is less than 10 µm

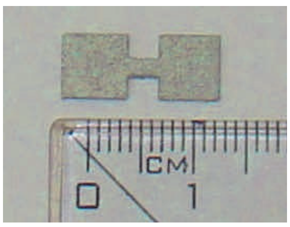
Sub-size specimens' dimensions and geometries were developed on the basis of available extracted piece of the experimental material. The material volume is limited and thus specimens' size and its distribution within the extracted material was carefully plan in order to utilize maximum of the material available for test-pieces. Specimens outline and cutting scheme within the extracted piece of material can be seen in **Figure 3.**



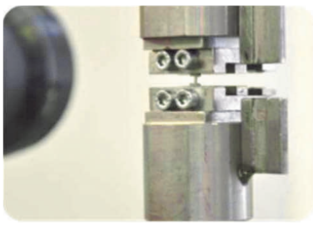
(a)

(b)

Figure 3 Specimens cutting scheme within EDSE extracted material (a) and relay sample (b)



a)



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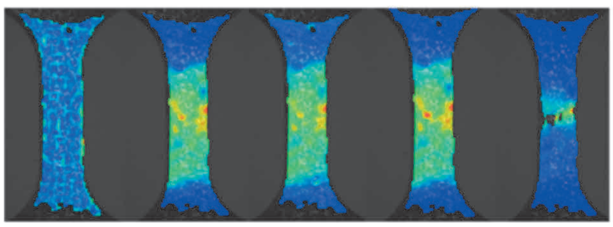

c)

Figure 4 a) M-TT sample, b) grips for micro-tensile testing, c) Strain measurement by means of DIC on micro-tensile samples

5. MICRO-TENSILE TEST (M-TT)

M-TTs were performed at room temperature at the same quasi-static strain rate as in the case of standard samples strain rate of 0.0004 sec^{-1}. Tests were performed with the use of the testing machine using a linear drive with a loading capacity of 10 kN. A tensile load was applied to a specimen until fracture. Strain measurement was done with the use of Digital Image Correlation (DIC) system, **Figure 4.**

Very good agreement between sub-size and standard size specimens can be clearly seen from the **Figure 5** there is not a huge scatter between standard and sub-size tensile test results. The crack occurred within the specimen gauge length and a significant necking process was observed during the test. Mechanical properties were reached without any numerical correlations except for an elongation (A5).

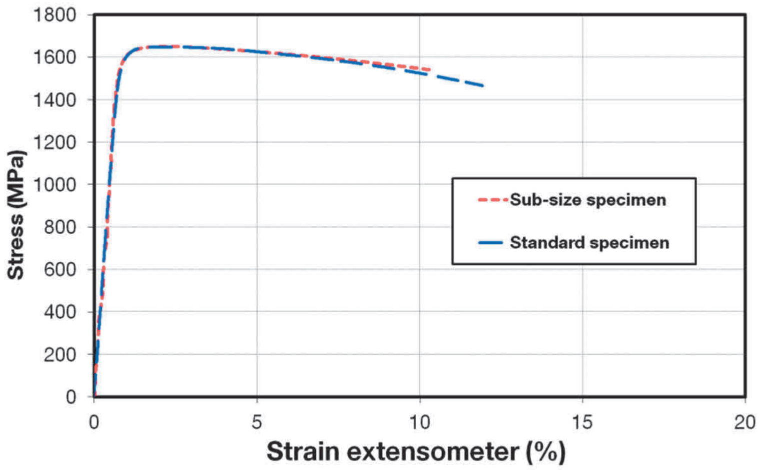

Figure 5 A micro- tensile test records in comparison with a standard tensile test record for X1CrNiMoAlTi

6. SUB-SIZE HIGH FATIGUE TEST

HCF tests on miniaturized specimens were conducted on the resonant fatigue testing machine Vibrophore Rumul for loads up to 20 kN in tension-compression mode and on servo-hydraulic testing machine MTS Bionix with load-carrying capacity of 25 kN. Tests were carried out in load control with load ratio of R = -1 at frequency of about 50 Hz. Each test was performed until failure occurred or after reaching 10^7 cycles. Size comparison with a standard HFC specimen can be seen in **Figure 6**.

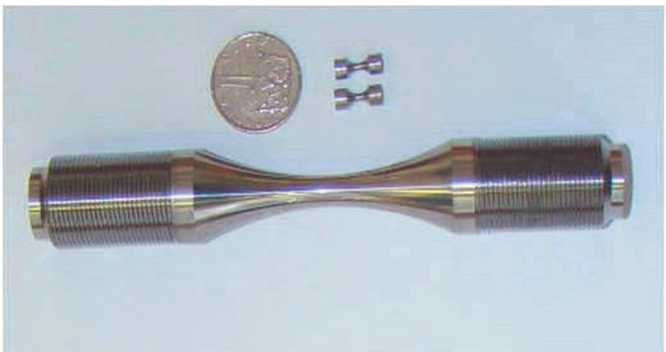

Figure 6 Comparison of HCF specimens

Obtained results from sub-size and standard fatigue tests are shown in **Figure 7**. This test results are presented as the number of cycles to failure which are plotted against the stress amplitude in the semi-logarithmic scale. Red dots represent sub-size HCF tests and the green line denotes its fatigue limit. Those of specimens which survived 10^7 cycles are denoted by arrows. Sub-size fatigue test results exhibit higher scatter and this corresponds to fit correlation coefficient R^2 of 0.66. This fact shows a worse fit of linear regression in comparison to the standard one. This is expected feature and it can be caused by several factors such as an inhomogeneity of steel which is represented by secondary particles in the matter, notch sensitivity, or surface conditions. The summary of fatigue limits is shown in **Table 1**. The results obtained with the use of both specimen batches yield very similar results that are very positive result.

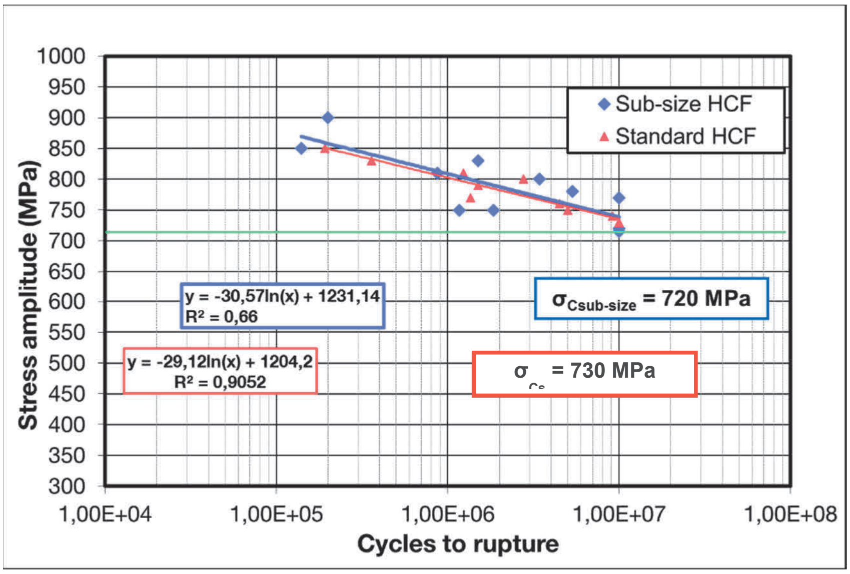

Figure 7 S-N curve of X1CrNiMoAlTi 12-11-2 steel for Sub-size and Standard HCF tests

Table 1 Results of standard and sub-size HCF tests of X1CrNiMoAlTi 12-11-2 steel

Type of test	Fatigue limit (MPa)
Non-standard HCF	720
Standard HCF	730

Table 2 Results of standard and sub-size HCF tests of 34CrNiMo3 steel

Type of test	Fatigue limit (MPa)
Non-standard HCF ø 1,5 mm	540
Non-standard HCF ø 4 mm	524
Standard HCF ø 8 mm	540

7. DISCUSSION

The effect of electro-erosion machining on the microstructure of a high strength stainless steel is evident in the **Figure 2** but on the other hand, in this case, the influence of 10 µm thick layer is negligible because this layer is removed during subsequent machining. The obtained stress - strain curves and results of sub-size tensile tests are fully comparable with the results of the standard ones. HCF Testing of smaller samples usually leads to a higher data scatter that is partly visible on the results obtained. However, the data scatter for sub-size specimens is very reasonable and fitted trends for both data sets overlap each other and the data obtained clearly belong to the same population. The slope of the regression line shows a similar trend and the intercept at 10^7 cycles is almost identical (difference of 2 %). In accordance with this, sub-size tests give very promising results, as it is shown in **Table 1** and **Table 2**. The results obtained provided very good agreement between sub-size and standard size test pieces, thus the specimens dimensions shown here is suitable for high cycle fatigue material behaviour assessment.

8. CONCLUSION

The presented work is dealing with mechanical properties evaluation of X1CrNiMoAlTi 12-11-2 and 34CrNiMo6. There are high demands on a safe service life of this kind of components and thus possibility of evaluation of actual material properties after several years of use is essential. Therefore some non-destructive or semi destructive method has to be applied in order to assess actual properties and out of that stemming residual service life. The work presented here shows results of high cycle fatigue tests and tensile test with the use of sub-size specimens loaded in the same manner as standard size specimens. The current results clearly shown that, there can be machined miniaturized tensile and high cycle fatigue specimens that yield fully comparable results with standard size specimens.

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