STRAIN RATE INFLUENCE ON FRACTURE TOUGHNESS DETERMINED BY SMALL SAMPLES

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Abstract

This paper describes a methodology of small sample test technique for fracture toughness determination in the upper shelf region. The effect of size and strain rate has been investigated and described. Standard and small sized samples for 3-point bend test were produced and tested from several steels. The results are promising for further usage in many fields, where only limited amount of material is available, like residual life assessment, additive manufacturing industry, local properties determination in case of heterogenic material, etc. In addition, competitive methods like small punch test will be discussed as well.

Keywords: Fracture toughness**,** miniaturized samples**,** Micro-Tensile Test, Digital Image Correlation (DIC)

1. INTRODUCTION

Determination of mechanical properties with the use of sub-sized specimens is a topic of high interest nowadays. The application of the sub-sized samples is quite wide for all cases where only limited amount of the experimental material is available such as evaluation of additively manufactured products properties, residual life of in-service components, properties determination of developed nanostructured materials, assessment of dilatometric samples used for thermal and thermo-mechanical treatment development, local properties of components, weld joints and so on.

A number of techniques have been developed to extract mechanical properties from sub-sized specimens [1-4]. These include specimens that are either miniaturized versions of their full-scale counterparts or specifically designed discs or coupon specimens of small dimensions. One of the most used methods is the Small Punch Test (SPT). SPT is widely used, but its application is traditionally bound with necessity of known correlation parameters valid for a specific material only and thus it is impossible to use it on a blind material [5]. Recently, there are assumptions to used trained neural networks for SPT evaluation [6] but again, neural networks can be trained for some material group but they are not generally valid. Therefore, development of small size specimen techniques using miniaturized standard size samples is important, because these tests maintain very important advantage - the same loading mode as standard test samples [7]. 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 [8], identification of ductile damage parameters [9] or characterization of material after thixoforming [10].

The aim of this work is to contribute to global knowledge in the field of miniaturized specimen with special focus on fracture toughness and strain rate influence. Therefore, the current work is dealing with fracture toughness employing master curve and J-R curve approaches for fracture toughness parameters determination with the use mini specimens.

2. EXPERIMENTAL MATERIAL

As the experimental material, two structural steels were chosen - namely 34CrNiMo6 and 27NiCrMoV 15-6. Both are currently used for production of several parts in energy industry like steam turbine parts and others highly stressed machine parts. Such above mentioned components in service can be degraded by stresses and temperature; therefore, the prediction of their remained life is critical. The chemical composition is summarized in **Table 1**.

Table 1 Chemical composition of investigated materials (wt.%)

Material	C	Mn	Si	Cr	Ni	Mo	P	S	V
27NiCrMoV	0.27	0.28	0.14	1.5	3.7	0.35	0.01	0.01	0.1
34CrNoMo6	0.36	0.75	0.22	1.55	1.67	0.25	0.01	0.01	-

3. TENSILE TEST

To prepare for testing from small volume of material, the recently-developed miniature-tensile test (M-TT) technique was chosen. M-TT specimen was suggested based on material volume requirement of specimen used for small punch test testing technique. The first suggested M-TT geometry was based on SPT specimen to prove that tensile test is possible to perform with the same amount of experimental material. FEM simulation confirmed the same loading and other condition as in the case of standard tensile test (see **Figure 1**).

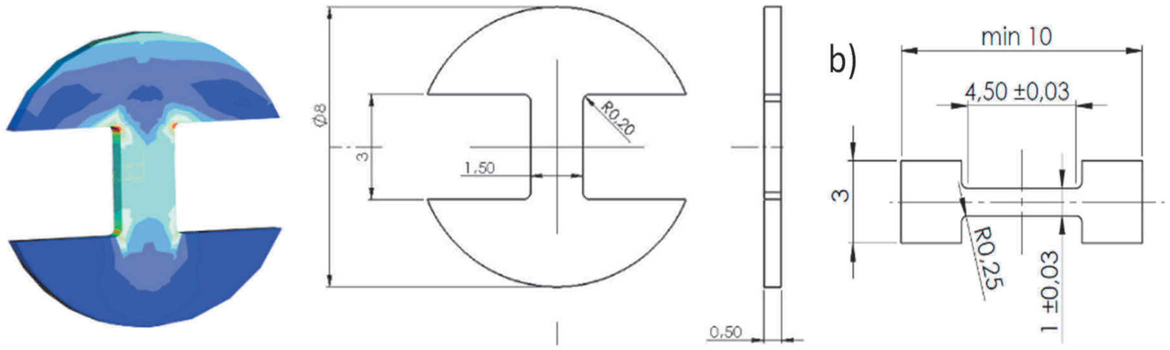

Figure 1 FEM simulation of M-TT specimen (right), M-TT initial geometry (middle), modified geometry (left)

In the case of this M-TT initial sample geometry, a shorter gauge length is used and thus elongation cannot be evaluated in the standard way. The elongation is evaluated with the use of following formula (1):

$$A_x = \frac{UA_m * L0_x + (A_m - AgUA_m) * L0_m}{L0_x} \qquad (1)$$

Where index m means gauge length used for the test evaluation and x is gauge length into which results are being converted.

M-TT is carried out using a special test device with high load cell sensitivity. Its linear motor runs smoothly at very slow speeds to fulfil all criteria given by the standard. The test piece is clamped in special flat grips which have been developed for this purpose. The axial extension is captured with a high-speed CCD camera integrated into the systems Mercury RT or ARAMIS™ that relies on digital image correlation (DIC), see **Figure 2**. As the force and extension data are captured accurately, the record need not be specially processed and the evaluation can follow the standard procedure.

Tensile tests were performed and evaluated based on ISO 6892-1 standard. The obtained engineering stress-strain record is depicted in **Figure 3**. Results of values from three tests for each material are shown in **Table. 2**, where $R_{p0,2}$ is Yield strength, R_m is Ultimate tensile strength, A_g is plastic extension at maximum force, A_5 is permanent elongation of the gauge length after fracture and Z is maximum change in cross-sectional area.

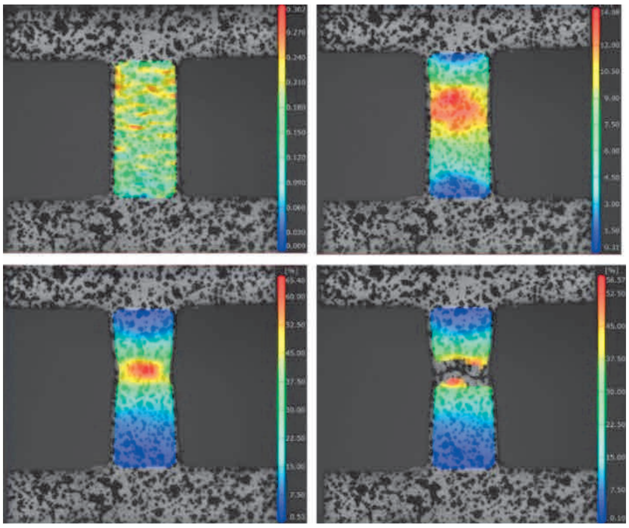

Figure 2 Example of strain measurement at different stages of tensile test for M-TT

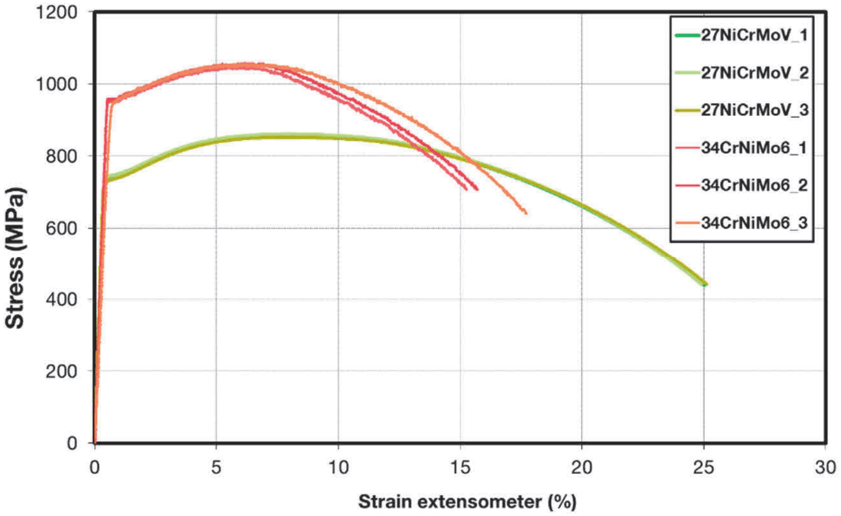

Figure 3 Tensile test records

Table 2 Results of tensile tests

Specimen	Rp0,2	Rm	Ag	A5	Z
	MPa	MPa	%	%	%
27NiCrMoV_1	739.0	858.8	7.3	22.2	75.1
27NiCrMoV_2	744.7	860.7	7.6	21.8	75.5
27NiCrMoV_3	732.0	852.8	7.4	22.0	74.6
34CrNiMo6_1	950.3	1047.8	5.9	15.3	59.5
34CrNiMo6_2	954.9	1058.8	5.6	16.0	60.4
34CrNiMo6_3	951.8	1054.7	6.2	18.4	63.0

4. RESULTS

The investigated materials exhibit fully upper shelf behavior at considered testing temperature, room temperature. Therefore J-R curve concept was applied for the fracture behavior assessment. The tests and evaluation were carried out according to ASTM 1820. Multiple specimen testing method was applied. Samples used were three point bend (3PB, see **Figure 4**) samples for both materials 34CrNiMo6 and material 27NiCrMoV 15-6. Specimens were V-notched at first and then fatigue pre-cracked up to crack length to specimen height ration of about 0,5W. Pre-cracking was performed with the use of magneto-resonant machine. Pre-cracking parameters were defined so that at the end of pre-cracking stress intensity factor K was kept below 20 MPa.m$^{1/2}$ in order to assure sharp crack tip. After samples pre-cracking, the samples were side-grooved by 20 %. Testing was performed on servo-hydraulic testing system MTS 810 for quasi-static condition and using Charpy pendulum for dynamic condition. Sample deflection was measured by a clip on gauge extensometer. After test execution samples were heat tinted and the initial crack length and stable crack extension was measured. The crack lengths were evaluated on the basis of crack area measurements performed with digital image processing software. The obtained J-R curves are depicted in **Figures 5 - 6**.

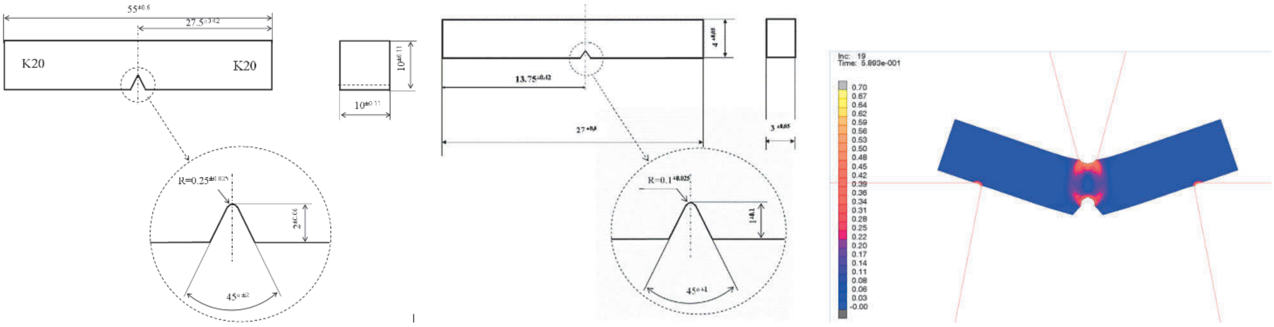

Figure 4 Charpy specimen geometry; 10 mm x10 mm x 55 mm (left), 3 mm x 4 mm x 27 mm (middle), scheme of loading (right)

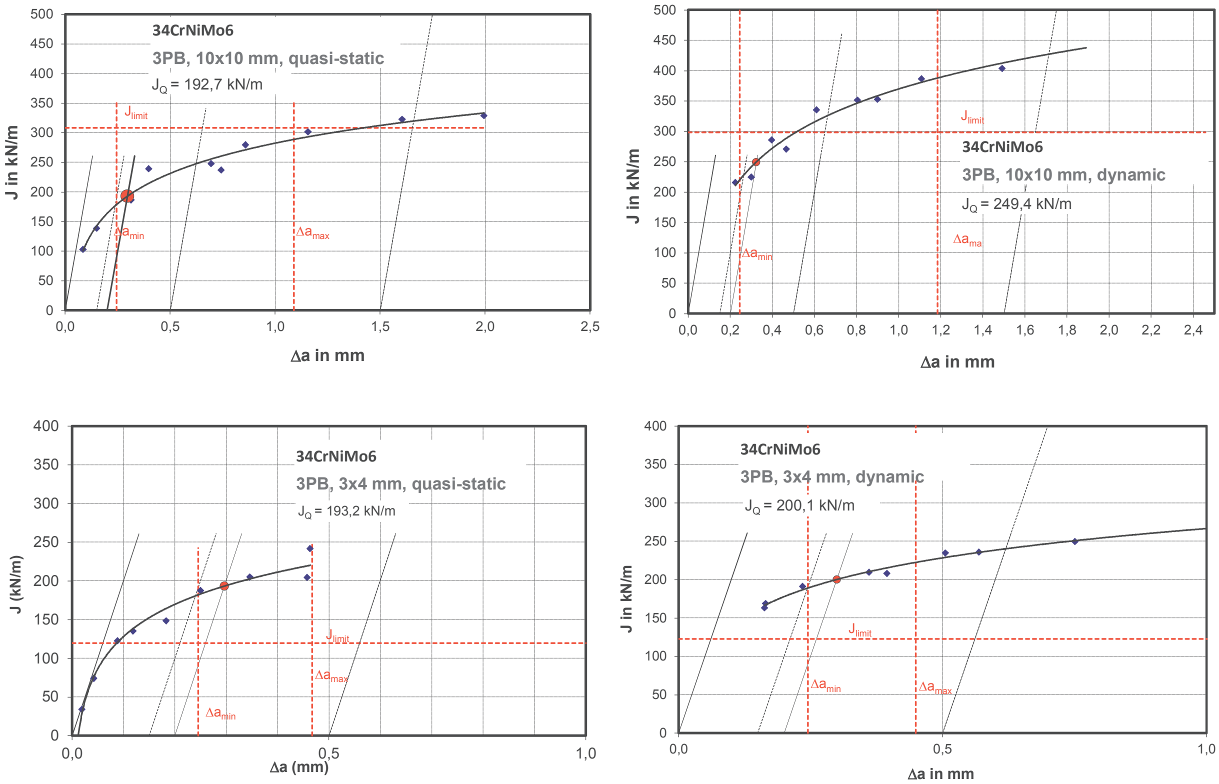

Figure 5 J-R curves; material 34CrNiMo6

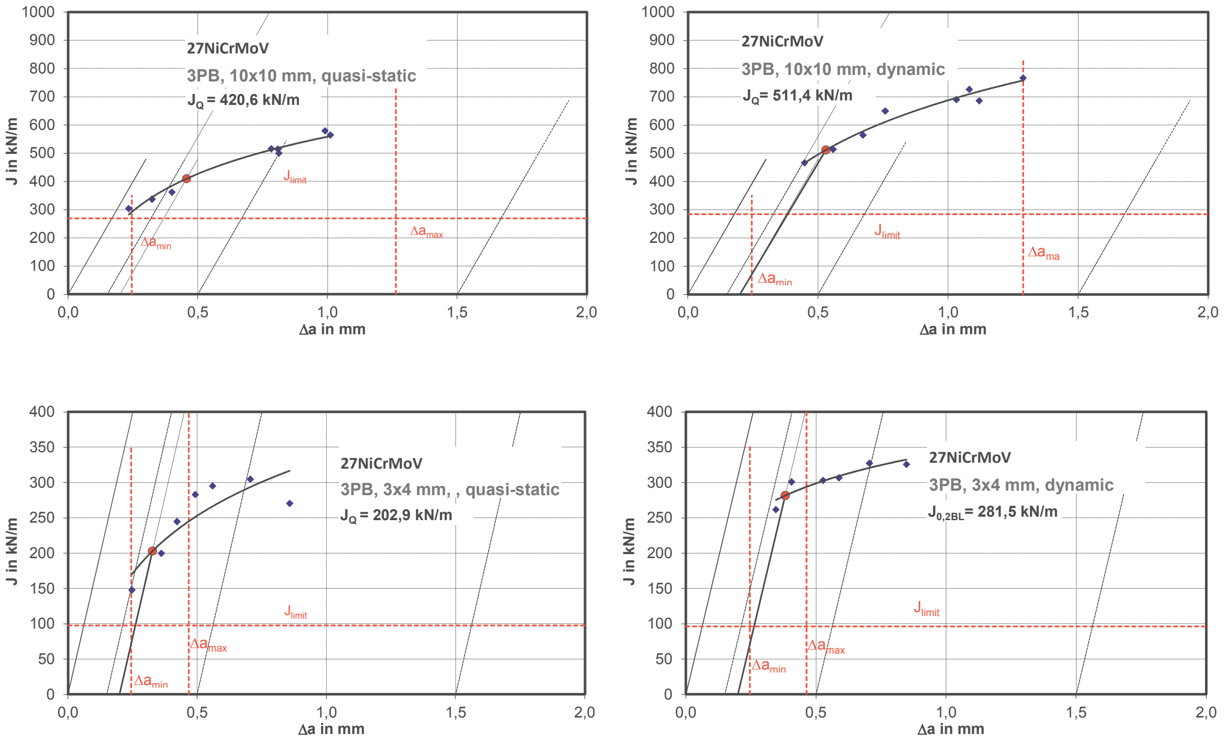

Figure 6 J-R curves; material 27NiCrMoV

5. RESULT DISCUSSION

Tensile test performed on both investigated materials show very homogenous results which is necessary for further investigation of size factor in case of fracture toughness. The result of fracture toughness summarized and depicted in **Figure 7** do not show clear trend for both materials. While the results for 27NiCrMoV 15-6 steel shows clear dependency of fracture toughness J_Q on specimen dimension and strain rate, the result for 34CrNiMo6 steel shows significantly JQ increasing only for dynamic loading of 10x10 specimen. This can be caused by higher tensile strength and less elongation of 34CrNiMo6 steel which may cause less plastic deformation on the tip of sharp fatigue crack and therefore, the crack resistance for material with higher strength is less.

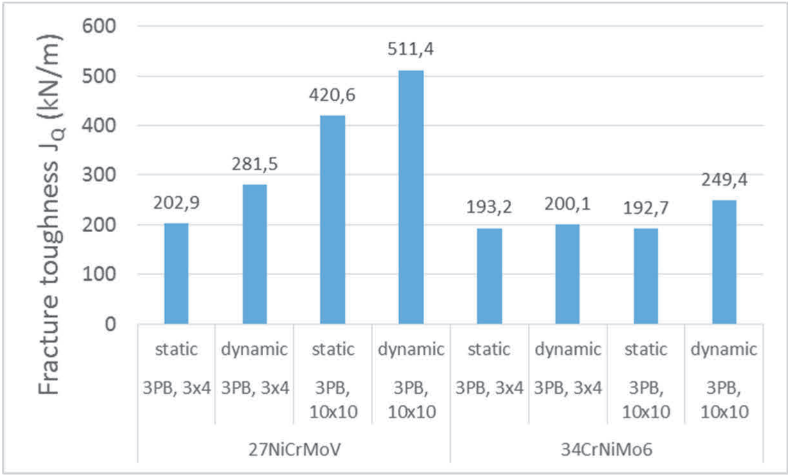

Figure 7 Fracture toughness results - graphical representation

6. CONCLUSION

Tensile test and fracture toughness tests were performed using standard and miniaturized Charpy specimens. The investigated materials were two steels used for production of several parts in energy industry - namely 34CrNiMo6 and 27NiCrMoV 15-6. The results indicates that fracture toughness do not depend only specimens size and strain rate but on other mechanical characteristics as well. The data contribute to global knowledge in this field. Further investigations with additional materials and specimen geometries are planned to provide sound base for the methods applicability for the currently investigated materials.

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