Optimization of test specimen dimensions for thermal power station exposure device

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Abstract. Degradation of metallic materials can decrease mechanical properties of metal constructions and components in thermal power plants during their operation and consequently lead to loss of safety and reliability. It is difficult to remove material from the pressure system of the equipment being operated. Therefore, the effort is to design, produce and subsequently install exposure channels, which will allow to remove and evaluate samples of exposed material without intervention into the pressure system. The exposure device for pressures and steam temperature in supercritical blocks, which would contain sufficient test material to produce conventional test specimens, is unrealistic in size, energy and economics. The way is to optimize the dimensions of the exposure device according to the miniaturized test specimens, which, in addition to the tensile test and the structural evaluation, can also carry out other required tests, such as bending impact tests with transition temperature, fracture toughness and fatigue tests. This paper deals with optimization of test specimens for the internal dimensions of the exposure device and shows the applicability of small sample methodologies for selected materials.

1 Introduction

The use of relatively new steels and alloys in thermal power plants, caused by the pressure to achieve the highest possible efficiency, also entails significant technical risks in the future. The gradual deterioration of the mechanical properties caused by the combined stresses, in particular the temperature exposure, can significantly limit the residual life of the pressure systems. The knowledge of the progress of material degradation and the linkage between the structural state and the mechanical and creep parameters can be obtained by evaluating the exposed samples in time periods. The residual lifetime of these machines and metal constructions, mainly turbines, boilers and steam pipelines, can be examined using standard mechanical tests as well as semi-destructive techniques using mini-specimens. Testing of operating constructions demands minimizing the volume of extracted material. For this reason, sub-sized specimen techniques have several advantages over standard ones, e.g., when the volume of tested material is insufficient or for the development of new alloys to ensure the lowest cost possible. Furthermore, testing of small samples allows for local properties to be evaluated (weld joints) and mechanical properties of in-service components investigated [1]. The data obtained using the newest measurement equipment and mini-specimen techniques can be used for calibration of fracture locus and in FEM simulations [2, 3].

The aim of the paper was to examine the effect of specimen dimensions on selected mechanical properties of materials applied in the power industry. Fundamental mechanical properties are tested using various miniature specimen testing methods, such as tensile test, fatigue test, impact test and
fracture toughness test. The results for standard size specimens were compared to specimens of reduced size. Based on this research, the possibilities and limitations of sub-size specimen methods and the application of these methods to testing components in the power industry are discussed. However, despite the potential small sample technique limitations, exposure device without specimens miniaturisation could not be realized at all.

2 Mechanical testing of sub-sized specimens
In this paper, mechanical properties of materials were investigated using mechanical tests on standard and small specimens. Applicability and reliability of sub-sized specimen techniques are discussed on the basis of the following mechanical tests: tensile test, impact test with transition temperature evaluation, fatigue test and fracture toughness evaluation.

2.1 Mini-Tensile Test (M-TT)
Tensile test is a basic and the most common method for mechanical properties evaluation. Using sub-sized specimen techniques there is a possibility to evaluate all standard mechanical characteristics including anisotropy. Furthermore, MTT can be advantageously used for strain rate sensitivity investigation of conventionally or additively manufactured materials [4-6].

In order to determine the tensile properties of small amounts of material, the geometry of sub-sized specimen was proposed [1]. For this type of specimen, it was necessary to design grips to enable gripping of the specimen in a universal testing machine. The deformation was measured using contactless measuring system ARAMIS, which is based on the Digital Image Correlation (DIC) method. A stochastic pattern is applied to the specimens for optical monitoring of displacement, which can be recorded by one (2D) or more (3D) cameras. During the test, the DIC software is tracking the pattern changes in each image in comparison with the reference image. Thanks to this method, it is possible to measure deformation and displacement of the whole specimen as well as locally in selected regions.

In this study, the tensile tests were performed on standard and sub-sized specimens. Different kinds of alloyed and non-alloyed ferrous and non-ferrous materials were tested. The results of the tensile tests are presented in Figure 1. The resulting curves show that the values of the yield strength, ultimate tensile strength and elongation for standard specimens are in agreement with the results of the small specimens in a wide range of stresses.

![Figure 1](image_url). Engineering stress-strain curves of tested materials using standard and MTT test.

2.2 Miniature fatigue test
Fatigue fracture can occur in many types of metal structures, e.g., turbines or reactor vessels [1, 7]. Therefore, it is necessary to determine the maximum stress values, at which no damage will appear. The
fatigue limit can be affected by impurities of the material as well as surface and environmental effects [8, 9].

Applicability of sub-sized specimens in fatigue testing was verified using XCrNiMoAlTi12-11-2 steel, which is commonly found in the power industry. Standard specimens were tested according to ASTM E466 and assessed according to ASTM E739 standard. All tests were performed using servo-hydraulic machine MTS BIONIX with a capacity of 25 kN at room temperature. The tests were conducted in tension-compression mode with controlled force and load ratio R=−1. The frequency of 50 Hz was applied. The fatigue test was conducted until failure or reaching $10^7$ cycles, if failure did not appear. Based on the obtained results, the Wöhler curve was constructed, where different stress amplitudes are plotted with a number of cycles to failure on the semi-logarithmic scale. The test results are shown in Figure 2. The results for both batches of specimens are in agreement. The fatigue limit received as a result of small specimen testing equals 710 MPa and for standard specimens it is 720 MPa. Sub-sized specimen results show a higher scatter than standard specimens. The scatter exhibited by both batches of specimens can be caused by the surface condition and the contaminations of steel.

![Wöhler curve](image)

**Figure 2.** Fatigue test results of standard and small specimens of XCrNiMoAlTi12-11-2 steel.

2.3 Impact test with FATT evaluation using mini-Charpy specimens

The impact tests were performed to determine ductile-to-brittle transition temperature. Many materials exhibit a transition temperature, which can be a reason of their limited application due to an increased risk of brittle fracture [10, 11].

Evaluation of DBTT was determined on the basis of impact tests using small (3x4x27 mm) and standard (10x10x55 mm) Charpy specimens. The transition temperature was calculated applying the equation (1), where C value is constant:

$$\text{FATT}_{\text{standard}} = \text{FATT}_{\text{sub-sized}} + C$$

It is necessary to calculate the value of coefficient C using mini-Charpy specimens, which expresses a shift of FATT related to the specimen dimensions. A weld joint consisting of two heat-resistant chromium-molybdenum steels and weld metal, commonly used in power engineering, was chosen as an experimental material. The tests were performed in 5 regions of the heterogeneous weld
according to the EN ISO 14556:2016 standard. The value of C was established at C=60±2°C. The tests were performed using an instrumented Charpy pendulum with impact energy of 300 J and 15 J. The results of the impact tests with calculated C values are summarized in Table 1.

Table 1. Results of FATT transition temperature evaluation using standard Charpy and mini-Charpy specimens.

| Material                  | FATT [°C] | Coefficient C  |
|---------------------------|-----------|----------------|
|                           | 10x10     | 3x4            |                |
| Basic Material 1          | 13.1      | -48.4          | 61.5           |
| Heat Affected Zone 1      | -11.7     | -69.9          | 58.2           |
| Weld Material             | 52.1      | -8.7           | 60.8           |
| Heat Affected Zone 2      | 21.1      | -39.4          | 60.5           |
| Basic Material 2          | 30.6      | -30.0          | 60.6           |

2.4 Fracture toughness evaluation using mini-Charpy specimens

Fracture mechanics is an important field of material investigation nowadays. It is helpful when common testing methods are not able to fully describe material properties. For metal components, such as rotors, pressure vessels and building constructions, fracture toughness testing is one of the main tools for determining the applicability of the material [12-17].

Standard specimens for a 3-point bending test and mini-Charpy specimens were manufactured from common steel 34CrNiMo6. Before testing, a precracking procedure on each specimen was performed with crack length a/W=0.5 and final value K=16 MPa m^{1/2}. Due to the loss of the constraint effect, side-grooves were applied. Tests were performed and J-R curves were evaluated according to ASTM E1820 standard using a multiple specimen test method. For each test different ductile crack growth was achieved. The crack length after the test was marked by the heat tinting process. Subsequently, specimens were cooled down in liquid nitrogen and cracked in the temperature region of brittle fracture. The crack length was measured using digital image processing. Based on the known crack length, the geometry of the specimen and applied force, the J-R curves were obtained and fracture toughness evaluated. The curves for both geometries are presented in Figure 3. Due to small dimensions of mini-Charpy specimens, the criteria established by the ASTM standard were not met. The evaluation of fracture toughness cannot be valid, therefore the provisional value J_c=J_0 was used. Despite this fact, the constructed curve for small specimens is in agreement with the curve for standard specimens for a 3-point bending test and estimated J_0 values differ by 1.7%.
Summary and conclusions

The relatively small size of the exposure device makes performing standard mechanical tests of in-service components impossible. It leads to need of developing miniature sample techniques. The aim of this study was to compare the results of selected mechanical tests using standard and small specimens to show the applicability of sub-sized specimen techniques in mechanical testing.

The stress-strain curves obtained for small specimens are fully comparable with the results of standard tests. All tensile test results show very good compliance with yield strength and ultimate strength and elongation for all tested materials.

Mini-Chary specimens were used to determine fracture toughness by a multiple specimen test method. Although the crack extension \( \Delta a \) in the J-R curve did not reach the value of 0.5 mm, the resulting fracture toughness \( J_0 \) was in good agreement with the fracture toughness \( J_c \) determined using standard 3PB specimens.

To determine the transition temperature using mini-Chary specimens, calculation of the coefficient C was necessary. The obtained transition temperatures for different regions of the weld joint were shifted by 60±2°C.

Fatigue limits obtained for standard and small specimens are almost identical. The performance of the fatigue test for both batches of specimens yielded reliable results without using any correlation. All presented applications show that it is possible to obtain reliable and repeatable results using sub-sized specimen techniques. Therefore, the exposure device can be designed based on miniature specimen size.

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