DETERMINATION OF LOCAL MECHANICAL PROPERTIES OF METAL COMPONENTS BY HOT MICRO-TENSILE TEST

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Abstract

Increasing demand on materials characterization together with improvements in apparatus testing lead to the development of new testing procedures such as sub-size specimens testing. Miniaturized specimens allow reliable properties determination while using very small amount of material.

These methods are widely used for local material properties determination. Basically, there are two main applications in industry: firstly, the determination of the distribution of mechanical properties in heterogeneous materials (e.g. heterogeneous weldments or weld deposits) and secondly the characterization of stamping parts which are usually too thin for the production of standard testing samples.

Other applications are also important, e.g. anisotropy determination on thin components, residual service life evaluation, or new materials development when there is a lack of material (e.g. severe plastic deformation).

In the last few years, a new methodology using small samples for tensile properties determination at RT has been developed. The newly proposed specimen is derived from the SPT specimen which has a diameter of 8 mm and a thickness of 0.5 mm. Therefore, the newly proposed specimen size is very small in comparison to standard size specimens and thus the new methodology is named a Micro-Tensile Test (M-TT). For precise strain measurement the ARAMIS system using the Digital Image Correlation method (DIC) is used.

Moreover, as many components are operated at elevated temperature, it was necessary to develop a Hot Micro-Tensile Test for tensile properties determination at elevated temperature. This paper presents the possibilities of performing the M-TT at elevated temperatures while maintaining high measurement precision.

Keywords: Tensile test, micro-tensile test, hot micro-tensile test, digital image correlation (DIC), small punch test

1. INTRODUCTION

A wide range of mechanical tests can be used for material characterization and its assessment. These data are necessary for many applications, e.g. as input data for FEM simulation or assessing the safety of designed structures. However, standard testing procedures require a large material volume for properties assessment and for many applications is not possible to use them.

Therefore, several non-destructive or semi-destructive methods such as the Small Punch Test (SPT) [1] or Automated Ball Indentation (ABI) [2] have been developed. The disadvantage of these methods is the fact that, for the material of interest, they require a previously established correlation relation between the considered property and these non-standard testing techniques. Moreover, these correlations have limited validity and higher tolerance bounds stemming from the measurement and evaluation uncertainties due to different loading modes between these methods and standard testing methods (e.g. SPT x tensile properties, ABI x fracture toughness, etc.).

Therefore, the development of small size specimen techniques using miniaturized standard size samples is important because these tests maintain a very important advantage - the same loading mode as standard test samples [3]. One of the most widely used techniques, the Micro-Tensile Test (M-TT), has been successfully used for measurement of current mechanical properties of components in service for residual life evaluation

[4], anisotropy measurement of thin-walled structures, measurement of local mechanical properties of weldments or new materials development when there is a lack of material (e.g. severe plastic deformation). A very perspective scientific field is ductile damage calibration [5] or strain rate sensitive measurement. However, as many components are operated at elevated temperature, it was necessary to develop a methodology for performing the M-TT at elevated temperatures, the Hot Micro-Tensile Test. This paper presents the possibilities of performing the M-TT at elevated temperatures while maintaining high measurement precision.

2. HOT MICRO-TENSILE TEST

The Hot Micro-Tensile Test has been developed on the basis of the Micro-Tensile Test. Therefore, the M-TT will be shortly introduced.

2.1. Micro-Tensile Test Development

A lot of attention has been paid to the development of the SPT within last two decades. Sampling devices as well as testing procedures were developed. Recently, thanks to the proposed code of practice (CWA 15627 [10]), the sample size has also been standardized and recommended disc geometry is the diameter of 8 mm and the thickness of 0.5 mm. There are already many applications using this sample size for example for surveillance programs (e.g. in nuclear power plants), thus this geometry was used as a base for the developed M-TT procedure. The aim was to perform a real tensile test (does not require any correlations based on previously established equations and which is useable for any unknown material) on specimens using the same material volume as the SPT. Some FEM calculations were performed and sample geometry shown in **Figure 1** was proposed. In the case of this 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 formula (1) suggested in [1]:

$$A_x = \frac{UA_m \bullet L0_x + \left(A_m - A_g UA_m\right) \bullet L_{0m}}{L0_x} \quad (1)$$

where A is elongation, UA is uniform elongation [-] and L_0 represents initial gauge length [mm]. Index m means gauge length used for the test evaluation and x is gauge length into which results are converted.

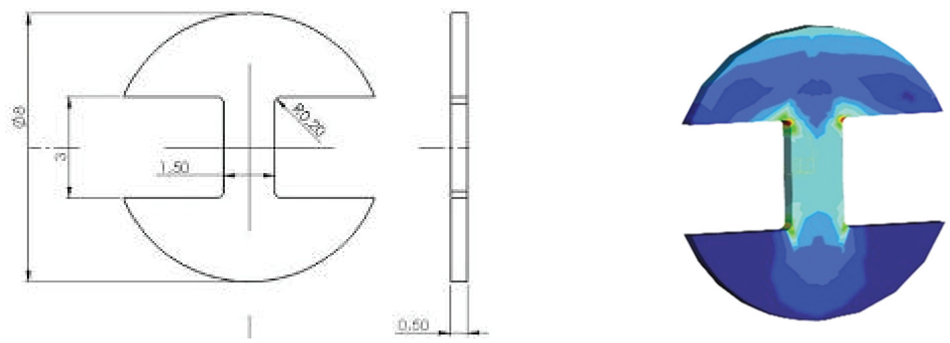


Figure 1 M-TT specimen, left: M-TT geometry, right: FEM simulation

Subsequently, the comparison of triaxiality development during tests between SPT, standard and micro-tensile test was done using FEM calculations (see **Figure 2**). It has been found that the SPT loading mode is completely different from the tensile mode and the reliability of the SPT is therefore limited to a narrow selection of materials as shown in many works (for example in [1]). On the other hand, the M-TT shows the same mode of loading and stress distribution as the standard tensile test. Deformation of the M-TT specimens is measured by ARAMIS. The grips for M-TT and an example of measurement of the deformation during the M-TT by ARAMIS can be seen in **Figure 3**.

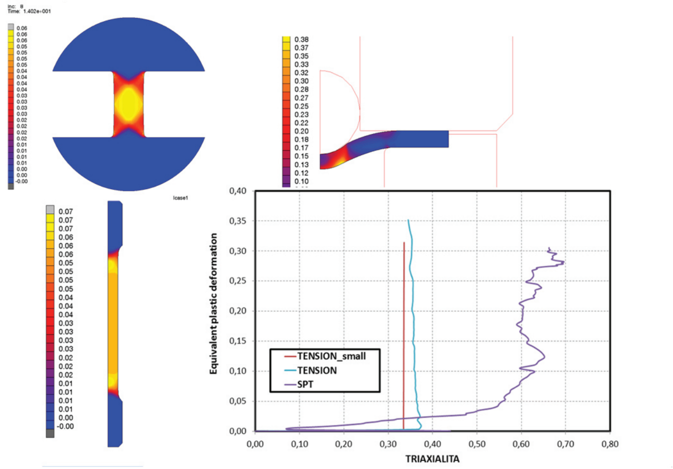


Figure 2 Comparison of triaxiality between SPT, standard and micro-tensile test

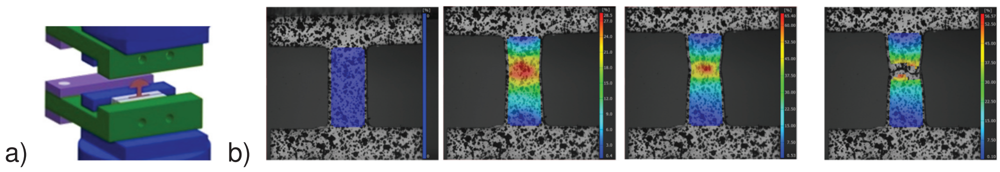


Figure 3 a) Grips for M-TT, b) Measurement of deformation during M-TT

Tests of several various materials with a wide range of tensile properties were carried out. Namely, Al-alloy, Ni-alloy, Titanium Gr. 5, and several steels were compared while tested on standard size specimens and with the use of the M-TT. Standard size samples were round with diameter ranging from 5 mm to 10 mm and in one case a steel segment of a pipe was tested.

The resulting curves of these tests are graphically summarized in **Figure 4** and the results are summarized in **Table 1**. Excellent agreement was found for all materials investigated between standard size specimens and M-TTs for the whole range of strength levels from about 250 MPa up to 1250 MPa.

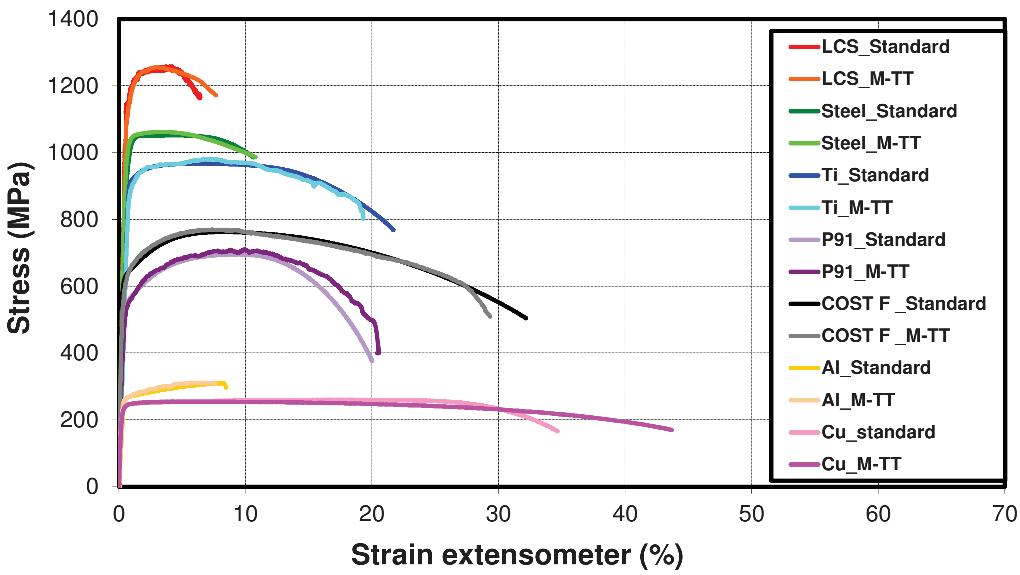


Figure 4 Comparison of tensile records obtained with DIC for M-TT measurement of various metallic materials

Table 1 Standard and Micro-Tensile Test results

Material	Specimen	Tensile tests results				
		Yield Stress	Ultimate Tensile Strength	Uniform Elongation	Elongation	Cross Section Reduction
		[MPa]	[MPa]	[%]	[%]	[%]
Experimental Low Carbon Steel	LCS_Standard	1143.4	1258.0	3.6	15.6	71.1
	LCS_M-TT	1133.0	1255.3	2.4	13.9	74.4
Low Carbon Steel (segments)	Steel_Standard	964.1	1051.6	4.0	15.9	62.7
	Steel_M-TT	990.1	1061.9	2.7	20.3	64.2
Titanium Gr.5	Ti_Standard	913.5	965.1	5.2	16.3	42.0
	Ti_M-TT	892.3	981.2	5.9	18.6	35.8
X14CrMoVNbN10-1	COST F _Standard	622.1	762.3	8.0	20.7	63.9
	COST F _M-TT	592.3	769.2	7.0	21.7	62.8
P91	P91_Standard	540.7	696.2	9.3	20.0	74.3
	P91_M-TT	520.9	710.4	9.5	22.8	74.4
Aluminium Alloy EN AW 6005 T6	Al_Standard	264.4	309.3	7.6	11.3	13.5
	Al_M-TT	264.1	311.0	5.6	8.2	11.4
Copper 99.99%	Cu_standard	234.6	260.0	16.3	34.2	73.7
	Cu_M-TT	235.7	254.5	4.4	35.4	70.5

2.2. Hot Micro-Tensile Test

On the basis of the M-TT, several heating methods maintaining the possibility of strain distribution measurement using the ARAMIS were suggested. Temperature homogeneity over the specimen gauge length was verified by a thermo-camera during the testing procedure development. The specimen has longer shoulders (see **Figure 5a**) in order to allow gauge length heating and to accommodate temperature gradient between grips and gauge length. However, if limited material is available for these tests, specimen geometry of M-TT specimen (see **Figure 1**), can be used for the middle section. The shoulders can be welded to the specimen, for example by laser welding, suppressing gauge length influence by welding heat. In the course of the test, the specimen temperature is measured by two thermocouples attached to both samples shoulders (see **Figure 5b**).

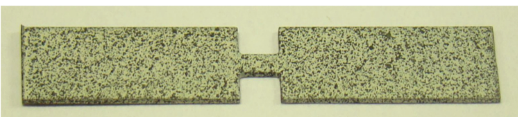
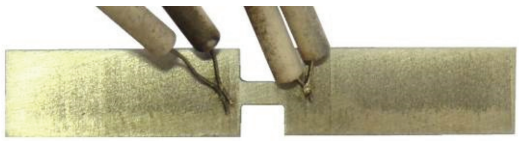
a)  b) 

Figure 5 High temperature sample coated for DIC strain measurement (a) with thermocouples for temperature control (b)

The temperature during these tests is attained by 1) a hot air gun, 2) a furnace or 3) a resistive heating system. All these methods are depicted in **Figure 6**. Using the hot air gun, temperatures up to 350 °C can be easily and quickly achieved. A big advantage of this testing setup is the duration of the whole test that is comparable with room temperature tests, thanks to fast heating of small specimen gauge length. The curves obtained with the use of the proposed testing setup can be seen in **Figure 7** for the austenitic steel (specimens designation in the plot consists of the first part meaning consecutive number in the set of specimens and the part after the underscore denotes testing temperature). Smooth curves with expected trends can be observed except for small waving at 150 °C where small temperature oscillations due to inappropriate regulation of common hot air guns can be observed. The second way of heating the specimens (using the temperature furnace) can be used for tempering specimens up to 800 °C. ARAMIS captures pictures through a small hole in the furnace. Though the quality of the pictures is lower, they are still sufficient for tracking two points on the gauge length for engineering strain measurement. Lastly, the setup with the resistive heating system allows heating up to the melting point of the tested metal. Thanks to the possibility of rapid heating or cooling, this system can be used not only for the currently investigated Hot Micro-Tensile Test but for supercooled austenite determination, too. The testing procedure consists of the specimen austenitization, followed by subsequent rapid cooling to the required test temperature in a few seconds with following temperature stabilization over the gauge section and test execution. The comparability of these results with standard specimens has been partly proved but these methodologies will be verified for different materials in the future.

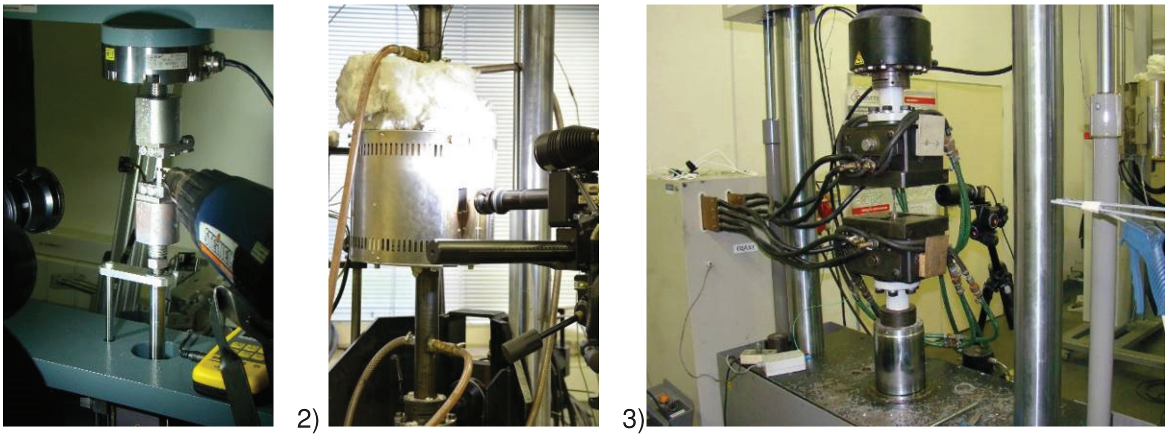
1)  2) 3)

Figure 6 Temperature can be attained by 1) a hot air gun, 2) a furnace or 3) resistive heating system

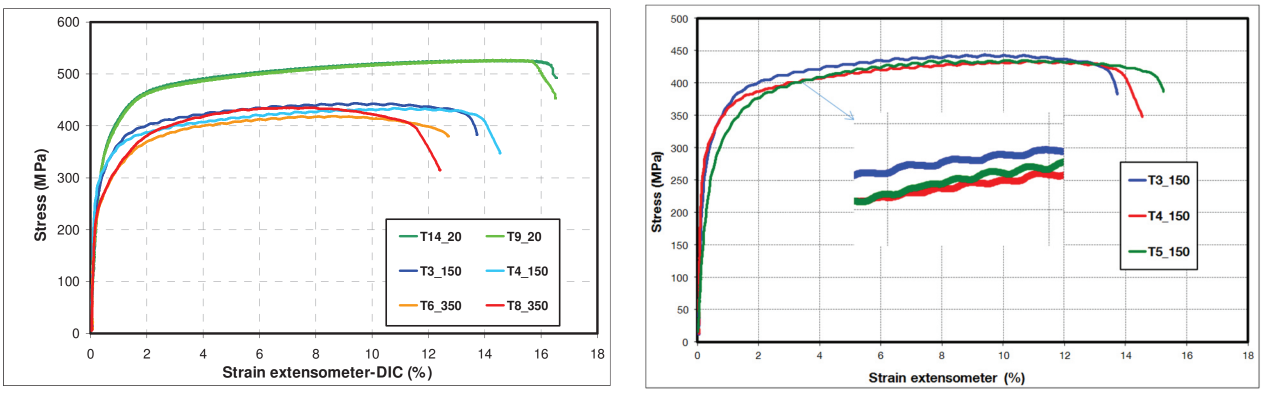


Figure 7 M-TT records at room and elevated temperatures

3. CONCLUSION

The presented work has suggested several heating methods of the M-TT specimens maintaining the possibility of strain distribution measurement using the ARAMIS. Heating micro-tensile specimens enables to extend the applicability of the M-TT to components operated under elevated temperatures. This paper suggested three methods of heating micro-tensile specimens: 1) a hot air gun, 2) a furnace or 3) a resistive heating system. Each method is suitable for a different temperature range and their advantages and disadvantages were discussed in this paper. However, the Hot-Micro Tensile Test is generally a very suitable method for tensile properties determination at elevated temperature up to 1300 °C for a wide range of metal materials without need for any previously established correlations.

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