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TENSILE TESTING OF MATERIALS AT ELEVATED TEMPERATURES ON A SMALL LABORATORY DEVICE

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Abstract: *Machine parts and constructions are often exposed to elevated or high temperatures in their working environment. The mechanical characteristics of metals obtained by tensile testing then change, so it is very important to know their properties under such conditions. Reliable and accurate values of the mechanical characteristics of metals can be obtained by tensile testing on a small laboratory device. By developing a simple and cost-effective module for testing metals at elevated and high temperatures, experimental tests of DC01 steel were performed at temperatures up to 600 °C, and the results were verified with the results available in the literature. The obtained values of the mechanical characteristics of the materials tested on a small laboratory tensile testing device are in accordance with the results obtained on a conventional tensile testing device.*

Keywords: *tensile testing, small laboratory device, elevated temperature, stress-strain curve.*

1. INTRODUCTION

The mechanical properties of the material's resistance and deformation are obtained by tensile testing the material, which describe the behavior of the material under the influence of external load, are used for the calculation and dimensioning of the elements of machines and structures, and are used to control the material of the product in production technological processes, as well as to test the characteristics of new materials.

Some machine parts and constructions (steam boilers and turbines, internal combustion engines, etc.) are exposed to elevated and high temperatures during use in a real working environment. Depending on the temperature, the mechanical characteristics of the metal also change, so there is a clear need to study its influence under static and dynamic loads. Tests are performed at elevated temperatures, including tensile testing.

The mechanical characteristics of metals and alloys change at elevated temperatures. With an increase in temperature, there is a decrease in the properties of resistance - the values of the modulus of elasticity, yield strength and tensile strength fall, the linear part and the yield strength are less prominent on the stress-strain curve and the properties of plasticity and toughness increase - the strain (percentage elongation) increases. [1].

When it comes to tests at elevated temperatures, the duration of the load significantly affects the results. The characteristics of the material at elevated temperatures must be determined as a function of the duration of the load and the height of the temperature [2].

A large number of researchers are working on the development of true stress-strain curves of materials during tensile testing at elevated or high temperatures [3-6]. The principle of data processing is the same as for testing at room temperatures. The actual stress-strain curves are divided into two main parts: the part before the neck is formed (reduction of the cross-section) and the part after the neck is formed until the specimen breaks.

Mechanical properties play an important role in the design of cold-formed steel structures in terms of safety, due to the rapid reduction of mechanical properties and with them the bearing capacity of the structure in fire conditions. The results showed that the influence of the steel class and the thickness of the specimen is negligible on the reduction factors of the elastic modulus [7, 8].

A review of the literature indicates that many conducted experiments evaluate the effect of temperature on the properties of conventional low-carbon, mild steel [5, 7, 9]. Most of these studies were conducted to evaluate the strength and stiffness properties of structural steel with a yield stress in the range of 250 to 350 MPa. There are very few studies in the literature on the effects of temperature on the strength and stiffness properties of high-strength steel structures [10-13]. Verification of experimental data is performed using FEM analysis [14, 15], and prediction of mechanical properties of materials using Artificial Neural Networks [16].

There is not a lot of information in literature sources about material tests on small laboratory tensile testing device SLTTD, where specimens with small cross-sections are used [17], which is the aim of this paper. A special module was developed that proved to be a reliable and economically viable system for testing materials at elevated and high temperatures. Thanks to a new clamping system of a SLTTD [18], the compliance in the contact of the specimen and grips was minimized, which led to test results that, compared to the literature results obtained on conventional device, had a large overlap.

2. DEVELOPMENT OF THE MODULE FOR TESTING MATERIALS AT ELEVATED TEMPERATURES

The development of non-conventional SLTTD basically represents the design of a tensile testing device which can be obtained reliable and accurate values of mechanical characteristics of materials on specimens of small cross-section, loaded with relatively low values of tensile forces. Within these assumptions, the rigidity of the device construction is easier to achieve [18]. Elongation and strain measurement of specimen with small cross-sections and dimensions used during testing are a real challenge. That's why software is implemented in the device, which automatically corrects the elastic strain of the gripe zone and the radius zone of the specimen, which are not taken into account in the case of standard specimens [17].

For the purposes of testing at elevated and high temperatures, a device module was developed that has a chamber for heating specimen to the desired temperature, Figure 1.

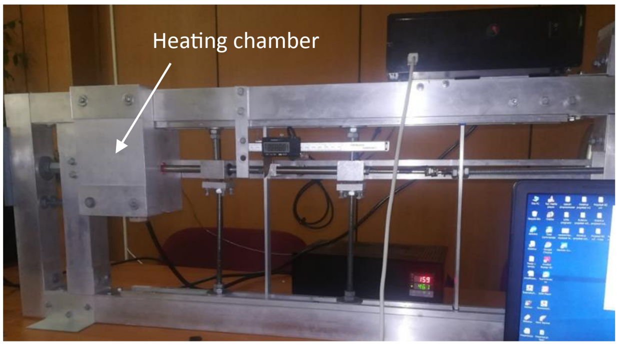

Figure 1. Tensile testing device with heating chamber

The module consists of a power cable and a power connector, a rectifier inside the box, which also houses a thermoregulator that communicates with the embedded temperature detector, which is placed in the chamber. The chamber can be moved thanks to the sliders located on the base structure. The whole specimen and clamping system are located in a zone that maintains a precisely defined set temperature. The capacity of the chamber and the heater allows the heating of samples up to 700 °C, which covers the area of steel [19]. Thanks to the high-quality insulation of the chamber, despite reaching high temperatures, the chamber can be touched freely. The developed module has the ability to easily maintain certain temperatures, as well as a short heating period.

3. EXPERIMENTAL RESEARCH

The plan of experimental tests foresees the determination of the mechanical characteristics of cold-rolled low-carbon steel EN10130 of DC01 quality. It is a material that is widely used in industry (in the automotive industry, the home appliances sector, the production of metal furniture, tanks, radiators, fans, pipes and small profiles), due to its accessibility and lower price. Chemical composition: ≤0.12% C, ≤0.6% Mn, ≤0.045% P, ≤0.045% S, ≤0.03% Si, ≤0.02% Al. The mechanical and physical characteristics of low carbon steel DC01 are: modulus of elasticity = 210 GPa, hardness = 105 HV, tensile strength = 270-410 MPa, yield strength = 280 MPa, Poisson's ratio = 0.29 and density = 7.800 g/cm^3.

Rectangular cross-section specimen with a width of 1 mm were cut from sheet metal with a thickness of 0.5 mm using a laser beam on the Electra FL 3015 machine, so the cross-sectional area of the tested specimen was 0.5 mm^2, Figure 2.

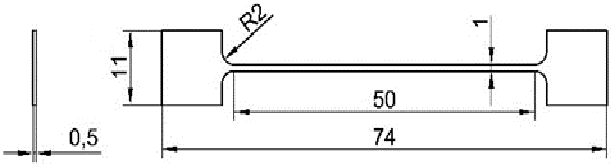

Figure 2. Shape of DC01 specimen for tensile testing on SLTTD

All tested specimens were cut from the same sheet metal with the same cutting direction and the same machine parameters. In order to know the mechanical characteristics of the material within the set temperature fields, it is necessary to perform numerous tests, because the behavior of the material structure at higher temperatures must be known already in the design phase. It should always keep in mind that the behavior of any structures under thermal load may differ from their behavior under mechanical load, depending on the operating temperature.

The experimental research plan envisages the testing of the specimen made of steel DC01 at elevated and high temperatures in the interval from 23±2 to 600 °C, and relative humidity 65±2%, in accordance with the basic regulations given in the standard [20]. All mentioned tension tests are with the same tension speeds in order to be able to compare the obtained data and will be 2.5 mm/min.

4. TEST RESULTS

With steel up to 180 °C, there are no significant changes in mechanical properties, so these temperatures are considered low. Working temperatures of 180÷450 °C for steel are elevated, and above 450 °C are high, because then steel creep begins, i.e. plastic strain occurs below the yield stress at elevated temperatures [21]. Specimens of DC01 were tested at room temperature and at elevated temperatures of 200÷600 °C. Figure 3 shows the specimens after tensile testing to failure, on a SLTTD with a chamber for heating the samples to the desired temperature.

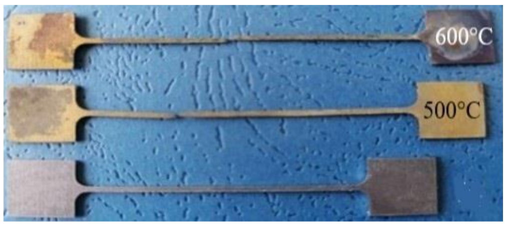

Figure 3. Specimens before and after fracture at temperatures of 500 °C and 600 °C

Based on the obtained experimental data for the tension force and the elongation of the specimen during the test, stress-strain curve are drawn, shown in Figure 4.

The tensile strength of steel DC01 at room temperature is 418.5 MPa, which is a value from the range of reference values given in the literature. At a temperature of 200 °C there is an increase in the value of tensile strength of 3.79%, while at a temperature of 300 °C it continues to grow up to 18.64% compared to the tensile strength at room temperature.

This is followed by a decrease in the value of the tensile strength, at a temperature of 400 °C, in the amount of 18.98% in relation to the tensile strength obtained at room temperature.

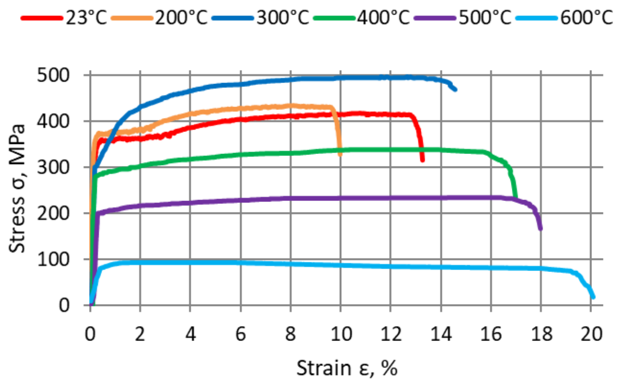

Figure 4. Stress-strain curves for material DC01 at room and elevated temperatures

The trend continues with a further increase in the temperature at which the test is performed, thus, at a temperature of 500 °C, the drop in the value of tensile strength is 44.16%, and at a temperature of 600 °C even 77.91%, all this in relation to the value of tensile strength at room temperature.

Table 1. Tensile strength values R_m and R_{mstvMD} (MPa) as a function of test temperatures

	Temperature [°C]					
	23	200	300	400	500	600
R_m [MPa]	418.5	434.3	496.4	339.0	233.6	92.4
R_{mstvMD} [MPa]	464.0	469.3	555.5	382.7	269.2	97.4

In the case of specimen with the shape and geometric characteristics as in Figure 2, the percentage of elongation of the specimen in the radius zone is 2.38%, and 0.24% in the gripe zone of the specimen. The percentage of elongation that occurred on the gauge length of the specimen is 97.38% of the total measured elongation. In that case, the measured elongation can be corrected by subtracting the calculated elongation values in the radius zone and the gripe zone of specimen, and the specimen elongation at its gauge length can be obtained [17]. Based on these values, corrected actual tensile strength values can be obtained, by observing the elongation only on the gauge length of the specimen, R_{mstvMD} at the specified test temperatures, as shown in Table 1. The differences between the actual tensile strength values, when taking into account the total measured elongation or only the elongation of the gauge length is less than 1%, and for temperatures of 500 °C and 600 °C less than 0.4%.

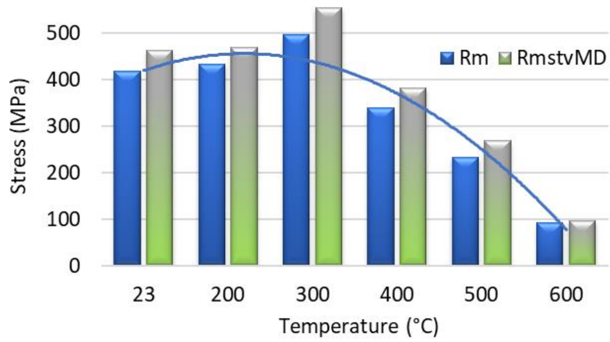

Figure 5. Dependence of tensile strength on test temperature for steel DC01

The blue line in the diagram from Figure 5 shows the trend of tensile strength growth up to 300 °C, and then a decrease in its values with a further increase in the temperature at which the material is tested for tension.

Table 2 gives an overview of the values of elongation Δl, strain occurring at the fracture point of the specimen ε_k, as well as corrected real strain occurring only at the gauge length of the specimen ε_{kstvMD}, at all temperatures at which the material was tested.

Table 2. Values of elongation Δl and strain ε_k and ε_{kstvMD} after fracture the specimen at room, elevated and high temperatures

	Temperature [°C]					
	23	200	300	400	500	600
Δl (mm)	6.64	4.98	7.29	8.48	8.99	10.04
ε_k (%)	13.28	9.96	14.58	16.97	17.98	20.08
ε_{kstvMD} (%)	11.62	8.83	12.68	14.62	15.43	17.08

On the diagrams from Figure 6, a clear trend of increasing elongation, i.e. strain of the specimen at the fracture point with increasing temperature can be observed. The exception is the results at a test temperature of 200 °C, where a drop in the material's plastic properties is noticeable. The true strain on the gauge length of the specimen ε_{stvMD} represent the corrected values of the true strain, when the corresponding percentage of the elongation created in the radius zone and the grip zone of specimen in the clamping system of the device is subtracted from the total elongation measured during the test.

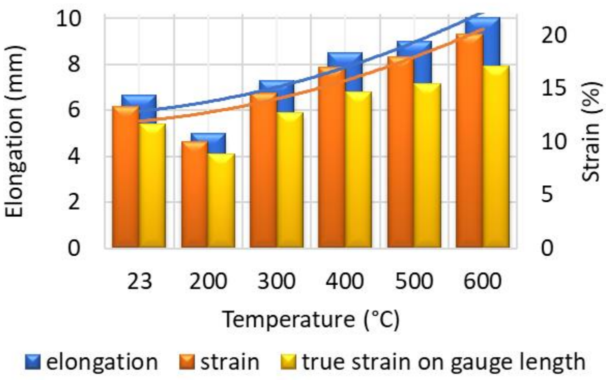

Figure 6. Diagrams of the dependence of elongation and strain at the fracture point of the specimen on the test temperature

5. DISCUSSION

The results of DC01 tensile tests at room, elevated and high temperatures on SLTTD were compared with reference values available in the literature.

In the diagrams from Figure 1, it can be seen that the material at temperatures of 200 °C and 300 °C behaves differently than at temperatures higher than those mentioned. Therefore, at a temperature of 200 °C, there is an evident increase in the value of the tensile strength of 3.79% in relation to its value at room temperature. At a temperature of 300 °C, the increase in tensile strength is even greater and amounts to 18.64%. Of all temperatures above 0 °C, steel has the highest tensile strength between 200 °C and 300 °C, says the Dobrzanski [22], which is in agreement with the obtained experimental results at SLTTD. The behavior of the material with a further increase in temperature shows a visible decrease in the value of the tensile strength, as well as the value of the yield stress and the modulus of elasticity. In the case of DC01 steel, there is a large increase in the creep effect when the temperature is higher than 450 ÷ 500 °C [22], which is also shown by the results obtained at SLTTD.

When the total strain up to failure are observed in the diagrams from Figure 1, for all test temperatures higher than room temperature, the strain of the specimen have an increasing trend with increasing temperature. The exception is the results obtained by testing the material at 200 °C, where the strain at failure point was 9.96%, while at room temperature this value was 13.28%. It is known that steels can show increased values of tensile strength in relation to reference values at ambient temperature in the range of 150 °C÷300 °C combined with a decrease in ductility properties. This specific behavior is a manifestation of the dynamic strain ageing [23], so the data obtained at SLTTD are completely in accordance with literature sources.

6. CONCLUSION

A small, laboratory tensile testing device SLTTD for testing materials at room temperatures, with the development of a special module that is shown in the paper, can be used for testing materials at elevated and high temperatures. The developed module enables more effective and efficient system management, while simultaneously reducing costs. The system is energy efficient, the process takes place relatively quickly and is completely safe. The experimental tests gave results in accordance with the relevant sources from the literature.

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