DETERMINATION OF THE TEMPERATURE INFLUENCE ON THE CHANGE OF YOUNG'S MODULUS

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Abstract

Materials commonly used in various branches of the engineering industries are very often tested under basic conditions. This is due not only to the frequent effort to determine e.g. mechanical properties of the tested material just under reference conditions but also to the assumption that some material characteristics remain constant over the entire range of material loading conditions. In this paper, the change of Young's modulus in dependence on temperature is studied. Stainless steel was selected as the test material. To determine the required Young's modulus of elasticity, a static tensile test was performed on a testing machine equipped with a split tube furnace which allowed the desired loading temperature to be adjusted (generally from RT to about 1,400 °C). The force channel was thus detected by means of a load cell (using bridge strain-gauge circuit) clamped in a testing machine. Specimen extension was simultaneously monitored using the external Mercury contact-less optical system, where the actual distance between two monitored points was measured. The entire system thus functioned as a "virtual" strain-gauge delivering the necessary specimen extension channel. From these measured characteristics, the corresponding Young´s modulus of elasticity was finally calculated as a function of temperature. The resulting temperature influence on the values of Young´s modulus change not only gives a better insight into the deformation behaviour of the tested material in the elastic deformation area, but can be also used in the numerical simulations of deformation processes.

Keywords: Young´s modulus, temperature, static tensile test, optical system, stainless steel

1. INTRODUCTION

Young´s modulus (or elastic modulus) represents, together with e.g. Poisson´s ration, one of the most important deformation material characteristics in the elastic region - thus in the elastic deformation. Its value can be graphically explained with the help of linear extrapolation of true stress σ from the elastic region up to true strain $\varepsilon = 1.0$. Young´s modulus is especially important when it comes to stiffness properties [1]. In light of atomic scale, its magnitude is primarily given by the interatomic bonds within the relevant crystal lattice. However, these are greatly influenced at the elevated temperatures and such change of properties is really necessary to take into account in situations of fire exposure. That´s why in this paper was investigated change of Young´s modulus upon temperature for stainless steel DIN 1.4301 (X5CrNi18-10).

The temperature effect on the mechanical response of engineering materials is (in light of temperature stress-strain rate relation) quite extensively described e.g. in work of Hertzberg [2]. In their works Ashby and coworkers used so-called deformation-mechanism maps to reveal stress-temperature dependences for different material groups. Moreover, Ashby used material property charts to show a lot of material properties in dependence on each other or different environment conditions - including temperature [3]. These charts can be very useful especially during the material selection. Own determination of the material mechanical properties (generally formability testing - in this case Young´s modulus) is described in e.g. [4,5].

There have already been done a lot of different researches about influence of elevated temperatures on the mechanical properties of different types of stainless steels - e.g. [6]. Major differences can be found in the chosen methodologies and thus accuracy of these measurements.

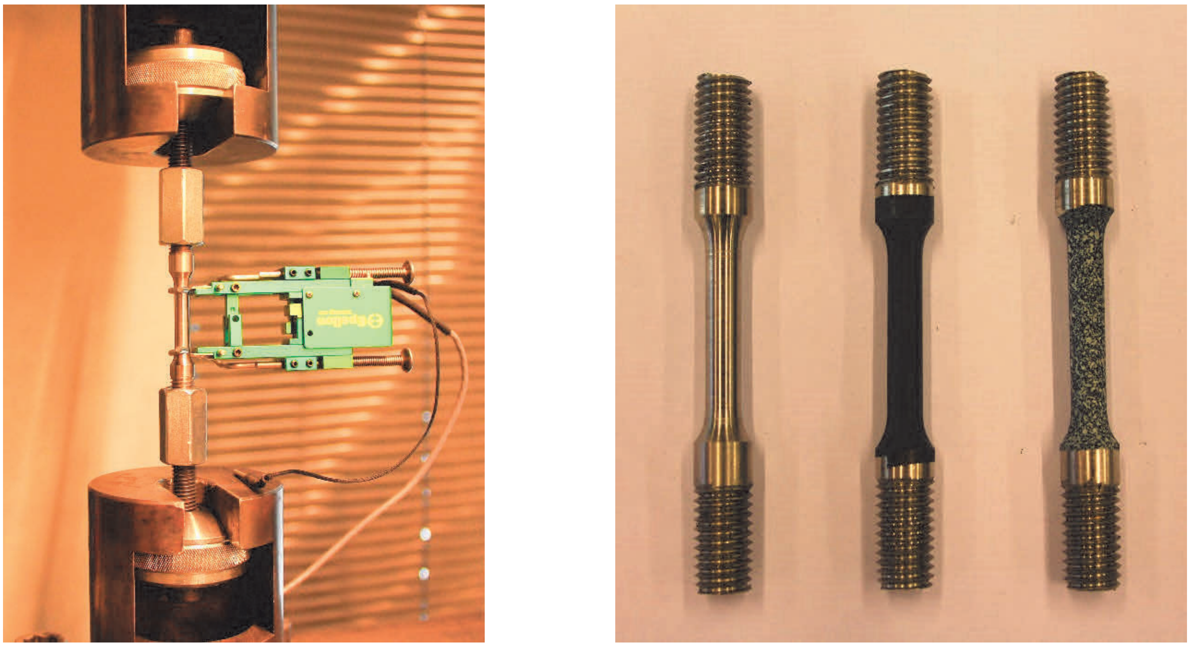
2. METHODOLOGICAL BASES - TESTING MATERIAL AND PREPARATION OF SPECIMENS

As a testing material there was used stainless steel DIN 1.4301 (AISI 304). It is austenitic stainless steel with EN symbol (short) as X5CrNi18-10. Its basic mechanical properties (under the room temperature - RT) are summarized in **Table 1**. Nevertheless, the major focus of this paper was concerned about determination dependence of the Young´s modulus on temperature and these properties were not further monitored here.

Table 1 Basic mechanical properties of tested stainless steel DIN 1.4301

Basic mechanical properties		**Proof yield strength** R_{p02} **(MPa)**	**Ultimate tensile strength** R_m **(MPa)**	**Uniform ductility** A_g **(%)**	**Total ductility** A_{50mm} **(%)**
Stainless steel DIN 1.4301	arithmetic mean **x**	331.2	654.3	45.22	50.62
	standard deviation **s**	5.2	6.1	0.23	0.37

Influence of elevated temperatures (from 100 °C up to 600 °C) was measured in the split tube furnace and by the contact-less optical system. But precise magnitude of Young´s modulus under the RT was determined by the universal tensile testing machine TIRAtest 2300 and high accuracy axial extensometer Epsilon model 3542 that is shown in **Figure 1a**. Subsequent data processing was performed in the same way for all used temperatures and is in detail described in chapter 3. Due to the application of non-contact extensometer (via a mono-camera), there was firstly needed to prepared the own testing specimens - see **Figure 1b**. Specimens of diameter 6 mm were machined and provided with threads. After their degreasing, there was applied stochastic (random) pattern that is scanned by the camera and where can be subsequently computed e.g. true strain distribution or just distance point-point, which was used in this case. So specimens were firstly sprayed by the ceramic black colour and then white spray was used to create small white dots on black background. Optical system requires such pattern, because it allocates the whole scanned surface onto facets in pixels and during measurement it just follows movement of these facets.



a) extensometer Epsilon model 3542

b) surface pattern on testing specimens

Figure 1 Axial extensometer Epsilon model 3542 and surface pattern on testing specimens

3. EXPERIMENTAL PART AND RESULTS

Own testing of the temperature influence on the magnitude of Young´s modulus was performed on the universal testing machine TESTOMETRIC FS100CT, which was equipped with the vertical high-temperature split tube furnace SOP 40x200/140 (see **Figure 2**). Thus force channel was measured by means of load cell in the testing machine. Extension of sample was simultaneously measured with the help of contact-less optical system Mercury RT v2.8 from Sobriety, Ltd. Regarding the utilization of cameras (just to measure distance between two points that serves as “virtual” extensometer), thus only one camera was used in this experiment. Specimens were prepared acc. to method that was described on the previous page and via threads were clamped in the centre of vertical split tube furnace.

Three was also important to adjust the contact-less optical system (here it consists just of mono-camera and lighting - see **Figure 2**) via its proper positioning (distance from the sample was 40 cm) and calibration by calibration panel with the distance of 5 mm. The blue lighting was used just because of high-temperature testing to avoid negative influence on camera from the thermal emissivity. Subsequently, the tube furnace was closed and before own heating of the sample, via the small “window” there was always performed the acquisition of image to check the position and scanned area. Finally, before the measurement of given stress-strain curves, the sample was heat up in the closed tube furnace on the relevant temperature.

There were used 7 testing temperatures - namely RT, 100 °C, 200 °C, 300 °C, 400 °C, 500 °C and 600 °C. As was already mentioned before, testing under RT was carried out with the high-accuracy axial extensometer (see **Figure 1a**). The other testing was performed with the help of tube furnace and camera. Due to the regulation of heating power, sometimes it was very time consuming testing (e.g. 3 hrs to get on 600 °C). After that, the experimental measurement of force F and absolute extension ΔL was started simultaneously.

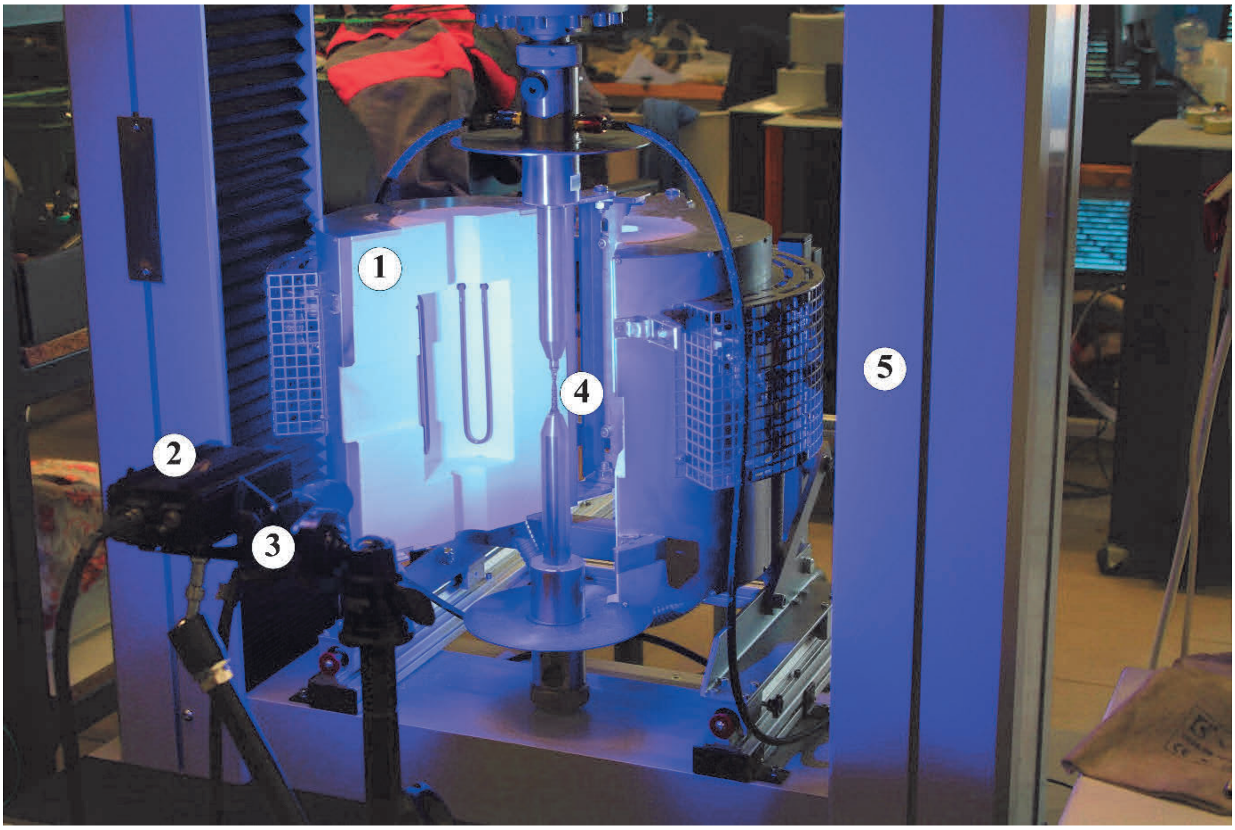
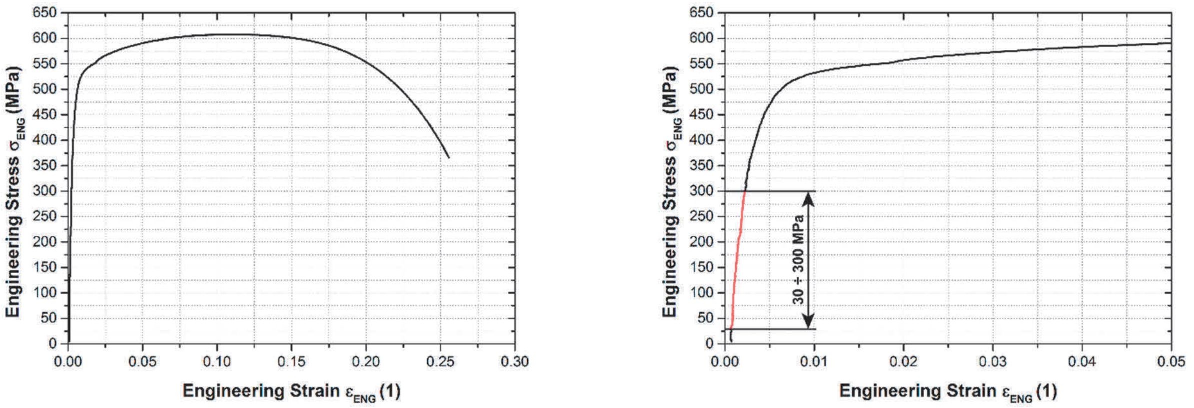


Figure 2 Workplace lay-out (1 - vertical split tube furnace SOP 40x200/140, 2 - lightning, 3 - camera, 4 - testing specimen, 5 - universal testing machine TESTOMETRIC FS100CT)

From the measured force-elongation curves were in the software LabNET computed relevant engineering stress-strain curves and determined mechanical properties (not mentioned here). In **Figure 3a** is shown such measured engineering stress-strain curve for testing temperature 100 °C. Subsequently, from the region of elastic deformation, there were within the interval from 30 MPa up to 300 MPa taken data to compute Young´s modulus *E* (MPa) by the least square method. Such procedure is shown in **Figure 3b**.



a) engineering stress-strain curve

b) detail of selected data within elastic deformation

Figure 3 Engineering stress-strain curve and detail of selected data range from 30 up to 300 MPa within elastic deformation - testing temperature 100 °C

Figure 4 shows these data within the interval from 30 up to 300 MPa (again for 100 °C). These “raw” data are shown in black colour. Red curve represents the applied linear fitting within this range, where the slope of this line is directly magnitude of the relevant Young´s modulus *E* (MPa). In this case (testing temperature of 100 °C) is such value equals to 178505 MPa. The same procedure was then used for all tested temperatures.

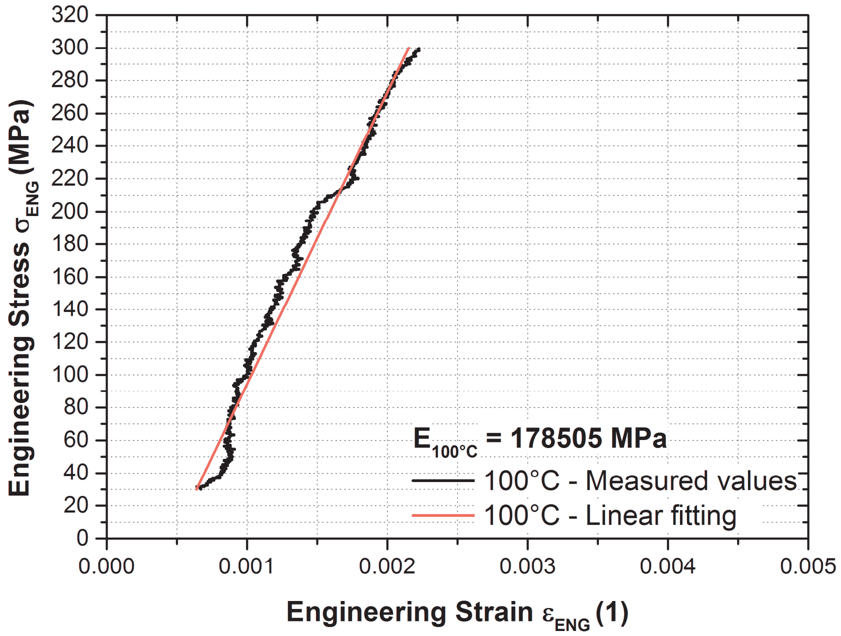


Figure 4 Linear fitting of measured data to obtain relevant Young´s modulus (here for 100 °C)

In **Table 2** are summarized all values of Young´s modulus in dependence on testing temperature. There were always tested 5 samples for one testing temperature, so as results there are used arithmetic mean x and standard deviation s. Moreover, there are also mentioned percentage values both with respect to RT (taken as 100 °C) and percentage differences between measured temperatures - thus per 100 °C.

Table 2 Young´s modulus vs. testing temperature for stainless steel DIN 1.4301

Testing Temperature ***T*** **(°C)**		**RT**	**100 °C**	**200 °C**	**300 °C**	**400 °C**	**500 °C**	**600 °C**
Young´s Modulus ***E*** **(MPa)**	arithmetic mean **x**	185035	178505	170892	163291	158997	146958	140709
	standard deviation **s**	457	895	954	942	1089	1124	1430
	Percentage regarding RT (per 100 °C)	100 %	96.47 % (-3.53 %)	92.86 % (-3.61 %)	88.73 % (-4.13 %)	86.40 % (-2.33 %)	79.85 % (-6.55 %)	76.46 % (-3.39 %)

Graphically are these results shown as column graph in **Figure 5**. There are illustrated average values and also standard deviations. Already from this graph (and **Table 2** as well) are evident two basic dependences. First is about decrease of Young´s modulus with increasing temperature as there was expected. Second variable means increasing standard deviation with increasing temperature. It seems that higher temperature has a negative effect on the accuracy of used optical system. At first, this effect looks to be not so important (increase by 973 MPa in light of standard deviation), but on the other hand, every determination of Young´s modulus is very sensitive on every device error and measurements (at least for 600 °C) should be repeated.

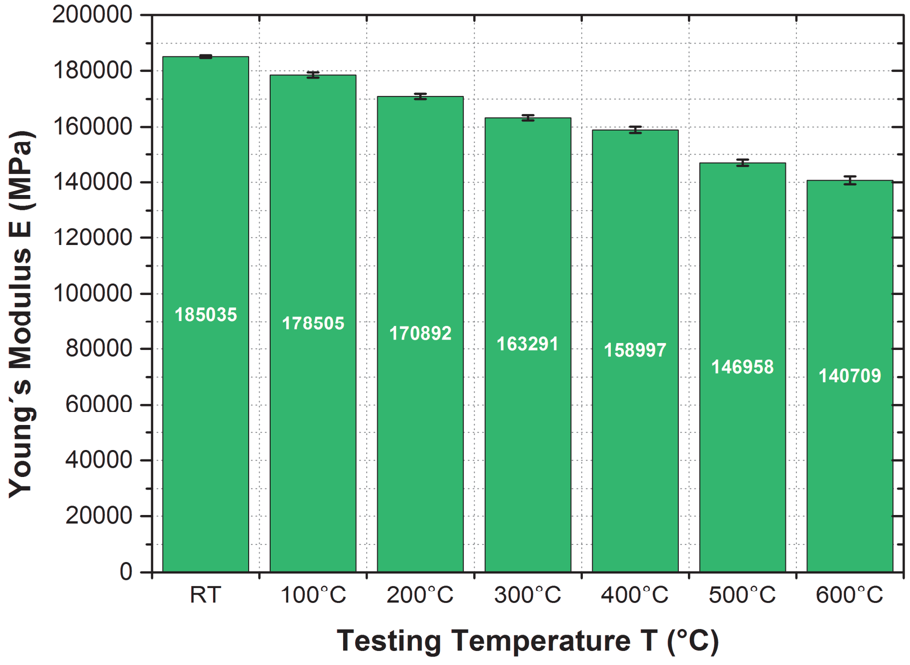


Figure 5 Young´s modulus vs testing temperature

4. CONCLUSION

Nowadays, it is quite common to apply non-contact extensometers at material testing. Nevertheless, there are problems with temperature influence on the accuracy of such optical systems. And just utilization of the contact-less optical system to scan specimen's extension upon loading force at elevated temperatures was also used in the experimental part of this paper. As a testing material, there was selected the stainless steel DIN 1.4301. Although acc. to Davies [7] can be stated, that stainless steels are not extensively used in the nowadays automobile industry, they have already found their place in many commercial vehicles (e.g. buses). Surely, their excellent corrosion resistance is taken as major advantage of stainless steel. Moreover, they reveal excellent formability (high magnitudes of uniform ductility and total ductility - almost without necking zone). On the other hand, they are quite expensive that is their major disadvantage. All of these properties were taken into account during selection testing material for this paper. Nevertheless, there is strong presumption about testing more material groups by experimental methods described in this paper. The major aim of this paper was to determine influence of testing temperature on Young´s modulus for austenitic stainless steel DIN 1. Two basic approaches were used to determine stress-strain curves, where their slopes in the elastic region represent the required magnitudes of Young´s modulus. First ("conventional") method was used only at RT and used high accuracy extensometer Epsilon. All other testing temperatures (from 100 °C up to 600 °C) were measured by the non-contact optical system Mercury. Mono-camera was used in this case. Subsequently, there was used the least square method to compute Young´s modulus within the stress interval from 30 up to 300 MPa. Results confirmed tendency of Young´s modulus to decrease with increasing temperature. It was lower by 76.46 % in comparison between RT and 600 °C. Steps between temperature intervals were mostly by 3.5 % - expect 500 °C, where it was by 6.5 %. These results also confirmed that there can be used photogrammetry to determine extension. On the other hand, it seems that sometimes there are some limits for such utilization, because standard deviation is much higher for 600 °C than RT or 100 °C. However, there should be used high temperature axial extensometers to prove such conclusion. Generally, there is effort to create 3D charts of mechanical properties dependences (with testing temperature as X-axis and strain rate as Y-axis) to be used in numerical simulations.

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