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The Influence of Temperature on the Physical and Structural Properties of X37CrMoV5-1 Steel: Numerical Model and Experimental Research

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This work concerns the theoretical and experimental study of the impact of temperature changes on the physical and microstructural properties of steel exposed to high temperatures. The study is performed, and a mathematical model is defined to determine the variable and temperature-dependent strength parameters. The article presents the experimental results obtained during a uniaxial tensile test (elastic modulus, yield strength, and tensile strength) in different thermal conditions. The heating process is done in an infrared oven at temperatures up to 1100°C. An MTS extensometer adapted to tests at high temperatures is used to measure strains. Microstructural tests and microhardness measurements are carried out for samples heated at various temperatures. Based on the obtained results, a numerical model of the static tensile test is developed using Abaqus/CAE software.

topics: tensile test, mechanical properties, heating

1. Introduction

Widely used in the tool and machine industry, X37CrMoV5-1 steel is known for its high strength and wear resistance. Its physical and structural properties are crucial for ensuring the reliability and durability of tools and components made of this material. One of the important factors influencing these properties is temperature, which can significantly change the microstructure and mechanical properties of the material. This article presents experimental studies on the effect of temperature on the physical and structural properties of X37CrMoV5-1 steel. Experimental studies were carried out on a universal static tensile tester, and numerical simulations were performed to obtain a full picture of the changes occurring in the material under the influence of different temperature conditions [1]. The numerical model allowed for the simulation of thermal and mechanical processes, while the experimental studies provided empirical data necessary for model validation.

The steel grade is widely used in various industrial sectors, including automotive, aerospace, and machine tools. Many cutting tool manufacturers use it to produce high-quality, durable, and wear-resistant tools. This steel is used for the production of tools for machining light metal alloys, for hot stamping, and for the production of nuts, rivets, and bolts. The stiffness and strength of steel components can decrease as a result of operation at elevated temperatures, which plays a key role in the design of fire resistance of steel structures. The properties of materials at elevated temperatures are specified in international specifications for steel structures, such as the European Standard (EC3), the American Specification (AISC Specification) and the Australian Standard (AS 4100). However, the properties of materials at elevated temperatures in these specifications are primarily based on experimental data conducted for hot-rolled normal-strength carbon steel [2]. Nowadays, numerical modelling is increasingly used in the initial stages of production.

2. Samples and infrared radiant heating chamber

The samples used for the static high-temperature tensile test are carefully prepared to ensure the accuracy and repeatability of the results. The samples are made in a cylindrical shape with threaded heads adapted to the ring grips according to EN ISO 6892-1:2009 (Fig. 1). The samples are mechanically processed to obtain the appropriate roughness of the measuring surface. It is important that the surface is smooth and free from defects that could affect the test results.

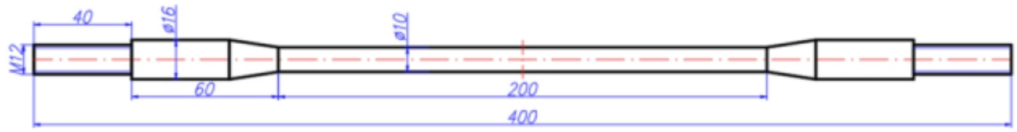

Fig. 1. Shape and dimensions of samples.

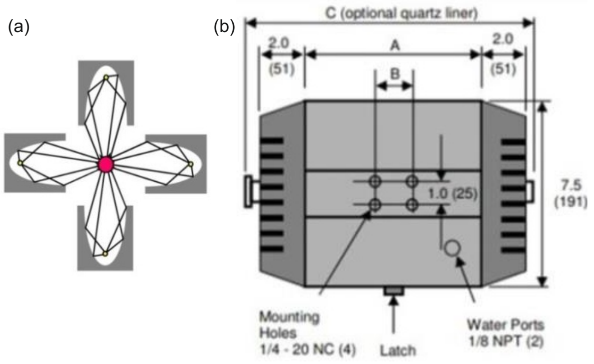

Fig. 2. Infrared heating chamber diagram (a) and dimensions (b).

TABLE I

Chemical composition of the tested steel.

C	Si	Mn	P	S	Cr	Mo	V
0.4	1.0	0.39	0.019	0.0020	5.14	1.18	0.36

An infrared heating chamber Model E4 is used in experimental tests of rod heating [3, 4]. Figure 2 shows a diagram of the heating chamber. The heating chamber allows for very quick heating of elements using highly concentrated infrared energy. This energy is generated by two halogen lamps and focused on the axis of the furnace using four elliptical reflectors. From a cold start, the lamps reach 90% of the operating temperature within 3 s. The device allows heating the elements up to 1100°C.

The samples were made of hot work tool steel X37CrMoV5-1 according to EN ISO 4957 in the annealed condition with a hardness of 215 (HB). Table I shows the chemical composition of the tested steel.

3. Measuring system

The universal testing machine Zwick/Roell Z100 with a maximum load of 100 kN and a precision of 1 N force/0.01 mm displacement (without extensometer, see Fig. 3) is used in the research.

The universal machine is coupled with a heating chamber that adjusts temperatures during the tensile test. The elongation measurement is carried out by determining the position of the movable cross-head and an additional MTS extensometer equipped with ceramic fingers that contact the tested sample inside the heating chamber during the measurement.

Fig. 3. Measurement system used in experimental tests.

In order to determine the strength properties (Young's modulus, elasticity and yield strength, ultimate tensile strength), a series of static tensile tests are carried out on samples with a circular cross-section and a threaded shank part [5]. The tests are performed for samples at the following temperatures: 20, 100, 200, 300, 400, and 600°C.

Numerical modelling may be a much more economical method of determining the strength properties of materials subjected to thermal loads.

4. Numerical modelling

Numerical simulations were performed in Abaqus. The results of experimental tests were used to build the numerical model. The calculations were limited to two different heating temperatures of 20°C and 200°C. A discrete model was developed according to the dimensions shown in Fig. 1.

Fig. 4. Numerical model of the sample.

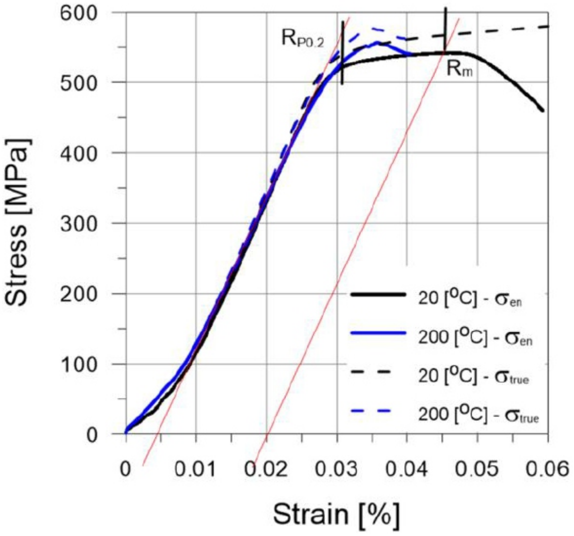

Fig. 5. Comparison of stress–strain diagrams (engineering and true).

Figure 4 shows the finite element method (FEM) mesh adopted for calculations. The mesh element dimension is 0.5 mm. In the calculations, the boundary conditions were assumed in accordance with the conditions occurring in the experiment. Based on the stress–strain diagram for the samples, a numerical model was developed for the X37CrMoV5-1 material (Fig. 5). The Abaqus program requires the input of material plasticity data in the real system [6, 7].

Figure 5 shows a comparison of the stress–strain curves obtained from the testing machine and after conversion to the true stress–strain of the system. The loading force in the program was implemented by assigning a displacement value consistent with experience.

5. Results

Numerical calculations were performed for both analyzed sample heating temperatures. Figure 6 shows the longitudinal displacement field for the sample heated to 20°C. Based on the material plasticity and fracture data entered into the calculations, a material fracture was obtained that was comparable to that obtained in the experiment.

Based on the calculations, numerically estimated stress–strain curves were generated for the numerically analyzed sample and are presented in Fig. 7.

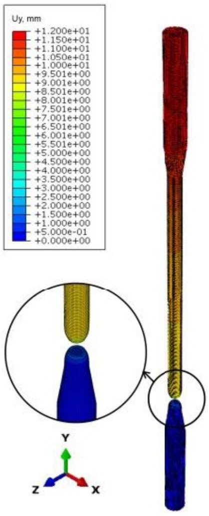

Fig. 6. Result of numerical simulation.

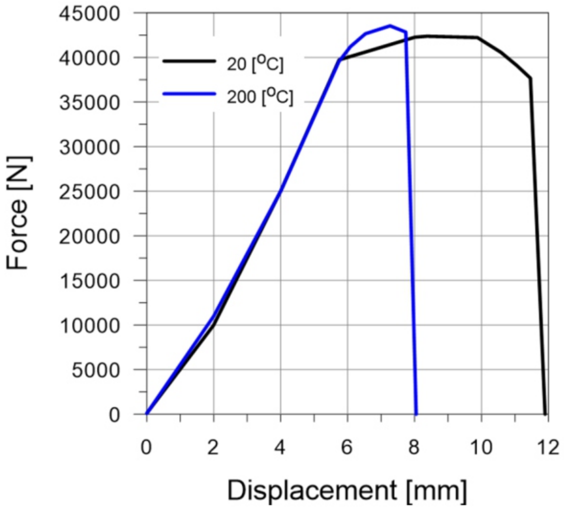

Fig. 7. Numerically predicted stress–strain curves.

The obtained curves are consistent with the experimental curves. This proves the correctness of the developed numerical model.

6. Conclusions

The analysis of the research results allows for a better understanding of the mechanisms influencing the properties of X37CrMoV5-1 steel at different temperatures, which is of great importance for the optimization of technological processes and the design of durable and reliable tools and components. The results presented in the article can be a valuable knowledge base for engineers and scientists dealing with materials science and heat treatment technology.

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