Microstructure influence on high temperature deformation of low carbon martensitic steel

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Abstract. Shaping of workpieces by the methods of plastic deformation is an advanced technology of fabrication of large dimension parts. In order to optimize the process of manufacturing, the optimal conditions of plastic deformation should be chosen based on knowledge of low carbon martensitic steel specific properties. In the present paper the influence of microstructure on high temperature deformation is investigated based on experimental data for 03Cr13Ni4Mo steel.

1. Introduction

Low carbon martensitic steel has extremely low carbon content and economy alloying, it provides a rare combination of properties of high corrosion resistance, strength and good weldability [1]. These types of steel are widely used in the oil, gas and hydropower industries. For example, they are used for the fabrication of parts of hydraulic turbines. One of the advanced manufacture methods of large dimension parts from this type of steel is the plastic or superplastic deformation. The usual temperature for such methods is from 800°C to 1100°C. However, martensitic steels undergo a phase transformation when heated [2]. It is known that structural transformations lead to substantial changes in the plastic properties of a material. Hence, it is expedient to investigate the influence of the structure of supermartensitic steel on its behavior at elevated temperatures in order to choose the optimal condition of deformation.

Due to the wide application of low carbon steels in welded structures a lot of works, for example, by Kleyner L.M. [1], Ma K.P. [3], Lee Y. S. [4], Courage D. [5] and others [6-7], are dedicated to the special features of microstructure and weldability properties of these steels as well as investigation mechanical properties at room temperature after welding or heat treatment [8-9]. However, only a few works describe the mechanical properties of these steels at high temperatures [10-11]. For example, the work by Bogachev I.N. [11] was devoted to the investigation of the temperature and grain size influence on the elongation of low carbon martensitic steel. In the present paper, the influence of the structure features on the high temperature deformation of low carbon supermartensitic 03Cr13Ni4Mo steel is investigated.

2. Investigation of microstructure special features influence on high temperature deformation

Optical and electron microscopes were used to study the microstructure. Steel 03Cr13Ni4Mo has the martensite structure at room temperature with grain size 2-7µm, figure 1, and the inclusion of delta-

ferrite. The presence of delta-ferrite in low carbon steels depends on heat treatment and the manufacturing method and can affect the kinetics and mechanism of phase transformations.
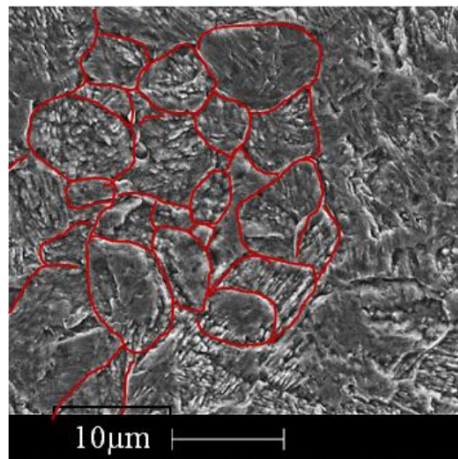

Figure 1. Microstructure of low carbon supermartensitic steel (martensite grains boundaries are highlighted with the red lines).

The dilatometric method was used to study structural transformations with continuous heating [12]. The dependence of austenite quantity on temperature was obtained by the analysis dilatometer curve using lever rule [13]. The morphology of the structure was studied using optical and electron microscopes and is consistent with data from earlier studies [3,5]. The phase transformation of martensite to austenite with continuous heating at a rate of 10°C/min occurs in the temperature range 680°C (A_{c1}) - 850°C (A_{c3}).

Based on the experimental data and the results of previous studies [1,5,9], it was found that when heated over A_{c1}, phase transformation of martensite to austenite begins, when small austenite grains are formed on the boundaries of the martensite plates and grains, figure 2a. Taking into account the specific properties of austenite and martensite at such temperatures, the structure of steel can be considered as dispersion-strengthened. With a further temperature increase to A_{c3}, the main phase is austenite, and the steel structure can be considered as austenitic with inclusions of martensite grains, figure 2b, c. It was also found that the latter undergoes a phase transformation the region around delta - ferrite. This is due to the fact that the decrease in nickel content was observed near delta-ferrite, which affects the rate of phase transformation. At temperatures above A_{c3}, only the austenitic phase exists. Thus, we can identify three types of phase morphology depending on temperature: single-phase with a known grain size (martensite ($<A_{c1}$) or austenite ($>A_{c3}$)); dispersion-strengthened martensite matrix (A_{c1} - A_{c3}); austenite phase with inclusions of martensite (A_{c1} - A_{c3}).

The high-temperature tensile tests were performed to determine the effect of the phase composition on the thermo-mechanical properties of supermartensitic steel. The mechanical experiments were conducted before failure at a constant strain rate in the temperature range from 680°C to 950°C. It has been established experimentally that the characters of the dependences of stresses on deformations for the martensitic and austenitic phases are very different. The deformation curves at temperatures of the austenitic phase demonstrate noticeable hardening of material, then a small region of constant stresses is observed, and then a long gradual decrease in stress until final failure, figure 3. Deformation at temperatures of the martensitic phase occurs without appreciable hardening, which indicates different deformation mechanisms. The results obtained are consistent with the results of earlier studies [9-11,14].
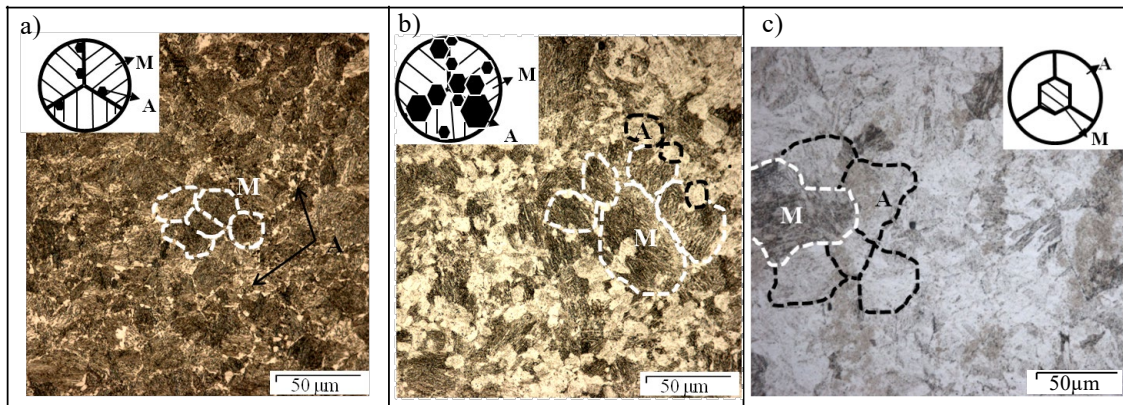
Figure 2. Morphology and microstructure of steel, depending on temperature (with continuous heating at a rate of 10°C/min): a) a martensitic grains with small austenitic grains on the boundaries, b) austenite-martensite structure, c) austenite structure with inclusions of martensite grains.
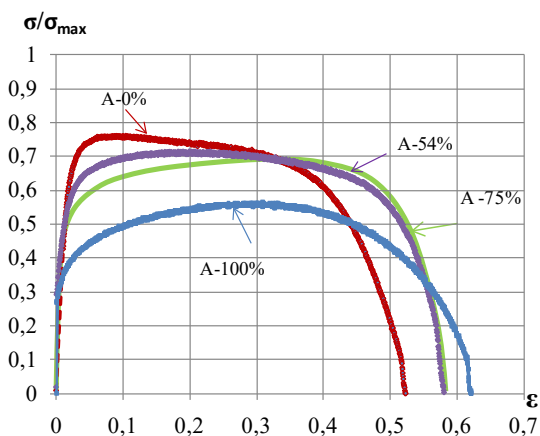

Figure 3. Deformation curves for tensile tests at different temperatures.

Based on experimental data, it was discovered that the phase composition and morphology of the phases significantly affect the mechanical properties. Therefore, for each of the phases (austenite and martensite), it is necessary to determine the state equation. And in the two-phase temperature range we should use such combinations of these equations, which take into account the morphology of the structure.

The most appropriate description of the deformation curves of the austenitic phase corresponds to the theory of creep hardening [15]:

$$\sigma_A = A_A \xi^{m_A} \varepsilon^{n_A} \tag{1}$$

where σ_A is the stress; ε is the creep deformation; ξ is the creep deformation rate; A_A is the experimental material constant; m_A is the parameter, characterizing strain rate sensitivity of the austenitic phase, n_A is the parameter, characterizing hardening of the austenitic phase.

For the most accurate description of steel properties, as well as to determine the mechanism of deformation, the dependence of grain size, temperature, and deformation activation energy on the stress was introduced into the equation:

$$\sigma_A = \left(B_A / d_A^{p_A} \right) \xi^{m_A} \varepsilon^{n_A} \exp\left(Q_A m_A / RT \right) \tag{2}$$

where B_A is the experimental material constant, d_A is the grain size of austenite, p_A is the parameter, characterizing sensitivity to grain size of the austenitic phase, Q_A is the deformation activation energy of the austenitic phase, R is the universal gas constant, T is the testing temperature.

However, equation (2) describes only homogeneous deformation of sample. Therefore, the damage parameter, ω, was introduced, to take into account the necking formation and the fracture process. The damage parameter ranges from 0 to 1, where, 0 is no damage, 1 is failure, to take into account the damage of sample.

$$\sigma_A = (1-\omega)^k \left(B_A / d_A^{\,p_A}\right) \xi^{m_A} \varepsilon^{n_A} \exp\left(Q_A m_A / RT\right) \tag{3}$$

where k is experimental constant; ω is damage parameter.

The theoretical curve, calculated by the equation (3), is shown on figure 4 by a dashed line, the experimental curve is represented by a solid line. As can be seen from the comparison of the curves, the theoretical curve is consistent with the experimental one.
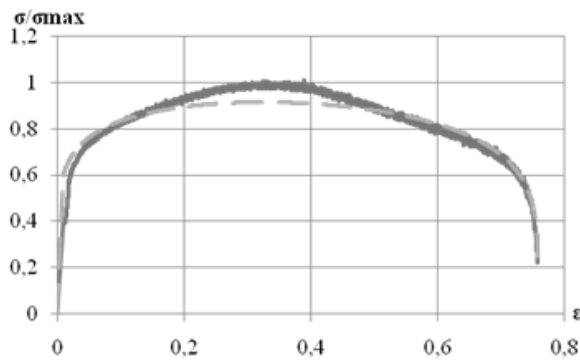

Figure 4. The deformation curve at 880°C (taking into account the fracture): solid line is the experimental data, dashed line is the theoretical curve.

To describe the behavior of the martensitic phase, the expression similar to equation (3) was used, taking into account that the martensite deformation curve shows no hardening of material [16]:

$$\sigma_M = (1-\omega)^k \left(B_M / d_M^{\,p_M}\right) \xi^{m_M} \exp\left(Q_M m_M / RT\right) \tag{4}$$

where B_M is the experimental material constant, d_M is the grain size of martensite, p_M is the parameter, characterizing sensitivity to grain size of the martensitic phase, m_M is the parameter, characterizing strain rate sensitivity of the martensitic phase, Q_M is the deformation activation energy of the martensitic phase.

In the two-phase temperature range, in accordance with morphology, two types of relations were used: the equation describing the dispersion-strengthened structure and the equation of state as the sum of stresses of the austenitic and martensitic phases. In accordance with the experimental data, figure 2a, b, the temperature of the beginning of the phase transformation is characterized by the microstructure, which can be considered as a martensite matrix reinforced with small austenite grains. The behavior of the material can be described by the following equation of state, provided that the second phase does not form a closed structure in the material and does not deform [17-18]:

$$\sigma_1 = (1-f)^{-h(m1)} \sigma_M \tag{5}$$

where f is the volume fraction of austenite at a given temperature (T), $h(m1)$ is the index of the hardening function, σ_M is the stress of martensitic phase, defined by the equation of state (4).

At temperatures at the end of the phase transformation, the microstructure consists of the martensitic and austenitic phases, figure 2c. Since the results of microstructural analysis of the samples after deformation at these temperatures showed that there are no discontinuities at the phase boundary, we can assume that the deformations of martensite and austenite are equal. Based on these facts, the equation of state can be written as the sum of stresses of the austenitic and martensitic phase [19–20]:

$$\sigma_2 = f\sigma_A + (1-f)\sigma_M \tag{6}$$

where f is the volume fraction of austenite at a given temperature (T), σ_A is the stress in the austenitic phase, defined by the equation of state (3), σ_M is the stress in the martensitic phase, defined by the equation of state (4).

Thus, using equations (3) - (6), we can describe the behavior of low carbon supermartensitic stainless steel in the temperature range from 680°C to 950°C. The research results showed that the structure of steel strongly affects the behavior of the material at high temperatures. The influence of temperature on maximum tensile stresses and deformations before failure is shown on figure 5.
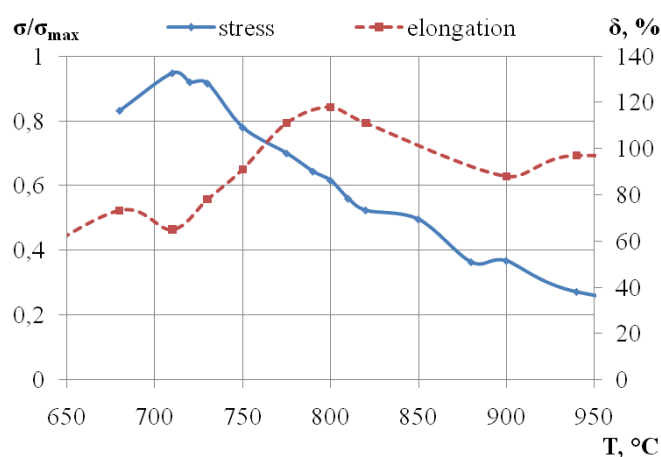

Figure 5. Maximum stresses and maximum strain to failure, depending on temperature.

The maximum stress decreases with increasing temperature, while the maximum deformation before failure increases, figure 5. However, maximum deformation strongly increases only until the end of the phase transformation temperature, A_{c3}. Based on this it can be concluded that the presence of the second phase during deformation allows obtaining the stable fine-grained structure. Therefore, the deformation in the two-phase temperature range may be of practical interest.

3. Conclusion
Experimental studies allowed to identify structural features and show its influence on the high-temperature deformation of low carbon supermartensitic steel, and also specify the equations of state that take into account the morphology of the phase of steel at a given temperature. The results of these studies can be used to determine the optimal condition of workpieces deformation from low carbon supermartensitic steel 03Cr13Ni4Mo.

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