Damage accumulation in supermartensitic stainless steel during plastic deformation

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Abstract. Supermartensitic stainless steel usually used in the oil, gas and hydropower industries. In order to optimize the process of manufacturing of workpieces from these steels, damage accumulation was investigated in supermartensitic stainless steel during plastic deformation. In the present paper dependence of damage on plastic strain, grain size and strain rate is presented based on experimental data for 03Cr13Ni4Mo steel. Also the modeling method of damage calculation due to critical pore accumulation is proposed.

1. Introduction
Supermartensitic stainless 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. The methods of manufacture of large dimension parts from this type of steel are the plastic or superplastic deformation at temperatures from 800°C to 1050°C. Hence, it is expedient to investigate the effect of temperature and rate of deformation on the accumulation of damage during plastic deformation of supermartensitic stainless steels. The damage accumulation which leads to fracture, could be associated with the number of pores per unit area of the undeformed grain face. Whereas the pore nucleation rate is mainly controlled by the intensity of the rate of inelastic deformation and temperature.

Due to the wide application of low carbon steels in welded structures, a lot of works are dedicated to the special features of microstructure [1-3], transformation [4-5] and weldability properties of these steels as well as investigation mechanical properties at room temperature after welding or heat treatment [6]. Some works describe the mechanical properties of these steels at high temperatures [7-8]. In this work, the influence of the structure features on the damage accumulation of supermartensitic 03Cr13Ni4Mo steel is investigated.

2. Investigation of the influence of grain size and strain rate on the fracture behavior of samples
Steel 03Cr13Ni4Mo at room temperature has a stable martensitic microstructure, and during heating it undergoes a phase transformation from martensite to austenite [2,3]. The mechanical experiments were carried out before failure at a constant strain rate in the temperature range from 680°C to 950°C to determine influence of grain size and strain rate on the damage accumulation in steel.
The deformation curve at temperatures of 800°C is presented in Figure 1. It should be noted, that deformation curve shows noticeable hardening of material, then a small region of constant stresses is observed, and then a long gradual decrease in stress until final failure. This dependence is characteristic of austenitic steels, which are consistent with the results of earlier studies [2,4,7-8]. Long-term stress reduction can be associated with the process of the neck formation.

![Deformation curves for tensile tests at temperature of 800°C.](image)

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The microstructure after mechanical experiment was observed in several place of the sample as shown in Figure 2, to determine the fracture behavior. Optical and electronical microscopes were used to observe the fracture zone after tensile tests.

![Scheme of the determination uniform deformation and necking zone.](image)

**Figure 2.** Scheme of the determination uniform deformation and necking zone.

The microstructure of the samples was revealed by chemical etching. Etching reagents were prepared in accordance with the recommendations of [9] and according to GOST 5639-82. The zones of observation are a zone of uniform deformation and a neck zone. The determination of these zones in the sample is shown in Figure 2.

The microstructure in the uniform deformation zone was studied to investigate the evolution of the microstructure during the tensile test since in this area the deformation and the rate of deformation are uniform. The microstructure in the neck area was analyzed to determine the mechanism of fracture, as well as the effect of temperature and strain rate on the damage accumulation.

A comparison of the microstructure of uniform deformation zone and the neck area is shown in Figure 3. In the initial state, the samples consist of large martensite grains, while microstructure of the uniform deformation zone of the sample after elongation revealed small grains of light contrast and larger grains of dark contrast. Also a noticeable decrease of the grain size in the neck area that is associated with dynamic recrystallization, as the strain rate is not constant in the neck area. The difference in contrast between initial and after deformation microstructure can be associated with retransformed grains [10,11]. As deformation is performed in full austenite zone initial martensite grains transformed to austenite grains but during cooling, microstructure came back to martensite with new-martensite grains. However, the new-martensite grains have some difference in chemical composition compared to initial martensite grains due to diffusion during phase transformation and deformation. That difference is shown in contrast during the microstructure etching [13]. Size of grain
at which performed deformation and size of grain which can be observed at room temperature is
different. However, martensite grain size at room temperature has a direct connection to austenite
grain size.

Figure 3. Comparison of the microstructure in the area of uniform deformation (a) and in the necking
zone (b) (optical microscope).

Figure 4 shows the fracture zone of samples at different temperatures of deformation. The neck of
the samples is presented in black and white contrast in order to qualitatively and quantitatively
investigate the presence of cavitations. The white areas inside the samples are cavities.

Figure 4. Cavities in the necking zone of samples after test at 800°C and 940°C.

Samples tested at 800°C and at 940°C have different grain sizes, which have a strong influence on
the shape of the neck and the formation of cavities. The sample at 800°C reveals strongest necking than
at 940°C that assumed to be the effect of not transformed martensitic grains. Decreasing of the cross
section is measured at 150 μm from the fracture, and it is 700 μm and 1190 μm, respectively. The
shape of the neck after testing at 940°C is irregular and the narrowing of the cross section is
insignificant relative to the zone of uniform deformation, which may indicate an intensification of the
processes of pore formation with increasing temperature. The sample after deformation at 940°C, has a
larger number and a larger pore size. At 800°C, the pores are elongated in the direction of elongation,
while at 940°C they look less oriented.

As these samples have a close history of loading and strain is in range 0,7-0,78 amount of cavities
was calculated like the relation of “white” area to “black” area at given distance from fracture with a
step of 1mm. Results are shown in Figure 5. The sum of the cavities was calculated at a given distance
from the rupture line with a step of 1 mm.

Figure 5 shows that amount of cavities decrease with distance from fracture and in uniform
defor mation zone (2mm) is stable and insignificant. As it was seen from microstructure observation at
940°C the amount of cavities is higher than at 800°C. It is also worth noting that a decrease in the
grain size leads to a decrease in not only the pore size but also their number. The sample after
elongation at 800°C has an average grain size of 20 μm and about 1% of pores in the neck area, and
the sample after elongation at 940°C has an average grain size of 35 μm, while the number of pores increases almost 3 times.

![Figure 5. The amount of cavities (%) depends on distance from fracture zone.](image)

It is assumed that the decrease in the grain size in the neck zone is associated with dynamic recrystallization in order to this the effect of strain rate on fracture was investigated. Figure 6 shows the dependence of the strain to failure as a function of the strain rate.

![Figure 6. The dependence of the strain to failure on the strain rate at 800°C.](image)

3. The modeling method of damage accumulation

The main mechanism of fracture is the damage accumulation along the grain boundaries. According to [14], a polycrystalline material is considered as a continuity of elementary cubic volumes with a size equal to the grain diameter, d. The measured stress, σ, in the process of uniaxial elongation differs from the effective stress, σ_{ef}, as follows [15]:

\[
\sigma_{ef} = \sigma \frac{1}{1 - A_c}
\]  

(1)

where \( A_c \) is the relative cross-sectional area, which is the ratio of the pore area to the area of the deformed surface of the grain.

The condition of the elementary volume failure with pores can be taken in the form:

\[
\frac{d\sigma}{d\varepsilon_p} = 0
\]

or

\[
(1 - A_c) \frac{d\sigma_{ef}}{d\varepsilon_p} - \sigma_{ef} \frac{dA_c}{d\varepsilon_p} = 0
\]

(2)

where \( d\varepsilon_p \) is increment of plastic deformation corresponding to the increment of stress, dσ. The pore nucleation rate can be represented as [14]:

\[
\text{pore nucleation rate} = \frac{dA_c}{d\varepsilon_p}
\]
\[
\frac{d\rho}{d\varepsilon_p} = C(T)(\rho_{\text{max}} - \rho)
\]

(3)

where \( \rho \) is the number of pores per unit area of the non-deformed grain, \( \rho_{\text{max}} \) is the maximum number of pore nucleation sites per unit area, \( C(T) \) is the material constant dependent on temperature.

The subsequent growth of pores caused by plastic deformation and diffusion, with a transition from a spherical shape to a lens shape, is presented in [16–17] as follows:

\[
\frac{dV}{d\varepsilon_p} = \frac{3}{2}\pi R^3
\]

(4)

where \( R \) is the radius of the pore, \( V \) is volume of the pore:

\[
V = \frac{4}{3}\pi R^3 \varphi(\alpha), \text{where } \varphi(\alpha) = \left(\frac{1}{1 + \cos \alpha} - \frac{\cos \alpha}{2}\right)\sin \alpha
\]

where \( \alpha \) is the angle between the tangent to the surface of the pore and the grain boundary.

Thus, the pore growth equation can be written as:

\[
\frac{dR}{d\varepsilon_p R} = \frac{3}{8} \varphi^{-1}(\alpha)
\]

(5)

Using the equations of mass and the above relations (3) and (5), we establish the expression for the relative pore area:

\[
A_c = \left[1 + \frac{V_c}{d}\right]^\frac{2}{3} S_c
\]

(6)

where

\[
V_c = \frac{4}{3}\pi R^3 \varphi(\alpha) \int_0^{\varepsilon_p} R^3 \rho d\varepsilon_p
\]

\[
S_c = \pi \int_0^{\varepsilon_p} R^2 \rho d\varepsilon_p
\]

Using the relation (6) and having the equation of state of the material, we fulfill the condition (2) and thereby find the failure deformation \( \varepsilon_f \). Accumulated damage can be calculated as:

\[
D = \int_0^{\varepsilon_f} \frac{d\varepsilon_p}{\varepsilon_f \left(\frac{\varepsilon_f}{\varepsilon_p}\right)}
\]

(7)

4. Conclusions

Experimental studies revealed the dependence of damage accumulation in the form of pores during plastic deformation on temperature and strain rates. It was found that temperature significantly affects the process of pore formation, as well as the neck formation and failure behavior. The results of the study can be used to determine the mode of deformation, in which dynamic recrystallization will occur in a homogeneous zone, which can significantly increase the deformation before fracture. A model for assessing fracture due to critical pore accumulation is proposed.
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