Study of Localized Plastic Deformation of Stainless Steel Electrically Saturated with Hydrogen

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Abstract. The effect of hydrogen embrittlement on the mechanical properties and plastic flow localization parameters in tensile tested corrosion resistant high-chromium steel has been investigated. The studies were performed for the original test samples of high-temperature tempered steel with sorbitic structure and after electrolytic hydrogenation for 6, 12 and 24 hours. It is found that the mechanical properties of stainless steel are affected adversely by hydrogen embrittlement. With the registration of the loading curve plastic-strain localization patterns were studied using a double-exposure speckle photography method. The hydrogenated counterpart of alloy has a lower degree of ductility relative to the original alloy. However, the plastic flow is of localized character and the evolution of localized-strain center distributions follows the law of plastic flow. The autowave parameters (autowave velocity and autowave length) were measured for the every state of high-chromium steel under investigation and the difference between them is of grate significance. The velocity of ultrasonic Rayleigh waves was measured simultaneously in the investigated steel in tension. It is shown that the dependence of the velocity of ultrasound in active loading is determined by the law of plastic flow, that is, the staging of the corresponding diagram of loading.

INTRODUCTION

This work objective is to study the interstitial hydrogen atoms impact to the wave parameters. The commonly accepted concepts of the process of plastic deformation are based on a great number of experimental evidence for different metals and alloys suggests that plastic deformation is always nonuniform and localized [1-4]. The localization obeys the law of plastic flow, i.e. it is determined by deformation stages of metal's deformation diagram, by the work-hardening coefficient $\theta(\varepsilon)$ in particular. In this case the study of hydrogen impact to the deformation behavior of engineering materials is of great importance.

Widely used high-chromium stainless steel possesses an appealing combination of strength and plastic properties, corrosion resistance in atmospheric, water-vapor, aquatic, and (on numerous occasions) acid environments, and is compositionally simple. In addition with low cost it gives rise to its widespread production for critical machine parts and as a structural metal, especially under exposure of atmospheric, aquatic and acid environments and other sever atmosphere with present of hydrogen, for example a chemical reactor or oil and gas equipment. Hence, knowing a hydrogen impact on stainless steel behavior under stress conditions is of great importance for critical machine parts and structural members reliability. Certification of this kind of materials makes

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it essential to determine the following characteristics: ductility margin, life time, and fracture mode, all being dependent in many respects on strain-localization patterns [1, 5]. The deformation behavior of high-chromium steel was investigated in [6].

As it mentioned above the plastic deformation process is found to be of a localized character and its evolution is in a strict correspondence with the deformation stage and the governing microscopic mechanism. By the way the determination of the boundaries of these stages and the corresponding mechanisms presents a complicated problem, especially for polycrystals, because, in most cases, reliable and informative external manifestations of the changes in the deformation mechanisms are absent. In this case acoustical methods of studying the properties of solids are quite promising [9-12]. In this case the velocity of ultrasound wave propagation, a kind of surface acoustic waves, is ideally suited to solve the problem.

From this point of view the deformation behavior and the variation of the propagation velocity of ultrasound in the plastic deformation of corrosion-resistant high-chromium steel electrically saturated with hydrogen have been studied.

EXPERIMENTAL PART

The investigation was performed for the test samples of a high chromium stainless steel (0.4%C–0.6%Si–0.55%Mn–12.5%Cr). The test samples having dog-bone shape with gage section of 50×10×2 mm were cut out from sheet steel along the rolling direction. After quench process at temperature T=1320 K for 3 hours with fast air-cooling this steel has a good corrosion resistance due to homogenization via intergranular carbides dissolving. For the structural metal this steel should be tempered at temperature T=873 K for 3 hours and furnace cooling. to increase plasticity [9]. Such treatment provides sorbitic structure (ferrite and carbide). The specimens thus prepared were subjected to electrolytic hydrogenation during 6, 12 and 24 hours.

The electrolytic hydrogenation of alloy samples was carried on for 24 h and 96 h under a controlled cathode potential. The sample was placed in an three-electrode electrochemical cell containing 0.1N sulfur acid solution to which 20 mg/l thiocarbonic acid diamide had been added to enhance the process at 323 K [13-15]. The electrochemical cell was equipped with a graphite anode; a chorine silver reference electrode was connected in the circuit to maintain a constant potential U= – 600 mV. To control the three-electrode cell and run the electrochemical reaction, a Potentiostat IPC-Compact unit was employed. Time between hydrogen charging and tensile testing did not exceed 30 min and testing time was less than 60 min.

The mechanical tests were carried on at the rate $6.67\cdot10^{-5}s^{-1}$ at room temperature in a universal testing machine LFM-125 (Switzerland). Displacement vector fields of points on the surface of the specimens were recorded by double-exposure speckle photography. Analysis of the spatial-periodical distribution of local elongation ε_{xx} of the specimen observed in the linear-hardening stage allows us to estimate the autowave spacing λ and velocity $V_{aw} = dX/dt$ as well.

Simultaneously with the processes mentioned above the velocity of ultrasonic surface waves (Rayleigh waves) was measured for the investigated steel in tension using an OWON RDS6062S device. The principle for measuring the velocity of propagation of Rayleigh waves is based on the pulse autocirculation method [11]. The error of the measurement amounts to 2×10^{-4}, and operation with the instrument does not require any special skills on the part of the operator. The basic principle of the autocirculation method consists of setting up a closed circuit to transmit the pulses. A radiating piezoelectric transducer, when acted upon by a short electric pulse, generates an acoustic wave in the sample. The wave traveling from the transmitting piezoelectric transducer to the receiving piezoelectric transducer is converted back into an electrical signal and again arrives at the radiating transducer. Hence, keeping the distance between the transducers fixed, the frequency at which a pulse appears at a certain point of the circuit will depend on the time taken for the acoustic signal to travel through the sample and the delay in the circuit. Since the delay in the circuit is negligibly small compared with the propagation time of the acoustic wave in the sample, the autocirculation frequency will characterize the velocity of propagation of the ultrasonic wave in the sample. In this case the Rayleigh surface waves have a frequency of 5 MHz.

The ultrasonic sensor, placed on the object being investigated, has two inclined piezoelectric transducers, situated at a fixed distance from one another, called the base. The inclination of the piezoelectric transducers is chosen in such a way that a surface Rayleigh wave is generated in the object. For reliable measurement of the velocity, it is necessary to ensure that the contact with the metal of the article being monitored is clean, the surface must be smooth, and the sensor must be pressed tightly in position. Acoustic contact with the piezoelectric transducer is provided by a no aggressive liquid lubrication, for example, transformer oil. One must bear in mind that the space between the piezoelectric transducers must remain dry and clean.

RESULTS AND DISCUSSION

The stress-strain curves obtained for the tempered material and after its hydronization in the electrolytical cell are shown in Figure 1.

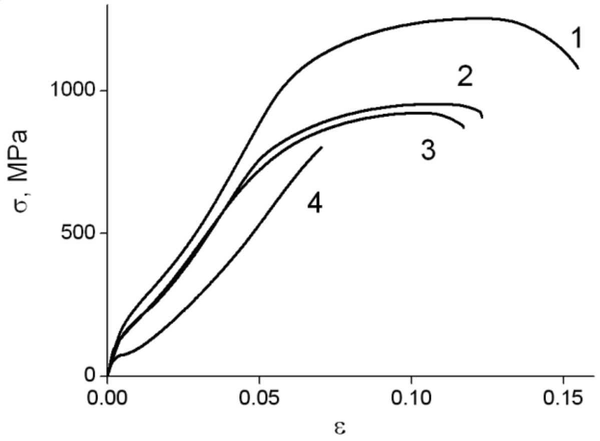


FIGURE 1. Stress-strain curves for high-chromium steel in the tempered state (1) and after electrolytic hydrogenation during 6 hours (2), 12 hours (3) and 24 hours (2)

Hydrogen charging of tempered steel test samples for 6, 12 and 24 hours results in remarkable changes of stress-strain curves. It is found that a 70 % decrease in the yield stress and 40% in the ultimate stress is observed for the counterpart subjected to hydrogenation for 24 hours, see curve 4, relative to the tempered samples of stainless steel, see curve 1, Figure 1. From the obtained stress-strain curves one can conclude that hydrogen has reduces markedly the elongation to the fracture of specimen. It is also found that a 67 % decrease in the in the elongation to rupture is observed for the counterpart subjected to hydrogenation for 24 hours relative to the tempered alloy.

The stress-strain curve for the alloy under review refers to diagrams for the general type and therefore can be described by the Lüdwick equation, see e.g. [16]

$$\sigma = \sigma_0 + \theta\varepsilon^n \qquad (1)$$

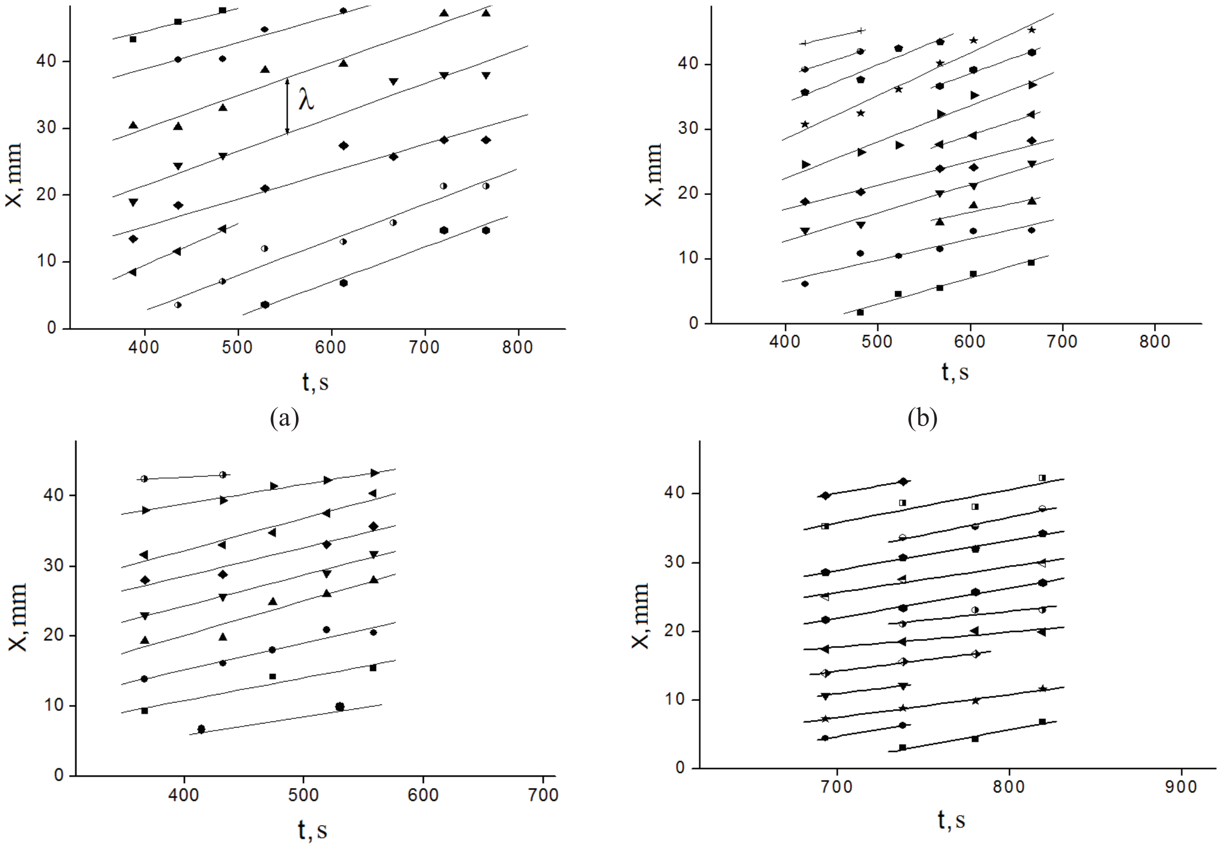
where σ_0 is a critical share stress, $\theta = d\sigma/d\varepsilon$ is a work hardening coefficient expressed in units of MPa as is a stress, and n is the work hardening exponent. Using the method reported in [7], the loading curve can be represented in the system of logarithmic coordinates as $\ln(s - s_0) - f(\ln e)$ (here *s* is the true stress which takes no account of reduction in the work cross-section and *e* is the true deformation). This enables individual segments to be singled out on the curve for a constant value of the exponent *n*, which varies discretely on going from one segment to the next. All the loading diagrams obtained in this study were analyzed by the above method. In addition one can single out linear-hardening flow stage from deformation diagrams by work hardening coefficient *θ*, as far as within the linear stage $\theta = d\sigma/d\varepsilon = const.$

The quantitative data on mechanical characteristics and deformation stages of alloys are listed in the Table 1.

TABLE 1. Mechanical characteristics of high-chromium stainless steel

	$\sigma_{0.2}$, MPa	**σ_B, MPa**	**δ, %**	**Linear hardening stage**	
				ε_{ini}	**ε_{fin}**
Tempered steel	206	1251	15.3	0.035	0.050
Hydrogenated within 6h	168	953	12.3	0.034	0.042
Hydrogenated within 12h	132	922	9.8	0.025	0.037
Hydrogenated within 24h	73	798	4.7	0.047	0.058

Using double-exposure speckle photography spatial distribution of local elongation of the specimen observed in the linear-hardening stage can be obtained for the tempered state and after electrolytic hydrogenation for 6, 12 and 24 hours respectively. The sequence of coordinates for each of the localized plastic deformation domains in this stage is approximated by nearly parallel straight lines, see Figure 2, where the slope of the curves enables the velocity of the domains to be estimated $V_{aw} = dX/dt$. The autowave length λ was found from the curve spacing measured along the axis X.



(a) (b)

(c) (d)

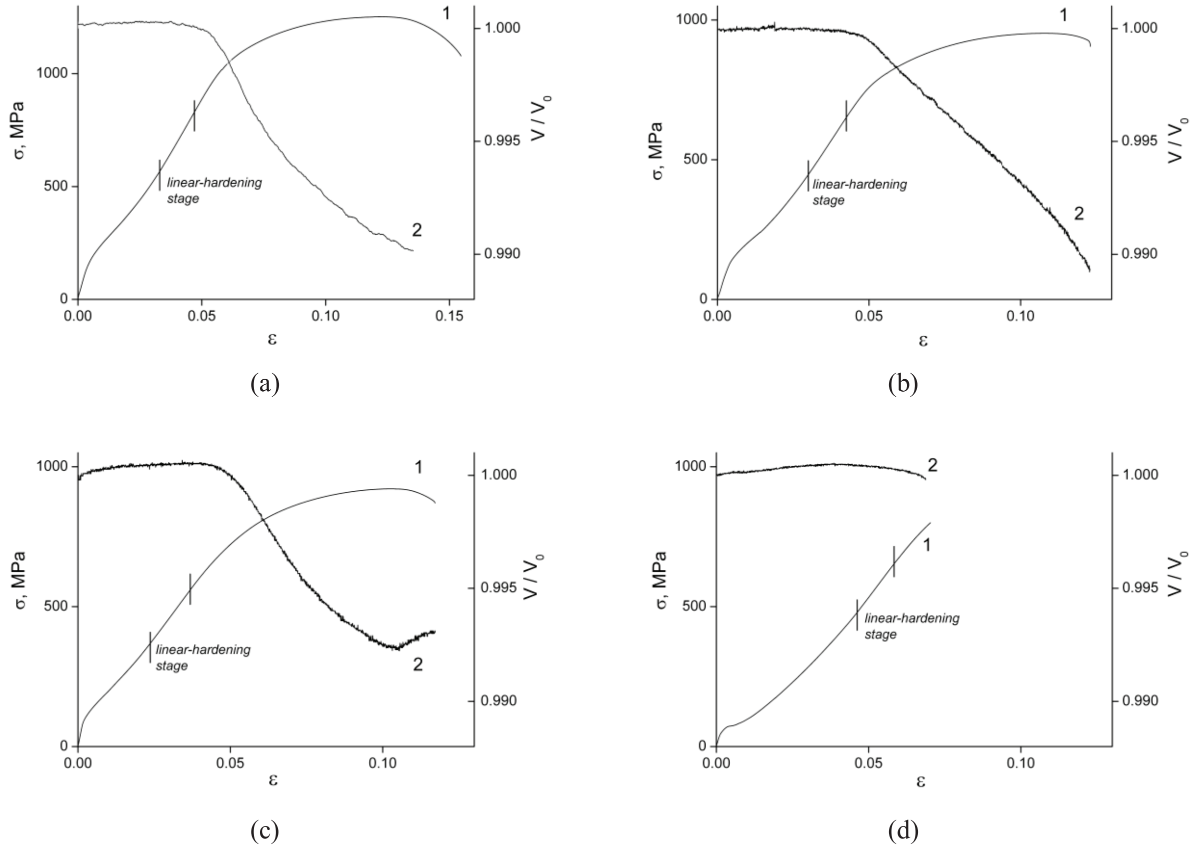
FIGURE 2. Motion of localized plastic flow domains in the linear-hardening stage for high-chromium steel in the tempered state (a) and after electrolytic hydrogenation for 6 hours (b), 12 hours (c) and 24 hours (d)

In such manner one can see that as for the localized-strain pattern in the linear hardening stage ($\theta(\varepsilon)=const$) it is a system of equidistant mobile localized-strain centers with characteristic inherent to a wave process. The autowave velocity and length for the states studied are given in Table 2 to show satisfactory agreement with the universal inversely proportional relation between the macrolocalized plastic-strain autowave velocity and the work-hardening coefficient normalized by the shear modulus of the material [1, 5].

TABLE 2. The characteristics of localized-strain autowaves

	$V_{aw}\times10^5$,m/s	$\lambda\times10^3$, m
Tempered steel	5.2±0.9	6.8±1.5
Hydrogenated within 6h	4.5±0.7	4.4±0.6
Hydrogenated within 12h	4.0±0.8	4.6±0.5
Hydrogenated within 24h	3.8±0.7	3.5±0.5

Using standard statistical processing data obtained such Student's t-criterion [19] it was determined that for the confidence level $\alpha = 0.95$ the resultant quantity $|t| \geq t_{\alpha,f}$ is true for the value of the autowave length. This fact suggests that the average λ-values obtained for the tempered alloy and the hydrogenated one differ significantly.



(a)

(b)

(c)

(d)

FIGURE 3. Stress–strain curve of the plastic flow (1) and the dependence of the velocity of ultrasound propagation against the total strain (2) for high-chromium steel in the tempered state (a) and after electrolytic hydrogenation for 6 hours (b), 12 hours (c) and 24 hours (d)

The diagrams plotted on Figure 3 are in a good correspondence with results obtained in [20]. It has been established that the velocity of propagation of an ultrasonic wave in a sample deformed by stretching depends on the overall strain, the stress time and the structure of the material. The analysis of the dependences of the velocity V/V_0 (V_0 is an initial velocity of ultrasound wave propagation) on the strain and the actual stress. It was found that the ultrasonic velocity considerably varies with tension, and the dependences $V(\varepsilon)$ and $V(\sigma)$ are fairly complicated. However the well known fact that the velocity of ultrasonic waves is unchangeable within the linear hardening stage is in a good coincidence with obtained results.

SUMMARY

The result of this study is the practical evidence of localized plastic flow of high-chromium stainless steel saturated with hydrogen. Because of this, mobile equidistaned localized-strain centers are observed (phase autowave). The velocity of the localized strain autowave as well as spatial period differs according to the hydrogen concentration. The more hydrogen in material so much the autowave parameters the less. Finally the increasing of hydrogen concentration leads to corrosion embrittlement of alloy.

The velocity of ultrasonic surface waves shows that the dependence of the velocity of ultrasound in active loading is determined by the law of plastic flow, that is, the staging of the corresponding diagram of loading. The data obtained from this investigation are of practical use for developing theoretical foundations of plastic working of high-chromium steel. This can provide, among other things, a reliable choice of limiting hydrogen concentratin for safety operation. The proposed method can also be used to estimate the tensile strength of high-chromium steels before the fracture.

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