Bulgarian Chemical Communications, Volume 49, Special Issue L (pp. 54 - 58) 2017

Cold plastic deformation effects on the mechanical properties and corrosion behaviour of low-alloyed (2% Cr) steel

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Submitted November 21, 2016; Accepted February 3, 2017

The effect of the cold plastic deformation (0÷80 %) on the main mechanical characteristics, microstructure and the residual stresses of low-alloyed (Cr~2 %) carbon steel have been investigated applying various physical and electrochemical methods.

The results revealed that with increase in the degree of deformation there was significant enhance in the ultimate tensile strength, the yield strength and the hardness of the steel tested. The relative elongation reduces at about one order of magnitude.

The model aqueous solutions of sulfuric acid allow observing the effect of the plastic deformation on the corrosion behavior of the steel: It was established that the highest corrosion rates corresponded to deformation range 40-50 %. The general corrosion behavior of the untreated steel alters in localized attack in the deformed steel along the elongated grains having shapes of scratches.

Keywords: low-alloyed steel, mechanical properties, corrosion

INTRODUCTION

The development and practical realization of new steels require various methods allowing deep understanding of the effects of many factors on the steel properties [1÷4, 10-11]. In this context, experiments allowing seeing how the assurance and the long-lasting of equipments based on such steels and on the corrosion losses are dependent are highly required.

The contemporary worldwide practice applying steels with increased content of chromium (less 3 %) is mainly for welded constructions working under corrosion attacks of see water, contaminated atmospheres, mineralized industrial waters, underground and waste waters. The alloying metal (chromium) does not change essentially the mechanical and technological properties of the steels but leads to two or three-fold increases in the intensities of the corrosion attacks, compared to similar cases with non-alloyed steels.

The effect of the cold mechanical treatment as well as the degree of plastic deformation on the corrosion behaviour of various steels commonly have been investigated with respect to the corrosion rates, corrosion potentials, anodic dissolution, etc. [5÷9].

This work presents results obtained during studies addressing effects of the degree of cold plastic deformation on both the mechanical properties and microstructure of low-alloyed by chromium steel related to their corrosion resistance in model aqueous solutions of sulfuric acid.

EXPERIMENTAL

Low-alloyed by chromium steel samples of flat profiled hot rolled sheets (of 3 mm thickness and chemical content, wt. %: C – 0.07; Cr - 1.88; P – 0.017; Mn – 0.67; Ni – 0.06; Cu – 0.15; Si – 0.22; Al – 0.081) were tested.

The cold rolling was carried out by a laboratory scale rolling mill „KWARTO", with the following characteristics:

- Diameter of the cold-rolling work-rolls – 130.10^{-3} m
- Diameter of the supporting rolls – 320. 10^{-3} m
- Roll width in the working zone – 180. 10^{-3} m
- Power of the motor – 170 kW
- Rolling rate – 0.1÷5.0 m/s
- Maximum roller force applied – 80 t
- Maximum gap between the rolls – 45.10^{-3} m
- Hardness of the surface of the rollers – HR = 52-56

The maximal degree of deformation obtained after the rolling (determined by measurements of the reduction in the sheet thicknesses) was about 80 %.

The tests to receiving the mechanical properties such as ultimate tensile strength R_m, the yield strength limit $R_{e,0.2}$ and the relative percentage elongation A_5, of cold-rolled steels used flat samples are conducted in accordance with the Bulgarian standard recommendations (BDS EN 10002-1: 2004) using tensile strength equipment FPZ-100.

The hardness of the rolled samples was

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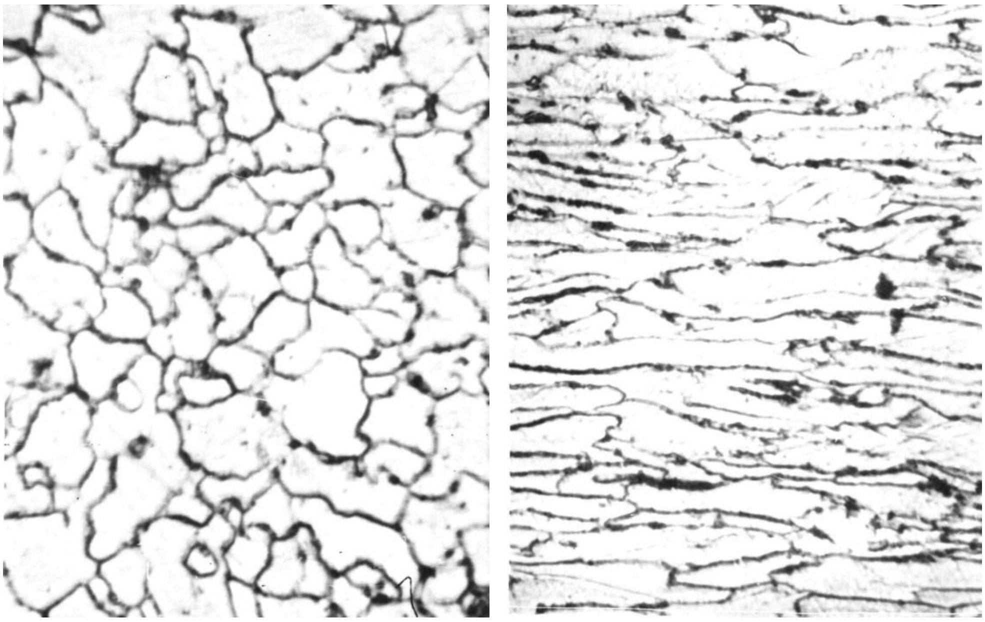
measured by the Brinell method and assessed in accordance with Bulgarian standard BDS EN ISO 6506-1: 2014.

The effects of the degree of the plastic deformation on the changes in the steel microstructures were determined by metallographic studies. The metallographic specimens were prepared in two orthogonal directions: parallel to the deformation plane and in the transversal plane. All samples were treated by grinding paper and polished by aqueous suspension of Cr_2O_3 and then revealed by a Nital solution. The observations were carried out with optical microscope EPITYP – 2. The original steel microstructure (ferito-pearlitic) of grade 7-8 and the microstructure of the deformed (about 50.18 %) one are shown in Fig. 1.



a) *b)*

Fig. 1. Microstructures of the tested steel samples
a) original samples ; b) rolled samples (50.18 % longitudinal deformation, x400)

The metallographic analysis allowed determining the grain sizes (Jeffries method) and the length of the lines at the boundaries (the method of Saltikov) [3].

It is well-known that the work of plastic deformation is greater than the liberation of heat under the body deformation. A part of this heat remains into the bulk of the deformed body and increases its internal energy. Metallographic methods such as the inverse photos of the moments allow determining the changes in the lattice structure after the steel deformation. Moreover, the metallographic method of the inverse pole figures allowed identification the texture developed as a result of the plastic deformation [4].

The effect of the cold-rolling on the corrosion behaviour of the steel was determined by the potentiodynamic polarization studies. The method, the equipment and preparation of the samples are described elsewhere [10]. The character of the corrosion attack was examined by scanning electron microscopy, using a EM-400 “Philips” electron microscope.

RESULTS AND DISCUSSION

The ultimate tensile strength R_m, the relative yield strength limit $R_{e,0.2}$, the hardness HB and the relative percent extension A_5 of the treated samples against the degree of plastic deformation ε are presented graphically in fig. 2. The plots reveal that R_m, $R_{e,0.2}$ и HB grow almost parabolically in the entire range of variations of ε. All parameters, i.e. R_m, $R_{e,0.2}$ и HB increase about twofold with a maximal degree of deformation comparing to samples without plastic treatment. The relative extension A_5 degreases almost exponentially and beyond $\varepsilon > 50$ % there are practically negligible changes in A_5.

The curves presented in Fig. 2 were approximated by quadratic polynomials [3], namely:

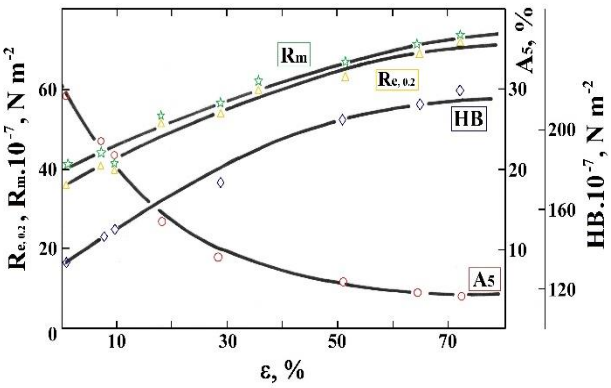


Fig. 2. Effect of the degree of deformation, ε on the mechanical parameters R_m, $R_{e,0.2}$, HB and A_5

$$y = a + b\varepsilon + c\varepsilon^2$$

The coefficients *a*, *b* and *c* are constants specific for each material and mechanical characteristic approximated, and they form sets of normal equations.

The changes in the mechanical characteristics of the deformed steel could be attributed to delayed slipping due to increased density of dislocations and re-orientation of the grains.

The microstructure changes observed as well as the consequent analyzes allow to state that the increase in the degree of deformation there is elongation of the grains and this effect is more pronounced for ε > 40 %. When the deformation is beyond 60 % the grains elongate about 3-4 times and there are onsets of bending and break-ups. At the same time, the deformation practically has no effect on the mean surface S_{av} and the diameter of the grains d_{av} as it is demonstrated in Fig. 3.

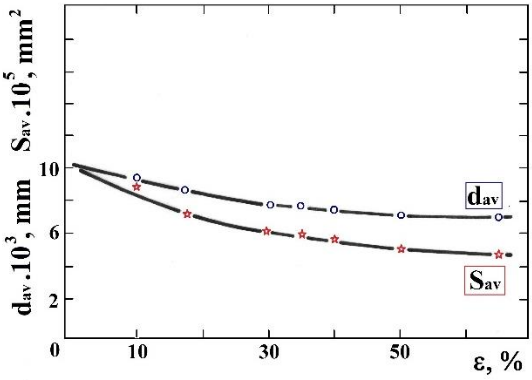


Fig. 3. The mean grain surface S_{av}, mm^{-2} and mean grain diameter d_{av}, mm as functions of the degree of grain deformation ε, %

The changes in the mean length of the grain boundary ΣP with the deformation degree are presented in Fig. 4. The plots indicate that ΣP increases strongly at ε > 35 % when detectable elongations of the grains start. The maximum in the grain elongation *ΣP* is about threefold the initial size.

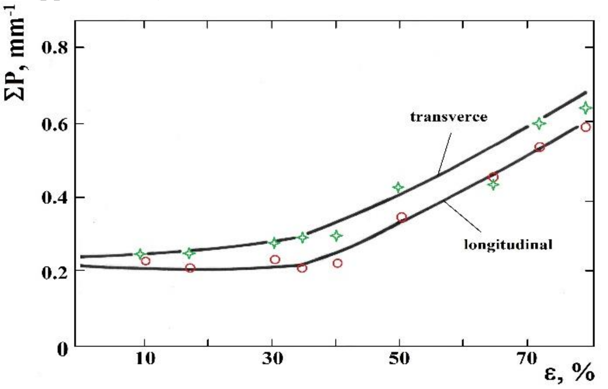


Fig. 4. Effect of the degree of deformation ε on the length of the grain boundary ΣP, mm^{-1}

The effect of the degree of plastic deformation on the internal stresses in the steel, represented by the ratio *Δa/a* (*Δa – is the maximal deviation of lattice period from its mean value a*) and the dimensions of the mosaic blocks D is demonstrated in Fig. 5. The data presented reveal that the dimension of the mosaic blocks decreases exponentially with the degree of deformation as a result of the blocks break-ups. The ratio *Δa/a* as a function of *ε* exhibits a maximum at about ε ≈ 50 % and a fall beyond this point. This behaviour could be attributed to excess of heat dissipated during the deformation process taking beyond 50 % and this heat enhance the diffusion processes in the steel structure with minor changes in the lattice thereof.

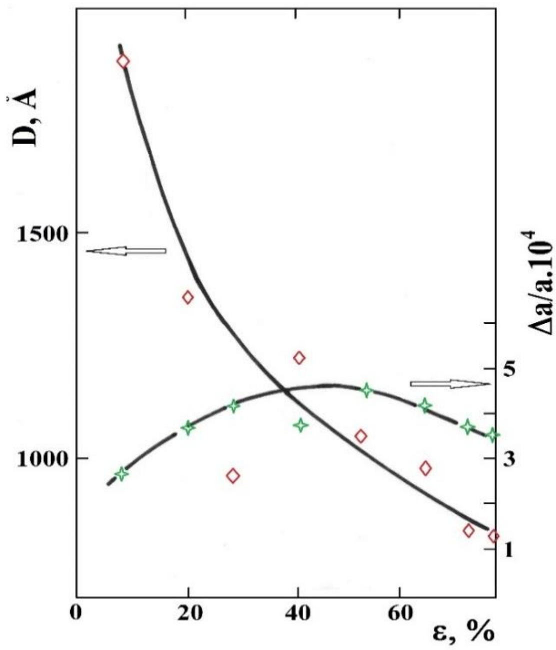


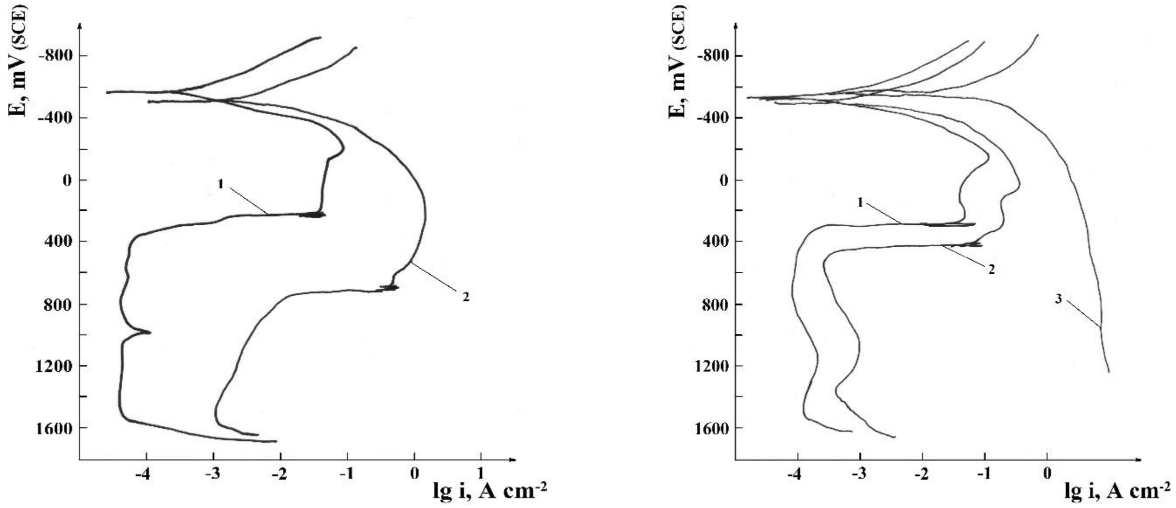
Fig. 5. Effect of the degree of deformation ε, % on the size of mosaic blocks D, Å and the ratio Δa/a

The studies on the texture of the deformed steel reveal that the preferred orientation of the grain slipping is the plane [100].

The corrosion behaviour of the low-alloyed steel and especially the effect of the cold deformation on it was studied in a model 1.0 M solution of sulfuric acid. In general, the plastic deformation increases the corrosion rate and this process is strongly exhibited in the deformation range 30-50 %.

Further, there is a strong effect of the degree of deformation on the anodic passivity of the steel, precisely, the passive current increases with increase in the deformation. At ε = 50.18 %, for example, the passive current is about 2 times greater than that when the original no-treated steel is tested (see Fig.6). This is quite important in cases of anodic protection of equipment using this steel, where due to local plastic deformations it would be possible to the passive state to be destroyed and the rapid dissolution of the steel on sulfuric acid media to be started.

The deformation of the steel does not affect strongly the corrosion potential E_{corr}, *mV* and its values remain almost equal to the ones corresponding to the non-deformed steel under the same conditions (see Fig. 6).



(a) (b)

Fig. 6. Potentiodynamic polarization relationships E, mV – lg i, A cm^{-2} obtained in 1.0 M H_2SO_4: a) non-deformed steel **1** - 20^{o}C, **2** - 60^{o}C; b) deformed steel (ε = 50.18 %) **1** - 20^{o}C, **2** - 40^{o}C, **3** - 60 ^{o}C

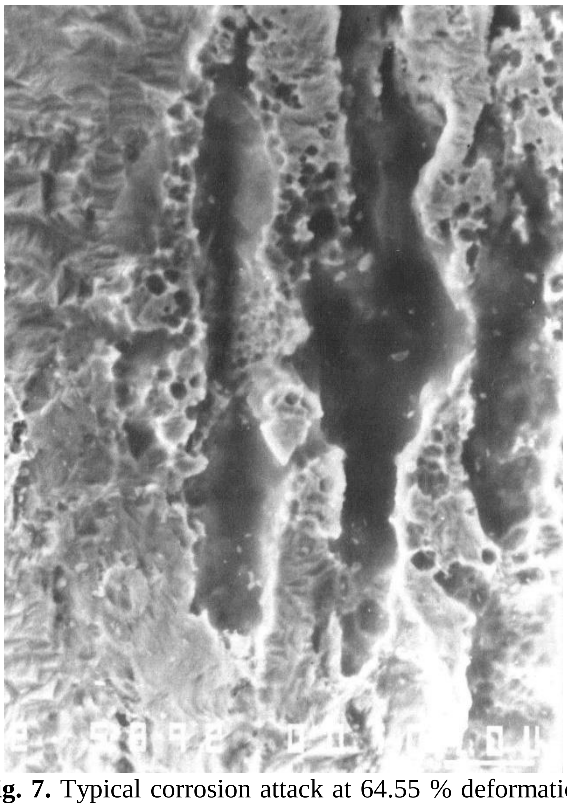


Fig. 7. Typical corrosion attack at 64.55 % deformation degree.

The character of the corrosion attack was determined visually by microscopic observations. In cases of both the non-deformed samples and deformed samples the low degrees of corrosion when low degrees of deformation take place the corrosion attacks is over the entire surfaces with slightly increases activity at the central parts of the samples and increased activity at the boundaries of the grains. With increase in the deformation degree, parallel to increased corrosion rate, strong local attacks take place; mainly as scratched strips oriented along the axis of the grain elongation (see Fig. 7).

CONCLUSIONS

Investigation of the degree of cold plastic deformation on the mechanical properties, microstructure and corrosion behaviour (in model sulfuric acid solutions) of low-alloyed by chrome mild steel was carried out. It was established that with increase in the degree of deformation the tensile strength and the yield strength, as well as the hardness (about 2 times) increase. At the same time, the relative extension reduces at about one order of magnitude. The grain lengths increase about 3 times while the residual stresses increase when the deformation rises to about 50 % degree of deformation. Beyond the 50% deformation the residual stresses reduces. The most preferred orientation of slipping during deformation is on the plain [100].

In the corrosion tests in model sulfuric acid solutions it was established that the highest corrosion rate was observed in the deformation range 40-50 %. With the non-deformed samples a general corrosion attack took place, but when the deformation was applied the corrosion attack was localized at the boundaries of the elongated grains and the affected areas were formed as scratched strips.

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ВЛИЯНИЕ НА СТУДЕНАТА ПЛАСТИЧНА ДЕФОРМАЦИЯ ВЪРХУ МЕХАНИЧНИТЕ СВОЙСТВА И КОРОЗИОННОТО ПОВЕДЕНИЕ НА НИСКОЛЕГИРАНА (2% Cr) СТОМАНА

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Постъпила на 21 ноември, 2016 г.; приета на 3 февруари, 2017 г.

(Резюме)

С помощта на разнообразни физични и електрохимични методи е изследвано влиянието на студената пластична деформация (0÷80%) върху най-важните механични показатели, микроструктурата, остатъчните след деформацията напрежения на нисколегирана с хром (~ 2%) стомана. Установено е, че с нарастване степента на деформация значително се повишават якостта на опън, границата на провлачване и твърдостта на стоманата, а относителното удължение се понижава близо с порядък. В моделни сернокисели разтвори най-висока скорост на корозия се наблюдава в деформационния диапазон 40-50%, когато от обща, корозионната атака се локализира по границите на удължените зърна под формата на бразди.