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# Effect of a plastic deformation in traction on the hardness, the thermal expansion and the corrosion behaviour of a ferritic steel

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## ABSTRACT

A ferritic steel was obtained with different states of plastic deformation by traction test. Metallographic samples were prepared for optical microstructure examination, Vickers indentation tests and corrosion tests in a sulphuric solution with electrochemical measurements, while dilatometry runs between room temperature and 700°C were performed on parallelepipeds. Hardness becomes significantly high in the most strained zones, especially for surface parallel to the tensile deformation. Thermal expansion is slightly decreased by the plastic deformation and it looses the good linearity observed for the not strained samples. The corrosion rate, in the active state, is greatly enhanced by plastic deformation, as shown by the significant decrease in polarization resistance. 

## KEYWORDS

Ferritic steel;
Tensile plastic deformation;
Hardness;
Thermal expansion;
Corrosion.

## INTRODUCTION

In mechanisms or structural parts some metallic pieces may undergo mechanical stresses which can lead to geometric deformations, elastic and even plastic if the applied stress is high enough. In the latter case the local increase in dislocations density induced by such plastic deformation can significantly modify the local properties of the alloy. The mechanical or thermome- chanical behaviour may have thereafter become inhomogeneous, the surface reactivity different with consequently possible phenomena of galvanic corrosion. The purpose of this study is to especially study the possible consequences of a tensile plastic deformation for the hardness, the thermal expansion and the corrosion behaviour of simple ferritic steel with regards to the orientation of the considered surface or direction.

## EXPERIMENTAL

### The steel of the study and the different deformed states obtained

A very low carbon steel, almost wholly ferritic, initially available in the form of a bar, was machined in order to obtain round sample for tensile strength experiments (geometry described in TABLE 1). Test was performed using a MTS QT/100 apparatus,

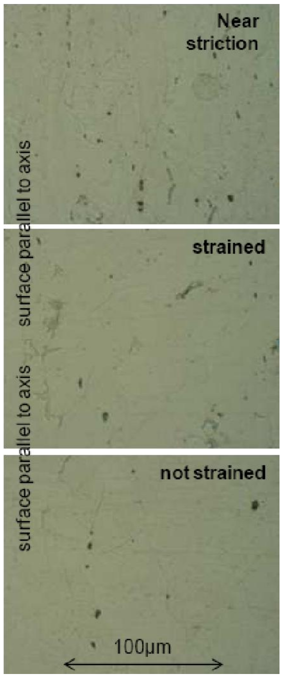


**Figure 1a : Microstructures of the steel for the three states of deformation and for the orientation parallel to the strain direction (optical micrograph after Nital4-etching)**

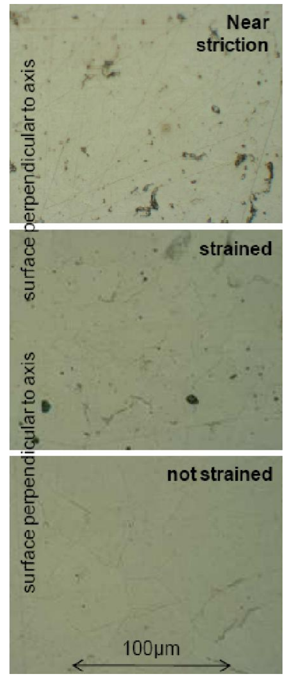


**Figure 1b : Microstructures of the steel for the three states of deformation and for the orientation perpendicular to the strain direction (optical micrograph after Nital4-etching)**

equipped with a 100kN cell. After rupture sample was cut in different locations in order to obtain parts without deformation (heads), homogeneously deformed (main part, far from the rupture surface), or with especially high deformation (very close to the ruptured surface). Mounted samples were prepared for metallographic examination: embedded in a cold resin+hardener mixture, polished with grinding papers from 240-grit to 1200-grit, then ultrasonic cleaned and polished until mirror state and etched with Nital4 (ethanol + 4% $HNO_3$). The steel is essentially ferritic (here and there some small pearlitic areas can be noted), with ferrite grains either isotropic (not deformed part and cross sections perpendicular to sample axis in the deformed part) or elongated (deformed parts, cross sections parallel to axis). The microstructures in the three locations are illustrated in figure 1a (cross sections parallel to sample axis) and in figure 1b (cross sections perpendicular to axis), with micrographs taken on Nital4-etched samples, using an optical microscope Olympus Vanox-T equipped with a numeric camera Olympus DP-11.

## Hardness measurements

Vickers hardness was measured using a Testwell Wolpert apparatus, under a load of 10kg. Three indentations were performed in three locations: in the not strained part, in the homogeneously strained part and in the neighbourhood of the surface of fracture (striction). In each case this was done on a cross section parallel to sample axis (i.e. axis of tensile deformation) and on a cross section perpendicular to this axis. The average value and the standard deviation value calculated from these three indentation results were considered.

## Thermal expansion

Four parallelepipedic samples for the dilatometry tests, of about 5×5×3 (dilatation direction) $mm^3$, were machined in the not strained part of the sample for the two orientations, and in the homogeneously deformed part for the two orientations too. Thermal expansion experiments were performed from room temperature up to 700°C (heating rate: 10°C/min), followed by an isothermal stage during 5 minutes, then from 700°C down to room temperature (cooling rate: -10°C/min).

## Electrochemical experiments

The corrosion behaviour of the different embedded

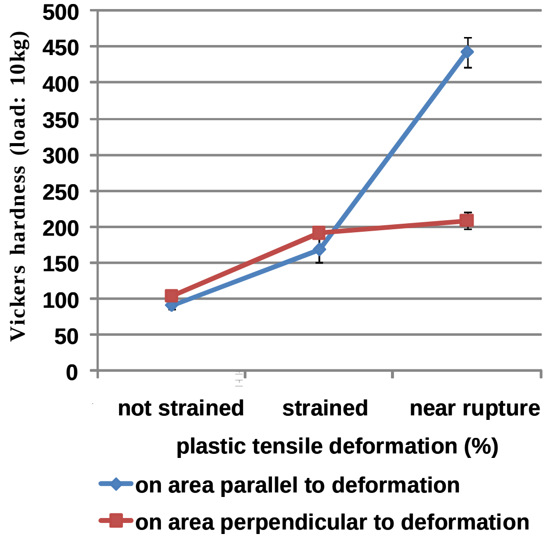


**Figure 2 : Evolution of the Vickers hardness with the state of strain for the two orientations (load 10kg)**

samples was characterized in the active state in an acid solution ($H_2SO_4$ 1N aqueous solution). This was done by noting three successive values of the open circuit potential ($E_{ocp}$) during about 15 minutes and by performing three times linear polarization for obtaining three successive values of polarization resistance (Stern-Geary method)[1]. The apparatus was composed of a special cell allowing to use embedded samples (connected to an electric wire on the other side, working electrode), a potensiostat / galvanostat (Princeton Applied Research, model 263A) driven by a computer supporting the software M352 of EGG/ Princeton, a graphite counter electrode and a Saturated Calomel Electrode as potential reference. The linear polarizations were performed from $E_{ocp}$-20mV up to $E_{ocp}$ + 20mV with the rate of 10mV/min.

## RESULTS AND DISCUSSION

### Hardness

All the obtained values are presented in TABLE 2, as well as the average values. There is a small mismatch between the two orientations in the not strained part, maybe due to the initial fabrication mode (probably extrusion) of the steel bar in which the sample was machined. In contrast, when one considers the values measured in the deformed part, it appears that hardness is become significantly higher (180-190 against 90-100 in the former part), but without clear dependence on the orientation. This increase in hardness goes on when one considers the neighbourhood of the rupture location, especially for one of the two orientations since indentation led to very high values for the surface parallel to the deformation direction (more than 400 $Hv_{10kg}$). This can be graphically illustrated by the curves presented in figure 2.

**TABLE 1 : Sample geometry for tensile test**

| Heads | | Main part | |
|---|---|---|---|
| length | diameter | length | diameter |
| 50 | 12 | 52 | 7 |

### Thermal expansion

The dilatation of the parallelepipedic samples taken in the not strained part is linear for the two orientations between ambient temperature and the maximal temperature (700°C), for the heating as well as for the cooling (figure 3a). The average thermal expansion coefficients (TABLE 3) do not depend on the sample orientation and are close to the usual values for pure iron[2] ($\alpha \cong 14 - 15 \times 10^{-6}$ per °C). Plastic deformation seemingly induced a small reduction of thermal expansion for the two orientations, but the more noticeable differences with the previous curves is that dilatation is no more strictly linear but is more disturbed, while the cooling part is not superposed with the heating part (figure 3b).

The plastic deformation has obviously perturbed the thermal expansion of the steel, probably because of a start of annealing/modification of the Franck's network when temperature is become high enough.

### Corrosion behaviour

In all its states (deformed or not), this ferritic steel is unsurprisingly in its active state, with open circuit potentials staying between -0.44mV / NHE (E° for $Fe^{2+}/Fe$) and 0 mV / NHE (E° for $H^+/H_2$) at pH = 0 (TABLE 4), i.e. in the corrosion domain of Fe[3]. The cathodic and anodic reactions are logically $2.H^+ + 2.e \rightarrow H_2$ and $Fe \rightarrow Fe^{2+} + 2e$, respectively. The $E_{ocp}$ values are variable and there is no evident relation versus the strained state, as illustrated by figure 4a. In contrast, the polarization resistances greatly depend

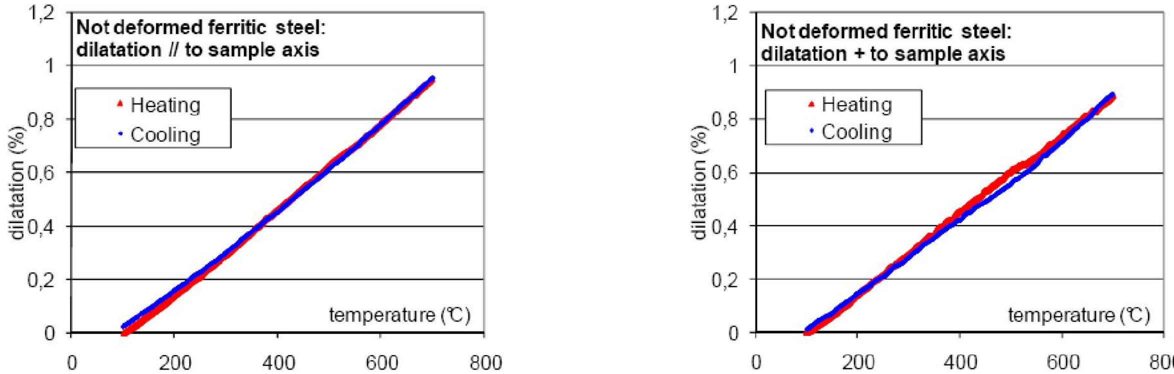


**Figure 3a : Dilatometry curves of the not strained state for the two orientations**

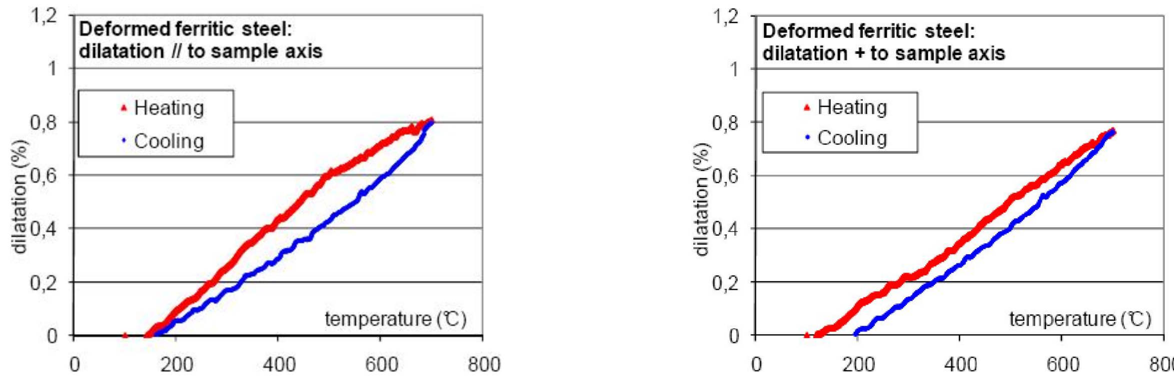


**Figure 3b : Dilatometry curves of the strained state for the two orientations**

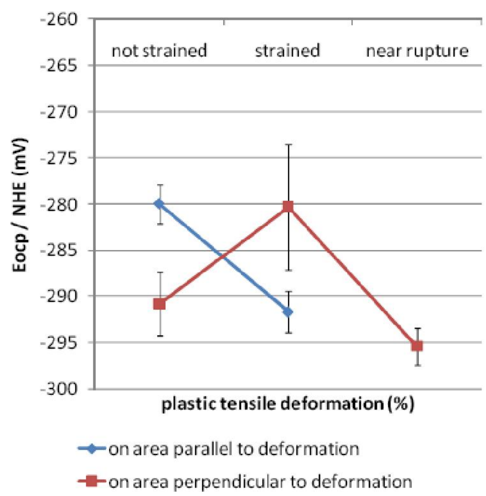


**Figure 4a : Evolution of the open circuit potential with the state of strain for the two orientations**

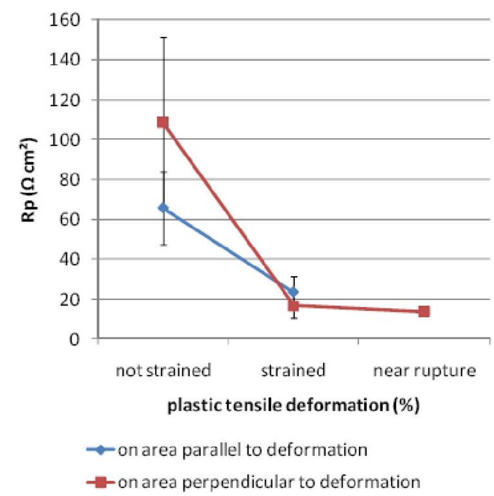


**Figure 4b : Evolution of the polarization resistance with the state of strain for the two orientations**

on the strained state: there are considerably lowered by the plastic deformation (figure 4b), as is to say the corrosion rate in the active state is accelerated.

## General commentaries

There are thus some differences of behaviour between the not deformed zone and the more or less deformed zones, about hardness, thermal expansion and corrosion behaviour. The increase in hardness with the plastic deformation is classical while it is interesting to observe that the strained state induces a less linear thermal dilatation. Another great difference is the corrosion behaviour, here simply studied in a common sulphuric solution in which iron remains in the active state.

There are already a lot of studies about the influence of a mechanical deformation on the corrosion behaviour of alloys, since at least forty years. They initially

TABLE 2 : Values of hardness $Hv_{10kg}$ for the two orientations and the three strained states

| Steel state | Surface parallel to sample axis (or deformation direction) | | | Surface perpendicular to sample axis (or deformation direction) | | |
|---|---|---|---|---|---|---|
| | Hv10kg | | | Hv10kg | | |
| | Value 1 | Value 2 | Value 3 | Value 1 | Value 2 | Value 3 |
| not strained | 96 | 88 | 90 | 105 | 105 | 103 |
| | | average: 91 | | | average: 104 | |
| homogeneously strained | 181 | 178 | 176 | 183 | 199 | 193 |
| | | average: 178 | | | average: 192 | |
| Especially strained (near striction) | 421 | 464 | 442 | 206 | 199 | 221 |
| | | average: 442 | | | average: 209 | |

TABLE 3 : Values of average thermal expansion coefficient for the heating part and for the cooling part

| Steel state | Thermal expansion in the strain direction (or along the sample axis) | | Thermal expansion perpendicular to the strain direction (or to the sample axis) | |
|---|---|---|---|---|
| | $\times 10^{-6}$ °C$^{-1}$ | | $\times 10^{-6}$ °C$^{-1}$ | |
| | Heating | Cooling | Heating | Cooling |
| Not strained | 16.0 | 15.6 | 15.0 | 14.4 |
| Homogeneously strained | 15.2 | 13.7 | 13.5 | 14.0 |

TABLE 4 : Values of the three successive values of $E_{ocp}$ and of Rp for the two orientations and the three strained states

| $E_{ocp}$ (mV / NHE) and Rp (? cm$^2$) steel state | Surface parallel to sample axis (or deformation direction) | | | Surface perpendicular to sample axis (or deformation direction) | | |
|---|---|---|---|---|---|---|
| | $E_{ocp1}$ | $E_{ocp2}$ | $E_{ocp3}$ | $E_{ocp1}$ | $E_{ocp2}$ | $E_{ocp3}$ |
| | $Rp_1$ | $Rp_2$ | $Rp_3$ | $Rp_1$ | $Rp_2$ | $Rp_3$ |
| Not strained | -281 | -282 | -278 | -287 | -292 | -294 |
| | 47 | 67 | 83 | 60 | 124 | 142 |
| Homogeneously strained | -294 | -291 | -290 | -288 | -279 | -275 |
| | 22 | 16 | 32 | 23 | 12 | 15 |
| Especially strained (near striction) | | Not done | | -298 | -294 | -295 |
| | | | | 14 | 14 | 13 |

concerned the behaviour of stainless steels (previously cold-worked or not) in solutions such as sulphuric acid too[4], solutions containing chlorides[5] or hydrochloric acids with addition of inhibitor[6]. More recently there are works about plastically deformed/cold-rolled titanium-based alloys in Ringer's solution[7] or sulphuric acid[8] again, magnesium-based[9] or aluminium-based[10] alloys. Concerning the effect of a plastic deformation of a ferritic steel on its corrosion rate in a pH = 0 sulfuric solution, this work dealing with a tensile deformation can be added to the previous ones. It notably comes completing a previous study concerning the effect of a plastic compression on the corrosion in the same electrolyte[11], in the case of ferritic iron too, as well as in the case of other pure metals.

## CONCLUSIONS

As it can be observed for a compressive plastic deformation, a tensile plastic strain improves the hardness of ferritic steel, which is a rather well known result. But it also modifies its corrosion behaviour in the active state, with notably here detrimental consequences for its resistance against corrosion. The problem may become more serious for strained parts of a piece by galvanic coupling with less strained parts. This new deterioration would come to be added to the first one which is the plastic strain itself, with as consequence the acceleration of the destruction of the piece.

## ACKNOWLEDGEMENTS

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