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On the Lifetime Evaluation for a Power Plant Steel Using the Vickers Microhardness Test

Viorel Goanţă, Marian Mareş,
Constantin Baciu, Bogdan Leiţoiu

Technical University "Gh. Asachi" din Iasi, Bdul. Mangeron 57
e-mail: vgoanta@mail.tuiasi.ro

Abstract

The paper is focused on the mechanical properties of power plant steel, after long-term functioning at high levels of temperature and pressure. The study aims to improve the accuracy of the available correlations between Vickers hardness and strain hardening level, on one hand, and, on the other hand, the remaining lifetime duration of the studied material.

Keywords: *microhardness, tensile strength, plastic deformation.*

Introduction

The long-term service at elevated pressure and temperature levels may affect the strength and toughness properties of the alloy steel that is used for building the steam lines from power-plants stations. At the same time, the material microstructure could also be affected, leading to some changes of material machinability and weldability.

The present paper is focused on some particular issues regarding a possible connection between the stress hardening of alloy steel and the estimation of its lifetime duration. The studied steel samples were cut out from disaffected live-steam pipe-lines that operated into a local power-plant station. The steam lines, with dimensions $\Phi \times h = 273\text{mm} \times 28\text{mm}$, had worked for 44 thousand hours at a maximum pressure level $p = 130\text{daN/cm}^2$ and at high temperature up to 530°C.

Previous Results

Hardness tests have for a long time been a standard method for material characterization as they provide an easy, inexpensive, non-destructive, and objective method of evaluating basic properties from small volumes of materials. As well as resistance to plastic deformation; stiffness, residual stresses near the surface, and the fracture toughness of the material are some basic properties that can be evaluated by hardness tests [3-4].

In the literature, Vickers hardness number (HV) has been the most popular in investigation of the relationship between hardness and the lifetime or tensile strength of the material because of two reasons: firstly, its superior resolution as compared to spherical indenters; and secondly, the Vickers indenter is self-similar, through which the hardness is ideally independent of the indentation load and indentation depth [7]. Therefore, in this study, Vickers indentation will be as well the main concern. A basic review of the first results is covered by Tabor [5]. Tabor has shown that the mean contact pressure P_m (or hardness) can be related to the yield stress σ_c or tensile strength R_m of the material, by an expression based on the theory of indentation of rigid-perfectly plastic solid:

$$HV = \frac{\text{Indenter Force (kg)}}{\text{Im pr int Surface Area (mm}^2\text{)}} \tag{1}$$

For non-strain hardening materials, the Vickers hardness number, which is defined as in the above formula, can be related to the constant yield stress, σ_C, by:

$$HV = (2.9 \div 3.0) \cdot \sigma_c \tag{2}$$

For strain hardening materials and on empirical bases, Tabor suggests to be used a similar expression as in the case of non-strain hardening materials, but using as yield stress the value that corresponds at a representative plastic strain:

$$HV = 2.9 \cdot \sigma_c \text{ (at an engineering plastic strain of 0.08)} \tag{3}$$

Figure 1 shows a comparison of Tabor's formula with his own experimental results. In this plot, φ designates the equivalent true plastic strain, experienced by the specimen before indentation. It can be observed that the agreement is rather good for mild steel, whereas for the annealed copper a scatter of about 15% is present. It should be emphasized that Tabor's formula is given at various places with slightly varying coefficients and representative strain values, as compared with the values that are given in *Eqn.3*.

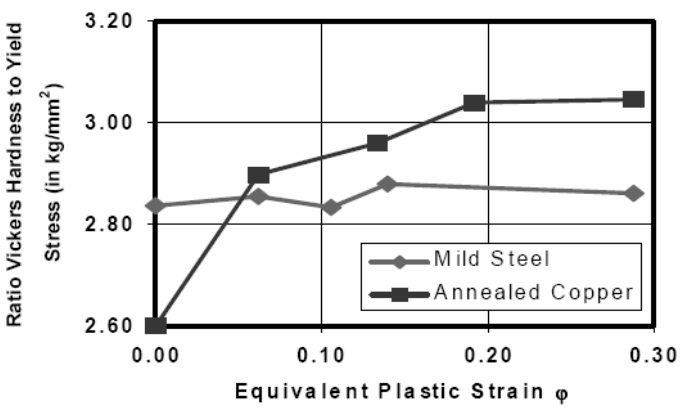


Fig. 1: Experimentally determined Vickers Hardness Number and Yield Stress ratios for various amounts of initial plastic strain [6]

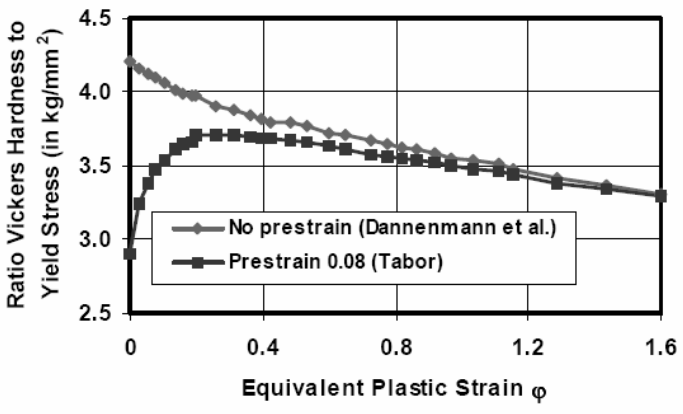


Fig. 2: Ratio of Vickers Hardness Number and Yield Stress, by Dannenmann and Wilhelm [1]

The relationship between Vickers hardness number and yield stress, as related to metal forming, is investigated by Dannenmann and Wilhelm [1].

The experimental results can be seen in *Figure 2*. In their original work, no use of Tabor's model as explained above was made, so that an interpretation of their experimental results utilizing Tabor's model is also given in this figure. However, even this improved curve indicates a conversion error of about 20%.

As an observation based on the above-cited researches, it can be said that the experimental studies lack the separation of various factors affecting the hardness and lifetime or tensile strength relationship. On the other hand, the analytical and numerical studies lack either quantitative accuracy and/or they don't cover metal-forming issues properly.

Material and Method

The present paper is focused on Vickers micro hardness determination for some samples of X20CrMoV121 steel, the basic material for the steam-lines that were proposed to be analyzed. The micro hardness tests were made for samples with different levels of strain hardening, as a result of some previous mechanical tests.

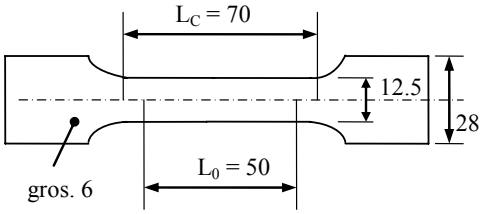


Fig. 3. Typical shape of tension test specimen

The high-chromium low-carbon steel of type X20CrMoV121 (containing about 12% of chromium) became, during the second half of 20th century, a traditional material for components operating in high-temperature conditions, thanks to its combination of favourable properties as ductility, high-strength and corrosion resistance [2].

The composition of alloy steel was established from chemical analysis of samples, as follows: 0,19-0,21%C, 0,33-0,42%Si, 0,54-0,56%Mn, 0,018-0,019%P, 0,017-0,023%S, 0,47-0,49%Ni, 11,3-11,4%Cr, 0,93-0,94%Mo, 0,35%V (the balance of the composition is iron). These values are in good agreement with those that are indicated for the X20CrMoV121, by the corresponding material standards [8].

The samples were firstly tested in tension, at ambient temperature, paying respect to the testing method description from standard specifications [9]. Some flat proportional specimens were used, with 6mm in thickness and a gage length of 50mm (Fig. 3). Figure 4 illustrates the tensile stress-strain behaviour for the studied material. It is important to observe the significant amount of plastic deformation that has occurred at fracture.

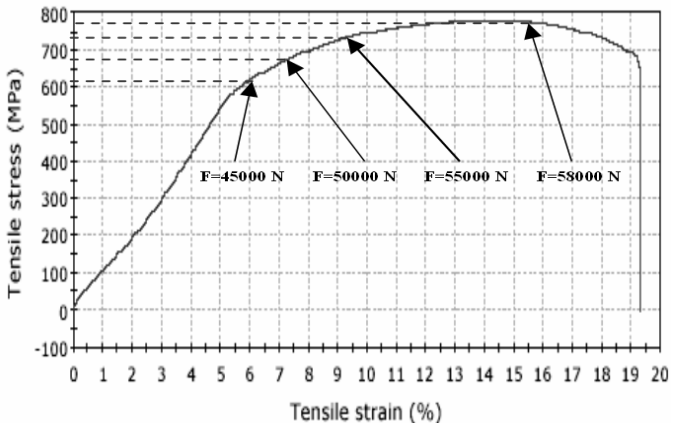


Fig. 4. Typical stress-strain dependence for studied alloy steel.

Results and Comments

The following table summarizes the numerical values of mechanical properties of the studied alloy steel, as resulted from the above-cited tension tests.

Tab. 1. Alloy steel mechanical properties

Yield stress ($R_{p\,0.2}$)	Tensile strength (R_m)	Elongation (A_5)	Red. in area (Z)	Young Modulus (E)	Poisson Coefficient
[MPa]	[MPa]	[%]	[%]	[GPa]	-
610-630	745-780	18-25	39-43	205.8	0.296

The tests were conducted completely, that is until the fracture of the steel specimens. The corresponding stress-strain dependence shows an important domain of elastic behaviour (under the level of about 600MPa), while the tensile strength was at the level of 750-780MPa. On the other hand, the yield zone does not include a straight horizontal line, which could precede the domain of strain hardening. Moreover, the appearance of fracture surfaces of tensile specimens confirmed the moderately ductile character of the present X20 alloy steel: a pronounced necking was observed before rupture, together with a closely cup-and-cone fracture configuration. That fact leads to a change in shape of the initial plane surface from the vicinity of the fracture zone, which is transformed into a certain profile, as it is presented in *Fig. 5*.

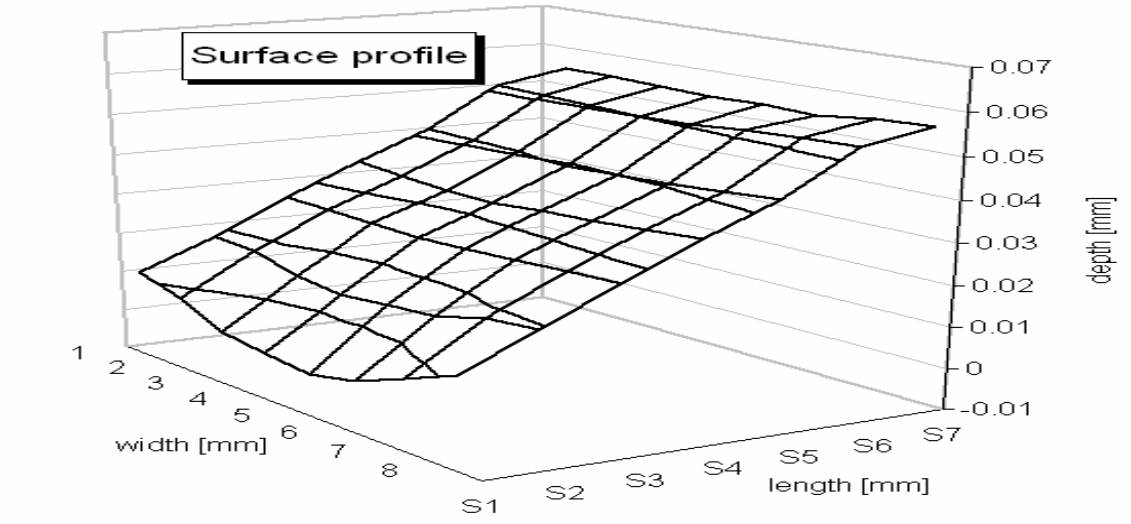
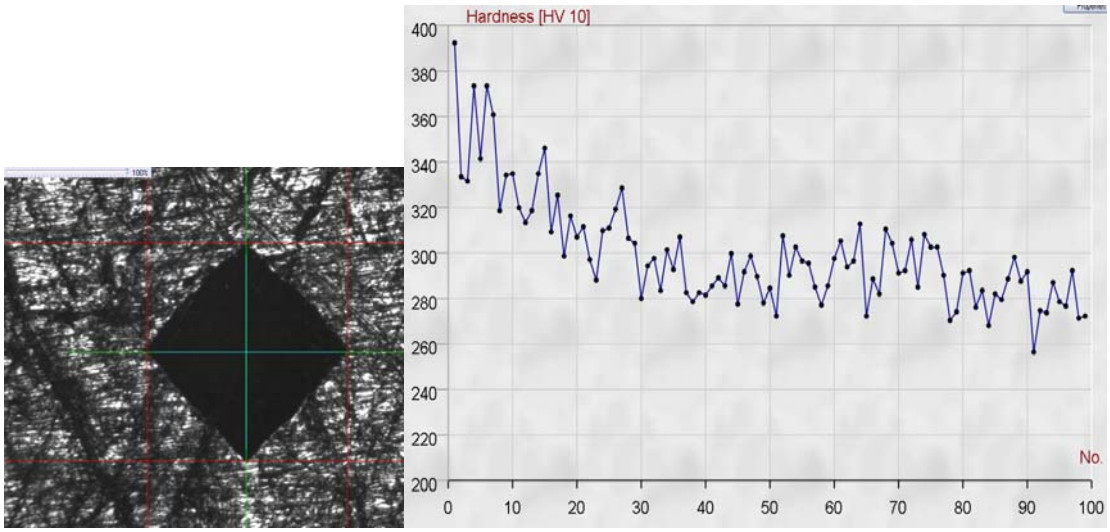


Fig. 5. The surface profile into the vicinity of the fracture section.

One can observe that the central region, placed in the proximity of the fracture surface, is strongly deformed, while the plastic deformation tends to decrease with the distance from the fracture zone, and near the specimen edges. These circumstances lead to the idea of a certain variation of mechanical properties values, for studied steel, in the vicinity of the specimens fracture surfaces. It is important to note the difficulty of any attempt to analyse the material properties in proximity of that region. Among few available test methods, one can use the microhardness Vickers indentation (see Fig. 6a).



(a) (b)

Fig. 6. a) The imprint of Vickers indenter; b) Vickers micro hardness values.

The tests were conducted using a Vickers micro hardness device having the capability of acquisition and processing of digital images. The indentations were made, for any specimen surface, in 98 measuring points, placed into a square arrangement in 14 rows and 7 columns (that were perpendicular and, respectively, parallel, with specimen longitudinal axis), with equal distances of 1mm. The imprint measurement and microhardness calculus were automatically and precisely made by the computer added device, and *Figure 6b* shows an example of the evolution of microhardness values for the above-cited 98 points (the counting was started with the points near the fracture zone). It is difficult to separate, from that graph, the microhardness values variation on specimen width (i.e. for any group of 7 consecutive points), but one can observe (as on the surface profile from *Fig. 5*) that a pronounced difference exists between the values from the central and, respectively, the exterior zones of the fracture region.

Figure 7 shows a significant variation of hardness as a function of distance towards the breaking area. At 1 mm from it (point 1 in Fig. 7), the hardness was approx. 360HV, while for the unloaded sample (point 15), the hardness number was 246HV.

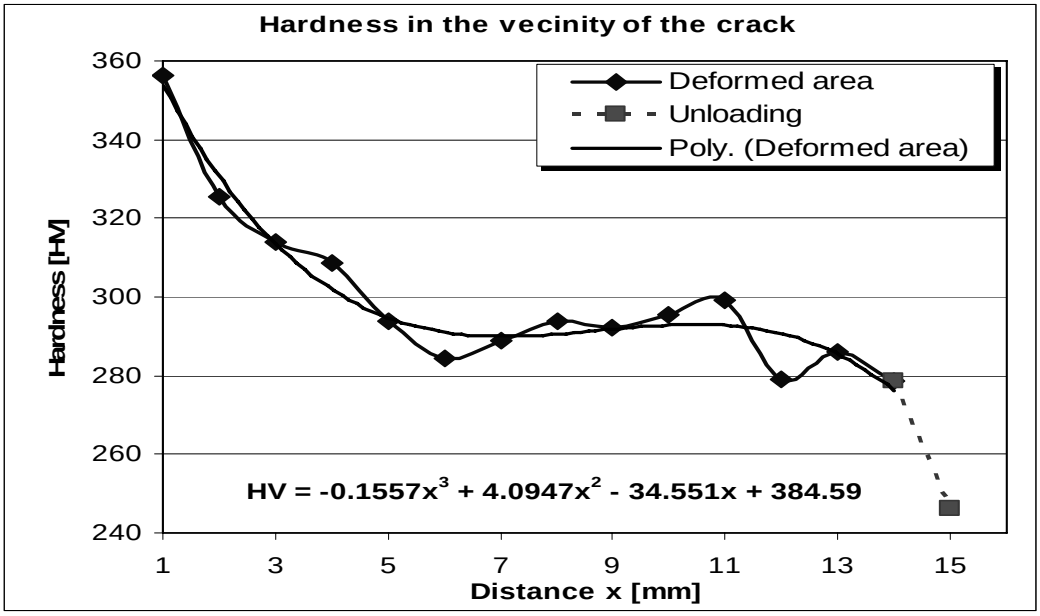


Fig. 7. Micro hardness values in dependence with the distance from the crack.

One can observe a substantial increase of Vickers microhardness in the vicinity of the crack, when comparing with the unloaded (so non-deformed) sample. However, when measuring at the distance of 6mm to 11mm, the hardness value remains approx. constant. Beyond the distance of 6 mm, the hardness starts to decrease again. The last two points of the graph from Fig. 6 are not representing a real variation.

Basing on these observations, it can be concluded that a correlation does exist, between the Vickers microhardness and the loaded or plastic deformed state of a component. In the opposite way, the plastic deformed state of a component (as a consequence of a previously applied load) may be evaluated, on the base of some Vickers microhardness tests. In these conditions, one can estimate the left period of lifetime, for a certain component that was plastic deformed in a certain way, as a consequence of a stress situated beyond its elastic limit. Taking into consideration the previous observations, it was tried to establish a correlation between the Vickers microhardness and the plastic deformed state of a sample, loaded in tension until a certain point on the stress-strain dependence curve.

Many sets of 4 samples were tested, together with 4 more samples loaded until fracture. In *Figure 7*, the characteristic curve for samples that were loaded until 45000N (corresponding to a

stress of approx. 625 MPa) is presented. It was noted with A_p, the area that corresponds to the permanent plastic deformation, which is established after the complete unload of the sample.

For all samples that were loaded in that way, Vickers microhardness tests were conducted. In fact, 14 indentations were made for each sample, placed in 2 rows of 7 tests, parallel to the braking surface, into the area corresponding to the middle of the sample. For each set of 4 samples, the average value (calculated without the maximum and minimum values) was taken into consideration. The results regarding Vickers microhardness, loading force and plastic deformation area (under the characteristic curve) are presented in *Table 2*.

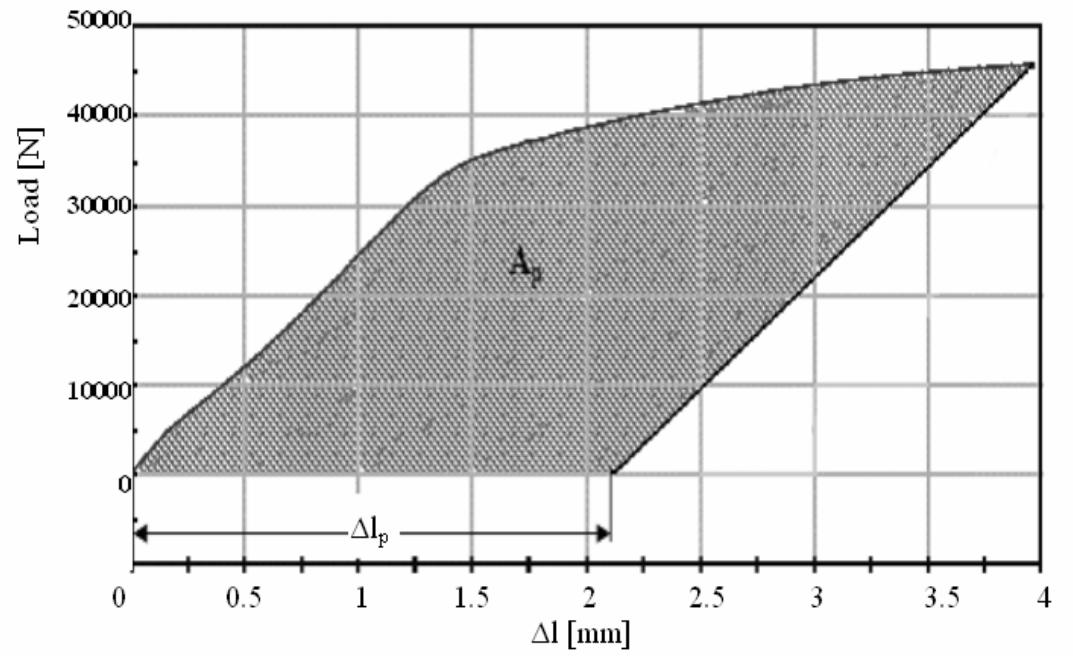


Fig. 8. The area (A_p) of the plastic strain domain.

Tab. 2. Average micro hardness values for some non-fractured tensile specimen

Tensile load [N]	0	45000	50000	52500	55000	58000
Hardness [HV]	246	256	262	282	288	320
Plastic area A_p	0	546	1217	3530	13000	13432

Using these data, the curves from *Figures 9a* and *9b* were drawn. The graph in *figure 9a* represents the variation of hardness in dependence with loading force. The first linear part – denoted as "elastic" – represents a connection between the non-deformed sample and the sample that was loaded immediately beyond the elastic domain. That line was drawn in order to unify the graph and does not represent an actual and continue variation.

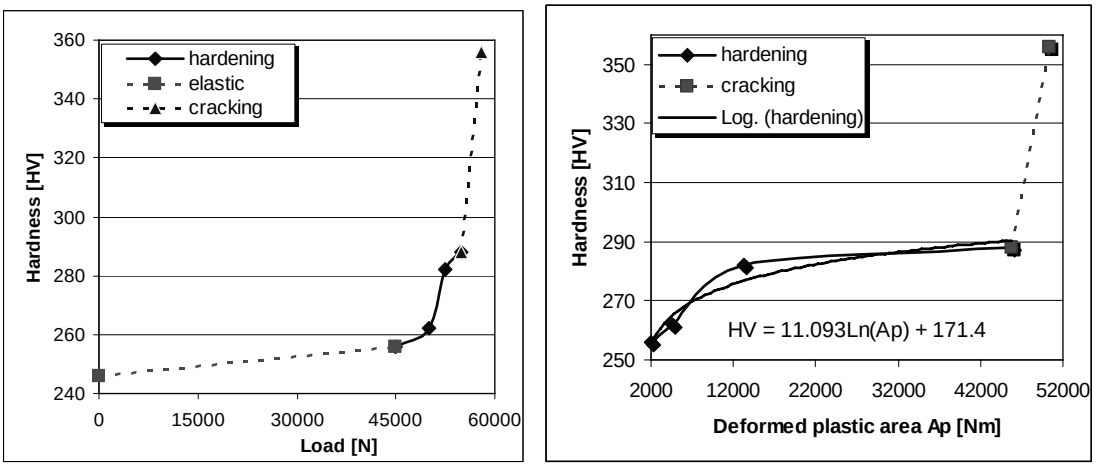
The variation of hardness with loading force into the strain hardening domain (of samples stress-strain dependence) is graphically represented by the points that are situated between 45000N and 55000N. This variation could be taken into consideration, in order to establish a correlation between the microhardness value and the tension load, for the strain hardening domain of studied material.

As presented in *Fig. 9a*, one can observe an increase of hardness with tensile load into the cited domain of material deformation. The last part of the graph, respectively the straight line linking the last two points, represents an extension from the plastic deformation domain to the breaking point, and it can not be taken into consideration as a proper variation.

The beginning part of the graph from *Figure 9b* – denoted as ”hardening” – represents the variation of hardness as a function of A_p area, the area under the characteristic curve in F-D coordinates, corresponding to the plastic deformation of the samples. The samples were loaded into the plastic domain, with different levels of tension load, followed by controlled and complete unloading.

Microhardness indentations were made on these samples, and the calculus of parameter A_p can be deduced from *Fig. 8*. The variation of Vickers hardness number with the area corresponding to plastic deformation is logarithmic in type, and could be expressed, for example, as follows:

$$HV = 11093 \ln(Ap) + 171.4 \quad (4)$$



(a) (b)

Fig. 9. a) Hardness - load dependence; b) Hardness - plastic area dependence.

It is obvious that this relation is available just for the studied material. One can assume, however, that a similar correlation between the plastic deformation status of a certain component, and its Vickers microhardness level, can be obtained in any practical situation.

As it was presented above, using the measurement of Vickers microhardness in several points that are situated into the plastic deformed area of the studied component, one can estimate the remained lifetime duration of the respective material

Conclusions

1. The plastically deformed area in the vicinity of fracture surface has a particular configuration, presented above, in Figure 4. One can assume that the mechanical characteristics of this material area depend on the plastic deformation that is determined by the applied load.
2. From *Figure 6* it was observed that, in vicinity of the fracture surface, the value of Vickers microhardness is much greater than for an unloaded sample. Moreover, on the length of a fractured sample, an increase of microhardness values was observed.
3. It can be concluded that the value of Vickers microhardness may represent a measure of the plastic deformation. It is important to note that Vickers micro-indentation is one of few tests that can be conducted in the vicinity of an area where a crack or break occurred.
4. In order to establish a correlation between the microhardness value and the plastic deformation of some samples loaded in tension, the curve in *Figure 9b* was drawn. In that way, one can obtain a mathematical expression for the variation of microhardness number, as a function of the amount of sample plastic deformation.

5. Using the above described procedure, the remaining lifetime for a certain component (that was plastically deformed) can be evaluated, on the base of Vickers microhardness measurements.

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Evaluarea duratei de viață a unui oțel utilizat în termocentrale, pe baza testelor de microduritate

Rezumat

În literatură este mult discutată legătura exisentă între valoarea durității unui material şi rezistența lui la tracțiune. Pe de altă parte, s-a constatat că se poate găsi o conexiune între nivelul deformării plastice a unui material şi mărimea durității stratului său superficial. Aceasta conduce la ideea că duritatea poate fi pusă în legătură cu durata de viață rămasă pentru un material care a funcționat, o anumită perioadă de timp, în condiții de presiuni şi temperaturi ridicate.

Materialul analizat în lucrarea de față este un oțel aliat care a fost folosit în construcția unor conducte de termocentrală, pentru transportul aburului viu. Conductele au funcționat 44 de mii de ore, la presiuni maxime de 130bar şi temperaturi de până la 530°C.

Datele experimentale prezentate în lucrare arată că există o legătură clară între nivelul deformării plastice produse prin solicitarea de tracțiune şi valoarea durității Vickers a materialului. În plus, s-a constatat o variație a durității în raport cu distanța față de zona ruperii din epruveta solicitată la tracțiune. Pe această bază se poate imagina posibilitatea de a se stabili, prin măsurarea durității, nivelul deformării plastice suportate de un anumit material după o anumită perioadă de funcționare. Ca urmare, în acest mod se poate evalua durata de viață rămasă pentru materialul analizat.