

CHECK OF RESIDUAL OPERATION LIFE VIA HARDNESS MEASUREMENT BY MOBILE ULTRASONIC CONTACT IMPEDANCE (UCI) HARDNESS TESTERS

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Abstract – The paper deals with the hardness measurement by mobile UCI hardness testers as a mean of determining the residual operation life of the power unit components. It aims to answer questions regarding the level of dependence of UCI hardness on Young's modulus of creep-resistant steels and determining the conditions of UCI hardness tester calibration. The experimental part describes comparative measurements of hardness values obtained using stationary hardness tester and UCI hardness tester.

Keywords: ultrasound hardness tester, Young's modulus of elasticity, calibration, creep-resistant steel, residual operation life

1. INTRODUCTION

At present there exists a trend of development of hardness measurements by portable hardness testers allowing "non-destructive" hardness measurements of large construction parts without any need of specimen separation for stationary hardness testers. Three physically distinct methods used are: UCI ultrasonic method, dynamic rebound method and optical method TIV (Through Indenter Viewing). In following text the focus was aimed only on the UCI method.

One of the many possibilities of using portable UCI hardness testers is the hardness measurement in assemblies (steam boilers, steam pipelines) functioning in energy units, which operate in the creep conditions (temperature app. 550 °C and a pressure app. 15 MPa). Long-term operation (2,5 · 10⁵ hours) in these conditions leads to degradation of the material accompanied by a decrease of the hardness values. UCI hardness measurement method should thus serve to detect thresholds hardness values that indicate the poor mechanical properties of the material, the risk of failure and the necessity of a more thorough examination of the experimental material state (microstructure evaluation, small punch samples preparation).

2. THE UCI METHOD OF HARDNESS MEASUREMENT

An UCI probe consists of a Vickers diamond tip attached to the end of a metal rod, which is excited into longitudinal oscillation of 70 kHz frequency by piezoelectric transducers (Fig. 1).

The UCI method does not require the diagonals of the test indentation to be measured which is necessary for the Vickers hardness determining. In this method, the shift of an ultrasonic frequency of the oscillating indenter is electronically related with the area of the indentation and thus resulting in the final hardness value. The deeper the diamond indenter penetrates, the larger is the indentation area, the larger is frequency shift of the diamond tip and the lower is then the resulting hardness, see equation (1), (2) and Fig. 2. [1]

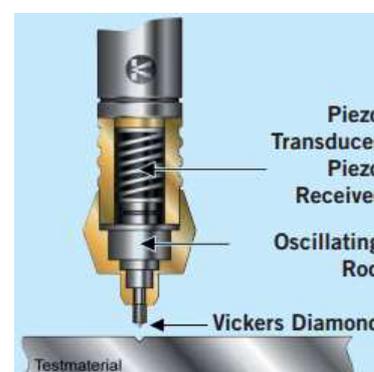


Fig. 1: UCI probe schematics [1]

$$\Delta f = f(E_{eff} \cdot A) \quad (1)$$

$$HV = F/A \quad (2)$$

Δf = frequency shift; E_{eff} = effective modulus of elasticity (contains the elastic constants of both the indenter and the test piece); A = area of indentation; HV = Vickers hardness value; F = test load

The equation (1) implies that a frequency shift depends on effective modulus of elasticity as well. Therefore, Young's modulus of elasticity in tension must be considered in practical use of the UCI method. Equipment must be calibrated if determining hardness of different materials with different hardness values. But the question is to what extent does the UCI hardness depend on the modulus of elasticity? [1]

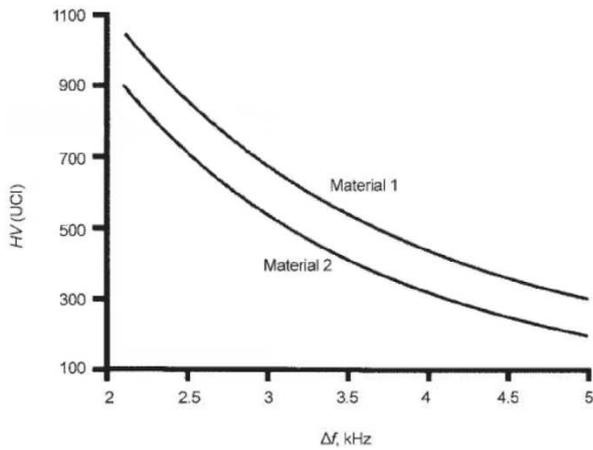


Fig. 2: Frequency shift of an ultrasonic contact impedance (UCI) probe as a function of hardness [2]

3. DEGRADATION MECHANISMS OF HIGH PRESSURE (HP) STEAM PIPELINES

The best resistance against operating in conditions of creep damage show CrMoV low-alloy steels in the normalized or heat-treated state (13CrMo4-5, 14MoV6-3, 10CrMo9-10). In case of higher operating parameters it is modified 9-12% Cr martensitic steel X10CrMoVNb9-1 (P91) and X10CrWMoVNb9-2 (P92) steel. The main factors affecting the lifetime of HP steam pipelines is a combination of their material properties and operating conditions. The main degradation mechanisms therefore include material degradation in the form of structural changes caused by coagulation of carbide particles and the nucleation and formation of cavities due to creep damage. This degradation is accompanied by a reduction of hardness. [3]

The structural changes are temperature and time dependent processes which could lead to a decrease in both short-term characteristics (yield strength, ultimate strength, hardness, and fracture toughness) and the long-term characteristics (creep strength, creep deformation, plasticity). In case of low-alloy creep-resistant steels there exists an area of predominant hardening and an area of predominant softening. Hardening of the material (up to 1000 hours of operation) in CrMoV steels is caused by additional precipitation of vanadium carbides, thereby increasing the number of new dispersed particles, reducing their average size, increasing their volume fraction and decreasing their interparticle distance. On the other hand, during material softening there occurs coarsening of dispersed particles via diffusion processes, resulting in increase of their average size, volume fraction decrease and increase of the interparticle distance. [3]

Stages of degradation of creep resistant, low-alloy steel of chemical composition of 0.5% Cr - 0.5% Mo - 0.25% V (14MoV6-3) subjected to creep exposure are in Fig. 3. Stage 0 corresponds to the initial state with ferritic-bainitic structure at the beginning of creep exposure (Fig. 3a). The first stage of structural changes is characterized by a moderate decomposition of bainite. That is accompanied by coagulation of M_3C carbides in these areas and further precipitation of $M_{23}C_6$ carbides along the ferritic grains

boundaries. At the same time, very fine MC carbides precipitate within the ferrite grains (Fig. 3b). The next stage is characterized by significant decomposition of bainite and coagulation of M_3C carbides into relatively large carbide particles at the grain boundaries. The $M_{23}C_6$ carbides precipitate on the boundaries of ferritic grains and form chains. Simultaneously, fine MC carbides are observed within ferritic grains (Fig. 3c). Final structural changes result into ferritic matrix containing MC and M_6C carbides inside ferrite grains and large $M_{23}C_6$ carbides precipitated along the grain boundaries (Fig. 3d). Depending on the operating conditions, the material may contain also other types of carbides, e.g. M_7C_3 carbides. After such a degradation of the material microstructure and further creep exposure the creep cavities are formed. [4]

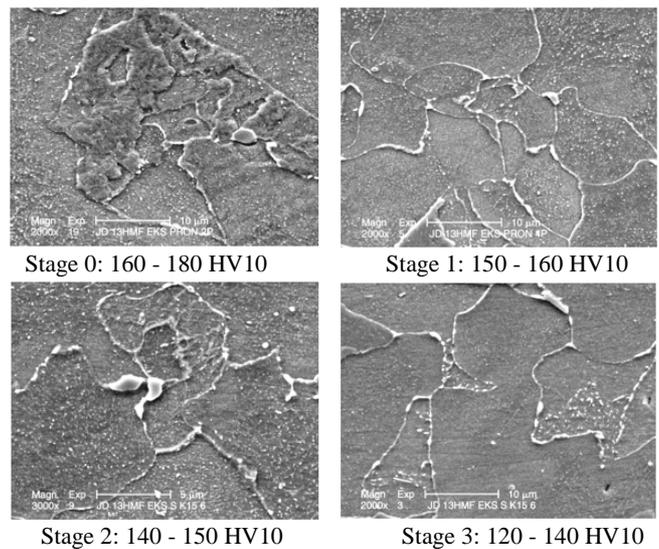


Fig. 3: Stages of microstructure degradation after the creep exposure [4]

3.1. Surface decarburization

Surface decarburization takes place most frequently on the outer surface of steel components and is accompanied by rapid reduction of carbon content on the surface due to diffusion caused by high temperature.

Decarburized layer has a lower hardness than the material below the layer due to reduced carbon content. Carbon content gradient in the decarburized layer increases with the distance from the outer surface. Therefore, the hardness values measured after removal of decarburized layer are higher. Since the hardness is measured on the outer surface components, it is imperative to remove this layer in order to achieve relevant results. Decarburized layer has a thickness usually of up to 1.0 mm.

4. EXPERIMENTAL

The experimental part was focused on determining UCI hardness dependence on Young's modulus of elasticity in tension via comparative measurement of hardness values obtained by classic HV10 Vickers method and values obtained using UCI hardness tester. Deviation of the mean

values measured by UCI hardness tester and by stationary (laboratory) hardness tester were evaluated.

4.1. Used measurement equipment

Comparative measurements as a mean of determining of UCI hardness on E were performed in accord with ČSN EN ISO 6507-1 standard using calibrated stationary hardness tester by Vickers method with load of HV10. As a representative of portable hardness testers the UCI hardness tester Krautkrämer MIC20 and Krautkrämer MIC10 with UCI probe MIC 2010 of load of 98 N was selected.

4.2. Experimental materials

Materials with different Young's modulus E were selected for comparative measurements (Table. 1). Values of Young's modulus E were verified using literary resources. The mean values without standard deviations are shown in Table 1. The experimental determination of the Young's modulus values was not carried out due to lack of time.

The experimental samples were removed from the steam pipe-lines or boiler tube in different states of degradation. In the case of steels X20CrMoV12-1 and X5CrNiCuNb17-4-4, it was possible to get the samples from the rotor blades. Table 2 shows a description of individual samples.

Table. 1: Selected materials and their Young's modulus values

Material	E [GPa]
X10CrMoVNB9-1 (P91) X10CrWMoVNB9-2 (P92)	218
14MoV6-3 T23 T24	210
X20CrMoV12-1 X5CrNiCuNb17-4-4	200

Table. 2: Selected samples of materials and their state of operating (laboratory) degradation

Material	Sample - State of degradation
X10CrMoVNB9-1	P6 – lab. ageing at 600 °C/10 000 hours P21 – initial state after heat treatment
X10CrWMoVNB9-2	BT3 – lab. ageing at 650 °C/20 000 hours T33 – lab. ageing at 650 °C/5 033 hours
14MoV6-3	K1 – degraded at 525 °C/240 000 hours EPR – degraded at 560 °C/261 800 hours EPC – degraded at 540 °C/240 066 hours
T23	V23 – initial state after heat treatment D23 – lab. ageing at 650 °C/5 033 hours
T24	V24 – initial state after heat treatment D24 – lab. ageing at 650 °C/5 033 hours
X20CrMoV12-1	L1 – Unknown
X5CrNiCuNb17-4-4	L2 – Unknown

4.3. Preparation of the measurement site

Hardness of the materials described above was measured always on the outer surface (approximately 0.5 to 1.0 mm was grinded off in order to remove decarburized layer), and across the tube wall thickness. In case of steels of a tensile modulus of 200 GPa hardness was measured only in the cross-section of the blade lock. The surface was prepared

using metallographic grinder with sandpaper grit of 400, thereby achieving the surface roughness Ra 0,07 – 0,12 µm (Measured by Surface Roughness Tester Hommelwerke LV-5E). Selected number of indentations on every surface was 10.

4.4. Measurement process

On the prepared surfaces of approximately 10 mm² area was at first measured hardness according to ČSN EN ISO 6507-1 using stationary hardness tester by Vickers method with load of HV10. Subsequently, UCI hardness tester was used for hardness measurement in close vicinity (approximately 5 mm) of these indentations.

During UCI tester measurements, following finding was observed. The probe MIC 2010 was firstly used for measuring of the initial state hardness (without perpendicularity providing fixture). Hardness values measured in this way showed significant deviations and unreal values. Therefore, it was decided to use the probe with perpendicularity providing fixture to solve the problem. It implies that when measuring the hardness it is necessary to keep the probe perpendicular to the surface, which can be achieved by installing the fixture or by a properly trained and experienced person performing the measurements.

4.5. Results of measurements

All results of hardness measurement are summarized in Table 3 - Table 10. The tables contain the average hardness value (10 measurements) measured on the surface and throughout the wall thickness, their standard deviation (STD) and the deviation of the average value of the UCI hardness from average values measured by stationary hardness tester (LAB).

a) Steels with E = 218 GPa

Table. 3: Steel X10CrMoVNB9-1; sample P21 and P6

X10CrMoVNB9-1; Sample P21 (Ø 324 x 28 mm); initial state after heat treatment						
	Measured on surface			Measured through the wall thickness		
	LAB	MIC 20	MIC 10	LAB	MIC 20	MIC 10
	HV10	UCI HV10	UCI HV10	HV10	UCI HV10	UCI HV10
Avg.	201	187	186	215	199	195
STD	± 5	± 6	± 9	± 5	± 11	± 10
Deviation		- 14	- 15		- 16	- 20
X10CrMoVNB9-1; Sample P6 (Ø 270 x 25 mm); laboratory ageing at 600 °C/10 000 hours						
Avg.	228	208	206	238	218	217
STD	± 5	± 5	± 5	± 4	± 6	± 6
Deviation		- 20	- 22		- 20	- 21

Table. 4: Steel X10CrWMoVNb9-2; sample BT3 and T33

X10CrWMoVNb9-2; Sample BT3 (Ø 350 x 39 mm); laboratory ageing at 650 °C/20 000 hours						
Measured on surface			Measured through the wall thickness			
	LAB	MIC 20	MIC 10	LAB	MIC 20	MIC 10
	HV10	UCI HV10	UCI HV10	HV10	UCI HV10	UCI HV10
Avg.	226	211	207	232	205	211
STD	± 2	± 9	± 9	± 3	± 5	± 7
Deviation	- 15	- 19		- 27	- 21	
X10CrWMoVNb9-2; Sample T33 (Ø 528 x 94 mm); laboratory ageing at 650 °C/5 033 hours						
Avg.	223	204	198	230	205	216
STD	± 3	± 12	± 6	± 3	± 7	± 6
Deviation	- 19	- 25		- 25	- 14	

In case of steels with the same Young's modulus (218 GPa) the measurements show that the values of the deviations of both UCI hardness testers (Krautkrämer MIC20 and MIC10) vary in the same trend. The average value of the deviations is approximately -21 HV (see Tables 3 and 4).

b) Steels with E = 210 GPa

Table. 5: Steel 14MoV6-3; sample PK1, EPR and EPC

14MoV6-3; Sample K1 (Ø 273 x 26 mm); degraded at 525 °C/240 000 hours						
Measured on surface			Measured through the wall thickness			
	LAB	MIC 20	MIC 10	LAB	MIC 20	MIC 10
	HV10	UCI HV10	UCI HV10	HV10	UCI HV10	UCI HV10
Avg.	201	191	187	214	202	202
STD	± 3	± 7	± 7	± 5	± 9	± 14
Deviation	- 10	- 14		- 12	- 12	
14MoV6-3; Sample EPR (Ø 245 x 36 mm); degraded at 560 °C/261 800 hours						
Avg.	151	137	133	150	138	133
STD	± 1	± 11	± 7	± 2	± 8	± 8
Deviation	- 14	- 18		- 12	- 17	
14MoV6-3; Sample EPC (Ø 324 x 48 mm); degraded at 540 °C/240 066 hours						
Avg.	128	121	119	133	117	119
STD	± 1	± 2	± 7	± 3	± 5	± 5
Deviation	- 7	- 9		- 16	- 14	

Table. 6: Steel T23; sample V23 and D23

T23; Sample V23 (Ø 38 x 5.6 mm); initial state after heat treatment						
Measured on surface			Measured through the wall thickness			
	LAB	MIC 20	MIC 10	LAB	MIC 20	MIC 10
	HV10	UCI HV10	UCI HV10	HV10	UCI HV10	UCI HV10
Avg.	205	222	214	201	221	210
STD	± 4	± 11	± 6	± 1	± 6	± 6
Deviation	17	9		20	9	

T23; Sample D23 (Ø 38 x 5.6 mm); laboratory ageing at 650 °C/5 033 hours						
Avg.	157	169	167	166	176	169
STD	± 2	± 8	± 8	± 3	± 9	± 9
Deviation	12	10		10	3	

Table. 7: Steel T24; sample V24 and D24

T24; Sample V24 (Ø 38 x 5.6 mm); initial state after heat treatment						
Measured on surface			Measured through the wall thickness			
	LAB	MIC 20	MIC 10	LAB	MIC 20	MIC 10
	HV10	UCI HV10	UCI HV10	HV10	UCI HV10	UCI HV10
Avg.	229	250	239	228	243	231
STD	± 2	± 12	± 7	± 5	± 6	± 11
Deviation	21	10		15	3	
T24; Sample D24 (Ø 38 x 5.6 mm); laboratory ageing at 650 °C/5 033 hours						
Avg.	175	186	192	176	199	190
STD	± 2	± 12	± 8	± 4	± 11	± 11
Deviation	11	17		23	14	

In case of 14Mo6-3 steel and T23, T24 steels with the same Young's modulus (210 GPa) it was observed that the values of the deviations of both UCI hardness testers (Krautkrämer MIC20 and MIC10) vary in the inverse trend. The average value of the deviations is approximately -13 HV for 14Mo6-3 steel and 13 HV for T23, T24 steels (see Table 5 - Table 7).

c) Steels with E = 200 GPa

Table. 8: Steel X20CrMoV12-1; sample L1

X20CrMoV12-1; Sample L1 (rotor blades); unknown state						
Measured through the cross-section			Measured through the cross-section			
	LAB	MIC 20	MIC 10	LAB	MIC 20	MIC 10
	HV10	UCI HV10	UCI HV10	HV10	UCI HV10	UCI HV10
Avg.	352	348	347	361	357	355
STD	± 5	± 11	± 13	± 5	± 7	± 7
Deviation	- 4	- 5		- 4	- 6	

Table. 9: Steel X5CrNiCuNb17-4-4; sample L2

X5CrNiCuNb17-4-4; Sample L2 (rotor blades); unknown state						
Measured through the cross-section			Measured through the cross-section			
	LAB	MIC 20	MIC 10	LAB	MIC 20	MIC 10
	HV10	UCI HV10	UCI HV10	HV10	UCI HV10	UCI HV10
Avg.	503	502	500	508	509	504
STD	± 7	± 8	± 7	± 3	± 10	± 6
Deviation	- 1	- 3		1	- 4	

The deviation values measured in steels with Young's modulus of 200 GPa of both UCI hardness testers (Krautkrämer MIC20 and MIC10) vary in the same trend. The average value of the deviations is approximately -3 HV, (see Tables 8 and 9).

5. CONCLUSION

The original idea of practice that hardness measurement by mobile UCI hardness testers is independent of the values of Young's modulus has proven not to be entirely correct.

The measured results showed the existing dependence of UCI hardness on Young's modulus. Although the dependence is very low, it is necessary to consider it and to perform the proposed calibration of UCI hardness testers using suitable calibration plates.

The measured results are summarized in Table 10. From the results it is possible to state that with increasing Young's modulus of elasticity E the value of the negative deviation of hardness values measured by UCI hardness tester increases in comparison with the values measured using a stationary (laboratory) tester. The dependence can be considered as linear. However, that doesn't apply in the case of T23 and T24 steels with Young's modulus of 210 GPa where deviation of UCI hardness vary in the opposite trend.

Table 10: A summary of the results of the average deviations

Materials	E [GPa]	Average deviations [HV10]
X10CrMoVNb9-1 (P91) X10CrWMoVNb9-2 (P92)	218	-21
14MoV6-3	210	-13
T23 T24	210	13
X20CrMoV12-1 X5CrNiCuNb17-4-4	200	-3

The general validity of these conclusions has not been confirmed in one case. T23 and T24 steels showed the deviation trend opposed to the deviation measured in 16MoV6-3 steel. The average value of the deviations is approximately -13 HV for 14Mo6-3 steel and 13 HV for T23, T24 steels.

Finding the reasons of this difference in deviations values is not yet completed. The observation of the influence of different wall thicknesses (steam and boiler tubes), the influence of microstructure and verification of the real Young's modulus will be subjects for the further research.

Considering the above measured results, we propose following groups of calibration plates:

- 1) Calibration plates for 9% Cr martensitic steel – made from P91 (P92) steel: E = 218 GPa
- 2) Calibration plates for low alloy CrMoV steels – made from 16MoV6-3 steel: E = 210 GPa

- 3) Calibration plates for 2% Cr steels – made from T23 (T24) steel: E = 210 GPa
- 4) Calibration plates for steels for rotor blades – made from X20CrMoV12-1 steel: E = 200 GPa

It will be necessary to determine the hardness of these calibration plates at the lower and upper limit of practically measured values of HV hardness in operating conditions.

The rebound method was not carried out because specimens on which the measurement was to be performed, did not reach the required minimum weight of 5 kg. Measured values would be thus misleading.

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