Dependence of ultrasonic contact impedance hardness on Young's modulus of elasticity of creep-resistant steels

Michal Junek, Jiří Janovec, Petr Ducháček

CTU in Prague, Faculty of mechanical engineering, Department of Materials Engineering, Praha 2, Karlovo náměstí 13, Czech Republic

ABSTRACT
The paper deals with the hardness measurements by mobile UCI hardness testers as a means of determining the residual operation life of 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 a UCI hardness tester calibration. The experimental part describes comparative measurements of hardness values obtained using stationary hardness testers and UCI hardness testers.

Corresponding author: M. Junek, e-mail: michal.junek@fs.cvut.cz

1. INTRODUCTION

At present a trend of developing hardness measurements by portable hardness testers exists, allowing "non-destructive" hardness measurements of large construction parts without any need of specimen separation for stationary hardness testers. Four physically distinct methods used are: UCI ultrasonic method, dynamic rebound method, optical method TIV (Through Indenter Viewing) and electrical resistance method (Handy Esatest). In the 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 pipe-lines) functioning in energy units, which operate in creep conditions (temperature approx. 550 °C and a pressure approx. 15 N·mm^{-2}). Long-term operation (2.5×10^5 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 to perform a longitudinal oscillation with a frequency of 70 kHz, by piezoelectric transducers (Figure 1).

T is the piezoelectric transducer, R the piezoelectric receiver, O the oscillating rod, V the indenter (for example Vickers diamond) and m is the test material.
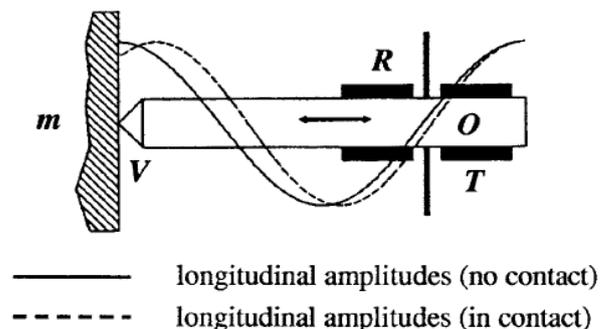
Figure 1. UCI probe schematics [1].

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 the frequency shift of the diamond tip and the lower the resulting hardness, see (1), (2) and Figure 2 [2].

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

$$HV = {F}/{A} , \qquad (2)$$

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

Equation (1) implies that a frequency shift depends on the effective modulus of elasticity as well. Therefore, Young's modulus of elasticity in tension must be considered using the UCI method in practice. The equipment must be calibrated when determining the 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? [2]

2.1. Calibration

The ASTM A1038 – 05 standard [1] states that a UCI hardness tester usually has been calibrated on non-alloyed and low-alloyed steel, that is, certified hardness reference blocks with Young's modulus of elasticity equal to 210 000 $N \cdot mm^{-2}$. Because unalloyed or low-alloy steels have a similar Young's modulus of elasticity, accurate results are obtained with the standard calibration. In many cases, the difference in Young's modulus of medium-alloy and high-alloy steels is so insignificant that the error created falls within the allowable tolerances of the part. But the question is: what is considered as a similar Young's modulus of elasticity?

Hardness reference blocks are needed for calibration to other materials with a different Young's modulus of elasticity. This paper should answer the question of calibration UCI hardness testers used for hardness measurement of components functioning in power units.
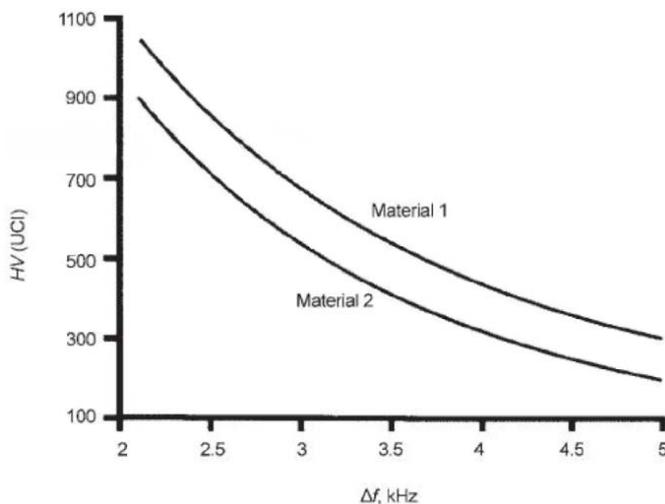
Figure 2. Frequency shift of an ultrasonic contact impedance (UCI) probe as a function of hardness [3].

2.2. Comparison of non-destructive methods of hardness measurement

Several methods for non-destructive hardness measurements are used in practice. Table 1 shows various methods for non-destructive measuring of hardness using portable hardness testers. Furthermore, a comparison of the areas of applications of each portable hardness testers is given. From this comparison, the UCI method seems to be best for hardness measurements of large construction parts functioning in energy units (steam pipe-lines, steam boilers and welds of these parts).

3. DEGRADATION MECHANISMS OF HIGH PRESSURE (HP) STEAM PIPE-LINES

The best resistance against operating in conditions of creep damage shows 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 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

Table 1. Recommended applications for hardness measurement by portable hardness testers [2].

Applications	Dynamic rebound method	UCI method	TIV method	Handy Esatest
Solid (big) parts	*	*	o	o
Coarse-grained materials	*	x	x	x
Steel and aluminium cast alloys	*	o	o	o
HAZ with welds	x	*	*	*
Tubes: wall thickness > 20 mm	*	*	*	*
Tubes: wall thickness < 20 mm	x	*	*	*
Inhomogeneous surfaces	o	x	x	x
Sheet metal, coils	x	o	*	*
Thin layers	x	o	*	*
Hard to get at positions	x	*	x	*
Coarse surfaces	*	x	x	o
Finally machined surfaces	o	*	*	*
Electrically conductive materials	*	*	*	x
Dusty environments	*	o	o	x

Explanatory notes to table:

x	Not recommended
o	Sometimes suitable (In the case of elimination conditions having adverse impacts on measurement results)
*	Especially well-suited

degradation is accompanied by a reduction of hardness. [4]

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 long-term characteristics (creep strength, creep deformation, plasticity). In case of low-alloy creep-resistant steels an area of predominant hardening and an area of predominant softening exists. 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 coarsening of dispersed particles via diffusion processes occurs, resulting in an increase of their average size, volume fraction decrease and increase of the interparticle distance [4].

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 Figure 3. Stage 0 corresponds to the initial state with a ferritic-bainitic structure at the beginning of creep exposure (Figure 3 - Stage 0). 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 (Figure 3 - Stage 1). 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 (Figure 3 - Stage 2). Final structural changes result in a ferritic matrix containing MC and M_6C carbides inside ferrite grains and large $M_{23}C_6$ carbides precipitated along the grain boundaries (Figure 3 - Stage 3). 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 creep cavities are formed [5].
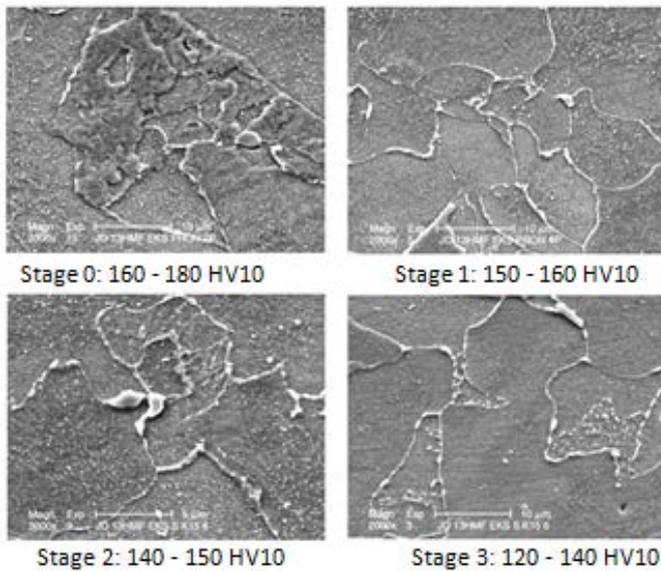
3.1. Surface Decarburization

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 temperatures.

A decarburized layer has a lower hardness than the material below the layer due to reduced carbon content. The carbon content gradient in the decarburized layer increases with the distance from the outer surface, see Figure 4 and Figure 5. Therefore, the hardness values measured after removal of the 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. The decarburized layer has a thickness usually of up to 1.0 mm.

4. EXPERIMENTS

The experimental part was focused on determining UCI hardness dependence on Young's modulus of elasticity in tension via comparative measurements of hardness values obtained by the classic HV10 Vickers method and values obtained using the UCI hardness tester. Deviation of the mean values measured by the UCI hardness tester and by the stationary (laboratory) hardness tester were evaluated.

4.1. Used Measurement Equipment

Comparative measurements as a means of determining the UCI hardness on Young's modulus of elasticity were performed in accord with the ČSN EN ISO 6507-1 standard using a calibrated stationary hardness tester by the Vickers method with a 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.
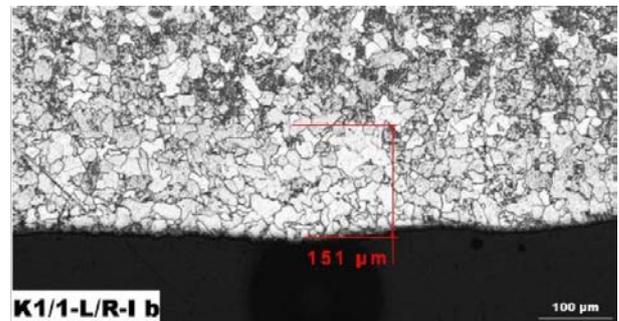
Figure 4. Surface decarburization of HP steam pipe-line of fossil fuel power plants.

Figure 3. Stages of microstructure degradation after creep exposure [5].
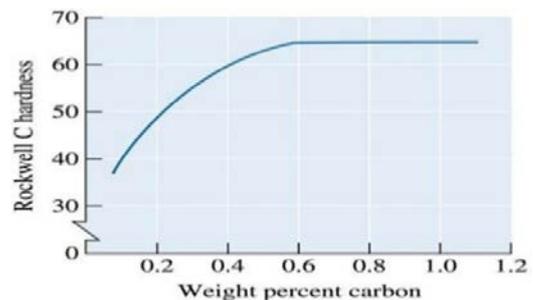
Figure 5. Dependence of Rockwell hardness on the carbon content [6].

4.2. Experimental Materials

Materials with different Young's modulus E were selected for comparative measurements. Values of Young's modulus E were verified using data from literature. The mean values without standard deviations are shown in Table 2. 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 3 shows a description of individual samples.

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 the decarburized layer), and across the tube wall thickness. In case of steels of a tensile modulus of 200 N·mm⁻² hardness was measured only in the cross-section of the blade lock. The surface was prepared using a metallographic grinder with sandpaper grit of 400, thereby achieving a surface roughness R_a of $0.07 - 0.12$ μm (measured by a Surface Roughness Tester Hommelwerke LV-5E). The selected number of indentations on every surface was 10.

4.4. Measurement Process

On the prepared surfaces with an approximate area of 10 mm² at first the hardness was measured according to ČSN EN ISO 6507-1 using a stationary hardness tester (Vickers method) with a 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 the following finding was observed. The probe MIC 2010 was firstly used for measuring

Table 2. Selected materials and their Young's modulus values.

Materials	E [N·mm⁻²]
X10CrMoVNb9-1 (P91) X10CrWMoVNb9-2 (P92)	218 000
14MoV6-3 T23 T24	210 000
X20CrMoV12-1 X5CrNiCuNb17-4-4	200 000
Steel Super 304H	193 000

Table 3. 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
Steel Super 304H	2030 – Dissolving annealing 1150 °C/2 min

the initial state hardness (without a fixture providing perpendicular positioning). Hardness values measured in this way showed significant deviations and unreal values. Therefore, it was decided to use the probe with a fixture providing perpendicular positioning 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 a fixture or by a properly trained and experienced person performing the measurements.

4.5. Measurements results

All hardness measurement results are summarized in Table 3 to Table 10. The tables contain the average hardness values from 10 measurements for each sample measured on the surface and throughout the wall thickness by the laboratory hardness tester and by UCI hardness testers. The tables further include standard deviations (STD) of measured values and the deviation of the average value of the UCI hardness from average values measured by the stationary hardness tester (LAB).

a) *Steels with E = 218 000 N·mm⁻²*

In case of steels with the same Young's modulus 218 000 N·mm⁻² 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 4 and 5).

b) *Steels with E = 210 000 N·mm⁻²*

In case of 14Mo6-3 steel and T23, T24 steels with the same Young's modulus 210 000 N·mm⁻² it was observed that the

Table 4. Steel X10CrMoVNb9-1; samples 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 **HV10**	**MIC 20** **UCI** **HV10**	**MIC 10** **UCI** **HV10**	**LAB** **HV10**	**MIC 20** **UCI** **HV10**	**MIC 10** **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 5. Steel X10CrWMoVNb9-2; samples 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 **HV10**	**MIC 20** **UCI** **HV10**	**MIC 10** **UCI** **HV10**	**LAB** **HV10**	**MIC 20** **UCI** **HV10**	**MIC 10** **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

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 6 - Table 8).

   c) *Steels with E = 200 000 N.mm-2*

The deviation values measured in steels with Young's

modulus of 200 000 N·mm-2 of both UCI hardness testers (Krautkrämer MIC20 and MIC10) are similar. The average value of the deviations is approximately -3 HV (see Tables 9 and 10).

   d) *Steels with E = 193 000 N·mm-2*

In case of austenitic steel Super 304H with Young's modulus 193 000 N·mm-2 it was observed that the measured values show large measurement errors. The standard deviation of the value measured by the UCI hardness tester is up to 59 HV. The measurement of hardness of austenitic steels is generally a problem due to their strengthening. The dynamic rebound method (Brinell 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 and minimum wall thickness 20 mm. The average value of the deviations is very different (see Tables 11).

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 experimental results show the following (see Table 12). The larger is Young's modulus the larger is the negative deviation of the measured hardness. The explanation of this dependence is

Table 6. Steel 14MoV6-3; samples 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 **HV10**	**MIC 20** **UCI** **HV10**	**MIC 10** **UCI** **HV10**	**LAB** **HV10**	**MIC 20** **UCI** **HV10**	**MIC 10** **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	**± 4**	± 2	± 7	**± 3**	± 5	± 5
Deviation		-7	-9		-16	-14

Table 7. Steel T23; samples 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 **HV10**	**MIC 20** **UCI** **HV10**	**MIC 10** **UCI** **HV10**	**LAB** **HV10**	**MIC 20** **UCI** **HV10**	**MIC 10** **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 8. Steel T24; samples 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 **HV10**	**MIC 20** **UCI** **HV10**	**MIC 10** **UCI** **HV10**	**LAB** **HV10**	**MIC 20** **UCI** **HV10**	**MIC 10** **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

Table 9. Steel X20CrMoV12-1; sample L1.

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

Table 10. 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 **HV10**	**MIC 20** **UCI** **HV10**	**MIC 10** **UCI** **HV10**	**LAB** **HV10**	**MIC 20** **UCI** **HV10**	**MIC 10** **UCI** **HV10**
Avg.	**503**	502	500	**508**	509	504
STD	**± 7**	± 8	± 7	**± 3**	± 10	± 6
Deviation		- 1	- 3		1	- 4

Table 11. Steel Super 304H; sample 2030.

Super 304H; Sample 2030 (Ø 38 x 6.3 mm); Dissolving annealing 1150 °C/2 min						
Measured on surface			**Measured through the wall thickness**			
	LAB **HV10**	**MIC 20** **UCI** **HV10**	**MIC 10** **UCI** **HV10**	**LAB** **HV10**	**MIC 20** **UCI** **HV10**	**MIC 10** **UCI** **HV10**
Avg.	**181**	366	-	**176**	227	-
STD	**± 2**	± 59	-	**± 4**	± 32	-
Deviation		185	-		49	-

Table 12. A summary of the results of the average deviations.

Materials	E [N·mm⁻²]	Average deviations HV10
X10CrMoVNb9-1 (P91) X10CrWMoVNb9-2 (P92)	218 000	-21
14MoV6-3	210 000	-13
T23 T24	210 000	13
X20CrMoV12-1 X5CrNiCuNb17-4-4	200 000	-3

evident from the Figure 2, which shows that the greater the frequency shift the smaller the measured hardness. Therefore, we can say that steel with a higher modulus of elasticity has a greater frequency shift. Therefore, we measured a lower hardness for steels with a higher Young's modulus.

The measured results showed the existing dependence of UCI hardness on Young's modulus. Although the dependence is very small, 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 12. 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 the 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 210 000 N·mm⁻² where the deviation of UCI hardness varies in the opposite direction.

The general validity of these conclusions has not been confirmed in one case. T23 and T24 steels showed the deviation trend opposite 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 for this difference in deviations values is not yet completed. A possible cause could be a different wall thickness, because boiler tubes from these materials have a wall thickness of 5.6 mm and steam pipe-lines from other materials have wall thicknesses from 20 up to 80 mm. 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 the following groups of calibration plates:

1) Calibration plates for 9 % Cr martensitic steel – made

from P91 (P92) steel: E = 218 000 N·mm⁻²

2) Calibration plates for low alloy CrMoV steels – made from 16MoV6-3 steel: E = 210 000 N·mm⁻²

3) Calibration plates for 2% Cr steels – made from T23 (T24) steel: E = 210 000 N·mm⁻²

4) Calibration plates for steels for rotor blades – made from X20CrMoV12-1 steel: E = 200 000 N·mm⁻²

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.

These results are used in normative technical documentation for requirements for hardness measurements by portable hardness testers in Czech classic power plants.

REFERENCES

[1] ASTM A1038 – 05. "Standard Practice for Portable Hardness Testing by the Ultrasonic Contact Impedance Method". West Conshohocken: ASTM International, 2005.

[2] S. Frank, "Mobile Hardness Testing Application Guide for Hardness Testers". General Electric Company [online]. 2005 [cit. 2015-02-13]. Available from: https://www.gemeasurement.com/sites/gemc.dev/files/hardness_testing_application_guide_english_0.pdf.

[3] K. Herrmann, "Hardness testing: principles and applications". Materials Park, Ohio: ASM International, 2011. ISBN 978-1-61503-832-9.

[4] M. Junek, "Posouzení životnosti VT parovodů v podmínkách creepového poškození". Diploma thesis. Praha: 2014. CTU in Prague, Faculty of mechanical engineering, Department of Material Engineering. p. 87.

[5] PA. PHILADELPHIA, "Power plant life management and performance improvement" Woodhead Pub. Ed. John E. Oakey, 2011, 684 p. ISBN 978-184-5697-266.

[6] Slide share. Slide share [online]. 2013 [cit. 2015-08-29]. Available from: http://image.slidesharecdn.com/f4-131118222248-phpapp02/95/hardening-14-638.jpg?cb=1384813955.