JOURNAL OF OPTOELECTRONICS AND ADVANCED MATERIALS Vol. 13, No. 2, February 2011, p. 106 - 110

Studies concerning the modification of longitudinal elastic modulus and logarithmic decrement while heat treating C45 steel

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The knowing of the thermo dynamical conditions, the mechanism and kinetics of the transformations suffered by Austenite on cooling and by Martensite on heating, represents the fundamental issue of heat treatment theory and practice. The evaluation of the results obtained after the transformations of Austenite on cooling, respectively analysis of the resultant structures, is usually made by mechanical testing (hardness, traction, resilience) and metallographic analysis. The main issue of the present article is the modification analysis of the dynamic elastic modulus, internal friction, hardness and resilience, suffered as a consequence of the normalizing, hardening and tempering of carbon steel C45 (OLC 45) appliance.

(Received November 10, 2010; accepted February 17, 2011)

Keywords: Internal friction, Logarithmic decrement, Heat treatment, Vibration, Elastic modulus.

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1. Introduction

The processes that take place on Austenite cooling have a great importance, both theoretically and practically, since their mechanism and kinetics influence the nature, shape, size and distribution of the resulting phases leading to obtaining some particular characteristics at the end of the heat treatment process. The knowing of the thermo dynamical conditions, the mechanism and kinetics of the transformations suffered by Austenite on cooling and by Martensite on heating, represents the fundamental issue of heat treatment theory and practice.

The evaluation of the results obtained after the Austenite on cooling transformations, respectively analysis of the resultant structures, is made usually by mechanical testing (hardness, traction, resilience) and metallographic analysis.

The main issue of the present article is the modification analysis of the dynamic elastic modulus, internal friction, hardness and resilience, suffered as a consequence of the normalizing, hardening and tempering of carbon steel C45 (OLC 45) appliance.

2. Phisical bases of determinations

Experience shows that the free oscillations of one body damp in time. In some situations the external environment influence upon oscillation damping is negligible, and the decreasing causes are to be found in the solid interior and are named internal friction. [1]

During oscillation damping process mechanical energy gradually turns in, being taken over by microscopic systems, and releases an equivalent heat quantity. So internal friction processes are irreversible. Usually, in technique extreme metallic materials behaviour as well as very low or high internal friction is being watched. In physical metallurgy, studies regarding internal friction assure a better knowledge about crystalline network dynamism and emphasise the presence of micro or macro defects, consistency of grain limits, including inter crystalline corrosion, tensile state created by various cold or warm machining, and last but not least heat treatment's influence over the materials.

Therefore, such studies of internal friction may fill up the information obtained by means of ordinary evaluation methods of metallic materials properties, such as: chemical analysis, non destructive control, traction-compression testing, hardness and resilience determinations, and also metallographic analysis. The advantage of the study regarding internal friction is brought by the fact that the obtained results refer to the global state of test sample and this way, the risk of global evaluation errors is diminished.

Internal friction evaluation can result from the analysis of the resonance curve of a test sample excited by a harmonic disturbing force. In order to establish the internal friction using forced vibrations, the logarithmic decrement (δ) should be determined by using the formula [7]:

$$\delta = \frac{2\pi \Delta f}{f_r} \frac{1}{\sqrt{\left(\frac{Xmax}{X}\right)^2 - 1}} \qquad (1)$$

where Δf, represents frequency variation of the disturbing force that causes damping of resonance amplitude, X_{max}, up to X_1, respectively X_2 value.

Amplitudes X_1 and X_2 can be chosen according to the following criteria:

a) when amplitudes correspond to half of the power oscillations;

$$X_1 = X_2 = \frac{X_{max}}{\sqrt{2}} = 0{,}707X_{max} \tag{2}$$

b) when amplitudes reach half of the value measured at resonance;

$$X_1 = X_2 = \frac{X_{max}}{2} = 0{,}5X_{max} \tag{3}$$

In order to obtain higher precision evaluation, $f_1$and f_2 frequencies, are to be measured, for X_1=X_2, on both sides of resonance frequency; in this case it results:

$$\delta_{(a)} = \frac{\pi \Delta f}{f_r} = 3{,}14\frac{f_2 - f_1}{f_r} \tag{4}$$

$$\delta_{(b)} = \frac{\pi \Delta f}{\sqrt{3} f_r} = 1.815\frac{f_2 - f_1}{f_r} \tag{5}$$

When dealing with materials with low amortisation, it is recommended the use of b) criterion, because due to the very sharp resonance curve the measurement of f_1, f_r, f_2 frequencies ensures lower measuring errors (Fig.1).

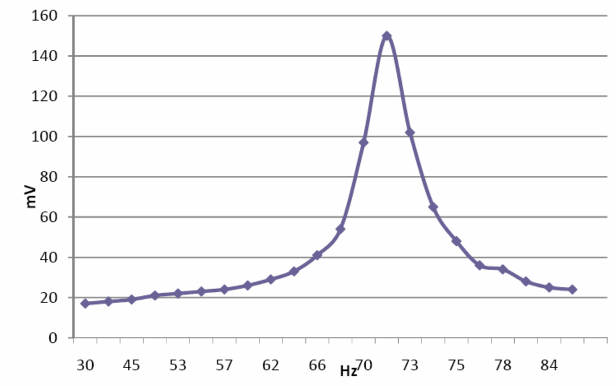

Fig. 1. Resonance curve

In this study the resonance curves of the test sampler were analyzed; as a consequence the logarithmic decrement and longitudinal elastic modulus was determined.

Using the known equations of both Material Resistance [5] and forced vibrations for one end embedded bars [2], we reach the relation by means of which the dynamic longitudinal elastic modulus can be calculated E_d:

$$E_d = \frac{64\pi^2 \rho}{m_1^4} \frac{l^4}{d^2} f_1^2 \tag{6}$$

where: ρ is material density;
m_1 - constant for harmonic 1;
l - test sample length out of embedded;
d - test sample diameter;
f_1 - resonance frequency on harmonic1.

3. Used devices

Fig. 2 represents the scheme of a device created for the purpose of determining dynamic elastic modulus and logarithmic decrement.

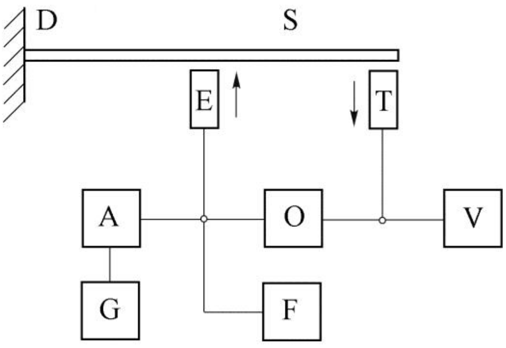

Fig. 2. Device scheme for establishing the measures requested for the determination of the dynamic elastic modulus and logarithmic decrement, from resonance curve analysis

D – device; S – test sample; G –frequency generator; A – power amplifier;
E – electromagnetic exciter; T – frequency + amplitude transducer; F – frequency meter; V – voltmeter; O - oscilloscope

By modifying sinusoidal current frequency produced by frequency generator, the test sample vibrates with different amplitudes. The electromagnetic transducer detects test sample's oscillations and generates different tensions, recorded by numerical voltmeter. When resonance is achieved, recorded tension value is maximum and the frequency oscillation can be recorded with great accuracy by using numerical frequency meter. By either reducing or increasing the frequency around resonance frequency, according to a) or b) evaluation criteria corresponding to the decrease of oscillations amplitude, logarithmic decrement can be calculated as a measure of internal friction inside test sample and from the resonance frequency the dynamic longitudinal elastic modulus results . The assembly from the scheme in fig.2 is made up and emphasised in figure no.3 photo.

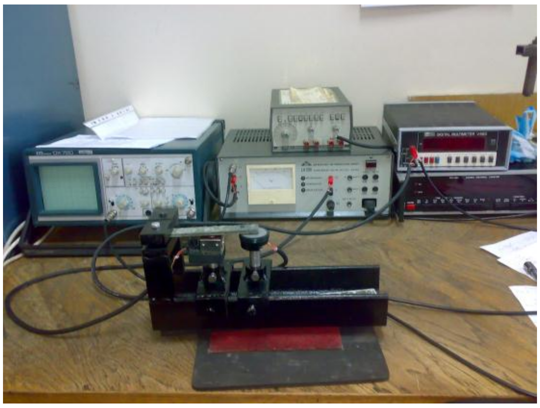

Fig. 3. Logarithmic decrement and dynamic longitudinal elastic modulus determination device

4. Testing material

Four Φ10x200mm test samples were made in order to determine the elastic modulus and logarithmic decrement in normalised state (Table 1), both after hardening (Table 2 and Table 3) and tempering (Table 4 and Table 5), together with other test samples used for determining the hardness, resilience and microstructure analysis. The chemical composition of C45 research steel is: C=0.46%; Si=0.36%; Mn =0.75%; P=0.036%; S=0.041%; Cr=0.28%; Ni=0.14%; Cu=0.12%.

Another purpose of this article is the study of mechanical vibrations influence applied during tempering. In this way, tempering was made in a warm bath excited with a calibrated resonance bar at 50 Hz frequency.

Table 1. Longitudinal elastic modulus, logarithmic decrement and hardness values – tempered test samples (Ø10x200mm).

After tempering						
Test Sample No.	**Frequency [Hz]**			**Logarithmic Decrement δ x 10^{-2}**	**Elastic modulus Ex10^{11} [N/m^2]**	**HRC**
	f_1	**f_r**	**f_2**			
1	143.8	144.0	144.8	2.180	2.395	23
2	143.2	143.7	144.0	1.748	2.385	23
3	142.1	142.5	143.0	1.983	2.345	23
4	143.2	143.7	144.1	1.966	2.398	23

Table 2. Longitudinal elastic modulus, logarithmic decrement and hardness values – test samples after hardening 1

After hardening 1						
Test Sample No.	**Frequency [Hz]**			**Logarithmic Decrement δ x 10^{-2}**	**Elastic modulus Ex10^{11} [N/m^2]**	**HRC**
	f_1	**f_r**	**f_2**			
1	136.9	137.3	137.9	2.286	2.177	48
2	139.4	139.9	140.5	2.468	2.260	50
3	140.0	140.6	141.2	2.679	2.283	50
4	136.5	137.0	137.5	2.291	2.167	49

Table 3. Longitudinal elastic modulus, logarithmic decrement and hardness values – test samples after hardening 2

After hardening 2						
Test Sample No.	**Frequency [Hz]**			**Logarithmic Decrement δ x 10^{-2}**	**Elastic modulus Ex10^{11} [N/m^2]**	**HRC**
	f_1	**f_r**	**f_2**			
1	136.6	137.2	137.8	2.746	2.174	51
2	138.0	138.7	139.4	3.169	2.221	52
3	138.2	138.7	139.5	2.943	2.221	50
4	136.6	137.2	137.8	2.746	2.174	52

Hardening was made under the following circumstances: $T_{heat}=840$˚C, $t_{menţ}=10$min, water cooling. For C45 steel the recommended tempering temperatures are between 550˚C and 650˚C. The present research was undertaken at a 580˚C temperature. The heating device and tuning system errors towards fixed temperature are of -5, +10˚C. Test samples were sunk into the hot bath and then extracted one by one at 15 minutes time range. Then f_1, f_r, f_2 frequencies were determined, and from their values the longitudinal elastic modulus and logarithmic decrement were extracted. Also hardness measurements were made.

Table 4. Longitudinal elastic modulus, logarithmic decrement and hardness values after tempering without vibrations

Tempering without vibrations							
Test Sample No.	**Tempering time**	**Frequency [Hz]**			**Logarithmic Decrement $\delta \times 10^{-2}$**	**Elastic Modulus $E \times 10^{11}$ [N/m^2]**	**HRC**
		f_1	**f_r**	**f_2**			
1	15 [min]	137.6	137.8	138.1	1.139	2.193	37
2	30 [min]	142.5	142.9	143.2	1.538	2.358	34
3	45 [min]	141.3	141.6	141.9	1.330	2.315	30
4	60 [min]	141.7	142.0	142.4	1.547	2.328	28

Table 5. Longitudinal elastic modulus, logarithmic decrement and hardness values after tempering with vibrations

Tempering with vibrations							
Test Sample No.	**Tempering time**	**Frequency [Hz]**			**Logarithmic Decrement $\delta \times 10^{-2}$**	**Elastic Modulus $E \times 10^{11}$ [N/m^2]**	**HRC**
		f_1	**f_r**	**f_2**			
1	15 [min]	140.1	140.4	140.6	1.118	2.276	32
2	30 [min]	143.0	143.2	143.5	1.096	2.368	28
3	45 [min]	141.8	142.0	142.2	0.084	2.328	25
4	60 [min]	141.6	142.8	142.1	0.099	2.355	22

5. Conclusions

Bearing in mind the results presented in tables 1, 2 and 3 the following conclusions have been drawn:

– The elastic modulus determined in dynamic conditions, respectively from tests made with forced bending vibrations, presents higher values than the elastic modulus determined in static tests (E_{static}=2.06-2.1*10^{11}N/m).

– After hardening it was determined a decrease of working frequency which led to the decrease of longitudinal elastic modulus in average by 6.68%. This thing was caused by the tension state produced during hardening.

– The increase of internal tensions during hardening influences the internal friction, too. Logarithmic decrement increases in average by 23.45% after hardening compared to the normalised state. Besides this, the increase in internal friction is owed to grain finishing, produced at incorrect choice of austenitic temperature and maintaining period.

– Concerning hardness, it could be seen that after a second hardening there is a slight increase of them.

By analyzing the results presented in tables 4 and 5 the following conclusions have been drawn:

– The elastic longitudinal modulus increases as compared to the one recorded after hardening this being caused by the decrease of tension state within material. In case of applying a usual annealing the increase average is 3.45%, whereas in case of annealing inside mechanical oscillation field, the increase is bigger 6.10%, almost double. This aspect shows the favourable effect of induced vibrations during annealing and confirms previous observations concerning tension relaxation under vibration action. It must be remarked that in both annealing versions the recorded values in normalised test sample could not be reached, which is normal and predictable.

– In case of analyzing internal friction a reverse effect towards elastic modulus was determined. Logarithmic decrement decreases in average by 42.8% on classic annealing and by 63.8% on mechanical oscillation field annealing. This is caused by the same influences that led to the increase of longitudinal elastic modulus.

– A behaviour similar to the one of the internal friction was also recorded in the case of hardness decrease.

Acknowledgement

This paper is supported by the Sectoral Operational Programme Human Resources Development (SOP HRD), financed from the European Social Fund and by the Romanian Government under the contract number POSDRU/89/1.5/S/59323.”.

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