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EXPERIMENTAL EVALUATION OF THE EFFECTS OF STRUCTURAL CHANGES ON THE VIBRATION PROPERTIES OF CK35 STEEL

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Abstract: The microstructure of some components which operate in high-temperature conditions (e.g. boiler components, turbine blades used in gas power plants, jet engines and reactors) is subjected to changes in long run, which leads to a degradation in the mechanical properties of these components and consequently, reduces their lifecycle. Therefore, it is so useful to detect the changes in the microstructure of these parts during their operation, employing an easy, fast and non-destructive method to determine their remaining life. In this study, we evaluate the effects of the microstructural changes on natural frequencies and the damping coefficient of CK35 steel, employing the experimental modal test. We aim to use the method for power plant components, if it has significant effects. To do so, we applied spheroidization heat treatment on CK35 steel samples having a primary structure of ferrite-pearlite for 24 and 48 hours. Then, we carried out the experimental modal test on samples having different metallurgical structures, but with the same dimensions and weights. According to the findings, the spherical ferrite-carbide particles in the ferrite structure increase the natural frequencies and damping coefficient. These tests show that the structural changes in this type of steel result in slight changes in the values of natural frequencies; however, it significantly changes the damping frequencies.

Keywords: microstructure, spheroidization heat treatment, modal analysis, natural frequency, damping

1. INTRODUCTION

Changes in metal microstructures can influence their macroscopic properties. A change in microstructure can be the formation of a new phase in the metal matrix, a change in the size of a grain or the size of a phase and/or sediment particles in a metal matrix. Some of the mechanical properties including toughness, yield strength and elasticity modulus, as well as some vibration properties such as natural frequencies and damping coefficient, may be influenced by changes in the metal microstructure. Numerous studies have been carried out regarding the influences of microstructure on the mechanical properties of metals. For example, Zieliński et al. (2017) evaluated the effects of ageing heat treatment on T24 steel microstructure and its mechanical properties. They concluded that as the ageing duration and its temperature increase, the steel mechanical properties degrade, which can be attributed to some reasons including the metal matrix recovery, removing the layers of bainitic structure, an increase in the size of carbides M23C6, as well as the formation of secondary sediments of M2C and M6C3 in the metal matrix. Carneiro et al. (2018) addressed the influence of ageing in the microstructural aspects in an A356 alloy and its impact in the static and damping. This study analyses the role of T6 heat treatments in the overall microstructure of A356 poured in ceramic block, associating the morphology transformations with the internal mechanisms that enhance yield strength and reduce damping. They suggested that these variables display an inverse proportionality and a linear model is determined for the design of alloys with tailored yield/damping by the use of different artificial ageing times. Carneiro, V.H., and Puga, H. (2018) investigated the influence of solution treatment in the microstructural aspects (e.g. eutectic Si spheroidization) in an A356 alloy and its impact in the static and damping. Their findings owing to eutectic Si coarsening/spheroidization, Mg2Si/π-phase dissolution and α-Al solution strengthening, the solution treatment can enhance both static (yield strength) and dynamic (damping ratio) mechanical properties. As well, several other studies can be found in the field of microstructure influences on the mechanical properties of a metal (Bhardwaj et al., 2021; Diehl et al., 2010; Yamada et al., 2006; Liu et al, 2012; Ghorbanhosseini et al., 2020; Korznikova et al., 2020; Wang et al., 2020; Ghosh et al., 2008).

Hamisi et al. (2018) studied the ageing effects on the mechanical and vibration properties of SA516 carbide steels. They suggested that an increase in the ageing duration can degrade the samples' mechanical properties, reduce their natural frequencies and increase the samples damping properties. Tsai, M. H. et al. (2011) addressed the effects of ageing heat treatment on vibration properties of an Mg-Zr alloy. They concluded that as the ageing heat-treatment temperature increases, some twin structures are formed in the alloy matrix, which plays a significant role in changing the samples' damping coefficients. El-Morsy, A. W., & Farahat, A. I (2015) investigated the effects of ageing heat-treatment duration on the damping of Mg-6Al-1Zn alloy. They found that increasing the ageing duration, the number of settled phases also increases. They showed that the ageing of this alloy up to 34 hours can increase its damping properties, and the damping value decreases, as the ageing duration increase. Carneiro, V.H., and Puga, H. (2019) studied the impact of microstructure and T6 heat treatment on Young's modulus and internal friction. Moreover, some other studies have addressed the influences of microstructure on metal vibration parameters (Lin et al., 2002; Limarga et al., 2007; Cai et al., 2005).

As mentioned earlier, the changes in metal structures may influence their mechanical and vibration properties. Therefore, by employing some methods to investigate the mechanical and vibration properties of metals, it is possible to find the changes in the data profile of their structure, without a need to use metallography methods. In this study, we employed a modal non-destructive test to find the data profile of metal structures. In other words, using a modal test and analysing its results, rather than employing destructive tests such as metallography and hardness measurement tests, can one discover the changes in data profiles of metal structures that operate in superheated conditions. Therefore, we chose the CK35 steel having a primary structure of ferrite-pearlite and observed that the maximum changes occurred in its structure, as spheroidization heat treatment applied. It is worth mentioning that we chose this kind of heat-treatment process to induce the maximum changes in the steel structure to conclude that how much the maximum changes in the structure will change the steel vibration properties of the steel. Then, we applied the modal experimental test and hammer test for samples having completely the same dimensions and different structures.

2. EXPERIMENTAL PROCESSES

2.1. Heat treatment

To study the effects of microstructure changes on the steel vibration properties, employing a heat-treatment process causing a significant change in the structure is considered suitable. In this study, we chose CK35 steel having the primary structure if ferrite-pearlite. The chemical composition of this steel is shown in Tab. 1, according to optical emission spectrometry test and ref. 21. The maximum change in ferrite-pearlite structure occurs when the cementite layers in the pearlite phase are dispersed spherically in the ferrite structure, which can be reached by applying the spheroidization heat-treatment process.

As the spheroidization heat-treatment process in the natural mode can be so time-consuming, the process can be much less time-consuming if the primary structure is martensite (Chandler, 1998; Totten, 2006). Therefore, the samples maintained in the furnace at an austenite temperature for enough time (about 1 hour) to reach a complete austenite structure, and immediately they were cooled, so that they reached a martensite structure. Then, the samples were heated at 700° to reach spherical structure in their matrix, 2 of which for 24 hours and the other 2 for 48 hours (Chandler, 1998). Following, the samples cooled in the furnace.

Tab. 1. Chemical properties of the CK35 steel, weight percentage (%)

	C	M	P	S
Optical emission spectrometry test	0.34	0.621	0.0121	0.018
Ref. 21	0.32–0.38	0.6–0.9	Max. 0.04	Max. 0.05

2.2. Frequency response

The modal test is an experimental technique to find the modal model for a vibration system. This theory is based on the relationship between the vibration response in a certain point of the structure and the excitation at the same point or other points as a response to the excitation frequency. The relationship that is often in a form of a mathematical complex function is called the frequency response function (FRF). The modal test includes the FRF measurements and the structure impact response. In other words, one can easily measure the FRF, exerting a (measured) force at a certain point of the structure, in the absence of other excitement forces, and measuring the vibration response in one or more points of the structure [24].

In this study, we employed the modal test, as well as the hammer test, by the help of which can one obtain the natural frequencies and damping values of the samples. As the samples' natural frequencies and the damping values are compared in this study, the samples should have as the same dimensions and weights as possible to investigate the effects of microstructure changes on the steel vibration properties. Fig. 1 shows the prepared samples for the test. The sample weights are equal to 633.33 ± 0.02 g, and their dimensions are the same in a 0.01-mm precision range (Fig. 1).

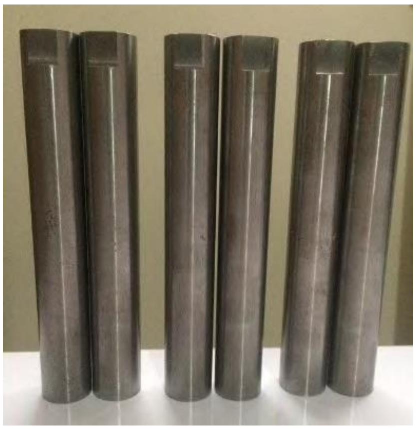

Fig. 1. Prepared samples for the modal test

Fig. 2 and Fig. 3 shows how this test is carried out and the tools used in the test. The test applied to samples in free-free boundary conditions. To obtain the samples' vibration properties, their frequency response (FRF) should be explored. To this end, a hammer (Type 8202 Bruel & Kjae) and a piezoelectric accelerometer employed to excite the samples and to measure their responses, respectively. It should be mentioned that the test was carried out in several different points of the samples. As well, applying 10 hits and averaging the responses, each sample frequency response was obtained.

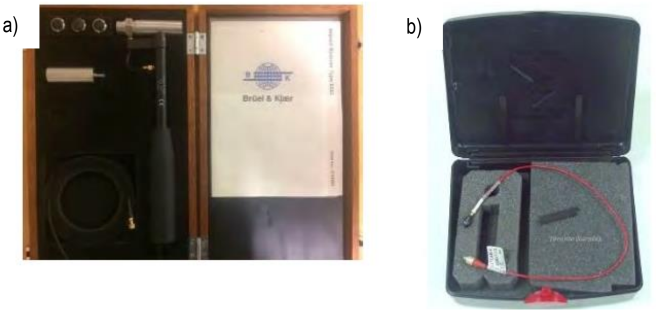

Fig. 2. Used tools in the modal test: a) Hammer and its accessories; b) piezoelectric accelerometer

Fig. 3 Four-channel data collection model, model 3560 c

Then, the damping coefficients were obtained, using frequency responses and employing the peak-peaking technique (half-power bandwidth) (Fig. 4). In this technique, the damping coefficient can be conveniently calculated, using eq. 1. In this method, the maximum amplitude (i.e. $|\alpha W_r|$) that is related to the natural frequencies of each vibration mode of the system is first obtained, and then the frequencies (W_b, W_a) are chosen at both sides of the resonance peak having an amplitude of $\frac{|\alpha W_r|}{2}$.

The damping loss factor is obtained from eq. 1, according to the peak resonance width (Fu, Z. F., & He, J, 2001).

$$\eta_r = \frac{W_b^2 - W_a^2}{2W_r^2} = \frac{W_b - W_a}{W_r} \quad (1)$$

where W_r is the maximum frequency of the diagram amplitude, and W_r and W_b are the frequencies at both sides of the peak resonance.

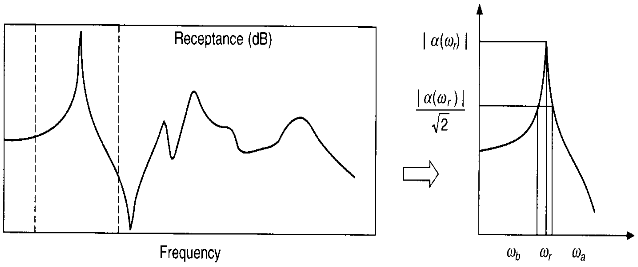

Fig. 4. Peak-peaking technique to calculate the damping loss factor

2.3. Tensile test

To study the effects of heat-treatment process on the steel elasticity modulus – that is considered as an important parameter influencing the natural frequency value – some samples were prepared according to ASTM E8/E8M. The gauge length and diameters of these samples were 25 and 6 mm, respectively, that is categorized as sub-size samples according to the standard.

3. FINDINGS AND DISCUSSIONS

3.1. Microstructure

Fig. 5a shows the steel microstructure before applying the spheroidization heat-treatment process. As can be seen, the steel structure consists of ferrite and pearlite phases; the ferrite phase is shown in white, while the pearlite phase is brown. Fig. 5b and 5c shows the steel microstructure after spheroidization heat treatment after 24 hours and 48 hours respectively. As can be observed in these figures, after applying the spheroidization heat-treatment process, the cementite phases which are placed in the pearlite structure in a layered manner will be distributed spherically and dispersedly in the ferrite matrix. According to Fig. 5b and 5c, one can conclude that there exists no significant difference between the samples heat treated for 24 hours and those processed for 48 hours. In other words, it seems that once the samples are heat treated for 24 hours, the cementite phase sizes are saturated, and increasing the heat-treatment time incurs no significant changes in the size of these phases. Therefore, according to the microstructures shown in the figures, it seems that the results of the modal test and the tensile test that was applied to samples heat treated for 24 and 48 hours have no significant differences.

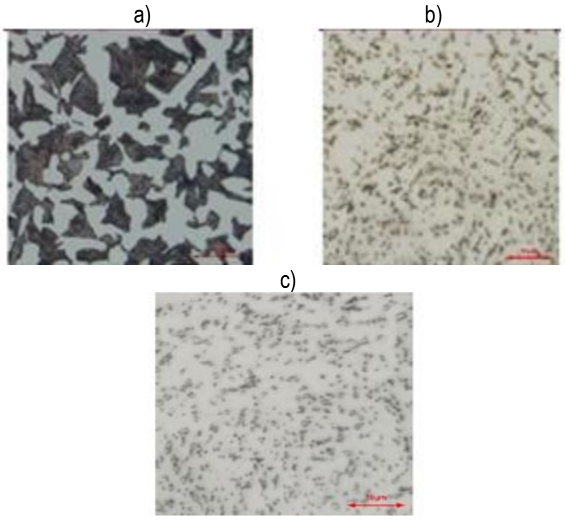

Fig. 5. Microstructures: (a) the sample before applying heat-treatment process, with a magnification factor of 200×, Nital etch solution 3%; (b) heat-treated sample for 24 hours with a magnification factor of 1000×, Picral etch solution, 4%; and (c) heat-treated sample for 48 hours with a magnification factor of 1000×, Picral etch solution, 4%

3.2. Results of the modal and tensile tests

As mentioned before, 2 samples of each heat-treatment process were prepared for the modal test. Figure 6 shows the obtained frequency response, following the sample excitation by the hammer. The results of the modal test are summarized in Table 2. It should be noted that these results are related to the case where the sensor installation and the hammer hit are both placed in the middle of the samples. According to the modal test results, it is observed that following the spheroidization process, the natural frequencies and the damping loss factor of the two modes of the first and second vibrations are increased. In other words, the dispersion of cementite particles within the ferrite matrix increases the natural frequencies, as well as damping loss factor. Moreover, the results show that although structural changes incur slight changes in natural frequencies, the phenomenon causes significant changes in the damping loss factor, so that the damping loss factor increases at least 14%, with a change in ferrite-pearlite structure to a spheroidized structure.

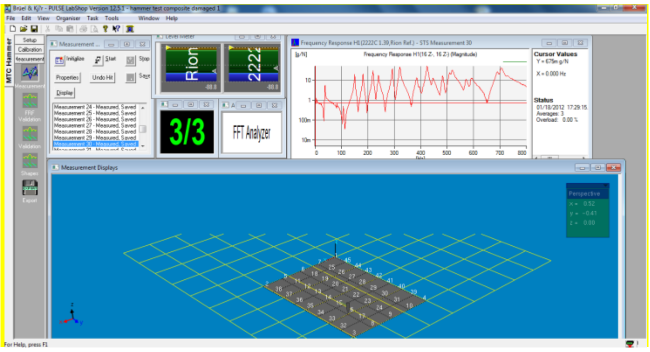

Fig. 6. Obtained frequency response following the sample excitation

Tab. 2. Results of modal test

Sample	Natural frequency (Hz)		Damping loss factor (percentage of difference compared to the non-heat-treated sample)	
	First mode	Second mode	First mode	Second mode
Non-heat treated	3722	9424	0.00204	0.00328
Heat treated for 24 hours	3735	9447	0.00257 (+0.14%)	0.00371 (+2.51%)
Heat treated for 48 hours	3734	9448	0.00280 (+0.15%)	0.00282 (+2.14%)

One can refer to the results of the tensile test (Table 3) to find a reason for the increase in natural frequencies. According to the results, the distribution of cementite particles in the ferrite phase causes the elasticity modulus to increase, which in turn leads to an increase in the natural frequency. As well, the spheroidization process can increase the phase continuity that causes an increase in damping (Visnapuu et al., 1987).

Tab. 3. Results of the tensile test

Sample	Elasticity modulus
Non-heat treated	204.80
Heat treated for 24 hours	208.50
Heat treated for 48 hours	207.29

According to the results of the modal and the tensile tests, one can see that increasing the heat-treatment duration from 24 hours to 48 hours, the natural frequencies, damping loss factor and the elasticity modulus don't change significantly. According to the microstructure similarities between samples that were heat treated for 24 hours and 48 hours, these results can be predictable.

4. CONCLUSION

This study has been carried out to find whether it is possible to use the modal test as a non-destructive test to discover the changes in metal microstructures. The experimental test results showed that the dispersion of carbide phases within the ferrite matrix increases the natural frequencies and damping loss factors. According to the results of the modal test, slight changes in the microstructure may lead to slight changes in natural frequency, while changing the structure incurs no significant changes in the damping loss factor value. According to findings, one can see that microstructure changes in this steel cause the vibration parameters to change. Therefore, the modal test – which is a cheap and fast method to obtain a system vibration data – can be employed as a non-destructive test to detect the structural changes in components that are operated in superheated conditions.

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