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ULTRASONIC STUDY OF OVERLAID NANOMODIFIED LAYERS

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Abstract - The purpose of this work is to present an ultrasonic comparative assessment of welded nanoimodified layers and to justify the non-destructive parameters for control of welded machine parts.

A comparative study of discontinuities in nanomodified layers overlaid on steel S 235JR samples with dimensions corresponding to the welding standard ISO / DIS 15614-7 has been carried out. Longitudinal and surface waves have been used in order discontinuities in the layers to be indentified.

Based on the experimental results obtained, the following conclusions can be drawn:

- The ultrasound scanning method gives possibilities to successfully register the discontinuities on the boundary between the steel base and the overlaid layer having size comparable with those in the base metal steel S 235JR.

- There is not found a distinctive boundary (layer) between the overlaid metal and the base metal. This finding is explained with the similar acoustic properties of the overlaid and the base metal, as well as their smooth fusion without any pronounced acoustic boundary between them.

- There is a dependence between the quantity of discontinuities in the overlaid layer on one hand, and the damping and the speed of the surface wave on the other. The damping factor of the Rayleigh wave can be successfully used for accelerated comparative assessment of discontinuities in the layer.

- It is experimentally proved the considerable variation of Rayleigh wave. It is probably due to the influence of substantial variation of the speed of longitudinal and transversal waves in the surface layer in another mode of surface wave.

Keywords: *Ultrasonic non-destructive testing of discontinuities in nanomodified layers*

1. INTRODUCTION

The manual arc overlay welding with coated electrodes is a widely applicable technology for recovery of the working capacity after wear of heavily loaded machine elements. The quality of the ready item depends both on the technological factors, including electrodes and operational mode, and on the subjective factors, such as qualification and overall psychophysical condition of the personnel.

Within the framework of project "Development of technology for arc overlay welding of wear resistant layers using manomaterials" are developed and manufactured electrodes with nanomodifiers in the coating [1] and are overlaid trial samples of steel S 235JR with dimensions 250x400 mm, compliant with standard ISO/DIS 15614-7, and thickness 20 mm. The preliminary examinations, both visually and through ultrasound scan, have found substantial discontinuities within the welded layer. It has been found that the layer substantially changes the speed and the damping of the surface wave of [2]. There is a suggestion about the transformation of the surface Rayleigh wave in another type of wave in its propagation through a layer with acoustic parameters close to those of the base material.

The purpose of this work is to make ultrasonic comparative assessment of welded nanoimodified layers and to justify the non-destructive parameters for control of welded machine parts.

2. DESCRIPTION OF THE STUDY

In the present study the experimental results from non-destructive examination of overlaid layers using electrodes with nanomodified coating are presented. The classification of the electrodes used for manual arc welding according to the type of the nanomodifier and the measured hardness of the welded surface is shown in Table 1.

Table 1. Classification of electrodes.

Sample No	Average value of hardness HV (15/15).	Nanomodifier	Quantity, %
1	486	TiN	A
2	476	TiN+Cr	A
3	462	TiN	A/2,
4	571	SiC	A/2
5	645	TiN+Cr	A/2

Herein A is a preliminary chosen basic quantity of nanomodifier, %.

After welding, the surface of the overlaid metal is polished. The Vickers hardness (HV15/15) of the polished surface is measured in eight points according to the diagram shown in Fig. 1.

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The results (Table 1) are calculated accounting for the average value of hardness after the measurement with maximal deviation from the average value has been neglected. The gahrdness varies considerably (up to 40%) due to the use of different nanomodifiers in the coating of the electrodes. In samples 4 and 5 there is a significant increase of the hardness observed. The samples are coated with nanomodified coatings correspondingly with titanium nitrite covered with chrome and silicon carbide. For most of the samples significant variation of results when measuring the hardness of the layers have been observed. Suspicion for availability of defects in the weld layer occurred. Experiment for ultrasonic non-destructive testing of the layer has been organized

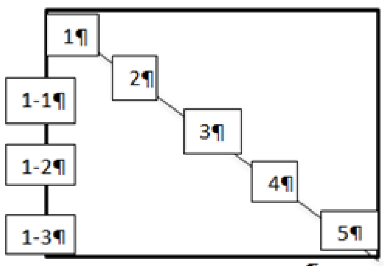

Figure 1. Diagram of the points for Vickers hardness measurement of the samples.

In Fig. 2 are shown the polished sections of the samples prepared for examination. The overlaid sections have dimensions approximately 40x60 mm.

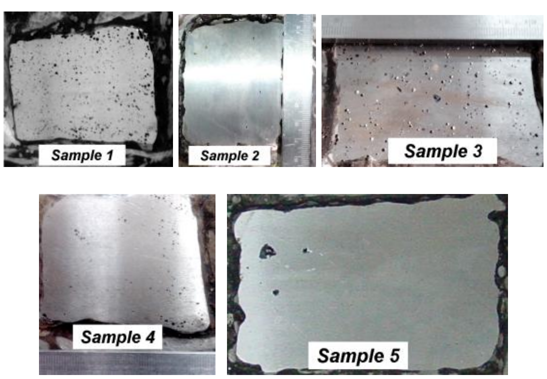

Figure 2. Photo images of the test samples.

The surface discontinuities are measured and for sample 4 their average dimensions are about 0.4 - 0.55 mm; for sample 2 they are 0.52 mm and are unevenly distributed across the examined surface area; for sample 7 the diameter of the imperfections is 1.07 – 1.4 mm; for samples 1 and 3 the imperfections are more evenly distributed and larger. The uneven distribution of the flaws observed is associated with the effect of the technological deviations from the preset conditions for overlay welding, such as inappropriate arc length, insufficient cleaning before laying the following layer, etc. The even distribution of flaws is explained with the effect of the modifier applied on the structure, the properties and the quality of the overlaid layers.

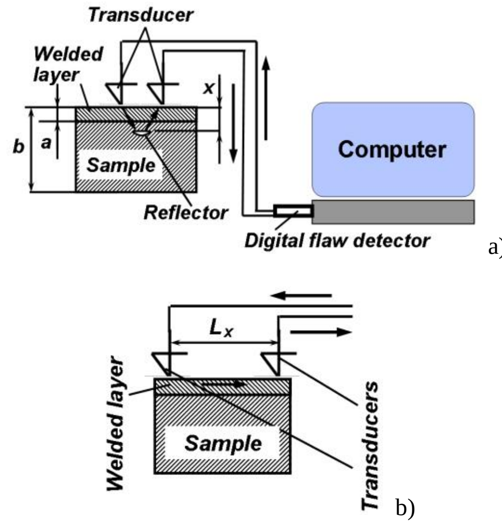

Figure 3. Experimental set-up for ultrasonic examination of the weld layer: a) using longitudinal waves; b) using surface waves.

In Fig. 3a is shown the experimental set-up for scanning with longitudinal waves. The double ultrasound transducer MSEB 5 with operation frequency 5 MHz is used for excitation and registration of longitudinal waves. In all experiments is used USB flaw detector made by company LECOEUR ELECTRONIQUE SARL, which operates together with appropriate software and computer. The flaw detector is set using control unit with flat-bottomed reflector with diameter of 3 mm. The locations x of reflectors are defined by measurement the times x' for propagation of the longitudinal wave through the sample using the equation:

$$x = \frac{x'.b}{b'}.c_1 \quad (1)$$

where b is thickness of the sample; b' is time for propagation of the bottom signal; c_1 is speed of the longitudinal wave through steel. In case the discontinuities are close to one another, it is possible that they might not be distinguished by amplitude by the flaw detector and may induce reflected signal with increased amplitude as well.

The following parameters are determined: damping factor α, speed of propagation c_R of the surface wave and spectrum of the registered signal for the samples from Fig. 1b, as well as alteration ΔL_x of the basic distance L_x between the transducers (Fig. 3b) of 15 mm. The damping factor α_R is calculated after measuring the difference in the length of wave when the distance between the converters is shifted with ΔL_x using the equation:

$$A = A_0.e^{-\alpha_R.\Delta L_x}, \quad (2)$$

where A_0 and A are amplitudes of the signal before and after shifting the converters at distance ΔL_x. The experiments are carried out using transducers with nominal frequency 4 MHz for generating surface waves using the wedge,

$$\left[2-\left(\frac{c_R}{c_t}\right)^2\right]^2 - 4.\sqrt{1-\left(\frac{c_R}{c_l}\right)^2}.\sqrt{1-\left(\frac{c_R}{c_t}\right)^2} = 0, \quad (3)$$

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where c_t и c_l are correspondingly speeds of longitudinal wave and transversal wave within elastic medium.

The damping of Rayleigh wave here is determined by theoretical approach in [4, 5], namely by presenting the damping factor of the longitudinal and transversal wave in complex type in the wave number:

$$k_i = k'_i + j.k''_i = k'_i.(1+\alpha'_i), \qquad (4)$$

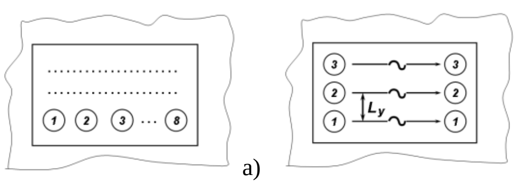
where k'_i are real parts, $k'_i = \omega / c_i$; ω is angular frequency; k''_i are complex parts representing damping of the waves through small fixes $\alpha'_{l,t,R}$ numerically equal to the damping factors $\alpha_{l,t,R}$ per unit length of the wave in the medium relative to 2. π ; the indices t, l, and R here stand for transverse, longitudinal, and Rayleigh wave, correspondingly. Since the Rayleigh equation is irrational, herein the real and the complex part are solved together by means of numerical methods to obtain both speed and damping factor.

Experimentally, the speed c_R of the surface wave is determined from the dependence:

$$c_R = \frac{\Delta L_x}{b'}. \qquad (5)$$

Here b' is the measured alteration of time for propagation of surface wave through the display of the flaw detector due to shift of the distance between transducers with ΔL_x .

In Fig. 4 are shown the scan routes of the examined samples with longitudinal (Fig. 4 a) and (Fig. 4 b) wave, correspondingly. The zone of overlay welding is examined using longitudinal waves along the walls of the overlaid surface with a step up to 5 mm. The experiments with surface wave are carried out along the larger dimension and in different sections.



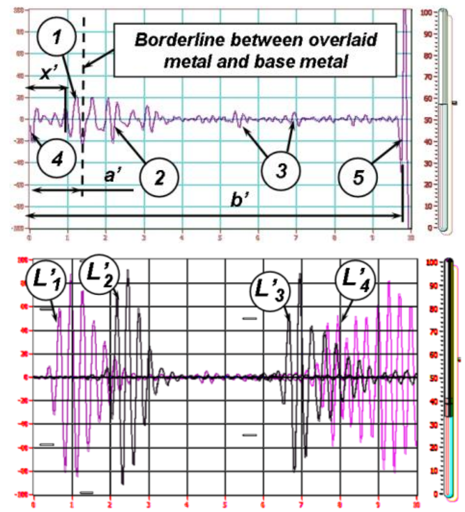
a) b)

Figure 4. Scheme for carrying out the experiments for scanning with longitudinal waves (a) and taking into account the width of the signal spectrum of the surface wave (b).

3. RESULTS OBTAINED

3.1. Longitudinal wave scanning

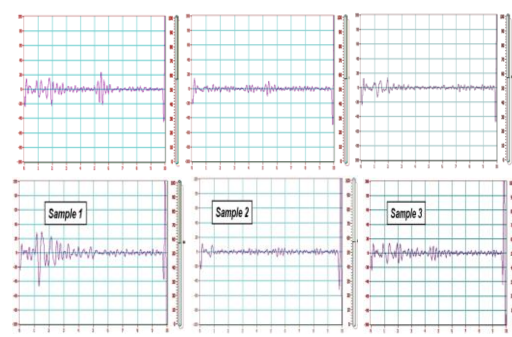
In Fig. 5a are shown the characteristic results from longitudinal waves scanning of the flaws within the sample. Herein 1 – 5 are signals reflected by discontinuities on the boundary between overlaid layer and base metal (1) and in the adjacent zones (2), or within the material S 235JR (3), or on the front (4), or the rear (5) surface of the sample. There are discontinuities different in size found in these portions through measuring the distance x' from the display of the flaw detector. In some experiments however the reflected signal from the boundary between the overlaid metal and the base metal is missing possibly due to the absence of both distinctive boundary and discontinuities of substantial size. The measured thickness of the overlaid layer is estimated on average within 2.1 - 2.8 mm by determining the value of a'.



a) b)

Figure 5. Characteristic results from ultrasound scanning of test samples; a) using longitudinal waves; b) using surface waves.

There are reflectors present within the overlaid layer and on the boundary between the layer and the base metal with dimensions of the order of the discontinuities in steel S 235JR. There are also amplitudes observed with much less size within 5 dB. The reason for their occurrence is associated mainly with the acoustic noise and they are not taken into account when the results are registered.



a) b)

Figure 6. Experimental results from ultrasound scanning of overlaid samples with longitudinal waves: a) sample 4; b) samples 1, 2, and 3.

In Fig. 6 are shown the results from ultrasound scanning of discontinuities in different points of sample 4 (Fig. 6a) and samples 1, 2, and 3 (Fig. 6b). There are discontinuities of different size in the different zones of the samples, including in different points of the same sample. The maximal dimensions of discontinuities in the overlaid layer are found in Sample 1. In all samples are found discontinuities/damages of the base metal within the zone of damage. In the overlaid metal of each sample are found inner discontinuities with conditional dimension smaller than the discontinuities in the zone of damage.

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In Fig. 7 are shown experimental results from examination of different areas of sample 5 using longitudinal waves. Here the results repeat to some extent the generalizations made so far. Obviously, there are a restricted number of surface discontinuities in the sample. Their occurrence is rather due to the insufficiently filled overlaid layer. There is a comparatively large zone found too (approximately 20x20 mm) with discontinuities between the overlaid layer and the base metal (Fig. 7, bottom right) under surface with no visible discontinuities. The amplitude of the signal reflected by that zone varies in the range from 35 dB to 45 dB indicative for the variation of the density and the dimensions of the discontinuities in this zone.

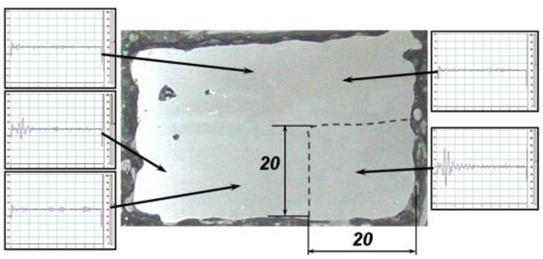

Figure 7. Experimental results from ultrasound scanning of sample 5 with longitudinal waves.

3.2. Rayleigh wave scanning

In Fig. 5b are shown the characteristic results from the examination of speed and damping of the Rayleigh's wave. The image shown is obtained through precise superimposing of the images obtained through photo method using markers. The shift of the signal L'_i resulting from the variation of the distance between transducers with L_i is determined. The distance between the transducers is varied using distance bodies with sizes 4.290, 15, 16.865, 19.96 mm. The values of L'_i are measured in CAD environment using markers with known length (time). The accuracy of the amplitude of the surface wave is assessed and the achieved accuracy is within 1 dB.

The experimental results for the damping factor α of the surface waves determined for unit wave length and obtained through scanning of different samples are shown in Fig. 8a. The higher values of α (within the range 0.82 to 1) are obtained for samples 1, 3, and 4 in which the number of registered surface discontinuities on unit surface is higher. For samples 2 and 5 with small number of unevenly distributed discontinuities the values of α obtained are within 0.25.

Sample 2 is scanned in two parallel sections at distance 10 mm from one another. The results for the damping factor α are shown in Fig. 8b and the values are between 0.14 and 0.24. It is found that the examined parameter varies within the range from 0.14 to 0.24 for the same sample. This finding is explained with different intensity of the discontinuities within the sample and the different scattering of the wave by them.

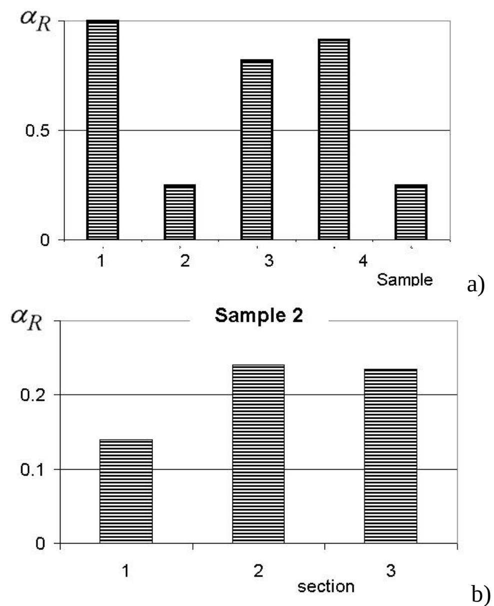

Figure 8. Results for the damping factor α of the surface wave at $\Delta L_x = 15mm$.

In Fig. 9 are shown the experimental results from examination of the dependence between the speed of Rayleigh wave and the parameter α'_R. The number of the sample is shown next to each result. For all samples is obtained considerable variation of the wave speed Δc_R . The wave speed is obtained through averaging of at least three results and the damping factor α_R - for variation of the distance between the converters with 16.865 mm. On the same figure are plotted part of the theoretical results on (3) and (4). The calculations are made for steel samples with different damping factors of the longitudinal α_l and the transversal α_t wave in elastic medium in absence of discontinuities defined under [6]. The presence of discontinuities is accounted for through proportional increase of the baseline values of these factors. The results indicate that with the increase of the parameter over 0.036, the speed of surface waves increases too. There is general matching in the character of the change of speed. We cannot but note the essential difference between theoretical and experimental results. This is probably due to the influence of other factors, such as substantial change in the speed of transversal and longitudinal wave, transformation of the wave in another mode of Rayleigh surface wave.

4. MAIN CONCLUSIONS

This work reports about a comparative study of discontinuities in nanomodified layers overlaid on steel S 235JR samples with dimensions corresponding to the welding standard ISO / DIS 15614-7. It is found beforehand that the discontinuities in a part of the samples are unevenly distributed, e.g. in the samples with nanomodifies TiN layer. This fact is attributed to the impact of the technological deviations from the preset conditions for welding, such as inappropriate arc length, poor cleaning before applying the next layer, and others. There are evenly distributed discontinuities in a part of the samples. Probably they are due

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to the effect of the nanomodifier introduced on the structure, properties and quality of overlaid layers.

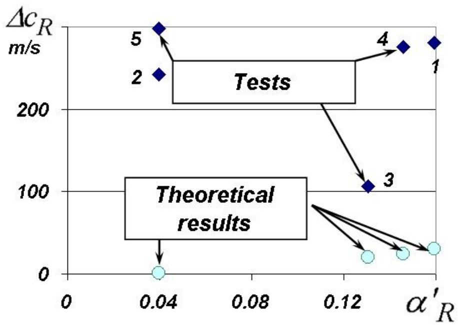

Figure 9. Results from examination of the speed Δc_R from α'_R.

Based on the experimental results obtained, the following conclusions can be drawn:
- The ultrasound scanning method gives possibilities to successfully register the discontinuities on the boundary between the steel base and the overlaid layer having size comparable with those in the base metal steel S 235JR. Group surface and subsurface discontinuities with single size 0.4 – 1.4 mm are registered. Most likely they are reason for observed variability of the surface hardness and could cause accelerated wear of welded machine parts.
- There is not found a distinctive boundary (layer) between the overlaid metal and the base metal. This finding is explained with the similar acoustic properties of the overlaid and the base metal, as well as their smooth fusion without any pronounced acoustic boundary between them.
- There is dependence between the quantity of discontinuities in the overlaid layer on one hand, and the damping and the speed of the surface wave on the other. The damping factor of the Rayleigh wave can be successfully used for accelerated comparative assessment of discontinuities in the layer.
- It is experimentally proved the considerable variation of Rayleigh wave. It is probably due to the influence of substantial variation of the speed of longitudinal and transversal waves in the surface layer in another mode of surface wave.

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