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Microdefect Detection in High-temperature Resistant Steel by Using Ultrasound Laser Interferometer

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Abstract

Large number of microdefects, each of which is too small to be individually detected by ultrasonic NDT methods, collectively may reduce the mechanical properties of components to an unacceptable degree. The investigation of the acoustic wave interaction with inhomogeneities with time resolution much less than wave period possible with ultrasound laser interferometry technique allowed to propose new informative parameters of acoustic fields related to microdefects.

Keywords: microdefect, laser interferometer, elastic wave scattering

1. Introduction

Material processing, manufacturing, aging and other in-service conditions often induce microdefects. The presence of large number of microdefects, each of which is too small to be individually detected by ultrasonic NDT methods, leads to reducing the mechanical properties of components to an unacceptable degree and material damaging. It's especially dangerous for industrial objects such as steam pipelines that have been subjected to enormous loads and pressures during long-term operation.

Early detection of microdefect areas in solids allows estimating the residual life of constructions and prevents catastrophic failures of components. But the difference between undamaged and damaged material obtained by using conventional ultrasonic techniques is small enough and often comparable with the accuracy of measurements. For example, by measuring the compressive wave velocity one can obtain the difference between undamaged material and material with microfefects being not above 1%. So, currently choice of new informative inspection parameters is still an urgent problem in developing new nondestructive testing techniques. The problem is that typical microdefect size is about 1000 times smaller than the ultrasonic wavelength and this restricts the application of conventional ultrasonic transducers and receivers which sensitivity is limited by the elastic wavelength. For this, methods with higher locality of measurements and broadband receivers are much preferable.

Ultrasound laser interferometry provides a unique inspection method that enables studying and visualizing of the processes of elastic wave interaction with microdefects embedded in solids[1]. Changes in material response due to the presence of microdefects could be detected with high resolution, determined by small diameter of laser beam, in a non-contact way. The aim of this research is to investigate the distributions of acoustic fields on the surface of metal specimens with microdefects of different types and to propose new informative parameters of acoustic fields related to microdefects.

2. Test samples and experimental method

In this paper, the longitudinal elastic wave fields in three disk-shaped specimens, each 25 mm in diameter and of ~5 mm thickness, made of high-temperature resistant steel 12Kh1MF that is widely used for producing steam pipelines, were considered. All specimens were cut from the bent section of a steam pipeline. Initial stresses appeared in the elbow region of the pipe due to metal curving and enormous loads and stresses applied during long-term operation make this pipe element the most problem region where microdefects appear the first. Specimens cut from different regions of the steam pipeline's elbow were exposed to different conditions. Specimen 1 was cut from the top region of the pipe elbow subjected to the hardest conditions (pressure P=20 MPa; temperature T=600°C, the time interval 16000 hours). Specimens 2 and 3 were cut from the bent section of a steam pipe that had been subjected to steam temperature of 550° C and pressure of 13 MPa for about 150000 hours in a heat-electric generating station. Specimen 2 was cut from the compressed (inner) side of pipe elbow while specimen 3 was cut from the stretched (top) region of the pipe elbow. Subsequent microscopic analysis revealed that specimen 1 contained a few large round micropores with diameters 4.3-28.2 μm; specimen 2 contained a number of small micropores with diameters 0.6-8.8 μm while many separate and coalesced micropores 0.5-15.6 μm in diameter occurred in specimen 3.

Ultrasonic waves were excited in the samples by piezoelectric transducers CLFS produced by "Krautkraemer" with a center frequency of 5 MHz. The transducer aperture was 5 mm in diameter. A PCUS-10 flaw detector was used in which the probing signal was about 1 μs in length. To obtain the time dependences of the normal component of particle velocities at different points on the specimen surfaces the OFV5000 Doppler laser interferometer produced by "Polytec" was used. Each sample had two flat surfaces. The piezoelectric transducer was placed on one of them; the other surface polished so that the roughness did not exceed 4μm was illuminated by a laser beam to detect the acoustic fields (Figure 1a). The output signals of the interferometer, that are the type-A scans, had been recorded and digitized by oscilloscope LeCroy 9361. A personal computer was used to analyze and capture the information.

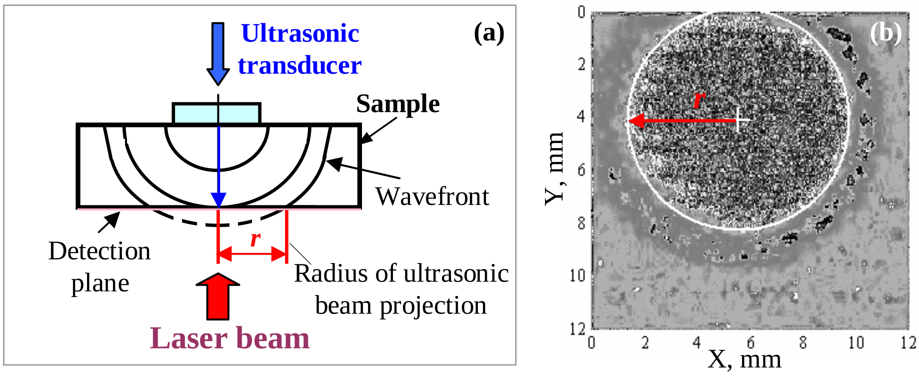

Figure 1. Laser Doppler interferometry: (a) sketch of acoustic fields detection; (b) snapshot of acoustic field corresponding to specimen 1; white circumference is the outer contour of the ultrasonic beam projection on the detection plane and cross is its geometrical center found

By scanning the specimen surface within the frame of the scanned field equals to 12×12 mm and typical scanner increment about 0.06 mm, the spatial distributions of acoustic fields on the surfaces of samples were obtained. The results were presented in the form of C-type scans, which demonstrate the spatial distributions of the maxima of the A-scans within the selected time gate. The equipment was also capable of obtaining instantaneous field distributions on the surface as a function of time in snapshot mode (Figure 1b).

The C type-scan of the surface of sample *1* is shown in Figure 2a. The time interval set for the measurement of the A-scan amplitude was established for the first pulse, *i. e.* the wave that has travelled through the sample once in the forward direction. It can be seen from this figure that the image contains significant noise component. This is the result of small number of averaging.

To minimize the noise, two-dimensional wavelet filtering technique was applied. Filtering based on wavelet transformation technique allows to smooth signals without losing information about small local disturbances. A detailed description of the wavelet-filtering algorithm can be found in Ref[2]. Here, Sym8 wavelet functions with four expansion levels and a soft thresholding strategy was used.

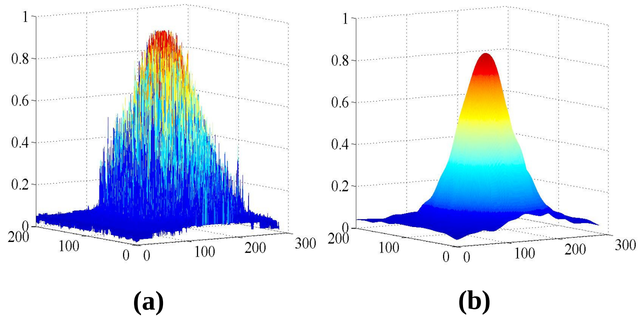

Figure 2. C-scan obtained for sample *1* (a) before and (b) after filtering

Besides filtering of two-dimensional images of acoustic fields the algorithm of wavelet filtering was also applied to filter out electrical noise from one-dimensional time dependences of particle velocity.

3. Results processing and analysis

The presence of microdefects in the material leads to sufficient scattering of elastic waves due to the acoustic mismatch at the discontinuities. Then the level of noise-like components in detected signal in case of microdefects would be sufficiently higher. In earlier works[3] it had been already found that the energy of acoustic noise-like components in detected A-scans is higher for specimens with large number of micropores than for those without micropores. In this research to thoroughly investigate changes in material response in case of different degree of microdamage the analysis of the two-dimensional distributions of acoustic noise-like signals that contain a considerable amount of microstructural information was performed. For this, the time intervals corresponding to pulse signals (the second pulse, t_1 interval, Figure 3) and the noise signals (t_2 interval between the second and third pulses, Figure 3) on filtered A-scans were investigated.

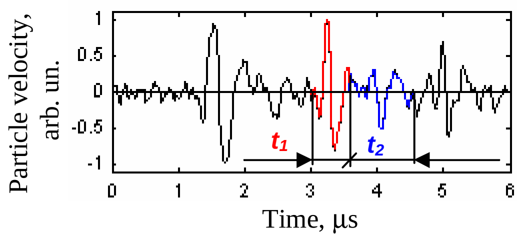

Figure 3. A-scans of particle velocities corresponding to the point at X = 8.1 mm; Y = 3 mm

Using numerical algorithms the visualization of acoustic noise energy in the form of 2-d and 3-d images was made for specimens under study. Obtained C-scans corresponding to the noisy t_2 interval are shown in Figure 4. As it can be seen, the noise-like distributions are more blurred for samples 1 where the mean diameter of micropores is the highest and 3 where the total number of microdefects is maximal than distribution found for sample 2.

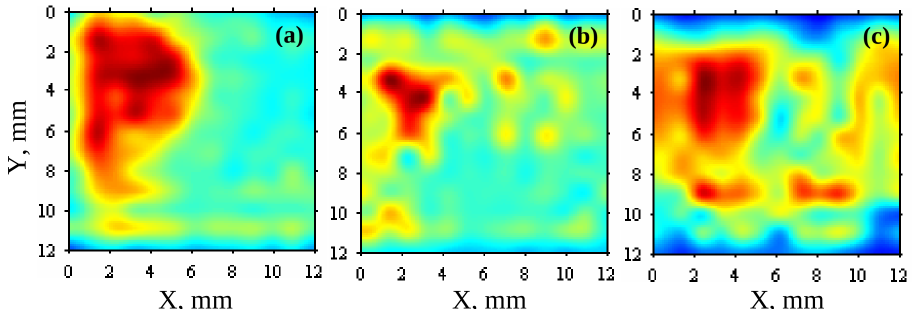

Figure 4. C-scan images of distribution of particle velocity amplitude obtained at noisy interval t_2 for samples 1 (a), 2 (b) and 3 (c)

Thus, spatial acoustic noise intensity distribution can be used to reveal qualitative changes in material response due to the presence of microdefects. To compare between samples, the spatial noise-like distributions found at time interval t_2 were normalized by distributions found for pulse signal at time interval t_1. By calculating the square of normalized displacement amplitudes, one can get the elastic wave energy distribution over the specimen surface. Relationship of noise energy distribution found at interval t_2 to pulse elastic wave energy distribution is presented in Figure 5.

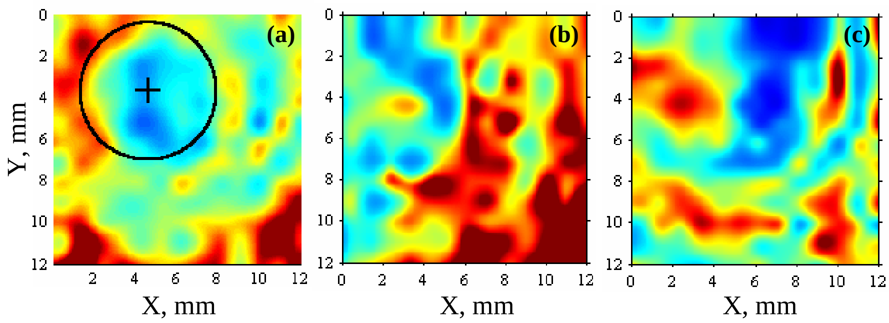

Figure 5. The result of division of C-scans obtained at noisy interval t_2 on C-scans found for pulse interval t_1 for samples 1 (a), 2 (b) and 3 (c)

As evident from Figure 5, the normalized elastic wave energy distribution for sample 1, which was loaded sufficiently and contained sizeable microdefects resembles a ring structure, which coincides with the position of the transducer plate which diameter was 5 mm. The diameter of the ring was also found to be about 5 mm. The distributions found for samples 2 and 3 that had been subjected to milder conditions have random character and do not contain any ring-like structures. As microdefects in sample 1 are the most sizeable, the scattering of elastic waves by larger microdefects is more significant, so the ring structure has to appear in this sample. This proves that the presence of developed microdefects in the material leads to sufficient ultrasound beam scattering and blurring what results in occurring the contrast rings on the beam boundaries[5].

For quantitative estimation the time history of the shape and dimensions of the projection of ultrasound beam on the detection plane was investigated. Snapshots that are instantaneous pictures of acoustic field in definite time points can give us information about radii of wavefront at different time points and their phase velocity of propagation. The method of circle and geometrical center detection on image by means Hough transform[4] was applied to evaluate the outer contour radii of the ultrasound beam projection at different time moments on the basis of snapshots of acoustic fields (Figure 1b). The time dependences of radii found and theoretically calculated one are shown in Figure 6.

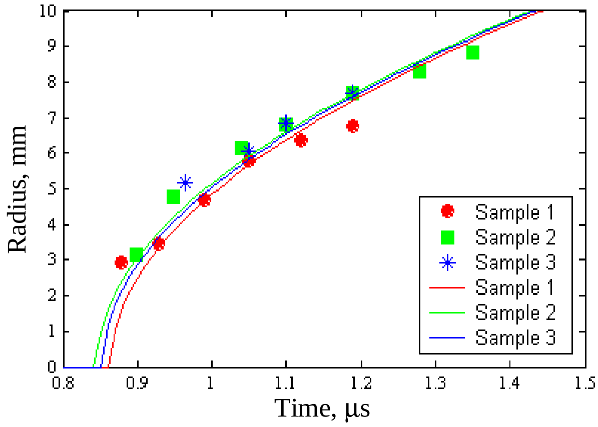

Figure 6. The time history of the outer contour radius of the beam projection on the detection plane for samples 1, 2 and 3: solid lines correspond to found theoretical curves, markers correspond to experimental results

Here, it can be seen that values of radii corresponding to sample 1 with micropores of greater size and where the longitudinal velocity was the lowest are lower than for samples 2 and 3. At the same time radii increase faster in sample 2 with the lower degree of microdamage than in sample 3. As ultrasound velocity is higher in undamaged media than in damaged ones, the radii of wavefront projection would increase faster with time in undamaged material than in microdamaged medium[6]. Also, reasonably good agreement can be observed between experimentally obtained data of radii of ultrasound beam projection and theoretical curves.

4. Conclusion

(1) Qualitative and quantitative information about acoustic field changes in material with microdefects was obtained with the use of laser Doppler interferometer and appropriate processing and visualization algorithms.

(2) Acoustic noise-like signals in time interval between ultrasonic echo-pulses is highly linked with the presence of microdefects in material. On the basis of obtained two-dimensional pictures of acoustic noise distributions the presence of microdefects can be revealed by contrast rings corresponding to the contour of transducer position. Due to snapshots of acoustic fields the time history of radii of ultrasound beam projection on the detection plane was traced. The use of this parameter can help in quantitative investigating of material microdamage.

(3) The research also highlights that processing algorithms based on wavelet filtering can be effective enough in tracing additional features of signals from ultrasonic laser interferometer.

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