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ULTRASONIC TECHNIQUE FOR INVESTIGATION OF RESIDUAL STRESSES IN CYLINDRICAL FORGINGS

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An ultrasonic method to examine statical stress fields in the subsurface layers of cylindrical steel forgings is described. The values of stresses are calculated from precise measurements of travel times of subsurface pulses of longitudinal and transverse waves propagating in the direction of generating line. Suitable apparatus is described and some results of investigations of a shipborne shaft forging with favourable and unfavourable distributions of residual stresses are shown. Longitudinal and hoop stresses in a steel mill roll are also examined.

1. Introduction

All revolving elements of machinery are required to exhibit sufficient homogeneity of the material and its residual stress components both in the circumferential and longitudinal (along the generating line) directions. The main purpose of this requirement is to avoid deformations that could develop as a result of a release of nonhomogeneous residual stresses. Large gradients of residual stresses can be encountered due to disadvantageous temperature distributions during heat treatment or can be caused by plastic strains accompanying, for instance, straightening of elements. The stresses can be released as a result of relaxation associated with vibrations during the operation of particular parts. These vibrations can additionally grow larger due to dynamic stresses of revolving elements and, in extreme cases, lead to failure.

That is why the heat treatment should be appropriately controled. Its check usually consists in maintaining a prescribed temperature regime and making hardness measurements in chosen regions. The most frequent procedure to assess the residual stresses is a classical technological test consisting in strain measurements during the radial saw cutting of a ring cut of from the end of a forging under examination. However, such a test provides information on the residual hoop stresses only near the end of the forging and cannot be extrapolated on the whole length of the forging that can reach several metres. That is why fast nondestructive methods to determine residual stresses are sought.

A partially nondestructive method to evaluate residual stresses is that based on drilling holes and measuring the resulting displacements [1]. A rosette of three resistance strain gauges is glued to the studied surface and the strains caused by the presence of a hole drilled in the middle of the rosette are measured. To determine stress components the stress-strain relationships are used under the assumption that the whole registered deformation took place due to the decay of stresses in the volume of material removed during drilling.

When strains are measured during a gradual counterboring of the hole, a certain amount of information can be gained on the stress changes in the direction perpendicular to the surface. The holes are usually several millimeters deep. However, reproducibility of results is found to be poor, the main reasons for that being: simplified stress-strain relationships masured, difficulties with the drilling of holes in a repeatable manner and generation of additional residual stresses due to plastic deformation around the drilled holes [2]. The described procedure is time-consuming and partially destructive. Low accuracy of results when considerable stress gradients are present lead to the practice of taking measurements at a limited number of points and usually before the final machining of the shaft under investigation.

A fully nondestructive method, allowing for fast measurements, is based on the registration of magnetic (Berkhausen) noises [3]. The Berkhausen noise is observed during the changes of magnetization fields which, in turn, are associated with an reorientation of magnetic domains. The changes in magnetic domain orientations occur in an abrupt manner provided the magnetic field is strong enough. Therefore the magnetic field in the magnetized element changes in a step-wise manner instead of the continuous one. These jumps are called the Berkhausen noises. Due to the fact that the existing stresses influence the movements of magnetic domains, it appears possible to determine stresses by employing their dependence on the Berkhausen noises. Both magnetization and registration of noises are made with the use of induction coils. Suitable apparatus makes it possible to process the measurements in a rapid way. This technique was used to examine residual stresses in steel mill rolls, railroad wheels and in welded structures. However, the results of the Berkhausen noise method and the stress release method due to cutting of elements under investigation [4] are found to be in a rather poor agreement. The main reasons for that are: a comparatively thin layer of material from which information on stresses are gathered, high sensitivity to the surface conditions and remarkable dependence on the chemical composition.

In this paper an ultrasonic method is employed to examine residual stresses. Moreover, certain variations in the elastic properties due to local changes in the internal structure and chemical composition can be also investigated. The algorithm used makes it possible to distinguish between the stress changes and the structural and chemical variations in the material.

The aim of the paper is to present a fast and nondestructive method for the assessment of the degree of homogeneity of elastic properties and residual stress distributions in large-scale forgings.

2. RELATIONSHIPS BETWEEN THE STRESSES AND THE VELOCITIES OF ULTRASOUND WAVES

The velocity of ultrasonic waves in solid bodies depends on elasticity moduli, mass density, temperature, ratio of a representative dimension of a body to the wavelength and the stress field in a zone of wave propagation. The last relationship, dependent on elastic nonlinearity of the considered material, lies at the roots of the ultrasonić tensometry.

In an infinite, isotropic, undeformed solid body the phase velocities of longitudinal waves V_{ii} and transverse waves V_{ij}, $i \neq j$, are given by the formulae

$$V_{ii} = \sqrt{\frac{\lambda + 2\mu}{\rho}} = \sqrt{\frac{E}{\rho}\frac{1-\nu}{(1+\nu)(1-2\nu)}}, \tag{2.1}$$

$$V_{ij\,i\neq j} = \sqrt{\frac{\mu}{\rho}} = \sqrt{\frac{G}{\rho}}, \tag{2.2}$$

where λ, μ – Lamé's constants, ν – Poisson's ratio, E – Young's modulus, G – Kirchohoff's shear modulus, ρ – mass density. The first subscript of V denotes the direction of propagation, the second the direction of particle vibrations.

The first paper in which an expression, relating the ultrasonic wave velocity to the stresses was presented and verified experimentally, was that by Hughes and Kelly [5]. The authors proposed the following relationships:

$$\rho_0 V_{111}^2 = \lambda + 2\mu - (\sigma_1/3K_0)\left[2l + \lambda + \frac{\lambda+\mu}{\mu}(4m + 4\lambda + 10\mu)\right], \tag{2.3}$$

$$\rho_0 V_{121}^2 = \mu - (\sigma_1/3K_0)\left[m + \frac{\lambda n}{4\mu} + 4\lambda + 4\mu\right], \tag{2.4}$$

$$\rho_0 V_{112}^2 = \lambda + 2\mu - (\sigma_2/3K_0)\left[2l - \frac{2\lambda}{\mu}(m + \lambda + 2\mu)\right], \tag{2.5}$$

$$\rho_0 V_{122}^2 = \mu - (\sigma_2/3K_0)\left[m + \frac{\lambda+n}{4\mu} + \lambda + 2\mu\right], \tag{2.6}$$

$$\rho_0 V_{123}^2 = \mu - (\sigma_3/3K_0)\left[m - \frac{\lambda+\mu}{2\mu}n - 2\lambda\right], \tag{2.7}$$

where ρ_0 – mass density in an unstressed state (for $\sigma = 0$), λ, μ – Lamé constants, K_0 – bulk modulus, m, l, n – third order elasticity constants (Murnaghan's constants), σ_1 – uniform uniaxial stress in the i-th direction, V – ultrasonic wave velocity, the subscripts denoting, respectively: direction of wave propagation, direction of particle vibrations (polarization direction), direction of the uniaxial stress.

Experimental evidence shows a negligibly small nonlinearity of relations between the wave velocity and the stress. In practice, for a given material an experimentally established wave velocity-stress relationship is used,

$$\frac{V - V_0}{V_0} = \frac{t_0 - t}{t} = \beta\sigma_1, \tag{2.8}$$

where V_0 and V – the wave velocities in the same material in a natural (unstressed) and stressed states, respectively; t_0 and t – respective travel times over a constant distance, β – elastoacoustic material constant for a given configuration of propagation, polarization and stresses, σ_1 – uniaxial stress.

Measurements of the travel time changes over a constant distance in a uniaxially stressed material indicate that, in the case of steel, the change of stress by 10 MPa results in an increase of the longitudinal wave travel time by 0.01% and of the transverse one by 0.001%. In order to measure stresses on the basis of such small time increments a time measuring device is necessary with a resolution better than $1 : 10^4$.

3. A METHOD TO EXAMINE RESIDUAL STRESS DISTRIBUTION IN SHAFTS

The technique employed to measure residual stresses in shafts and steel mill rolls is a development of the method which was worked out in the Institute of Fundamental Technological Research of PAS and used to measure residual stresses in rails and railroad wheels [6–8, 11].

A system of probeheads for tests by means of subsurface waves and a way in which times of ultrasonic wave travel are measured is shown in Fig. 1.

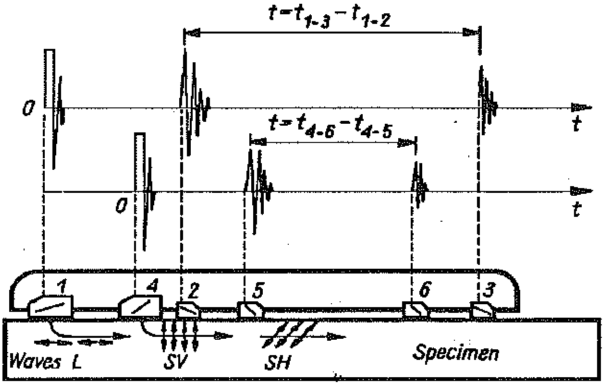

FIG. 1. Layout of ultrasonic transducers to measure the differences in travel times of subsurface ultrasonic longitudinal waves (*1* – transmitter, *2,3* – receivers) and transverse waves (*4* – transmitter, *5,6* – receivers). Relevant pulses are shown above.

The heads contain systems of piezo-electric transmitting and receiving transducers with 3 MHz frequency. The transmitter probehead *1* generates the pulses of longitudinal waves that propagate along a series of transducers below the surface of the material. These pulses are received by the receiving probeheads *2* and *3*. The transmitter probehead *4* generates the pulses of transverse waves that reach the receivers *5* and *6*. During the tests on stress field in cylindrical forgings subsurface transverse waves were used that were polarized perpendicularly to the surface of the specimen (the so-called SV waves) as well as parallel to surface (the so-called SH waves). The layouts *1, 2, 3* and *4, 5, 6* are similar and only the distances between the receiver heads are different. The heads *1* and *4* serve as transmitters whereas the heads *2, 3, 5, 6* are receivers. In between the ultrasonic probeheads the temperature gauges and magnetic grips are located.

A procedure of stress measurement consists of eight sequences and current automatic measurement of temperature. In consecutive successions the times between the transmitter pulse and the pulse received by subsequent receivers are measured. The difference between the measured times is interpreted as a travel time of ultrasonic waves along a distance between the receiver heads. For longitudinal waves generated by the transmitter *1* we have

$$t = t_{1-3} - t_{1-2}\,. \tag{3.1}$$

The measurements of travel times of the longitudinal and transverse waves are taken for two opposite directions of propagation, i.e. when the waves are sent from the transmitters located on the left-hand side and the right-hand side of the system of probeheads. An average value of the travel time of a pulse in two propagation directions is almost insensitive to the acoustic coupling changes resulting from the surface roughness.

The obtained results are referred to one temperature by means of automatic addition of a travel time correction resulting from the experimentally established relationship between the travel time in a chosen layout of probeheads and the temperature. The measured travel times of longitudinal and transverse waves in an examined element and the known travel times of those waves in a reference, unstressed specimen made from the same material enable the values of stresses to be calculated. Relevant relationships to compute stresses are given in [6–8].

Stress components in a cylinder are shown in Fig. 2: σ_1 is an axial stress along the generatrix, σ_2 is radial stress and σ_3 is a circumferential, or hoop, stress. Each of these stress components affects the wave velocity and these effects are additive due to their linear character. Relative time changes

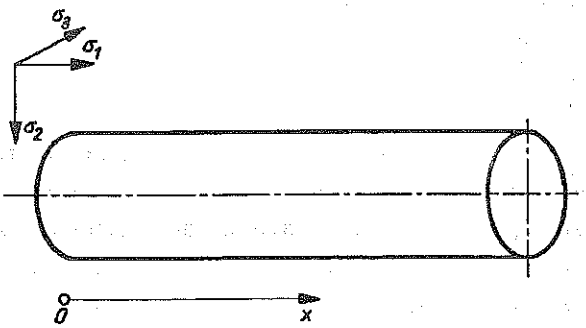

FIG. 2. Stress components in a cylinder.

for the propagation of longitudinal and transverse waves over constant distances, caused by the presence of stresses, can be expressed by:

$$\frac{t_{11}^0 - t_{11}}{t_{11}} = \beta_{111}\sigma_1 + \beta_{112}(\sigma_2 + \sigma_3), \tag{3.2}$$

$$\frac{t_{12}^0 - t_{12}}{t_{12}} = \beta_{121}\sigma_1 + \beta_{122}\sigma_2 + \beta_{123}\sigma_3, \tag{3.3}$$

$$\frac{t_{13}^0 - t_{13}}{t_{13}} = \beta_{131}\sigma_1 + \beta_{132}\sigma_2 + \beta_{133}\sigma_3. \tag{3.4}$$

The subscripts of t denote, as before, the direction of wave propagation and the direction of vibrations of particles in a wave.

The formulae (3.2)–(3.4) enable all the three stress components to be determined. Possibility of using the longitudinal and the transverse waves in the direction of generatrix and the surface waves propagating around the circumference to measure residual stresses was discussed in [9].

Investigations of residual stresses in steel mill rolls with the use of the longitudinal waves in the generatrix direction and along the chord are presented in [10].

4. CALIBRATION

The values of reference travel times t_{ij}^0, appearing in the formulae (3.2)–(3.4) were determined with the use of the same system of probeheads that was employed to examine the forgings with the help of unstressed specimens cut off from those forgings. A measure of a correct annealing of the specimen was the uniform distribution of travel time for the longitudinal and the transverse waves on the surface of the specimen. The elasto-acoustic constants β for particular modes of waves and for various directions of propagation with respect to the stress direction were found in the uniaxial tension tests.

A test arrangement is shown in Fig. 3, some results are depicted in Fig. 4, 5 and 6. The determined elasticity constants of the second and the third order are given in Table 1. The values of elasto-acoustic constants are listed in Table 2. The consecutive β subscripts denote the propagation directions, vibration directions of particles (polarization) and the stress direction.

Allowing for the determined values of the elasto-acoustic constants the formulae (3.2)–(3.4) for the shaft under test take the form:

$$\frac{t_{11}^0 - t_{11}}{t_{11}} = [-1.1\sigma_1 + 0.16(\sigma_2 + \sigma_3)] \times 10^{-5}\,, \tag{4.1}$$

$$\frac{t_{12}^0 - t_{12}}{t_{12}} = [-0.18\sigma_1 - 0.74\sigma_2 + 0.1\sigma_3] \times 10^{-5}\,, \tag{4.2}$$

$$\frac{t_{13}^0 - t_{13}}{t_{13}} = [-0.18\sigma_1 + 0.1\sigma_2 - 0.74\sigma_3] \times 10^{-5}\,. \tag{4.3}$$

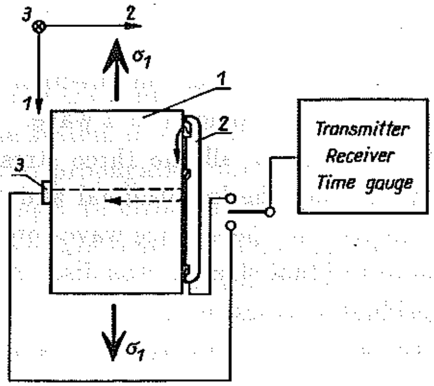

FIG. 3. Test arrangement to determine the elasto-acoustic constants. *1* – specimen under investigation, *2* – system of probeheads for subsurface longitudinal and transverse waves propagating in direction of the stress component σ_1, *3* – standard probehead to transmit either the transverse or the longitudinal waves propagating in the direction perpendicular to the direction of the stress component σ_1.

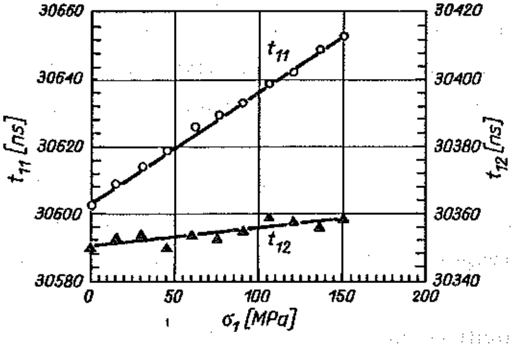

FIG. 4. Relationship between the stress and the travel times of longitudinal waves t_{11} and transverse waves t_{12} propagating in the direction of σ_1.

As seen in the formula (4.1), the stress components σ_2 and σ_3 exert a small influence on the travel time of the longitudinal waves propagating in the direction *1*. Remembering that close to the surface of the shaft the radial stress component σ_2 is, according to the boundary condition, near to zero, the increments $t_{11}^0 - t_{11}$ can be assumed to reflect the changes in the axial stress component σ_1.

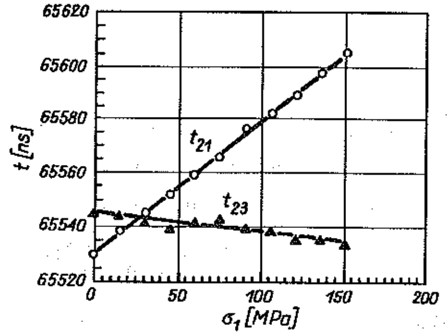

FIG. 5. Relationship between the stress and the travel times of transverse waves propagating perpendicularly to the stress and polarized in the direction of the stress t_{21} and normally to the stress t_{23}.

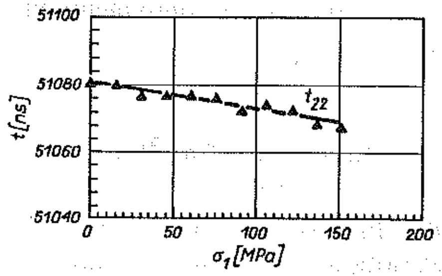

FIG. 6. Relationship between the stress and the travel time of the longitudinal wave propagating normally to the direction of stress.

Table 1. **Elasticity moduli of the second and the third order for steel to be used in shipborne shafts, in [MPa].**

$\lambda = 110 \times 10^3$	$l = -270 \times 10^3$
$\mu = 81 \times 10^3$	$m = -580 \times 10^3$
$E = 208 \times 10^3$	$n = -710 \times 10^3$

In the case of transverse waves it is the stress component acting in the direction of particle vibrations that exerts the largest influence on the wave velocity (travel time). The changes in the travel time of the transverse waves

Table 2. Elasto-acoustic coefficients for the material of the shafts tested.

Coefficient	Value [MPa^{-1}]	Coefficient	Value [MPa^{-1}]
β_{111}	-1.10×10^{-5}	β_{121}	-0.18×10^{-5}
β_{221}	0.16×10^{-5}	β_{211}	-0.74×10^{-5}
β_{331}	0.16×10^{-5}	β_{231}	0.10×10^{-5}

t_{13}, propagating along the generatrix and polarized tangentially to the circumference of the shaft (SH waves), are mainly caused by the hoop stresses σ_3 (formula (4.3)). The stress component σ_2 vanishes on the surface. The changes in the travel times of the transverse waves t_{12} (SV waves) caused by the stress components σ_1 and σ_3 are smaller by one order of magnitude than the corresponding travel times of the longitudinal and transverse SH waves. Thus it can be assumed that the changes in the travel times of the transverse SV waves are a measure of local differences in the elastic properties of the material instead of stress differences. These transverse waves can serve as reference waves in the measurements of stresses. The relationships (4.1)–(4.3) provide all the three stress components in a subsurface layer of the material under consideration.

5. EXAMPLES OF APPLICATIONS

To demonstrate the application of the ultrasonic technique stress measurements in cylindrical forgings, the results of examination of residual stress homogeneity in the shipborne shafts and in the steel mill rolls will be presented. In the former case only the axial stress component σ_1 was of interest. To determine σ_1 the travel times of the longitudinal waves t_{11} and the transverse waves t_{12} were necessary to be measured. The value of stress was calculated in the arithmetical system of the stress measuring device according to the formula [6]

$$\sigma_1 = \frac{1}{\beta_{111} t_{11}} \left[t_{11}^0 + \Delta t^s - t_{11} \right], \tag{5.1}$$

where

$$\Delta t^s = 4/3 \left[\frac{l_{13}}{l_{11}} \right]^2 \left[\frac{t_{11}}{t_{12}} \right]^3 (t_{12}^0 - t_{12}). \tag{5.2}$$

The following notation is used in the expressions (4.1)–(5.2):

Δt^s – correction of the differences of elastic properties, i.e. a difference between the travel time of the longitudinal waves in the reference unstressed material and the travel time of these waves at the location of measurements in the examined material, provided no stresses in it would be present;

σ_1	stress component in the direction of wave propagation,
β_{111}	elasto-acoustic constant for the longitudinal waves propagating in the direction of σ_1,
t_{12}	travel time of the transverse waves propagating in the direction of σ_1,
t_{11}^0	travel time of the longitudinal waves in the reference unstressed material,
t_{12}^0	travel time of the transverse waves in the reference unstressed material,
t_{11}	travel time of the longitudinal waves in the material of an element under test,
l_{12}	distance for measuring the travel time of the transverse waves,
l_{11}	distance for measuring the travel time of the longitudinal waves.

The method of determination of the structural correction is presented in [6] and [11].

Stress distributions along the shaft were found by displacing the ultrasonic probehead in the direction of an arbitrarily chosen generator. Circumferential distributions of the stress σ_1 were taken in those locations in which some anomalies were observed along a generatrix. The travel times of the longitudinal waves t_{11} and the transerve radially polarized waves t_{12} were registered together with the values of stresses from an ultrasonic stress gauge.

A shipborne shaft forging is schematically shown in Fig. 7. The diagrams in Figs. 8, 9, 10 present, respectively: distributions of the travel time of the longitudinal wave t_{11} along the generator, of the transverse wave t_{12} along

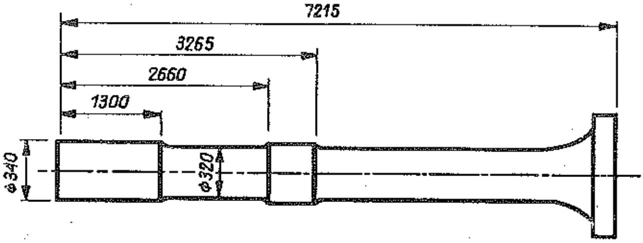

FIG. 7. Shipborne shaft forging.

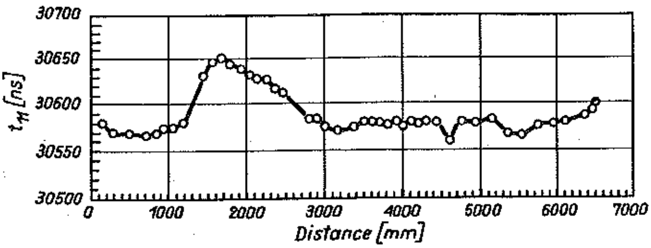

FIG. 8. Changes in travel times of the longitudinal waves along the shaft I.

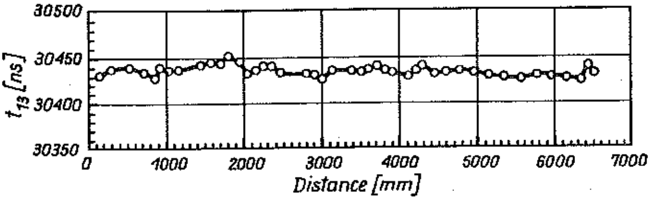

FIG. 9. Changes in travel times of the transverse wave along the shaft I.

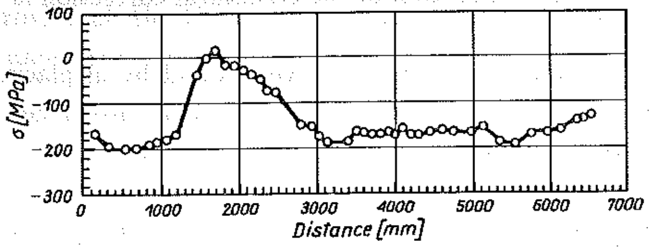

FIG. 10. Distribution of the axial stress σ_1, along the generator of the shaft I.

the same direction and the distribution of the axial stress σ_1 in the shaft I. Circumferential distribution of the stresses σ_1 at the anomalous cross-section of the shaft I is shown in Fig. 11.

Relevant results for the shaft II are shown in Figs. 12, 13, 14. Anomaly in the shaft I occurs between 1300 and 2660 mm. This means that the homogeneity of the residual stress field is disturbed. The fact that no changes in travel times of the transverse waves t_{12} are observed (insensitive to the axial stress in the direction 1) in the region of strong extremum of the travel time of the longitudinal waves t_{11} (sensitive to the stress σ_1) is the evidnce that the reason of t_{11} pike are the changes in residual stresses. Constancy of the travel time of the transverse waves indicates that the elastic properties

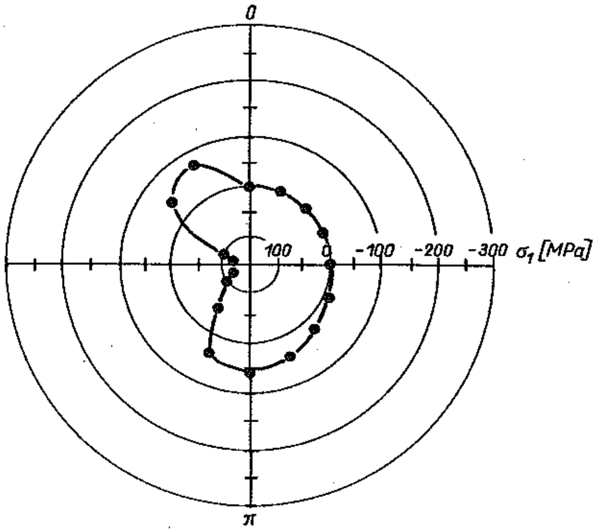

FIG. 11. Circumferential distribution of the axial stresses at the distance of 1600 mm measured from the left end of the shaft I.

of the material remain uniformly distributed. Nonsymmetric distribution of hoop stresses at the location of extremum suggests a danger of generation of the bending moment in the shaft in the case of its unstressing.

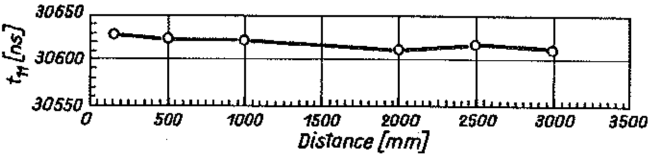

FIG. 12. Distribution of travel time of the longitudinal wave along the shaft II.

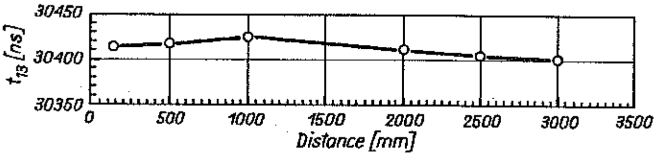

FIG. 13. Distribution of travel time of the transverse wave along the shaft II.

The distribution of the residual stresses in the shaft II is uniform to within the accuracy of a scatter of results, as is seen in Fig. 15.

In the steel mill rolls the distributions of the stress components σ_1 and σ_3 along the generatrix and around the circumference were determined. To this end, the measurements of t_{11}, t_{12} and t_{13} were taken. Some distributions of the stress components σ_1 and σ_3 along the roll are shown in Fig. 16.

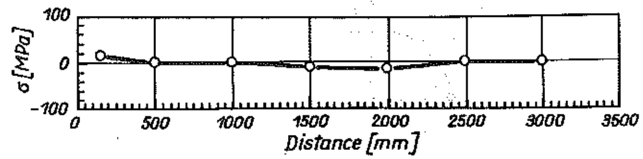

FIG. 14. Distribution of the axial stress σ_1 along the shaft II.

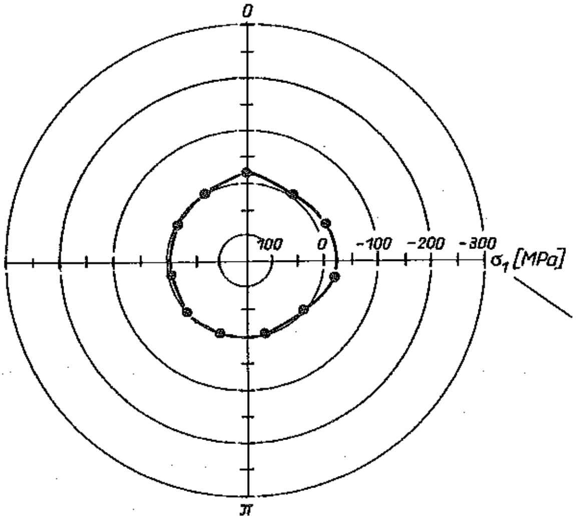

FIG. 15. Circumferential distribution of the axial stresses in the shaft II at the distance of 1600 mm measured from the left end of the shaft II.

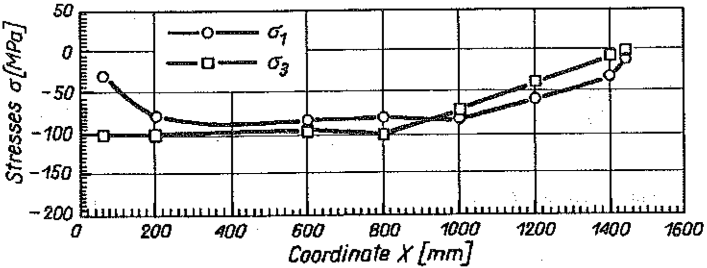

FIG. 16. Distributions of the stress components σ_1 and σ_3 along the cylinder generating line of the roll.

6. SUMMING UP

It was shown that with the use of precise measurements of travel times for various types of ultrasonic waves over a constant distance in a material under test, homogeneity of its elastic properties can be assessed and the distributions of residual stresses can be found. In the case of steel cylindrical forgings all the three stress components in the subsurface layer can be determined with the use of the longitudinal and the transverse subsurface waves propagating along the generatrix. The transverse waves must exhibit polarization in both the radial and the tangential directions. Industrial tests have shown that the described technique is sufficiently sensitive to detect anomalies of the residual stress distributions in the shipsborne shafts and in the steel mill rolls.

7. ACKNOWLEDGEMENTS

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