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Nondestructive detection and analysis of stress states with polarized ultrasonic waves

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THE APPLICATION of linear polarized shear waves is especially recommended in order to determine the (residual) stress states in structural elements. This technique results in equations for the stress evaluation which are independent of the ultrasonic path length measurement and in which only one of the three third-order elastic constants, namely *n*, must be known. Experimental results show that the third-order elastic constant *n* is, in contrast to *l* and *m*, constant over a considerable range of prestrain and changes only by about a few %, if the microstructure state is changed from a ferritic pearlitic over a bainitic to a martensitic-bainitic state. And, finally, theoretical and experimental investigations of the dispersion of shear waves polarized || and ⊥ to the rolling direction indicate a very promising way in order to determine the (residual) stress states in cubic materials with rolling texture.

Zastosowanie fal ścinania jest szczególnie owocne przy określaniu naprężeń (resztkowych) w konstrukcjach inżynierskich. Metoda ta prowadzi do takich równań dla naprężeń, które są niezależne od pomiarów drogi fal ultradźwiękowych i które wymagają jedynie znajomości jednej stałej sprężystości trzeciego rzędu, mianowicie stałej *n*. Wyniki doświadczalne wskazują, że stała ta — w odróżnieniu od stałych *l* oraz *m* — pozostaje istotnie stała w dużym przedziale zmienności odkształcenia i zmienia się zaledwie o kilka procent przy przejściu mikrostruktury od ferrytyczno-perlitycznej poprzez bainityczną do martenzytyczno-bainitycznej. Teoretyczne i doświadczalne badania przeprowadzone nad dyspersją fal ścinania spolaryzowanych równolegle i prostopadle do kierunku walcowania prowadzą do bardzo obiecujących wyników jeśli chodzi o wyznaczanie stanów naprężeń resztkowych w materiałach o strukturze regularnej (sześciennej) i teksturze wynikającej z walcowania.

Применение волн сдвига является особенно многообещающим при определении напряжений (остаточных) в инженерских конструкциях. Такой метод приводит к таким уравнениям для напряжений, которые независимы от измерений пути ультразвуковых волн и которые требуют только знания одной постоянной упругости третьего порядка, именно постоянной *n*. Экспериментальные результаты показывают, что эта постоянная — в отличие от постоянных *l* и *m* — остается существенно постоянной в большом интервале переменности деформации и изменяется лишь на несколько процентов при переходе микроструктуры от ферритно-перлитной через бейнитную к мартенситно-бейнитную. Теоретические и экспериментальные исследования, проведенные по дисперсии волн сдвига поляризованных параллельно и перпендикулярно к направлению прокатки, приводят к очень обещающим результатам, если имеется в виду определение напряженных состояний (остаточных) в материалах с регулярной (кубической) структурой и текстурой, вытекающей из прокатки.

1. Introduction

IN ORDER to determine stress states in structural elements, the application of shear waves has some essential advantages: The most important stress states in constructed parts are those which effect in the plane parallel to the surface. Shear waves, polarized perpendicular to each other, which propagate through the thickness have, at least in ferritic steels, the highest sensitivity to these stress states as it was originally shown by EGLE and BRAY [2]. The birefringence effect of shear waves enables the determination of the principal stress axes and finally, the application of shear waves, polarized perpendicular to each other, results in equations for the stress evaluation which are independent of the ultrasonic path length and in which only one higher order elastic constant must be taken into account.

The first part of this paper reviews briefly some experimental results which demonstrate the applicability of this technique. The main part concerns two difficulties in the nondestructive determination of stress states with ultrasonic techniques, namely the stress determination in textured materials and the influence of prestrain and changes of microstructure on the sound velocities and their stress dependences.

2. Birefringence in samples without texture or with a known texture influence

Based on nonlinear elasticity theory, HUGHES and KELLY [6] derived fundamental equations which describe the sound velocities in solids as functions of elastic strain. Using the relationship for the shear wave velocities, the following equation can be derived (SCHNEIDER *et al.*, [7]):

$$(t_{ij}-t_{ik})/t_{ik} = (\sigma_k-\sigma_j)(4\mu+n)/(8\mu^2),$$

$$i = 1, 2, 3, \quad j = 1, 2, 3, \quad k = 1, 2, 3, \quad i \neq j \neq k.$$

The variables i, j, k represent the axes of a Cartesian coordinate system which coincide with the principal axes of stress 1, 2 and 3. $t_{i,j}$ is the time of flight of a shear wave propagating in the i-direction and vibration parallel to the j-direction. σ_k is the principal stress acting in the k-direction. μ is the shear modulus and n is one of the three third-order elastic constants of the material under consideration. With these equations a one- and two-dimensional stress state can be determined quantitatively, if the elastic constants μ and n and

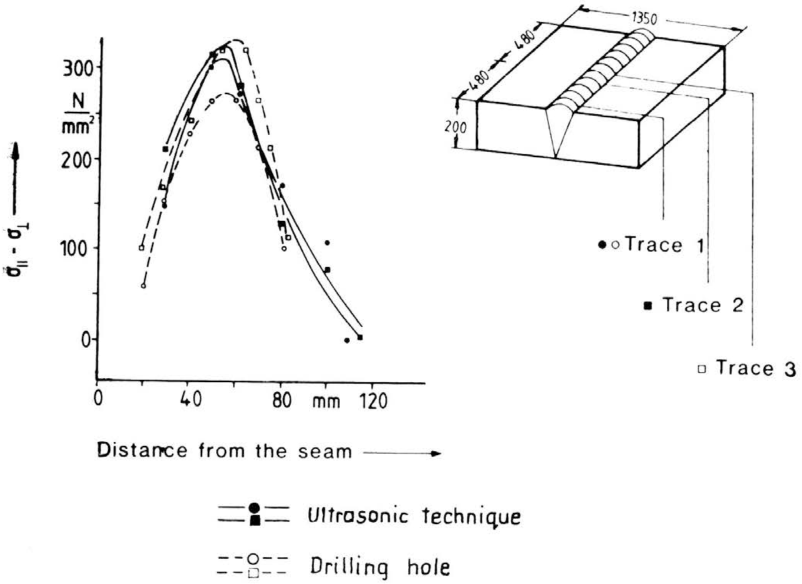

FIG. 1. Residual stress difference $\sigma_{\parallel}-\sigma_{\perp}$ versus distance from a ferritic weld seam.

the principal axes of stress are known. A three-axial stress state can be characterized by three differences of two principal stresses. For a lot of applications it is sufficient to know these differences in addition to e.g. the stress equilibrium conditions or further information.

The experiments were made with a commercial ultrasonic apparatus and a dual-channel oscilloscope with a crystal reference for time-interval measurements. The polarization directions of the commercial shear-wave transducers were determined separately. The frequencies used in the measurements were between 3 and 5 MHz.

The Figures 1 and 2 show the differences of the principal stresses parallel ($\sigma_{||}$) and perpendicular ($\sigma_{\perp}$) to weld seams in thick plates as function of the distances from the seams.

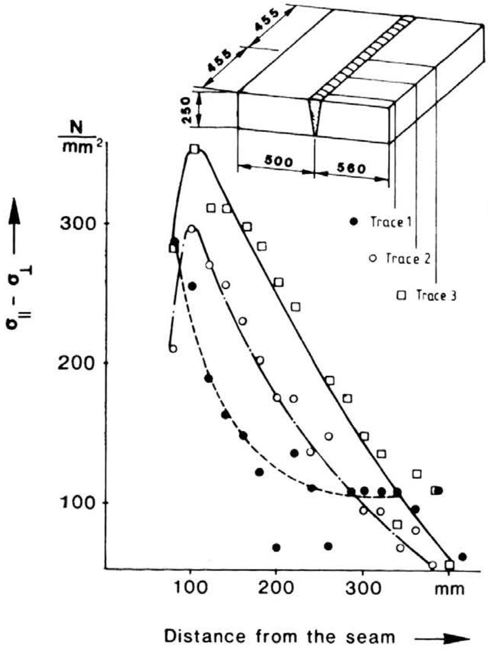

FIG. 2. Residual stress difference $\sigma_{||}-\sigma_{\perp}$ versus distance from a ferritic weld seam.

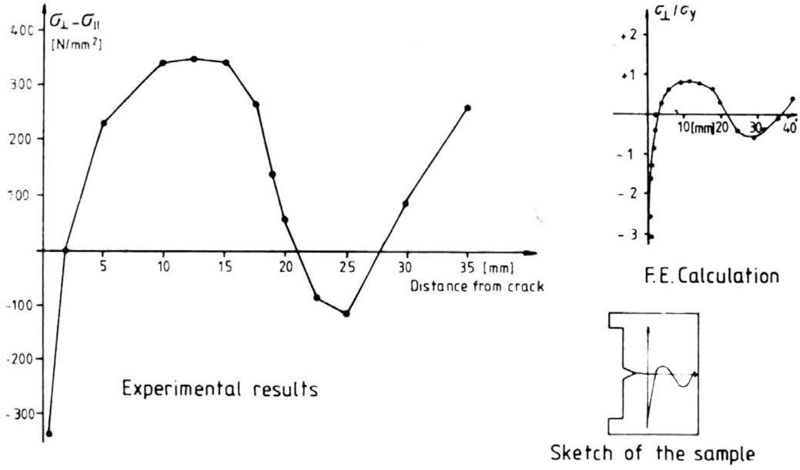

FIG. 3. Change of the residual stress difference $\sigma_{\perp}-\sigma_{||}$ as a function of the distance from the crack end

In Fig. 3 the differences of the principal stress parallel ($\sigma_{||}$) and perpendicular ($\sigma_{\perp}$) to the direction of a growing fatigue crack is displayed together with the result of a finite element (FE) calculation. Absolute time-of-flight values indicate that the stress $\sigma_{\perp}$ is

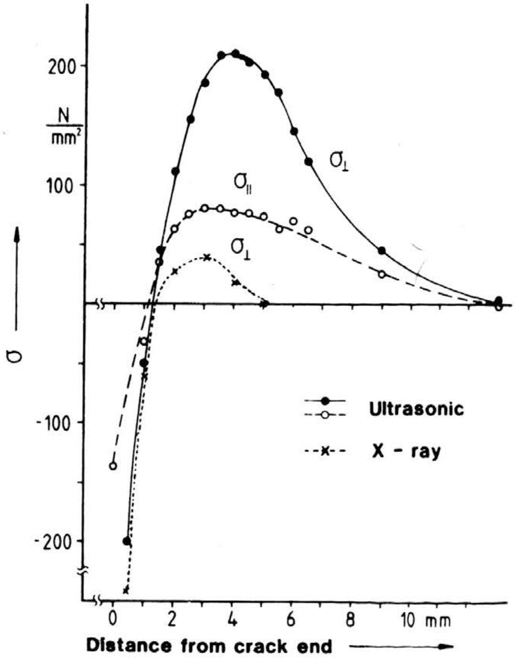

FIG. 4. Change of principal stresses $\sigma_{\perp}$ and $\sigma_{||}$ as function of distance from crack end.

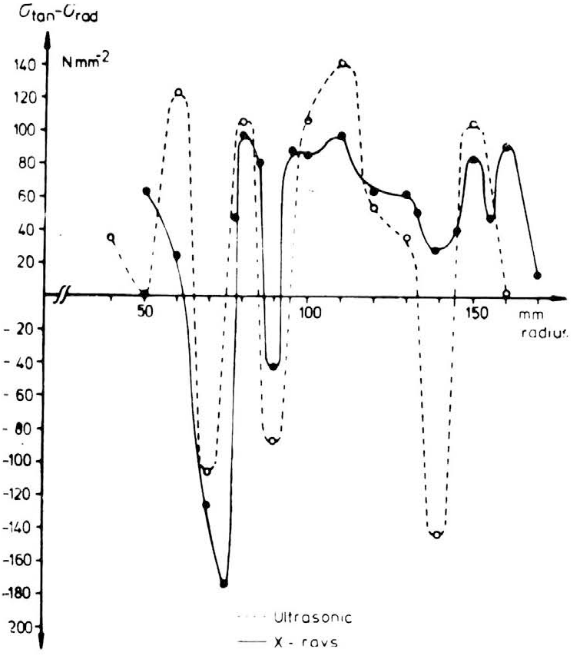

FIG. 5. Change of $\sigma_{\tan}-\sigma_{\mathrm{rad}}$ over the radius of a saw blade.

much greater than $\sigma_{||}$, so that the curve shows the typical change of $\sigma_{\perp}$ as function of the distance from the end of the crack.

The additional measurement of the times-of-flight of two shear waves, vibrating parallel to principal directions, which propagate along another principal axis, or the additional measurement of the longitudinal wave velocity, enables one to evaluate the absolute values of $\sigma_{\perp}$ and $\sigma_{||}$ as it is shown in Fig. 4 for another fatigue crack sample.

An example, where the influence of texture on the birefringence effect was known, is shown in Fig. 5. As described by SCHNEIDER and GOEBBELS [8], the additional measurement of the ultrasonic absorption was used to determine the texture influence. Although the agreement of the ultrasonic results with X-ray is good, the applicability of these techniques seem to be limited to special cases.

3. Approach to separate stress and texture birefringence–dispersion

The texture induced part of the birefringence effect is caused by the elastic anisotropy of each grain. In contrast to this, the stress influenced change of sound velocities is caused by a stress-affected change of the interatomic potential resulting in changes of the elastic behaviour, which is described as contributions of higher order elastic constants. In order to determine the first influence mentioned on the sound velocities, the elastic anisotropy of each grain and the influence on the sound velocities was investigated. A theoretical description of the ultrasonic propagation in polycrystals with randomly oriented grains

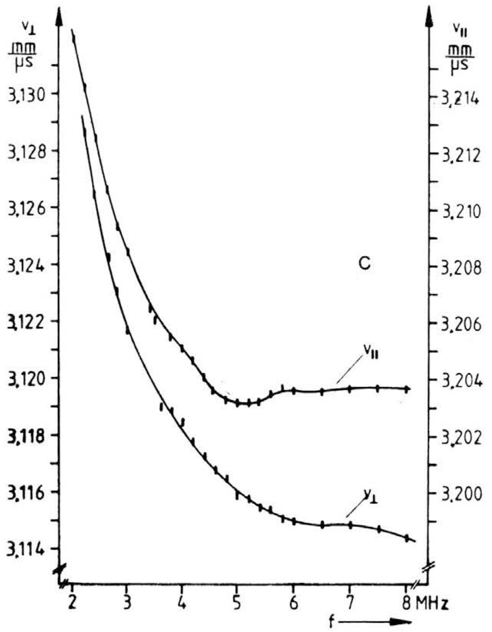

FIG. 6. Velocities of shear waves polarized || and ⊥ to the rolling direction versus the frequency.

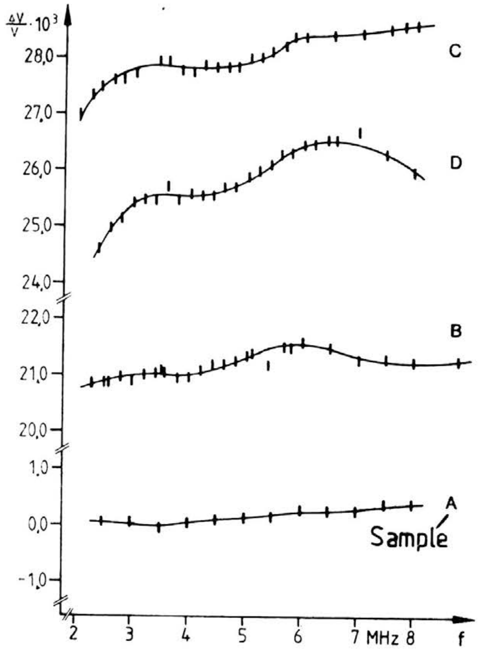

FIG. 7. Relative velocity differences of two shear waves polarized perpendicular to each other versus the frequency.

shows that the longitudinal and shear wave velocities are frequency-dependent. This dispersion effect is caused by the ultrasonic scattering and is mainly determined by the anisotropy constant of the material (HIRSEKORN, [3, 4]. A generalization of this theory for cubic polycrystals with a texture which has an orthorhombic symmetry (rolling texture) is done by HIRSEKORN [5] in second-order perturbation theory using the assumptions that the changes of the elastic constants from grain to grain are small and caused by different orientations only. The density is assumed to be constant; the grains are treated as spheres. In order to determine the averaged elastic constants and their mean quadratic fluctuations, the representation in generalized spherical functions of the orientation distribution function must be known. Using the elastic constants and the orientation distribution functions for cold-rolled steel and brass samples, published by BUNGE [1], numerical calculations are made.

From the viewpoint of application, especially the results for shear waves which propagate through the thickness of rolled plates and vibrate parallel and perpendicular to the rolling direction are of interest. For comparison, some experimental results are shown at first. Figures 6 and 7 display experimental results measured in textured steel plates with a grain size of about 10 μm. The velocites of the two shear waves decrease with increasing frequency. The relative difference of these velocities is affected by the different degrees of texture. In the textureless sample, the measuring quantity is independent of frequency. With increasing degree of texture, indicated by the texture coefficients above 1, the intersection on the $\Delta v/v$ axes increases and there are special curves which are comparable to quadratic functions of the frequency. The numerical results show the same quantity $\Delta v/v$ as function of the wave-number k times the grain radius a. In the 70% cold-rolled steel plate with a given constant grain size, the relative velocity difference increases also in a quadratic form with increasing frequency; this means with increasing k while a is constant (Fig. 8 and 9).

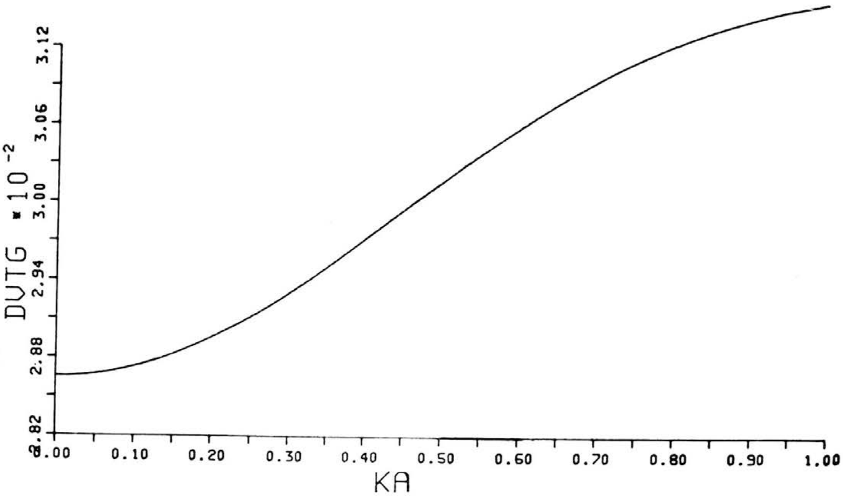

FIG. 8. 70% cold-rolled steel plate. Relative velocity difference of shear-waves polarized || and ⊥ to rolling direction.

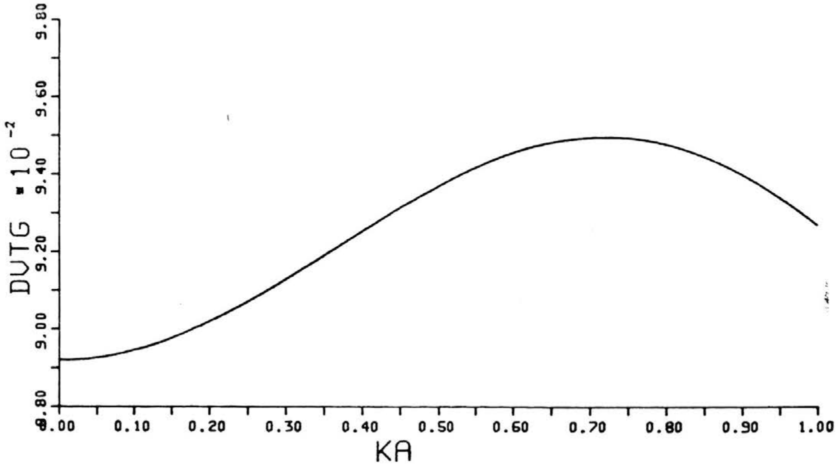

FIG. 9. 95% cold-rolled copper-plate. Relative velocity difference of shear waves || and ⊥ to rolling direction.

The theory predicts this quadratic function of frequency as long as *ka* is within the Rayleigh region (HIRSEKORN, [5]).

Numerical calculations with the corresponding values for plates with different percentages of thickness reduction by rolling show that the slope of the quadratic curve and the $\Delta v/v$ intersection are influenced by the degree of texture and that there is a linear relationship between the texture induced part of the $\Delta v/v$ intersection C_1 and the slope C_2 of the curve. Figure 10 displays this relationship for cold-rolled steel and α-brass samples.

In the case of α-brass, both values C_1 and C_2 increase with the thickness reduction; this is not the case in the steel samples, probably due to the recrystallization process; but nevertheless, there is a good linear relationship between the slope of the curve $\Delta v/v$ as function of frequency and the texture-induced part of the birefringence.

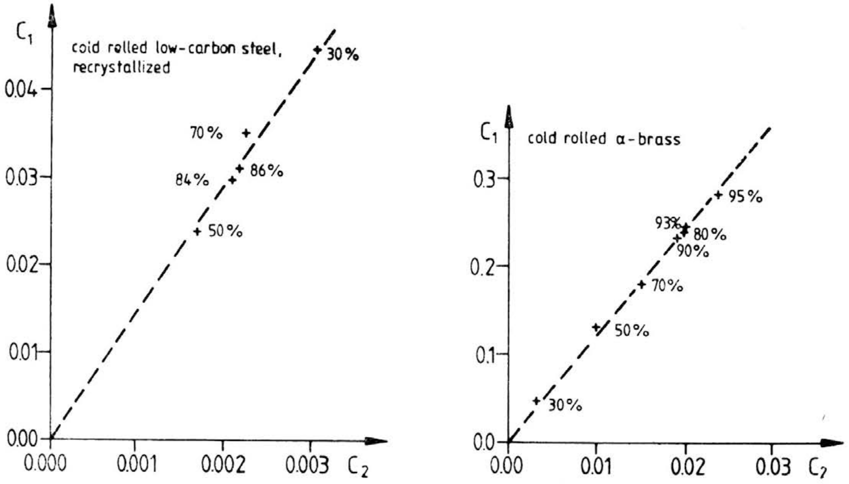

FIG. 10. Correlation between the texture induced part of the $\Delta v/v$ intersection C_1 and the slope C_2 of the quadratic curve $\Delta v/v$ as function of the frequency.

In order to determine the (residual) stress state in cubic materials with rolling texture, the dispersion of the relative velocity difference (identical to the relative time-of-flight difference) of shear waves polarized | | and ⊥ to the rolling direction must be measured. With the determined slope of this dispersion curve, the texture induced part of the birefringence effect can be evaluated using corresponding correlations like those in Fig. 10. The remainder part of $\Delta v/v$ or $\Delta t/t$ caused by the stress states can be determined using the equations mentioned above. The advantage of this approach is twofold: The actual degree of texture is taken into consideration, so that the application is not limited to slightly anisotropic cubic materials, and the method is independent of accurate velocity measurements; the measurement of relative time-of-flight differences is sufficient.

4. Influence of prestrain and changes of mictostructure on the birefringence effect

Until now, there is no satisfying theory available which describes the influence of elastic strain (or stress states) on the propagation velocities of ultrasonic waves in prestrained materials. From the viewpoint of application, especially the prestrain dependence of the higher order elastic constants is of interest. This dependence is investigated experimentally assuming that the equations given by EGLE and BRAY [2] are applicable. Ferritic and austenitic steel samples with different amounts of prestrain were elastically deformed, while the velocities of longitudinal and shear waves were measured. The propagation direction was ⊥ to the applied tensile stress, the polarization of the shear waves were | |

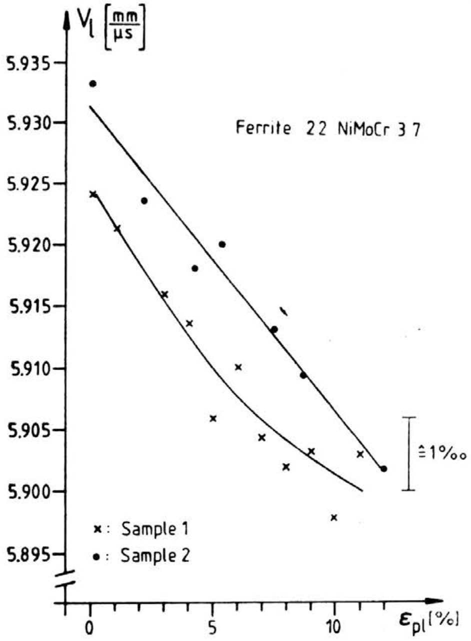

FIG. 11. Change of velocity of longitudinal waves in ferritic steel as a function of plastic strain.

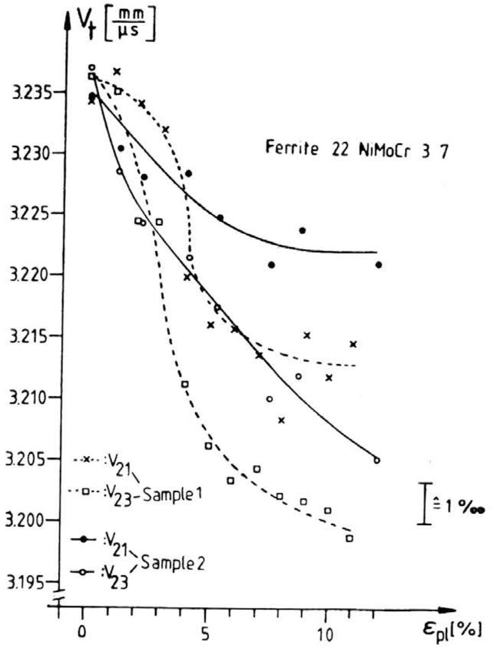

FIG. 12. Change of shear-wave velocity in ferritic steel as a function of plastic strain.

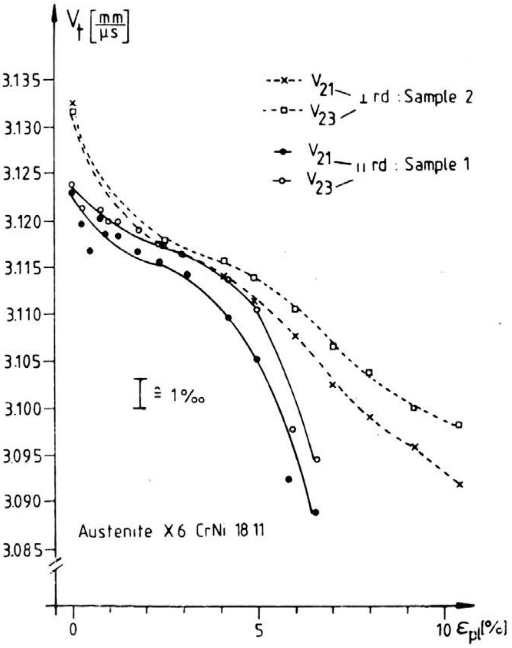

FIG. 13. Change of shear-wave velocity in austenitic steel as a function of plastic strain.

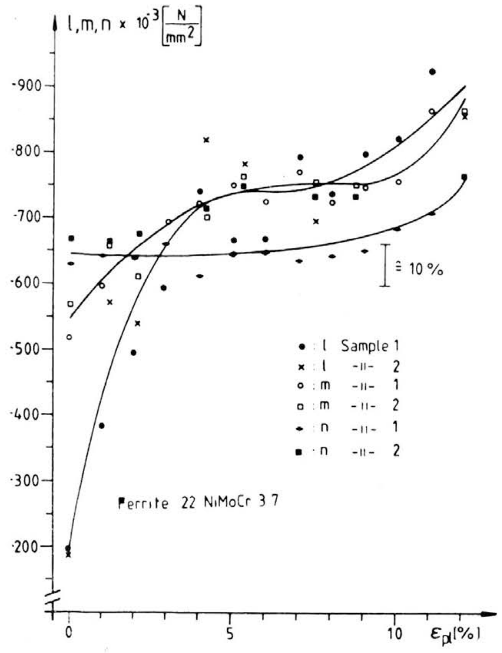

FIG. 14. Third order elastic constants as functions of plastic strain.

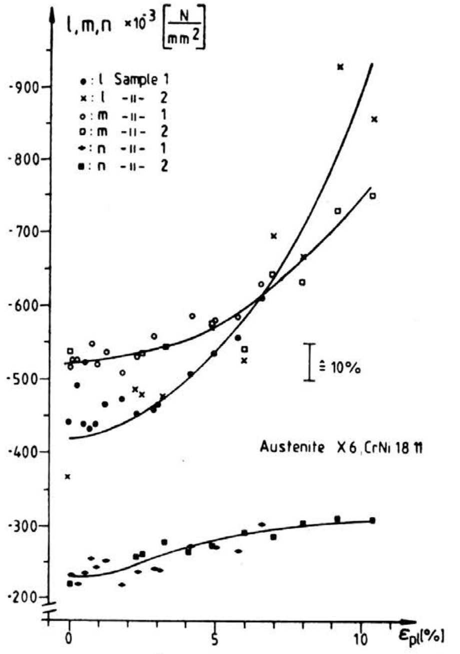

FIG. 15. Third order elastic constants as functions of plastic strain.

and ⊥ to the stress. In Fig. 11–13 the absolute wave velocities are shown as function of the plastic prestrain.

The calculated third-order elastic constants *l*, *m*, *n* of a ferritic and austenitic steel are displayed in Fig. 14, 15. The constant *n* of the ferritic sample remains constant until about 8% ε_{pl} and increases then by about 10%. In contrast to this, the constants *l* and *m* are much more affected by prestrain. Also in the austentic sample, the constant *n* has the lowest prestrain dependence.

The experimental results indicate that, for general purpose, the state of prestrain must be taken into account in order to evaluate stress states using ultrasonic techniques, and that in components with lower amounts of prestrain the birefringence effect described in the above equation can be used. In order to determine the influence of changes in the microstructure on the third-order elastic constants, ferritic steel samples were heat treated, so that a homogeneous ferrite-pearlite, bainite and martensite-bainite structure was generated. Figures 16 and 17 show the changes of longitudinal and shear wave velocities due to moving the probe over the simulated zone.

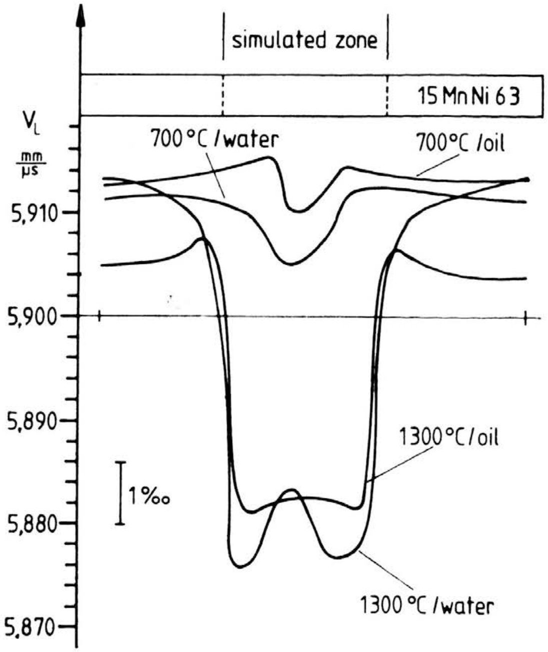

FIG. 16. Velocity of longitudinal waves at different structural conditions.

The velocity of the shear wave polarized | | to the longitudinal axes of the martensitic-bainitic sample changes drastically in the middle of the simulated zone. Of course, this microstructure has a strong anisotropy, but in how far this effect is caused by structure conditions is not yet investigated. Bonding the ultrasonic transducers in the middle of the treated zones, the longitudinal and shear wave velocities were measured as functions of the applied tensile stress in order to evaluate the third-order elastic constants. The Table 1 gives the elastic constants for different microstructures. Although the absolute velocities are strongly affected by changes in microstructure (see Figs. 16, 17), the thir-order elastic

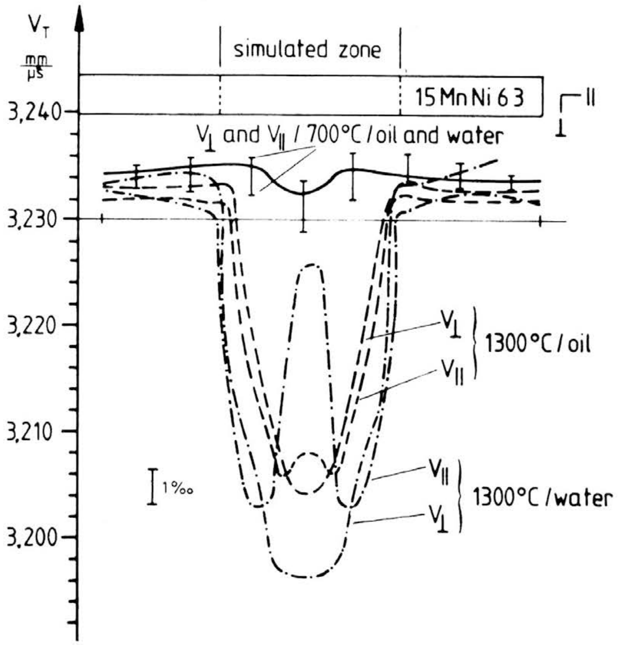

FIG. 17. Velocity of two shear waves polarized perpendicular to each other at different structural conditions.

Table 1.

Microstructure	Treatment	Elastic Constants $\times 10^{-3}$ MPa					Poisson ratio
		λ	μ	l	m	n	
Ferrite + pearlite	700°C/ oil-quenched	110	81	−270	−580	−710	0.29
Ferrite + pearlite	700°C/ water-quenched	110	81	−340	−600	−700	0.29
Bainite	1300°C/ oil-quenched	110	80	−320	−600	−730	0.29
Martensite-bainite	1300°C/ water-quenched	109	80	−350	−610	−750	0.29

constants do not show a significant dependence on it. Especially the value of Murnaghan constant n varies only < 10 percent. But within the accuracy of measurement this change is negligible.

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