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Ultrasonic investigation of thermal stresses

J. SZELĄŻEK

Institute of Fundamental Technological Research
Świętokrzyska 21, 00-049 Warszawa, Poland
jszela@ippt.gov.pl

1. Introduction

There are many branches of technology which need fast and nondestructive evaluation of stresses. The sum of both applied and residual stresses can decisively influence the state of the element of the machine or a structure. A well-known example of such dangerous stresses are welding stresses created during assembling of rigid structures like tanks. High residual stresses in such structures can lead to cracking or construction deformation. Another example of stresses are thermal stresses observed in structures subjected to nonuniform temperature fields.

To monitor stresses numerous nondestructive or quasi-nondestructive methods were developed. Destructive techniques, based on the displacement due to stress relieving measured in the course of element cutting or sectioning, are used for residual stress evaluation. They are usually very laborious and expensive (also the element under test is destroyed).

Some of nondestructive techniques, like Barkhausen noise technique or X-ray diffraction, have a long history and found numerous industrial applications. But these methods are able to evaluate surface stress only. They also need very careful surface preparation or results are influenced by plastic deformation of material surface what can be often observed during service. This was the reason why Barkhausen noise technique failed when applied to the stress measurements in monoblock wheels which surfaces during service are subjected to local mechanical deformations.

The most popular technique of stress monitoring is based on resistance strain gauges. They are used for measurement of deformation on the material surface what allows to calculate surface stress. Their disadvantage, in some application, is that delicate gauges glued to the material surface must stay on it all the time. If the object under test is subjected to heating for example, gauges usually are destroyed.

This paper describes theoretical background and applications of a nondestructive, ultrasonic technique of stress monitoring. This technique, however not so accurate like resistance strain gauges method, can replace them in several situations. One of such a situation is monitoring of thermal stresses in various location on continuously welded rails.

2. Ultrasonic stress evaluation

The dependence of ultrasonic waves velocity on stress occurring in the material is called the elastoacoustic effect. Ultrasonic stress measurements are based on this effect. The theoretical description of stress-velocity dependence is given by the nonlinear theory of elasticity [1].

The wave velocity depends on the material elastic constants. In the linear theory of elasticity the elastic constants and the wave velocity do not depend on the elastic strain. The second and higher order elastic constants however depend on strain and they connect small amplitude elastic wave velocity with stress [2].

Figure 1 presents the results of measurements performed on the steel sample during tensile test. The time of flight (TOF) of ultrasonic pulses in the sample material over the determined distance was measured. The aim of measurement was to determine the dependence TOF–stress. The diagram shows the comparative changes of TOF for various ultrasonic waves propagated in various directions with respect to stress.

The stress-velocity dependence in compression is simply the extrapolation of lines describing the dependence in tension.

The "sensitivity" of the ultrasonic wave to stress is described by elastoacoustic constant. The value of this constant is calculated follows:

$$\beta_{ijk} = \frac{V - V_o}{V\sigma} = \frac{T_0 - t}{t\,\sigma}$$

where:

V and V_o – phase velocities in stress free and stressed medium respectively,

t and T_0 – times of flight in stress free and stressed medium respectively,

β_{ijk} – elastoacoustic constant, indices i, j, and k denote direction of wave propagation, wave polarization and stress,

σ – stress.

It can be seen that the most "sensitive" to stress is longitudinal wave propagated along the stress. The second high elastoacoustic constant wave is

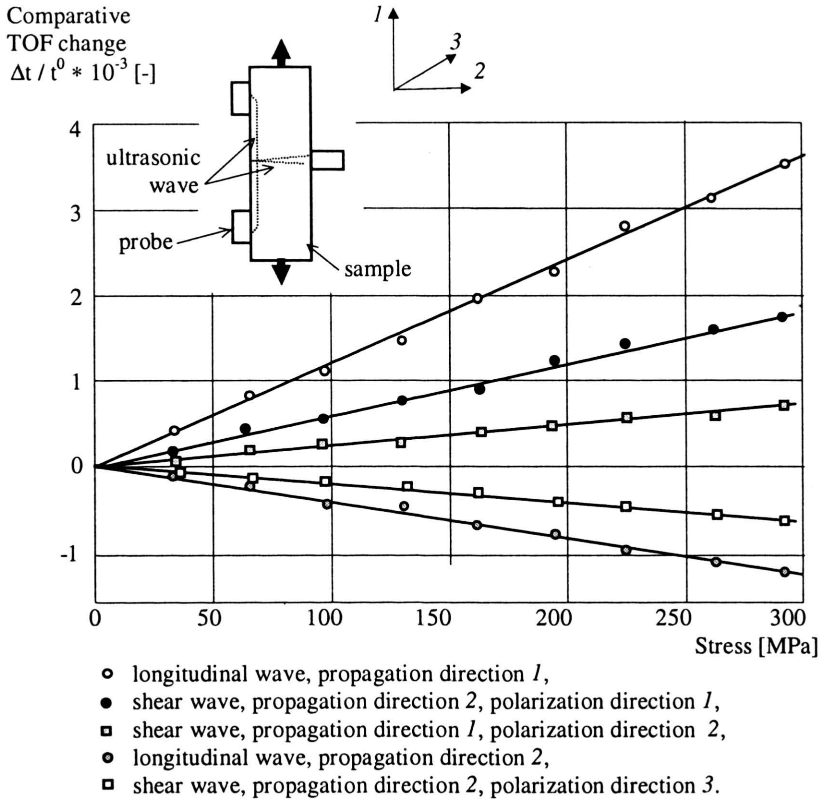

FIGURE 1. Results of measurements of ultrasonic pulses time of flight (TOFs), for various wave types and directions of propagation on the steel sample subjected to tension.

shear wave propagated perpendicular and polarized parallel to stress. These two waves are most often used in ultrasonic tensometry.

Values of elastoacoustic constants for various ultrasonic waves propagated in steel are presented in Table 1 of [3].

TOF changes due to stress are unfortunately small. In the most expedient case of longitudinal wave propagated parallel to stress in steel, the increment of tensile stress by 10 MPa causes the increase of TOF by 0.0125% only. This TOF change is equivalent to velocity decrease by 0.74m/s. Assuming the possible maximum change of stress in steel construction member from -500 MPa to +500 MPa one can extract the corresponding velocity change of longitudinal wave propagating in the direction of stress of the range of 74 m/s. Such change of velocity, when measured over the distance 200 mm in steel, causes the change of TOF of the order of 400 ns. Therefore in ultrasonic stress measurements TOFs has to be measured with a very high,

TABLE 1. Elastoacoustic constants for steel.

Wave type	**Direction of wave propagation**	**Direction of wave polarization**	**Elastoacoustic constant [MPa^{-1}]**
longitudinal	parallel to stress	—	$-1.25 \cdot 10^{-5}$
shear	perpendicular to stress	parallel to stress	$-0.79 \cdot 10^{-5}$
shear	parallel to stress	perpendicular to stress	$0.14 \cdot 10^{-5}$
longitudinal	perpendicular to stress	—	$0.13 \cdot 10^{-5}$
shear	perpendicular to stress	perpendicular to stress	$0.02 \cdot 10^{-5}$

10^{-9} (nanosecond) accuracy. It means that in ultrasonic tensometry special equipment and special sets of ultrasonic probes have to be used.

Most of technical materials are anisotropic. The anisotropy is a result of manufacturing processes like rolling, casting or forging. During these operations grains of metal become oriented creating a texture. In anisotropic materials velocity of waves propagation depend on direction of propagation versus acoustic axes determined by texture directions. Velocity changes due to texture can be even higher than those due to stresses and elimination of texture influence on results of ultrasonic tensometry is still a great challenge.

A linear velocity-stress dependencies in anisotropic media, as presented in Fig. 1, are observed only for waves propagated along the acoustic axis of a medium. In practice this fact limits the applications of ultrasonic tensometry for elements in which directions of texture and main stresses coincide. Such coincidence is observed in numerous construction members like for example steel beams subjected to tension, compression or bending. In these elements the direction of texture due to rolling and direction of main stresses coincide.

If the absolute value of stress is to be evaluated the only practical way to eliminate the influence of usually unknown material texture on readings is calibration of the measuring device on stress free sample. Calibration sample has to be made of the material exhibiting the same chemical composition and texture as the object to be tested. Such approach can be used for test on objects manufactured in series, in a repetitive way like railroad rails or steel plates. In such cases the calibration sample can be made of a piece of the rail or plate subjected to stress relieving annealing. During calibration TOFs in zero stress state are measured. The difference between calibration sample TOF and element under test TOF is proportional to stress value.

If in the given location of the object, stress changes only are to be evaluated the texture of the material does not influence ultrasonic readings. Measurements in such a case are repeated at the same location and one can assume that the texture of material is constant and the only factors influencing velocities of ultrasonic waves are stress and temperature changes.

3. Measuring technique

Thermal stress evaluation in the CWR is based on the measurement of TOF of longitudinal, subsurface wave propagated along the ail axis. The scheme of the elementary set of probes (one transmitting and one receiving) used in the measurement is presented in Fig. 2. The distance between both probes is determined by a metal plate connecting probes.

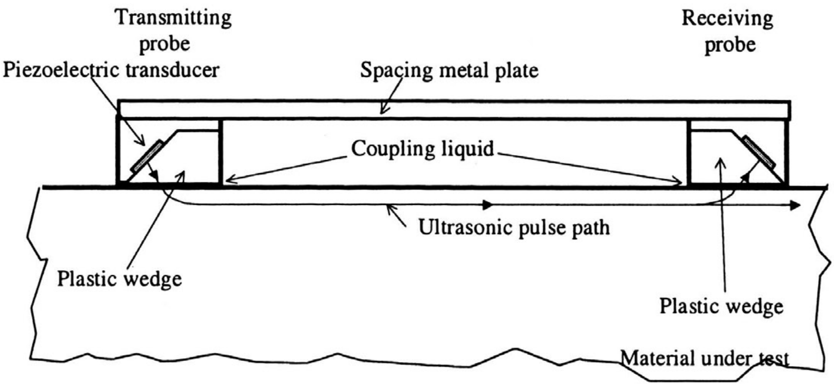

FIGURE 2. Scheme of the elementary set of probes (one transmitting and one receiving) used for subsurface wave TOF measurement.

Piezoelectric transducers in both probes are positioned on plastic wedges coupled to the element surface with a coupling liquid or gel. The wedge angle is equal to the first critical angle. Longitudinal wave generated by the transducer propagates in the wedge and than, on the wedge-steel boundary, refracts and propagates in the steel, parallel to the surface, as longitudinal subsurface wave. In the same way the wave is received by the receiving transducer.

TOF measured between moments of pulse transmission and reception depends on travel time in both plastic wedges, in the coupling liquid layers and in the object under test.

The thickness of coupling layer depends on local surface roughness. To eliminate undesired influence of coupling variations on measured TOFs multitransducer set of probes are used. The simple example of such a probe set is the set consisting of one transmitting probe and two receiving probes arranged in one line, presented in Fig. 3. In this case two TOFs are measured: between Transmitter and Receiver 1 and between Transmitter and Receiver 2. The difference between these two measured TOFs gives time of flight of the pulse in the sample material, over the distance L, eliminating times of flight in plastic wedges (assuming wedges in two receiving probes are the same) and in coupling liquid (assuming that coupling liquid layers are the same for both receiving probes). Such a set eliminates significantly undesired influence of couplant variations on readings but for practical applications sets consisting of 6 to 10 probes are used. Such multitransducer sets of probes allow us to perform precise TOF measurements without time consuming preparation of the object under test surface (which in industrial conditions is often rusty or rough).

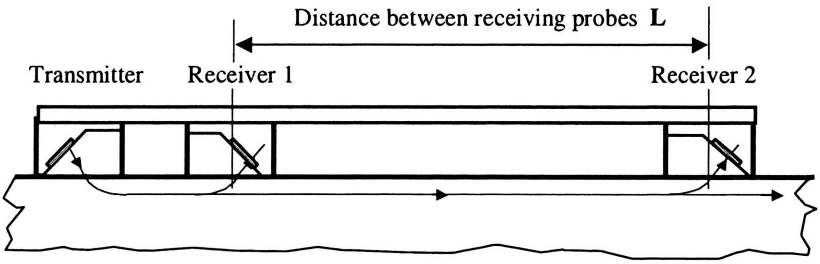

FIGURE 3. The set of three probes for subsurface wave TOF measurements.

Figure 4 presents TOF scatter due to the surface roughness, caused by variations in coupling liquid layer thickness, measured on railroad rail surface with various sets of probes. Rail surface was prepared only by removing the rust and dirt. The measurements of TOF were performed along the rail; sets of probes were coupled to the rail surface every 15 mm. TOFs were measured with three sets of probes:

- consisting of one transmitter and one receiver (as shown in Fig. 2),
- consisting of one transmitter and two receivers (as shown in Fig. 3),
- consisting 6 probes, two transmitters and four receivers (two sets like in Fig. 3).

It can be seen that for 6-transducer probe set measured TOF variations, due to coupling changes, are equal to a few nanoseconds only. It means that in industrial conditions, the velocity of ultrasonic wave can be evaluated with the accuracy of about ± 3 m/s ($\pm 0.05\%$).

TOFs of subsurface waves measured with probe sets presented above are significantly influenced by temperature. Velocity of ultrasonic wave propaga-

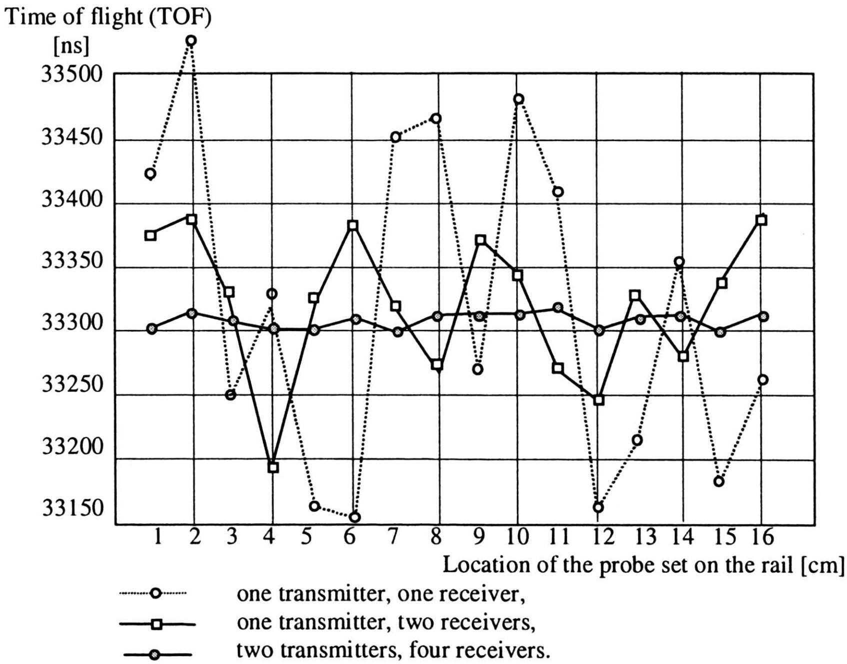

FIGURE 4. The influence of coupling variations on TOF ,measured with various sets of probes on rough rail surface.

tion depends on temperature and the highest velocity changes are observed for plastics. For Plexiglas, the material used for probe wedges, 1°C temperature change results in 2.3-3.0 m/s velocity change, depending on the material grade. For steel the temperature-velocity change is lower and for longitudinal wave is equal to about 0.55 m/s.

Temperature change results also in the elongation of spacing plate (shown in Fig. 2) determining the distance between probes, and in the expansion of plastic wedges.

The changes in the velocities of ultrasonic wave in wedges and in the object under test result also in the change of the refraction angle in the receiving probe wedge. All the above factors result in a significant TOF increase with temperature and have to be taken into account during ultrasonic stress evaluation. To do so, the temperature correction for a given set of probes and for a given material under set is measured experimentally in the temperature chamber. TOFs are measured in various temperatures and the example of such experiment results is shown in Fig. 5.

It can be seen that for limited temperature range one can assume linear dependence TOF – temperature. In such a case the temperature correction Pt

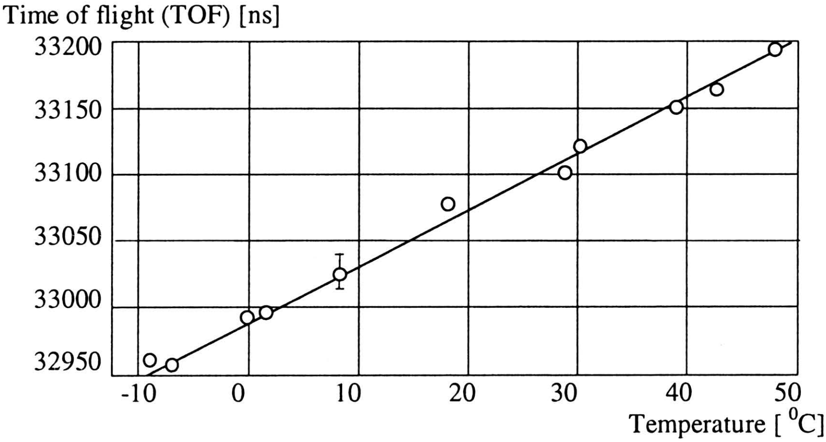

FIGURE 5. Dependence of TOF on temperature measured for steel. Spacing plate determining the distances between probes made of brass.

is given by:

$$Pt = \frac{t_M - t_0}{T_M - T_0},$$

where:

t_M – time of flight measured for the temperature T_M [°C],

t_0 – time of flight measured for the temperature T_0 [°C].

The value of temperature correction Pt depends on the probe set design. For a set of probes equipped with brass spacing plate and with the measuring distance equal to about 200 mm in steel, Pt is equal to about 3-4 ns/°C. It means that temperature change equal to 1°C can result in TOF shift equal to the shift caused by stress change equal to a few MPa.

The temperature correction allows us to calculate the temperature corrected TOF t_K (temperature independent time of flight which would be measured in the object in the reference temperature T_0):

$$t_K = t_M + Pt(T_M - T_0),$$

where:

t_M – time of flight measured for temperature T_M,

Pt – temperature correction [ns/^{0}C],

T_0 – reference temperature,

T_M – temperature of the object during TOF measurement.

To minimize the influence of temperature on subsurface wave TOF measured with described probe sets, a spacing plate is made of Invar (material with zero thermal expansion coefficient) and the dimensions of plastic wedges are reduced. Proper design of the set of probes allows also to minimize the time necessary for the probe set temperature stabilization. This feature of the probe set is important during the measurement of thermal stresses when, for example, time of flight has to be measured after coupling of a cold probes to a hot object. Figure 6 presents the results of TOF measurements performed after coupling of warm probe set to a cold steel sample. Set of probes was designed to minimize its heat capacity and Invar spacing plate was used.

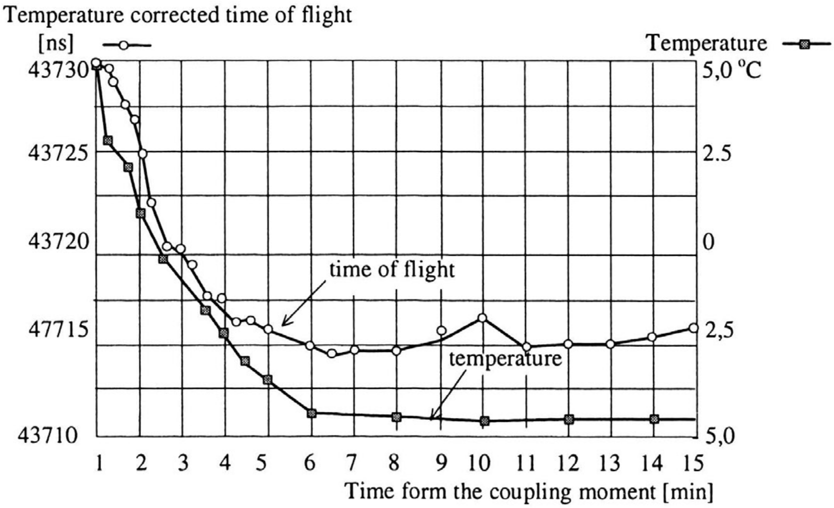

FIGURE 6. TOF changes observed after temperature stabilization. Room temperature set of probes (23°C) coupled to the cold (-4°C) steel sample.

It can be seen that TOF value is stable after 6 minutes after coupling.

4. Examples of application

Below we present the results of longitudinal stress monitoring in continuously welded rails (CWR). In CWR all segments or rails are welded together what reduces track maintenance costs and lengthens the rail life. The disadvantage of CWR are longitudinal forces observed in such a track. High compressive force, together with dynamic loads from passing trains, can lead to track buckling and derailment. Tensile forces, observed in Winter, can result in rail cracking.

Longitudinal forces in the CWR are mostly a result of thermal stress and stress due to track displacement. The last one is a result of longitudinal loads applied to the CWR by braking or accelerating trains. Longitudinal CWR displacements can also be observed when the temperature along the CWR significantly differs due to uneven sun operations. As a result of all three mentioned stress sources the rails are subjected to longitudinal forces the values of which change in time, in day-night cycle, depend on the weather, track design and on the track bed stiffness. In some places on the track, before stop signs for example, continuous rise of compressive force can be expected. Forces in each rail can be different what can lead to track buckling in lower temperature than expected.

Longitudinal stress due to the thermal expansion and train forces are on the order of ± 100 MPa only. Therefore, to be able to measure these comparatively low stresses it is necessary to select the wave exhibiting the highest elastoacoustic constants and therefore the longitudinal wave propagating along the rail, parallel to stress, is used.

The thermal force in the rail fixed to the ground (longitudinal displacement equal to zero) can be calculated as:

$$F_t = \alpha \, \Delta t \, E \, A$$

where:

F_t – thermal force in the rail,

α – thermal expansion coefficient for steel equal to $1.15 \cdot 10^{-5}$ [1/°C],

Δt – temperature change in relation to zero force temperature [°C],

$E = 2.1 \cdot 10^{-5}$ [MPa],

A – rail cross section area [mm^2].

For a typical rail, according to above formula, temperature change equal 1°C results in longitudinal stress equal to 2,5 MPa. For UIC-60 rail (cross section area 7687 mm^2) it refers to longitudinal thermal force equal to 18.6 kN. It means that in extreme climate conditions the longitudinal force changes in one UIC-60 rail can be equal to 300 tons [4].

Figure 7 presents the result of laboratory test performed on a UIC-60 rail sample subjected to tensile and compressive test. The measurements were performed with probe set for longitudinal subsurface waves coupled to the rail head side. The measuring distance L for this probe set was equal to about 300 mm.

Linear dependence TOF-force was found for both tensile and compressive stresses applied to the rail sample. This experiments shows how ultrasonic technique, assuming that the influence of the temperature on readings can be eliminated, can be used for monitoring the longitudinal force in the rail.

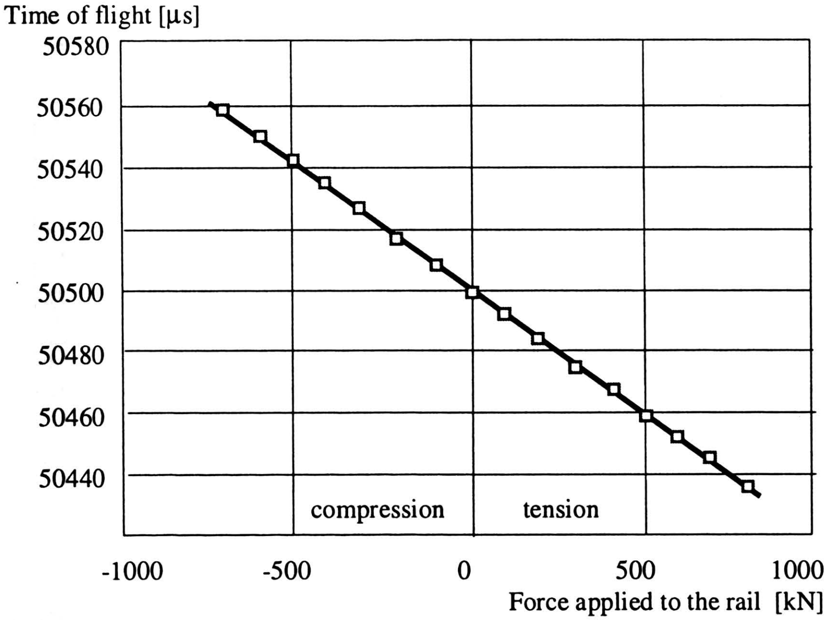

FIGURE 7. The dependence between time of flight of longitudinal subsurface wave propagated along the rail and longitudinal force applied to the rail.

In the case where for a given location on the rail TOF can be measured on external and thermal stress free rail (during track construction for example), absolute value of the force in the rail can be evaluated. Such a force is proportional to the difference between temperature corrected TOFs measured on stress free rail (calibration) and on the rail subjected to thermal or external stresses.

4.1. Measurements of the dependence thermal stress – temperature

If the rail can displace in the longitudinal direction during thermal stress build-up, stress increments will be lower than theoretical equal to 2.5 MPa/°C. Such a rail, during thermal stress build up, make small "jumps" which can be easily heard when on the track in a hot day, close to loose bolted joints for example. Below we present the are results of ultrasonic measurements performed during one day, on various tracks and showing what are stress changes resulting from 1°C rail temperature increment. Figure 8 shows thermal stress changes measured during one day on a straight, subjected to sun operation on all its length and well maintained UIC-60 CWR. It can be seen

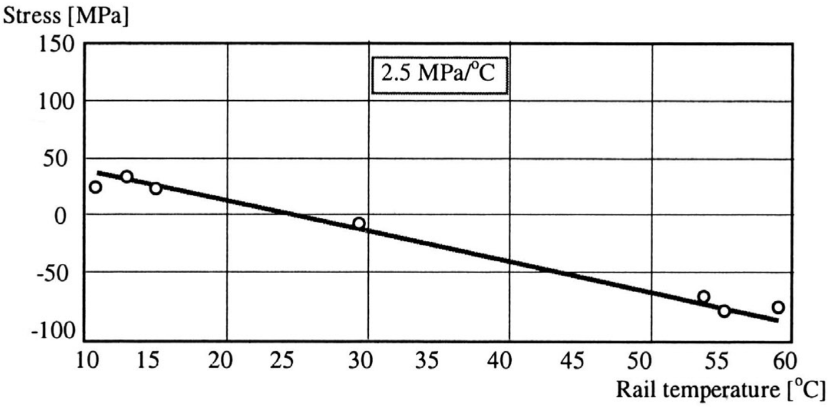

FIGURE 8. Thermal stress – rail temperature relation measured on the straight CWR.

that measured thermal stress changes are linear and very close to theoretical predictions. It means that there was no longitudinal displacement of the rail during the day temperature changes.

The next figure presents similar measurements performed on the CWR close to bolted joint which exhibited marks of rail ends displacement. During the measurement the displacement of a few millimeters in the joint was noticed. Thermal stress changes, for 1°C rail temperature change, measured in this rail were equal to 1.75 MPa.

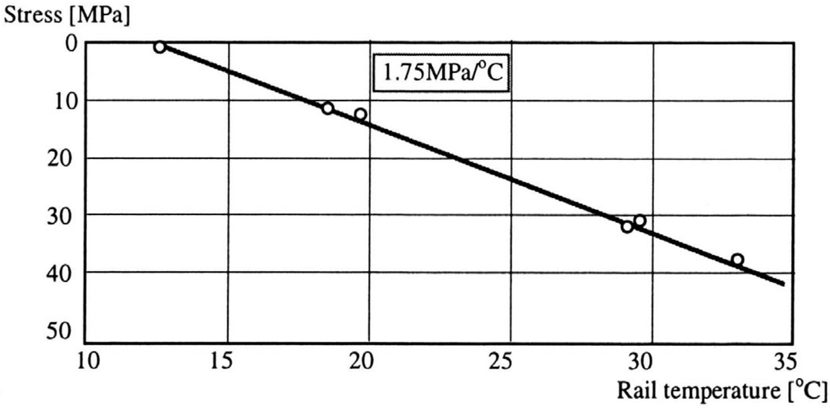

FIGURE 9. Thermal stress – rail temperature relation measured close to the loose bolted joint.

Lower MPa/°C ratio is a result of partial release of thermal stress during the period of measurement. Displacement took place in numerous small steps when the thermal stress reached higher value than the friction in the joint. It means that, depending on how quickly compressive thermal stress develops during the sun operation and depending on the friction in the joint, temperature-stress relation in the location where the rail can move may be not linear. It means also that temperature-thermal stress relation can differ along the track. Stress/temperature ration can be low close to the loose joint and can reach higher, close or equal to 2.5 MPa/°C value in some distance from the joint.

Figure 10 shows similar measurements but performed in numerous locations along the CWR partially and temporarily shadowed by trees [5]. The measurements were performed during one sunny day, starting before sunrise, when all the rails were cold after the night. Readings were taken several times during the day, on both rails of the track (rail A and rail B). The last readings were taken when the rails reached the highest temperature.

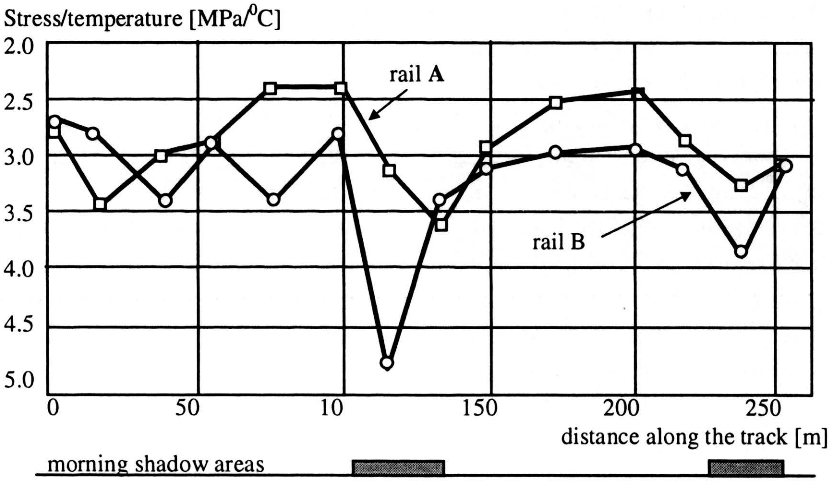

FIGURE 10. Thermal stress changes along both rails of the track subjected to uneven sun operation.

The diagram presents the distribution of thermal stress changes caused by 1°C rail temperature increment (vertical axis) along the rail (horizontal axis). In general stress-temperature ratio for this track section is higher than theoretically predicted and mean value of this ratio is equal to about 3.7 MPa/°C. The reason of such a high thermal stress increment is not explained. However, it can be noticed that minima of stress-temperature ratio are located in the same regions in both rails and these regions correspond to regions where the rails were shadowed in the morning.

High stress increments in these parts of the track can be explained by small, measured in fraction of millimeters, longitudinal rails displacements. In the morning, when parts of the track were in shadow, thermal stress built-up in the rail parts subjected to sun operation. Thermal stress caused longitudinal rail displacement towards shadowed parts, where the thermal stresses were lower. In the midday, when all length of the track was in the sun, thermal stresses started to build-up also in the regions previously in the shadow. In these regions thermal stress and stress from rail displacement summed up. It resulted with the highest stress-temperature factors for these track regions. Numerous trains passing along the track during the measurements, both passenger and freight, helped the partially compressed rails to move in the longitudinal direction.

4.2. Rail neutral temperature determination

It is assumed that at the so called neutral temperature (or zero force temperature) longitudinal force in the CWR is equal to zero. The neutral temperature of the rail is the one measured during the closure welding. Closure weld is the one closing the rail into a CWR and usually is closes a rail sector about 200-400 m long. It was observed that the rail temperature changes during construction works, depending on the weather and sun operation. If some parts of the rail section are in the shadow, their neutral temperature can be higher than those of the rail in the sun. During construction of a new track, after the last closure welding, the geometry of the track is adjusted. It means that the track is displaced, mostly in vertical and horizontal directions. All factors mentioned result in variations of the neutral temperature along the CWR sector. The aim of presented measurements was to check what are the longitudinal forces in the CWR at neutral temperature and what is the distribution of these forces along the rails.

The measurements were performed in thirteen locations on both rails of 400 m long track section [6]. The first serious of measurements was performed on the external forces free rail, lying on the ties, before it was mounted to them. It was assumed that during the first measurements there was no longitudinal, external force applied to the rail. The measurements of the second series were taken in the same locations but after fixing of the rails to the ties, welding into the CWR and track geometry regulation. Intentionally all measurements were performed for almost the same rails temperature, very close to the neutral temperature. It means that the difference between first and second readings is not due to the thermal stress but due to the forces introduced into the rails during fixing them to the ties and track geometry regulation. Thermal stress which could occur in the rails was evaluated as lower than ± 5 MPa.

The results of the measurements are presented in Fig. 11. The vertical axis of the diagram presents longitudinal stress in the rail, horizontal – the position of the measuring location along the rail. It can be seen that stresses measured in rails are not equal to zero. They are distributed in a similar way along the track in both rails and vary from -25 up to +30 MPa. It means that neutral rails temperature is not constant along the track section.

Similar distribution of longitudinal forces in both rails denotes that they were probably introduced into the CWR during track geometry regulation, when both rails fixed to the ties were lifted and displaced simultaneously.

The measurements presented in Fig. 11 were performed in July. After 13 months of track service, in October next year, the measurements were repeated with the rail A. The results are presented in Fig. 12 where dashed line shows the result of measurements performed in July on new track. The average temperature of the rail in October was about 15°C lower than in July. Lower rail temperature resulted in higher tensile stresses in the rail. The averaged stress difference between July and October measurements is 28 MPa. Similar stress distribution along the rail can be observed with a minimum of stress at the beginning of the section, maximum for the locations 80-120 m and the second minimum at the location 190 m.

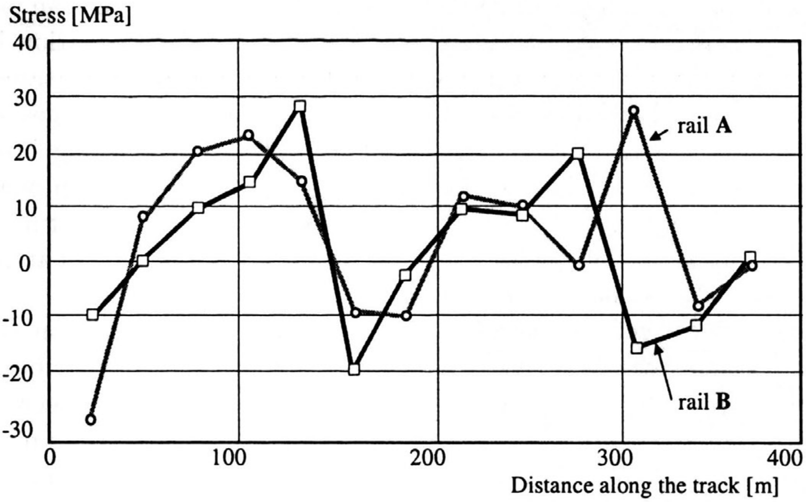

FIGURE 11. Longitudinal stress distribution along the 400 m long segment of CWR at "neutral temperature".

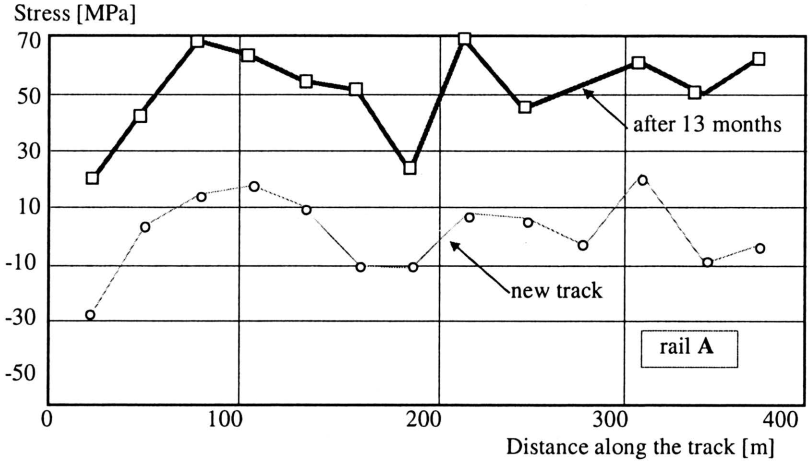

FIGURE 12. Longitudinal stress distribution along the 400 m long segment of CWR measured after 13 months of track service.

5. Conclusions

Longitudinal subsurface wave proved to be sensitive to stress and provides valuable information concerning changes of longitudinal force in the CWR. The data presented are not compared with other nondestructive method because ultrasonic technique seems to be today the only one which can be used on various rails, in field conditions, without special rail preparation before the measurement. For example, to compare data obtained during track construction with resistance strain gauges, more than 200 strain gauges should be glued to the rail, all of them should be covered with strong boxes to survive construction works and should be in service for more than one year.

These measurements showed that the exact zero force temperature is not always known and can vary along the rail. Force gradient in the rail at neutral temperature can be high – up to 300 kN per 100 m.

The measurements of thermal stress – rail temperature relation showed that stress increment depends on track condition and on the distribution of the rail temperature along the track. Higher and lower than theoretically predicted thermal stress changes were measured. Long time stress monitoring showed that thermal stress-temperature relation seems to be a constant feature for a given CWR.

Various stress-temperature dependencies, expressed in MPa/°C, were observed during one day cycle. One can expect that these dependencies can vary in time and can change with weather (sunny or cloudy day). So the distribution of longitudinal force in the rail can change in time. It means that to obtain the important for railroad companies information about the maximum compressive force for a given track location (or to find location where compressive force rises in long term period), stress readings should be repeated in the same rail temperature. Readings taken in various rail temperatures can show high scatter resulting from day-night temperature changes and can make difficult to distinguish locations where constant and dangerous compressive stress increase takes place.

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