EFFECT OF THE WIDMANNSTÄTTEN STRUCTURE IN THE RAILWAY AXLES ON ATTENUATION OF ULTRASOUND

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Abstract
Measurement of attenuation of the ultrasonic waves in the Widmannstätten ferrite-pearlitic structure showed the factors influencing passage of ultrasound through materials used for manufacture of railway axles. By implementing the hypothetic mean grain size of the structure the theory of Rayleigh’s scatter is interpreted in practical utilization by checking the structure in as heat-treated state.

Key words Non-destructive Testing, Ultrasonic Testing, Ultrasonic Attenuation, Widmannstätten Structure, Railway Axle

1. INTRODUCTION

The railway axles are being subjected more and more to ultrasonic examination both at the acceptance tests in the producer’s works and in full-scale operation, namely, on the occasion of regular inspection performed for ensuring safe operation. The principal precondition for successful procedure at ultrasonic testing is reasonable ultrasonic permeability that varies with numerous physical and geometrical parameters. The geometry of an axle and the applied steel grade are governed by the International Railway Union /UIC and ISO/, whereby the producer is allowed to change only some metallurgical factors that influence the structure of material. In view of the above-cited requirements and due especially to improvement of the safety factor, the effect of the Widmannstätten structure on attenuation of the ultrasonic waves has been investigated; in this respect it is worth noting that the Widmannstätten structure encounters frequently in the axle due to incorrect heat treatment. This study deals with the mechanism of passage of the ultrasonic waves through carbon steel, having the Widmannstätten ferrite-pearlitic structure, used for manufacture of the railway axles.

2. ATTENUATION OF THE ULTRASONIC WAVES

If an ultrasonic wave is passing through any material, its energy is getting lost and its acoustic pressure is falling down. The drop in the acoustic pressure of a wave in relation with the material properties is called attenuation of the ultrasonic waves. Such attenuation in metals is caused by the absorption loss as a result of intrinsic friction, the hysteresis losses, the plastic creep, the relaxation and thermal phenomena; moreover, it encounters due to loss by
scattering. The magnitude of attenuation is considered by means of the coefficient of attenuation $\alpha$ consisting of two components [1]:

$$\alpha = \alpha_a + \alpha_s = a_1 \psi(f) + a_2 \xi(f)$$  \hspace{1cm} (1)

where

- $\alpha_a$ is the absorbing coefficient of attenuation,
- $\alpha_s$ the scattering coefficient of attenuation,
- $a_1$ the loss number referring to the loss by absorption,
- $a_2$ the loss number referring to the loss by scatter and
- $f$ the frequency of ultrasonic wave

The two attenuating terms of Eq (1) are the function of frequency.

The ratio of mean grain size $\bar{D}$ and the length of ultrasonic wave $\lambda$ govern both the applicability of either loss and the dependence of the scatter loss on the frequency.

The scatter of the ultrasonic waves is obvious speciality from metals that are not completely homogeneous or isotropic. As the loss by scatter, apart from the frequency dependence, varies with the elastic constants and the structural parameters of the material, then it is possible, by means of the value of the coefficient of attenuation, to perform evaluation of the structure of metals. The effect of scatter of the ultrasonic waves on the grains of structure is evident from the mutual ratio of the mean grain size $D$ and the length of ultrasonic wave. For evaluation of the structure, the most suitable zone is that of the Rayleigh scatter in which the wave length is many times greater than the mean grain diameter $/\lambda > \bar{D}/$. The attenuation loss in the zone of the Rayleigh scatter varies proportionally with the cube of the mean grain diameter and with the fourth power of the frequency:

$$\alpha_s \approx \bar{D}^3 \cdot f^4$$  \hspace{1cm} (2)

For a wave length compatible with the mean grain diameter $/\lambda \approx \bar{D}/$ the zone of the Rayleigh scatter is connected with the zone of stochastic scatter in which the loss is growing proportionally with the mean grain size:

$$\alpha_s \approx \bar{D} \cdot f^2$$  \hspace{1cm} (3)

The narrow range of stochastic scatter is passing into the zone of diffusive scatter that starts with $\lambda < \bar{D}$. In the zone of diffusive scatter the loss is independent of frequency and varies inversely with the mean grain diameter:

$$\alpha_s \approx \bar{D}^{-1}$$  \hspace{1cm} (4)

In the case of high frequencies in the zone of $\lambda < \bar{D}$, the ultrasound is absorbed in each grain and simultaneously, ultrasound is reflected, if various admixtures have precipitated at the grain boundaries. This zone can be called as the heterogeneous scatter:

$$\alpha_s \approx \bar{D}^{-1} \cdot R \cdot f^2$$  \hspace{1cm} (5)

($R$ - mean reflection factor at the grain boundaries).
3. THE WIDMANNSTÄTTEN STRUCTURE

The Widmannstätten structure, called by A. Widmannstätten, who has discovered it with a meteorite / i.e. Fe-Ni alloy/ and described it already in 1807, originates at rapid cooling of a carbon steel in which, by reheating to a high temperature, the grain size is growing. The ferrite precipitates not only at the boundaries of the austenite grains, but even inside the individual crystals of austenite in the crystallographic planes occupied by atoms of a high density. Precipitation takes place in form of needles and/or platelets. There are originating the ferritic arrows here, to form the characteristic Widmannstätten patterns. This mode of precipitation is more expressive with a higher cooling speed and with a coarser primary grain. The Widmannstätten structure originates especially with less than 0.4 % C in steel. With low C-content and with a coarse-grained austenite, the Widmannstätten structure may originate even with a rather slow cooling rate, say 30 to 100° C per min. In a higher C-steel the superheating is associated as a rule with a coarse ferrite network in the matrix of fine-grained pearlite. The network indicates the size of the original grains of austenite. At normal grain size the Widmannstätten structure is liable to crinimate only with high cooling rates within a narrow zone lying approximately between 0,15 and 0.35 % C and displacing towards a lower C-content with elevated cooling rate. In the case of large grains the Widmannstätten structure starts to originate already with substantially lower cooling rates and simultaneously, the zone of occurrence of that structure is enlarging towards a higher C-content. In conformity with studies published elsewhere [2, 3] the morphologic classification of the Widmannstätten structure can be made as follows:

3.1. The Widmannstätten platelets are plate-like configurations encountering as needles in a metallographic thin section

3.1.1 The primary Widmannstätten platelets are nucleating at the austenitic-grain boundaries and are growing into grains (Fig. 1)

3.1.2 The secondary Widmannstätten platelets are developed of crystals of the same phase, but of different morphology, as a rule from the allotriomorphous particles at the grain boundaries and are growing into grains (Fig. 2)

3.1.2 The intergranular Widmannstätten platelets originate, immediately in the centre of the austenitic grains (Fig. 3)

3.2. The Widmannstätten saw-tooth configurations are characterized by a triangular sectional area in the thin-section plane

3.2.1. The primary Widmannstätten saw-tooth configurations are growing immediately from the grain boundaries (Fig. 4)

3.2.2 The secondary Widmannstätten saw-tooth configurations are developed of the allotriomorphous particles ((Fig. 5)

The primary platelets are nucleating and growing directly from the grain boundaries of austenite. They occurrence is limited to the boundaries among the grains of austenite with a small difference in orientation. Such boundaries are small in number and thus, one comes rarely across such primary platelets. The majority of austenite boundaries reveal a not-arranged structure and thus, the allotriomorphous particles are easily originating here, whereby the secondary Widmannstätten platelets may develop of them. The secondary platelets are growing out from the allotriomorphous configurations at the grain boundaries of the saw-tooth configurations, especially with steels containing less than 0.3 – 0.4 % C and with larger austenite grains at the medium temperatures of reaction. The intergranular platelets are originating almost exclusively in the coarse-grained steels by nucleation at the
non-metallic inclusions. The low temperature of transformation, limiting the kinetic advantage of formation of a configuration at the grain boundaries and the low C-content, prolonging the time required pearlite, promote origination of the intergranular platelets.

The stability of the Widmannstätten platelets is considerable. They do not spheroid, when annealed for a long period. Just on the contrary, a longer dwell at high temperatures brings about the particle to take the shape of more perfect platelets. Their density is decreasing due to dissolution of platelets less perfect in shape, while the thickness of platelets perfect in shape is increasing. If the structure has the Widmannstätten morphology, then it can hardly be phercidized by annealing without recrystallization.

Fig. 1: The Widmannstätten structure - type 1a – of the primary Widmannstätten plates (etched with nital, x 100)
Fig. 2: The Widmannstätten structure – type 1b – the secondary Widmannstätten plates (etched with nital, x 100)

Fig. 3: The Widmannstätten structure – type 1c – of the intergranular Widmannstätten plates (etched with nital, x 100)
Fig. 4: The Widmannstätten structure – 2a – the primary Widmannstätten saw-tooth configurations (etched with nital, x 100)

Fig. 5: The Widmannstätten structure – type 2b – the secondary Widmannstätten saw-tooth configurations (etched with nital, x 100)
4. EXPERIMENTAL METHOD AND RESULTS.

To determine the attenuation in ferrite-pearlitic steel we have applied the mode of investigation having been used for already the second decade at examination of attenuation of the ultrasonic waves [4-6]. This is due to the well-proven mode with reasonable sensitivity for our purposes and even the results can be used for the sake of comparison with the previous experiments.

The attenuation of ultrasound in material for the railway axles has been measured by the pulse reflection method with application of the contact acoustic linkage. The tests were run with the ultrasonic pulse detectors UID-S manufactured by the Laboratory Devices of Chotutice /Czechoslovakia/ and USIP 11 of Krautkrämer Co. /Germany/ and the probes with frequency of 2 to 12 MHz with effective converter dia. of 18 to 24 mm were applied here. The wiring of device was made over a voltage regulator. The convertors were made of quartz and of piezoceramic. To achieve constant acoustic linkage at the samples the probe was attached in special fixtures to ensure uniform pressure. The engine oil was applied as the connecting and linking medium. To provide a uniform film of oil under the probe, the measurements were repeated in 3-min. intervals after setting-up the probe with the fixture for sample. Samples of exact thickness of 50 and 25 mm were prepared for measurement of both the coefficient of attenuation and the reflection factor. The chemical composition of the applied materials (0.25 to 0.33 % C; 0.75 to 1.00% Mn; 0.25 to 0.40% Si; 0.04 % P max. and 0.04 % S max) was in conformity with the prescriptions of the International Railway Union /UIC/.

To determine the behaviour of attenuation with the ultrasonic waves in the Widmannstätten ferrite-pearlitic structure of material, used for manufacture of the railway axles, we have chosen various modes of heat treatment so as to reach all sorts of the Widmannstätten structure. The reheating temperature was selected so as to lie within 1100° and 1300° C, the holding time was 4 hours and the cooling process was run in free air and in air flow.

The structure of railway axles, when reasonably normalized, is ferrite-pearlitic with mean grain size $D = 0.022$ to 0.036 mm, which refers to the degree of 7-8 by the ASTM-standard, over the entire sectional area. By the selected modes of heat treatment we have reached various sorts of the Widmannstätten structure with the hypothetic mean grain dia. of $D_{h} = 0.088$ to 0.25 mm.

To determine the coefficient of attenuation samples 50 mm thick were applied, whereby their surface parallel and surface quality were kept constant. The attenuation has been measured from the difference of amplitudes of the first and the second terminal echo at frequencies within 2 and 12 MHz. For calculation of the coefficient of attenuation we have used special equation providing the loss due to the geometry of the ultrasonic field and the reflection losses.

[7]

To determine the losses in scatter all the samples were subjected to a profound investigation with full sensitivity of an ultrasonic detector. The probes were consecutively switched-on with increasing frequency till "grass" appeared at the screen, as a totality of echoes due to the structure, between the starting pulse and the first terminal echo. At all samples the scatter appeared remarkably already with connection of the probe with the frequency of 2 MHz and 4 MHz (Fig. 6, 7, 8). This simple mode of investigation of scatter is based on the fact that the reflections from the structure are best indicated between the starting pulse and the first terminal echo. Investigation into scatter is associated with occurrence of "grass" that is reasonably indicated when moving the probe alternatively to the left and right-hand side at the surface. The echoes from structure take in the screen different positions down the height. The "grass" is also indicated between the second and the third terminal echo, however, the
interference of waves appears simultaneously at the screen; that interference is not so unequivocal for indication of scatter as it should be between the starting pulse and the first terminal echo.

Fig. 6: The oscillogrammes of investigation into loss by scatter of a sample with the Widmannstätten structure $D = 0.088$ mm with a frequency of 2 and 4 MHz
Fig. 7: The oscillographmes of investigation into loss by scatter of a sample with the Widmannstätten structure $Dh=0.177$ mm with a frequency of 2 and 4 MHz
Fig 8: The oscillogrammes of investigation into loss by scatter of a sample with the Widmannstätten structure $D = 0.250$ mm with a frequency of 2 and 4 MHz
5. DISCUSSION

The Widmannstätten structure originates in steels for a variety of reasons; its feature is ferrite precipitated in form of needles or of platelets. The metallographic examinations showed the generally oriented plate-like configurations of the ferrite grains, when subjected to static and/or dynamic shock loading, to encounter as the fictive equiaxial grains whose hypothetic mean diameter would occur between the mean length and the mean width of the plate-like and/or needle-like configurations. This knowledge consists in the possible replacement of the plate-like grains by the equiaxial ones, at which the mean diameter can be determined on the basis of approximation of the area of irregular plate-like and/or needle-like grains to the fictive equalled grains.

The primary Widmannstätten structure occurs in a product after casting, if the relevant conditions for its origination are fulfilled. It encounters in the railway axles in a reduced amount in sites with the least stage of material forging, i.e. in the seating sites.

The secondary Widmannstätten structure occurs in the railway-axle material after improper heat treatment. The grain size of the Widmannstätten structure should not be characterized by the original austenitic grain revealing the network structure of ferrite. Therefore, the mean grain size is interpreted as the fictive size of the secondary grains of the Widmannstätten structure.

The plate-like form of the structural components cannot be characterized by a single size. The effect of such configurations on penetration of an ultrasonic beam will vary, apart from the sizes, with their spatial orientation and with mutual arrangement. The plate-like configurations in the statistical concept are considered to act similarly as the hypothetic equiaxial grains the size of which will occur between the mean thickness and length of the Widmannstätten platelets. We assume this size to be characterized by the mean size of the secondary grain determined graphically. As it is an abstract magnitude, from the viewpoint of analysis made into attenuation of ultrasound, it is called the fictive grain size of the Widmannstätten structure.

If compared with the fine-grained polyedric structure, the Widmannstätten structure reveals substantially greater attenuation of the ultrasonic waves. Nevertheless, somewhat more pronounced enhancement of attenuation of ultrasound, in comparison with the Widmannstätten structure, occurs with the coarse-grained polyedric ferrite-pearlitic structure with mean grain size. In this respect and in view of the above-cited experiments one can discriminate the two structures. This is of utmost practical significance in the process of heat treatment and for expedition of axles at the acceptance testing. The occurrence of the Widmannstätten structure in the axles up to a certain hypothetic grain size need not be the reason for improper melt the axles are made of, but, on the contrary, the occurrence of a coarse-grained polyedric structure with continuous ferritic network at the grain boundaries is always the reason for improper mechanical properties. Thus, at determination of the Widmannstätten structure, when measuring the attenuation in the structure of axles, satisfactory properties can be achieved by reasonable heat treatment, instead of rejecting the heat, as performed hitherto.

In line with evaluation of the measured results of attenuation of the carbon steels used for manufacture of railway axles with the Widmannstätten ferrite-pearlitic structure, the attenuation of the ultrasonic waves in the Rayleigh zone varies with the following factors:

5.1 The fictive size of the secondary grain expressed by the hypothetic mean grain diameter $D_h$. The scatter of ultrasound is widening with increasing fictive size of the
secondary grain, with its cube like to the polyedric structure of steel. Small changes in the grain size are associated with large variations in the coefficient of attenuation.

5.2 The proportion of pseudo-pearlitic grains owing to the as-normalized state expressed in percents of increase. The attenuation of the ultrasonic waves in material, the railway axles are made-of, is rising with increasing proportion of ferrite in the structure. However, the fictive grain size is the primary reason for enhancement of the attenuation.

5.3 The fourth power of the working frequency. Like to other structures of the polycrystalline materials, the attenuation is rising with increasing frequency even in the Widmannstätten ferrite-pearlitic structure.

5.4 The square of the elastic anisotropy

5.5 The mean interlamellar distance of pearlite. The attenuation of the ultrasonic waves in steels, used for manufacture of railway axles, with pearlite in structure is rising with growing mean interlamellar distance with the same mean size of the hypothetic grains. All the sorts of the Widmannstätten structure reveal the distance of the cementite lamellae of pearlite to be greater than the common polyedric ferrite-pearlite structure of axles. Therefore, the effect of that parameter on the loss by scatter may not be neglected; as it was in the case of fine-grained structure.

5.6 Factor characterizing the grain boundaries expressed by the percentage and distribution of the alloying elements and/or impurities at the grain boundaries, by the length and thickness of the ferrite network surrounding the pearlitic blocks.

5.7 Factor characterizing the substructure of grains. One has to assume that the passage of ultrasound over a grain would be influenced even by occurrence of twins and by the content and/or distribution of the alloying elements or impurities inside of grains. This factor varies above all with the micro cleanness of steel and the mode of solidification and of heat treatment.

5.8 The stage of forging. This factor is characterized by grain form that is the outcome of both mechanical and heat treatment of a product. By metal forming the attenuation by scatter is changing more quickly than would refer to the achieved grain refinement. Because of the occurrence of the primary Widmannstätten structure in the axles subjected to insufficient heat treatment, the effect of the thermal history of a product on the scatter with that structure is negligible.

On the basis of the available experimental results and by analysing them, the scatter of the ultrasonic energy when passing through the Widmannstätten ferrite-pearlitic structure of the railway axles, can be written, in the zone of the Rayleigh scatter, in terms of the following approximating function:

\[ \alpha_S = \Phi \left( f^4, \frac{\bar{D}h^3}{\mu^2}, P_p, \bar{S}, B, G_i, F, K \right) \]  \hspace{1cm} (6)

where

- \( f \) is frequency
- \( \bar{D}h \) - the hypothetic mean grain diameter of the Widmannstätten structure
- \( \mu \) - the elastic anisotropy
- \( P_p \) - the proportion of the grains of pseudopearlite
6. CONCLUSION

On the basis of the analysis and experiments it can be said: Occurrence of the Widmannstätten structure in railway axles is possible. The least frequency for ascertaining is 4 MHz. Till now; however, the individual sorts of the Widmannstätten structure cannot be distinguished.

The test results and the relevant analysis into the available results provided full definition of the qualitative structural characteristic of the axles with the Widmannstätten structure; they contributed substantially in throwing more light into the unknown phenomena of the theory of propagation of the ultrasonic waves in the zone of the Rayleigh scatter.

7. REFERENCES

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