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The Sound Velocity in an Alloy Steel at High-Temperature Conditions

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Abstract In this article, results of the measurements of the longitudinal and transverse wave velocities in steel have been presented as a function of temperature. The conducted tests involved two types of corrosion-resistant steel: X14CrMoS17 and X90CrMoV18. The tests were based on the ultrasonic wave transition method using transducers operating at 5.4 MHz for the longitudinal wave and 3.2 MHz for the transverse wave. Measurements of the wave velocity were taken at temperatures from 293 K to 1,173 K. The longitudinal wave velocity in X14CrMoS17 steel varies from 6,002 $\text{m}\cdot\text{s}^{-1}$ at 293 K to 5,115 $\text{m}\cdot\text{s}^{-1}$ at 1,173 K, while the velocity in the X90CrMoV18 steel changes from 5,975 $\text{m}\cdot\text{s}^{-1}$ at 293 K to 5,381 $\text{m}\cdot\text{s}^{-1}$ at 1,023 K. The transverse wave velocities vary from 3,239 $\text{m}\cdot\text{s}^{-1}$ at 293 K to 2,449 $\text{m}\cdot\text{s}^{-1}$ at 1,173 K in X14CrMoS17 steel, and from 3,251 $\text{m}\cdot\text{s}^{-1}$ at 293 K to 2,478 $\text{m}\cdot\text{s}^{-1}$ at 1,173 K in X90CrMoV18 steel. The obtained results represented a basis for determination of the properties of the steels examined, such as Young's modulus, Poisson's ratio, Helmholtz's modulus of volume elasticity, or Lame's constants. The results have been verified by comparing the Young's modulus obtained with the values corresponding to individual steel grades and temperatures (293 K, 373 K, 473 K, 573 K, and 673 K) obtained by traditional methods of measuring mechanical properties as provided in PN-EN 10088-1:2007. The results of this comparison confirmed the reliability of the conducted investigation.

Keywords High temperature · Sound velocity · Steel

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1 Introduction

The development of materials engineering in recent decades has made it possible to find many new materials that have allowed improvement in the performance of many existing processes. This relates, for instance, to the structure of power transducers in which piezoelectric ceramics have replaced crystals (such as quartz crystals) or magnetostrictive materials used previously.

The use of such technologies as high-temperature piezoelectric ceramics allows the power head to work more efficiently compared to magnetostrictive transducers for steel sonication used previously under laboratory conditions [1–5]. Research concerning the shaping of cast steel structures using sound waves has been carried out at the Department of Metallurgy of the Silesian University of Technology.

The tests require a design and structure for a power head which will be immersed in liquid steel at a temperature of approx. 1,873 K. In order to design this analytical system correctly, one needs to know the acoustic properties of the materials used to build it under elevated temperature conditions.

The results shown in this article were used to develop an acoustic head for liquid steel sonication [6].

2 Testing Methodology

The measuring system shown in Fig. 1 was built to determine the change of velocity of the sound wave in steel as a function of temperature. The sound wave velocity was measured using the transition method [7]. A computer was used in the analysis equipped with an oscilloscope card, including an integrated pulse emitter. A single channel transmitter/receiver system was implemented on the card with two switchable inputs, allowing the card to operate with a single ultrasonic head in the transmission/receiving (PE) mode, as well as with two heads, one being a transmitter and the other—a receiver (TT). According to the card manufacturer, the measurement uncertainty for the signal course time is less than 1 ns. The uncertainty of the measurement of the steel sample velocity by means of a defectoscope card depends generally on the measuring accuracy of the sample length. Calculations show that the relative uncertainty is between 3.5 % and 5.2 %.

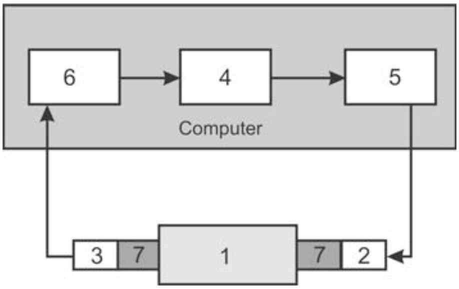

Fig. 1 Measuring system: 1—sample, 2—ultrasonic transducer (transmitter), 3—ultrasonic transducer (receiver), 4—computer with oscilloscope card, 5—impulse generator, 6— amplifier, 7—high-temperature ceramic (delay line)

Table 1 Chemical composition of the steel types analyzed

Steel	Composition (mass%)									
	C	Mn	Si	P	S	Cr	Ni	V	Mo	Cu
X14CrMoS17	0.16	0.71	0.27	0.024	0.205	15.9	0.17	–	0.27	0.05
X90CrMoV18	0.9	0.78	0.45	0.031	0.010	17.5	0.25	0.112	1.06	0.12

In order to measure the sound wave velocity as a function of temperature in the range of 293 K to 1,173 K, transducers used during the tests needed to be modified compared to traditional transducers. In order to do this, high-temperature ceramic delay line transducers were designed and built. The ceramics attached to the transducers caused additional propagating wave reflections, it was therefore necessary to adjust the standard defectoscope card software. The reliability of the designed measurement system was verified according to measurements performed at a temperature of 293 K with delay line transducers and standard ultrasonic transducers. It has been determined that for the velocity of a longitudinal wave, the difference is $12\,\mathrm{m}\cdot\mathrm{s}^{-1}$ which constitutes 0.20 %, whereas the same difference for a transverse wave comes to $3\,\mathrm{m}\cdot\mathrm{s}^{-1}$ which corresponds to 0.09 %. During the tests, ultrasonic transducers of operating frequencies of 5 MHz (longitudinal wave) and 3 MHz (transverse wave) were used.

Two steel grades were selected for the analysis, and their chemical compositions are shown in Table 1. The samples had the following geometrical dimensions: diameter —60 mm to 65 mm, height —65 mm to 95 mm. The samples were heated through an in-chamber furnace, and then their temperature was measured by means of a pyrometer. The temperature measuring error was 5 K.

Ten measurements of the sound wave propagation velocity were performed for each temperature at three measurement points.

3 Test Results

The measurement results obtained for the propagation velocity of the longitudinal and transverse acoustic waves in the steels being examined are provided in Tables 2 and 3. One sample of X14CrMoS17 grade steel and two samples of X90CrMoV18 grade steel (marked as A and B) were tested. The tables include average measurement values for the individual temperatures and the standard deviation for every temperature.

The measurements performed made it possible to determine the trend of changes in the sound speed of wave propagation in the analyzed steel grades at temperatures ranging from 293 K to 1,173 K. The values of the coefficients of polynomials fitted to the experimental data are presented in Table 4. The results obtained for steel grade X14CrMoS17 are shown in Figs. 2 and 3, and for X90CrMoV18 steel—in Figs. 4 and 5. Owing to high signal interferences, the longitudinal wave velocity measurements in X90CrMoV18 steel samples were stopped at a temperature of 1,023 K. Such a situation was caused by an earlier mathematical simulation based on the example of the X14CrMoS17 steel which implied that the differences in the results obtained were:

Table 2 Acoustic wave propagation velocity in the X14CrMoS17 steel

Longitudinal wave				Transverse wave			
Temperature (K)	Wave velocity ($m \cdot s^{-1}$)	Standard deviation ($m \cdot s^{-1}$)	Number of measurements	Temperature (K)	Wave velocity ($m \cdot s^{-1}$)	Standard deviation ($m \cdot s^{-1}$)	Number of measurements
293	5,955	2.43	30	293	3,243	2.94	30
332	5,990	59.13	30	329	3,218	29.43	30
365	5,963	2.48	30	368	3,204	21.45	30
389	5,942	60.62	29	444	3,188	15.66	30
442	5,840	11.59	30	519	2,147	21.03	30
487	5,787	9.07	30	618	3,088	13.90	30
562	5,817	4.73	30	702	2,976	33.14	30
630	5,756	10.22	27	809	2,895	5.25	30
736	5,661	14.94	30	885	2,774	18.03	30
806	5,502	17.41	30	1,037	2,667	56.33	30
895	5,406	39.41	30	1,163	2,410	37.06	27
1,007	5,233	18.74	30				
1,156	5,240	55.30	20				

Table 3 Acoustic wave propagation velocity in the X90CrMoV18 steel

Longitudinal wave				Transverse wave			
Temperature (K)	Wave velocity ($m \cdot s^{-1}$)	Standard deviation ($m \cdot s^{-1}$)	Number of measurements	Temperature (K)	Wave velocity ($m \cdot s^{-1}$)	Standard deviation ($m \cdot s^{-1}$)	Number of measurements
Sample A							
293	5,988	3.86	30	293	3,295	2.57	30
328	5,961	3.72	30	323	3,257	13.89	30
371	5,925	5.99	30	366	3,231	27.05	30
403	5,981	8.44	29	462	3,210	20.18	30
437	5,881	5.43	30	530	3,181	4.20	30
540	5,839	13.27	30	671	3,092	5.28	30
561	5,855	10.21	30	705	3,070	3.33	32
628	5,809	12.07	30	831	3,013	10.19	30
756	5,700	15.21	30	933	2,901	20.64	30
805	5,624	19.25	30	983	2,809	44.19	40
917	5,468	28.89	30	1,065	2,586	122.23	30
1,027	5,355	34.68	30	1,164	2,515	21.72	9
Sample B							
293	5,978	20.34	30	293	3,267	23.29	30
332	5,986	25.86	30	318	3,242	25.73	30

Table 3 continued

Longitudinal wave				Transverse wave			
Temperature (K)	Wave velocity $(\mathrm{m \cdot s^{-1}})$	Standard deviation $(\mathrm{m \cdot s^{-1}})$	Number of measurements	Temperature (K)	Wave velocity $(\mathrm{m \cdot s^{-1}})$	Standard deviation $(\mathrm{m \cdot s^{-1}})$	Number of measurements
381	5,903	5.27	30	362	3,228	24.93	30
393	5,943	15.92	30	446	3,199	13.89	30
417	5,886	11.05	30	527	3,146	18.41	30
511	5,790	13.93	28	642	3,086	2.06	30
572	5,813	21.35	28	706	3,019	12.84	30
630	5,805	28.68	30	800	2,998	9.45	30
719	5,677	7.37	30	912	2,908	28.49	30
819	5,632	33.57	30	993	2,837	31.05	30
894	5,514	13.18	30	1,064	2,638	38.69	30
1,023	5,390	50.34	27				

Table 4 Coefficients of polynomials $v_{\mathrm{L \cdot T}} = AT^2 + BT + \mathrm{C}$ which show the velocity change tendency of the acoustic wave propagation as a function of the temperature in investigated steel

	Coefficients		
	A	B	C
Steel X14CrMoS17			
Longitudinal wave	−0.00021	−0.73	6,230
Transverse wave	−0.00072	0.15	3,258
Steel X90CrMoV18			
Longitudinal wave	−0.00065	−0.016	6,032
Transverse wave	−0.00092	0.41	3,203

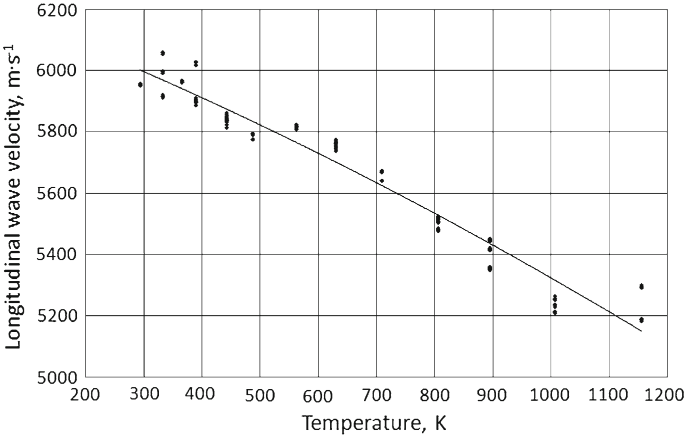

Fig. 2 Longitudinal wave velocity in X14CrMoS17 steel

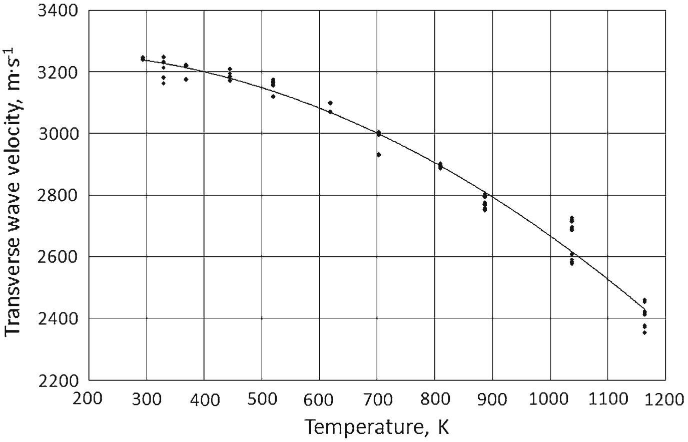

Fig. 3 Transverse wave velocity in X14CrMoS17 steel

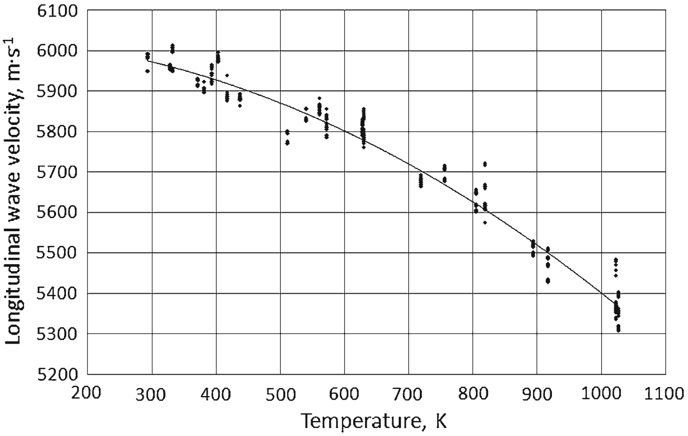

Fig. 4 Longitudinal wave velocity in X90CrMoV18 steel

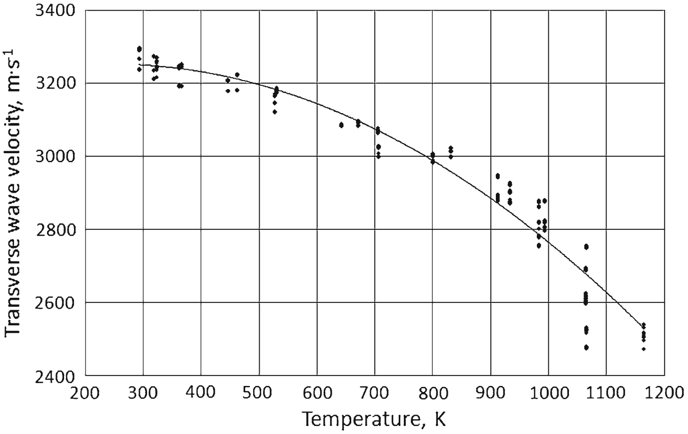

Fig. 5 Transverse wave velocity in X90CrMoV18 steel

- for the longitudinal wave: at a temperature of 332 K—2.33 $\text{m} \cdot \text{s}^{-1}$, at a temperature of 630 K—19.40 $\text{m} \cdot \text{s}^{-1}$, and at a temperature of 1,156 K— 45.23 $\text{m} \cdot \text{s}^{-1}$,
- for the transverse wave: at a temperature of 329 K—1.16 $\text{m} \cdot \text{s}^{-1}$, at a temperature of 618 K—10.04 $\text{m} \cdot \text{s}^{-1}$, and at a temperature of 1,163 K—20.97 $\text{m} \cdot \text{s}^{-1}$.

The obtained results are consistent with literature data [8].

The linear dilatation of the examined materials was not taken into account during the tests. This was determined by the mathematical analysis performed earlier, showing that the impact of that parameter on the result was slight. It was expected that the potential difference in the result was less than the admissible measurement error defined in PN EN 27963.

The results that were obtained could be used to determine the change of strength parameters as a function of temperature. The following functions were used to calculate the modulus of elasticity E, the modulus of rigidity G, the modulus of volume elasticity B, Poisson's ratio υ, and Lame's constants λ and μ [9]:

$$E = \frac{\rho v_{\mathrm{T}}^2 \left(3v_{\mathrm{L}}^2 - 4v_{\mathrm{T}}^2\right)}{v_{\mathrm{L}}^2 - v_{\mathrm{T}}^2} \tag{1}$$

$$\upsilon = \frac{v_{\mathrm{L}}^2 - 2v_{\mathrm{T}}^2}{2\left(v_{\mathrm{L}}^2 - v_{\mathrm{T}}^2\right)} \tag{2}$$

$$G = \frac{E}{2\,(1+\upsilon)} \tag{3}$$

$$B = \frac{E}{3\,(1-2\upsilon)} \tag{4}$$

$$\mu = G \tag{5}$$

$$\lambda = \frac{E\upsilon}{(1-2\upsilon)\,(1+\upsilon)} \tag{6}$$

where ρ is the density, v_{L} is the longitudinal wave velocity, and v_{T} is the transverse wave velocity.

For the sake of determination of the mechanical parameters of the samples tested, variations of the steel density at the individual temperatures were taken into consideration. The density variation as a function of temperature was calculated based on the following equation that included the cubical expansion of steel at individual temperatures:

$$\rho_{\mathrm{T}} = \frac{m}{v_0\,(1+3\alpha\Delta T)} \tag{7}$$

where m is the mass, v is the volume at 293 K, α is the coefficient of thermal expansion ($12 \times 10^{-6}\,\text{K}^{-1}$ for steel), and ΔT is the change in temperature. The results obtained for the resistance parameters are provided in Figs. 6 and 7.

In the case of X14CrMoS17 steel, all the strength coefficients decrease with increasing temperature. It was observed that λ decreased for X90CrMoV18 steel, reaching a minimum at 773 K, and increasing slightly after that. It should be pointed

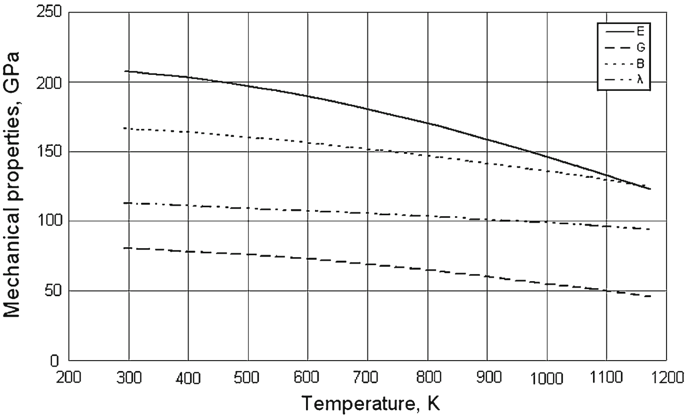

Fig. 6 Mechanical properties of X14CrMoS17 steel determined using the acoustic method

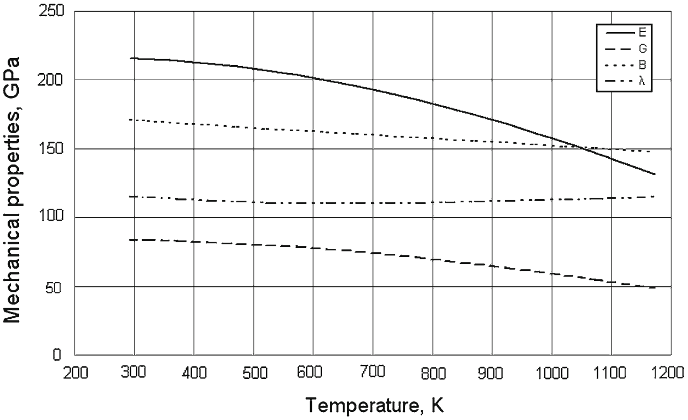

Fig. 7 Mechanical properties of X90CrMoV18 steel determined using the acoustic method

out, however, that the value of λ falls within the range of 110 GPa to 115 GPa. The other coefficients decrease.

The reliability of the results obtained was verified by comparing the determined values of the modulus of elasticity E with the data in PN-EN 10088-1:2007 [10]. For the steels that were analyzed, the E values were reported for the 297 K to 673 K temperature range. The following differences between the results and PN-EN 10088-1:2007 were observed:

- for X14CrMoS17 steel: 6 GPa to 8 GPa, i.e., a difference of 3 % to 4 %,
- for X90CrMoV18 steel: 1 GPa to 6 GPa, i.e., a difference of 0.3 % to 3 %.

One has to remember, however, that the standards indicate averaged values for groups of steel grades that have similar properties. It was also observed that the E value determined for X14CrMoS17 steel was always lower than the values indicated in the standard, whereas in the case of X90CrMoV18 steel, the coefficient was always higher than the reference value. For both steel grades, however, it was observed that

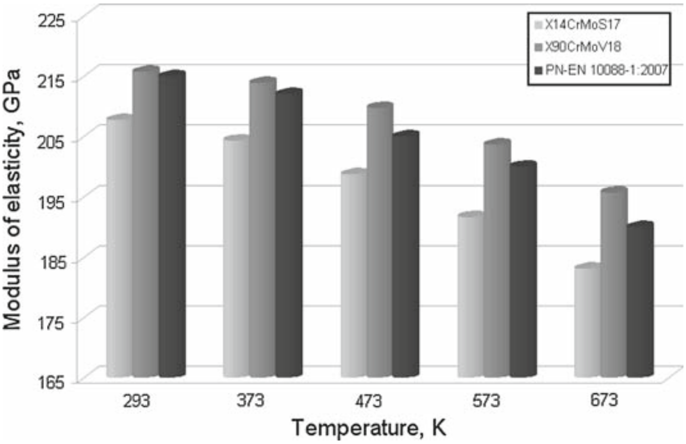

Fig. 8 Verification of obtained results

the modulus of elasticity decreased with increasing temperature, in agreement with the requirements in the PN-EN 10088-1:2007 standard. Conformity of the results obtained (Fig. 8) demonstrates that the testing method and the tests that were performed had been selected correctly.

4 Conclusion

The tests that were performed made it possible to measure acoustic properties such as the sound wave propagation velocity directly in materials at elevated temperatures. Such tests require an analyzer (e.g., a computer oscilloscope card) and the ultrasonic transducers to be adapted for these measurements.

The methodology that was adopted made it possible to determine material properties at a determined temperature in an indirect and non-destructive manner. The methodology enables indirect and non-destructive determination of material constants as a function of temperature.

The sound wave propagation velocity in steel decreases with increasing temperature, reaching the following values at a temperature of 1,173 K in the analyzed cases:

- approx. 5,100 $\mathrm{m \cdot s^{-1}}$ (longitudinal wave),
- approx. 2,450 $\mathrm{m \cdot s^{-1}}$ (transverse wave).

The test results may prove useful, for instance, if one wishes to simulate the operation of the acoustic power head under elevated temperature conditions.

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References

1. O.V. Abramov, *High-Intensity Ultrasonics: Theory and Industrial Applications* (Gordon and Breach Science Publishers, Amsterdam, 1998)
2. S.V. Komarov, O.V. Abramov, M. Kuwabara, ISIJ Int. **45**, 1765 (2005)
3. O.V. Abramov, S.G. Khorbenko, S. Shvelga, *Ultrasonic Processing of Materials* (Mashinostroenie, Moscow, 1984) [in Russian]
4. A. Orłowicz, *The Using of Ultrasounds in Founding* (Wyd. PAN, Katowice, 2000) [in Polish]
5. K. Nowacki, H. Kania, Hutnik—wiadomości hutnicze, no. 7 (2005), pp. 470–473
6. W. Kasprzyk, K. Nowacki, in *Proceedings of the* 38th *Winter School on Wave and Quantum Acoustics*, Korbielów, 23–27 February 2009
7. A. Lewińska-Romicka, *Non-destructive Testings. The Basics of Defectoscopy* (WNT, Warszawa, 2001) [in Polish]
8. S.E. Kruger, E.B. Damm, in *Proceedings of the* 1st *International Symposium on Laser Ultrasonics: Science, Technology and Applications*, Montreal, Canada, July 16–18 2008
9. J. Wehr, *The Measurements of Speer and the Suppression an Ultrasonic Waves* (Wyd. PWN, Warszawa 1972) [in Polish]
10. PN-EN 10088-1:2007, Wyd. PKN, Warszawa (2007)