Development of Certified Reference Materials for Ensuring the Traceability of Mechanical Stress Measurements in Acoustic Non-destructive Testing

Ilona N. Matveeva and Vladimir V. Tolmachev

Abstract The article concerns the development of certified reference materials (CRMs) for steel mechanical properties. At present, in mechanical stress measurements, traceability of measurement results is ensured by the standard of time, rather than by the standard of mechanical stress. Therefore, a systematic approach to ensuring the uniformity of mechanical stress measurements requires the development of a reference. The present study is focused on the development and certification of CRMs having a special shape, traceable to SI units of force and length, and intended for transferring a unit of mechanical stress to measuring instruments, where the time-of-flight method of acoustic non-destructive testing is realized on the basis of the acoustoelasticity phenomenon. The key stages of developing CRMs, including the selection of the initial material, performing a homogeneity study, carrying out experimental studies using a certified reference (1st echelon state standard of the force unit), as well as establishing, on the basis of these studies, metrological characteristics of the developed CRMs. As a result of pattern approval tests, the GSO 11,544–2020/11545–2020 set of CRMs for steel mechanical properties was approved. The certified characteristics of the CRMs in the set involve the proportional limit mechanical stress; proof strength, plastic extension 0.2% R_p; tensile strength R_m; modulus of elasticity E. For the CRMs, the relative error of certified values do not exceed 12% at a confidence level of 0.95. The authors believe that, when applied as a reference in the verification schedule, the GSO 11544–2020/11545–2020 CRM set of steel mechanical properties will provide metrological traceability of the results in measuring mechanical stresses by instruments implementing the time-of-flight method of acoustic non-destructive testing.

Keywords Mechanical properties of steel · Stress–strain state · Temporary method of acoustic type of nondestructive check · The phenomenon of acoustoelasticity · Proof strength · Plastic extension 0.2% · Tensile strength · Modulus of elasticity · Certified reference material

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Abbreviations

CRM Certified Reference Material
SSS Stress–Strain State
NDT Non-Destructive Testing

Introduction

Acoustic NDT is widely applied at hazardous production facilities in the gas, oil, and petrochemical industries, as well as in mechanical and nuclear engineering, utilities, and other industries due to the need for safety analysis of the feasibility of operating metal structures (main pipelines, NPP units, pressure vessels, supporting building structures, etc.) [1–13].

The probability of plastic destruction in critical components of structures and equipment can be evaluated using devices implementing the time-of-flight method of the acoustic NDT and providing the measurement of the current mechanical stresses arising from technological influences.

In order to ensure the reliability of results obtained in measuring mechanical stresses, such devices should have a traceability to the standard of the corresponding physical quantity (Fig. 1). However, as shown by the analysis of the register of approved patterns of measuring instruments, the measured value in these devices is represented by the transmission time of various type (P and S) elastic waves excited

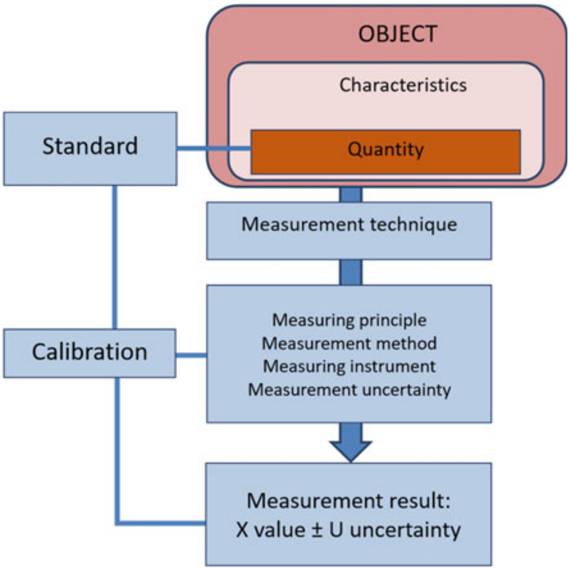

Fig. 1 Ensuring traceability of measurements to standards reproducing SI units

in the material of the controlled object, i.e., traceability is ensured to a time, not a mechanical stress, standard. The analysis of the verification procedures confirmed that the standards used for verification (oscilloscope, pulse generator, and frequency meter) do not transfer a unit of mechanical stress to the devices under verification.

In order to control SSS, standardized measurement techniques are used [14–18], which provide for the transfer of the dimension of a mechanical stress unit by constructing a calibration characteristic using a sample made of a material similar to that of the structure or equipment under study. At the same time, the fact that the properties of materials in the structure (equipment) under study were evaluated using samples of a different shape and dimensions is completely ignored, the contribution from the heterogeneity of the initial material in mechanical properties is not taken into account, and no uncertainty is estimated for the calibration characteristic obtained by the method of regression analysis. Thus, the basic principle of ensuring traceability in SSS measurements is violated: the result can be correlated with the reference system through a documented continuous chain of calibrations, each of which contributes to the measurement uncertainty [19].

Ensuring the traceability of mechanical stress measurements has two alternative perspectives.

The authors of [20] believe that, during the calibration of instruments implementing the time-of-flight method of the acoustic NDT, traceability to mass and length units is ensured, therefore, CRMs with an assigned value of the second kind modulus of elasticity (Young’s modulus) can be applied for calibration.

The studies [21, 22] propose apply only CRMs for ensuring traceability to the mechanical stress unit, since obtaining a response from the stresses arising in the material during loading depends on external factors, i.e., the stresses are method-dependent and the traceability to the primary reference procedures of the National Metrology Institute is required.

Both methodological approaches recognize the use of CRMs as a necessary condition for ensuring the traceability of mechanical stresses.

Therefore, for mechanical stresses, the concept of traceability can be represented by Fig. 2, where the reference system consists of a material, sufficiently homogeneous and stable with respect to a certain property established in order to be used in the measurement process, i.e., a CRM [23].

The present study was aimed at the development and certification of special shape CRMs traceable to SI units of force and length and intended for transferring a unit of mechanical stress to measuring instruments, where a time-of-flight method of acoustic NDT is realized.

Materials and Methods

In order to ensure the representativeness of mechanical stress measurements in objects manufactured using various technological processing techniques, the CRM material was represented by:

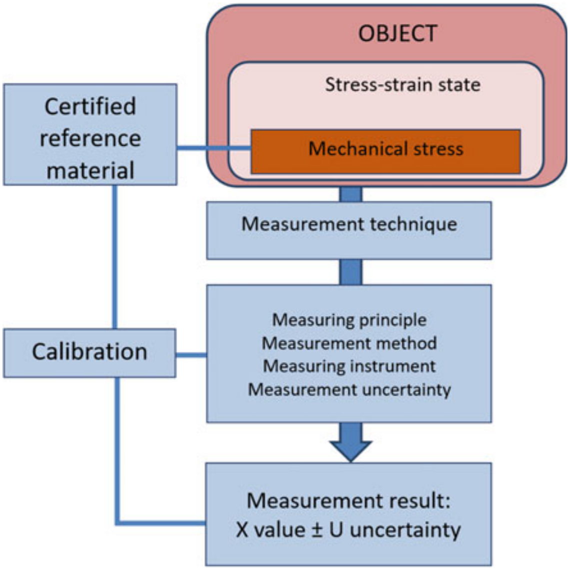

Fig. 2 Concept of traceability for mechanical stress

- rolled sheet made of structural steel;
- forging made of high-quality structural high-alloy steel.

The homogeneity study of the CRM in the form of a sheet or forging was a complex methodological task. Firstly, for calibration of measuring instruments implementing the time-of-flight method of the acoustic NDT, a CRM should have a shape and dimensions (hereinafter referred to as the form factor) different from proportional CRMs used to determine the mechanical properties under static tension [24]. Secondly, the main feature of measuring the mechanical properties of materials involves the fact that measurements cannot be repeated on the same sample due to its failure under loading.

The CRM inhomogeneity represents a source of a significant error (uncertainty) component; therefore, at the first stage, the acoustic anisotropy was estimated by an indirect method [18] in order to select an area, sufficient for the manufacture of a CRM on a sheet or forging according to the form factor and homogeneous in acoustic parameters. The results of evaluating the acoustic anisotropy are graphically represented in Fig. 3.

At the second stage, using proportional CRMs, the spatial homogeneity in the distribution of mechanical property was estimated in accordance with the algorithm provided in [25] by the method of static tension [24].

The CRMs were recognized as homogeneous. The obtained estimates of the error (uncertainty) from heterogeneity cannot be neglected; therefore, these values should be taken into account in estimating the error (uncertainty) of the CRM certified values.

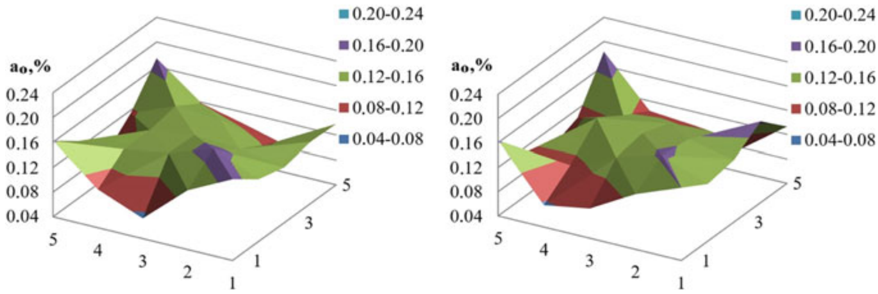

Fig. 3 Results of evaluating the acoustic anisotropy

The establishment of the CRM certified values, as well as the estimation of their errors, was carried out using the 1st echelon state standard of the force unit in accordance with the algorithms provided in [25].

The shelf life of the CRMs was established on the basis of the data about the shelf life for similar CRMs of the steel mechanical properties (GSO 10957–2017). The CRM shelf life comprises 10 years for all certified characteristics.

The developed CRM set was included in the State Register of approved patterns of certified reference materials as GSO 11544–2020/11545–2020.

The values of the GSO 11544–2020/11545–2020 metrological characteristics are presented in Tables 1 and 2.

The traceability of certified values to SI units was realized by means of direct measurements using the 1st echelon State standard of force unit in accordance with the State verification schedule for force measuring instruments and State verification schedule for length measuring instruments in the ranges from $1 \cdot 10^{-9}$ to 100 m and 0.2 to 50 μm (wavelengths).

CRMs are designed for pattern approval testing of instruments measuring mechanical stress using a time-of-flight method of acoustic non-destructive testing based

Table 1 Metrological characteristics of GSO 11544–2020

Certified characteristic	Unit designation	Interval of certified values	Absolute error of the certified value at a confidence level of 0.95, (± Δ)
Proportional limit[a]	MPa (N/mm^2)	100	± 12
Proof strength, plastic extension 0.2% R_p	MPa (N/mm^2)	166	± 12
Tensile strength R_m	MPa (N/mm^2)	307	± 12
Modulus of elasticity E	GPa	95	± 9

[a] The designation of the certified characteristics correspond to [24]

Table 2 Metrological characteristics of GSO 11545–2020

Certified characteristic	Unit designation	Interval of certified values	Absolute error of the certified value at a confidence level of 0.95, (± Δ)
Proportional limit[a]	MPa (N/mm^2)	830	± 19
Proof strength, plastic extension 0.2% R_p	MPa (N/mm^2)	1017	± 22
Tensile strength R_m	MPa (N/mm^2)	1198	± 12
Modulus of elasticity E	GPa	195	± 5

[a] The designation of the certified characteristics correspond to [24]

on the phenomenon of acoustoelasticity, verification and calibration of instruments measuring mechanical stress using a time-of-flight method of acoustic non-destructive testing, and the accuracy control in mechanical stress measurements.

Discussion and Conclusions

In the course of the study, unique CRMs of steel mechanical properties for ensuring the uniformity of mechanical stress measurements were developed and approved.

A distinctive feature of the developed CRMs involves the certification of the "proportional limit" and "modulus of elasticity E" characteristics. The certified values of these characteristics promoted for unambiguously setting the area of elastic deformation during verification and (or) calibration of the instruments measuring mechanical stress using the acoustoelasticity phenomenon, as well as for establishing the coefficients of elastic-acoustic coupling [16].

It should be noted that the certified values of the "modulus of elasticity E" characteristic differ from the reference data. The certified values of the characteristic for GSO 11544–2020, made of structural steel, and GSO 11545–2020, made of high quality structural high alloy steel, comprise 95 and 195 GPa, respectively, while their reference values are equal to 200 and 215 GPa. This difference is due to a number of reasons, each of which contributes to the reliability of the reference data. First, the available reference data contain no information on the uncertainty of the values obtained. Secondly, for reference data, no information is provided on the method of material processing for obtaining the reference data. For example, the CRM, made from rolled sheet, has surface hardening affecting the values of material properties obtained during testing. Therefore, the key task of ensuring the reliability of the results of mechanical property measurements involves the availability of the CRMs for calibration of non-destructive testing instruments associated with the technology of manufacturing controlled materials.

It should be noted that not only standards, but also reference systems in the form of GSO (State certified reference materials) and primary reference procedures should be used in verification schedules, representing the urgent task of legal metrology in the Russian Federation. The local verification schedule, based on the principles of Fig. 2, ensures using the GSO for pattern approval tests for instruments measuring mechanical stresses and implementing various methods of the acoustic NDT.

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Author Contributions Ilona N. Matveeva: implementation of a formal analysis, writing a draft version of the article, creating visual materials.

Vladimir V. Tolmachev: development of the research concept, conducting research work, checking and editing the text of the article, management of research work.

Conflict of Interest The article was prepared on the basis of a report presented at the IV International Scientific Conference “Reference Materials in Measurement and Technology” (St. Petersburg, December 1–3, 2020). The article was admitted for publication after the abstract was revised, the article was formalized and the review procedure was carried out.

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References

1. Motova EA, Nikitina NY (2011) The possibility of ultrasonic testing of compressor blades after exploitation and repair. VESTNIK of Samara University. Aerospace Mechan Eng 10(3–2):52–56. https://doi.org/10.18287/2541-7533-2011-0-3-2(27)-52-56 (In Russ.)
2. Nikitina NE, Motova EA, Tarasenko YP (2012) Nondestructive testing of the working compressor blades of the aviation engine. VESTNIK of Samara University. Aerospace Mechan Eng 11(3–1):291–295. https://doi.org/10.18287/2541-7533-2012-0-3-1(34)-291-295 (In Russ.)
3. Nikitina NY, Kamyshev AV, Kazachek SV (2015) The application of the acoustoelasticity method for the determination of stresses in anisotropic pipe steels. Defektoskopiya 3:171–178 (In Russ.)
4. Nikitina NY, Kamyshev AV, Kazachek SV (2009) Using the phenomenon of acoustoelasticity in the study of the stress state of technological pipelines. Defektoskopiya 12:53–59 (In Russ.)
5. Nikitina NE, Kamyshev AV, Mironov NA (2009) Measurement of stresses in technological pipelines by the method of acoustoelasticity. Gazovaia promyshlennost’ 5:64–67 (In Russ.)
6. Muravieva OV, Muraviev VV, Gabbasova MA, Petrov KV, Zorin VA (2016) Electromagnetic-acoustic structural analysis of rolled bars. AIP Conf Proc 1785(1):030017. https://doi.org/10.1063/1.4967038
7. Muravyev VV, Muravyeva OV, Strizhak VA, Pryakhin AV, Balobanov EN, Volkova LV (2011) Evaluation of residual stresses in rims of wagon wheels using the electromagnetic-acoustic method. Defektoskopiya 47(8):512–521 (In Russ.)
8. Motova EA, Nikitina NYe, Tarasenko Ur P (2016) Study of acoustic anisotropy of structural materials under variable loading. In: Problems and prospects for the development of engine building: materials of reports of the international scientific and technical conference, Samara, June 22–24 2016. Samara: Samara National Research University named after academician S.P. Queen, pp 16–17 (In Russ)

9. Mishakin VV, Gonchar AV, Knrashkin KV, Danilova NV (2009) The joint weld destruction study after static loading by acoustic method. Russian J Heavy Machin 7:27–30 (In Russ)
10. Belyaev AK, Polyanskiy VA, Grishchenko AI, Lobachev AM, Mansyrev DI, Modestov VS et al (2016) Application of the acoustic anisotropy approach for technical diagnostics of structures with large plastic deformations. AIP Conf Proc 1785(1):030004. https://doi.org/10.1063/1.4967025
11. Belyaev AK, Lobachev AM, Modestov VS et al (2016) Estimating the plastic strain with the use of acoustic anisotropy. Mech Solids 51:606–611. https://doi.org/10.3103/S0025654416050149
12. Grishchenko AI, Modestov VS, Polyanskiy VA, Tretyakov DA, Shtukin LV (2017) Experimental investigation of the acoustic anisotropy field in the sample with a stress concentrator. St. Petersburg Polytechn Univ J Phy Mathem 3(1):77–82. https://doi.org/10.1016/j.spjpm.2017.02.005
13. Alekseeva E, Alhimenko A, Belyaev A, Lobachev A, Polyanskiy V, Rostovykh G et al (2016) Evaluation of stress-strain state and cracking of weather-proof structural steel by acoustoelasticity. Constr Unique Build Struct 12(51):33–44 (In Russ.)
14. GOST R 52330–2005 (2005) Non-destructive testing. Evaluation of deformations in industrial and vehicle structures. General requirements. Standartinform, Moscow, p 5 (In Russ.)
15. GOST R 53966–2010 (2011) Non-destructive testing. Evaluation of mechanical stresses in constructions material. General requirements for the order of methods choice. Standartinform, Moscow, p 4 (In Russ.)
16. GOST R 55043–2012 (2014) Non-destructive testing. Evaluation of elastic-acoustic coefficients. General requirements. Standartinform, Moscow, p 8 (In Russ.)
17. GOST R 56664–2015 (2016) Non-destructive testing. Evaluation of stress state material engineering products by acoustoelastic methods. General requirements. Standartinform, Moscow, p 16 (In Russ.)
18. GOST R 52731–2007 (2007) Non-destructive testing. Stress evaluation by ultrasound. General requirements. Standartinform, Moscow, p 7(In Russ.)
19. RMG 29–2013 (2014) State system for ensuring the uniformity of measurements. Metrology. Basic terms and definitions. Standartinform, Moscow, p 60 (In Russ.)
20. Roebben G, Linsinger T, Lamberty A, Emons H (2010) Metrological traceability of the measured values of properties of engineering materials. Metrologia 47(2):23–31. https://doi.org/10.1088/0026-1394/47/2/S03
21. Bahng GW, Kim JJ, Lee HM, Huh YH (2010) Establishment of traceability in the measurement of the mechanical properties of materials. Metrologia 47(2):32–40
22. Czichos H, Saito T, Smith L (2011) Springer Handbook of Metrology and Testing. Springer, Berlin. https://doi.org/10.1007/978-3-642-16641-9
23. GOST ISO Guide 30–2019 (2019) Reference materials. Selected terms and definitions. Standartinform, Moscow, p 9 (In Russ.)
24. GOST 1497–84 Metals (1997) Methods of tension test. PPC Izdatel'stvo Standartov, Moscow, p 35 (In Russ.)
25. RMG 53–2002 (2004) State system for ensuring the uniformity of measurements. Reference materials. Evaluation of metrological characteristics with the use of measurement standards and reference devices. PPC Izdatel'stvo Standartov, Moscow, p 6 (In Russ.)

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