Resistive Method to Measure Residual Stresses in Parts from Heat-Resistant Alloys

D V Vasilkov¹, S D Vasilkov², A V Nikitin³

¹ Baltic State Technical University “Voenmeh” named after D.F. Ustinov, 1, 1-ya Krasnoarmeiskaya, 190005, St. Petersburg, Russia
² Saint-Petersburg National Research University of Information Technologies, Mechanics and Optics, 49, Kronverkskiy Prospekt, 197101, St. Petersburg, Russia
³ Peter the Great St. Petersburg Polytechnic University, 29, Polytechnic Street, 195251, St. Petersburg, Russia

E-mail: vasilkovdv@mail.ru

Abstract. The resistive electrical contact method of measuring residual stresses in the surface layer of various metals and alloys is considered. Studies are carried out to determine technological residual stresses in the process of manufacturing parts from heat-resistant alloys applied in thermal control systems for spacecraft, as well as aerospace, mining and power engineering.

1. Introduction
The sequence of critical part manufacturing implies the directed formation of surface layer properties ensuring the best performance characteristics [1-4]. Operational experience has shown that the greatest number of failures occurs because the stress-strain state does not correspond to the operational requirements within specified zones of critical units where the residual stress (RS) is the dominant factor. Indeed, there is a constant presence of defects in the surface layer. However, in some cases they are actively developing and in others they are preserved and do not manifest themselves.

The analysis of the existing methods aimed at RS determining has shown the importance of the issue of developing new methods that would combine the advantages of destructive methods (high reliability, assigned error in determining the RS, ability to determine the RD distribution along the depth from the surface) and non-destructive operating principle, and would have high performance [5-7]. In this paper a resistive electrical contact method [4, 8, 9], which is quite universal with respect to the shape and dimensions of parts manufactured from various metals and alloys, both ferromagnetic and nonmagnetic, with high and low electric conductivity is proposed.

2. Materials and methods
The resistive electrical contact method of RS non-destructive testing is based on the correlation between the integral electrical and mechanical characteristics of conductive materials, i.e. the specific electric resistance (SER) ($\rho$) in the metal layer $h$ and the deforming ability of RS. As a result of measuring the electrical parameters, it is possible to determine the mechanical stresses in parts and products. In this case, it is necessary to obtain the values of electrical parameters and mechanical stresses in the form of a diagram of the distribution of these values along the product material depth.
In order to measure the depth distribution of SER, one can apply the skin effect phenomenon during which the high-frequency currents are concentrated at the surface of the conductor which is the closest to the source of the field causing the appearance of currents [9]. On the basis of Maxwell’s equations for the conducting half-space the depth of the skin layer \( h \) is determined by the following expression

\[
h = \frac{1}{\sqrt{\pi f \mu}_h},
\]

where \( f \) is the current frequency; \( \mu \) is the material permeability.

Application of the skin effect phenomenon allows to study parts and products layer-by-layer by means of electromagnetic field excitation of various frequencies and measuring the signal-response the parameters of which are related to the change in the stress state of a product. In accordance with the expression (1) a decrease in the frequency of the alternating current sent to the product makes it possible to increase the thickness of the studied layer. The choice of the operating frequencies is determined by the depth range at which the extremes of the residual mechanical stresses are observed.

The SER depends on the frequency of a current and the properties of product material. It can be measured at various frequencies \( f_i \), including DC:

\[
\rho_i = \frac{U_i h_i}{I_i},
\]

where the subscript \( i \) means that the measurements of the current \( I_i \) and voltage \( U_i \) are made at the \( i^{th} \) frequency \((i = 1, 2, ..., m)\) and the values of \( h_i \) are calculated basing on the formula (1) for frequency \( f_i \).

It is important to note that in formula (2) the in-phase component of the electrical voltage of signal-response to the applied current \( I_i \) is implied by measured voltage \( U_i \), which is easy to implement, for example, by phase detection of the denoted signal. Thus, by specifying the current sequence of different frequencies \( f_i \), measuring the current \( I_i \) and the voltage \( U_i \), as well as calculating distribution \( \rho_i \) along the depth of a product material it becomes possible to determine the mechanical stresses \( \sigma_i \).

The RS occurs in almost all types of technological impacts [4, 8]. However, there is a problem as far as the choice of quantitative characteristics for estimating their values concerns. In the aircraft engineering industry there is a tendency to specify technological RS in accordance with which special points A, B, C, D, E are marked on the RS diagram (Fig. 1, a) with the following characteristics:

- \( A(0, \sigma_s) \) are the surface technological RSs;
- \( B(h_{ss1}, \sigma_{ss1}) \) are the first maximum subsurface technological RSs;
- \( C(h_0, 0) \) is the transition point through zero of the technological RS diagrams;
- \( D(h_{ss2}, \sigma_{ss2}) \) is the second maximum subsurface technological RSs;
- \( E(h_{max}, 0) \) is a tendency to asymptote to the diagram of residual stresses.

From the indicated characteristics the following parameters are regulated in the design and technological documents:

- \( \sigma_s \) are the surface technological RSs;
- \( h_0 \) is the depth of zero crossing of technological RS diagrams;
- \( \sigma_{ss} \) are the maximum subsurface technological RSs, \( \sigma_{ss} = \max(\sigma_{ss1}, \sigma_{ss2}) \).

In addition to parametric estimation of the RS, there is a nonparametric criterion, which integrally estimates the action of residual stresses, i.e. their deforming capacity \( q \) [8] determined by the following expression

\[
q = \int_{0}^{h_{max}} \sigma_{\text{residual}} dh,
\]

where \( h_{max} \) is the maximum depth of technological RSs.
The dependence of deforming capacity $q$ on the depth $h$ is shown in Fig. 1, b. It is important for engineering calculations since it is a measure of the effect of technological RS.

The average stresses in the layer of depth $h_i$ are determined on the basis of correlation dependence between the integral electrical and mechanical characteristics

$$\sigma_{\text{average}}(h_i) = q(h_i) = k \cdot \rho_i \cdot (f_i)^2,$$

where $k$ is the experimental coefficient obtained during measuring system calibration (Fig. 2).

The implementation of the resistive electrical contact method is shown in Fig. 2. The operation is based on the principle of layer-by-level measurement of electrical quantities in a specimen material by excitation of electromagnetic field of various amplitudes and frequency followed by the measurement of signal-response the parameters of which are associated with the change in the stress-strain state of a specimen material. The depth of the study is related to the frequency of expression (1). The outer pair of sensor electrodes is the source of electromagnetic field and the internal pair of electrodes receives the signal-response [9].

The measuring system functions according to the following algorithm:
- current of different frequency enters the surface layer of a specimen under study through the external electrodes;
- current is measured at each of the specified frequencies;
- signal-response voltage is measured at each of the specified frequencies;
- SER distribution along the depth in the specimen material is calculated;
- calibration relationship between SER and mechanical stresses in the specimen material at the depths corresponding to the penetration depths of current at the specified frequencies is calculated;
- calculated SER distribution is transformed into the distribution of mechanical stresses along the depth of specimen material under study.
The measurement of the applied current strength makes it possible to directly calculate the SER and its distribution along the depth of a surface layer of the specimen and, in addition, it increases the stability of the measurements. The external impact is not only set and measured directly in the product, but also appears to be a normalized factor.

3. Discussion of research results

When studying the details, one can choose the necessary depth for investigation. For a selected frequency range regarding various materials it is possible to calculate the series of depths that will differ due to the difference in both electrical and magnetic properties. Table 1 shows the calculated depth values for different frequencies of the transmitted signal.

Table 1. Frequency and depth dependence (µm)

| Frequency, Hz | Cu   | Al   | 3X13 | X17 |
|--------------|------|------|------|-----|
| 16.8x10⁶     | 15.9 | 20.2 | 2.9  | 3.1 |
| 8.4x10⁶      | 22.5 | 28.5 | 4.2  | 4.4 |
| 4.2x10⁶      | 31.8 | 40.3 | 5.9  | 6.3 |
| 2.1x10⁶      | 44.9 | 57.0 | 8.3  | 8.9 |
| 1.0x10⁶      | 63.6 | 80.6 | 11.7 | 12.5|
| 0.52x10⁶     | 90.0 | 114.0| 16.6 | 17.7|
| 0.26x10⁶     | 127.1| 161.2| 23.5 | 25.1|
| 0.13x10⁶     | 179.8| 228.0| 33.2 | 35.4|
| 65.5x10³     | 254.3| 322.4| 46.9 | 50.1|
| 32.8x10³     | 359.6| 456.0| 66.4 | 70.9|
| 16.4x10³     | 508.6| 644.9| 93.9 | 100|
| 8.2x10³      | 719.2| 912.0| 133  | 142|
| 4.1x10³      | 1020 | 1290 | 188  | 200|
| 2.0x10³      | 1440 | 1830 | 266  | 284|
| 1.0x10³      | 2030 | 2580 | 375  | 401|
| 0.5x10³      | 2880 | 3650 | 531  | 567|

On the basis of this method, a set of studies was carried out to determine the technological modes that ensure a minimum of the elastic aftereffect of the deforming ability of technological RS during treatment by turning, milling and grinding. The precision parts of pumps of spacecraft thermal control systems, thin-walled cover plates and labyrinth seals of aircraft engines, working blades of steam and gas turbines, parts of the hull and chassis of aircraft, parts of power cylinders of mining equipment, etc. were selected to carry out the study [4, 8].

During the multi-transitive machining, accuracy is largely determined by technological inheritance in the residual stresses. This is especially true during the machining of thin-walled parts. Each of the subsequent machining of the functional surface of a part; rough, semi-finished, fine, and thin must preserve the shape of a part, i.e. to eliminate the elastic aftereffect (buckling) of the deforming ability of technological RS. This is achieved with the help of redistribution of the RS curves by varying the technological modes.

4. Conclusion
In the process of manufacturing the precision parts with thin-walled elements, the determining factor is to ensure the accuracy of the dimensions, shape and location of surfaces, as well as the quality of the surface layer. These factors limit the processing capacity; however, they provide the quality requirements regarding parts and products. An indispensable condition for quality assurance is a continuous non-destructive testing by the resistive electrical contact method of magnitude and the nature of RS distribution.

5. Acknowledgments
The work is carried out with the financial support of the Ministry of Education and Science of the Russian Federation (agreement No. 14.577.21.0270, unique project number RFMEFI57717X0270).

References
[1] Maksarov V V, Krasnyi V 2015 The formation of surface roughness of piston rings for the purpose of improving the adhesion of wear-resistant coatings. Key Engineering Materials 736 73-78
[2] Maksarov V V, Ol Ju 2015 Improving the precision of manufacturing power hydraulic cylinders of powered roof supports based on a vibration-damping tooling system. Journal of mining institute 214 71-84
[3] Maksarov V V, Viushin R V, Efimov A E 2017 Technological roughness of the surface layer on the basis of modeling of transitional processes. Metalworking 2 39-45
[4] Valetov V A, Vasilkov D V, Ivanov S Y 2005 Einrichtung zur zerstorunglosen Kontrolle der Restspannungen in Maschinen- und Gerateteilen. Mechanical Engineering from Macro to Nano, 50. (Internationales Wissenschaftliches Kolloquium. Ilmenau) pp. 279-280
[5] Karapetyan K G, Denisova O V 2017 Non-destructive control of graphite electrodes with use of current displacement effect. IOP Conf. Series: Earth and Environmental Science 87 1-4
[6] Sorokin A G, Filimonova O V 2017 Examining microstructure of industrial brass blanks with purpose for quality control in respect of defects of technological origin. IOP Conf. Series: Earth and Environmental Science 87 1-8
[7] Fediuk R S, Smoliakov A K, Timokhin R A, Batarshin V O, Yevdokimova Yu G 2017 Microstructure and mechanical properties of Al-12Si produced by selective laser melting. IOP Conf. Series: Earth and Environmental Science 87 1-6
[8] Vasilkov D V, Petrov V M, Ivanov S Y, Prima V I 1998 Complex investigation of the state of the surface layer of vital components in machine units. Heavy engineering 3 31-34
[9] Vasilkov D V, Vasilkov S D, Nikitin A V 2017 Measurement of residual stresses by resistive electrocontact method. Metal treatment 6(102) 30-34