Evaluation of the Magnet Breakaway Force Measurement Accuracy of the NT-800 Sensors for Early Detection of Defects of Their Manufacturing

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Abstract

Control of mechanical stresses formed with the deposition of nickel coatings plays an important role in the diagnosis of coatings' technical condition. Large internal stresses can lead to cracking or flaking of coatings which is completely unacceptable for critical parts and assembly units used, for example, in space technology for which reliability is of paramount importance. An important aspect of internal stresses monitoring is the measurement error of the instruments used. The purpose of this work was to determine the characteristics of the device sensors, which make the assessment of their manufacturing possible at the preliminary stage of the measuring equipment assembling in order to maintain the required accuracy of subsequent measurements.

In most cases the measurement error assessment is possible only after the equipment manufacture and calibration. In this paper it is proposed to evaluate the accuracy characteristics of device sensors based on the precision (repeatability and reproducibility) of the primary informative parameter recording. In the case of the NT-800 device that was developed at the Institute of Applied Physics of the National Academy of Sciences of Belarus the effect of precision characteristics deterioration on the eventual measurement error is demonstrated. Determining the precision parameters before establishing correlation dependences between the primary informative parameter and the measured characteristic is proposed in order to reject poorly manufactured sensors and reduce labor costs.

In particular, measurements of the magnitude proportional to the magnetic breakaway force were carried out using the NT-800 device with nickel specimens simulating coatings with a thickness of 200 to 700 μm and a rolling value from 0 to 40 %. It was established that in the case of well-made sensors the variation coefficient calculated from the dispersion of repeatability is in the range 0.2–0.6 %, and the variation coefficient calculated from the dispersion of reproducibility does not exceed 0.9 %. In the case of a sensor with the sensitive element parameters worsened, the variation coefficient of repeatability and reproducibility were up by one and a half times. Deterioration of the precision characteristics resulted in significant changes in the readings of the calibrated instrument. Thus the absolute measurement error for a sensor with a poorly made sensitive element turned out to be approximately 3 times higher in the range of 200–300 MPa than that for a sensor with good precision parameters.

Keywords: accuracy, repeatability, reproducibility, internal stress, magnet breakaway force.

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Оценка точности измерения магнитоотрывного усилия датчиками прибора НТ-800 для раннего выявления дефектов их изготовления

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Контроль механических напряжений, возникающих при нанесении никелевых покрытий, играет важную роль при диагностике их технического состояния. Большие внутренние напряжения могут приводить к растрескиванию или отслаиванию покрытий, что совершенно недопустимо для ответственных деталей и сборочных единиц, использующихся, например, в космической технике, для которых надёжность имеет первостепенное значение. Важным аспектом контроля внутренних напряжений является погрешность измерений используемых приборов. Целью настоящей работы являлось определение характеристик датчиков приборов, позволяющих оценить качество их изготовления на предварительной стадии сборки измерительной техники, для соблюдения необходимой точности последующих измерений.

В большинстве случаев оценка погрешности измерений возможна только после изготовления оборудования и проведения градуировки. В настоящей работе предложено оценивать точностные характеристики датчиков приборов исходя из прецизионности (повторяемости и воспроизводимости) регистрации первичного информативного параметра. На примере прибора «НТ-800», разработанного в Институте прикладной физики Национальной академии наук Беларуси, показано влияние ухудшения характеристик прецизионности датчиков на итоговую погрешность измерений. Предложено определять параметры прецизионности до установления корреляционных зависимостей между первичным информативным параметром и измеряемой характеристикой с целью отбраковки некачественно изготовленных датчиков и снижения трудозатрат.

В частности, проведены измерения величины, пропорциональной магнитоотрывному усилию (имеющей корреляционную связь с остаточными напряжениями), прибором НТ-800 на никелевых образцах, имитирующих покрытия, толщиной от 200 до 700 мкм и величиной прокатки от 0 до 40 %. Установлено, что в случае качественно изготовленного первичного преобразователя коэффициент вариации дисперсии повторяемости находится в диапазоне 0,2–0,6 %, а коэффициент вариации, рассчитанный по значениям дисперсии воспроизводимости, не превышает 0,9 %. В случае датчика с ухудшенными параметрами чувствительного элемента коэффициенты вариации повторяемости и воспроизводимости были в 1,5 раза выше. Ухудшение характеристик прецизионности привело к значительному увеличению погрешности измерения остаточных напряжений. Так, абсолютная погрешность измерений напряжений у некачественно изготовленного датчика в диапазоне 200–300 МПа была приблизительно в 3 раза выше, чем у датчика с высокими показателями прецизионности.

Ключевые слова: точность, повторяемость, воспроизводимость, внутренние напряжения, магнитоотрывное усилие.

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Introduction

Nickel coatings are most often used for thermal protection of mechanical engineering products, as well as space and aviation industry products. One of the main durability and reliability conditions of such products is compliance with the technological process of coating, the violation of which can lead to the appearance of unevenly distributed or high mechanical stresses. If the magnitude of stresses exceeds the adhesion force it may lead to delamination, and uneven distribution can lead to cracking. Thus the control of residual stresses plays an important role in diagnosing the state of both individual products and various elements of load-bearing structures in general, and the development of new reliable testing methods is a paramount task to improve the quality and reliability of products.

At present a number of devices have been developed for internal stresses monitoring using various measurement principles: X-ray, ultrasonic, magnetic, and others [1–5]. The calibration of each of them is a unique procedure. For example standard samples with certain crystal lattice parameters can be used for diffractometers. However these samples cannot be used to calibrate instruments using other physical measurement principles. This is because their readings will be influenced by the different characteristics of the samples such as the presence of plastic deformation, residual magnetization, etc.

This fully applies to the NT-800 device developed at the Institute of Applied Physics of the National Academy of Sciences of Belarus. This fully applies to the NT-800 device developed at the Institute of Applied Physics of the National Academy of Sciences of Belarus. The principle of operation of this device is based on recording the magnitude of the magneto-detachable (ponderomotive) force when a permanent magnet interacts with a ferromagnetic base. The value of the force as shown in [6] depends on two factors: the thickness of the coating and the level of internal stresses. And the sensitivity of measurements to operating voltages is much higher in weak magnetic fields. However, this leads to an increase in the requirements for the magnet breakaway force recording accuracy, the value of which also decreases and is in the range of 80–300 mN. Calibration of the NT-800 device presupposes the use of additional equipment – a testing machine and specially prepared nickel samples. The work requires tests on stepwise tension-compression of samples with simultaneous fixation of the magnitude of the magnet breakaway force and the stresses created by the tensile machine. To remove residual stresses, the samples must first undergo vacuum annealing. Thus the calibration procedure itself is rather complicated, labor-intensive and expensive.

The fact that the metrological characteristics of sensors: the error (or uncertainty) of measurements – are evaluated only after the end of the calibration is an even greater problem. This often leads to the fact that a poorly manufactured sensor is rejected only after the entire test cycle, when the samples are already unusable and the repetition of the calibration procedure requires new costs.

The aim of the work was to determine the characteristics of the sensors which make it possible to assess the quality of their manufacture at the preliminary stage, in order to reduce labor costs and maintain the required accuracy of subsequent measurements.

Equipment and materials

The NT-800 is designed to assess the level of effective stresses build a map of stress distribution over the surface area as well as measure the thickness of nickel coatings in the range from 200 to 800 µm.

One of the main elements of the device are primary measuring transducers (sensors), which can be one of two types: 1) for use on flat surfaces and 2) for testing in hard-to-reach places of products. The formation of the measuring signal and the direct registration of the magnet breakaway force are carried out using them.

The level of internal stresses is estimated by the K_f value, which is proportional to the magnet breakaway force and is used to construct the calibration curves. Figure 1 shows the calibration dependence $K_f = f(\sigma)$ (ABC line). Here σ – applied stress, formed in nickel specimen using universal testing machine.

It is also shown in the Figure 1 that the change of K_f value is influenced by type I stress (ABC line) as well as by residual stresses, formed by plastic deformation. If the sample is unloaded at an intermediate time (at point B), then after complete removal of the load ($\sigma = 0$) points A and D don't match. This discrepancy is caused by the appearance of plastic deformations in the sample which affect K_f. Figure 1 illustrates the complex nature of the graduation, which is also discussed in [7]. Therefore a thorough experiment is required and in the absence of standards a different algorithm is required for determining the metrological characteristics and assessing the sensor manufacturing quality at the preliminary stage.

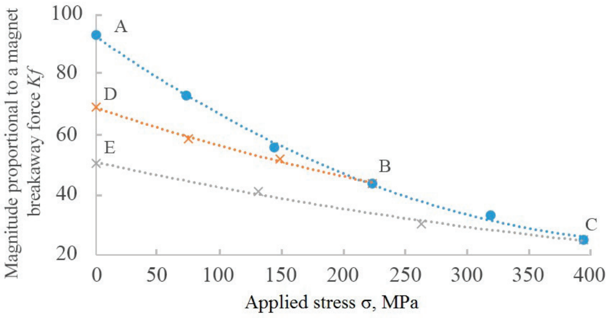

Figure 1 – K_f change depending on applied stresses for an annealed sample with a thickness of 400 µm (with removed stresses) using a sensor for flat surfaces during load (ABC) and unload (BD and CE)

To carry out work on the evaluation of the metrological characteristics of the NT-800 device sensors, that are proposed below we used special nickel samples imitating coatings with various thicknesses and internal stresses. The characteristics of these samples are presented in the Table. The cold rolling of the nickel samples ratio of which is indicated in the table, allowed to form internal stresses values of which cover the real range of stress variation (0–200 MPa) in nickel coatings using galvanic plating technology. The zero level of internal stresses in nickel samples imitating coatings was set up by heat treating: annealing the samples.

Table

Description of the nickel samples

Sample number	Thickness, µm	Rolling reduction ratio, %
1	200	0
2	215	14
3	240	0
4	300	0
5	330	34
6	400	0
7	400	10
8	400	40
9	500	0
10	500	30
11	580	13
12	700	0

Determined metrological characteristics

As mentioned in ISO/IEC Guide 98-3:2008[1] and ISO 5725-2-2002[2] a range of characteristics can be presented as accuracy rate indicators: uncertainty, error, trueness and precision. All the formulae used herein are taken from ISO 5725-2-2002.

In the absence of a standard for the measured quantity correctness means the closeness of the average value obtained from a large series of measurement results (or test results) to the accepted reference value. The systematic error (bias) is usually the trueness indicator. And precision refers to the degree to which independent measurement results obtained under specific specified conditions are close to each other. This characteristic depends only on random factors and is not related to the value of the measured quantity. A measure of precision is usually calculated as the standard deviation of measurements made under specified conditions. The extremes of precision measure are repeatability and reproducibility.

That is from the metrology point of view such characteristics as repeatability and reproducibility do not require reference to the true value of the measured value and can be used for preliminary assessment of the sensor manufacturing quality.

Experimental research

It is important to understand such important concepts as level of the test and cell in a precision experiment (Figure 2).

A level of the test in a precision experiment is a mean value of the measurements, from every lab for one specific tested material or specimen (in our case these are nickels specimen with different rolling reduction ratios as in Table). A set of cells related to one specimen can also be named as the level of the test.

A cell in a precision experiment is a set of measurement values for one specimen acquired in one lab. There were 72 cells in this work in total.

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[1] ISO/IEC Guide 98-3:2008 Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM: 1995)

[2] ISO 5725-2:2019 Accuracy (trueness and precision) of measurement methods and results – Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method

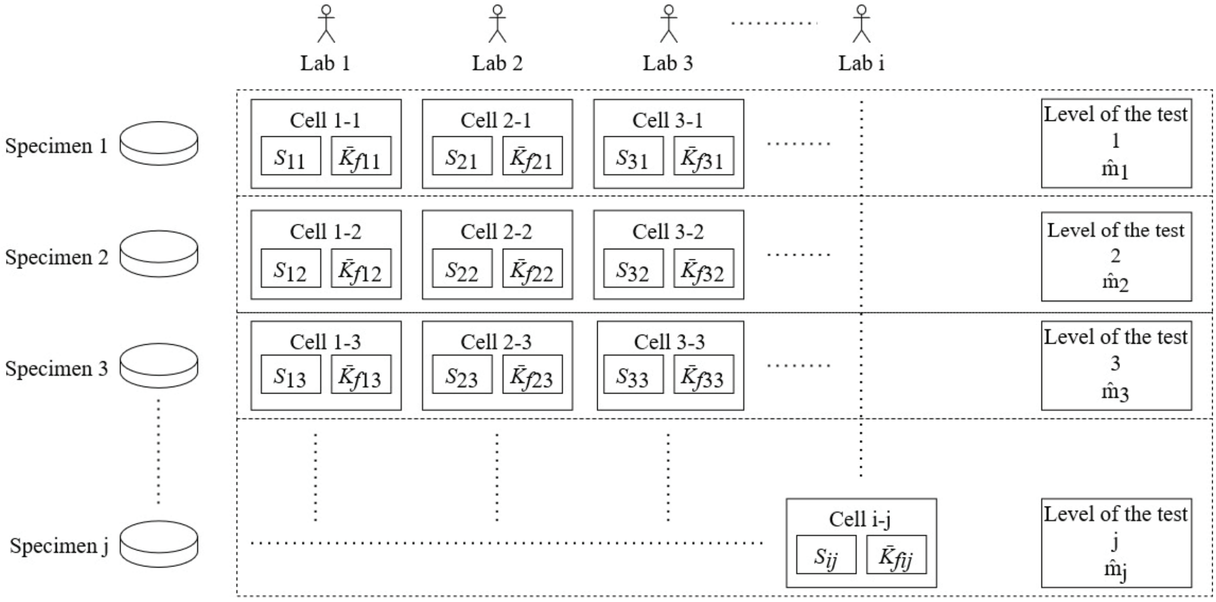

Figure 2 – General test scheme for the precision assessment

Every lab has conducted 10 measurements at every level for the repeatability evaluation. And 6 labs were involved for the reproducibility evaluation.

Arithmetic mean for the K_f values were calculated for every level for every lab as well as cell standard deviation. After that mean values for each level were calculated (averaged measurement results between labs).

Cell standard deviation was calculated using a formula:

$$s_{ij} = \sqrt{\frac{1}{n_{ij}-1}\sum_{z=1}^{n_{ij}}\left(y_{ijz}-\overline{y}_{ij}\right)^2},$$

where i – lab number; j – level; z – measurement number; y – cell; n – number of measurements in one cell.

Since the presence of laboratories or values incompatible with other laboratories or values can change the repeatability and reproducibility estimates, a decision should be made to exclude data after careful analysis. There are two approaches for such decisions: graphical compatibility analysis and statistical testing. In order to simplify the calculations and to present a visual interpretation of the results, herein we began with the first option, in which two measures are used, called Mandel's statistics h and k. It should be noted that they help to assess not only the variability of the results of the measurement method, but also the quality of measurements of individual laboratories. The general procedure for calculating Mandel's statistics processing outliers and then estimating variances of precision is shown in Figure 3.

Statistic k is used to determine stability of measurement results and their repeatability for one laboratory by comparing the repeatability of the standard deviation of the laboratory data with the repeatability of the standard deviation of other laboratories.

Statistic h is used to determine stability of measurement results between laboratories, indicating whether the overall measurement results of an individual laboratory are not reliable.

Statistic h was calculated using formula:

$$h_{ij} = \frac{\overline{y}_{ij}-\widehat{m}_j}{\sqrt{\frac{1}{\left(p_j-1\right)}\sum_{i=1}^{p_j}\left(\overline{y}_{ij}-\widehat{m}_j\right)^2}},$$

where $\widehat{m}$ – common mean value for every specimen (every level); p – number of labs.

The results of calculating statistics k and h for two types of sensors are presented in Figures 4–7.

To determine which of the calculated h_{ij} values are outliers, critical values lines were added to the diagram (Figure 4), that were determined for levels of significance of α = 1 % and 5 % (for $p = 6$ these are 1.87 and 1.66 for 1 % and 5 % accordingly) [8].

If the value of statistic *h* exceeds the line for *h* = 1.66, corresponding to 5 % significance level, then the according cell is marked as a possible outlier, and if the value of statistic *h* exceeds the line for *h* = 1.87, corresponding 1 % significance level, then the according cell is marked as an outlier.

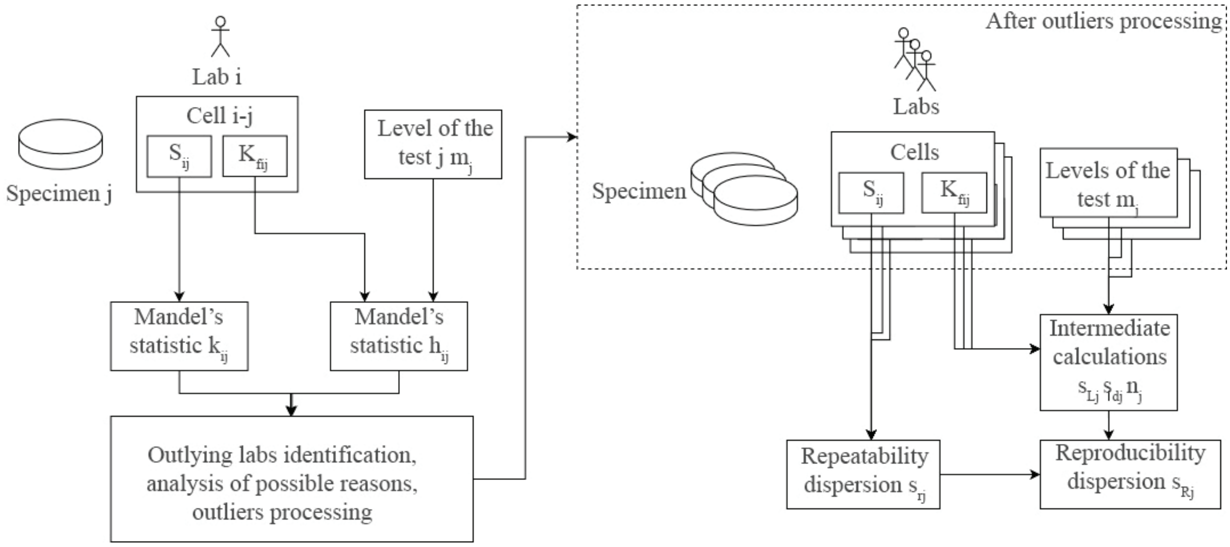

Figure 3 – General precision dispersions evaluation procedure

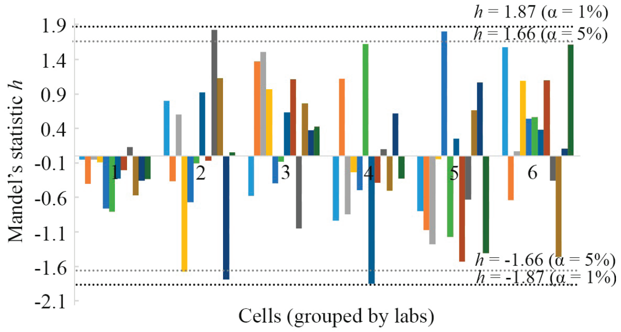

Figure 4 – Mandel's *h* statistics for the measurements using sensor for flat surfaces

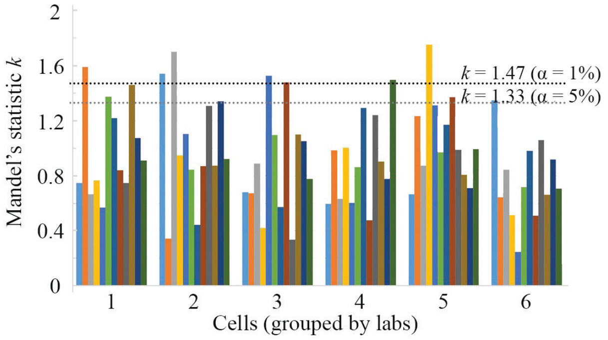

Figure 6 – Mandel's *k* statistics for the measurements using sensor for flat surfaces

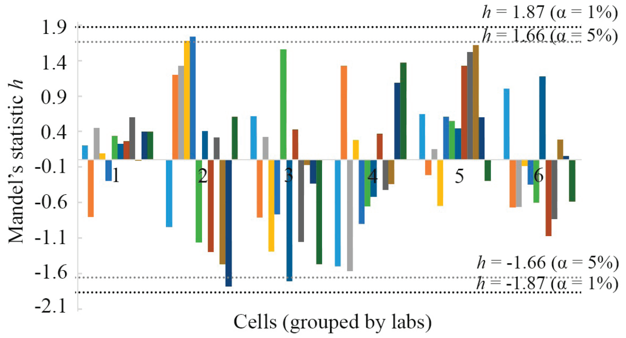

Figure 5 – Mandel's *h* statistics for the measurements using sensor for hard-to-reach places

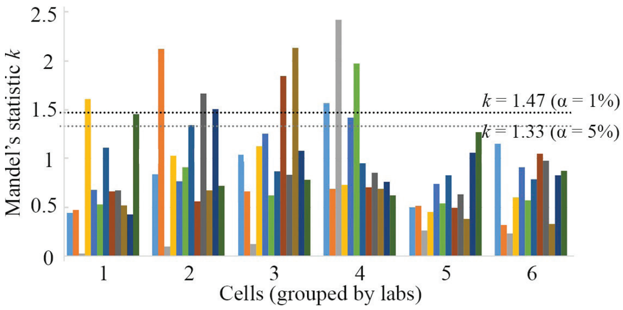

Figure 7 – Mandel's *k* statistics for the measurements using sensor for hard-to-reach places

Statistic k was calculated using formula:

$$k_{ij} = \frac{s_{ij}\sqrt{p_j}}{\sqrt{\sum s_{ij}^2}}.$$

In turn to determine which of the calculated k_{ij} values are outliers or possible outliers, a procedure was carried out similar to outlier analysis for statistic h. For $p = 6$ and the number of measurements in the cell equal to 10, critical values equal to 1.47 and 1.3 for 1 % and 5 % accordingly.

The outliers and possible outliers were determined among cells using diagrams presented on Figures 4–7 these are all the values, exceeding significance levels $\alpha = 1$ % и 5 % accordingly. For example, for lab 1, test results on level 2 were marked as outliers, levels 6 and 10 as possible outliers (Figure 7). The calculation of Mandel's statistics and graphical analysis is necessary to determine the reason of a worse repeatability in individual labs and to eliminate those reasons, and for subsequent statistical outliers testing. Since the outliers and possible outliers are singular and do not have a common underlying cause, we consider outliers as true outliers and cells, that were marked as outliers were deleted from calculations.

After statistical outliers testing, we've calculated the repeatability and reproducibility characteristics. Repeatability variance was determined for each level using formula:

$$s_{rj}^2 = \frac{1}{\sum_{i=1}^{p}\left(n_{ij}-1\right)} \sum_{i=1}^{p} s_{ij}^2\left(n_{ij}-1\right).$$

Lab variance was determined for each level using formula:

$$s_{Lj}^2 = \frac{s_{dj}^2 - s_{rj}^2}{\bar{\bar{n}}_j},$$

where

$$s_{dj}^2 = \frac{1}{p-1}\sum_{i=1}^{p} n_{ij}\left(\bar{y}_{ij} - \hat{m}_j\right)^2;$$

$$\bar{\bar{n}}_j = \frac{1}{p-1}\left[\sum_{i=1}^{p} n_{ij} - \frac{\sum_{i=1}^{p} n_{ij}^2}{\sum_{i=1}^{p} n_{ij}}\right].$$

Reproducibility variances were calculated after the lab variances was determined using formula:

$$s_{Rj}^2 = s_{rj}^2 + s_{Lj}^2.$$

For a better presentation, reproducibility and repeatability variances were calculated into variance coefficients (VC) and displayed as a function of K_f (Figures 8 and 9).

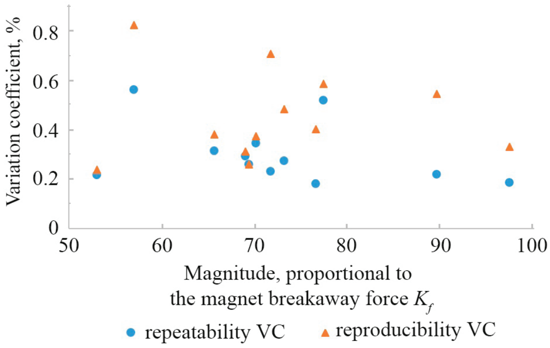

Figure 8 – Repeatability and reproducibility variation coefficient using sensors for flat surfaces

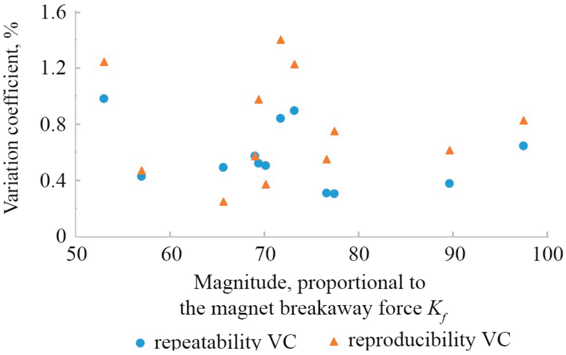

Figure 9 – Repeatability and reproducibility variation coefficient using sensors for hard-to-reach places

Figure 8 shows, that repeatability VC is concentrated between 0.2–0.4 %, and reproducibility VC is concentrated between 0.2–0.6 %. Both characteristics are not dependent on the magnet breakaway force, and the maximum value of reproducibility VC does not exceed 0.9 %, while repeatability VC does not exceed 0.6 %. Figure 9 shows a similar picture, but all VC values are ≈ 1.7 higher, which means that the sensor for hard-to-reach places had worse accuracy characteristics.

Indeed, after the close inspection of the sensor for hard-to-reach places it was determined that the surface of the magnet had accumulated metallic dust the presence of which worsened the sensor accuracy. Several sensors were graduated with the goal of evaluating their measurement accuracy then stress measurement of these sensors was compared with the stresses induced by testing machine. Wherein the surface of the sensitive element of a sensor with worse precision characteristic was not cleared.

As it can be seen in the Figure 10 worsening the precision characteristics leads to significant deviation of sensor measurements when directly measuring stress in nickel specimen.

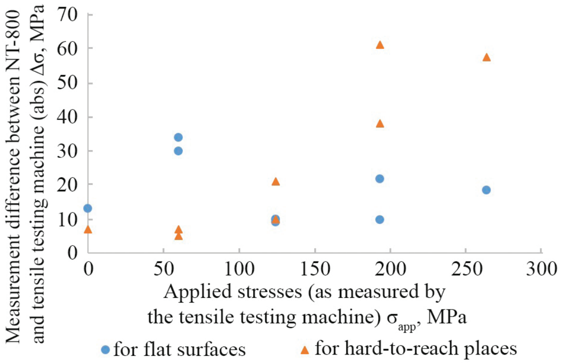

Figure 10 – Scatter plot of the difference between the readings of the NT-800 and the tensile machine against the applied stresses according to the readings of the tensile machine

From the data shown in Figure 10, it can be seen that degradation in precision performance leads to significant changes in device readings. Thus, the absolute measurement error of the sensor for hard-to-reach places was ≈ 3 times higher than that of the sensor for flat surfaces in the range of 200–300 MPa. Taking into account that the dependence of the magnet breakaway force on stresses is inverse (Figure 1) then the measurement errors of sensors at high voltages should decrease. In the case of a sensor for hard-to-reach places, this pattern is not present. This confirms the importance of defining the characteristics of precision: repeatability and reproducibility and the possibility of their use for rejection of sensors in the preliminary stage. Extensive research carried out later yielded similar results. Sensors which had an unstable operation of spring elements, friction in the bearing units of motors, also had an increased repeatability and reproducibility VC (by more than 1.5 %) which ultimately affected the absolute measurement error. These studies also helped to establish that with the repeatability and reproducibility VC not exceeding 1 %, the absolute error in the stress range of 1–300 MPa does not exceed 35 MPa, which meets the requirements of most consumers.

Conclusion

The repeatability and reproducibility variation coefficients allow you to get an idea of the accuracy characteristics of the device, and compare different devices and sensors with each other at the preliminary stage of their manufacture. This makes it possible to identify sensors with insufficient quality in time and avoid additional labor costs.

The mean values and variances of the K_f value were determined for all cells (combinations of laboratory and test level). The repeatability variances s_r^2 and reproducibility variances s_R^2 were calculated, on their basis the corresponding variation coefficients were calculated. I case of the sensor for flat surfaces, repeatability variation coefficients were concentrated in the 0.2–0.4 % range and did not exceed 0.6 %, and reproducibility variation coefficients were concentrated in the 0.2–0.6 % range and did not exceed 0.9 %. Repeatability and reproducibility variation coefficients of the sensor with worsened accuracy characteristics were 1.7 higher due to impurity of the sensitive element.

It was determined that the values of variances s_r^2 and s_R^2 practically do not depend on the thickness of the tested specimen or on its internal stresses and can be used as an objective characteristic to make decision on sensors rejection.

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