TRANSFORMING AND PROCESSING THE MEASUREMENT SIGNALS

EVALUATION OF COMPONENTS UNCERTAINTY IN COMPOSITE MATERIAL WEAR RESISTANCE

Kateryna Chornoivanenko, PhD, As.-Prof., Anatoliy Dolzhanskiy, Dr. Sc., Prof.
Ukrainian State University of Science and Technologies, Ukraine,
e-mail: ekatmovchan@gmail.com

https://doi.org/10.23939/istcmtm2025.01.086

Abstract. Accurately estimating measurement uncertainty is crucial for reliable and meaningful results in material abrasive wear resistance testing. In general, the process of assessing uncertainty involves several steps, including identifying sources of uncertainty, determining correlations between input quantities, and calculating various types of uncertainties. Knowing the measurement uncertainty allows for: ensuring compliance with established standards, monitoring and improving the accuracy and reliability of the testing process. The components of the measurement uncertainty of abrasive wear resistance are studied in detail in the paper. It is revealed that indirect factors can have a predominant effect on the total uncertainty of the method. The methodology for assessing uncertainty should be described in regulatory documents to ensure consistency and comparability across different testing laboratories. By incorporating uncertainty assessment into abrasive wear resistance testing, researchers and engineers can improve the quality and reliability of their results, leading to better decision-making in materials selection and process optimization.

Keywords: Measurement uncertainty, Abrasive wear resistance, Uncertainty assessment, Sources of uncertainty, Accuracy, Composite material.

1. Introduction

Calculation of accuracy is necessary in designing technical systems and calculating their parameters, determining the characteristics of devices and instruments used in production and processing measurement results [1–4].

The expressing of the measurement results, control and testing in measurement uncertainties has become the norm at the international level [5–7]. Meanwhile, methods for assessing measurement uncertainty are not prescribed in all regulatory documents on control and testing methods in many areas of industry, including mechanical engineering in Ukraine.

Evaluation of measurement uncertainty is a rather labor-intensive process. It requires the study and identification of all sources of uncertainty, the formulation of a measurement equation, the identification of a correlation between input quantities, the identification of distribution laws of input quantities, the calculation of standard, total and expanded uncertainty [8, 9]. That is difficult in practice. Therefore, there is an urgent task to develop methods for evaluation measurement uncertainty for specific control methods. Additionally, identification and comparison of uncertainty components for specific materials and their operating conditions can provide information for improving both their laboratory research methods and application technologies.

2. Goal

The goal of the current article is development of the evaluation methodology for the measurement uncertainty and uncertainty components for abrasive wear tests of composite material.

3. Methodology for the uncertainty evaluation ofcomposite material wear resistance

Goal: determination of abrasive wear resistance of composite material.

Determination of the measured value:

Abrasive wear (mg/mm^2) of the tested alloys is calculated by the formula:

$$I_{wear} = \frac{\Delta m}{S}\ [\text{mg}\cdot\text{mm}^{-2}], \qquad (1)$$

where $\Delta m = m_1 - m_2$– difference in mass of sample before (m_1) and after (m_2) testing, [mg]; S – cross-sectional area of the sample, [mm^2]:

$$S = \pi(d/2)^2,\ [\text{mm}^2], \qquad (2)$$

where d – diameter of the cylindrical sample, [mm].

Testing equipment:

a) Machine for preparing metallographic samples (friction machine):

set clamping force – 20 N;

rotation speed – 2.5 rps;

total vibration – 2.5 m/s^2;

b) Digital caliper from 0 to 250 mm (maximum permissible absolute error – ±0.02 mm);

c) Analytical scales (maximum weighing limit – 200 g, resolution – 0.1 mg, permissible weighing error – up to 25 g – ± 0.25 mg; from 25 to 100 g – ± 0.5 mg; from 100 to 200 g – ± 0.75 mg);

d) stopwatch timer (error ±1 s);

e) P360 grade abrasive paper with an average grain size of 40.5 μm, permissible deviation ±1.5 μm (the value is determined according to the requirements of ISO 6344 [10]).

The results of the abrasive wear resistance measuring of the composite material are given in Table 1.

Table 1. The results of the abrasive wear resistance measuring

m_1, mg	m_2, mg	d, mg
1622.9	1597.3	10.01
1622.8	1597.5	10.00
1623.0	1597.3	9.99
1623.1	1597.1	9.99
1622.9	1597.2	10.01
1623.1	1597.4	10.01
1622.7	1597.4	9.99
1622.9	1597.3	10.00
1622.8	1597.1	10.00
1623.0	1597.2	10.01
$\overline{m_1} = 1622.92$	$\overline{m_2} = 1597.28$	$\bar{d} = 10.001$

Identifying sources of uncertainty.

The goal of this stage is to identify the main sources of uncertainty and understand their impact on the measurand and its uncertainty. This is one of the most difficult stages in the evaluation of measurement uncertainty. Because, on the one hand, there is a risk of neglecting some sources of uncertainty, on the other hand, there is a risk of double counting them.

Using a "cause – effect" Ishikawa diagram is one possible way to prevent this [3]. The first stage of the formation of such diagram consists in specifying the main parameters in the equation of the measured value – the main branches of the diagram. Then, each step of the method is considered. The influencing quantities are added to the diagram. They are taken as factors acting outside the main effects. This is done for each main branch until the resulting additional effects become sufficiently small. In other words, until their influence on the result becomes negligible.

As mentioned above, the parameters included in the measurement equations can be sources of uncertainty. In this case, these are: the difference in mass and the cross-section of the samples. The measurement process and the metrological characteristics of the used equipment are considered to identify additional sources of uncertainty. The measurement conditions are the main requirements for the measurement. These are temperature (20±5) °C, relative humidity not less than 55 % and the absence of vibration.

The corresponding source sofun certainty are shownin the Fig. 1.

At first glance, the error of the laboratory scales for determining the mass and the caliper for determining the cross-section is one of the main sources of uncertainty. However, the analysis of the test method showed that secondary factors affect the main sources of uncertainty. They make a significant contribution to the total uncertainty of the method.

Further, the analysis of the main sources of uncertainty is performed in accordance with the presented data.

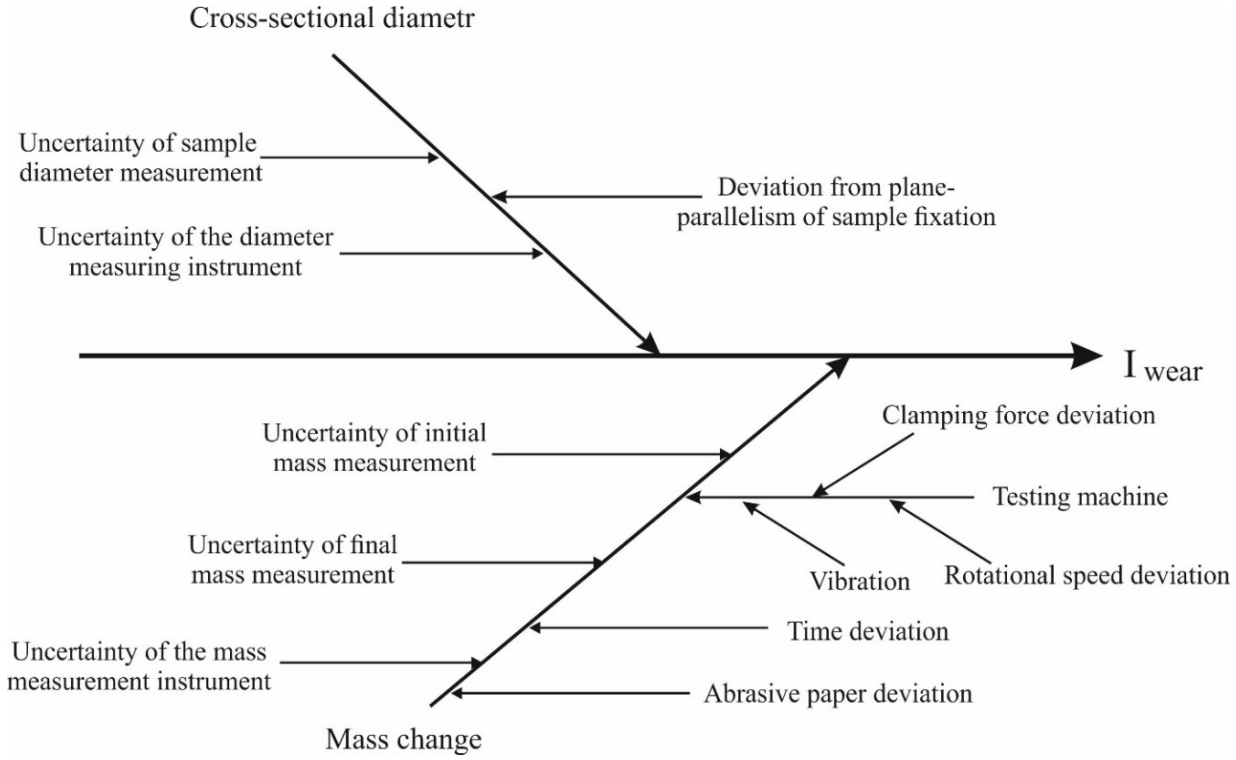

Fig. 1. Ishikawa cause-effect diagram

Contribution of the testing machine to the total uncertainty (Δ_{clamp}, Δ_{rotat}, Δ_{vibr}).

The limit of the permissible relative error of the clamping force is specified in the documentation for the machine for preparing metallographic samples. It is ±1.0 % of the applied load. The documentation also establishes the maximum permissible relative error of ±1.0 % of the rotation speed of the planetary mechanism. There is no other additional information.

Therefore, we adopt a rectangular distribution of probability density [4] and determine the type B of standard uncertainty [3] at the first approximation. The standard uncertainty is determined by the formula [7] for a rectangular distribution:

$$u_B = \frac{a}{\sqrt{3}}, \quad (3)$$

where a – half-width of the confidence interval.

However, it is logical to assume that vibrations appear in the testing machine during the abrasive wear test. Their presence cannot be neglected. Analysis of additional sources of information [11] showed that the total vibration of such grinding machines is 2.5 m/s^2. The error of the measured vibration value is 0.2 of the total vibration. This data is established using the current international document CEN EN 12096-1997 Mechanical vibration – Declaration and verification of vibration emission values [12]. Thus, the error of the measured vibration value is ±0.5 m/s^2 in our case.

Contribution of mass measurement to total uncertainty (m_1, m_2, Δ_{scal})

The mass of sample is determined by weighing on analytical scales. The uncertainty associated with the mass of sample is also estimated using the balance calibration certificate and manufacturer documentation.

If there is an array of experimental data, we calculate type A of standard uncertainty [7]. That is, the standard uncertainty of mass measuring the samples is determined by the formula [4]:

$$u_A = \sqrt{\frac{1}{n(n-1)} \cdot \sum_{i=1}^{n} (X_i - \bar{X})^2}, \quad (4)$$

where X_i is the i-th measurement result; $\bar{X}$ is the arithmetic mean of the measurement results; n is the number of observations.

Detailed calculations of the components of mass uncertainty can be very complicated. Therefore, it is advisable to refer to the manufacturer's recommendations.

The manufacturer's documentation states that the uncertainty of analytical laboratory scales depends on the uncertainty of the scale calibration. This is caused by changes in sensitivity and nonlinearity of the calibration function. Changes in sensitivity can be neglected due to the fact that the mass difference is obtained on the same scales in a very narrow measurements range.

The documentation for the analytical laboratory scales defines a measurement error of ±0.25 mg for weighing up to 25 g. This is the maximum difference between the actual weight on the scales and fixed value on the scale. The scale manufacturer recommends using a rectangular distribution to calculate the non-linearity contribution to the standard uncertainty.

The correction for air buoyancy is not taken into account here. Since all results are given for air weighing as agreed [13]. The remaining uncertainties are too small to justify accounting for them.

Contribution of cross-sectional area measurement to the total uncertainty (d, Δ_{calip}, Δ_{plane})

The cross-sectional area of the samples (S) is calculated using formula (2) based on its measured diameter, using a digital caliper. The measurement uncertainty due to repeated measurements of the sample diameter is determined by type A of standard uncertainty using formula (4) [4].

The value of the standard deviation of the measurement uncertainty, caused by the measurement error of the caliper of the diameter of the samples, can be taken from the verification protocol. It is necessary to keep in mind that the methods for assessing the measurement uncertainty during its verification / calibration are absent in the verification methods of calipers. In practice, only the recognition of the suitability of a given caliper for use is indicated in the verification/calibration certificate. In this case, if the caliper is recognized as suitable for use, considering that all its metrological characteristics are within the permissible limits, caused by the error of the caliper, the measurement uncertainty can be determined by expression (3), assuming that it can be described by a rectangular distribution.

The samples are fixed in special clamps during testing, it is important to ensure that the sample surface is strictly parallel to the surface of the abrasive paper. It is based on the above that some uncertainty arises due to the deviation from the plane-parallelism of the surface. In this case, it is assumed that this could introduce an additional contribution to the uncertainty of 2 % of the determined cross-sectional area at 95 % confidence level. The standard uncertainty is calculated based on the assumption of a triangular probability distribution [9]:

$$u_B = \frac{a}{\sqrt{6}}, \quad (5)$$

where a – half-width of the confidence interval.

The nominal values of deviation from plane-parallelism are more probable than the extreme values in the real process of fixing samples in special clamps. Therefore, the triangular distribution is chosen. Thus, the probability distribution is better approximated by a triangular distribution than by a rectangular one.

Contribution of time to the total measurement uncertainty (Δ_τ)

The fixing exact test time significantly effects on the obtained mass loss during processing in the considered abrasive wear test method. Therefore, it is important to strictly adhere to the test time that specified in the method.

The proposed method sets the test duration at 90 s. Time is controlled with an accuracy of ±1 s. Assuming that the distribution within the specified limits has a rectangular shape, the standard uncertainty is calculated taking into account the division of the time variation by √3 according to formula (3) [7].

Contribution of abrasive paper grain to the total uncertainty (Δ_{grain})

The abrasive wear test method based on the principle of abrasion of contacting surfaces is analyzed also. It is determined that the grain size of the abrasive paper also needs to be taken into account when considering sources of uncertainty. The provisions of the international document ISO 6344-1 [10] are used to calculate the acceptable grain deviation. A deviation of 1.5 µm is acceptable for P360 grade abrasive paper with an average grain size of 40.5 µm.

If measurements are made under normal conditions and without external vibration, then standard uncertainties due to temperature deviation from the nominal and the presence of vibration are not calculated. A study of the dependence of changes in standard uncertainties on changes in temperature and vibration must be carried out when the measurement conditions deviate from the nominal ones.

Thus, *the measurement function (model)* in our case has the form:

$$\mathrm{I}_{wear} = f\begin{pmatrix} m_1, m_2, d, \Delta_{clamp}, \Delta_{rev}, \\ \Delta_{vibr}, \Delta_{scal}, \Delta_{calip}, \Delta_{plane}, \Delta_\tau, \Delta_{grain} \end{pmatrix}, \quad (6)$$

where Δ_{scal} – error of analytical laboratory scales, [mg]; Δ_{calip} – caliper error, [mm]; Δ_{plane} – deviation from plane-parallelism of the sample surface, %; Δ_{clamp} – clamping force error, %; Δ_{rotat} – error of rotation speed of the planetary mechanism of the testing machine, %; Δ_{vibr} – vibration error of the testing machine, [m/s^2]; Δ_τ – time error, [s]; Δ_{grain} – deviation from the average grain size of the abrasive paper, [µm].

Quantitative expression of uncertainty components

At this stage, the uncertainty from each source (revealed at the stage of identifying sources of uncertainty) should be quantified and then converted into a standard uncertainty.

Testing machine

$$u(\Delta_{clamp}) = \frac{\Delta_{clamp}}{\sqrt{3}} = \frac{0.2}{\sqrt{3}} = 0.12 \text{ H.}$$

$$u(\Delta_{rotat}) = \frac{\Delta_{rotat}}{\sqrt{3}} = \frac{0.025}{\sqrt{3}} = 0{,}014 \text{ rps.}$$

$$u(\Delta_{vibr}) = \frac{\Delta_{vibr}}{\sqrt{3}} = \frac{0.5}{\sqrt{3}} = 0.29 \text{ m/s}^{2.}$$

Mass

$$u_{\mathrm{A}}(m_1) = \sqrt{\frac{1}{n(n-1)} \cdot \sum_{i=1}^{n} \left(m_{1i} - \overline{m_1}\right)^2} = 0.042 \text{ mg.}$$

$$u_{\mathrm{A}}(m_2) = \sqrt{\frac{1}{n(n-1)} \cdot \sum_{i=1}^{n} \left(m_{2i} - \overline{m_2}\right)^2} = 0.042 \text{ mg.}$$

$$u(\Delta_{scal}) = \frac{\Delta_{scal}}{\sqrt{3}} = \frac{0.25}{\sqrt{3}} = 0.14 \text{ mg.}$$

Time

$$u(\Delta_\tau) = \frac{\Delta_\tau}{\sqrt{3}} = \frac{1}{\sqrt{3}} = 0.58 \text{ s.}$$

Abrasive paper (Δ_{grain})

$$\left(\Delta_{grain}\right) = \frac{\Delta_{grain}}{\sqrt{3}} = \frac{1.5}{\sqrt{3}} = 0.87 \text{ µm.}$$

All the above-mentioned indicators affect the total uncertainty of mass measurement. It is determined by the formula:

$$\frac{u_{\mathrm{c}}(m_1)}{m_1} = \sqrt{\left(\frac{u_A(m_1)}{m_1}\right)^2 + \left(\frac{u(\Delta_{scal})}{m_1}\right)^2 + \left(\frac{u(\Delta_{clamp})}{F_{clamp}}\right)^2 + \left(\frac{u(\Delta_{rotat})}{V_{rotat}}\right)^2 + \left(\frac{u(\Delta_{vibr})}{a_{vibr}}\right)^2 + \left(\frac{u(\Delta_\tau)}{\tau}\right)^2 + \left(\frac{u(\Delta_{grain})}{a_{grain}}\right)^2}$$

Calculations have shown that $\frac{u_{\mathrm{c}}(m_1)}{m_1}$ is equal 0.12.

Consequently, $u_{\mathrm{c}}(m_1) = m_1 \cdot 0.12 = 192.21$ mg.

$$\frac{u_{\mathrm{c}}(m_2)}{m_2} = \sqrt{\left(\frac{u_A(m_2)}{m_2}\right)^2 + \left(\frac{u(\Delta_{scal})}{m_2}\right)^2 + \left(\frac{u(\Delta_{clamp})}{F_{clamp}}\right)^2 + \left(\frac{u(\Delta_{rotat})}{V_{rotat}}\right)^2 + \left(\frac{u(\Delta_{vibr})}{a_{vibr}}\right)^2 + \left(\frac{u(\Delta_\tau)}{\tau}\right)^2 + \left(\frac{u(\Delta_{grain})}{a_{grain}}\right)^2}$$

Calculations have shown that $\frac{u_{\mathrm{c}}(m_2)}{m_2}$ is equal 0.12.

Consequently, $u_{\mathrm{c}}(m_2) = m_2 \cdot 0.12 = 189.17$ mg.

The identified sources of uncertainty affect the change of the mass sample Δm during the test, so we calculated the standard uncertainty of Δm:

$$\frac{u_{\mathrm{c}}(\Delta m)}{\Delta m} = \sqrt{\left(\frac{u_A(m_1)}{m_1}\right)^2 + \left(\frac{u(\Delta_{scal})}{m_1}\right)^2 + \left(\frac{u(\Delta_{clamp})}{F_{clamp}}\right)^2 + \left(\frac{u(\Delta_{rotat})}{V_{rotat}}\right)^2 + \left(\frac{u(\Delta_{vibr})}{a_{vibr}}\right)^2 + \left(\frac{u(\Delta_\tau)}{\tau}\right)^2 + \left(\frac{u(\Delta_{grain})}{a_{grain}}\right)^2}$$

Calculations have shown that $\frac{u_{\mathrm{c}}(\Delta m)}{\Delta m}$ is equal 0.12.

Consequently, $u_{\mathrm{c}}(\Delta m) = \Delta m \cdot 0.12 = 3.04$ mg.

It is convenient to present intermediate results in the form of an uncertainty budget (Table 2). The uncertainty budget includes a list of all input quantities, their estimates, along with their assigned standard measurement uncertainties and distribution type.

In addition to information about the input quantities, it is convenient to include information about the measured value in the budget: measurement result, total standard uncertainty, effective number of degrees of freedom, coverage ratio and expanded uncertainty.

Table 2. Uncertainty budget of mass change Δm of the sample during the test

The input value	Designation	Type of uncertainty assessment	Distribution type	$\frac{u(\Delta x_i)}{\Delta x_i}$	Contribution to the total uncertainty, %
The difference in the mass of the sample before (m_1) and after (m_2) the test	Δm	A	Gaussian	0.0024	1.5
Error of analytical laboratory scales	Δ_{scal}	B	rectangular	0.0055	3.3
Clamping force error	Δ_{clamp}	B	rectangular	0.006	3.7
Error of rotation speed of the planetary mechanism of the testing machine	Δ_{rotat}	B	rectangular	0.0056	3.4
Vibration error of the testing machine	Δ_{vibr}	B	rectangular	0.116	71.0
Time error	Δ_τ	B	rectangular	0.0064	3.9
Deviation from the average grain size of the abrasive paper	Δ_{grain}	B	rectangular	0.021	13.1

Table 3. Uncertainty budget of cross-sectional diameter of the sample

The input value	Designation	Type of uncertainty assessment	Distribution type	$\frac{u(\Delta x_i)}{\Delta x_i}$	Contribution to the total uncertainty, %
Diameter of the cylindrical sample	d	A	Gaussian	0.00028	2.9
Caliper error	Δ_{calip}	B	rectangular	0.0012	12.5
Deviation from plane-parallelism of the sample surface	Δ_{plane}	B	triangular	0.008	84.6

Cross-sectional area (d, Δ_{calip}, Δ_{plane})

$u_A(d) = \sqrt{\frac{1}{n(n-1)} \cdot \sum_{i=1}^{n} \left(d_i - \bar{d}\right)^2}$=0.0028 mm.

$u\left(\Delta_{calip}\right) = \frac{\Delta_{calip}}{\sqrt{3}} = \frac{0.02}{\sqrt{3}} = 0.012$ mm.

$u\left(\Delta_{plane}\right) = \frac{\Delta_{plane}}{\sqrt{6}} = \frac{S \cdot 2\%}{\sqrt{6}} = \frac{1.57}{\sqrt{6}} = 0.64$ mm.

These three contributions sum up to obtain the standard uncertainty $u(d)$ of the diameter:

$$\frac{u(d)}{d} = \sqrt{\left(\frac{\mathrm{u_A(d)}}{\mathrm{d}}\right)^2 + \left(\frac{\mathrm{u}\left(\Delta_{calip}\right)}{\mathrm{d}}\right)^2 + \left(\frac{\mathrm{u}\left(\Delta_{plane}\right)}{\mathrm{S}}\right)^2}$$

Calculations have shown that $\frac{u(d)}{d}$ is equal 0.0082.

Consequently, $u(d) = d \cdot 0.0082 = 0.082$ mm.

The uncertainty budget for measuring the cross-sectional diameter of the sample is given in Table 3.

Calculation of total standard uncertainty

Abrasive wear (I_{wear}) of the experimental alloys is determined by the formula:

$$\mathrm{I}_{wear} = \frac{\Delta m}{s} = \frac{m_1 - m_2}{\pi \cdot \left(\frac{d}{2}\right)^2} \text{ [mg·mm}^{-2}\text{]}. \quad (7)$$

The values of the input quantities, their standard uncertainties and relative standard uncertainties are given in Table 4.

Using these values, we find the abrasive wear resistance of the composite material:

$$\mathrm{I}_{wear} = \frac{\Delta m}{s} = \frac{m_1 - m_2}{\pi \cdot \left(\frac{d}{2}\right)^2} = \frac{1622.9 - 1597.3}{\pi \cdot \left(\frac{10.001}{2}\right)^2} = 0.3266 \text{mg·mm}^{-2}.$$

The correlation between input quantities is found to determine the total uncertainty. In our case, there is a correlation between the cross-sectional diameter of the sample d and the difference in mass Δm.

Table 4. Input quantities and their uncertainties

Quantity	The value of x	$u(\Delta x_i)$	$u(\Delta x_i)/\Delta x_i$
Initial mass of the sample before testing (m_1)	1622.9 mg	192.21 mg	0.12
Mass of the sample after the wear test(m_2)	1597.3 mg	189.17 mg	0.12
Δm	25.64 mg	3.04 mg	0.12
Diameter of the sample (d)	10.001 mm	0.082 mm	0.0082

The total standard uncertainty is determined by the following expression, considering that two of the input quantities are correlated with each other [7]:

$$u_t{}^2(I_{wear}) = \sum_{i=1}^{n} c_i^2 u^2(x_i) + 2\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} c_{\Delta m} c_d u(\Delta m) u(d) r(\Delta m, d), \quad (8)$$

where $u(x_i)$ – standard uncertainty of the i-th input quantity; $r(\Delta m, d)$ – correlation degree between Δm and d; $c_{\Delta m}$ and c_d – sensitivity coefficients; n – number of input quantities.

The sensitivity coefficients show how the initial estimate φ changes with a change in the input estimates $x_1, \dots x_n$ and are equal to [4]:

$$c_i = \frac{\partial \varphi}{\partial x_i}, \quad (9)$$

$$c_{\Delta m} = \frac{\partial\left(\frac{\Delta m}{\pi\cdot\left(\frac{d}{2}\right)^2}\right)}{\partial \Delta m} = \frac{1}{\pi\cdot\left(\frac{d}{2}\right)^2}, \quad (10)$$

$$c_d = \frac{\partial\left(\frac{\Delta m}{\pi\cdot\left(\frac{d}{2}\right)^2}\right)}{\partial d} = -\frac{8\cdot\Delta m\cdot d^{-3}}{\pi}. \quad (11)$$

In our case, the sensitivity coefficients are:

$$c_{\Delta m} = 0.013 \text{ and } c_d = -0.065.$$

The degree of correlation between $x_{\Delta m}$ and x_d is characterized by the estimation of the correlation coefficient, which is determined based on formula:

$$r(x_{\Delta m}, x_d) = \frac{u(\Delta m, d)}{u(\Delta m) u(d)}. \quad (12)$$

The covariance estimate of two correlated input quantities Δm and d, obtained during repeated observations, is calculated according to the formula [9]:

$$u(\Delta m, d) = s(\overline{m_1}, \overline{m_2}, d), \quad (13)$$

where $s(\overline{m_1}, \overline{m_2}, d)$ is found by expression:

$$s(\overline{m_1}, \overline{m_2}, \bar{d}) = \frac{1}{n(n-1)}\sum_{i=1}^{n}\left(\left(m_{1_i} - m_{2_i}\right) - \left(\overline{m_{1_i}} - \overline{m_{2_i}}\right)\right)\left(d_i - \bar{d}\right), \quad (14)$$

where m_{1_i}, m_{2_i} and d_i – the results of the measurement of quantities m_1, m_2 and d respectively, $\overline{m_1}, \overline{m_2}, \bar{d}$ – their averages.

Thus, $u(x_{\Delta m}, x_d) = s(\overline{m_1}, \overline{m_2}, d) = 1.78 \cdot 10^{-5}$.

$$r(x_{\Delta m}, x_d) = \frac{u(\Delta m, d)}{u(\Delta m) u(d)} = \frac{1.78\cdot 10^{-5}}{3.04\cdot 0.082} = 7.1 \cdot 10^{-5}.$$

Therefore, the total standard uncertainty for the determining abrasive wear resistance of the composite material is:

$$u_t{}^2(I_{wear}) = c_{\Delta m}^2 u^2(\Delta m) + c_d^2 u^2(d) + 2c_{\Delta m} c_d u(\Delta m) u(d) r(\Delta m, d) =$$
$$= 0.013^2 \cdot 3.04^2 + (-0.065)^2 \cdot 0.082^2 + 2 \cdot 0.013 \cdot (-0.065) \cdot 3.04 \cdot 0.082 \cdot 7.1 \cdot 10^{-5} =$$
$$= 0.0015.$$

$$u_t(I_{wear}) = \sqrt{0.0015} = 0.039 \text{ mg·mm}^{-2}.$$

The contributions of different factors to the total uncertainty are presented in Fig. 2. The contribution associated with the impact of vibration on the test machine is the largest and most predominant. Therefore, this component should be investigated in more detail in the future. And it is also necessary to develop ways to reduce it.

The expanded uncertainty $U(I_{wear})$ is obtained by multiplying the total standard uncertainty by the coverage factor according to the formula [2]:

$$U(I_{wear}) = k \cdot u_t(I_{wear}), \quad (15)$$

where k – coverage ratio.

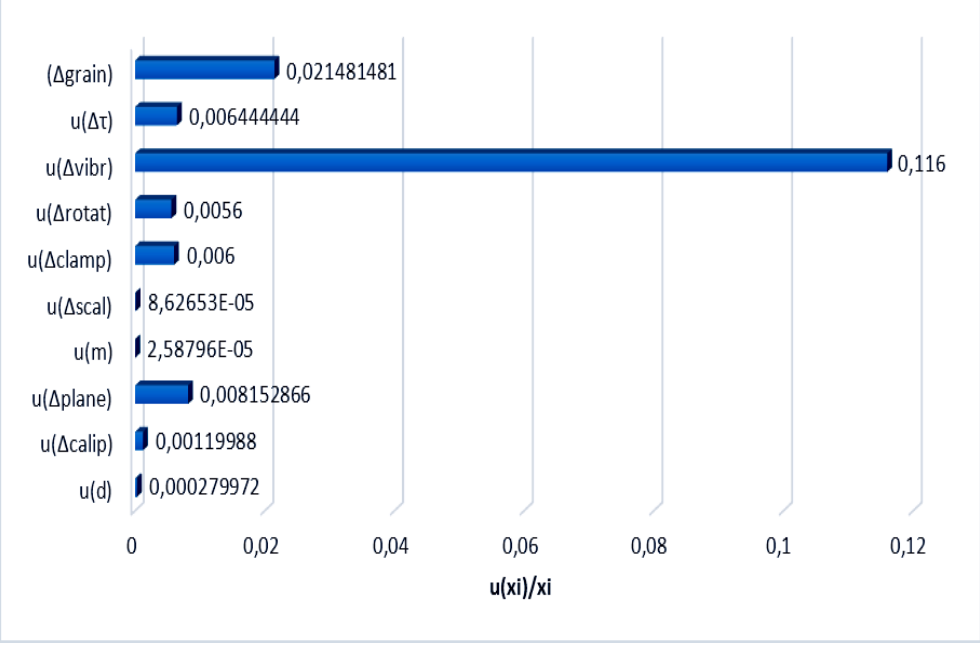

Fig. 2. Contributions of component uncertainties of the abrasive wear resistance measuring of the composite material to the total uncertainty

In the Guide to the Expression of Uncertainly in Measurement [7], it is recommended to take the value of 2 of the coverage coefficient at a confidence probability of 0.95. For $k = 2$, the expanded uncertainty will be equal to:

$$U(I_{wear}) = 2 \cdot 0.039 = 0.078\, mg{\cdot}\text{mm}^{-2}.$$

Thus, the notation of the result of the abrasive wear resistance measuring of the composite material looks like this:

$$I_{wear} = (0.327 \pm 0.078)\text{mg}{\cdot}\text{mm}^{-2},\ p{=}0.95.$$

4. Conclusions

The method for assessing the uncertainty for abrasive wear resistance measuring has been developed. According to international regulatory documents, estimating measurement uncertainty must involve identifying sources of uncertainty, the presence of a correlation between input quantities, determining the distribution laws of input quantities, sensitivity coefficients, standard, total and expanded uncertainties. Knowledge of the measurement uncertainty allows us to compare measurement results with established requirements during assessing compliance. It also makes it possible to control the measurement and technological processes. In the process of studying the wear of composite materials on a friction machine using the developed uncertainty assessment method, it was established that the main contribution to the total uncertainty is made by vibration effects. The task of reducing equipment vibration is set to increase the reliability of the results of such measurements. The presented approach can be used in scientific and industrial laboratories to increase the reliability of other types of measurements.

Conflict of Interest

The authors state that there are no financial or other potential conflicts regarding this work

References

[1] I. Farrance, R. Frenkel,“Uncertainty of Measurement: A Review of the Rules for Calculating Uncertainty Components through Functional Relationships”, Clin Biochem Rev., Vol. 33, 2012, pp. 49–75.

[2] G. H. White, “Basics of estimating measurement uncertainty”, *Clin Biochem. Rev.*, Vol. 29, 2008, pp. 53–60.

[3] A. Deacon, *Calculations in Laboratory Science*. London: ACB Venture Publications, 2009.

[4] L. Kirkup, B. Frenkel,*An Introduction to Uncertainty in Measurement.* Cambridge University Press, 2006.

[5] Joint Committee for Guides in Metrology Evaluation of measurement data – Guide to the expression of uncertainty in measurement (GUM) JCGM 100:2008. http://www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf

[6] Joint Committee for Guides in Metrology Evaluation of measurement data – An introduction to the “Guide to the expression of uncertainty in measurement” and related documents.
JCGM104:2009. http://www.bipm.org/utils/common/documents/jcgm/JCGM_104_2009_E.pdf

[7] Guide to the Expression of Uncertainly in Measurement. Switerland: ISO, 1993. 101 p.

[8] N. F. Zhang,“Calculation of the uncertainty of the mean of autocorrelated measurements”, *Metrologia*, Vol. 43, 2006, pp. 76–81.

[9] J. R. Taylor, “An Introduction to Error Analysis, the study of uncertainties in physical measurements”. California: University Science Books, 1997.

[10] ISO 6344-1:1998 Coated abrasives. Grain size analysis. Part 1: Grain size distribution test. Switzerland: ISO, 1998.

[11] Available: https://uk.qiantongutmtester.com/

[12] CEN EN 12096-1997 Mechanical vibration –- Declaration and verification of vibration emission values, 1997.

[13] OIML D 28:2004 Conventional value of the result of weighing in air, 2004.