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Verification of Equipment for Measurements of Resistance Welding Parameters - Standard Requirements and Testing Equipment

Abstract: The article discusses parameters affecting the resistance welding process as well as methods and equipment used to measure such parameters. The verification of actual welding parameters involves the use of portable meters, measurement systems or monitoring systems, which, in accordance with related standards, should be periodically verified for the accuracy of indications. The accuracy of indications can be verified using a dedicated testing station, developed and constructed at the Łukasiewicz Research Network – Institute of Welding. The above-named station enables the performance of the simultaneous verification of root-mean-square welding current, current flow time and electrode force. The article also describes the general design of the testing station, its crucial elements as well as software applied during the verification of related equipment. In addition, the article presents testing station accuracy in relation to measurements concerning both welding current and electrode force.

Keywords: resistance welding, device, meter, equipment, welding current, electrode force, verification, calibration, Rogowski coil

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Introduction

The maintaining of high manufacturing standards necessitates the periodic or continuous monitoring of production process parameters and entails the use of appropriate measurement tools, which owing to the intensity of their operation, aging, the culture of handling or other external factors, may develop measurement deviations. To maintain the metrological reliability of measurement devices, they should be subjected to periodic checks or calibration performed using appropriate equipment [12].

In industrial plants, tools used for immediate checks of resistance welding process parameters include meters or measurement systems, which enable measurements of primary parameters including root-mean-square welding current, electrode (pressure) force and the time of welding current flow. In accordance with appropriate normative acts, the aforesaid devices should be periodically checked for the correctness of indications. Testing should be performed under laboratory conditions and involve the use of equipment representing an appropriately higher class of accuracy [12].

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Resistance welding process parameters

The resistance welding process consists in the making of permanent spot or butt welded joints of metallic elements. The formation of a welded joint results from the flow of high density current and the exertion of compressive force affecting metallic elements in the area of current flow. Current flowing through elements subjected to welding and located between copper electrodes generates heat (resulting from the resistance of the aforesaid elements) in accordance with the Joule-Lenz law:

$$Q = \int_0^T i^2 R \mathrm{d}t \tag{1}$$

where R – resistance of elements subjected to welding and located between copper electrodes, i – welding current and T – time of welding current flow [3].

The welding process is performed through the powering of electrodes with alternating current having a frequency of 50 Hz (in AC welding machines) or, in more recent solutions, with a direct current having a frequency of 1000 Hz (in inverter welding machines also known as DC welding machines). Depending on materials subjected to welding, welding current is usually restricted within the range of 0.5 kA to 100 kA [13].

Another important parameter of the resistance welding process is time. During the welding process performed using current having a frequency of 50 Hz, welding time is measured as the multiple of a single period of sinusoidal waveform, which, in relation to a frequency of 50 Hz amounts to 20 ms. In inverter welding machines (1000 Hz), welding time constitutes the multiple of a period being 1 ms in duration. A typical welding time in relation to the 50 Hz welding technology is restricted within the range of 2 to 25 periods, i.e. between 40 ms and 500 ms [3].

Welding current and welding time constitute parameters adjusted and controlled by electronic microprocessor control systems of resistance welding machines and displayed on control panels.

Electrode force, ensuring the proper positioning of elements being welded and affecting both the shape and the mechanical parameters of the weld, depends on the thickness and grades of materials and is calculated on the basis of appropriate guidelines. Typical values are restricted within the range of 100 daN to1000 daN and, usually, do not exceed 2000 daN. Electrode force can be adjusted by means of pneumatic or servomechanical systems [3], [5], [6].

To sum up, the most important parameters characteristic of the resistance welding process include welding current (or more precisely, root-mean-square welding current), welding time (or, in other words, welding current flow time) and electrode force.

The measurement and monitoring of resistance welding process parameters

The measurement of welding current is complicated due to high values of current and performed on a non-contact basis, using measurement transducers such as the current sensing coil (also known as the Rogowski coil or the toroid). The current sensing coil is installed in the secondary circuit of the welding machine. The primary advantage of the coil is the fact that it does not have a magnetic core and, as a result, enables the performance of current measurements within wide ranges (between several and as many as hundreds of thousands of amperes) without the risk of saturating the magnetic core. Another advantage of the coil results from its linear characteristic, independent of the value of current being measured. As a result, the coil can be calibrated using low current. Other coil-related advantages include the wide range of applicable frequencies (up to between ten and twenty MHz) and the fact that the coil constitutes the galvanic insulation separating the measuring line from the current-carrying wire. The Rogowski coil is usually made of a flexible core with an insulated wire wound around it. The only disadvantage of the coil is the obtainment of usable signals.

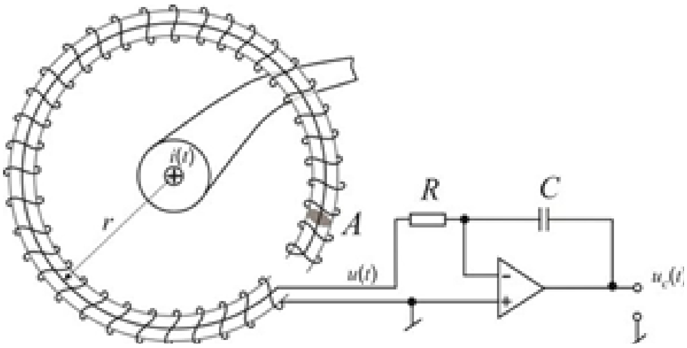

Fig. 1. Measurement of welding current using the Rogowski coil and the integrating circuit [1]

The principle of the measurement of alternating current performed using the Rogowski coil and the integrating circuit is presented in Figure 1. Current induced on coil terminals during the flow of current through the conductor is proportional to the derivative of this current and is expressed by the following equations:

$$u(t) = -M\frac{\mathrm{d}i}{\mathrm{d}t} \quad (2)$$

$$u(t) = -\mu_0 N\frac{A}{l}\frac{\mathrm{d}i}{\mathrm{d}t} \quad (3)$$

where M – mutual inductance between the current-carrying wire and the coil, N – number of winding turns of the coil, A – surface of the winding turn of the coil having radius r, $l=2\pi r$ – length of the coil, di/dt – rate of changes of current in the wire and μ_0 – vacuum magnetic permeability [1].

As follows from equations (2) and (3), the derivative of measured current is obtained on the terminals of the Rogowski coil. Because of this, the obtainment of a voltage signal proportional to the value of measured current requires the integration of coil output voltage [1]. In welding current meters, such operations are performed using analogue or digital integrating circuits, also knowns as integrators. A processed signal is transmitted from the integrator to electronic units tasked with the acquisition of the signal, its mathematical processing and, consequently, the calculation and the presentation of a given current value in the numerical or graphic form.

Figure 2 presents an oscillogram of a typical waveform of welding current *i(t)* (root-mean-square welding current being of approximately 0.5 kA and one AC welding period amounting to 20 ms) and the waveform of voltage *u(t)* induced in the Rogowski coil.

Typical values of Rogowski coil sensitivity, recommended during welding current measurements, include 100 mV/1 kA, 150 mV/1 kA, 220 mV/1 kA and 1.5 V/1 kA.

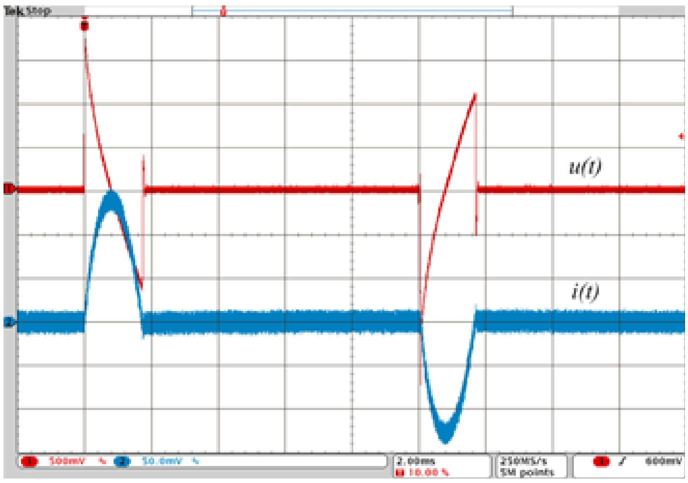

Fig. 2. Oscillogram of the waveform of one period of welding current *i(t)* and of voltage *u(t)* induced in the Rogowski coil – current derivative

Another important aspect, often ignored during measurements performed using Rogowski coils, is the position of the coil in relation to the current-carrying wire. The improper positioning of the coil in relation to the conductor may generate significant measurement errors. As can be seen in Figure 3, the smallest error accompanying measurements performed using the Rogowski coil is obtained when the conductor is located inside the coil, i.e. in the centre of the coil. In turn, the greatest error (of up to as many as 6%) is obtained if the conductor is located near the closing clamp [10].

Welding current can also be measured using non-inductive shunts or sensors using the Hall effect [16]. Regrettably, the complicated installation of the above-named transducers on

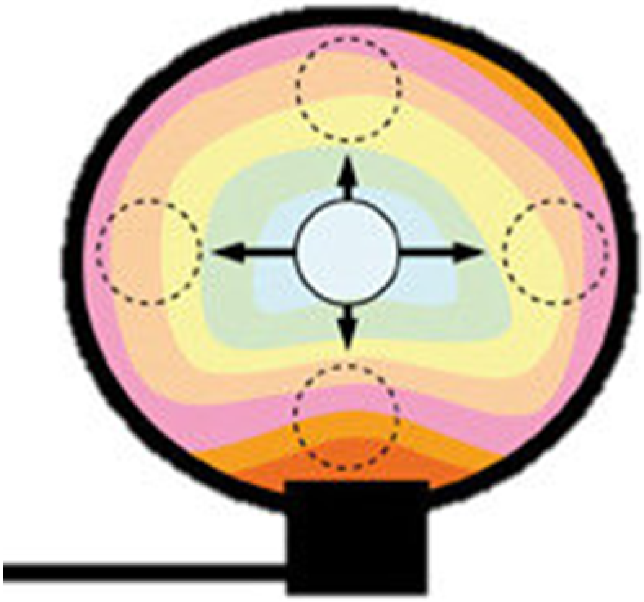

Fig. 3. Effect of the location of the current-carrying wire on Rogowski coil measurement errors [10]

welding machines precludes their large-scale application. Electrode force is measured using transducers based on extensometric bridges and special transducers of signals from extensometric bridges (signal amplifiers). Due to the risk of damage to the device, electrode force should only be measured with the flow of welding current switched off.

The correctness of preset welding parameters can be verified using various types of measurement tools. Some of the most popular measurement devices are portable meters of resistance welding parameters (also knowns as weld testers), used in everyday/occasional checks and enabling measurements of welding current, welding time and electrode force. Such testers are typically equipped with Rogowski coils (for current measurements) and extensometric transducers (used in force-related measurements). More advanced measurement and monitoring systems additionally enable the archiving of parameters concerning each weld, the performance of statistical analysis concerning recent (tens of) welds or verification if a preset current value is restricted within an appropriate range. The possibilities of currently used devices for the monitoring of resistance welding process parameters depend primarily on software programmes installed on related equipment.

The market offer also includes special force gauges with analogue (clock) or digital readouts, intended only for the verification of electrode force. Regardless of functionalities and components of testers or measurement systems, each of the above-presented measurement tools should undergo periodic verification concerning the deterioration (if any) of metrological properties.

There are several metrological procedures verifying the usability and properties of measurement devices. The most important of the aforesaid procedures include verification and calibration. Verification includes a number of activities making it possible to determine whether indications of a given measurement system are consistent with values of parameters restricted within acceptable error limits (defined by the producer of the device or specified in related standards) [16].

In turn, calibration involves activities, which, in relation to specific conditions, link values indicated by a measurement device or a measurement system with actual values indicated by a measurement device or a measurement system characterised by higher (and appropriately confirmed) accuracy [16]. In practice, the verification of the correctness of indications provided by a given device is performed using equipment characterised by at least the same metrological parameters. In turn, the calibration process requires the application of equipment, the accuracy class of which is higher (and whose metrological properties are confirmed by related tests and certificates) than that of a device subjected to calibration [12].

Requirements of standards in relation to equipment and procedures used during measurements of resistance welding parameters

All aspects related to measurements of welding current and welding time are governed by a currently effective set of the PN-EN ISO 17657 series of standards, composed of five parts, the titles and scopes of which are presented in Table 1.

The PN-EN ISO 17657-1 standard introduces the classification of measurement equipment used to measure welding current and indicate welding time. In accordance with the terminology used in the above-named standard, the lowest classified devices used for measurements of welding current and welding time are *welding current sensors* and *welding current measurement systems*, portable or embedded in the

Table 1. List of standards specifying requirements concerning measurement equipment and procedures applied during verification and calibration of devices measuring welding current and welding time

Standard number	Title	Scope
PN-EN ISO 17657-1:2009	Resistance welding. Welding current measurement for resistance welding. Part 1: Guidelines for measurement	The standard specifies requirements concerning the equipment used in the calibration of systems measuring welding current and indicating welding time in relation to resistance welding performed using single-phase alternating current having a frequency of 50 Hz or 60 Hz or using direct current. The standard provides definitions of primary terms as well as information for users of welding current measurement systems featuring a current meter with a current sensing coil. The standard provides definitions of 13 terms.
PN-EN ISO 17657-2:2007	Resistance welding. Welding current measurement for resistance welding. Part 2: Welding current meter with current sensing coil.	The standard specifies requirements concerning the welding current meter with the current sensing coil in relation to measurements concerning welding time and root-mean-square welding current within a specific time interval for resistance welding processes performed using single-phase alternating current having a frequency of 50 Hz or 60 Hz or using direct current. The standard specifies requirements concerning welding current measurement systems with a display or a calibrated output port, which can be connected to the welding machine control system. The standard provides definitions of 6 terms.
PN-EN ISO 17657-3:2007	Resistance welding. Welding current measurement for resistance welding. Part3: Current sensing coil.	The standard specifies requirements concerning toroidal current sensing coils as welding current sensors or welding current measurement systems used to monitor welding current in relation to both types of current, i.e. alternating current having a frequency of 50 Hz or 60 Hz or direct current.
PN-EN ISO 17657-4:2007	Resistance welding. Welding current measurement for resistance welding. Part 4: Calibration system.	The standard specifies calibration systems and calibration procedures concerning welding current measurement systems, current sensors, welding current meters and monitoring equipment with current sensors, used in measurements of welding current restricted within the range of 0.5 kA to 25 kA in relation to welding processes performed using alternating current having a frequency of 50 Hz or 60 Hz or welding processes performed using direct current.
PN-EN ISO 17657-5:2007	Resistance welding. Welding current measurement for resistance welding. Part 5: Verification of welding current measurement system	The standard specifies a procedure used in the verification of welding current meters and monitoring equipment with a current sensing coil in relation to current restricted within the range of 0.5 kA to 25 kA, used in measurements of welding current in relation to welding processes performed using alternating current having a frequency of 50 Hz or 60 Hz or welding processes performed using direct current.

welding current regulator. The aforesaid devices should be checked using the *main welding current measurement system* or calibrated using a *reference welding current measurement system*. The standard also introduces the term of the *main welding current measurement system* for applications in factory workshops or in production departments, which also should be calibrated using a *reference welding current measurement system*. Another element specified in the classification is the *reference welding current measurement system* for laboratory applications and for the calibration of lower classified equipment. The *reference welding current measurement system* must be characterised by higher measurement accuracy than *welding current meters* and the *main welding current measurement system*. Individual elements (Rogowski coil, measurement module) of the *reference welding current measurement system* should be calibrated separately using *certified reference equipment*. In turn, the certified reference equipment should be calibrated by a certification body (accredited laboratory) and have identifiable certificates or other documentation issued by the certification body confirming the metrological properties of such equipment [16].

In accordance with the PN-EN ISO 17657-2 standard, a popular industrial welding current meter should be provided with a current sensing coil (Rogowski coil), a data processing unit and a display showing measurement results, i.e. values of welding current and welding time. The value of welding current should be displayed in true r.m.s values, whereas measurement time should be displayed in welding cycles or in milliseconds [17]. In accordance with the PN-EN ISO 17657-2 standard, the accuracy of welding current meters featuring the current sensing coil (Rogowski coil) depends on their intended use and is as presented in Table 2 [17]:

As can be seen in Table 2, industrial applications usually involve measurement equipment having an accuracy of ±2.0% of the entire measurement scale, yet most of the devices offered presently by manufacturers are characterised by an accuracy of ±1.0% of the entire measurement range.

Part 4 of the PN-EN ISO 17657 standard presents requirements concerning the *reference welding current measurement system* and its individual components as well as calibration procedures concerning welding current measurement systems, current sensors, welding current meters and monitoring devices with current sensors, used in measurements of welding current restricted within the range of 0.5 kA to 25 kA.

The verification procedure and requirements concerning equipment used to check welding current measurements is discussed in detail in the PN-EN ISO 17657–5 standard. The aforesaid verification procedure consists in the comparison of readouts provided by welding current meters with the *main welding current measurement system*, the measurement accuracy of which within the entire measurement range should amount to ±2.0% (in relation to the verification of meters having an accuracy of ±5.0%) or to ±1.0% (in relation to the verification of meters having an accuracy of ±2.0% or ±5.0%). The comparison of indications takes place during the flow of actual welding current in the secondary circuit of the resistance welding machine or an equivalent welding power source (welding current source) enabling the excitation of current, the value of is included in the measurement range of a meter subjected to verification. During measurements, the time of current flow should exceed 100 ms.

Table 2. Measurement accuracy-related classification of welding current meters provided with the current sensing coil [17]

Classification	**Measurement accuracy**	**Application**
Very accurate class	±1.0% of the entire scale	laboratory applications
Accurate class	±2.0% of the entire scale	ordinary applications in very accurate systems
Ordinary class	±5.0% of the entire scale	ordinary applications in ordinary systems

Each verification should be concluded with a report or a test certificate including, among other things, calculated deviations from the calibration value in accordance with equation (4):

$$\delta = \frac{x - x_0}{range} \cdot 100\% \qquad (4)$$

where δ – deviation from the reference value of an indication of the main measurement system, x – value of current read out of a measurement device subjected to verification, x_0 – value of current measured by the main welding current measurement system, *range* – measurement range of a device subjected to verification [19].

It is recommended that resistance welding parameter meters or measurement systems should be subjected to verification at least once a year. Because of the fact that there are no normative acts regulating electrode (pressure) force (one of the primary parameters of the welding process), it is recommended that, in accordance with good engineering practice, electrode force–related issues should be referred to general metrological rules as well as to principles and norms used in the calibration of force gauges and force transducers. Mostly, the measurement accuracy of presently available electrode force meters amounts to ±3.0%. For this reason, it could be stated that, by analogy with current measurements, sufficient accuracy adopted during the verification of electrode force meters should amount to ±2.0%. Similar to current measurements, the electrode force-related verification procedure involves the comparison of indications provided by a force gauge subjected to verification with those provided by a reference (calibrated) force gauge, where both devices should be located at the static source of compressive force.

Testing station for the verification of welding parameter measurement devices

Presently, none of the Polish laboratories is in possession of technical equipment enabling the performance of measurements involving resistance welding parameters. As a result, many users send their meters to be verified by the manufacturer, which significantly extends the time of the verification procedure and increases verification procedure-related costs. To address existing needs in this area, the researchers of Łukasiewicz – Instytut Spawalnictwa undertook to develop and construct a universal tool enabling the performance of the aforesaid measurements.

The concept of constructing the aforesaid "tool" (station) assumed the possibility of the complex verification of welding parameter measurement devices. The foregoing necessitated the simultaneous and cohesive integration of several separate elements, i.e. a welding power (welding current) source, a static compressive force source and a measurement module. It was assumed that the station would be provided with two independent control systems, i.e. one related to the excitation of current flow (reflecting actual conditions accompanying the welding process) and the other one related to the exertion of compressive force (reflecting actual electrode force). In addition, the station should be equipped with two independent measurement systems for the acquisition of signals from current and force transducers. The metrological properties of the station should be consistent with the requirements contained in the PN-EN ISO 17657 series of standards. In accordance with the classification presented in Part 1 and Part 4 of the PN-EN ISO 17657 standard, the station should satisfy the requirements of the *reference welding current measurement system* and be characterised by current measurement accuracy not worse than ±0.5% of the entire measurement range.

The design and construction works led to the integration of individual components into one control and measurement device (Fig. 5), composed of the following elements:

– AC welding machine, enabling the generation and adjustment of current subjected to measurements,

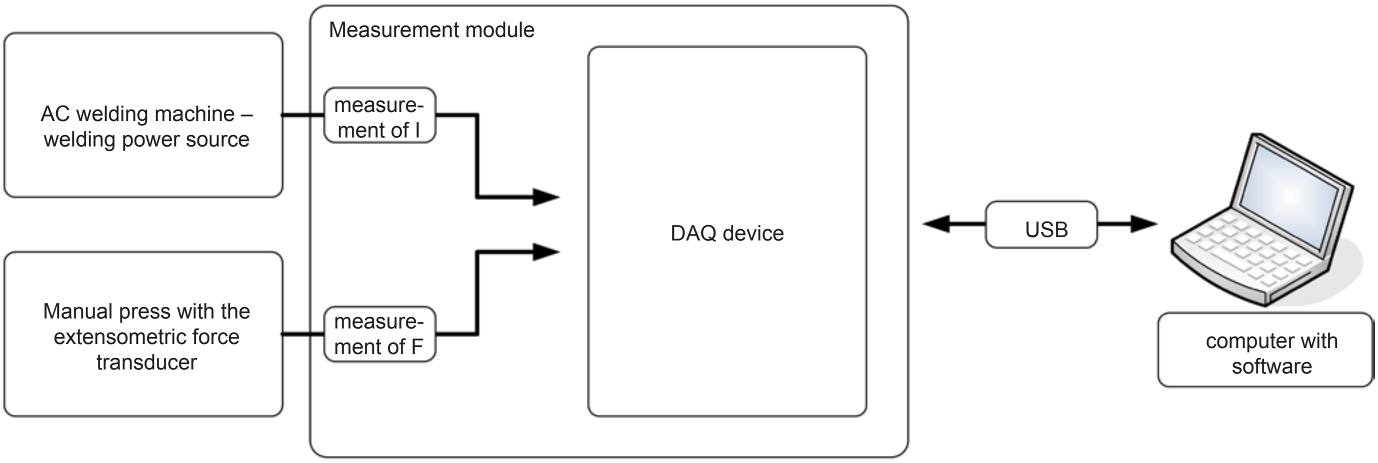

Fig. 4. Schematic diagram of the station for the verification of equipment used in measurement of resistance welding parameters

- manual screw press with transducers, enabling the exertion of compressing force,
- measurement module, enabling the acquisition and processing of signals from the transducers,
- computer and software.

The primary metrological features and properties of the station enabling the verification of devises used for measurements of resistance welding parameters were the following:

- adjustment and measurement of welding current within the range of 0.5 kA to 20 kA,
- current measurement accuracy of ±0.5%,
- adjustment and measurement of current flow time within the range of 20 ms to 1980 ms,
- adjustment and measurement of (pressure) force within the range of 10 daN to 3000 daN,
- force measurement accuracy of ±0.5%.

Figure 4 contains the schematic diagram presenting all key elements of the testing station. Figure 5 presents the entire station provided with control and measurement equipment.

The welding power source (Fig. 6) included elements of resistance spot welding machine, a transformer with a thyristor controller and a control system (without the system of welding electrodes and a pneumatic system controlling the operation of electrodes). The secondary winding of the welding transformer was short-circuited and formed the permanently closed circuit for measurement current. The control system enabled the stepless adjustment of welding current restricted within the range of 0.5 kA to 20 kA. The secondary circuit was provided with a measurement (current sensing)

Fig. 5. Station for the verification of devices used for measurements of resistance welding parameters

Fig. 6. Welding power source

coil. Because of the metrological requirements, the coil used in the secondary circuit should be characterised by an accuracy of ±0.25%. The foregoing necessitated the use of the Rogowski coil, which, according to specifications provided by the manufacturer, was characterised by a measurement error of ±0.03%.

The source of exerting static compressive force was a manual screw press. The force measurement system was composed of an extensometric force transducer and a transducer of signals from the extensometric bridge (signal amplifier), which transformed the signal from the force transducer to the level of voltage adjusted to the level of signal acceptable by the input of a DAQ device. The extensometric force transducer enabled the performance of static force measurements of up to 50 kN, which fully overlapped with the range of most commonly used industrial force sensors. The accuracy of the force transducer and that of the transducer of signals from the extensometric bridge amounted to 0.2, classifying the above-named components under the category of precise (laboratory) transducers. The schematic diagram of the transducers installed on the manual press is presented in Figure 7.

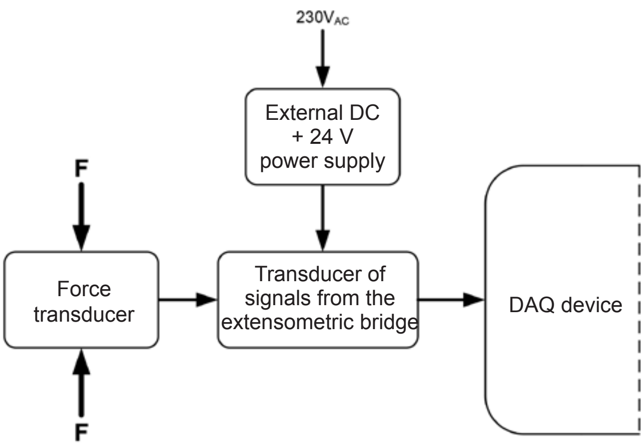

Fig. 7. Schematic diagram of transducers installed on the manual press used for the exertion of compressive force

Another crucial element of the system was the measurement module, tasked with the acquisition and the processing of signals from the Rogowski coil, the zeroing of the integrator, the detection of welding current as well as the acquisition of signals form the force measurement transducer. The acquisition of signals and the control of individual elements of the measurement module were performed using a National Instruments USB-6210 DAQ device. The DAQ device was connected to the computer via a USB interface. The software programme installed on the computer enabled the performance of verification procedures.

Software programme

The software of the measurement system was controlled by the Windows operating system. The primary tasks of the software programme were the following:

- automatic detection of welding current,
- acquisition and recording of welding current,
- acquisition of measurement signals from the extensometric transducer,
- performance of numerical calculations – calculation of root-mean-square welding current and compressive force,
- generation of reports with calculated deviations,
- self-diagnostics.

The user graphic interface was divided into several modules, each of which was located under a separate bookmark. In addition, the user interface was provided with spaces for entering data identifying a device subjected to verification and basic software operation controls (Fig. 8). Individual bookmarks of the software programme were the following:

- section *Device data*,
- bookmark *Calibration of welding current*,
- bookmark *Calibration of electrode force*,
- bookmark *Generator of reports*,
- bookmark *Calibration*.

In the section *Device data*, the user can enter data identifying a device undergoing verification, e.g. *Producer, Model, Type* or *Serial number*. In addition, the user can enter the type and the serial number of tested sensors separately for the current transducer and for the force transducer.

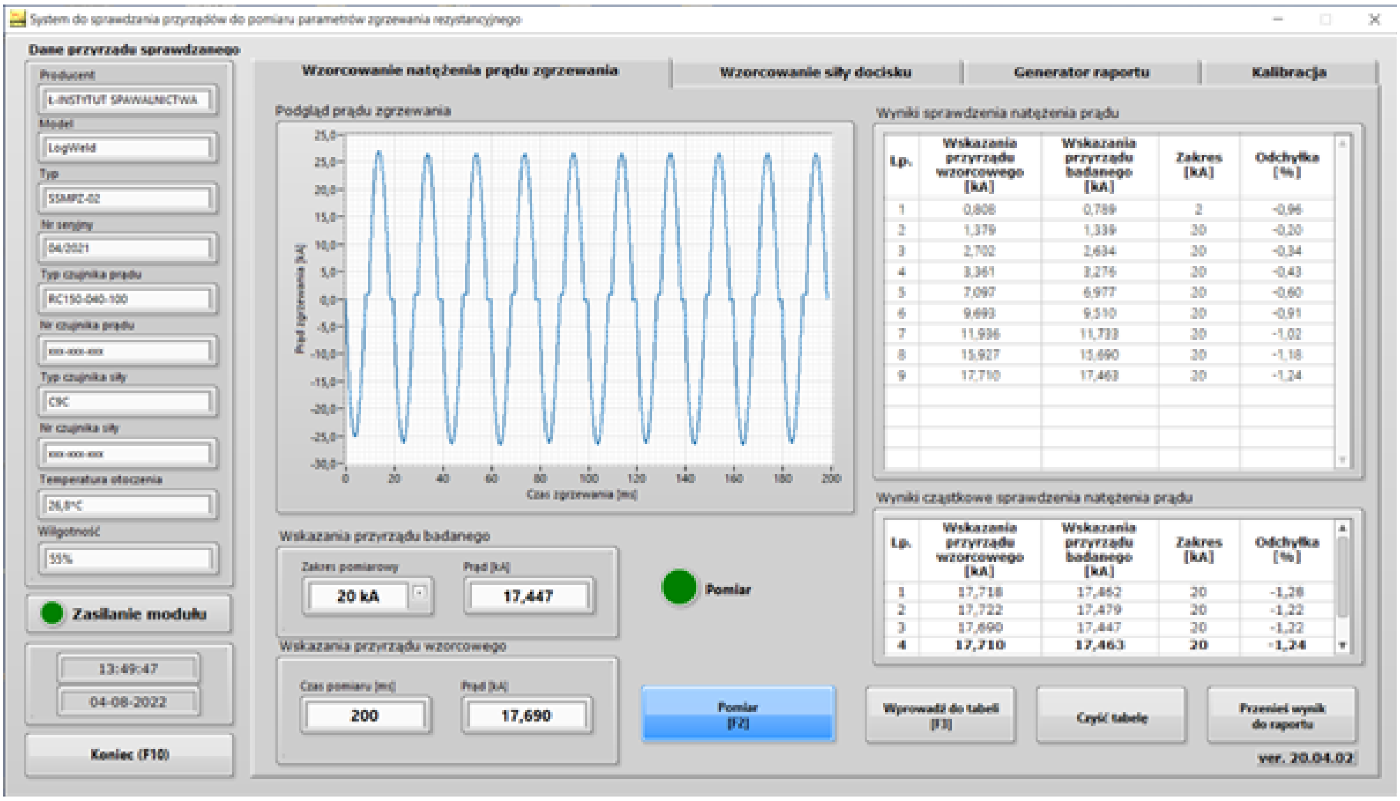

Fig. 8. Window of the software programme for the calibration of devices used in measurements of resistance welding parameters – bookmark Calibration of welding current

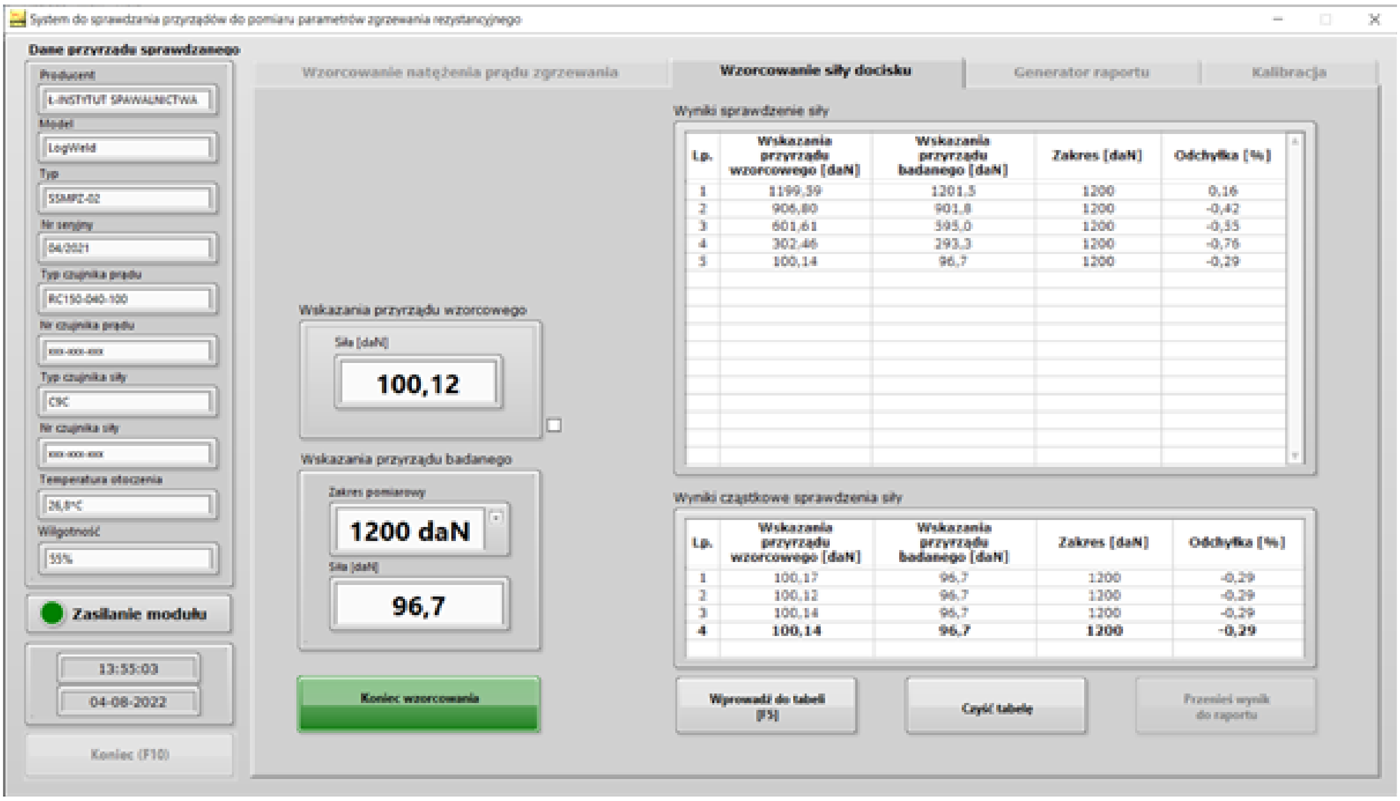

Fig. 9. Window of the software programme for the calibration of devices used in measurements of resistance welding parameters – bookmark *Calibration of electrode force*

In the bookmark *Calibration of welding current*, the operator can verify current-related indications. The measurement procedure starts by pressing the pushbutton *Measurement* (F2). Afterwards, the software starts detecting the flow of current in the circuit of the resistance welding machine. After the excitation of the flow of current in the measurement circuit, the software automatically records the flow, measuring current and calculating its root-mean-square value in relation to an actual current flow time (defined in detail in the standard) [16]. The value of current and the time of its flow are presented in the section of display *Reference device indications*. In addition, the waveform of welding current is displayed in the window *Welding current waveform*. Repeatability is tested in a series of three measurements concerned with one preset value of welding current. The result of each measurement (performed within the above-named series) is entered into the Table *Partial results of welding current verification* and used subsequently to calculate the average value. After the performance of the three measurements and the calculation of the average value, the user can save the result and enter it into the Table *Result of welding current verification*. The final result of the verification procedure is documented in a related verification certificate. A deviation from the standard value is calculated using equation (4) contained in the standard [19].

The bookmark *Calibration of electrode force* (Fig. 9) enables the user to perform the verification of sensors identifying electrode force. Similar to the verification of welding current, the process starts when the user presses the push-button *Start calibration* (F4). The manual setting of force by means of the screw press in the window *Reference device indications* is followed by the display of a recently measured force value expressed in daN. In the section *Verified device indications*, the user (by means of a related drop-down menu) enters the measurement range of the device subjected to verification (possible options include 200 daN, 1200 daN, 2000 daN and 5000 daN) as well as the value of force read out of the display of the device being tested. Similar to the procedure of welding current calibration, each partial measurement value is entered into the Table *Partial results of electrode force verification* and used subsequently to calculate one average value. After the performance of the three measurements and the calculation of the average value, the user can save the result and enter it into the Table *Result of electrode force verification*. The final result of the verification procedure is documented in a related verification certificate.

The bookmark *Generator of reports* (Fig. 10) is used to generate reports concerning the

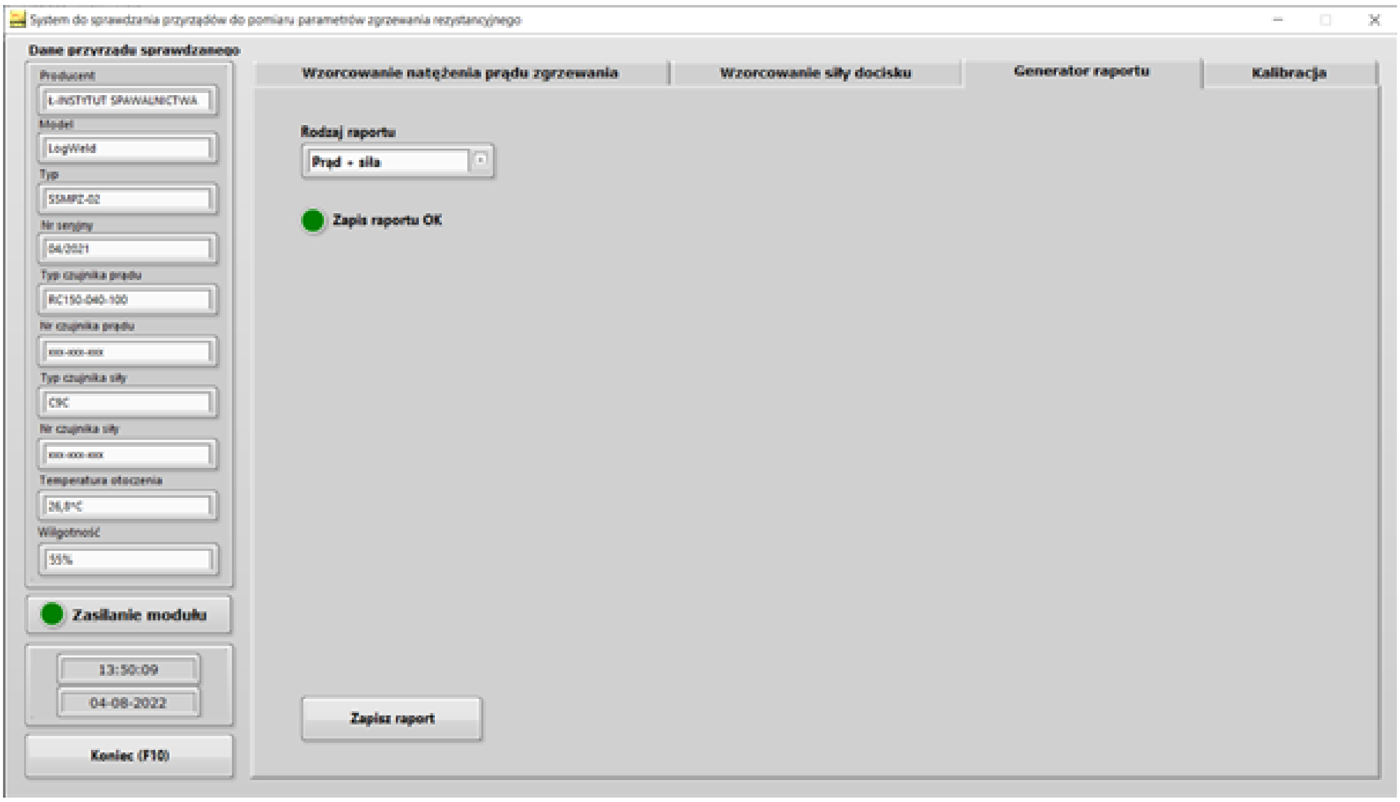

Fig. 10. Window of the software programme for the verification of devices used in measurements of resistance welding parameters – bookmark *Generator of reports*

verification of measurement devices. Depending on the range of verification, the user can generate three types of reports:
- report only containing information related to the verification of welding current indications,
- report only containing information related to the verification of electrode force indications,
- report containing information related to the verification of both welding current and electrode force indications.

The type of a given report is selected using the drop-down list *Type of report*.

The measurement system should satisfy related metrological requirements, therefore it will be obligatory to periodically calibrate measuring lines in accredited laboratories. The bookmark Calibration makes it possible to calibrate a measuring line responsible for measurements of welding current without the toroid, which means that only the measurement module (integrator, DAQ device and numerical calculations) is subjected to calibration. In accordance with the requirements of related standards, the toroid should be calibrated outside the measurement module. The software is also provided with diagnostic functions detecting the lack of a USB-based connection between the measurement module and the computer as well as the lack of power supply to the measurement module.

Measurement accuracy and calibration

Based on the components used in the construction of the station it was possible to analytically identify the limiting errors of individual measuring lines. The accuracy of the welding current measuring line was affected by the following errors:
- error of the measurement transducer (Rogowski coil),
- error of the integrator,
- error of the analogue-digital transducer of the DAQ device,
- errors of numerical calculations.

The accuracy of the electrode force measuring line was affected by the following errors:
- error of the force transducer,
- error of the extensometric transducer (measurement amplifier),
- error of the analogue-digital transducer of the DAQ device,
- errors of numerical calculations.

Input data applied to identify the measurement accuracy of individual measuring lines were data provided by the manufacturers and concerning maximum errors of the components used in the construction of the measurement system.

The performance of related calculations revealed that the maximum measurement error of the entire welding current measuring line amounted to 0.1%, whereas the maximum measurement error of the electrode force measuring line amounted to 0.3%. The calculation results did not take into account the actual measurement conditions or numerical errors generated by the software.

The verification of calculation results included the verification of the metrological properties of individual elements of the measurement station and involved calibration performed in accredited laboratories. The Rogowski coil and the welding current measuring line in the measurement module were calibrated

Table 3. Results of the calibration of the welding current measuring line

No.	Reference value	Measured value	Measurement error	Relative measurement error*
	mV	mV	mV	%
1	150	150.5	0.5	0.33
2	200	200.6	0.6	0.30
3	500	501.6	1.6	0.32
4	1000	1002.9	2.9	0.29
5	1500	1502.9	2.9	0.19
6	2000	2004.1	4.1	0.20
7	2500	2505.2	5.2	0.21

*relative measurement error expressed in % and calculated as the quotient of the measurement error and of the reference value in two different measurement laboratories. The calibration of the welding current measuring line in the measurement module involved all its elements, i.e. the integrator, the analogue-digital transducer and numerical errors. The results of calibration are presented in Tables 3 and 4.

Table 4. Results of the calibration of the current sensing coil (Rogowski coil)

No.	Reference value	Reference value	Measured value	Measurement error	Relative measurement error*
	A	mV	mV	mV	%
1	50	5	5.008	0.008	0.16
2	500	50	49.7972	−0.2028	−0.41
3	1000	100	99.5998	−0.4002	−0.40
4	1250	125	125.542	0.542	0.43
5	2500	250	249.400	−0.6	−0.24
6	5000	500	499.826	−0.174	−0.03

* error calculation results were referred to the value of reference voltage in relation to toroid sensitivity (100 mV/1 kA)

The calibration results presented in Table 3 revealed that the maximum measurement error of the measurement module amounted to 0.33%, whereas the dispersion of errors was restricted within the range of 0.19% to 0.33%, thus confirming relatively good metrological properties of the welding current measuring line and the regular nature of the error.

Table 5. Results of the calibration of the electrode force measuring line

No.	Reference value	Measured value	Measurement error	Relative measurement error*
	daN	daN	daN	%
1	498.13	500.00	1.87	0.37
2	996.4	1000.0	3.6	0.36
3	1495.4	1500.0	4.6	0.31
4	1994.0	2000.0	6.0	0.30

*relative measurement error expressed in % and calculated as the quotient of the measurement error and of the reference value

The maximum limiting current of the Rogowski coil amounted to 0.43%, yet the relatively high dispersion of errors (restricted within the range of −0.41% to +0.43%) revealed imperfections of the toroid-based method of welding current measurements and the stochastic nature of the error.

The principle of error propagation was used to calculate the total error of the welding current measuring line. The value of the error, which amounted to 0.5%, was determined using the following equation:

$$\delta = \sqrt{\delta_{\mathrm{PP}}^2 + \delta_{\mathrm{DAQ\_I}}^2} = \sqrt{0.43^2 + 0.33^2} = 0.5\% \quad (5)$$

where δ_{PP} – maximum relative error of the measurement transducer (Rogowski coil) and δ_{DAQ_I} – maximum relative error of the welding current measuring line of the measurement module.

The comparison of the analytical determination of welding current measurement accuracy with the calibration procedure revealed the existence of significant differences. The analytically calculated maximum welding current measurement error amounted to 0.1%, whereas the error confirmed by actual measurements amounted to 0.5%. It is not possible (and without thorough tests difficult) to unequivocally identify the reason for the aforesaid difference. One of the possible reasons could be the problem resulting from the nature of measurements performed using the Rogowski coil, i.e. the accuracy of coil positioning in relation to the transducer with current. In addition, the analytical determination of the measurement error did not take into account numerical errors and the mathematical method applied to identify the root-mean-square waveform. In spite of the foregoing, the confirmed measurement accuracy proved sufficient for the welding current measuring line to be rated among laboratory-class devices.

The final stage involved the calibration of the entire electrode force measuring line including all the elements, i.e. the extensometric bridge, the extensometric transducer, the DAQ device and numerical calculations. The calibration results are presented in Table 5.

The calibration, performed by an accredited laboratory, confirmed the favourable metrological properties of the electrode force measuring line, where errors did not exceed 0.37%. In terms of the electrode force measuring line, the maximum analytically calculated error value amounted to 0.3% and was similar to the values obtained during the calibration procedure. Similar to the electrode force measuring line, also the welding current measuring line can be qualified as meeting the requirements concerning laboratory-class measurement equipment.

Summary

One of the most important advantages of the above-presented measurement solution consists in the integration of the control and measurement equipment in one universal machine, which significantly simplifies and shortens the verification of devices used for measurements of resistance welding parameters as well as reduces the costs of verification-related tests.

The measurement system software programme enables the simple and intuitive verification of measurement devices and reduces the impact of human factor on errors (if any).

The metrological properties of the individual measuring lines were confirmed through calibration procedures performed in accredited laboratories. Based on the calibration results it could be stated that both the welding current measuring line and the electrode force measuring line can be rated among laboratory-class measurement equipment. In accordance with the requirements of the PN-EN ISO 17657-4 standard, the measurement system meets the criteria related to the *reference welding current measurement system*. According to the Author's knowledge, presently, none of the Polish laboratories possess appropriate technical equipment enabling the verification of welding current meters. The solution developed at Łukasiewicz – Instytut Spawalnictwa fills the gap and constitutes an alternative to the verification of welding current meters performed at producers' or by overseas laboratories.

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