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Original Article

Comparison of temperature measurement methods in welding conditions of basic structure materials

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Abstract: Controlling the conditions and parameters of heat treatment requires reliable temperature measurements. These measurements should be carried out with appropriate accuracy and repeatability. The article presents an experiment illustrating the influence of the choice of temperature measurement method on the quality and accuracy of measurements in relation to basic. Measurements were compared using a thermocouple, a pyrometer, a thermal imaging camera and a thermopencil.

Keywords: temperature measurement, emissivity coefficient, control of the welding process, pyrometer, thermocouple

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Introduction

In fuzion welding and [1], it is important to control the preheat and interpass temperatures. Supplementary measurements of the maintained temperature and the drying preheat temperature can be performed. Temperature measurements for research purposes [2][3], heat treatment [4], or service (repair) purposes in operating machines and devices [5] constitute a separate issue.

The choice of method (**Tab. 1**). device and technique for temperature measurement depends, among others, on: the purpose of the measurement (workshop evaluation, laboratory evaluation, determination of process conditions, recording, validation, etc.), its value, assumed accuracy, as well as the condition and type of the measured surface [6]. With the development of welding, measurement techniques and methods, including temperature, are improved, and their correct selection and operation are crucial for the correct and repeatable course of the welding technological process [7][8].

The starting point for measurement and classification methods is the EN ISO 13916 standard [9]. It specifies requirements for measuring the preheat temperature, interpass temperature and holding temperature for welding excluding post-weld heat treatment.

The following section briefly describes the various temperature measurement methods. Themperature indicator pens, also known as thermo-crayons (symbol TS):

- for approximate temperature determination in welding and heat treatment up to approx. 800 °C,
- a convenient and quick method of checking the preheat and interpass temperatures,
- the temperature is determined by the melting trace applied to the surface of the object,
- step measurement, detecting only when the indicator's rated temperature is exceeded,
- not recommended in the immediate vicinity of the weld.

Tab. 1. Summary of basic temperature measurement methods used in welding processes [9]

Type of measurement	Typical device	Measurement conditions
Non-electric contact	"thermo-crayons"	Waiting for the crayon mark to liquefy for different temperature thresholds
Contact electric	Contact thermometers and thermocouples	By touching the measuring probe or measuring connector (thermocouple) to the surface being tested
		Galvanic connection of the measuring connector (thermocouple) with the measured surface
Contactless - optical devices	Pyrometers	Spot measurement from a specific distance and area
	Thermal imaging cameras	Surface measurement (image or video) from a specific distance and area

Thermocouples:

- A thermocouple uses the Seebeck effect – it generates a voltage depending on the temperature difference between the measuring junction (made of a pair of wires made of different metals and connected by contact) and the reference end.
- Measurements in the range of approx. –200 ÷ +2300 °C [10].
- They enable the measurement of the temperature in the weld pool, e.g. during submerged arc welding.
- They do not require external power supply to the sensor.
- Small size – possibility of local measurement.
- Low thermal capacity, low time inertia, wide measurement range with good linearity.
- In the simplest case, the sensor can be made from a welded pair of dissimilar metals and placed directly on the measured surface. To eliminate contact errors with the measured surface, it is recommended to mechanically secure the measuring connector [11].
- The best results are achieved with a mechanical and, above all, galvanic connection of the thermocouple with the measured surface (eliminates operator errors) [7].
- Special probes can also be used, in which the measuring connector is connected to the measured surface via a contact plate. In this case, the measurement is subject to additional error; the greater the temperature difference between the heated element and the surroundings (due to the probe cooling in cold air) [7].
- Various temperature indicators (analog and digital), recorders and even universal multimeters with thermocouple function are possible.

Non-contact thermometers – pyrometers:

- Measurement of the emitted infrared radiation coming from an object to its lens.
- Measuring range approx. -30 ÷ +3000 °C. Optical resolution of a pyrometer – the ratio of the measurement distance (D) to the measurement field diameter (S), expressed as "D:S", which determines how small an object can be measured at a given distance (eg. 12:1, 50:1).
- The intensity of emitted thermal radiation depends on the temperature and emissivity coefficient of the tested element.
- The emissivity coefficient (0÷1) depends on: the type of material, its structure, surface condition (including oxidation) and temperature.In the available devices, the emissivity coefficient can be constant or adjustable.
- The measurement should be carried out from a distance that guarantees observation of the measured area over the entire sensor surface (requires taking into account the optical resolution).
- Laser pointer "sight": single (orientation) or multi-point (indicating the approximate area of correct measurement).

Non-contact thermometers – thermal imaging cameras:

- Measurement of emitted infrared radiation.
- Full thermal image of the examined area (photo and even video)
- Measuring range approx. -20÷1200 °C.
- Image resolution affects the accuracy of measurements (number of detection points).
- Temperature sensitivity (detection of temperature differences between adjacent areas).
- Emissivity coefficient of the dominant area (fixed or adjustable).

A common feature of non-contact measurements is sensitivity to the type and condition of the heat-emitting surface, reflected radiation (welding arc), fumes, humidity, and the angle of incidence of the measurement beam [12][13] and the physical state of the metal [14]. They are also characterized by a strong dependence on the emissivity of the measured surface (which depends on its smoothness and color). Materials with a matte and dark surface emit infrared radiation better than materials with a smooth and bright surface. Correct measurement requires taking into account the appropriate coefficient or calibrating the instrument based on a measurement that guarantees adequate accuracy, e.g., contact. Significant errors in measurements with a pyrometer (with a single detector) are caused by observing too large an area within which elements of different temperatures will overlap.

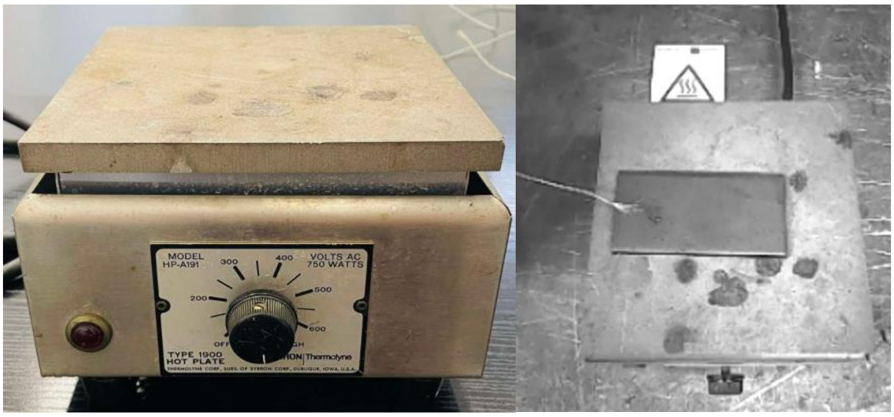
Materials and methods

In order to assess the influence of the choice of temperature measurement method on the quality and accuracy of measurements in relation to selected construction materials with different surface conditions, experiments were carried out with the following assumptions:

1. Temperature measurements of samples made of structural materials with various surface conditions (**Tab. 2**). Samples measuring approximately 50x100x4-8 mm were cleaned and degreased.
2. A range of measuring instruments and tools were used (**Tab. 3**).
3. Samples were heated using a Sybron Thermolyne HPA191 heating plate, with a temperature control range of 0 ÷ 370 °C (**Fig. 1a**).
4. In accordance with available knowledge and practice [7], contact measurement using a thermocouple galvanically attached (heated) to a non-alloy steel sample was considered the reference method (**Fig. 1b**).
5. A commonly used and readily available type K (Chromel–Alumel) thermocouple was used for the tests, with a measured temperature range of -200 °C ÷ 1200 °C. 6. Once the set temperature was reached, it was recorded using a K thermocouple welded to a carbon steel sample. Since it was impossible to weld the thermocouple to other samples, a simplifying assumption was made – during their testing, a reference sample was placed on a heating plate.
6. For measurements using pyrometers, they were placed at a distance selected based on their nominal optical resolution, ensuring that only the heated sample was within the sensor's field of view.
7. For pyrometers and thermal imaging cameras with adjustable emissivity coefficients, the emissivity coefficient was selected using two methods: by matching the reference method to obtain similar readings, and based on technical documentation (instructions) for similar materials.

Tab. 2. List of materials used during testing

Materia	Specimets surface condition
Low alloy steel S235	non-corroded surface
	superficially corroded
304 stainless steel	shiny
Unalloyed steel S235 galvanized	shiny
Aluminum PA2	slightly matte



(a) (b)

Fig. 1. Measuring station. Heating plate -a. Sample with galvanically attached thermocouple -b

Tab. 3. List of measuring instruments used during the tests

Device type	Main properties	Configuration
Temperature gauge	• digital display, • 4-channel, • supports many types of thermocouples,	Thermocouple K: welded to a non-alloy steel sample or just the thermocouple connector without a sheath
Pyrometer 1	• no emission factor adjustment, • measurement range up to 420 °C, • single-point laser pointer,	Constant emission factor 0.95

	• 8:1 optical resolution	
Pyrometer 2	• with adjustable emissivity, • measuring range up to 1850 °C, • 3-point laser pointer, • optical resolution 75:1	Emission coefficient: adjusted to the thermocouple measurement readings and set based on the technical documentation
Thermal imaging camera	• with adjustable emission coefficient, • infrared resolution 256x192 pixels, • 640x480 photos and videos, • measurement range up to 550 °C	Emission coefficient as for pyrometer 2
Temperature indicator pens	• melting point temperature: 125 and 150 °C	Traces drawn in the center of unalloyed steel samples

Results

Due to the selection of the reference method, the recorded measurements were supplemented with calculated errors, where: x - exact (reference) value, xo - measured value:

Relative error expressed as a percentage :

$$\delta = \frac{\Delta x}{x} = \frac{|x - x_0|}{x} * 100\% \qquad (1)$$

Absolute error:

$$\Delta x = |x - x_0| \qquad (2)$$

The reading obtained for the thermocouple galvanically attached to the unalloyed steel sample was considered as the exact (reference) value (for each sample).

In addition, measurements may be accompanied by qualitative errors (unmeasurable), e.g.:

- Excessive – resulting, for example, from careless measurement (rejected).
- Systematic – resulting from failure to take into account some factor that consistently influences the measurement.
- Random – not resulting from systematic and repeatable factors, random.

The results obtained for the unalloyed steel samples are summarized in **Tab. 4**, and **Fig. 2** shows the images recorded by the thermal imaging camera. A significant difference was observed between measurements with a heated and applied thermocouple. Manually applying the thermocouple resulted in a significant reduction in the indicated temperature, which could be caused by difficult contact between the thermocouple junction and the sample, its faulty construction, or its cooling slightly in cold air. The constant emissivity coefficient in pyrometer 1 (0.95) was close to the value obtained as a result of the fitting (0.8), resulting in a relative error of 7.72%. Of the coefficients available in the documentation for pyrometer 2, only the highest value of 0.9 gave a result close to the standard. The remaining values gave significantly overestimated readings. In the case of samples made of non-alloy corroded steel, similar dependencies were observed, however, in accordance with the theoretical assumptions, the adjusted emissivity coefficient increased from 0.8 to 0.95 (darker body), which perfectly matched the properties of the pyrometer without coefficient adjustment (with a constant value of 0.95).

Tab. 4. Measurement results for S235 steel samples

Non-alloy steel S235, non-corroded		Emission coefficient			
		according to the instructions			fitted
		0,6	0,7	0,9	**0,8**
Measuring device		Measurement			
Temperature gauge with welded K thermocouple	Temperature	**313,50**			
Pyrometer 1	Temperature [°C]	**289,30**			

	Absolute error [°C]	24,20			
	Relative error [%]	7,72			
Pyrometer 2	Temperature [°C]	396,20	358,80	308,20	**310,10**
	Absolute error [°C]	82,70	45,30	5,30	3,40
	Relative error [%]	30,30	16,62	1,94	1,25
Thermal imaging camera	Temperature [°C]	376,20	348,90	306,40	**304,70**
	Absolute error [°C]	62,70	35,40	7,10	8,80
	Relative error [%]	23,01	12,99	2,61	3,23

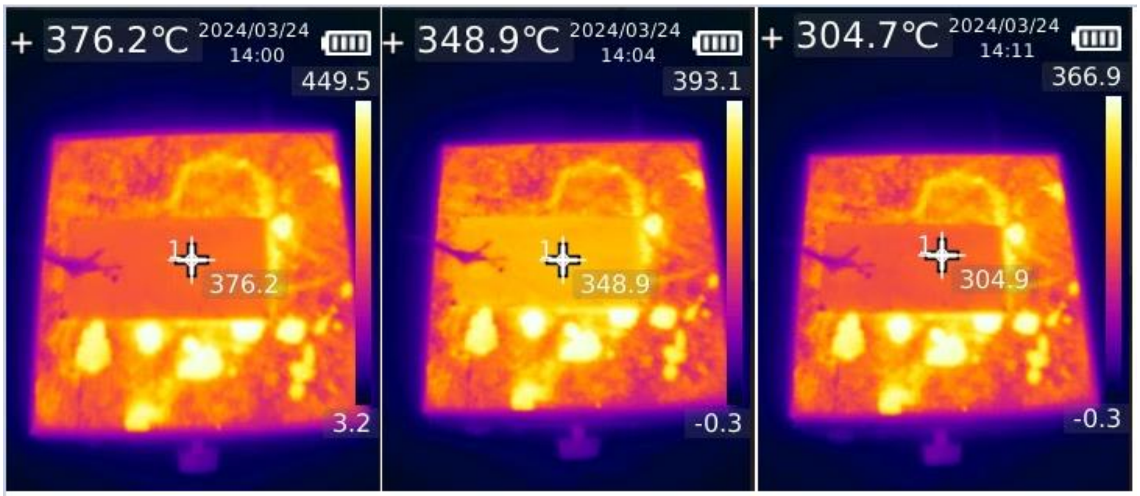


Fig. 2. Images from a thermal camera for various emissivity factors (0.6, 0.7, 0.8)

The results obtained for samples made of stainless steel (304) are summarized in **Tab. 5**, and **Fig. 3** shows the recorded images from the thermal imaging camera. In this case, the reference sample with a thermocouple attached was placed on the heating plate next to the test sample. Due to the analog (potentiometric) temperature controller, a different, lower heating temperature was obtained in subsequent series of measurements.

It was observed that the constant emissivity coefficient in pyrometer 1 (0.95) turned out to be completely useless compared to the value obtained as a result of fitting (0.35), which resulted in a relative error of 51.57%. Among the coefficients available in the documentation for pyrometer 2 (0.6÷0.8), none of the values allowed obtaining a correct measurement with the pyrometer and the thermal imaging camera. All values gave significantly lower results. The coefficient of 0.35 obtained by fitting allowed for obtaining a result with a relative error of 6.89% for pyrometer 2 and 0.40% for the camera.

Tab. 5. Measurement results for 304 steel samples

304 stainless steel		Pyrometer emissivity coefficient			
		according to the instructions			fitted
		0,6	0,7	0,8	**0,35**
Device		Measurement			
Temperature gauge with welded K thermocouple	Temperature [°C]	**274,20**			
Pyrometer 1	Temperature [°C]	**132,80**			
	Absolute error [°C]	141,40			
	Relative error [%]	51,57			
Pyrometer 2	Temperature [°C]	174,10	160,10	154,30	**255,30**
	Absolute error [°C]	100,10	114,10	119,90	18,90
	Relative error [%]	36,51	41,61	43,73	6,89

Thermal imaging camera UTi260B	Temperatura [°C]	197,90	183,40	177,90	**273,10**
	Absolute error [°C]	76,30	90,80	96,30	1,10
	Relative error [%]	27,83	33,11	35,12	0,40

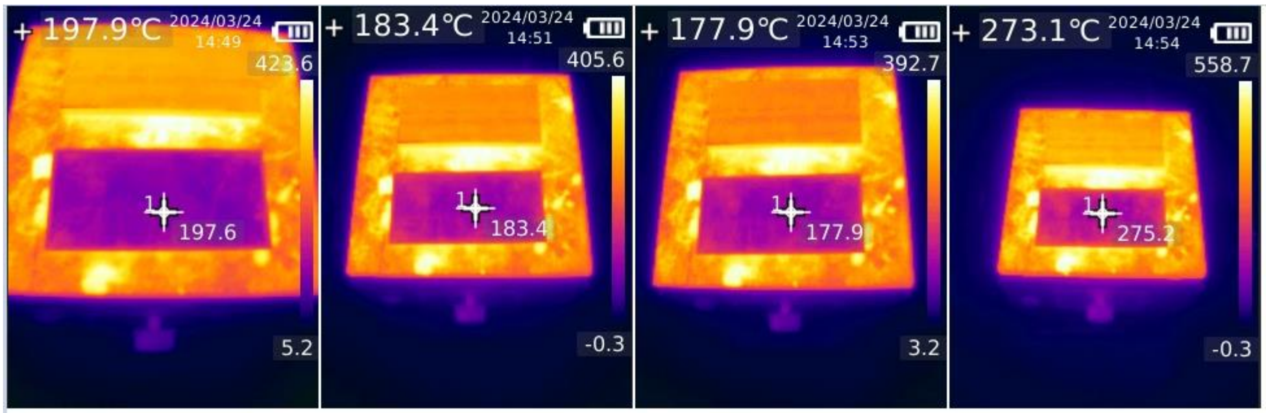


Fig. 3. Thermal camera images for different coefficients (0.6, 0.7, 0.8, 0.35)

The results obtained for the galvanized S235 unalloyed steel samples are summarized in **Tab. 6**, and the images recorded with the thermal imaging camera are shown in **Fig. 4**. A reference sample with an attached thermocouple was placed on a heating plate next to the test sample.

It was observed that the constant emissivity coefficient in pyrometer 1 (0.95) proved completely inappropriate compared to the value obtained as a result of matching (0.07), resulting in a relative error of 76.9%. Of the coefficients available in the documentation for pyrometer 2 (0.2–0.8), none of the values allowed for obtaining correct measurements using the pyrometer and the thermal imaging camera. All values gave significantly underestimated readings. The coefficient of 0.07 obtained through matching resulted in a result with a relative error of 29.63% for pyrometer 2 and 1.02% for the camera. In this case, the match proved better for the camera. The difference in camera and pyrometer readings may be due to the low precision of manually adjusting the pyrometer's field of view, indicated approximately by laser pointers, due to its optical resolution.

Tab. 6. Measurement results for samples made of galvanized unalloyed steel S235

Galvanized unalloyed steel		Pyrometer emissivity coefficienti			
		According to the instructions			Selected
		0,2	0,35	0,8	0,07
Device	Measurement				
Temperature gauge with welded K thermocouple	Temperature [°C]	**295,30**			
Pirometer 1	Temperature [°C]	**68,20**			
	Absolute error [°C]	227,10			
	Relative error [%]	76,90			
Pirometer 2	Temperature [°C]	124,10	98,10	80,20	**207,80**
	Absolute error [°C]	171,20	197,20	215,10	87,50
	Relative error [%]	57,97	66,78	72,84C	29,63
Thermal imaging camera	Temperature [°C]	155,40	127,80	114,80	**298,30**
	Absolute error [°C]	139,90	167,50	180,50	3,00
	Relative error [%]	47,38	56,72	61,12	1,02

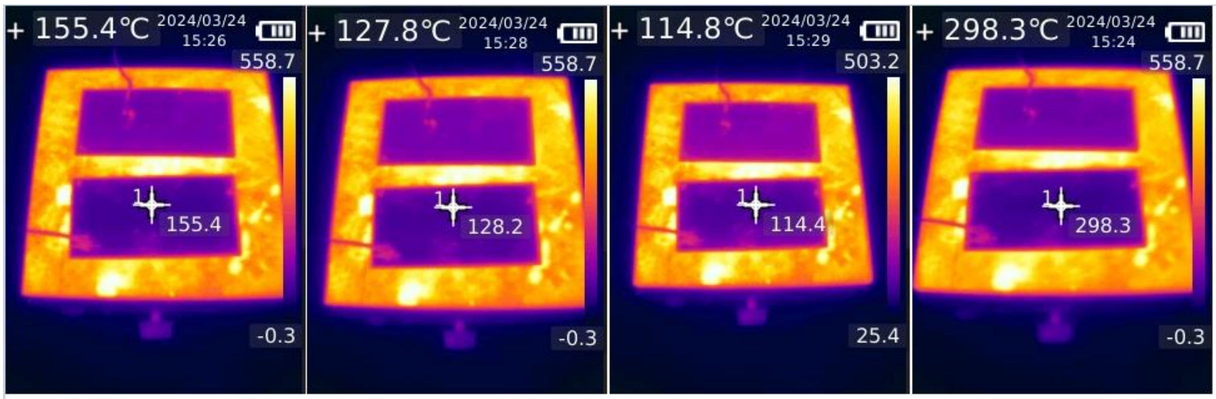


Fig. 4. Thermal imaging camera images for different emissivity coefficients (0.2, 0.35, 0.8, 0.7)

The results obtained for the PA2 aluminum alloy samples are summarized in **Tab. 7**, and the images recorded with the thermal imaging camera are shown in **Fig. 5**. As before, the reference sample with the attached thermocouple was placed on the heating plate next to the test sample.

It was observed that the constant emissivity coefficient in pyrometer 1 (0.95) proved to be completely useless in relation to the value obtained as a result of matching (0.12), which resulted in a relative error of 72.23%. Of the coefficients available in the documentation of pyrometer 2 (0.1÷0.4), only the first value allowed for obtaining a similar measurement with the pyrometer (error of 10.16%) and the thermal imaging camera (error of 1.44%). The remaining coefficients gave significantly underestimated readings. The coefficient of 0.12 obtained through matching allowed for obtaining very good results with a relative error of 2.74% for pyrometer 2 and 0.32% for the camera. Again, the matching turned out to be better in the case of the camera.

The results obtained for the thermperature indicator pens, also known as "thermocrayon" or tempilstik are summarized in **Tab. 8**, and **Fig. 6** shows the sample undergoing measurement. For this purpose, a non-alloy steel sample with an attached thermocouple was used, placed on a heating plate. Two thermo-crayons were used, with nominal melting point temperatures of 125 and 150 °C. During the test, the temperature at which the trace drawn with the temperature indicator pen melted was recorded.

Tab. 7. Measurement results for aluminum alloy samples PA2

Aluminium alloy PA2		Pyrometer emissivity coefficient			
		according to the device instructions			individually selected
		0,1	0,25	0,4	0,12
Device	Measurement				
Temperature gauge with welded K thermocouple	Temperature	**284,50**			
Pirometer 1	Temperature [°C]	**79,00**			
	Absolute error [°C]	205,50			
	Relative error [%]	72,23			
Pirometer 2	Temperatura [°C]	255,60	148,70	114,90	**292,30**
	Absolute error [°C]	28,90	135,80	169,60	7,80
	Relative error [%]	10,16	47,73	59,61	2,74
Thermal imaging camera	Temperatura [°C]	280,40	186,20	146,20	**285,40**
	Absolute error [°C]	4,10	98,30	138,30	0,90
	Relative error [%]	1,44	34,55	48,61	0,32

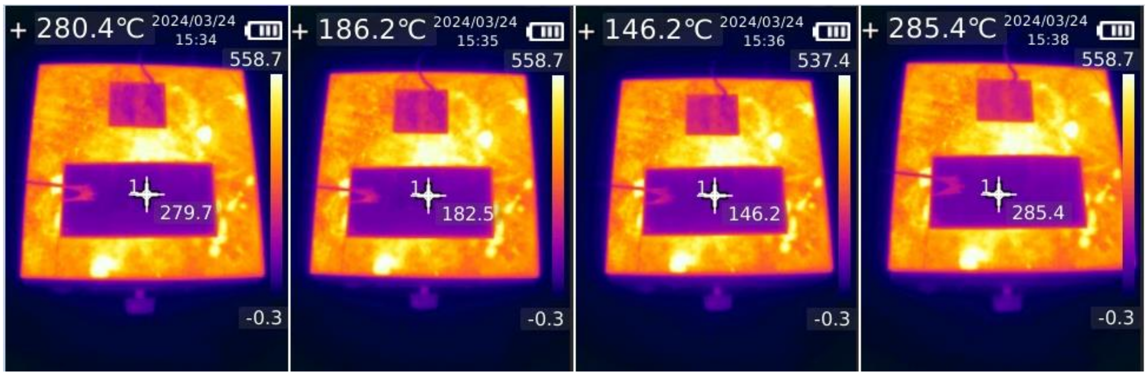


Fig. 5. Thermal imaging camera images for different emissivity coefficients (0.1, 0.25, 0.4, 0.12)

Tab. 8. Measurement results for temperature indicator pen

Temperature indicator pen	Nominal temperature [°C]	Measured temperature [°C]	Relative error [°C]	Absolute error [%]
1	125	112,4	10,08	12,6
2	150	131,3	12,47	18,7

Fig. 6. Speciment during temperature indicator pens investigation

Summary and conclusions

Reliable and accurate temperature measurements of basic construction materials can be performed using a temperature meter with a thermocouple (e.g. K), preferably mechanically attached to the measured surface [8].

During testing, significant differences in meter readings were revealed between the variants with a welded K thermocouple and one manually applied to the measured surface. If using a welded thermocouple to the measured surface is not possible, ensure good contact and separation from interference, e.g., by using a thermal shield and a rigid, mechanical clamp. [11].

Tests revealed the complete inadequacy of a pyrometer with a constant emissivity coefficient for direct temperature measurements of many structural materials. This means that it is impossible to directly compare temperature values obtained under the same thermal conditions for materials with different emissivities using a pyrometer without emissivity adjustment.

A constant coefficient of 0.95 proved useful for steel with a corroded surface, while for metals with a metallic gray shade (resembling silver) and shiny surfaces, such as stainless steel, aluminum, and galvanized cathodic protection, it produced significantly lower results. Experience has shown that this type of instrument can be effective for measuring a range of building structures (concrete, brick), paint coatings (many colors), and some types of rubber.

The ability to adjust the emissivity coefficient allows the pyrometer's readings to match the measured material (its color and surface condition). Measurements revealed the inadequacy of the coefficients suggested in the instrument's manuals, for example, due to ambiguous descriptions. To determine its optimal value, calibration (adjustment) should be performed, for example, based on measurement using a thermocouple. For this purpose, some pyrometers are equipped with the ability to connect a thermocouple, typically a K-type.

Tests have shown the significant difficulty of reliably measuring the temperature of small objects using optical instruments, especially pyrometers. This involves a single sensor, which must be precisely aligned with the area being measured; otherwise, the measurements will be significantly distorted. To facilitate aiming, multi-beam systems, which approximate the sensor's field of view, and even precise optical viewfinders, are used instead of a single laser beam.

Unlike pyrometers, thermal imaging cameras operate using measurement arrays that provide a live view of the wider area being measured and indicate its temperature. In this case, it is also necessary to set the emissivity coefficient for the material or dominant area whose temperature is to be reliably measured. Additional parameters of thermal imaging cameras that are important for their usefulness include imaging resolution (number of detection points) and temperature sensitivity (ability to detect temperature differences).

Studies have confirmed the significant convenience, safety, and comfort of non-contact measurements. Their reliability requires meeting the previously discussed conditions. Given their numerous drawbacks, such as sensitivity to the type and condition of the measured surface and interference (reflected radiation, welding arc, smoke, etc.), they are not an ideal tool for ad hoc inspections. It seems they can be used in established, repeatable conditions during mass production, especially automated production.

The least accurate measurement, using thermal crayons, allows for ad hoc inspection during welding work. It's important to remember that in this case, the measurement result will depend on the observation and skill of the operator or welder.

In conclusion, the following conclusions can be drawn:

1. The choice of the appropriate temperature measurement method depends on its intended use in the production process, e.g. ad hoc control, type and variety of materials, manual work, or automation.
2. According to common knowledge and practice, the highest accuracy and repeatability of measurements is possible when using a thermocouple meter.
3. Non-contact measurements, using a pyrometer and a thermal imaging camera, are extremely convenient and safe, but require considerable attention and care during measurements (determining emissivity coefficients, maintaining the measurement distance).
4. Measurements using thermo-crayons are a convenient method for ad hoc setting of the threshold temperature in production conditions.

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