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Research Article

MEASUREMENTS OF A STEEL CHARGE EMISSIVITY UNDER STRONG IRRADIANCE CONDITIONS

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ABSTRACT

Steel bars are manufactured in the rolling process, whereby they are characterized by strain hardening and poor plastic properties. In many application cases such properties are improper, therefore, additional heat treatment is required. Crucial influence on the products quality after heat treatment has an appropriate selection of process parameters. In many modern technologies of heat treatment the charge of porous structure is subjected to the heating process. Proper control of heat treatment parameters of bundles of rods requires knowledge on their thermal properties. However, it also requires accurate identification of complex heat transfer processes occurring in the porous material. Such analysis, with respect to bundles of bars, provide a response of qualitative nature of the heat exchange area of these charges. The article describes the emissivity measurements of samples of the steel charge using a thermal imaging camera.

Keywords: porous charge, thermal radiation, thermal resistance, long elements bundles, effective thermal conductivity, radiative thermal conductivity.

INTRODUCTION

For several steel products, one of the stages of the manufacturing process is heat treatment. This is related to the need to heat the workpiece up to a temperature whose value is determined by the position of the critical points in the equilibrium diagram of Fe-Fe3C. In practice, the recommended values of the heat treatment temperature are selected from the standards [1].Another important factor is the heat treatment time. This is due to the fact that the transformation processes of the material's microstructure which occur during heating are diffusive in character. Too short a heating time does not assure the transformation to be completed, whereas too long heating can, in turn, lead to a grain growth, excessive phase coagulation, oxidation and decarburization increase and, due to the energy consumption of heating, it is not economical. For these reasons, proper selection of the heat treatment parameters has a decisive impact on the quality of products.

The charge warm-up time can be theoretically based on the solutions of the Fourier-Kirchhoff equation [2, 3]. Obtaining the correct solution requires the determination of the net heat flux absorbed by the heated material. This value can be calculated with the use of the method of brightness radiation balance [4]. For this reason, the analysis of the radiative heat transfer in the system is a key issue for the calculations of steel charge heating. Obtaining the correct measurement results requires precise knowledge of the emissivity of heated steel. This value can be read from the tabular data reported in the literature [5–7]. However, this information should be considered as merely indicative. This is due to the fact that the emissivity of steel depends on a number of factors, which can take very different values. The most reliable source of knowledge on this parameter are measurements performed on samples made of the material of interest.

The article describes the emissivity measurements of samples taken from a batch of steel performed with the use of a thermal imaging camera. The measurements were carried out in the temperature range of 200–700 ºC.

DEFINITION AND TYPES OF EMISSIVITY

Emissivity is a fundamental property of radiant bodies. Generally, it determines the derogation relating to the ability of thermal radiation emission of real bodies from a black body for the same temperature [5]. This formulation can be presented in a form of the following relation:

$$\varepsilon = \frac{\dot{e}}{\dot{e}_C} \tag{1}$$

where: $\dot{e}$ – stream of the radiation emission of a grey body;
$\dot{e}_C$ – stream of the radiation emission of a black body.

According to the radiative heat transfer theory there are several types of emission. In general, emissivity can be divided into the total and the monochromatic emissivity, as well as the directional and the half space emissivity. This allows to distinguish four basic types of this quantity, which are [4, 5]:

- directional monochromatic emissivity – $\varepsilon_{\lambda,\varphi}$;
- half-space monochromatic emissivity – ε_{λ};
- directional total emissivity – ε_{φ};
- half-space total emissivity – ε.

The value of emissivity is affected by many factors. The total emissivity depends on temperature; moreover, the monochrome emissivity varies with the wavelength. Both types of emission depend on the viewing angle φ of the emitting surface. At the same time, emissivity is an integral feature of the material itself, depending on its internal structure, the nature of the substrate and the working conditions of the emitting material. Determining the impact of various parameters on the emissivity value poses serious difficulties and it is not possible theoretically. This can be done only empirically by means of examining the emissivity as a function of various parameters, while maintaining the stability of the other ones. Emissivity measurements can be performed directly or indirectly [6]. Direct methods are based on measuring the radiant size of the tested body and the reference body, as well as determining – mostly based on their ratio – the values of ε. These methods are versatile and can be applied to any measurement temperatures and to all types of materials. They are usually used to measure the total directional emissivity or the monochromatic emissivity. Indirect methods usually allow the determination of the half space emissivity and they rely on the measurement of the optical or thermal quantities associated with the heat exchange process. On the basis of the measured quantities, the searched for emissivity value is determined from the energy balance equations. We can distinguish between several indirect methods [5, 6]:

- Calorimeter – involving an indirect measurement of the amount of energy given up radiatively by the body whose emissivity is being measured;
- Total reflection – involving the measurement of reflectivity, based on which the radiation absorptivity A is determined, the value of which is equal to that of emissivity. This method is most often used to determine the emissivity at room temperature,
- Measurement of the physical quantities, such as resistivity and optical constants of polarized radiation, based on which the emissivity is determined directly or indirectly, by way of integrating, in a specific wavelength range l and the previously calculated monochromatic emissivity.

RESEARCH METHODOLOGY

The emissivity measurements within the frames of the research were performed by a direct-type method. In general, the method consists of a simultaneous measurement of the temperature of the examined body by means of a thermocouple and a pyrometer [6]. During the tests, the value of emissivity in the pyrometer should be adjusted in such a away so that the temperature shown by the device can correspond to the value of the contact measurement. If this condition is fulfilled, we can assume that the emissivity set in the pyrometer is equal to the emissivity of the examined object. In the case of tests conducted at higher temperatures, the presented method has a certain flaw, which is the fact that, under such conditions, the measurement result is affected by the radiation stream emitted by the environment which reaches the examined surface. In the theory of radiative heat exchange, this stream is called irradiance. The environment of the examined object is understood as all the surfaces emitting heat radiation towards this object. The higher the ambient temperature, i.e. the temperature of these surfaces, the higher the irradiance. This phenomenon causes the fact that, during the tests, the radiation related to the emission of the examined object itself is the only one which does not reach the pyrometer's lens. The radiation reflected by that surface may be a significant part. Pyrometers, due to their simple measurement model, does not allow for a correction of this phenomenon. And so, the emissivity value obtained with their use, in direct measurements, can be burdened with a hard-to-estimate error.

The effect of irradiance in emissivity tests can be eliminated by way of using a thermovision camera instead of a pyrometer. That is because thermovision cameras, in comparison to pyrometers, characterize in a much more complex mathematical measurement model. The principle of those models, which results from the situation occurring during a thermovision measurement, is illustrated in Figure 1 [7]. As can be seen, the measurement result is affected by the following objects being the sources of radiation: the environment (1), the examined body (2) and the atmosphere (3). The symbols visible in the discussed figure denote the following: e – the emissivity of the examined object, t – the atmosphere transmittance, W_{refl}, W_{obj}, W_{atm} – the power of particular radiation sources which reaches the camera, T_{refl}, T_{obj}, T_{atm} – the temperatures of those sources.

And so, three heat radiation streams reach the camera lens during the measurements. They are: the stream emitted by the examined object, the stream emitted by the environment (the irradiance stream) and reflected from the examined object and the stream emitted by the atmosphere. Those streams are also attenuated by the medium present in the way of the measurement. The total infrared radiation power recorded by the camera is expressed by the following equation:

$$W_{tot} = \varepsilon \cdot \tau \cdot W_{obj} + (1-\varepsilon) \cdot \tau \cdot W_{ref} + (1-\tau) \cdot W_{atm} \quad (2)$$

Relation (2) can be treated as a simplified mathematical model of the thermovision measurement [7]. It should be noted that the stream of the radiation reflected by the examined object and the stream of the atmosphere radiation, to which powers W_{refl} and W_{atm} correspond, are factors which disturb the measurement. However, modern cameras perform an automatic compensation of those factors. This is realized by way of introducing the following data into the camera menu: the emissivity of the examined object, the environment temperature, the distance from the examined object and the temperature and humidity of the atmosphere. From this we can infer that, in the direct measurement of the emissivity with the use of a camera, we can make a compensation of a negative effect of the radiation. This is realized by way of setting the correct value of the ambient temperature in the camera's menu. A correctly adjusted value of this parameter eliminates the effect of the irradiance on the measurement result. This possibility was used during the described examinations.

RESEARCH IMPLEMENTATION

The emissivity investigations were performed for three low-carbon steel samples. Two of them were made of bars, 30 and 40 mm in diameter. They characterized in a raw state of the surface. The third sample was made of a square profile, 40 mm in diameter. The samples were marked

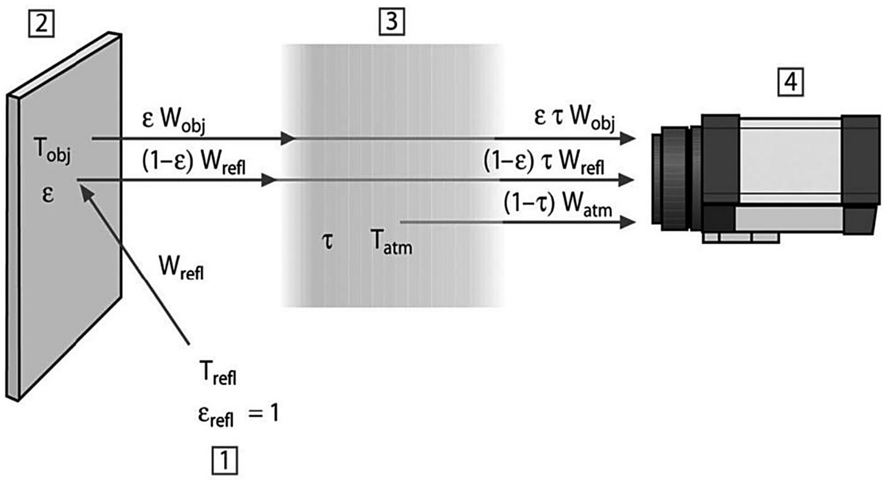

Fig. 1. Explanation of the principle of the mathematical model of a thermovision measurement

as follows: bar 30, bar 40 and the section. All the samples were about 200 mm long. Thermocouples type K were adjusted to each sample by means of heat-resisting silicon. They were shell thermocouples, 0.5 mm in diameter. Those detectors were used for a contact measurement of the temperature of the examined samples. An image of samples: bar 30 and bar 40 with the adjusted thermocouples is shown in Figure 2.

Fig. 2. Image of samples: bar 30 and bar 40 with shell thermocouples adjusted to their surface

An electric chamber furnace was used to heat the samples. The furnace chamber had the following diameters: 1000×300×250 mm (length, width, height). The examined samples were situated in such a way so that the surface with the adjusted thermocouples would be directed towards the charging hole of the furnace. The way of the sample arrangement in the furnace is shown in Figure 3a.

The test methodology required observation of the samples by means of a thermovision camera. For this reason, the charging hole of the furnace was covered by a ceramic needled cloth board with a hole cut out in the middle of it (Fig. 3b). The purpose of this procedure was to limit the heat loss from the chamber. At the same time, this assured stability of the thermal conditions in the furnace area during the tests.

The experiment itself consisted in heating the samples together with the furnace up to 700 °C. After reaching that value, the heating system of the furnace was activated. In consequence, in the further stage, the furnace slowly cooled down together with the samples. During that process, at the specified time intervals, thermogram registration of the examined samples was performed. Each thermogram corresponded to a specific temperature of the furnace. This quantity was measured by means of a thermocouple being part of the equipment of the regulation system of the furnace. At the moment of the thermogram registration, also registered were the temperatures measured by the thermocouples adjusted to the surface of the samples. For the assumed test range, a total of 10 thermograms were registered. Two exemplary thermograms are presented in Figure 4.

The further test methodology consisted in an analysis of the obtained thermograms. To that end, a special software was used, which was part of the equipment of the camera used for the tests. The thermogram analysis was connected with introducing the proper values of the ambient temperature T_{refl} and the emissivity e. The value of temperature T_{refl} was selected to be the temperature value of the furnace corresponding to a given thermogram. Next, the emissivity of given samples was set in such a way so that the sample temperature shown by the camera would correspond to the temperature shown by the thermocouple. After this condition was fulfilled, it was assumed that the set value of emissivity corresponded to the emissivity of the examined sample.

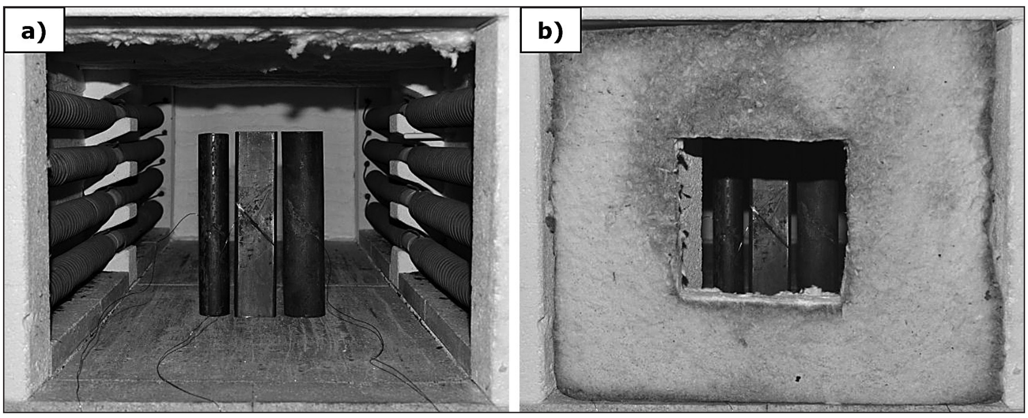

Fig. 3. a) Image of the examined sample in the furnace chamber, b) furnace charging hole covered by a ceramic needled cloth board

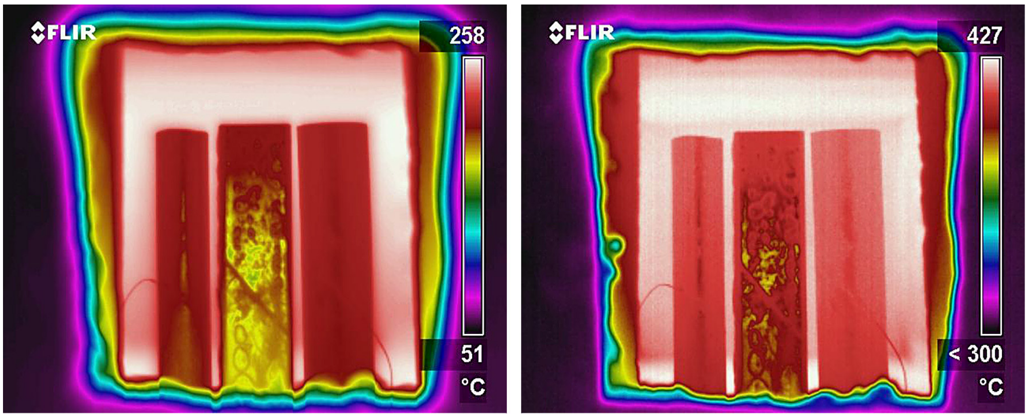

Fig. 4. Exemplary thermograms registered during the tests

The emissivity values of the samples in the function of temperature obtained in this way are presented in Figure 5. For all the samples, emissivity in the function of temperature increases almost linearly. For the bars, the obtained results were very similar. In the considered temperature range, the measured values of parameter *e* for those samples varied from 0.67 to 0.78. Slightly higher values were obtained for the sample made from the profile. The emissivity of that charge, together with the temperature, changed within the range of 0.83–0.93. This effect can be easily explained. The sample made from the profile, due to its low mass, heated up rapidly. At the same time, this resulted in a rapid oxidation of surface. The scale being the effect of this process, in comparison to the initial surface, has a higher emissivity.

The results of particular samples from Figure 5 were approximated by the least square method with the use of linear functions. The following relations were obtained in this way:

sample bar 30 $\varepsilon = 0{,}0002 \cdot t + 0{,}643$ (3)

sample bar 40 $\varepsilon = 0{,}0002 \cdot t + 0{,}635$ (4)

sample section $\varepsilon = 0{,}0002 \cdot t + 0{,}798$ (5)

It is worth mentioning that all the samples characterize in the same dynamics of emissivity increase. This is proved by the similar values of the slopes in equations (3) – (5).

The importance of the effect of irradiance on the values of emissivity determined by the presented method is shown in a diagram in Figure 6, where we can see the values of parameter *e* obtained for samples: bar 30 and bar 40, in the case when, in the analysis of the thermograms, the ambient temperature value was assumed as 25 °C (297 K). Figure 4 does not include the results for the profile. For this element, with an underrated value of the ambi-

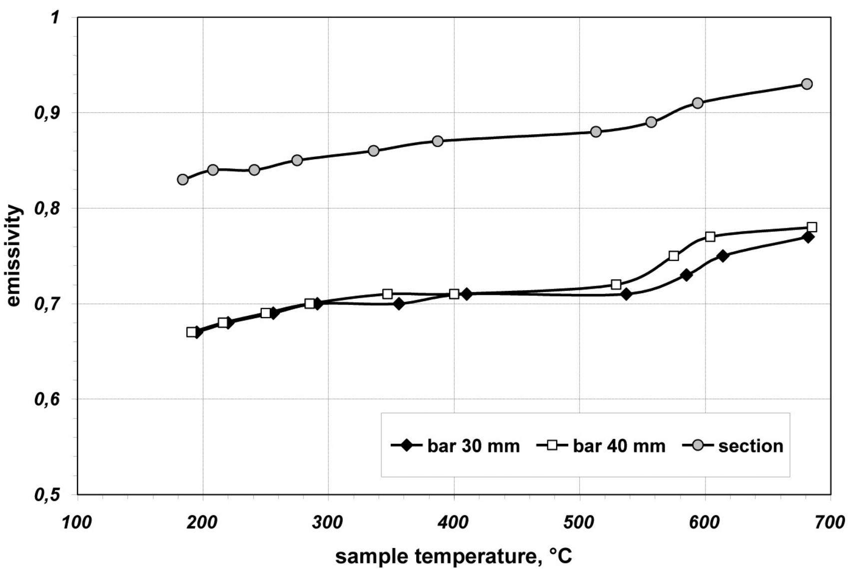

Fig. 5. Emissivity of the examined samples in the function of temperature

ent temperature, it was impossible to adjust the emissivity to the range of up to 1.0. As can be seen, with an underrated value of temperature T_{refl}, which means almost no irradiance of the samples, we obtained an overrated value of emissivity. The excessive values, as compared to the correct results, increase together with the temperature and equal about 0.1–0.2. Precisely, the differences between the results in Figure 3 and 4 can be expressed by means of a relative difference of emissivity. This parameter was defined as follows:

$$\Delta\varepsilon = \frac{\varepsilon_{25} - \varepsilon}{\varepsilon} \cdot 100\% \qquad (6)$$

where: ε_{25} – emissivity determined for the ambient temperature of 25 °C,
ε – emissivity determined for the ambient temperature equal to the temperature of the furnace.

The changes of parameter $\Delta\varepsilon$ depending on the sample temperature are shown in Figure 7. The data included there show clearly how important is the selection of the proper ambient temperature in the determination of emissivity. For the initial temperature range, the result discrepancy equals about 15%. However, for higher temperatures, parameter $\Delta\varepsilon$ increases and reaches the values of 24% and 27% at 700 °C.

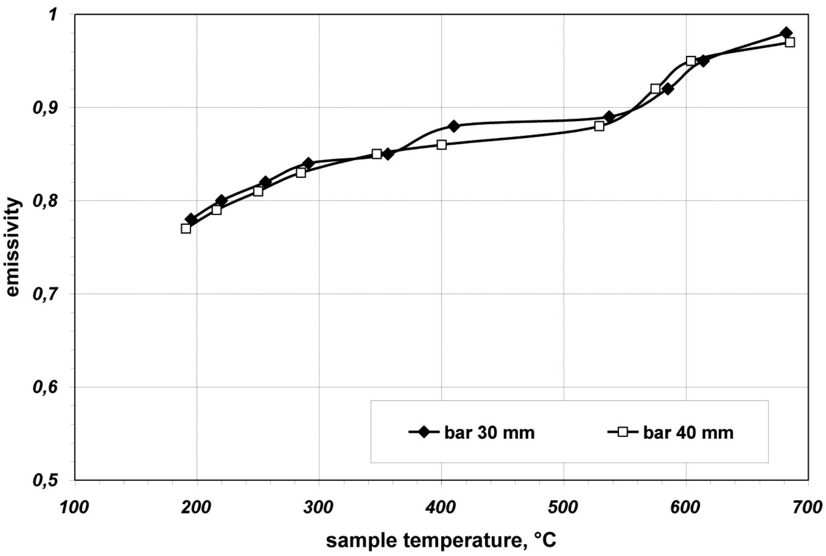

Fig. 6. Emissivity of the examined samples in the function of temperature determined for the ambient temperature of 25 °C

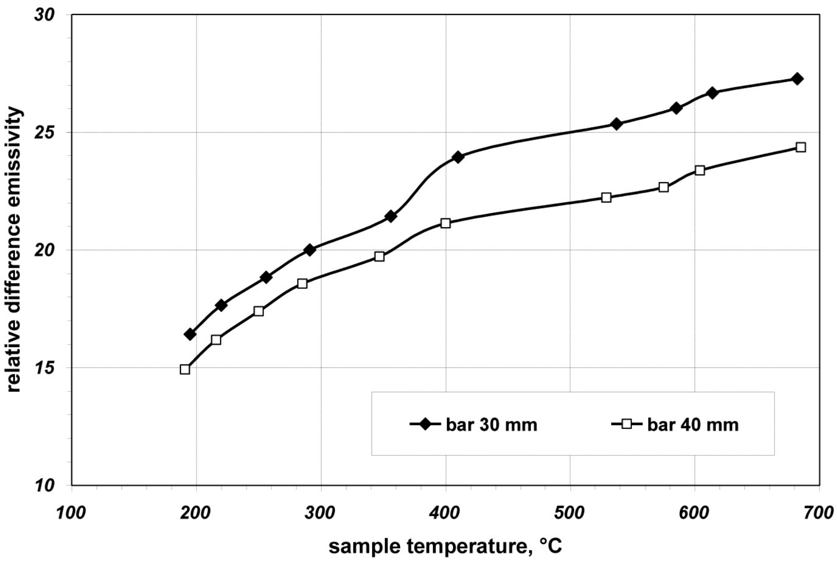

Fig. 7. Relative difference of emissivity for samples: bar 30 and bar 40 in the function of temperature

CONCLUSION

The results of emissivity measurements for steel charge samples were performed by way of a direct method consisting in a simultaneous measurement of the temperature of the examined charges with the use of thermocouples and a thermovision camera. The samples were heated in an electric chamber furnace in the temperature range of 200–700 °C. This way of heating caused a strong irradiance of the sample surfaces. The application of a thermovision camera allowed for a correction of this disturbance phenomenon. It was performed in the analysis of the thermograms by way of introducing an appropriate value of the ambient temperature. The value of this parameter is crucial for the quality of the obtained emissivity measurement results.

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