Development of methodological approaches for non-destructive testing of welded joints of steel finned panels by the active thermography method

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Abstract. This paper examines methodical approaches to non-destructive testing (NDT) of thin steel T-welded joints made by ultrasound welding. The choice of the active thermography method is justified. Numerical parameters were developed for characterize the operational properties of the plate-fin heat exchanger and the results of finned panel inspection by the active thermography method. These parameters were compared and the correlation was found. The developed methodological approaches will be useful in the future for developing an NDT technique that allows detecting internal defects in welded seams which decrease breaking load and worsen the operational properties of products made by finned panels.

1. Introduction

The relevance of the developing methodological approaches to NDT of welded seams of steel finned panels is due to the peculiarities of the production technology of finned panels and products made from them. Finned panels are used in systems with separation of gas and liquid flows (plate-fin heat exchangers), which means that through defects are strictly not allowed. Practice has shown that through defects can occur in a product during operation process.

The manufacturing technology of the plate-fin heat exchangers from finned panels consists of the following main stages:

1. Thin steel sheets (thickness about 1.5 mm) are wound on a special reel.
2. The automatic welding machine feeds the perpendicular steel sheet, which will be the fin of the panel.
3. The fins are unilaterally welded to the panel by the ultrasonic welding during the reel rotation process (type T1 of the welded seams according to GOST 5264-80).
4. The finned panel is removed from the drum and unfolded.
5. Several finned panels are stacked on top of each other to form the body of the final product.
6. Finned panels are welded to each other by manual arc welding.
7. Carrying out NDT of welded joints obtained at stage 6.
8. The finalizing of the product.

To date, quality control of welded joints of finned panels is carried out by penetrant test method and only after the end of the manufacture of the heat-exchange sub product (after stage 6). Through defects with a characteristic size of from 0.1 mm, arising after manual welding, are reliably detected by this method. This method has such disadvantages as low control productivity, the necessity of work with toxic substances, and the impossibility of detecting internal defects.

A violation of the conditions of the welding environment, imperceptible to the operator, during the process of automated ultrasonic welding, can lead to the occurrence of internal defects such as lack of fusion. Technological stage 4 leads to the occurrence of mechanical stress in the welded seams, which can cause the occurrence of internal defects. Thereby, an internal defect in the T-welded seams of finned panels, that reduce the strength of the welded joint, may appear during stage 3 and stage 4 of the production process. Further technological operations cannot lead to the occurrence of internal defects, and after welding the panels to each other (stage 6), the seams made by ultrasound welding will become inaccessible for NDT. Thus, the checking for internal defects in finned panels after their unfolding (stage 4) is technologically justified.

Internal defects of finned panels are not detected by NDT tools used today. To identify them, it is proposed to use the thermal method of inspection - active thermography. This paper describes the development of the main methodological approaches to the creation of a technique for NDT of T-shaped welded joints of thin-walled plates of plate-fin heat exchangers obtained by ultrasonic welding.

Due to the peculiarities of the production technology of finned panels and operation conditions of the product, the active thermography method was chosen to search for internal defects. This NDT method use thermal excitation of the part surface and registration of the dynamics of its thermal response using an infrared (IR) camera [1-5]. Four halogen lamps were used for thermal excitation in this research. The active thermography system registers the dynamics of the controlled object surface temperature in the form of a sequence of IR images (thermograms). Further, using special software, the obtained information about the temperature dynamics is processed by software algorithms [6].

The thermal response of the controlled object surface is determined by such factors as the thermophysical properties of the material, the thickness of the object, peculiarities of the internal structure, the presence of internal defects, etc. One of the effective approaches for flaw detection by the active thermography method is to compare the obtained thermograms with the reference ones obtained for defect-free samples under the same conditions.

The purpose of this research is to develop methodological approaches to the control of welded joints of steel finned panels for the presence of internal defects. To achieve this goal, the following tasks were formulated:

1. To identify the features of displaying a defective welded joint on a thermogram.
2. To reveal the parameter numerically characterizing the presence of unacceptable internal defects on the thermograms of the welded joints.
3. To reveal the correlation between the operational properties of the products and thermal response of the welded joints on the thermograms.

2. Research
For the research, samples were prepared, which are fragments of finned panels, shown in Figure 1. In order to identify the peculiarities of the imaging of a defective welded joint on the thermogram, all samples were tested using an active thermography system, from the flat side. The presence of fins on the reverse side of the samples leads to heat removal in the zone of welded seams. Thus, seams should appear on the thermogram as darker areas relative to the surrounding area. If the seam contains internal defects such as lack of fusion, then in the zone of defects, the thermal conductivity process will be disrupted, and the defective seam will have an inhomogeneous thermal image on the thermogram.
The samples are fragments of two finned panels. Each sample is numbered in accordance with its belonging to one of the two panels and the order in which it follows (Figure 1).

Figure 1. General view of the researched samples (fragments of finned panels).

2.1. Thermographic research of samples
The features of the researched welded joints cause to the following features of their thermograms: edge effect, reflections of foreign objects on the metal surface of the controlled object, the influence of surface inhomogeneities (such as scratches) on the thermal response, and inhomogeneity of heating along the seams. Thus, the NDT technique of finned panels using active thermography method should include the following approaches: matting the surface with black paint to eliminate glares and the influence of scratches; do not evaluate the defectiveness of welded seams areas located close to the edges of the panel.

Figure 2 shows thermographic images of the studied samples, which are fragments of finned panels. Seams 1.2.2 and 1.3.6 have an inhomogeneous thermal response, which can be caused by internal defects such as lack of fusion.

Thus, a qualitative parameter for defectiveness can be considered the brightness difference (inhomogeneous thermal response) along the welded joint, as in the areas highlighted by ellipses in Figure 2.

The parameter that numerically characterizes the presence of internal defects such as lack of fusion in the thermograms of the welded joints can be the "delta" parameter:

\[ \Delta = I_{\text{max}} - I_{\text{min}} \text{, where} \]

\( I_{\text{max}} \) is the maximum intensity of IR radiation along the section of the welded seam, and \( I_{\text{min}} \) is the minimum intensity. Both intensity values should take into account the edge effect: at the edges of the fragments, the intensity of the thermal response is overestimated.
Figure 2. Thermograms of samples 1.1-1.3. Ellipses mark seams with inhomogeneous thermal response that can be defects such as lack of fusion.

2.2. Evaluation of the breaking load of the samples’ seams

One of the key performance characteristics of the welded joints of the finned heat exchanger panels is the breaking load. By exerting pressure on a poorly welded wall, gas or liquid can destroy the T-welded joint. The load, after which the fracture of the welded joint occurs, corresponds to the maximum allowable stress of the product, called the breaking load. The higher the breaking load of the welded seams of the fragments, which characterizes the strength of the finned panel, the higher the reliability of the finished product and longer its life cycle. Therefore the breaking load can numerically describe the performance characteristics of the products. To reveal the correlation between the breaking load of the researched welded seams and their thermal response on the thermograms, the strength of the welded joints was evaluated by the destructive method. Before testing, each fragment was cut into pieces containing one seam equidistant from the edges of the piece. The test procedure used is described in the relevant standards [7-8].

The algorithm for evaluating the welded joints breaking load was as follows:

1. Preparation of samples-pieces of a welded joint.
2. Place the specimen in the test bench with the welded bead facing down as shown in Figure 3.
3. Vertical loading by using special tooling.
4. Registration of the graph of the load on time.
5. Determination and registration of the maximum load $P_{\text{max}}$, after which the sample failed (fracture occurred).
2.3. **Comparison between the operational properties of products and thermal response of the welded joints on the thermograms**

According to the results of the study, the values of the breaking load and the "delta" parameter were obtained for samples of welded joints of finned panels. To search for correlations between the values of $\Delta$, characterizing the results of NDT by the active thermography method and the values of $P_{\text{max}}$, characterizing the operational properties of products, a comparative diagram was built, shown in Figure 4. It can be seen from the diagram that welded seams, with a sharp excess of the average value of the parameter "delta" (seams #8, 15, 18 in the diagram), have significantly lower strength than seams with a homogeneous thermal response.

For defect-free seams with a breaking load value $P_{\text{max}} \geq 1.5$ kN, the average value of the parameter is $\Delta \approx 5 \pm 2$ c.u. (conventional units).

![Figure 4](image)

Figure 4. Comparative diagram of strength and parameter $\Delta$ of the researched seams. The dotted lines mark the points corresponding to seams 1.2.2, 1.3.6 and 1.5.1.
3. Conclusions and perspectives
The defectiveness of seams with a high value of the parameter Δ – welded seams 1.2.2, 1.3.6 and 1.5.1 is confirmed. An inverse dependence of the strength of the welded seam on its Δ parameter, obtained during NDT by the active thermography method, is observed: the higher the “delta” value means the lower the strength of the welded joint. In this case, the main factor that reduces the strength of the welded joint is the presence of internal defects such as lack of fusion in the seam. Therefore, the developed parameter Δ numerically characterizes the presence of internal defects that reduce the strength of the welded joint.

The $P_{\text{max}}$ value is influenced by many factors, and not all seams with a high value of the Δ parameter failed at a load of less than 1.5 kN. However, all seams with a value of the thermal response inhomogeneity parameter $\Delta > 5 \pm 2$ c.u. had a reduced strength. Thus, according to the currently developed approaches, there is an over rejection. It should be noted that all rejected welded seams have an excess of the threshold level by 1 c.u., which is less than the measurement error of the $\Delta$ parameter.

For the further development of the NDT technique, it is necessary to increase the number of samples and carry out work on scaling the developed methodological approaches for longer welded seams.

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