ARCHIVES of FOUNDRY ENGINEERING

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

ISSN (1897-3310)
Volume 14
Special Issue
1/2014
175-180

36/1

Analysis of Thermal Stresses in Components of Pallets Operating in Furnaces for the Carburising Treatment

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Received 28.03.2014; accepted in revised form 14.04.2014

Abstract

The study is devoted to an analysis of thermal stresses arising in the basic elements of pallets used in furnaces for the carburising treatment. The construction of a pallet was presented and an example of its operating cycle was described. Using finite element method, a simulation analysis of the kinetics of cooling and heating of selected pallet components was performed. The results obtained were verified experimentally and used as a basis for the analysis of thermal stresses generated in these components during their cooling.

Keywords: Application of Information Technology to the Foundry Industry, Pallet, Heat flow, Thermal stresses

1. Introduction

Pallets operating as part of accessories in heat treatment furnaces are exposed to the effect of very unfavourable factors such as high temperature and rapid changes of this temperature, strongly carburising atmosphere, and loading. All these factors can significantly change the service life of the pallet. As a result of operation under such conditions, pallets suffer cracks and deformation, making further operation impossible. Therefore it is very important to optimise the design of pallets and minimise the formation of stresses during their operation. Since analytical calculations and experimental determination of stresses responsible for the deformation and failure of pallets are the task very difficult in practical execution, the finite element method (FEM) was used for this purpose.

Elements operating under the conditions of rapid temperature changes are exposed to the effect of stresses due to, among others, phase transformations, different thermal expansion coefficients of the occurring phases, the presence of precipitates and inclusions, and temperature gradients [1, 2, 3]. Studies described in [4] have showed that alloys with a nickel content above 20%, used in the manufacture of equipment for carburising furnaces (pallets included), have a stable austenitic structure in which phase transformations do not occur. The problem of micro-stresses arising in alloys of this type is discussed, among others, in [2, 5, 6]. These are mainly stresses due to some differences in the thermal expansion of carbides and austenite surrounding these carbides. The stresses reach very high values in carbides "outgoing" to the surface of the alloy, but relatively small area of their impact reduces the consequences of their occurrence. Therefore, even though these stresses can initiate the formation of local cracks, the main cause of the destruction of pallets in a macroscopic scale are considered to be the thermal stresses. Due to a large area of their operation, it is assumed that the value of the thermal stresses can be controlled not only through modification of the alloy composition, but also through changes introduced to the design of the pallets examined.

2. Object of studies

Pallets are part of the furnace accessories which carry items loaded into the furnace for heat treatment [1]. A sample pallet and its operating cycle are shown in Figure 1. Hence it clearly follows that the pallet is composed of many identical elements such as a vertical rib, a Y-type connection, a U-type stress relief element, and rings connecting the ribs. These elements are shown in Figure 2. Full stress analysis should cover the entire pallet design, allowing for the mechanical and thermal effect of load placed on the pallet. However, such an analysis, even if FEM is used, is a task very complex and time-consuming. For this reason, in a first stage of the analysis, the impact of the load was disregarded, and numerical calculations were carried out for the individual pallet components.

a) b)

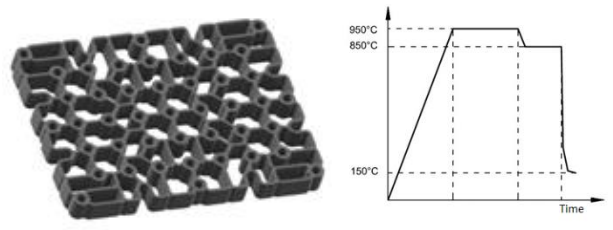


Fig. 1. Example of the main pallet (a) and its operating cycle (b)

The basic element of each pallet is a vertical rib (Fig. 2a). Therefore the analysis of thermal stresses formed in a pallets at the time of its operation started from this element. Since the vertical rib is symmetrical with respect to the three mutually perpendicular planes, its model could be reduced to 1/8 (Fig. 3a), thus significantly shortening the calculation time. The calculations were made in the Nei Nastran engineering software using a finite element mesh shown in Figure 3b.

a) b)

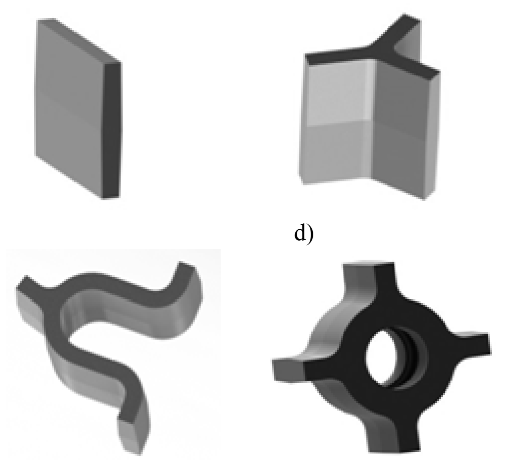


Fig. 2. Pallet components: a) vertical rib, b) Y-shaped connection, c) U-type stress relief element, d) ring connecting four ribs

a)

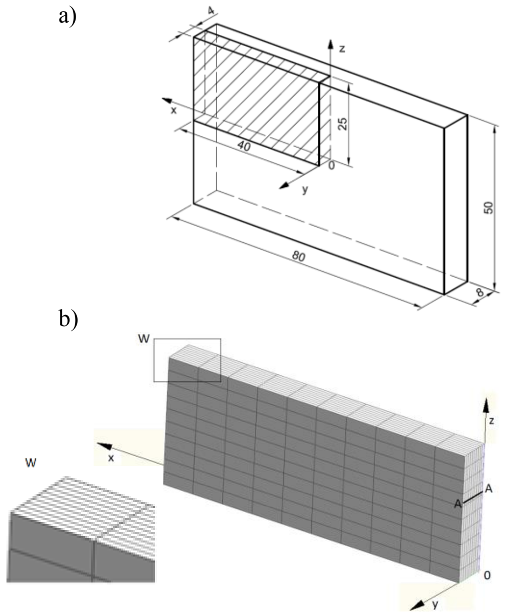


Fig. 3.
Model used in calculations: a) the technique of making the model, b) the applied finite element mesh

3. Studies of changes in the temperature distribution

The information that is necessary for proper analysis of the thermal stresses arising in any element is the knowledge of the kinetics of cooling or heating of this element, and hence the knowledge of changes in temperature distribution in the cross-section of the analysed element in function of time. The kinetics depends on three parameters associated with the heat flow and exchange. These are the following parameters: thermal conductivity λ and specific heat c of the analysed element, as well as the heat transfer (penetration) coefficient h. The functional dependence of thermal conductivity on temperature was determined from the data contained in EN 10295:2002 standard [7], listed in Table 1. The value of the specific heat of the examined cast steel c = 500 J / (kg · K) was also adopted from this standard.

Table 1.
The coefficient of thermal conduction λ vs temperature of cast 1.4849 steel [7]

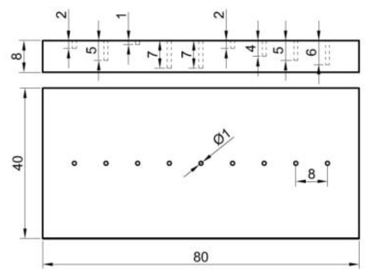
Temperature T, °C	20	100	800	1000
Coefficient λ, W/(m · K)	12	12,3	23,3	26,5

The heating process takes place entirely in a gas atmosphere which is air. Therefore, in this case, one constant value of the heat transfer coefficient h could be adopted for the entire process. The cooling process takes place in a liquid medium. The values of the heat transfer coefficient are comprised in different ranges for the temperature below and above the boiling point. Under real conditions, the pallets are most often cooled in oil. In the example discussed here it has been assumed that this is an OH 70 oil with a boiling point of 300°C. Since the value of the heat transfer coefficient depends on many factors such as the temperature and shape of the heat exchange surface, the coefficient λ, specific heat, density, the coefficient of dynamic viscosity of the fluid, etc. [8], the data in the literature provide a wide range of values for this coefficient depending on the type of the medium applied. It could not therefore be assumed that the values would be chosen correctly only on the basis of theoretical analysis.

Therefore, an experimental study was carried out to determine real changes in temperature distribution in the model of a vertical rib at the time of cooling and heating. The aim of these studies was to verify the values of the parameters (λ, c, h) adopted during simulation tests. The model was a rectangular sample with dimensions of 80x40x8 mm, imitating with its shape and size the rib of a pallet (Fig. 4). It was cast of the same steel of which the examined pallets are cast (1.4849). Holes of varying depth were drilled in the sample, and in these holes during the test, the thermocouples were placed. To prevent an uncontrolled movement of the thermocouple, the sample was provided with special holder stabilising the position of the sensors. A photograph of the sample and holder is shown in Figure 4b.

During measurements, the sample was heated to 900°C in a KS 520/14 chamber furnace, and then cooled in the OH 70 quenching oil at 45°C. During cooling and heating of the sample,

a)



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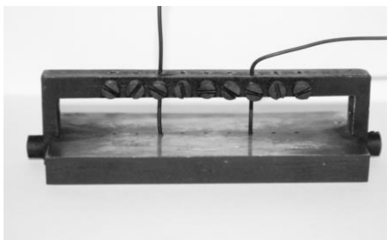
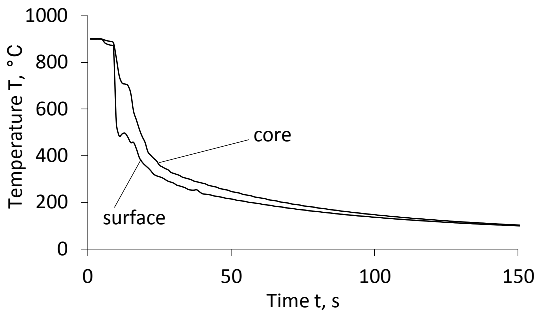


Fig. 4. Sample for experimental analysis of temperature changes: a) the place of temperature measurement, b) a photograph of the sample with holder for the thermocouple

temperature changes were recorded at selected points of the sample cross-section using a CHY506a recorder. The time difference between the two consecutive recorded measurements was 1 s.

The results of measurements taken in the subsurface zone of the sample (1 mm from the surface) and in the core of the sample (4 mm from the surface) are shown in Figure 5. The resulting curves are not smooth. This is probably due to the process of the precipitation of fine-dispersed secondary chromium carbides $M_{23}C_6$ [9].

a)



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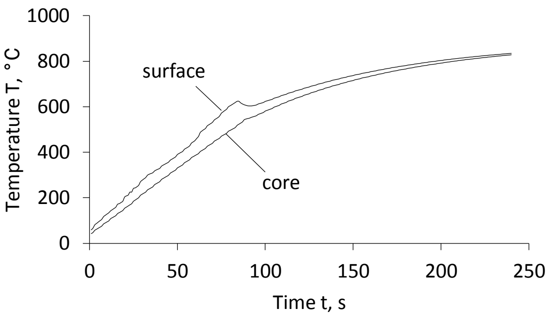
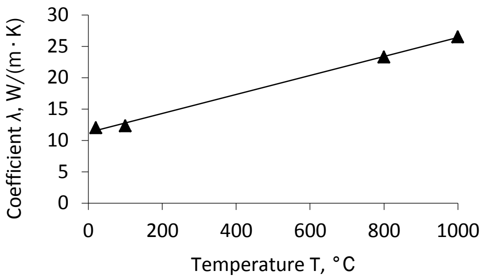


Fig. 5. The experimental results of temperature changes on the surface and inside the rib: a) during cooling, b) during heating

In simulation analysis of the kinetics of cooling and heating, as the initial condition was adopted the assumption that the temperature was the same within the entire examined sample. The initial and final temperature of both processes and the media in which those processes took place were the same as those adopted in the experimental studies. The heat exchange with the environment took place through the walls of the examined element via a convection mechanism, while heat flow inside the element took place by conduction. The value of the coefficient of conduction was chosen in accordance with the characteristics shown in Figure 6a, basing on the data contained in Table 1. In the case of the heat transfer coefficient h, its value was determined from the reference data, and then, in subsequent iterations, those values were corrected adjusting the calculation model to experimental data to minimise the differences between the experimentally determined temperature distribution and the distribution obtained by model analysis. Finally, for the process of heating, one constant value of the heat transfer coefficient h amounting to 120 W/(m^2·K) was adopted. On the other hand, for the cooling process, the functional relationship shown in Figure 6b was adopted. Results of temperature changes on the a)



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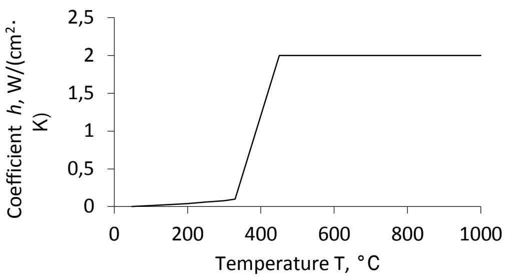
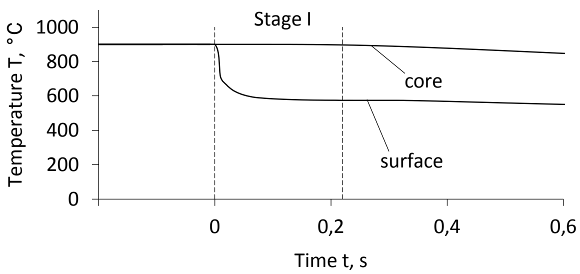


Fig. 6. Relationships adopted in the calculations: a) coefficient of thermal conduction λ , b) coefficient of heat transfer h during cooling

surface and inside the sample during cooling and heating, generated for the adopted parameters, are plotted in Figures 7 and 8.

a)



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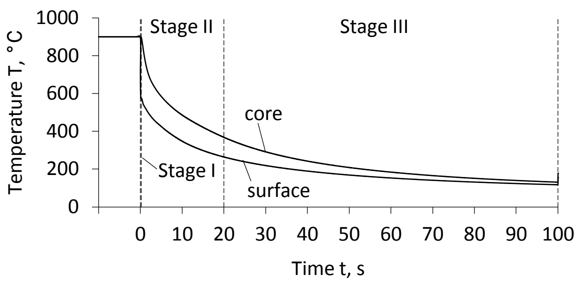


Fig. 7. Temperature changes on the surface and inside the rib during cooling: a) stage I, b) all stages

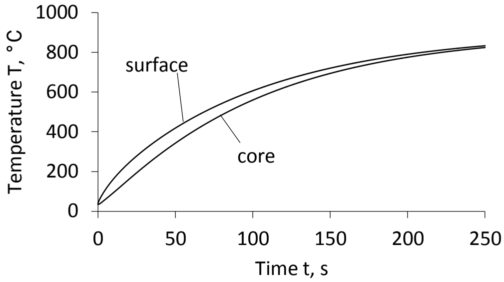
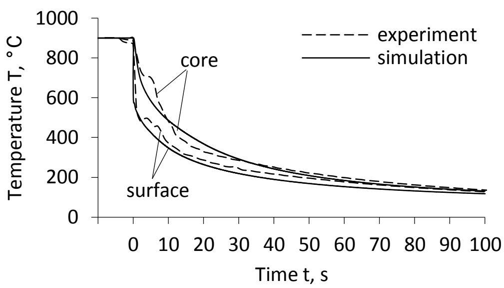


Fig. 8. Temperature changes on the surface and inside the rib during heating

Charts comparing the results of simulation analysis with the results of experimental studies are presented in Figure 9. The results are characterised by a high degree of consistency, which proves the correctness of the adopted computational model. Therefore, the determined values of the parameters λ, c, h can be used in an analysis of the distribution of thermal stresses during heating and cooling of the pallet components.

a)



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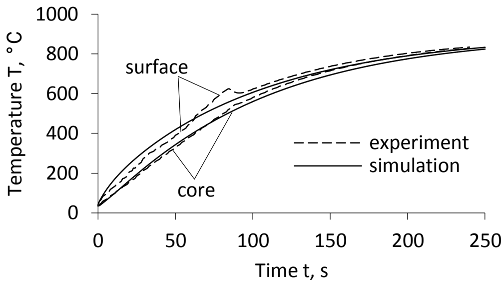


Fig. 9. The results of numerical calculations compared with the results of experimental studies of the kinetics of: a) cooling, b) heating

4. Analysis of thermal stresses

This study shows the results of analysis done for cooling. Cooling is a process that occurs more rapidly and is characterised by larger temperature gradient on the cross-section of the cooled element than the gradient obtained on heating. Thermal stress analysis was performed on the previously presented computational mesh (Fig. 3b). When determining the degrees of freedom for each node, the symmetry of the examined sample relative to the three mutually perpendicular planes was also used. The nodes located on planes *0xy, 0yz, 0zx* were deprived of the degrees of freedom in the directions perpendicular to these planes. This means that the node at point 0, which is the intersection of *x, y, z* axes, was deprived of the three degrees of freedom, while nodes along these axes were deprived of the two degrees of freedom each. Nodes that were not lying on the planes of symmetry were free [10]. To simplify calculations, in the analysis, the adopted values of the mechanical properties of cast steel were the values obtained at room temperature. Based on the literature [1, 7, 11], the following values were adopted:

- Young's modulus: $E = 1{,}86 \cdot 10^5$ N/mm^2,
- yield strength: $R_{0,2} = 220$ N/mm^2,
- coefficient of thermal expansion $\alpha = 17 \cdot 10^{-6}$ 1/K.

The analysis assumed a perfectly elastic-plastic model of the examined cast steel.

The cooling process was conventionally divided into three stages selected on the basis of changes in the temperature distribution in the examined element. In the first step lasting from the start of cooling for about 0.22 second, in accordance with the results obtained in earlier studies, the surface temperature was changing faster than the temperature in the interior of the sample (Fig. 7). The second of the analysed steps lasted from 0.22 to 20 seconds (Fig. 7b). The choice of the upper limit in this step was dictated by the drop of surface temperature below 300°C, and thus by transition to the low heat transfer coefficient values (Fig. 6b). In this step, the temperature of both the surface and the interior of the sample was changing relatively quickly, but it was the temperature inside the sample that underwent more violent changes. The third step lasted from 20 to 100 seconds (Fig. 7b). During that stage of cooling, the changes of temperature in both the surface and the core of the rib were obviously less intense than in the previous stages, and gradient of these changes assumed the values lower on the surface compared with the interior of the sample. Owing to this division of the cooling process it was possible to follow changes in the nature of the stresses formed during cooling and allow to some extent for the fact that stresses formed in the first few seconds would undergo relaxation.

Figure 10 shows the distribution of reduced stresses (according to Huber hypothesis) after each of the above mentioned stages of cooling. The graphs in Figure 11 show the distribution of stresses in the direction of the *x*-axis on the cross-section of the examined element (along the A-A line as indicated in Fig. 3b) after each of the three stages. They show how the nature of stresses formed in the rib changes during cooling.

The stress distribution obtained from the conducted analysis was consistent with expectations. In the first step of cooling, high tensile stresses were formed on the surface and compressive stresses inside the examined material. In the second step, this trend assumed a reverse direction. High stresses developed in the first and second cooling step exceeded the yield strength of the examined cast steel, and as such underwent relaxation, causing plastic deformation. Stresses developed in the third cooling step were similar to those of the second step, i.e. they were compressive on the surface and tensile inside the sample. Yet, because their value was much lower, they would not be relaxated, and would remain in the material in the form of residual stresses.

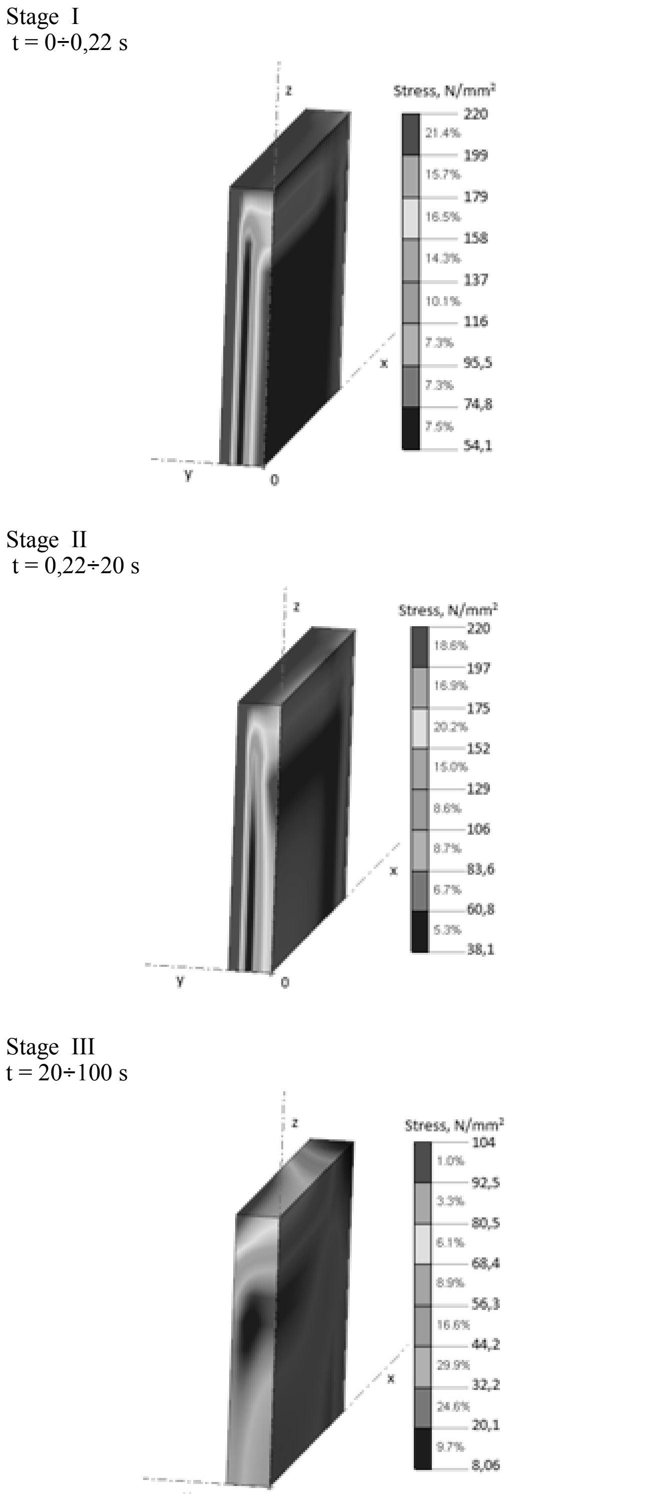
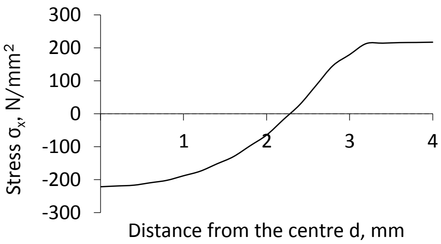
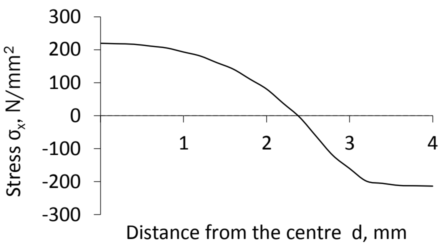


Fig. 10. Changes in the reduced stress distribution (σ_{red}) for each of the three stages of cooling

Stage I, t = 0÷0,22 s



Stage II, t = 0,22÷20 s



Stage III, t = 20÷100 s

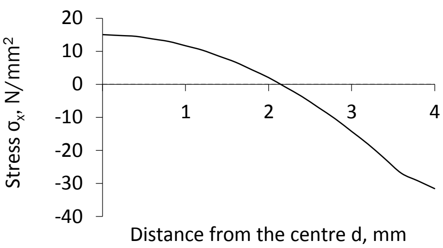


Fig. 11. Stress distribution changing in the direction of the *x*-axis (σ_x) in the cross-section of the rib for each of the three stages of cooling

5. Summary

The conducted calculations show that even if the discussion is limited to the basic component of the pallets which is a vertical rib, the thermal stresses formed during cooling (particularly in the first stage of this cooling) can cause plastic deformation. This demonstrates the great importance that these stresses have for components operating under the conditions of sudden temperature changes, such as pallets used in the carburising furnaces.

It can be assumed that stresses formed in more complex elements of pallets, particularly in the areas of non-uniform wall thickness (the formation of hot spots) will achieve much higher values. The problem is much more complex in the case of abnormal heat flow between individual areas of the pallet, caused by more slowly cooling mass of the load arranged on a pallet. Further studies should take into account the factors mentioned above.

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