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Design Options to Decrease the Thermal Stresses in Cast Accessories for Heat and Chemical Treatment Furnaces

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Abstract

By the very nature of their work, castings used in furnaces for heat treatment and thermo-chemical treatment are exposed to the effect of many unfavorable factors causing their deformation and cracking, significantly shortening the lifetime. The main source of damage are the micro- and macro-thermal stresses appearing in each cycle. As the cost of furnace instrumentation forms a significant part of the total furnace cost, in designing this type of tooling it is important to develop solutions that delay the damage formation process and thus extend the casting operation time. In this article, two structural modifications introduced to pallets castings to reduce thermal stresses arising at various stages of the cooling process are proposed. The essence of the first modification consists in making technological recesses in the wall connections, while the aim of the second one is to reduce the stiffness of the pallet by placing expanders in the external walls. Using the results of simulation analyses carried out by the finite element method, the impact of both proposed solutions on the level of thermal stresses was evaluated.

Keywords: Application of Information Technology to the Foundry Industry, Cast grates, Thermal stresses, Heat treatment equipment

1. Introduction

High temperature rapidly changing in cycles, strongly carburizing atmosphere and mechanical loading with the batch of heat-treated items create an environment conducive to the destruction of the equipment of carburizing furnaces, such as pallets, baskets, etc. usually made of stable austenitic Fe-Ni-Cr alloys. As a result of operation under such unfavorable conditions, the mechanical properties of castings are degraded due to fatigue processes taking place in the heated and rapidly cooled material and the increase of carburized layer caused by carbon diffusion towards the core of the casting. As a result of these changes, the initially elastic-plastic material with relatively high strength properties becomes brittle with much lower strength and impact resistance. Rapid temperature changes are additionally the source of micro- and macro-stresses, which in subsequent cycles of operation of the furnace equipment may, as a result of fatigue-initiated changes, lead to the formation and accumulation of deformations and to the nucleation and development of cracks eliminating castings from further use[1-7].

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 structural components, and temperature gradient which arises on the cross-section of the casts during rapid cooling.

Casts – pallets, baskets, spacers etc. used to charge transport in heat treatment furnaces are usually made of alloys with an increased content of nickel (over 20%). Such a high content of this element ensures a stable austenitic structure in the entire temperature range of the cast work [8]. On the other hand the differences between the thermal expansion of the austenitic matrix and non-metallic inclusions and precipitates are so great that the stresses formed by them during rapid cooling, may cause local permanent deformation or may lead to the formation of local microcracks [7]. Stresses that do not relax due to plastic deformation or cracks will remain in the material in the form of residual stresses, contributing to the intensification of fatigue processes [9-11].

In the conditions of temperature changes, residual stresses are also created on the cross-section of the cooled element, as a result of the temperature gradient that forms between the surface of the element and its core, as well as near the thermal nodes and also as a result of differences in thermal influence of the transported charge. At high temperatures, when the mechanical properties of the material are clearly reduced, plastic deformations may occur in the casts. As a result, during the cooling process, when the material's ability to relax the stresses is much lower, the residual stresses arise in the casting. The cyclic nature of the work of the furnace tooling elements causes that the deformations appearing in subsequent cycles can accumulate, eventually leading to too large deformations of the element or its cracking.

The conditions under which the pallets are expected to operate, i.e., among others, the recurring in cycles rapid changes in temperature, are closely related to the treatment process that the feedstock has to undergo and thus to the stress-generating factor which cannot be eliminated. In spite of this, it is possible to mitigate the adverse effects by choosing appropriate design solutions for the pallets used [12-14].

This article presents the quantitative results of numerical analyses carried out by the finite element method, illustrating the effect of structural changes on the distribution and value of stress and strain generated in the pallet during its cooling.

2. Research object

Examples of pallets used for transport of the furnace charge are shown in Figure 1 and 2. They are openwork, thin-walled structures usually cast from creep-resistant alloys with a high nickel content (above 20%). Their composition ensures relatively good mechanical properties and a stable austenitic structure in the entire temperature range in which they are used [1-5].

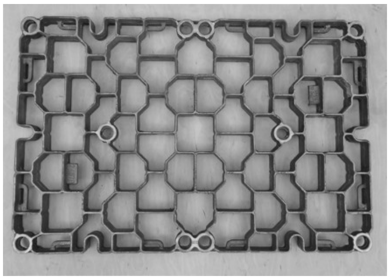

Fig 1. Sample pallet used in heat treatment furnaces

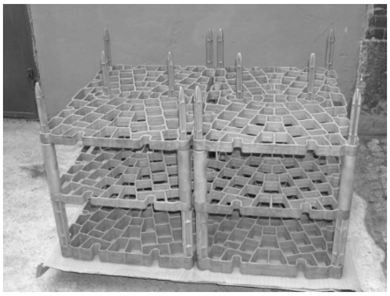

Fig. 2. Pallets working in a multi-level set

The mere nature of the work, closely related to the conditions to which the heat-treated batch must be subjected, makes pallets exposed to the effect of the heating and cooling cycles. Under such conditions, due to temperature gradients and different thermal expansion of the structural constituents (carbides and austenite) of cast steel, stresses arise in pallets. Over time, the cyclic effect of stress causes the formation and growth of permanent deformations and cracks (Fig. 3), which result in the need to regenerate pallets or even to completely withdraw them from use.

a)

b)

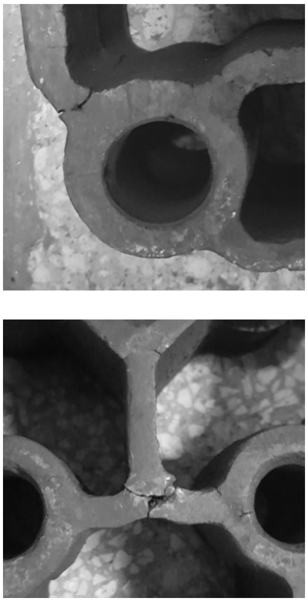

Fig. 3. Cracks arisen during operation: a) corner area, b) wall connection

As the price of furnace equipment is a significant component of the total operating cost of the furnace, it is important to maximize the working time of this equipment. However, the achievement of this goal is not possible without studies of the mechanisms responsible for the occurrence of the damage.

3. Wall connections and thermal nods

In the casting of the pallet, the areas particularly susceptible to the formation of cracks are the connections of pallet walls. Due to the large volume of material, thermal nodes are formed in them, and during the heating and cooling process, they undergo slower temperature changes than the adjacent ribs. The difference in the speed of temperature changes between the connection centre and the adjacent walls results in a temperature gradient, which introduces additional thermal stresses to the pallet structure during each cycle.

Figure 4 presents typical design solutions for wall connections used in pallets, i.e. **T**, **Y** and **X** connections. In terms of thermal nodes, and hence in terms of the amount of heat accumulated during heating and given up during cooling, they differ from each other mainly in the distance of connection centre from the surface of the walls. This distance can be determined by the radius of the circle inscribed in the joined ribs of the pallet. The larger is this radius, the greater will be the temperature differences between the connection centre and the adjacent walls, and thus the temperature gradient generated in this direction. Figure 3c and d also shows modified equivalents $\mathbf{T_m}$ and $\mathbf{Y_m}$ of **T** and **Y** connections, in which the so-called technological recesses have been made to reduce the negative impact of thermal nodes by removing part of the material and thus reducing the radius of the circle inscribed in the joined ribs.

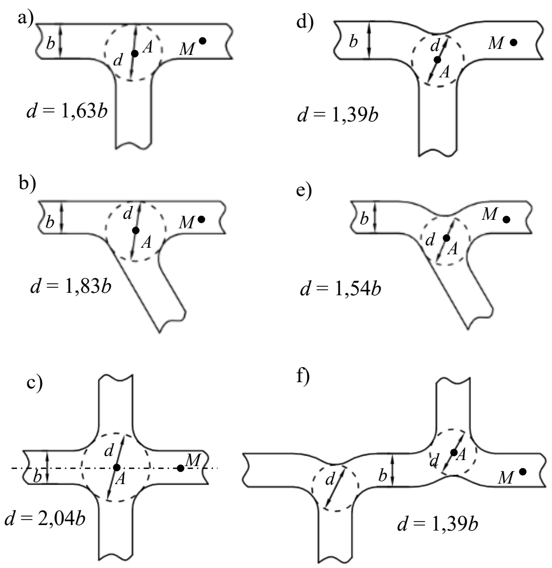

Fig. 4. Types of grate walls connections: a) **T**, b) **Y**, c) **X**; and their modified versions: d) $\mathbf{T_m}$, e) $\mathbf{Y_m}$, f) double $\mathbf{T_m}$

The effect of the applied design solutions on temperature differences between the connection centre (point *A* in Fig. 4) and centre of wall cross-section (point *M*) located at a distance of 3*b* from the centre *A* is shown for the process of cooling in Figure 5. The drawing comprises the results of simulation analysis of the cooling process of the above-described types of pallet wall connections, and more precisely the course of changes in the temperature differences. In this analysis, it was assumed that the pallet wall thickness was b = 8 mm and cooling of the examined components from the initial temperature T_o = 900°C was carried out in oil of the temperature T_1 = 40°C. In calculations, the thermal properties specific to cast steel 1.4849 were adopted in accordance with the standard EN 10295:2002 [15], i.e. specific heat c = 500 J/kg·K and temperature-dependent thermal conductivity coefficient λ in the range of 12.6 ÷ 26.6 W/m·K. The first 20 s of cooling process were conducted. The calculations were made by the finite element method using a Midas NFX 2014 software.

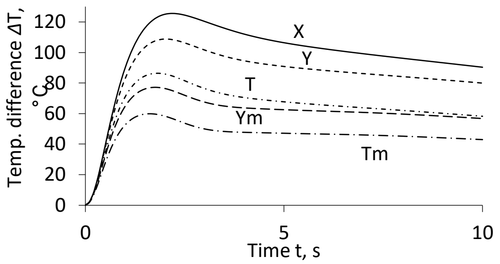

Fig. 5. Changes in the temperature differences between points *A* and *M* for various types of wall connections; cooling process

From diagrams given in Figure 5, it is clearly seen that the largest differences in temperature rise in the X-type connection, which has the largest diameter *d* of the circle inscribed in the joined ribs (Fig. 4). It means, that in terms of the additional thermal stresses, this connection tends to create, it is the worst one among all the examined types of connections.

The graphs also show that the introduction of technological recesses affects temperature differences arising in the redesigned connections. In $\mathbf{T_m}$ connection, the maximum temperature difference has been reduced by approximately 31%, and in $\mathbf{Y_m}$ connection – by approximately 29%. When the **X** connection was replaced with a $\mathbf{T_m}$ or double $\mathbf{T_m}$ connection, the maximum tempe-rature difference between points *A* and *M* decreased by about 52%.

The impact of thermal nodes on the distribution of reduced stresses is graphically presented in Figure 6. It shows the distribution of stresses between the connection centre and its lateral surface (laying in the same *xy* plane) for connections of the **X**, **T** and $\mathbf{T_m}$ type. The load in the analysis was assumed to be a rapid temperature change from the same, equal to T_0, a temperature in all nodes to such its temporary distribution in the connection, for which the differences between the previously defined (Fig. 4) points *A* and *M* are the most critical.

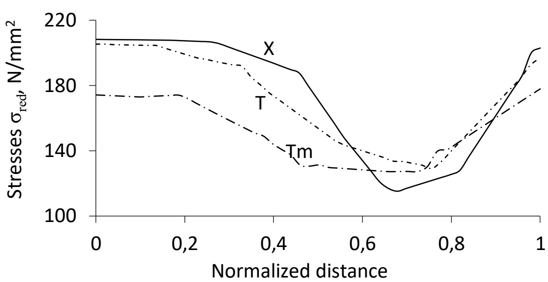

Fig. 6. Distribution of reduced stresses between the centre of various wall connections and their lateral surface

Figure 5 shows that, depending on the type of connection, the maximum temperature differences between these points fall to the initial time of cooling, i.e. 1.6 ÷ 2.2 s. Based on the graphs in Figure 6, it can be concluded that the size of the formed thermal nodes has a clear effect on the stresses generated in the first moments of the cooling process. The introduction of the recesses has significantly reduced the maximum and average stresses and thus is the optimal solution for wall connections.

4. Changes in flexibility of outer ribs

Cracks and visible deformations arising during operation of cast pallets are often located in areas near the corners. This is mainly due to the specific nature of thermal and mechanical loads which the pallet transferring the batch must withstand. During operation, the structure of the pallet can be divided into two main areas − the inner part under the load and the outer contour. The location and size of the batch are important factors that shape the differences in temperature between these areas. When the batch being processed is compact and has a large volume, during cooling it behaves like a heat accumulator, slowing down the cooling process in the layers of the pallet material which are lying directly below the batch. On the other hand, in the unloaded external contour, temperature changes very rapidly, speeding up changes in dimensions caused by thermal expansion. Due to this difference, depending on the process (heating or cooling) and its stage, the contour is subjected to the recurring in cycles alternate effect of tension and compression. Over time, this effect becomes visible in the form of permanent deformations, e.g. characteristic pushes.

To find out what impact the stiffness of the contour can have on stresses arising in the pallet ribs adjacent to the corners, stress distribution analysis was carried out during cooling of four pallet structure variants (Fig. 7). The study focused on comparing the initial pallet structure with **X** connections (Fig. 7a) to its counterparts in which, according to the results presented in the previous chapter, these connections were replaced with a double $\mathbf{T_m}$ connection (Fig. 7b) and with its further modifications, i.e. $\mathbf{T_{m1}}$ and $\mathbf{T_{m2}}$ (Fig. 7c and d), in which the U-shaped outer contour expanders were used. The task of the expanders was to reduce the stiffness of the outer contour [8]. Due to the symmetry of the tested structures (with load placed on them) relative to the two main planes of the coordinate system, the models used in the calculations represented ¼ of the entire structure, which significantly reduced the calculation time.

To determine the temperature gradient introduced in the studies as a source of stresses, heat flow calculations were performed for the adopted design solutions of pallets loaded with cuboidal charge, resting on their internal area and reaching half of the *OB* ribs (as shown in Fig. 7). In the calculations, the initial temperature of 900°C was again adopted, but it was assumed that cooling takes place in the air at 40°C. The change in temperature distribution for points *B* and *O* in the palette with T_m connections is graphically shown in Figure 8.

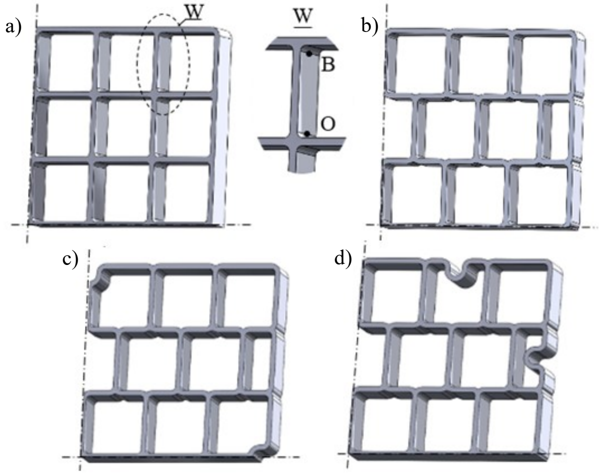

Fig. 7. Quarters of the grates models used for the stress analysis in corner ribs: a) **X**, b) $\mathbf{T_m}$, c) $\mathbf{T_{m1}}$, d) $\mathbf{T_{m2}}$

It is easy to notice that with time, as a result of the batch interaction, the difference in temperature between the outer contour (point *B*) and the inner part (point *O*) of the pallet increases until a maximum of about 138 °C is reached at time t_d.

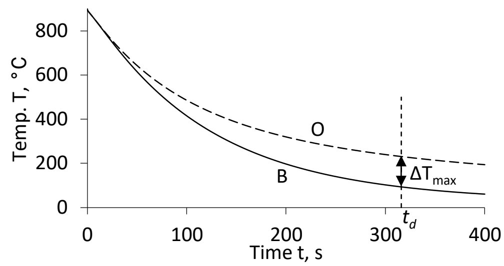

Fig. 8. Temperature change at points *O* and *B* during cooling

In the analysis of stress distributions, nodes lying on the main planes of the coordinate system were deprived of the degrees of freedom in the directions perpendicular to these planes, and the value of load was set by changing the temperature distribution from the starting temperature T_o = 900°C to the distribution obtained after time t_d (Fig. 8). The calculations made for an austenitic material were based on an elastic-plastic model with nonlinear hardening, where the true tensile curve was approximated with several straight lines with different strain hardening moduli E_{ai}. The following data was adopted − the coefficient of thermal expansion α = 17.7 · 10^{-6} 1/K, Poisson's number ν_a = 0.253, Young's modulus E_a = 1.73 · 10^5 N/mm^2, yield strength $R_{0.2}$ = 208 N/mm^2 and, with the yield strength exceeded, the strain hardening modulus E_{a1} = 4.09 · 10^3 N/mm^2.

The results of the calculations are plotted in the form of diagrams in Figure 9. They show the obtained distributions of reduced stresses σ_{red}, determined in accordance with the Huber-Mises yield criterion, in a bounded rib of the pallet between points *O* and *B* for the four variants examined.

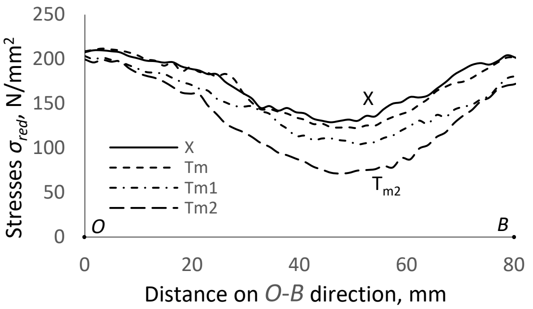

Fig. 9. Distribution of reduced stresses in OB rib of the tested grate design after t_d time

As demonstrated by the results obtained, the mere change of connections from **X** to double $\mathbf{T_m}$ has only a minor effect on the change in stress distribution under the thermal load after time t_d. According to the results presented in Figure 4, this is due to the fact that the temperature gradient caused by different wall joint thicknesses assumes its highest value in the initial moments of the rapidly occurring processes (mainly cooling when temperature of the surface can change about 200 °C during first second) and is local in nature. The differences in temperature between the outer zone and the inner zone, responsible for deformations in the corner areas of the pallet according to the graph in Figure 7, reach the maximum much later.

The introduction of expanders to the design significantly reduces the resulting stresses. This is most evident in the $\mathbf{T_{m2}}$ structure, where these elements are more numerous and situated closer to the corners of the pallet. The application of expanders reduces the stiffness of the outer contour of the pallet, since the introduced segments are capable of undergoing much larger deformations in the direction parallel to the wall on which they are placed than straight ribs. In this way, stresses in the ribs adjacent to the corners are lower, and consequently plastic deformation of the structure is reduced, both of which reduce the risk of crack formation in these areas.

Regardless of whether the stresses are generated by the thermal influence of the charge or by the temperature gradient caused by the existence of thermal nodes, the introduction of constructional changes aimed at decrease of the stresses value can significantly contribute to the reduction of deformations arising at elevated temperatures, and thus to lower the residual stresses remaining in the casts after each work cycle.

5. Summary

Two examples of modifications introduced to the pallet construction to reduce stresses arising during pallet operation in the furnace are presented.

The essence of the first modification consisted in the design of a connection which, owing to the introduction of technological recesses, produced the smallest possible thermal nodes. The obtained results indicate that by reducing the size of nodes, it is possible to significantly reduce the temperature differences appearing in the first moments of rapid cooling, and in this way reduce the level of thermal stresses induced at that time.

However, this change had only a minor effect on stresses, which in the case of longer and slower cooling were formed in the pallet structure due to the presence of thermal load caused by the transferred charge. Since the source of stresses was different in this case, to reduce them, a modification to the pallet contour making it less stiff was proposed. For this purpose, U-type expanders were used, and the consequence was a significant decrease in the value of the generated stresses.

The destruction of castings operating under the conditions inherently related to the type of the performed heat treatment is a complex process. Depending on the stage of this process and the conditions under which it occurs (temperature, cooling medium, the atmosphere inside the furnace), various factors can be responsible for the occurrence of damage. However, in each case, the appearance of deformation or cracks depends on the presence of stresses in a castings component.

For this reason, understanding the mechanisms of stresses formation caused by different (mentioned above) factors and developing ways to reduce these stresses is an important factor that could slow down the fatigue processes occurring in real elements, during their exploitation.

Studies have shown that through appropriate design solutions it is possible to significantly reduce the thermal stresses that arise in the structure, and this should contribute to the extended service life of pallets casts.

References

[1] Lai, G.Y. (2007). *High-Temperature Corrosion and Materials Applications*. ASM International.
[2] Davis, J.R. (Ed.). (1997). *Industrial Applications of Heat-Resistant Materials*. In Heat Resistant Materials (67-85). ASM International.
[3] Dossett, J.L., Boyer, H.E. (2006). *Practical Heat Treating*. ASM International, 2nd ed.
[4] Lo, K.H. et al. (2009). Recent developments in stainless steels. *Materials Science and Engineering R*. 65, 39-104.
[5] Piekarski, B. (2012). *Creep-resistant castings used in heat treatment furnaces*. Szczecin: West Pomeranian University of Technology Publishing House, (in Polish).
[6] Nandwana, D., et al. (2010). Design, Finite Element analysis and optimization of HRC trays used in heat treatment process. Proceedings of the World Congress on Engineering WCE 2010, (II), 1149-1154.
[7] Bajwoluk, A. & Gutowski, P. (2019). Stress and crack propagation in the surface layer of carburized stable austenitic alloys during cooling. *Materials at High Temperatures*. 36(1), 9-18, DOI: 10.1080/09603409.2018.1448528.
[8] Kubicki, J., Christodulu, P. (1983) The stability of chromium-nickel steel under condition of carburising treatment and thermal shock. In IX Symp. Nauk. z okazji Dnia Odlewnika, part 1. (93-99). Kraków: Wyd. AGH. (in Polish).
[9] Ravichandran, K.S. (1995) Thermal residual stresses in a Functionally Graded Material system. *Materials Science and Engineering A*. 201, 269-276.

[10] Rossini, N.S. et al. (2012). Methods of measuring residual stresses in components. *Materials and Design*. 35, 572-588, DOI: 10.1016/j.matdes.2011.08.022.
[11] Senczyk, D. (1996) *Residual stresses: introduction to generate, control and use*. Poznan Univeristy of Technology Publishing House. (in Polish).
[12] Drotlew, A. et al. (2013). Structure of guide grate in heat treatment technological equipment. *Transactions of foundry research institute*. 53(3), 59-71. DOI: 10.7356/iod.2013.16.
[13] Bajwoluk, A. & Gutowski, P. (2015). The effect of pallet component geometry on temperature gradient during cooling. *Archives of Foundry Engineering*. 15(1), 5-8. DOI: 10.1515/afe-2015-0001.
[14] Bajwoluk, A. & Gutowski, P. (2016). Thermal Stresses in the Wall Connections of Cast Grate Structures. *Archives of Foundry Engineering.* 16(4), 11-16. DOI: 10.1515/afe-2016-0075.
[15] Standard EN 10295:2002. Heat resistant steel castings.