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Mechanical Stresses Induced by Compression in Castings of the Load-carrying Grate

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Abstract

The main aim of this study was to examine the compression-induced state of stress arising in castings of the guide grates during operation in pusher-type furnaces for heat treatment. The effect of grate compression is caused by its forced movement in the furnace. The introduction of flexible segments to the grate structure changes in a significant way the stress distribution, mainly by decreasing its value, and consequently considerably extends the lifetime of the grates. The stress distribution was examined in the grates with flexible segments arranged crosswise (normal to the direction of the grate compression) and lengthwise (following the direction of force). A regression equation was derived to describe the relationship between the stress level in a row of ribs in the grate and the number of flexible segments of a lengthwise orientation placed in this row. It was found that, regardless of the distribution of the flexible segments in a row, the stress values were similar in all the ribs included in this row, and in a given row of the ribs/flexible segments a similar state of stress prevailed, irrespective of the position of this row in the whole structure of the grate and of the number of the ribs/flexible segments introduced therein. Parts of the grate responsible for the stress transfer were indicated and also parts which play the role of an element bonding the structure.

Keywords: Innovative Foundry Technologies and Materials, Castings for Heat Treatment Plants, Grates

1. Introduction

Providing the elements of machines and equipment with adequate durability (service life) during the period of operation is one of the major tasks facing the designer, particularly important in all those cases where failure entails a long downtime and significant costs.

Durability depends not only on the properties of the material itself, but also on the size and shape of the whole structure and its individual parts, on the way these parts are connected to each other, and on the type of constraints resulting from the tasks that a given structure has to fulfil under the specified operating conditions [1, 2].

Grate - an essential element of the accessories used in pusher furnaces (load carrier), usually cast - is an example of the structure which during its operation is subjected to the effect of alternating mechanical and thermal loads. When the row of grates is moving in a furnace, individual grates are exposed to the effect of compression changing in cycles and combined with simultaneous heating followed by cooling. The thermal expansion of the grate material further increases the areas of stress concentration occurring in the structure of the grate [3].

The replacement of rigid ribs in a grate (Fig. 1a) with flexible segments (Fig. 1b) increases the flexibility of the whole system (lower rigidity of the cast structure), eliminating some of the structural notches [4-6]. A number of flexible segments in

crosswise configuration will improve the grate flexibility in a much more efficient manner than the same number of flexible segments arranged in a lengthwise configuration ($N_{fs\parallel}$, [5]). Also, the same number of flexible segments, whether arranged crosswise or lengthwise, will raise by the same value the overall grate flexibility, no matter in which part of the entire structure of the grate these segments will be positioned [5]. The aim of this study was to examine the values of reduced von Mises stress in a grate operating at ambient temperature under the effect of mechanical loads only. Another aim was to analyze the consequences of stress reduction as a result of the presence of flexible segments introduced to the grate design. In subsequent studies, the analysis will also cover more complex simulated conditions of the grate operation, allowing for, among others, changes in the operating temperature.

2. Methodology of studies

Current analysis of stresses occurring in the grate, the design of which has been modified with flexible segments, is a continuation of the studies presented in [5]. Therefore, the same assumptions were also adopted in this analysis [5]:

1. Structural elements of the grate include rigid ribs (Fig. 1a) and flexible segments (Fig. 1b). The shape and size of the guide grate (before modification of its design) is shown in Figure 2.

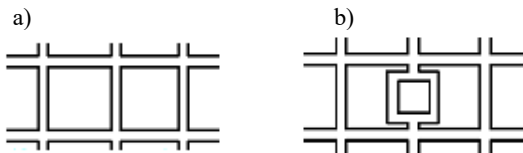


Fig. 1. Structural elements of the grate:
a) rigid rib, b) flexible segment

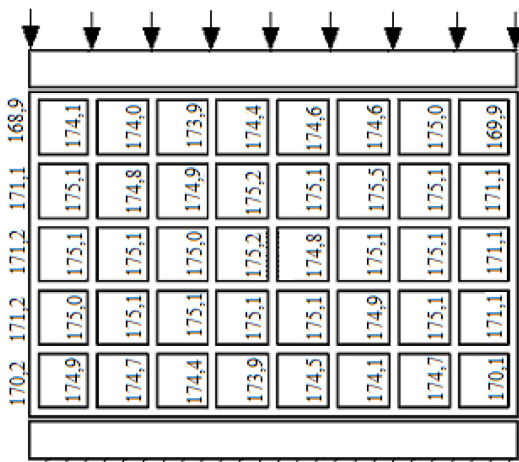


Fig. 2. Map of the distribution of compression-induced reduced von Mises stress in an unmodified design of the grate (stress [MPa] on the left side was measured in the centre of ribs). The grate dimensions were $407 \times 257 \times 30$ mm, thickness of the rib: 7 mm

2. Modified design of the grate. The original design of the grate (Fig. 2) was modified with flexible segments placed on the grate axes of symmetry. Four grates with modified configuration were designed (Fig. 3). It is planned to measure the stress state in these grates and compare the results with the results obtained in an unmodified structure (Fig. 2). It has been assumed that the selected grates form a representative group, which should help in the estimation of stress distribution in other flexible segments of the grates in crosswise or lengthwise arrangement [5].
3. The grate material is cast GX40NiCrSiNb38-19 steel (1.4849). Selected characteristics of the alloy are given in Table 1.

Table 1.

The mechanical and physical properties of cast steel used in calculations

Elastic modulus; MPa	173000
Poisson's ratio	0.253
Transverse elastic modulus MPa	318.9
Density; kg/m^3	7800
Tensile strength; MPa	440
Yield strength; MPa	230
Coefficient of thermal expansion; K^{-1}	1.6
Thermal conductivity; $\text{W}/(\text{m}\cdot\text{K})$	14.6
Specific heat; $\text{J}/(\text{kg}\cdot\text{K})$	500

4. Measurement of stress in the grate. Each grate was placed between two rigid, non-deformable beams. One beam was permanently fixed, while to the other beam force was applied, producing the grate deformation of 0.25 mm in the direction of compression. The assumed value of strain was corresponding to an increment in the grate dimensions caused by the instantaneous temperature difference of 300°C occurring between individual fragments of the grate, e.g. at the beginning of the heating process [5]. The reduced von Mises stress was measured in central part of the ribs parallel to the direction of compression (perpendicular ribs carry much lower stresses than the ribs of parallel orientation, and therefore at this stage of studies they were not included in the analysis).
5. Measurement of stress in the grate. Each grate was placed between two rigid, non-deformable beams. One beam was permanently fixed, while to the other beam force was applied, producing the grate deformation of 0.25 mm in the direction of compression. The assumed value of strain was corresponding to an increment in the grate dimensions caused by the instantaneous temperature difference of 300°C occurring between individual fragments of the grate, e.g. at the beginning of the heating process [5]. The reduced von Mises stress was measured in central part of the ribs parallel to the direction of compression (perpendicular ribs carry much lower stresses than the ribs of parallel orientation, and therefore at this stage of studies they were not included in the analysis).

3. Results

The map of stresses which occur in the unmodified structure of the grate (Fig. 2) shows that stresses in the ribs parallel to the direction of force are much higher than the stresses in the ribs normal to the direction of force (the measured value of stresses is approx. 4 MPa). It has also been noted that in the centre of parallel ribs placed in the opposite ends of the grate (right and left), stresses were slightly lower than in the ribs placed in other parts of the grate.

The grate configuration allows for buckling of the extreme ribs, due to which the force of compression shortens their neutral

axis less than it does with other ribs. Thus, the stress normal to the direction of force is reduced, and force under such loading conditions is its main component. Due to buckling, on the cross-section of the extreme ribs, the variations in stresses are larger than in the remaining ribs, but - compared with the values of stresses in the ribs perpendicular to the direction of force (approx. 4 MPa) - the parallel ribs in both extreme and other positions carry much higher stresses. Since the difference in stresses between the extreme parallel ribs (approx. 171 MPa) and other parallel ribs (approx. 175 MPa) is small (approx. 2.3%), the stress distribution in parallel ribs may be considered uniform.

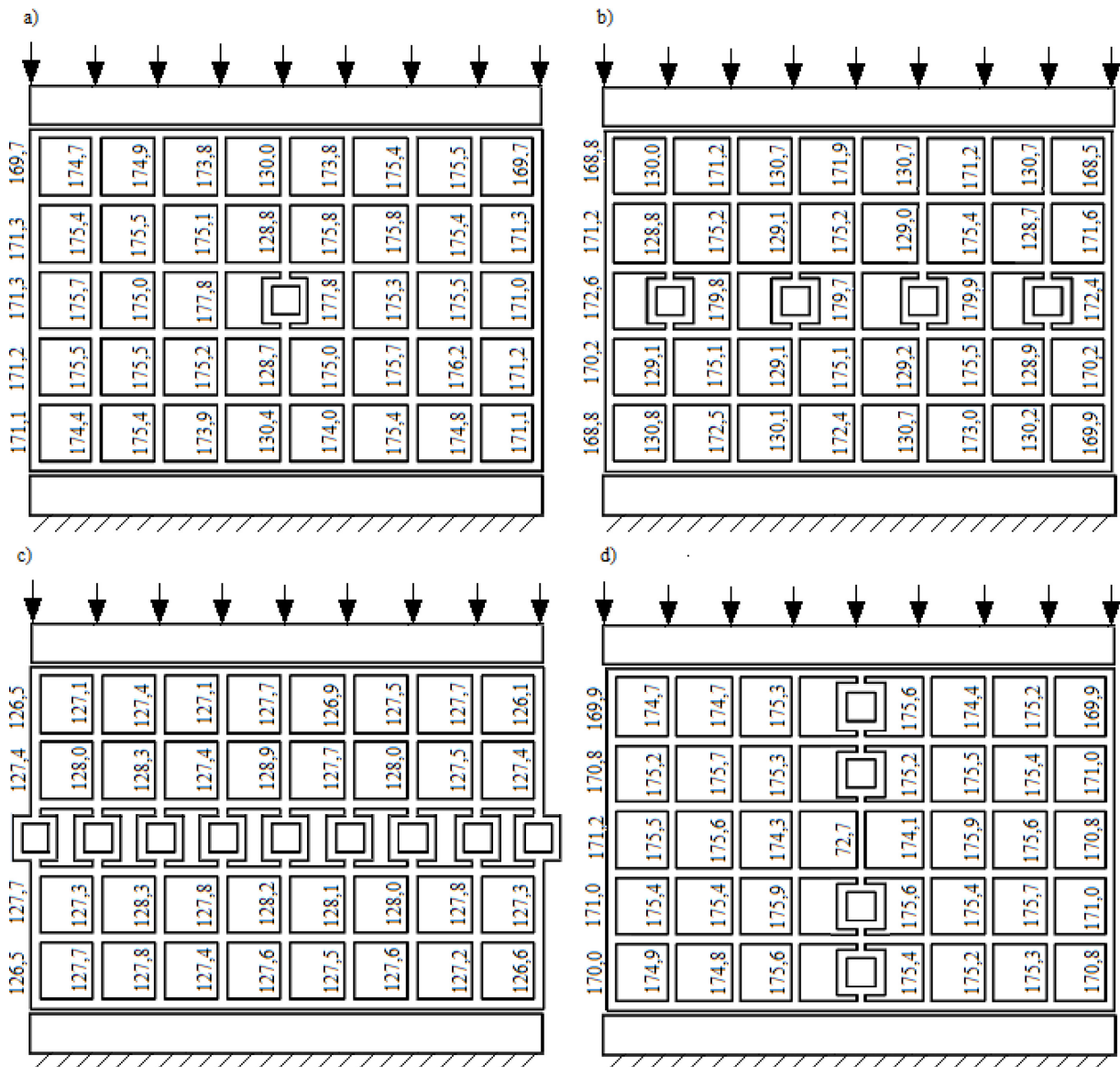


Fig. 3. Map of the distribution of compression-induced reduced von Mises stress in a modified design of the grate:

- a) with one flexible segment of central configuration, b) with four flexible segments of crosswise configuration, c) with nine flexible segments of crosswise configuration, d) with four flexible segments of lengthwise configuration.

Introducing flexible segments to the structure of the grate considerably reduced the stress level in the row of parallel ribs where the flexible segments were placed (Fig. 3). The stress value in other ribs was close to the value observed in the original grate design shown in Figure 2.

The occurrence of this state of stress (Fig. 3a-c) leads to the conclusion that in structures of this type, stress is directly proportional to the deformation, but it is not directly proportional to the value of the applied force, since the latter one varies in individual grates. At the same time, it suggests that in the case of different geometries of the rows of ribs/segments parallel to the direction of movement, the distribution of force values is non-uniform. The same geometry of the row of parallel ribs/segments generates a similar state of stress, regardless of the position and number of these elements in a grate. A large number of the flexible segments in one row was reported to further reduce the stress value in the ribs (Fig. 3d), and therefore it was decided to examine stresses in the rows of ribs provided with a different number of the flexible segments (Fig. 4, Table 2). According to the adopted methodology of studies (Chapter 2, Item 4), stresses were measured in ribs placed in the rows where the flexible segments were located. Studies covered all the grates in which the flexible segments were arranged in a lengthwise configuration on the axis of symmetry [5].

Table 2.

The number of flexible segments of lengthwise configuration (Nfs_{\parallel}) vs the value of stress σ in ribs located in the same row

Nfs_{\parallel}	σ_{mean} , MPa	Standard deviation, MPa
0	174.8	0.6
1	130.7	1.2
2	104.5	5.0
3	86.9	3.2
4	74.3	2.0

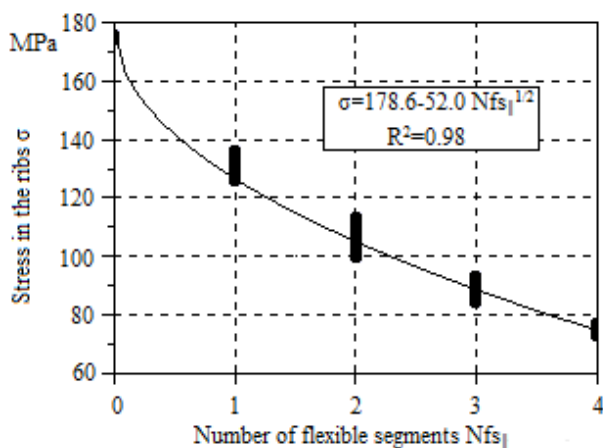


Fig. 4. Stress σ changing in the ribs relative to the number of flexible segments of a lengthwise configuration (Nfs_{\parallel}) provided in a row of the ribs/segments

4. Conclusions

Tests and studies of the state of stress induced in the grates by compression enable drawing the following conclusions:

1. The stress values measured in all the examined structures of the grates indicate that ribs normal to the direction of force mainly play the role of a bonding element. The stresses occurring in them are of a relatively low value, and therefore both the configuration of those ribs as well as their number are of little importance for the flexibility of the whole structure. Hence it can be concluded that when the configuration of the ribs is designed, the simplest possible solutions should be sought, and straight ribs should be made.
2. The state of stress in a row of the ribs/segments parallel to the compressive force is always the same under the conditions of constant deformation and unchanged design, regardless of the location and number of the ribs/segments in a grate. On the other hand, the level of stress in the ribs depends on the number of flexible segments Nfs_{\parallel} in one row, and with the increasing number of these segments, the stress value decreases (Fig. 4).
3. The configuration of flexible segments in a row has a minor effect on the value of stress occurring in the ribs placed in this row. This is evidenced by a low value of the standard deviation obtained for all the values of Nfs_{\parallel} (the number of flexible segments in a lengthwise configuration) - Table 2.

5. References

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