Thermal-stress analysis of vulcanization molds to determine the dilatation gap between aluminum segments

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Abstract. The aim of the paper is to present a methodology for calculating the gap between segments of a tire vulcanizing mold in order to prevent rubber from flowing out of the mold when heated to 165 °C. The analysis will be performed for four types of molds for the manufacturing of tires for passenger cars. Segments for containers K1 to K4 with their minimum and maximum dimensions were selected for analysis. Deformation values in radial and tangential directions for all four segment types were evaluated by computational analysis. The finite element method (FEM) was used for the analysis using the ANSYS computational program. The calculation was made on the finite-element models of the aluminum segment, its carrier and the tightening ring. The boundary conditions were selected for each load case to really characterize the physical phenomenon.

1. Introduction

Tire manufacturing is a complex process that consists of several steps. Tires get their final shape and tread profile in the vulcanizing press. The shaping and vulcanization of the tire takes place inside the hot mold. The mold has the shape of a future tread pattern with the manufacturer's logo on the sidewalls and other mandatory markings. The problem is that there is a considerable outflow of rubber from the mold during the tire casting process. This requires additional finishing and reduces the efficiency of the tire production.

The paper presents the application of numerical methods in order to improve tire production. The study of the possibility of minimizing finishing by manual trimming of excess material was carried out. A computational methodology is proposed to simulate the prediction of the dilatation gap between vulcanization mold segments with the aim of minimizing the flow of rubber from the mold when heated to 165 °C [1–4]. The solution of the problem is important especially from the point of view of increasing the mentioned production efficiency [5–7]. Based on the data from the client, the analysis was carried out on finite element models of the Al segment, its carrier and the tightening ring (figure 1). Based on the obtained results, a methodology was developed to predict the dilatation gap needed to zero the gap between the Al segment and its support at 165 °C [8, 9].
2. Determination of radial displacement of selected points of Al segment

According to the technical documentation, finite-element models of segment carriers and tightening rings were created for four types of containers (K1, K2, K3 and K4) [10–12]. Individual members of the analyzed system were connected to a state that corresponds to the system in the pre-heating state. The calculation has been done using the finite element method and using the MATLAB and ANSYS program system [13, 14].

The difficulty of analyzes has been simplified by the possibility of prescribing symmetry conditions. The boundary conditions (figure 2) are prescribed on the surfaces and correspond to the state when the container is closed but not compressed to the operating state [10, 12, 15].
Places on the surfaces that come into contact with the upper or lower plate of a given container type have been designed to evaluate radial displacements. The values at eight points were analyzed (figure 3). This method was chosen primarily because the radial displacements of the monitored areas did not have a constant value [4, 16].

![Figure 3. Examined points on contact surface of Al segment.](image)

Analyze were processed for realized prescribed dilatation gaps of half of one segment, i.e. for 0.1 and 0.5 mm. The resulting radial displacements for the individual containers at the prescribed tangential displacement of the Al segment are shown in figures 4 to 7.

![Figure 4. Radial displacement of K1 container segment for prescribed displacements of 0.1 and 0.5 mm.](image)
Figure 5. Radial displacement of K2 container segment for prescribed displacements of 0.1 and 0.5 mm.

Figure 6. Radial displacement of K3 container segment for prescribed displacements of 0.1 and 0.5 mm.

Figure 7. Radial displacement of K4 container segment for prescribed displacements of 0.1 and 0.5 mm.
3. Determination of radial displacement of the upper and lower pressure plates

To determine the expansion gap, it was also necessary to calculate the radial displacements of the upper and lower plates for the individual containers as they come into contact with the Al segment surface. The boundary conditions are shown in figure 8 and correspond to the storage in a closed container [4, 10, 17].

The finite element models (figures 9 to 10) were generated for the purpose of calculations in the ANSYS program package and the radial displacements were subsequently analyzed.

**Figure 8.** Boundary conditions on the pressure plates.

**Figure 9.** Finite element mesh on upper (left) and lower (right) plate models of the K1 container.
The resulting average values of the radial displacement of the upper and lower plates of the monitored contact surface are shown in Table 1.

| Container type | Average value of the radial displacement (upper plate) (mm) | Average value of the radial displacement (lower plate) (mm) | Used average radial displacement of plates (mm) |
|----------------|----------------------------------------------------------|----------------------------------------------------------|---------------------------------------------|
| K1             | 0.39432                                                  | 0.39925                                                  | 0.3968                                      |
| K2             | 0.44828                                                  | 0.44876                                                  | 0.4485                                      |
| K3             | 0.49672                                                  | 0.49690                                                  | 0.4968                                      |
| K4             | 0.49661                                                  | 0.49660                                                  | 0.4966                                      |

4. Dilatation gap determination between Al segments and carriers requiring zeroing at 165 °C

The main idea of the methodology for determining the dilatation gap between Al segments was based on a series of simulation calculations to determine the value of the prescribed tangential displacement of the Al segment so that the resulting radial displacements of the Al segment contact surface and the upper (or lower) plate are equal when heated to 165 °C. This modeled a state where gaps in contact between individual system members should be zero [11, 18–20].

Proposal of the methodology for determining the dilatation gap:

- analysis of radial displacements of the upper and lower plates due to a temperature gradient of 145 °C [1, 10],
- analysis of the resulting radial displacements of Al segments due to a temperature gradient of 145 °C [1, 15],
- analysis of dependence of radial displacements of Al segments on prescribed dilatation gap defined in the range of 0.1 to 0.5 mm in half of the segment, which corresponded to the total prescribed gap in the range of 1.6 mm to 8 mm,
- linear extrapolation of the observed functional dependence to a point with the same radial displacement value as in the case of a plate; this resets the gap between the Al segment and the plate,
- determination of the resulting dilatation gaps for individual types of containers [4, 14].

When calculating the resulting dilatation gap, the average values of the investigated variables on the monitored areas were considered. A graphical representation of the extrapolation of the radial displacement of the Al segment to the dilatation gap for the container K1 to K4 is shown in Figure 11.
By extrapolating the functional dependence of the radial displacement of the Al segment to the size of the dilatation gap, the size of the dilatation gap per half of the segment was determined. By multiplying the obtained value by 16, the resulting value of the dilatation gap required to zeroing the radial gap between the Al segments and the upper (or lower) plate when heated to 165 °C was obtained [1, 10, 20]. The results are shown in table 2.

Table 2. The resulting value of the dilatation gap.

| Container type | Average radial displacement of horizontal plates (mm) | Extrapolated average value of radial displacement of Al segment (mm) | Resulting extrapolated value of the dilatation gap between Al segments (mm) |
|----------------|------------------------------------------------------|-----------------------------------------------------------------|---------------------------------------------------------------------|
| K1             | 0.3968                                               | 0.3968                                                          | 16 × 0.0852 = 1.36                                                  |
| K2             | 0.4485                                               | 0.4485                                                          | 16 × 0.1151 = 1.84                                                 |
| K3             | 0.4968                                               | 0.4968                                                          | 16 × 0.1739 = 2.58                                                 |
| K4             | 0.4966                                               | 0.4966                                                          | 16 × 0.1225 = 1.96                                                 |

5. Conclusion
The presented contribution is of great application importance and its aim is to present the methodology and possibilities of using a series of suitably controlled calculations using the finite element method for computer prediction of the dilatation gap between Al segments of the vulcanization mold with the aim of zeroing at 165 °C.

It should be noted that the obtained results have the character of an initial study. In order to obtain reliable results, it is necessary to describe the technological process more precisely, control measurements to refine the input data and modify the model, to define more precisely the thermal interaction between individual system members and to carry out subsequent verification under real conditions.

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