

Elaboration of Parameters of Large-Size Rings Production Process Taking into Account the Evolution of Material Relative Density

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Abstract. The paper presents the selected problems in production chain of large-size rings for the offshore industry. There are two goals of the technology: 1) to obtain the correct shape of the rings, 2) to achieve required properties. A significant problem in the processes of large size forgings production is a proper prediction of the as-cast structure defects and their behaviour during deformation (forging). This study examines a method of prediction of relative density changes of the material during forging. Experimental procedure includes a forging test at the laboratory scale and numerical modelling. These results as well as boundary conditions were used as input data for the computer simulations of the large rings production processes. The presented procedure allows for a comprehensive analysis of the production process of large-size rings, taking into account areas with insufficient material compaction. The analysis allows for changes in the production chain at the design stage, which significantly reduces the costs associated with pre-implementation tests.

Introduction

Industrial ring-rolling processes have been used widely since the 19th Century to produce heavy seamless rings [1]. The ring-rolling process may be classified into two groups, i.e. radial rolling and radial-axial rolling [2]. The deformation is based on squeezing the ring in a radial direction by decreasing the gap between a main roll and mandrel. Besides, a guide rolls control the circularity and axial rolls control the ring height during the process [1-4]. In mass production there is a main need to estimate the required forces and torques, understanding the metal flow, and how to get the exact final product shape, avoiding fractures, laps and other defects [5-7]. Rings are used in lots of applications, including gear manufacturing, aerospace and offshore use cases as bearings, rims and flanges. The majority of heavy rings are made of steels, but other metals (aluminium, titan) and polymers can also be processed by ring rolling [8, 9].

The presented ring rolling process of the large-size parts includes preform forging (upsetting, punching, trimming) and ring rolling on a multi-tool ring rolling mill. This combination gives an opportunity to achieve a precise shape of the products, especially in the case of rings with relatively thin wall thickness. During the production processes the billet (cylindrical shape, of a height equal to 1700 mm and diameter 800 mm) is heated to a hot forging temperature (1230 - 1250°C). The forming process begins with the upsetting of the hot billet on a hydraulic press with maximum capacity equal to 32 MN. Next a punch forms a cavity (punching operation) and leaves only a thin part of metal at the hole bottom. In the trimming step, another tool removes this part of metal. The billet, with a complete hole in the centre, is referred to as preform and in the next step, after reheating in gas furnace (1230 - 1250°C), is rolled on a ring rolling mill. The final result is a ring 410 mm high, with an outer diameter of 3400 mm.

The presented work focuses on estimating the quality of the final rings. The main goal of the research was to analyse a relative density distribution in the volume of the part in different production steps. It was assumed the optimum relative density equal to 99.9% (full compaction of the material)

in 90% of final ring volume. A production process of heavy ring of 30CrNiMo8 construction steel was considered. In particular, the formation of basic defects such as fractures, laps and shape defects has been analysed. The adopted model took into account the change of the relative density of the material, affecting the closing of internal defects in the form of voids. Assumptions developed for porous materials were adopted. The industrial "void compression parameter" is also taken into account [10]. The compaction analysis of the analysed material was performed in laboratory conditions, by forging samples taken from different areas of forging ingot. On this basis, models for simulation of the technological process were calibrated. The simulation of whole production chain in QForm software was prepared.

The research methodology includes a technology analysis applicated in ZARMEN FPA forging plant. The production offer has been extended to include large-size rings. The Company has developed and verified in real conditions an innovative, low-waste technology of shaping large-size rings using forging and rolling operations. The obtained solution allowed to offer rings with a diameter of up to 3800 mm and a height of up to 1000 mm with a complex cross-sectional geometry, made of the entire range of steel grades, including special steels and non-ferrous metal alloys. The launched technological line with a unique defectoscopic inspection station and an automated material transfer system allow for the production of ring products with minimum machining allowances, characterized by a homogeneous material structure throughout the entire cross-section.

Assumptions

Relative density analysis. In presented simulations results, a model dedicated to porous materials was used. On this basis, the initial relative density of the material was calculated and its change during the shaping process was analysed. During simulation of a porous material, no elastic deformation is taken into account, but its compressibility at the expense of the increase in density. The equations characterizing the flow of porous material include two main terms: 1) characterizes the change in the shape of the workpiece (stress and strain deviations proportionality), 2) the change in the volume of the workpiece as a result of the density change (the compressibility equation) [4, 11]:

$$\sigma'_{ij} = \frac{2}{A} \frac{\sigma_R}{\dot{\epsilon}_R} \dot{\epsilon}'_{ij} \quad (1)$$

$$\sigma_m = \frac{1}{9B} \frac{\sigma_R}{\dot{\epsilon}_R} \dot{\epsilon}_v \quad (2)$$

where: σ_R - reduced yield stress of noncompact material, $\dot{\epsilon}_R$ - reduced effective strain rate, A, B – porosity function, σ'_{ij} – stress deviator, σ_m – mean stress.

In matrix form the relation between the stress and strain deviators:

$$\{\sigma'\} = \frac{\sigma_R}{\dot{\epsilon}_R} [D_R] \{\dot{\epsilon}'\} \quad (3)$$

where: $\{\sigma'\}$ - stress deviator column matrix, $\{\dot{\epsilon}'\}$ - strain rate deviator column matrix, $[D_R]$ – symmetric matrix that depends on porosity function

A porous material is considered to be an isotropic continuous medium having the properties of an incompressible material. In computer simulations, the material flow condition of this type of material was determined by the R. Green equation [1,4]:

$$f(\sigma_{ij}) = AJ_2 + BI_1^2 = \sigma_R^2 \quad (4)$$

where: A, B - the functions of material relative density ($B = 1 - 1/3A$), σ_R - the reduced yield stress for porous material with relative density R at uniaxial tension, J_2 - the second invariant of stress deviator, I_1 - the first invariant of stress deviator.

Reduced strain rate intensity for non-compact material is determined from the condition of powers equality:

$$\sigma_{ij} \dot{\varepsilon}_{ij} = \sigma_R \dot{\varepsilon}_R \quad (5)$$

and is equal to:

$$(\dot{\varepsilon}_R)^2 = \frac{3}{A} \cdot \dot{\varepsilon}^2 + \frac{1}{9B} \dot{\varepsilon}_v^2 \quad (6)$$

Yield stress for porous material (σ_R) is related to yield stress of base material (material flow stress with relative density of 100%) (σ_S) by the relation:

$$\sigma_R^2 = \eta \sigma_S^2 \quad (7)$$

where η is the function of relative density.

Relative density of porous material is determined with the ratio of current density of representative volume of porous body to base material density:

$$R = \frac{\rho_R}{\rho} < 1 \quad (8)$$

As shown in [12] model of relative density is dedicated to analysis of the forging technology of heavy parts. In this work, the above model of the relative density analysis was used in a computer simulation of selected technology variants and simulation of forging tests in laboratory conditions. The aim of the work was to demonstrate the increase in relative density under the influence of a given deformation, to determine its nonuniformity and to identify areas with reduced material compaction.

Void compression parameter. Another model used in the analysis, dedicated to closing of internal discontinuities during open die forging, is the determination of void compression parameter Q . In the work [10], the limit value of this coefficient ($Q = 0.55$) was determined, beyond which it is assumed to achieve a satisfactory consolidation of the material. It was taken into account that at 100% compaction of the material, the value of the void compression parameter tends to 1. The advantage of the coefficient Q is that it does not depend on the initial relative density of the batch material.

$$Q = - \int_0^{\bar{\varepsilon}} \frac{\sigma_m}{\bar{\sigma}} d\bar{\varepsilon} \quad (9)$$

Importantly, the authors of [10] showed that the local compaction of the material is not only related to the forging reduction ratio. Extremely important parameters affecting the penetration of the deformation into the forged element are, among others: the width of the tools and the relative feed (calculated as the ratio of the forgings shift after each given deformation and the distance between the tools at the moment of starting the deformation).

The above assumptions were verified in industrial conditions, and the technology modifications introduced on their basis improved the efficiency of the production line by 7% [10], which contributed to the selection of this model for this analysis.

Ring Rolling simulation. Ring rolling is characterized continuous cyclic plastic deformation of the workpiece with moved along the ring the plastic zone. This type of the process requires the special approach for simulation that differ then for bulk forging simulation approach. The main features of ring rolling process simulation are the following: many cycles of rotation and simulation that causes to increasing the time of simulation and amount information in the FE nodes. The number of records during ring rolling simulation may reach up to several thousand.

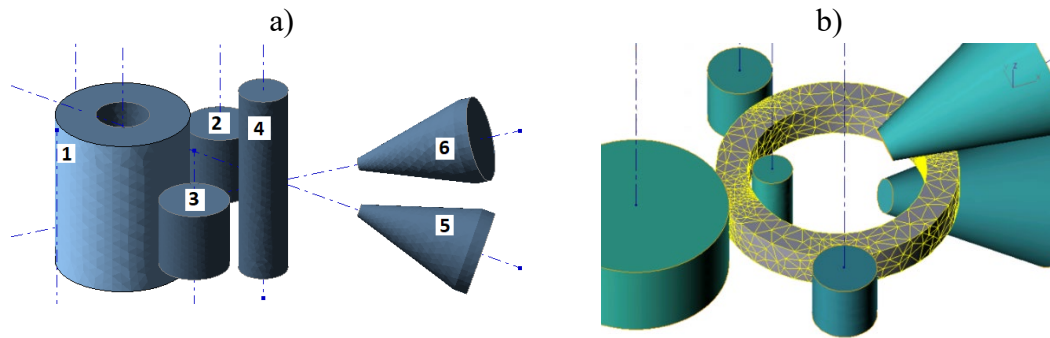


Fig. 1. Ring Rolling simulation: a) a tool set, where: 1 - Main Roll, 2,3 - Guide Rolls, 4 - Mandrel, 5,6 - Axial Rolls, b) computational FE mesh

In the commercial QForm-Ring Rolling software, the double mesh method was implemented to simulate this cyclic process [1]:

- On the base of the computational mesh the stiffness matrix is created and then the system of equations of plastic flow is calculated. This type of mesh is used to solve the mechanical problem. It is highly variable in size and it is very fine in zones of deformation, while quite coarse in “rigid” zones outside of the contact with the rolls [1].
- The geometrical mesh contains the information about thermo-mechanical fields and contains the description of the geometry deformed body. The geometrical mesh is more regular, but all the elements have very small size. It accurately records the history of deformation (the deformed shape of the ring and the strain distribution it) [1, 4, 11].

The tools are not rotate during simulation because they are axisymmetric. The FE mesh in the tools has got the local densification in the contact area with workpiece (ring) This approach provides the good balance between accuracy and speed of simulation [1]. The FE mesh is creating automatically. The size of elements depends on a shape of the objects. Remeshing is executed after single step time. In the analysed case, a total simulation time is equal to 510.2 s.

Experimental Procedure

Based on the numerical analysis of the shaping of large-size rings, two points were identified where the change in the effective strain and temperature during the production process was examined. The location of points on the cross-sectional area of the element is shown in the Fig. 2. Point P2 represents an area of taking samples for ring quality control in the industrial conditions. Point P1 is located in the middle of ring wall cross section (area of low values of effective strain).

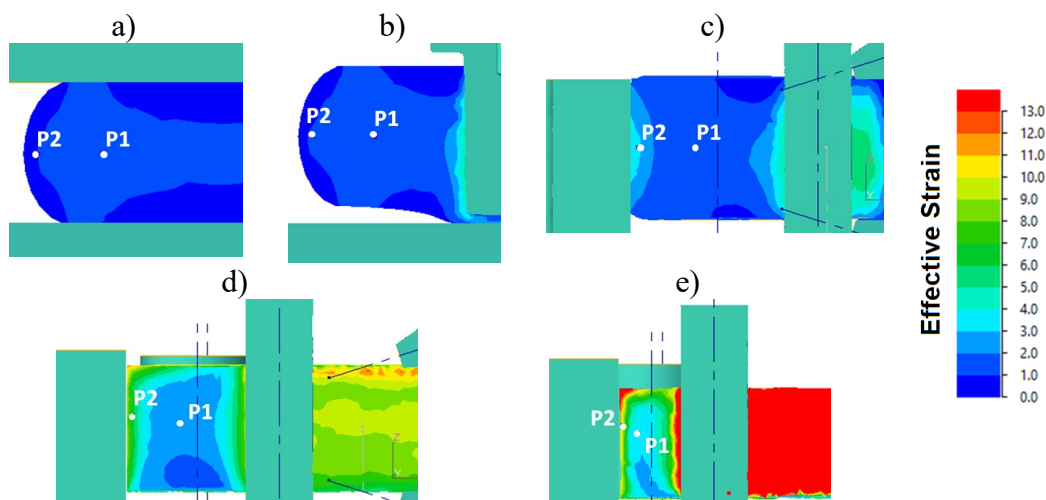


Fig. 2. Distribution of the effective strain on the cross-section of the element with the marked points of tracing the process parameters during the operation: a) upsetting, b) punching, c) the first stage of the rolling, d) the second stage of rolling, e) the last stage of rolling

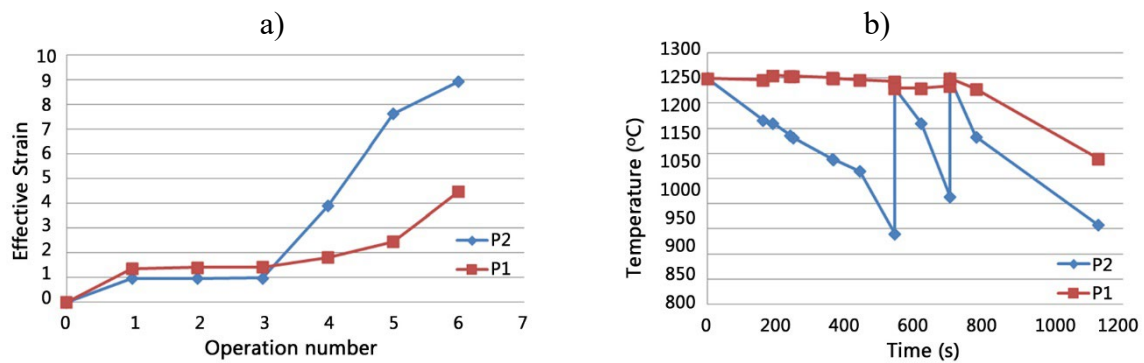




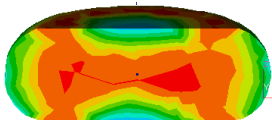
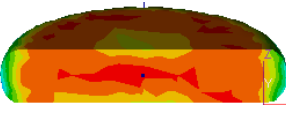


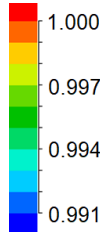
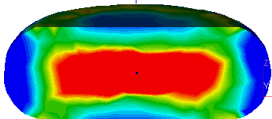
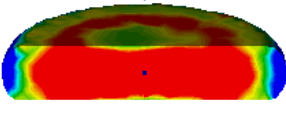
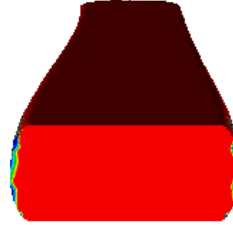
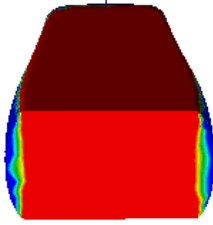
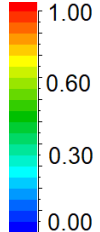


Fig. 3. Parameters changing during heavy ring production: a) effective strain, b) temperature

Based on the tracking of the points, the change in the history of effective strain and temperature was determined for individual operations included in the technological chain.

The measurement results are shown in Fig. 3. In the Fig. 3a the change in the effective strain is defined in relation to the number of individual operations, where: 1 - upsetting, 2 - punching, 3 - trimming, 4 - rolling stage no 1, 5 - rolling stage no 2, 6 - rolling stage no 3.

Table 1. Samples after forging in laboratory condition

Upsetting and Punching		Ring Rolling	
P2	P1	P2	P1
			
Relative Density			
			
			
Void Compression Parameter (Q)			
			
			

By analysing the change in the effective strain at two selected points of the element, it can be observed that in the initial operations (open die forging), the effective strain is lower near the surface of the element (point P2) than at half the radius length (point P1). In rolling operations, this value increases sharply, which indicates a significant deformation of the areas at the outer surface of the element.

In the case of the analysis of the temperature change, more rapid drops can be observed during the shaping at the point P2. It is a natural phenomenon due to the fact that this point is located at the surface of the element, where there is more intense heat emission to the environment.

Based on the above analysis, the parameters of forging in laboratory conditions of samples taken from ingots were developed. The aim of the research was to recreate the deformation history determined for the measurement points P1 and P2.

The test consisted in recreating the course of deformation that is subjected to a given area of the element during the production process of large-size rings by controlling the change in the effective strain and temperature. The course of the laboratory process assumed heating the sample to the forging temperature and then deforming it by upsetting and cogging, while maintaining the flow direction of the material identical for a given operation in the technological cycle. Two steps of the process were analysed - after forging operation (Upsetting and Punching) and after rolling (Ring Rolling) (Table 1). Two samples were deformed in every conditions in laboratory forging test. The operations were separated by reheating treatments.

Table 2. Results of the density measurements

Steel Grade	Relative density [%]		
	Laboratory tests		Simulation
	Before forging	After forging	
30CrNiMo8	98,86	100,00	99,81
	98,62	99,32	99,87
	99,00	100,00	99,98
	99,11	100,00	99,96

After the laboratory tests, the density of the samples was analysed using the Archimedes method. Table 2 shows the results of measurements of samples before forging (cast material) and after forging in laboratory conditions. Additionally, a numerical simulation of laboratory tests was performed with full mapping of real conditions. The simulation includes models of the relative density and the void compression parameter (Table 1).

Results Discussion

Calibrated models for predicting the relative density and closing internal discontinuities have been implemented to simulation of the shaping of large-size rings.

When analysing the course of the process in terms of material compaction, a correlation between the distribution of the effective strain and the distribution of the relative density was noticed (Fig. 4). When observing the cross-section of the element after upsetting, punching and trimming, the places deformed with the effective strain above 1 are found to be completely densified.

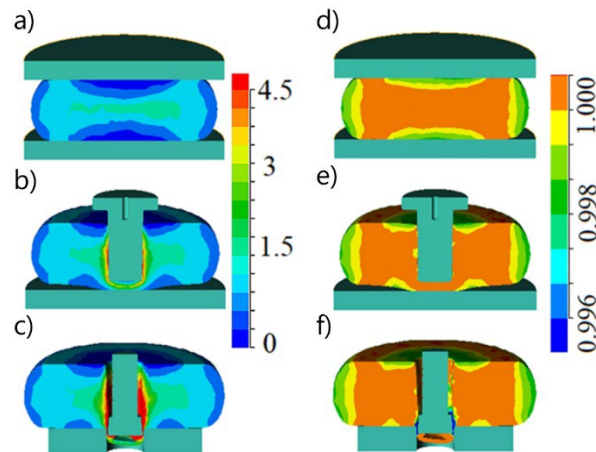


Fig. 4. Parameters changing during open die forging operations: a-c) effective strain, d-f) relative density

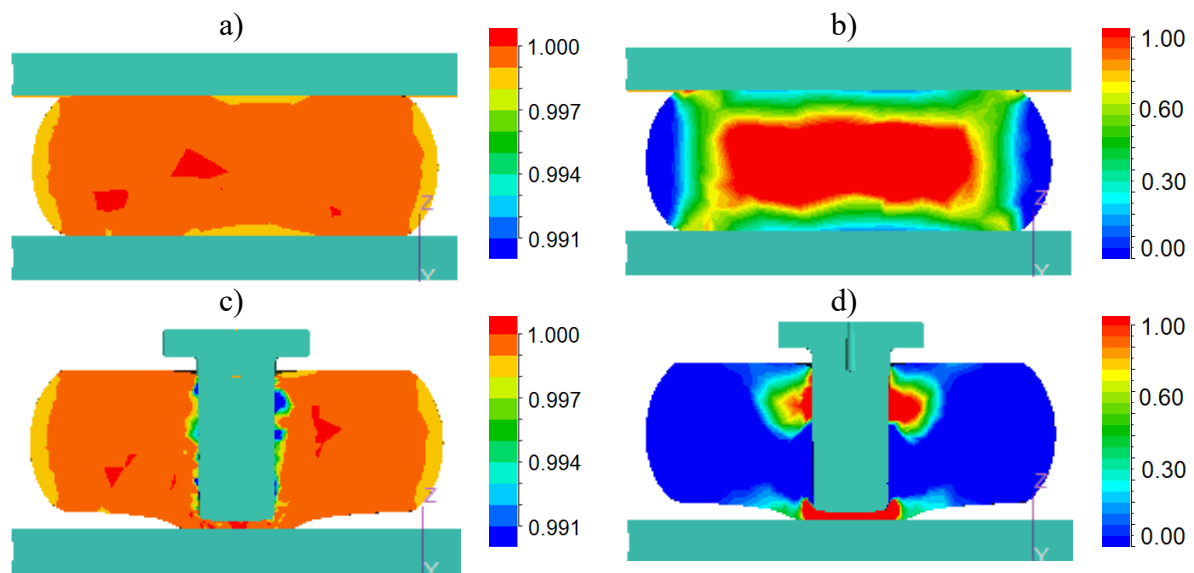


Fig. 5. Comparison of relative density (a, c) and void compression parameter (b, d) in upsetting (a, b) and punching (c, d)

The distribution of the relative density on the cross-section of the elements after upsetting and punching was also compared with the distribution of the void compression parameter (Q) (Fig. 5). In the case of upsetting the Q factor reaches the value 1 (complete closure of the discontinuities) in the zone of the greatest deformation. At the lateral surface, the values are much lower, which is confirmed by the relative density distribution. The material was not completely compacted in these areas. In the case of punching operations, the coefficient Q reaches the highest values in the area of the resulting bottom and in the upper part of the element. During punching, the relative density at the side surface does not increase. On the other hand, the distribution of this parameter in the central part of the element (in the vicinity of the punch) becomes more even. In this area, the material is fully densified already at the stage of the punching operation.

Presented analysis included the determination of the distribution of the Q parameter on the cross-section of the ring wall (Fig. 7). It can be seen that the closure of the discontinuities occurs in the vicinity of the side walls of the rings and in the vicinity of the top wall.

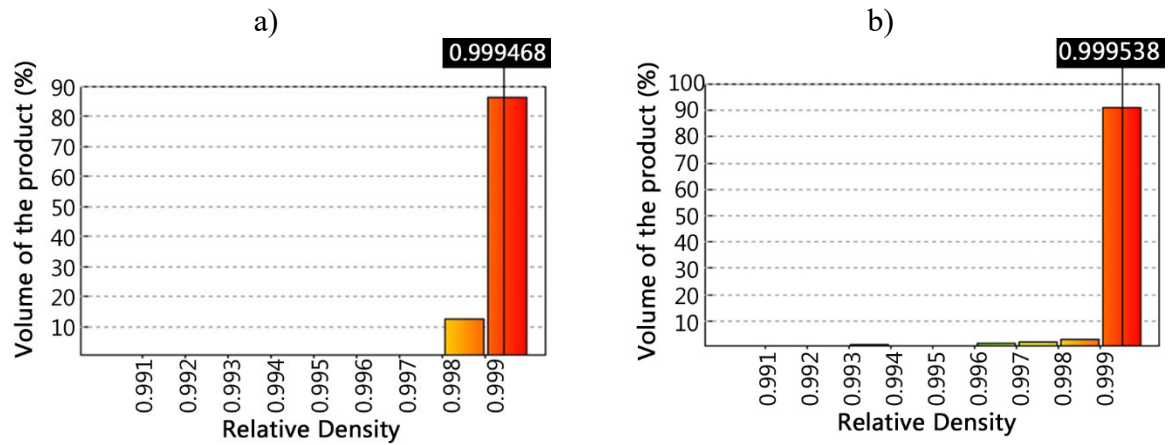


Fig. 6. Distribution of relative density of the volume of product:
a) after punching, b) after final rolling

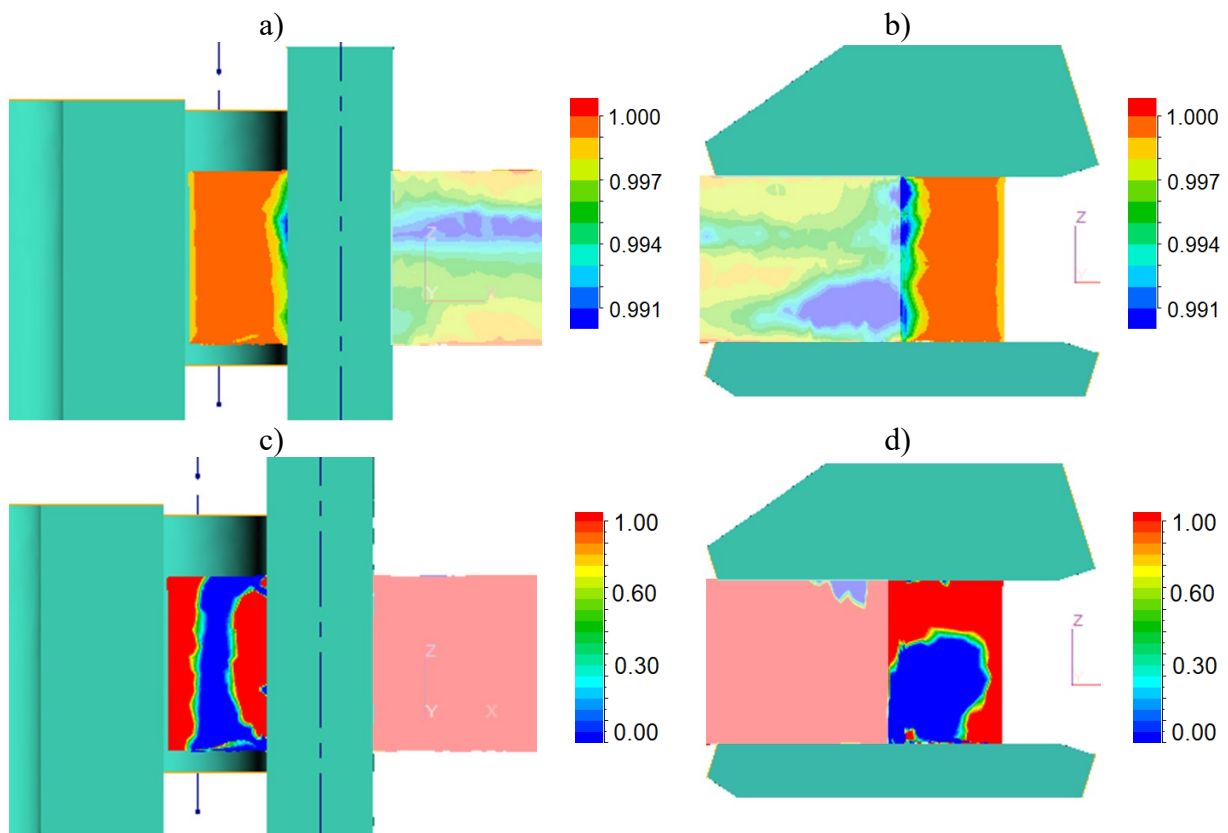


Fig. 7. Comparison of relative density (a, b) and void compression parameter (c, d)
in different zones of the ring during rolling

Analysis of the material density in the volume of the ring during the process (Fig. 6), it can be seen that after the punching operation more than 80% of the material was completely densified. The rolling process causes further compaction of the material. Ultimately, the density above 99.9% was achieved for 91.5% of the material volume. The remaining part of volume with lower density is related to numerical errors appearing on the inner wall of the ring. The analysis of the distribution of the voids compression parameter shows that also in this area the material is completely densified.

Summary

On the basis of the presented results, it can be concluded that the two analysed models - relative density and void compression parameter - complement each other and give a complete analysis of material compaction in multi-operational ring rolling production processes, taking into account both the open-die forging and rolling operations.

The analysis combining laboratory tests (forging in laboratory conditions and density measurement) with numerical simulation allows for:

- Verification of material compaction models (model of changing the relative density and closing internal discontinuities)
- Analysis of the multi-operational process of shaping large-size rings, taking into account the changes related to the increase in the relative density.

The above analysis showed that the developed technological variants will allow the material to be compacted at the level of at least 99.9% in the entire volume of the finished product.

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