Numerical modelling of forming load on pre-stressed dies

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Abstract. The article presents a method of numerical modelling of the load on pre-stressed dies. Numerical modelling was performed in two stages. In the first stage, a simulation of the process of extruding with stiff tools was performed. In the second stage, load on the tools obtained in the first stage was implemented and strength tests of the dies were performed. Four construction variants of the tools made of steel and sintered carbide were analysed. In the first set of tools, a monolithic die with a container was used. In the second set, a die and a divided container were applied. In the third set, a die and a container stressed with a singular ring were used. In the last set, a die with a container stressed with two rings was analysed. As a result, distributions of reduced, radial, tangential, and axial stresses were presented for various construction variants. Die and container made of sintered carbide stressed with two rings ensure the necessary strength of tools and correct progression of the process.

1. Introduction
Metal forming is one of the principles of manufacturing technologies. The processes of forming use plasticity of metals for the production of semi-finished materials and structural parts [1]. A wide variety of metal alloys can be plastically deformed. Even though deformability or plasticity of the non-ferrous metal alloys [2–4] and composites [5–7] are being evaluated, still ferrous alloys seem to be the most popular group of materials applied for plastic forming processes [8]. Moreover, systematic progress in structural materials engineering accelerates the metal forming processes development. Therefore, plenty of innovative techniques and processes are being examined. One of the processes recently studied by G. Winiarski’s group is a metal forming technique for producing flanged hollow parts, which has been preliminarily described in previous papers [9–12]. The idea of the process relies on flanges forming using a movable sleeve, which moves in the opposite direction to the punch. The movement of the sleeve causes a closed impression to open, due to which the flange is also formed in a semi-free impression.

Although most of the published research papers study the behaviour of billet material [13–16] and evaluate forming tools durability improvement by the heat treatment or coatings application [17–20], few papers research into the selection of the material for forming equipment elements. Thus, this paper considers the application of the steel and sintered carbides for the set of metal forming tools. The research idea is justified by the fact that especially in processes of cold metal forging dies and punches are subjected to forces of exceedingly high values [21–24]. Forces acting on the punches are usually...
compressing their mandrels, whereas the forces acting on dies cause tension in the tangential direction. As a result of forces of high values, damage to tools may occur [25–27].

In order to increase the life of tools for cold metal forging structures, the pre-stressed tools are used [28, 29]. Stressing consists of placing a forming tool inside a compressive ring. Creating a great enough stress during mounting ought to compensate for the significant tensile stress during forging. Depending on the amount of stress, rings dies with one or more rings may be found [30, 31]. Depending on the shape of the outer surface of the die, where the stressing ring is fixed, two methods for stressing tools can be defined: the method of cylindrical joints and conical joints [32].

This article presents a method of numerical modelling of tool load in the process of extrusion. The paper aimed to compare four construction ideas and select the most effective solution for the fabrication of sleeves made of 42CrMo4 steel. Therefore, distributions of reduced, radial, tangential, and axial stresses were comparatively analysed.

2. Objective of research
The scheme of the analysed extrusion was presented in Figure 1. In the process of extruding from a thick-walled tube, a billet for extruding flanged sleeves was obtained. Stress calculations were performed in Deform 2D. Calculation methodology was comprised of two stages. In the first stage, FEM calculations of the extrusion process using rigid tools were performed, where only the behaviour of the formed material was analysed. In the second stage, the discretisation of tools and their loading with node forces, determined in the first stage, was performed. Applying such a methodology allowed one to determine the distribution of stresses and displacement in tools at the moment of the maximum load.

The numerical model of the analysed extrusion process (Figure 1) was constructed from the following elements: tube-shaped billet with dimensions Ø22.8 x Ø12.8 x 46 mm, punch, die with a container, and a mandrel calibrating the inner hole of the billet. The tube was made of normalised steel grade 42CrMo4 (details given in previous work [33]) modelled as an elastic-plastic element. The punch moved at the constant speed of 1.66 mm/s, whereas the mandrel was set in free motion. It was assumed that the friction conditions were described with the constant friction model with the friction factor equal to 0.3. The extrusion process was conducted in cold metal forming conditions at room temperature.

On the basis of the calculations conducted in the first stage of research, the moment of the greatest tool load was determined and located on the 455th step of the numerical simulation (Figure 2). The extruding force was the greatest at that moment. In the next stage, stress calculations were conducted
for the selected moment. The load values in the form of node force, obtained in the first stage were applied to tools discredited with finite elements, which was shown in Figure 3. The calculations at the second stage of the analysis were conducted for the range of the linear material characteristic (elastic range). In the calculations, an isotopic material model of tools was assumed.

![Figure 2. Progression of the extruding force.](image1.png)

Steel tools were characterised by the longitudinal elasticity modulus $E = 2.1 \times 10^5$ MPa and the Poisson coefficient $\nu = 0.3$. In the case of tools made of sintered carbide $E = 5.2 \times 10^5$ MPa and $\nu = 0.23$. The calculations were conducted for four construction variants of the die and the container. In the first variant, a homogenous die connected to a container and made of steel was used. In the second variant, the steel die and container were divided. In the third variant, the die and container from sintered carbide were stressed with a single steel ring. In the last variant, the die and container were stressed with two steel rings.

![Figure 3. Distribution of node forces established in the first stage of simulation.](image2.png)
3. Results of the calculations

3.1. Calculations variant 1 – die and container as a homogenous tool

In the first variant, the strength calculations were conducted for the case in which the die and the container had a homogenous structure. In this case, all tools were modelled as steel. Figure 4a presents the distributions of effective stresses according to von Mises for all the elements of the analysed system. The presented distribution of stresses indicates that the most loaded element is the die. In the spot between the roll hole of the container and the conical part of the die, a geometric notch was created in which a stress ridge, reaching 2500 MPa occurred. The conical area of the input part of the die was also subjected to significant stress, up to 2190 MPa. A similar value was reached by the part of the mandrel located in the hole of the die. Reduced stresses on the punch were the smallest and oscillate around 1250 MPa. In those cases, not only the value of the stress but also its character is important, whereas the most beneficial one is compressive stress.

Figure 4b presents the distribution of axial stresses. In the analysed case these stresses were directed toward the y axis of the global coordinate system of the Deform 2D. In the axial direction, compressive stresses which were located on the punch dominated. The value of the compressive stress in the punch did not exceed 1250 MPa, which could have transferred tool steels for cold working. Insignificant tensile stress, not exceeding 100 MPa, can occur in the die and container. In the conical part of the die compressive stresses up to 981 MPa occurred. Stresses on the mandrel reached 641 MPa. The tension of the mandrel was caused by the fact that the material constricted on the mandrel in the area of the container was moving slower than the material located in the area of the die. Differences in speed were caused by the material elongating during extrusion. Material exiting the die was moving at a higher speed than the material entering the die.

![Figure 4](image)

Figure 4. Components of the stress tensor: a) effective stress according to the von Mises hypothesis, b) stress in the axial direction, c) stress in the radial direction, d) stress in the tangential direction.

Figure 4c presents the distribution of stresses in the radial direction, where compressive stresses are the most frequent. Maximum compressive stresses occurred in the area of the cone of the die and reached the value of 1800 MPa. Similar values of the compressive stresses in the radial direction can be observed in the area of the mandrel near the die. In the remaining part of the mandrel, near the container, and inside of the container the values were smaller, up to 1320 MPa. In the remaining tools, that is the punch, mandrel apart from the area in contact with the extruded material, and outside the container and the die
the stresses were tensile with small values not exceeding 91.1 MPa. Stresses in the radial direction, due to their compressive character did not pose a significant threat to the tool materials. High-speed steels can transfer compressive stress up to 2500 MPa.

Figure 4d presents the distribution of stresses in the tangential direction. In this direction, exceedingly high compressive and tensile stresses occurred. Compressive stresses occurred on the calibrating mandrel and reached the values of 1630 MPa. In the die and the container, the stresses were tensile and reached the values of 1350 MPa. The highest values can be observed in the area of the hole of the container and the die. The stresses decreased along with the distance from the axis of symmetry of tools. On the outer walls of the container and die the stress value was 232 MPa. Moreover, in the case of a construction solution with a homogenous die and a container, a stress ridge occurred in the area of joining of the die and the container. This phenomenon may cause damage to tools. In the case of the remaining tools, that is punch and mandrel, tangential stresses did not cause damage to those elements.

3.2. Calculations variant 2 – die and container as separate tools

In the second variant, the die and container, both made of steel, were separated. Figure 5a presents the distribution of effective stresses according to von Mises hypothesis for this calculation variant. Separating the die and container eliminated the stress concentration in the area of the die-container joining. Moreover, the implemented construction change did not decrease the values of effective stress. In the case of the container on the wall of the hole, an increase of the effective stresses from 1880 MPa for homogenous die and container to 2190 MPa for the separated tools was observed. Separation of the die and container caused an increase in the area in which stresses with the value 625 MPa occur.

Figure 5b presents the distribution of stress in the axial direction. The division of die and container did not cause any changes to the axial stresses. The greatest values of compressive stress occurred in the area of the working cone of the die. The division of the tool increased the maximum stresses in comparison to the first solution. In the case of separated tools, maximum compressive stresses in the axial direction equalled to 1120 MPa. Figure 5c presents the distribution of radial stresses. This distribution is quite similar to the variant with a homogenous die and a container. Maximum stresses in the radial direction also occurred in the area of the working cone of the die and reached the values of 1820 MPa. Similarly, to the first variant, the stresses were compressive. In the case of the area of the container separation of tools caused an increase in stress in the area of the hole from 1090 MPa to 1350 MPa. Figure 5d presents the distribution of stresses in the tangential direction after separating tools. It caused a decrease in the tensile stress in the area of the die from 977 MPa (not considering the local stress ridge to 1350 MPa) to around 730 MPa. In the case of the container, the situation was opposite since the separation of the tools caused an increase in tensile stress in the tangential direction to 1500 MPa.

![Figure 5. Components of the stress tensor: a) effective stress according to von Mises hypothesis, b) stress in the axial direction, c) stress in the radial direction, d) stress in the tangential direction.](image)
3.3 Calculations variant 3 – die and container stressed with a single ring

In this calculation variant stressing of the die and container with a single ring was applied. The die and container were separated, and it was assumed in the calculations that they would have been made of sintered carbide. Sintered carbide is highly resistant to friction and compression load. The limitation of their use is their strength to tension, which ought not to exceed 600 MPa \[34\]. The compressing rings would have been made of chrome-molybdenum 42CrMo4 grade steel, for which the acceptable tensile stress is 1100 MPa. It was assumed that this joining would have been performed by the means of cold injection and the surfaces of the joints would have been conical with the cone angle equal 1°.

![Figure 6](image)

**Figure 6.** Components of the stress tensor for the interference size \(w = 0.15\) mm: a) effective stress according to von Mises hypothesis, b) stress in the axial direction, c) stress in the radial direction, d) stress in the tangential direction.

In the calculations performed, the interference size \(w = 0.15\) mm. Figure 6 presents the distributions of stress in tools with the same interference. Similarly to the previous cases, the distribution of stress in the axial and radial direction did not change significantly. Stress in the tangential direction in the area of the die and container was tensile. The value of tensile stress in the stressed tools in comparison to the value of these stresses in unstressed tools decreased to 289 MPa for the die and 924 MPa for the container.

3.4 Calculations variant 4 – die and container stressed with two rings

In this calculation variant stressing of the die and container with two tools was applied. The die and the container were separated, and it was assumed in the calculations that the material was sintered carbide. Compressed rings would have to be made of chrome-molybdenum 42CrMo4 steel. It was assumed that the joining would be cold injected, and the joint surfaces would be conical with the cone angle equal 1°. Figure 7 presents the distributions of tools for the injections \(w_1 = 0.12\) mm and \(w_2 = 0.18\) mm. Injection \(w_1 = 0.12\) mm was placed between the die, container, and stressing rings. Injection \(w_2 = 0.18\) mm was placed between the rings.

Axial stress in the top part of the container was tensile but did not exceed the acceptable value of 600 MPa. Stress in the radial direction was mostly compressive and the amount of tensile stress was insignificant and did not exceed 80 MPa in the area of the container, die, and the outer stressing ring. Tensile stress in the tangential direction for the container and the die decreased below the acceptable value and reached 415 MPa. In the case of the stressing rings, tensile stress in the tangential direction did not exceed 682 MPa and therefore did not exceed the acceptable value for 42CrMo4 grade steel, which was 1100 MPa. The presented variant fulfilled the requirements for tools of sintered carbide (die, container) stressed with two rings of 42CrMo4 grade steel.
**Figure 7.** Components of the stress tensor for the injection $w_1 = 0.12$ mm and $w_2 = 0.18$ mm: a) effective stress according to von Mises hypothesis, b) stress in the axial direction, c) stress in the radial direction, d) stress in the tangential direction.

**4. Conclusion**

For the purpose of the numerical strength calculations, it can be stated that in the case of the assumed scheme of extrusion of hollow forgings:

- Mandrel and punch used for extrusion can be made of high-speed steel,
- Homogenous die and container made of steel cannot transfer the load resulting from the proposed extrusion process,
- Using the die and container as separate steel tools also does not allow for transferring the load due to high tensile stress acting in the tangential direction,
- The die and container made of sintered carbide stressed with a single ring also do not ensure the required strength due to a limited tension strength of the carbides,
- The die and container made of sintered carbide stressed with two rings ensure the necessary strength of tools and correct progression of the process.

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