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NUMERIČKA SIMULACIJA EFEKTA STEZANJA KOD TOKARENJA ALATA ZA STAKLENU AMBALAŽU

NUMERICAL SIMULATION OF CLAMPING EFFECTS IN TURNING OF GLASS PACKAGING TOOLING

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SAŽETAK

Kod procesa tokarenja, stezanje obratka u steznoj glavi često dovodi do deformacija koje mogu biti elastične i plastične. Te deformacije izravno utječu na dimenzijsku točnost, čime se smanjuje ukupna kvaliteta i pouzdanost konačnih proizvoda, a u nekim slučajevima mogu dovesti i do odbacivanja dijelova te povećanja troškova proizvodnje. Problem postaje još kritičniji pri obradi preciznih dijelova alata namijenjenih proizvodnji staklene ambalaže, gdje je visoka točnost ključna za funkcionalnost i trajnost. Ovaj rad detaljno analizira ovaj izazov pomoću naprednih numeričkih simulacija provedenih metodom konačnih elemenata (MKE). U softverskom okruženju Hexagon Marc/Mentat provedena je detaljna analiza utjecaja različitog broja čeljusti stezne glave na deformaciju, oblik i raspodjelu naprezanja u obratku. Na temelju rezultata simulacija, rad daje jasne preporuke za optimiziranu konfiguraciju stezanja, određujući idealan broj čeljusti koji će smanjiti deformaciju i povećati točnost konačnih dijelova.

Ključne riječi: *stezanje, deformacije, numeričke simulacije, metoda konačnih elemenata, Marc/Mentat*

ABSTRACT

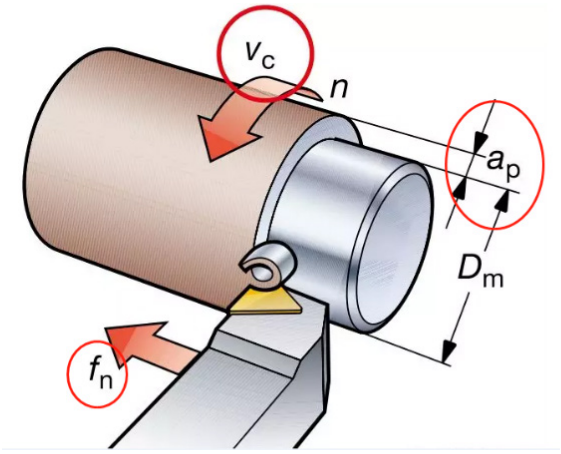
In the turning process, clamping the workpiece in the chuck often leads to deformation, which can be both elastic and plastic. These deformations directly affect dimensional accuracy, consequently reducing the overall quality and reliability of the final products and potentially leading to rejections and increased production costs. The issue becomes even more critical when machining precision tool components intended for the production of glass packaging, where high accuracy is essential for functionality and durability. This paper thoroughly examines this challenge through advanced numerical simulations conducted using the finite element method (FEM). Using the Hexagon Marc/Mentat software environment, a detailed analysis was performed to investigate the influence of using different numbers of chuck jaws on the deformation, shape, and stress distribution of the workpiece. Based on the simulation results, the paper provides clear recommendations for an optimized clamping configuration, specifying the ideal number of chuck jaws to minimize deformation and enhance final part accuracy.

Keywords: *clamping, deformations, numerical simulations, finite element method, Marc/Mentat*

1. UVOD

1. INTRODUCTION

The production of glass packaging requires exact manufacturing of the tools used in glass forming processes. The quality of these tools directly affects the geometric and functional accuracy of the final products, making them a key factor in achieving a stable and high-quality production process. Components of tools for glass packaging are produced using various machining methods, among which turning plays a significant role [1-4]. A schematic representation of the turning process is shown in Figure 1.



Slika 1 *Shematski prikaz procesa tokarenja [5]*

Figure 1 *Schematic representation of turning process [5]*

During turning, workpieces are clamped in a chuck (Figure 2), and it is precisely in this phase that deformations frequently occur. These deformations can be elastic, partially or completely recovering after the clamping force is removed, or plastic, causing permanent geometric deviations in the workpiece [6]. Such deviations reduce dimensional accuracy and can lead to functional or aesthetic nonconformities in the final product [7].

Slika 2 *Stezna glava s četiri stezne čeljusti [8]*

Figure 2 *Four-jaw lathe chuck [8]*

This paper aims to analyze the deformations that occur during the clamping of the workpiece in the turning process of tool components used in the production of glass packaging. The main causes of these deformations will be investigated, and based on the analysis, solutions will be proposed for their reduction or complete elimination, with the goal of improving manufacturing quality and process reliability.

2. PROIZVODNJA GRLA
2. NECK RING MANUFACTURING

In the production of glass packaging, a set of specialized tools is used (Figure 3), including: the mold, mold bottom, parison mold, parison mold bottom, neck ring, neck ring holder, and the plunger [4,9,10]. Each of these components serves a specific function within the mold assembly, and their manufacturing precision directly affects the shape, functionality, and surface quality of the final glass product. This work focuses specifically on the production of the neck ring, which represents one of the most geometrically and mechanically sensitive parts of the tooling.

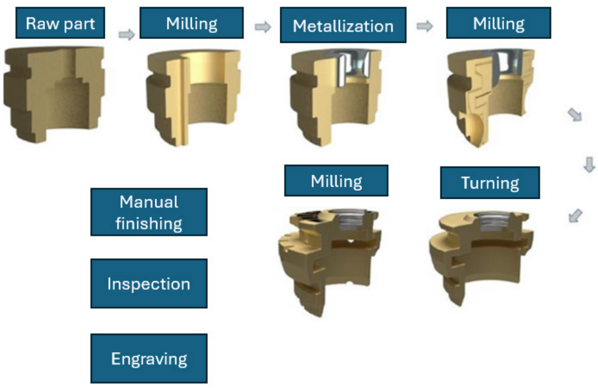
Slika 3 *Kalupi za proizvodnju staklenih boca [11]*

Figure 3 *Molds for glass bottle production [11]*

Slika 4 *Grlo [12]*

Figure 4 *Neck ring [12]*

The manufacturing process of the neck ring (Figure 4) is largely standardized, with possible minor variations in the number and order of operations depending on specific product variants or design requirements. The process begins with material cutting, followed by rough milling, metalizing, and subsequent milling of the metalized areas (Figure 5). A key phase in the process is turning, during which the functional surfaces are precisely shaped. This is followed by finish milling to achieve the final geometry and surface quality. In some cases, additional engraving or manual finishing is performed, with the final stage consisting of quality control of the completed part.



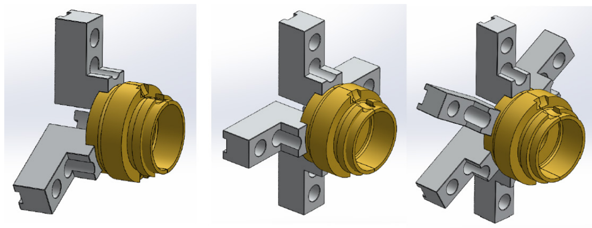
Slika 5 *Proces izrade grla*

Figure 5 *Neck mold manufacturing process*

3. METODOLOGIJA
3. METHODOLOGY

A numerical simulation was conducted using the Hexagon Marc/Mentat software package [13], based on the finite element method (FEM), to analyze the deformation behavior of a bottle neck mold workpiece under clamping loads. This quasi-static analysis enables a detailed evaluation of stress and displacements for various clamping configurations without the need for expensive and time-intensive experimental procedures.

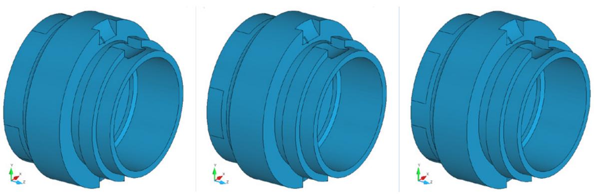
This chapter systematically presents all essential steps in the simulation process, including the development of the geometric model, mesh generation, the definition of material properties, the formulation of boundary conditions and loads, and the execution of the simulation. Simulations were performed for clamping systems with three, four, and six jaws (Figure 6), corresponding to the common configurations used in industrial practice. For all cases, total gripping force and individual jaw contact geometry were held constant to ensure a direct comparison of the resulting workpiece deformation. This is also the most practical and realistic comparison since the hydraulic chuck cylinder can supply a limited amount of force, which is then redistributed by the chuck to the clamping jaws.



Slika 6 *SolidWorks model obratka i stezne glave u izvedbama s tri, četiri i šest čeljusti*

Figure 6 *SolidWorks model of workpiece and clamping systems with three, four, and six jaws*

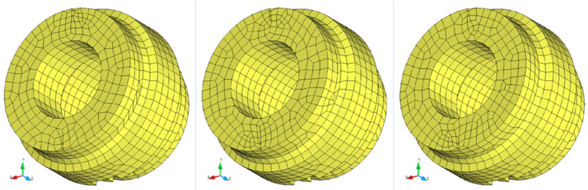
The initial 3D model of the bottle neck mold was created in CAD software (SolidWorks) and imported into Hexagon Mentat. To simulate the interaction with the jaws without modelling the jaw bodies themselves, the geometric profiles of the jaw contact patches were imprinted directly onto the workpiece's outer surface (Figure 7) using the *Imprint* operation. The workpiece has an overall length of 70 mm, and a 10 mm section is clamped by 30 mm wide jaws. This clamped region has an inner diameter of 48 mm and an outer diameter of 88 mm.



Slika 7 *Otisnute kontaktne površine steznih čeljusti za stezanje s tri, četiri i šest čeljusti*

Figure 7 *Imprinted jaw contact patches for clamping with three, four, and six jaws*

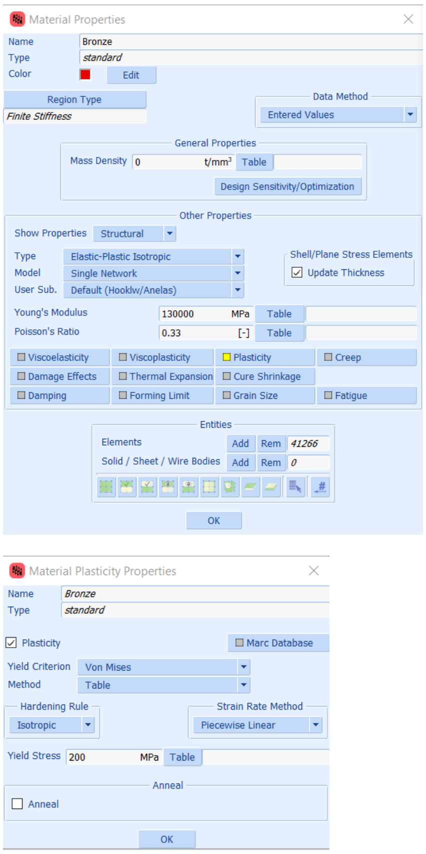
The solid volume was then meshed using the *Automesh: Volumes* tool with a hybrid scheme, resulting in a high-quality, unstructured mesh composed primarily of four-node enhanced-strain tetrahedral elements (Marc element type 134). Mesh density was controlled via a surface element scale factor of 0.5 and a core element scale factor of 0.6 to ensure a sufficient number of elements in critical areas. The mesh for the three-, four-, and six-jaw models consisted of 41266, 41262 and 41257 elements, respectively (Figure 8).



Slika 8 *Konačna mreža elemenata kod stezanja s tri, četiri i šest čeljusti*

Figure 8 *Finite Element Mesh for clamping with three, four, and six jaws*

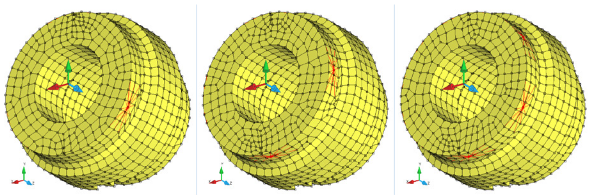
For the meshed models, a new material was specified under *Material Properties* (Figure 9). The workpiece material is bronze, modelled as a linear elastic material with a Young's Modulus of $E = 130$ GPa and a Poisson's Ratio of $v = 0.33$. As the analysis is quasi-static, material density (*Mass Density*) was not required. To ensure that plastic deformation of the workpiece was avoided, material plasticity was also defined by checking the *Plasticity* option and setting the *Yield Stress* as a fixed value of 200 MPa.



Slika 9 *Definiranje svojstava materijala*

Figure 9 *Definition of material properties*

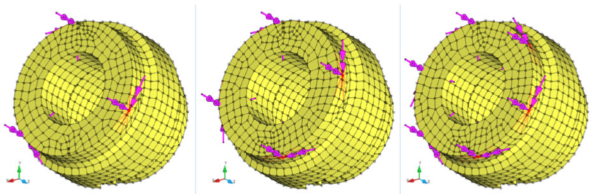
A critical aspect of the simulation was the realistic modelling of the rigid, kinematically constrained motion of the chuck jaws. The functionally rigid nature of the jaws was simulated using *RBE2's* (Rigid Body Elements) command, accessible via the *Links* menu. For each jaw, an independent master node was created at the geometric center of its contact patch. The nodes of the workpiece mesh on that patch were then rigidly coupled as slave nodes to their respective master node by the RBE2 link, constraining all six degrees of freedom, as shown in Figure 10. This formulation forces the entire contact patch to move like a single, non-deforming body. To enforce the purely radial motion characteristic of a chuck mechanism, a local cylindrical coordinate system was established, and a nodal transformation was applied to all master and slave nodes.



Slika 10 *Definiranje svakog kontaktnog područja čeljusti kao krutog pomoću elementa krutog tijela (RBE2s)*

Figure 10 *Defining each jaw contact patch as rigid with Rigid Body Elements (RBE2s)*

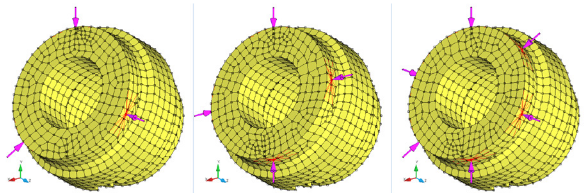
To define kinematic constraints of the jaws, a boundary condition was applied to the jaws' master nodes, constraining their motion in the circumferential and axial directions, as well as all three rotations (Figure 11). This is done by selecting the *Fixed Displacement* command under the *Boundary Conditions* menu. The radial degree of freedom was left unconstrained to be driven by the clamping force. This set of constraints, representing the physical guideways of the chuck, was sufficient to ensure numerical stability by preventing all rigid body motions for the three-, four-, and six-jaw configurations.



Slika 11 *Primjena kinematičkih rubnih uvjeta na glavni čvor svake čečljusti za konfiguracije s tri, četiri i šest čeljusti*

Figure 11 *Applying a kinematic boundary condition to master node of each jaw for three-, four-, and six-jaw configurations*

Within the same menu, the clamping load was defined as a force per jaw using the Point Load command. This load was applied directly to the master node of each jaw in the negative radial direction, as shown in Figure 12. The magnitude of the load was obtained by dividing the total grip force by the number of jaws, with the total grip force set to 50 kN.

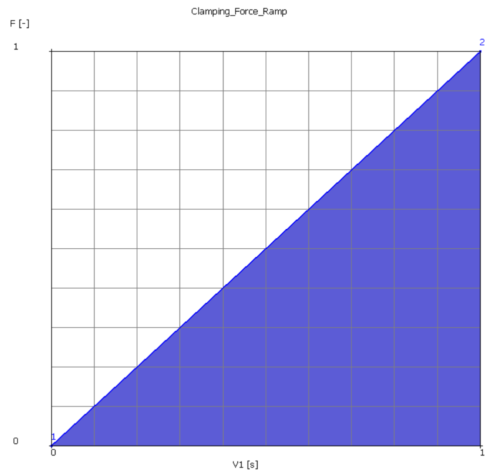


Slika 12 *Primjena rubnog uvjeta točkastog opterećenja na glavni čvor svake čeljusti za konfiguracije s tri, četiri i šest čeljusti*

Figure 12 *Applying Point Load boundary condition to master node of each jaw for three-, four-, and six-jaw configurations*

To perform the quasi-static simulation, the *Static* option was selected under *Loadcases*. Quasi-static analysis is essentially a series of static analyses conducted at different time points. The problem is treated as static, but boundary conditions and constraints are allowed to vary over time, thereby avoiding a sudden load impact, which would not realistically represent actual process conditions. This was managed by gradually increasing the clamping load from 0% to 100% over a one-second pseudo-time interval using a *Table* definition under the *Tables & Coord. Syst.* menu, as shown in Figure 13. As a result, a sequence of static solutions at different time intervals was obtained, allowing the visualization of how deformation develops during the clamping process. Previously defined boundary conditions and loads were selected, with the *Total Loadcase Time* set to 1 second and the number of *Steps* set to 10.

Under the *Job* menu, the analysis was configured as *Structural*, with the *Large Strains* option enabled to account for geometric nonlinearity. The previously defined load case was applied, and kinematic constraints for the jaws were selected under the *Initial Loads*. In *Job Results*, the output parameters of interest were specified. The primary outputs requested were *Displacement*, to determine the maximum deformation caused by the clamping jaws and workpiece interaction; *Equivalent Von Mises Stress*, to analyze the stress distribution; and *Total Equivalent Plastic Strain*, to check whether plastic deformation of the workpiece was avoided. The simulation was initiated after a successful pre-check for errors, and the results are presented in the subsequent chapter.



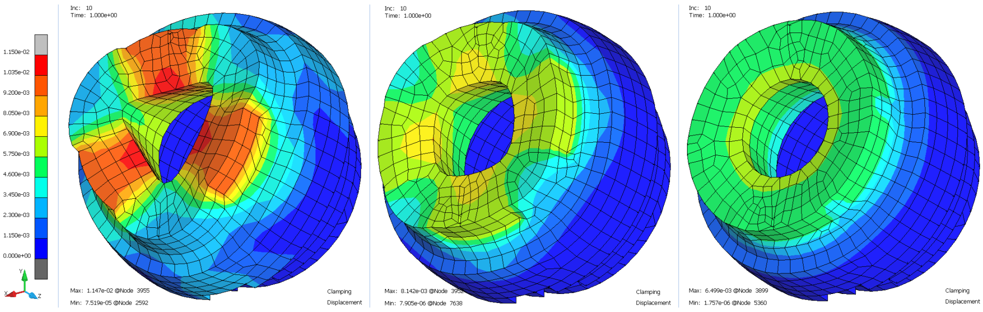
Slika 13 *Tablično definirana rastuća sila stezanja*

Figure 13 *Table definition of ramped clamping force*

4. REZULTATI
4. RESULTS

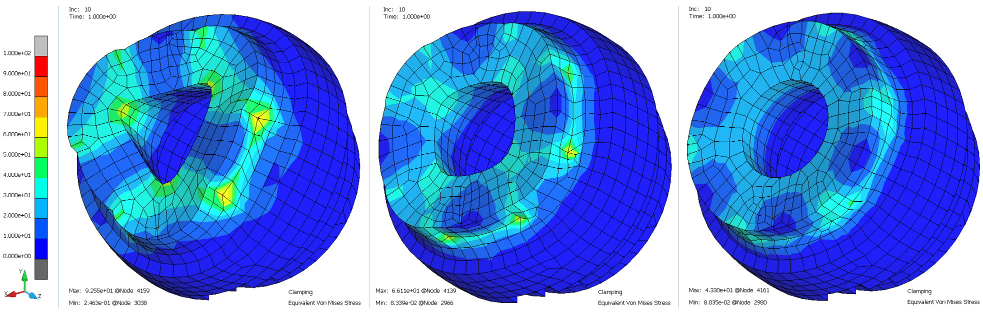
Simulation results demonstrate a clear relationship between the number of chuck jaws and the magnitude of deformation and stress distribution in the neck mold during clamping. Furthermore, in no case was any plastic deformation of the workpiece observed. The von Mises stress remained below the yield strength of the material (200 MPa), and the Total Equivalent Plastic Strain was equal to zero at the end of the simulation, confirming that the process remained entirely within the elastic regime.

The three-jaw configuration produced the greatest neck deformation, with a maximum displacement of 11.466 µm. In the four-jaw configuration, the displacement decreased to 8.142 µm, while the six-jaw configuration resulted in the lowest displacement, measured at 6.499 µm. This progressive reduction in deformation is directly linked to the improved load distribution as the number of jaws increases. Figure 14 shows a comparison of displacements using identical color bar spans, from 0 µm (blue) to 11.5 µm (red), and with an identical deformation scaling factor of 1000.



Slika 14 *Usporedba pomaka za konfiguracije s tri, četiri i šest čeljusti*

Figure 14 *Displacement comparison for three-, four-, and six-jaw configurations*



Slika 15 *Usporedba raspodjele naprezanja kod konfiguracije s tri, četiri i šest čeljusti*

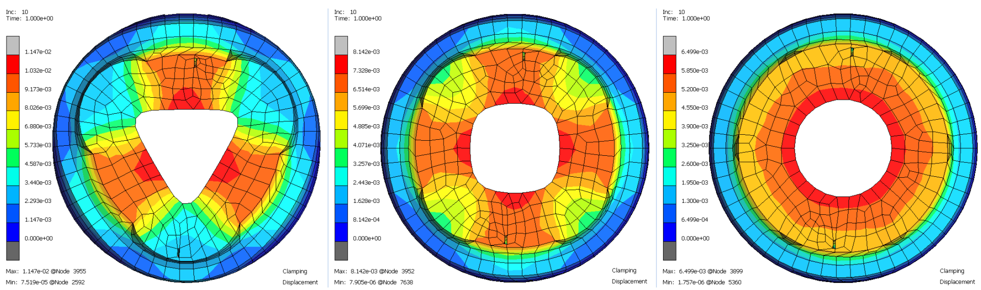
Figure 15 *Stress distribution comparison for three-, four-, and, six-jaw configurations*

The equivalent von Mises stress analysis further supports this conclusion. In the three-jaw case, stresses were highly concentrated at the contact points, with a maximum value of 92.55 MPa, indicating uneven clamping pressure. With four jaws, the stress was more evenly distributed across the surface of the neck mold, with a maximum stress of 66.11 MPa. The six-jaw configuration exhibited the most uniform stress distribution of all, with a maximum stress of 43.3 MPa, minimizing localized peaks and providing greater structural stability. In Figure 15, a comparison of equivalent von Mises stress distribution is shown with an identical color bar span, from 0 MPa (blue) to 100 MPa (red), and with an identical deformation scaling factor of 1000.

This also reflects on the preservation of circularity. As shown in Figure 16, the three-jaw chuck, due to its triangular load distribution, showed the most pronounced ovality. The four-jaw configuration, with square-patterned pressure distribution, improved circular accuracy. The six-jaw setup, thanks to its symmetrical and balanced clamping pattern, provided the best roundness, as confirmed by the minimal and uniformly distributed deformation.

Thus, increasing the number of jaws leads to better deformation control, improved stress balance, and enhanced dimensional accuracy of the workpiece.

Table 1 presents the maximum displacement values recorded for the three-, four-, and six-jaw configurations. This allows for a direct comparison of all three cases. A graphical representation of the results is shown in Figure 17, clearly illustrating the trend of decreasing displacement and improved stress distribution with an increased number of clamping jaws.



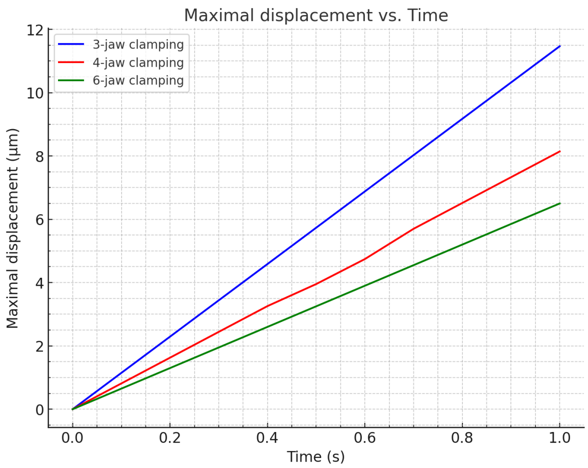
Slika 16 *Očuvanje kružnosti kod konfiguracija s tri, četiri i šest čeljusti*

Figure 16 *Preservation of circularity for three-, four-, and six-jaw configurations*

***Tablica 1** Maksimalni pomaci kod konfiguracije s tri, četiri i šest čeljusti*

***Table 1** Maximal displacements obtained with three-, four-, and six-jaw configurations*

Time, s	Maximal displacement, μm		
	3 jaws	4 jaws	6 jaws
0	0	0	0
0.1	1.147	0.814	0.650
0.2	2.293	1.628	1.300
0.3	3.440	2.443	1.950
0.4	4.586	3.257	2.600
0.5	5.733	3.953	3.250
0.6	6.880	4.743	3.900
0.7	8.026	5.699	4.550
0.8	9.173	6.514	5.200
0.9	10.320	7.328	5.850
1.0	11.466	8.142	6.499



***Slika 17** Maksimalni pomaci obratka tijekom vremena za različite konfiguracije stezanja*

***Figure 17** Maximum displacement of the workpiece over time for different jaw clamping configurations*

The blue line in the diagram corresponds to clamping with three jaws, the red line represents four-jaw clamping, and the green line depicts six-jaw clamping. The X-axis denotes the time interval, while the Y-axis shows the maximum displacement of the workpiece. The results clearly demonstrate that the configuration with six jaws exhibits the slowest increase in displacement as the clamping force is applied over time. Once the operational gripping force is reached, the maximum displacement remains lowest for the six-jaw configuration.

It is important to emphasize that the total gripping force was kept constant in all cases. Consequently, the force exerted by a single jaw was inversely proportional to the number of jaws, i.e., 50 kN divided by the number of jaws. Thus, increasing the number of jaws not only ensures a more uniform spatial distribution of the clamping force but also reduces the load per jaw. This combined effect results in lower maximum displacement and, consequently, reduced deformation of the workpiece.

While the numerical model provided valuable insight into clamping-induced deformation, several limitations should be noted. The workpiece material was modelled as linear elastic, which is a valid assumption because the induced stress remained below the yield strength. However, the model also assumed the material was homogeneous and isotropic, neglecting real-world factors such as residual anisotropy from previous machining or heat treatment, along with local variations in microstructure and surface roughness. Furthermore, the chuck jaws were idealized as perfectly rigid bodies with ideal contact conditions, neglecting potential micro-slip, frictional effects, and surface irregularities that occur under real clamping conditions. These simplifications can influence deformation behavior.

To improve the reliability of the results, future work should include experimental validation using strain gauges, laser displacement sensors, or 3D optical measurement systems to measure actual displacements during clamping. Such experimental verification would increase confidence in the numerical predictions and allow further refinement of boundary conditions, friction coefficients, and material parameters, thereby enhancing the accuracy and industrial applicability of the model.

5. ZAKLJUČAK
5. CONCLUSION

The results of this study highlight the importance of applying numerical simulations, particularly software based on finite element analysis (FEA) technology. Such simulations enable efficient and accurate evaluation of mechanical behavior without the need for expensive and time-consuming experimental procedures.

Through a series of simulations, the influence of the number of chuck jaws on stress distribution and neck mold deformation was investigated. The analysis examined configurations with three, four, and six jaws, focusing on the evaluation of the workpiece's maximum displacement and circularity accuracy under a fixed total gripping force.

The number of jaws has a direct impact on the dimensional accuracy of the workpiece. Clamping with three jaws showed the highest levels of deformation and uneven stress distribution, resulting in a notable loss of circularity. Switching to a four-jaw configuration resulted in improved performance, reducing maximum displacement and promoting a more uniform stress distribution, which contributed to greater dimensional accuracy. The six-jaw configuration provided the best overall performance, with the lowest displacements and the most uniform stress distribution, which preserved the circular shape of the workpiece most effectively.

These findings carry significant implications for the glass packaging industry, where precision and dimensional accuracy are critical for product quality and process efficiency. Choosing the correct number of jaws can reduce deformation, decrease material waste, and improve production reliability. Furthermore, the insights from this study are not limited to analyzing neck mold clamping but provide a useful framework for a wide range of applications in the glass packaging industry. This includes different types of molds, such as blank molds and finishing molds, as well as tools for handling the molds, including robotic grippers and automated assembly tools. This approach enables manufacturers to achieve higher accuracy and consistency across a wide range of operations.

6. REFERENCE

6. REFERENCES

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• Igor Ciganović - završio je preddiplomski studij na Fakultetu strojarstva i brodogradnje (FSB) 2021. godine, a diplomski studij na istom fakultetu 2023. godine. Iste godine upisao je doktorski studij iz područja naprednih proizvodnih postupaka. Uz znanstveno-istraživački rad, zaposlen je na FSB-u kao asistent, gdje drži auditorne vježbe iz kolegija skupine oblikovanja deformiranjem. Kroz svoj akademski i istraživački angažman razvija stručnost u području suvremenih tehnologija te nastoji doprinositi njihovoj primjeni u industriji. Osim akademskih aktivnosti, Igor je osnivač studentske udruge mladih Lumen, koja okuplja ambiciozne pojedince i potiče razmjenu ideja, suradnju te osobni i profesionalni razvoj članova.

• Zdenka Keran - izvanredna je profesorica na Fakultetu strojarstva i brodogradnje u Zagrebu. Na istom fakultetu je diplomirala 2000. godine te doktorirala 2010. godine. Voditeljica je Katedre za oblikovanje deformiranjem. Njena znanstvena djelatnost usmjerena je na područje strojarskih tehnologija, napose na tehnologiju oblikovanja deformiranjem. Autorica je i koautorica 28 znanstvenih radova u časopisima A i B kategorije, 4 poglavlja u knjigama, 2 autorske knjige te 37 radova na međunarodnim znanstvenim skupovima. Na Fakultetu strojarstva i brodogradnje u Zagrebu nositeljica je nekoliko kolegija na prijediplomskom, diplomskom i poslijediplomskom studiju. Kao suradnica, sudjelovala je u izvođenju nekoliko znanstvenih projekata. Surađivala je sa veleučilištem Algebra na projektima izrade više standarda zanimanja, kompetencija i programa obrazovanja odraslih u okviru HKO. Članica je Hrvatskog interdisciplinarnog društva, Hrvatske udruge za PLM te Hrvatske udruge proizvodnog strojarstva.

• Leon Vukmanić - je magistar inženjer strojarstva, a diplomirao je na Fakultetu strojarstva i brodogradnje Sveučilišta u Zagrebu 2025. godine, gdje je godinu ranije stekao i titulu sveučilišnog prvostupnika. Tijekom studija usmjerio je interes na područje obrade metala, s posebnim naglaskom na CNC i aditivne tehnologije (3D ispis). U diplomskom radu pod naslovom „Razvoj rješenja za smanjenje deformacija kod izrade alata za staklenu ambalažu“ istraživao je optimizaciju proizvodnih procesa. Trenutno radi kao tehnolog za 5-osne CNC strojeve u tvrtki OMCO Croatia.