

K. BALAWENDER^{1,2*}, T. BALAWENDER³, T. WILCZEK⁴

THE USE OF SEGMENTED DIES FOR PLASTIC FORMING THE HEADS OF BOLTS ON FORGING MACHINES

Fasteners such as bolts constitute an important group of products in the metal industry. Owing to their wide industrial use, methods ensuring dimensional accuracy, process repeatability, and low manufacturing costs are crucial. Bolt heads are most commonly formed by cold forging. The aim of the article is to analyze the application of segmented dies for forming bolt heads with a concave–convex lateral surface in the cold forging process. The authors seek to demonstrate that the use of such tooling enables high dimensional accuracy to be achieved without the need for additional machining. The obtained results indicate that, the modular design of the dies makes it possible to obtain the required geometry within a five-operation process, which shortens the production cycle, reduces tool wear, and lowers manufacturing costs, while improving overall process efficiency. The shape of the head can be effectively controlled through strategic modifications of die geometry, careful sequencing of dies, and the implementation of supplementary radius smoothing during rolling. The presented approach constitutes a significant contribution to the development of cold forging technology, offering more economical and efficient methods for manufacturing fasteners with complex geometries.

Keywords: Cold forging; Fasteners manufacturing; Segmented dies

1. Introduction

Plastic deformation of metals is a widely adopted manufacturing technology for the production of components with complex geometries, offering enhanced mechanical and structural properties compared to casting or subtractive machining methods. Processes such as die forging, rolling, and extrusion facilitate the fabrication of structural elements with high dimensional precision and reproducible material characteristics [1].

In the production of fasteners such as screws, studies have addressed both material and technological aspects of the forming process. In [2], it was highlighted that selecting a material with high yield strength and adequate ductility is essential for the efficient plastic forming of high-strength screws. The study demonstrated that intrinsic material properties, including fracture resistance and the capacity for uniform deformation, directly influence both the precision of geometry replication and the overall durability of the forming process.

Numerical simulations [3-5] of a multi-stage cold forging of hexagonal-head screws using FEM showed full shape agreement at successive stages, confirming the accuracy of

the modeling. Analysis of key process parameters, including strain and temperature, provided insights into the distribution of mechanical properties within the screw. The results indicate that numerical simulations effectively replicate the process and support evaluation of deformation and material property changes during cold forging.

Literature analyses indicate that traditional methods, such as conventional rolling, are effective for components with simpler geometries but encounter limitations when forming more complex parts. In studies focusing on screw and thread production, the design of tools must accurately replicate intricate curves, which is challenging when using solid rolls and often requires advanced numerical analysis and specialized tooling [1,6]. To overcome these limitations, segmented rolling tools and multi-stage rolling processes have been implemented, enabling the gradual guidance of material toward the desired geometry while reducing defects and stress concentrations.

Precision forging was initially applied to simple axially symmetric components, its use has expanded with the development of tooling and process control. Today, precision forgings are employed for products requiring high dimensional accuracy,

¹ DOCTORAL SCHOOL OF THE RZESZÓW UNIVERSITY OF TECHNOLOGY, 12 POWSTAŃCÓW WARSZAWY AV., 35-959 RZESZÓW, POLAND

² KOELNER RAWPLUG IP SP. Z O.O., 41 PODZWIERZYNYEC STR., 37-100 ŁAŃCUT, POLAND

³ RZESZÓW UNIVERSITY OF TECHNOLOGY, 12 POWSTAŃCÓW WARSZAWY AV., 35-959 RZESZÓW, POLAND

⁴ KOELNER RAWPLUG IP SP. Z O.O., 41 PODZWIERZYNYEC STR., 37-100 ŁAŃCUT, POLAND

* Corresponding author: katarzyna.balawender@rawlplug.com



shape repeatability, and mechanical strength. Flashless forging concepts in the literature typically involve specialized machines with multiple tools, operated via wedge systems and spring-locked dies. A review of the literature indicates that the main application area of precision forgings is the automotive industry [7,8,10]. Segmented dies are used to produce forgings with complex geometries [7,11-13]. In industrial practice, segmented dies are commonly used in cold forging of nuts and constitute a key component of the tooling in nut former machines [9]. The design of such dies is based on a set of precisely fitted working segments, allowing the shaping of the external geometry of the nut while ensuring high dimensional accuracy. Despite the availability of literature on segmented dies, existing studies have paid limited attention to their application in the production of fasteners with complex geometries. Moreover, current publications do not comprehensively address issues related to the cold forging of steel fasteners, leaving this topic still insufficiently explored. Literature analysis demonstrates that optimizing the plastic forming process, in conjunction with the careful selection of both tool and segment materials, is essential for the manufacture of screws intended for specialized applications and exhibiting complex geometries.

2. Experimental procedures

2.1. Subject of the study

The research was conducted in three stages: the design of the upsetting sequence and the corresponding tooling, technological trials accompanied by analysis of the obtained results, and the development of the final production process for the finished component.

In the first stage, two sets of tools were designed and manufactured for forming the head of the stabilizer link bolt using two different upsetting sequences. The design of the tools was based on the drawing of the finished component. The shape and dimensions of the working surfaces of the movable die elements depended on the chosen sequence of upsetting operations, the predicted upsetting force, and the dimensions of the die seats in the forging press block.

The technological trials stage involved forging the stabilizer link bolt using the manufactured tools, metrological measurements of the head shape and dimensions, and metallographic examination of the material flow lines in the bolt. During this stage, press settings were also optimized to achieve the best replication of the intended component geometry.

Technological trials focused on developing a method to manufacture a bolt with a concave–convex head (Fig. 1) used in a vehicle stabilizer assembly. Its complex head geometry,

with concave and convex surfaces connected by precise transition radii, requires strict dimensional control to ensure proper function in the suspension.

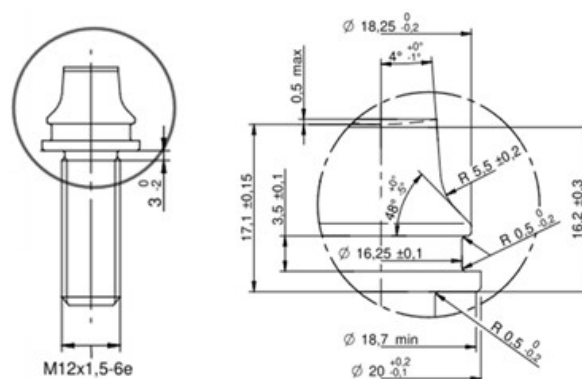


Fig. 1. Sketch of an M12×1,5×31,5 bolt

A stabilizer link (sway bar link) is a suspension component that transmits forces from the stabilizer bar to the wheel suspension, reducing body roll and improving vehicle stability and steering precision [14,15]. In the analyzed case, the spherical element is welded to the bolt head, but the welding process is not considered here. The link consists of a metal rod with two ball joints allowing multi-plane movement, ensuring proper force transmission. The joints are protected by rubber covers to prevent contamination and corrosion, and some models use additional bushings or bearings to improve vibration damping and reduce noise [16,17]. In the plastic forming process of bolts with specialized geometry, the proper selection of materials is critical for both the workpiece and the segmented forming tools. The bolts are manufactured from 23MnB4 (EN 1.5535), alloy steel, which exhibits high mechanical strength, favorable plasticity, and enhanced resistance to cracking under conditions of plastic deformation. These properties determine the deformation forces acting on the die segments and influence the design of their geometry as well as the sequence of their arrangement. The chemical composition and mechanical properties of material 23MnB4 shown in TABLE 1.

After plastic forming, the bolt underwent heat treatment, with parameters chosen to meet ISO 898-1 [18] requirements for strength class 10.9. The obtained results are shown in TABLE 2.

2.2. Technological Process

The objective of the study was to develop a technology for manufacturing a stabilizer link bolt with an unusual concave–convex head using cold forging on a forging press. The application of cold forging required balancing quality requirements

TABLE 1

Chemical composition (wt.%) of 23MnB4 according to EN 10263-4:2017 and mechanical properties of 23MnB4 in delivery condition U+C+AC+LC [13], where: U – untreated, C – cold drawn, AC – spheroidised, LC – skin passed

C, %	Mn, %	Cr, %	B, %	Si, %	P, %	S, %	Al, %	Ti, %	R _m max, MPa	Z min, %
0.22	0.97	0.27	0.003	0.1	0.01	0.006	0.027	0.048	540	64

TABLE 2

Results of the dimensional and mechanical parameter inspection of the M12×1.5×31 screw following the heat treatment process

	Specified requirement for bolts of property class 10.9 in accordance with ISO 898-1 standards	Obtained results
Tensile strength, R_m	min 1040 MPa	1068÷1079 MPa
Hardness, HRC	32÷39 HRC	33÷34 HRC

with manufacturing costs, as well as analyzing the influence of operation sequences and technological parameters on the overall process efficiency. Despite the high plasticity of 23MnB4 alloy steel, forming bolt heads with complex geometry using conventional solid dies is significantly limited. The primary challenge lies in the shape of the head's lateral surface, which requires a transition from a concave to a convex profile in two stages. Conventional solid dies are unable to accurately reproduce this type of profile; therefore, the plastic forming of bolts with specialized geometry necessitates the use of segmented dies. The use of segmented dies in the plastic forming of bolts enables the creation of a concave–convex outline. Accurate replication of the complex bolt shapes requires high surface pressures, which are undesirable when using segmented dies.

Prototype stabilizer link bolts were initially produced by machining, forming the head geometry, including the spherical element (Fig. 2) and the pin, followed by thread rolling. Machining ensured precise shape and high-quality surface finish, suitable for prototypes or small batches. However, it is inefficient for mass production and can reduce fatigue strength due to disruption of the material's grain continuity under high operational loads.



Fig. 2. Machined prototype of the stabilizer link with spherical element

Segmented dies were used to form the concave–convex lateral surface of the plastically formed bolts. The literature provides descriptions of segmented dies applied in bolt forging technologies, e.g., [20,21]. They typically consist of several precisely fitted working parts arranged symmetrically around the forging axis within a ring-shaped body. Each segment corresponds to a specific portion of the bolt head shape, allowing even distribution of contact loads with the forging [20]. The segments are precisely fitted in the die body, allowing slight radial movement while maintaining position under load. During die closure, they wrap around the component, ensuring complete filling of varying cross-sections and reducing voids. Closing springs press the segments together, provide uniform radial force, and return them to their initial position after forming, facilitating transfer to the next operation [20]. Technological trials were conducted on a forging press using a five-operation cold forging process.

Segmented dies were installed at the fourth station of the fixed anvil. The study analyzed the effect of different preforms in the preceding operation on process performance and bolt quality, particularly die filling in the transition radii between concave and convex surfaces. Two process variants were developed, both with operations I, II, III, and V using solid dies, and operation IV using segmented dies for precise concave–convex filling. Finishing operations, including chamfer machining and thread rolling were performed immediately after forging on a horizontal press.

3. Results and discussion

The technological process consisted of five consecutive forging stages. In the first operation, the material was preliminarily reduced in diameter, while in the second operation the preform was shaped for the initial formation of the bolt head. The subsequent operations differed in the preform shape and the geometry of the segmented die, depending on the variant of the technological trials.

3.1. Variant I of the Technological Trials

In Variant I, the third operation involved forming the upper flange of the head using a solid die. In the fourth operation, the shaping of the lower flange was carried out using a segmented die. The fifth operation was designed to form the bolt drive, which in this case is located on the shank of the bolt. The shape of the preform in Operation IV, where the segmented die was applied, as well as in the preceding operation, is shown in Fig. 3.

Fig. 4 shows the forging press stations, highlighting Operation IV with the segmented die shown.

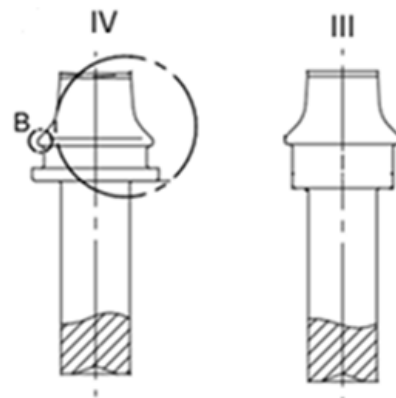


Fig. 3. Shape of the preform after Operations III and IV – Variant I of the technological trial

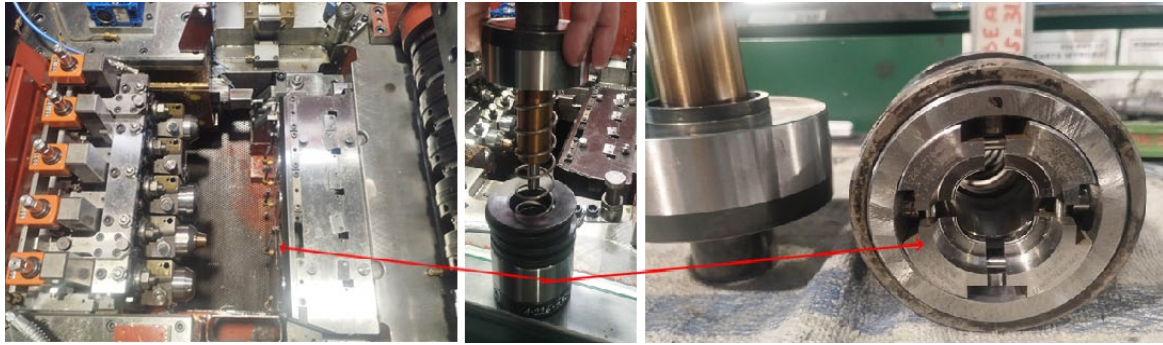


Fig. 4. Arrangement of the working stations in the forging press, indicating Operation IV and segmented die used in Operation IV

Variant I of the trials was unsuccessful. Only preforms could be formed in Operations I-III, as the fourth operation failed due to uncontrolled opening of the die segments. This was caused by the occurrence of high pressures resulting from significant deformation resistance. Alternatively, the problem may have originated from the selection of springs with insufficient stiffness, leading to inadequate clamping force of the die segments during forging. Additionally, the upper flange radius did not meet specifications, measuring 0.27 mm instead of the intended 0.5 mm, indicating inadequate die filling (Fig. 5).

Investigations of the material fiber flow pattern were also conducted to determine whether it had been disturbed during the forging process and whether the fiber structure remained compliant with the requirements of the USCAR 8 [22] standard, which specifies proper material flow in strength-critical regions of bolts. This analysis made it possible to assess the effect of the technological process on microstructural integrity and material strength, constituting an important element in verifying the correctness of the forging operations. In Variant I, the fiber arrangement of the preform from Operation III was examined. The results of these

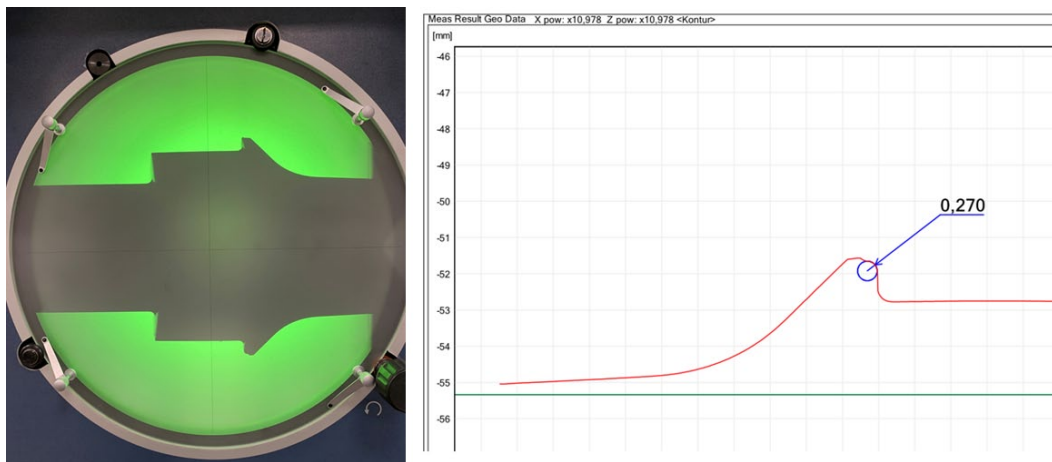


Fig. 5. Shape of the preform head after Operation III in Variant I of the technological trials – from left: projection image; profilometer image showing the measurement of the upper flange radius

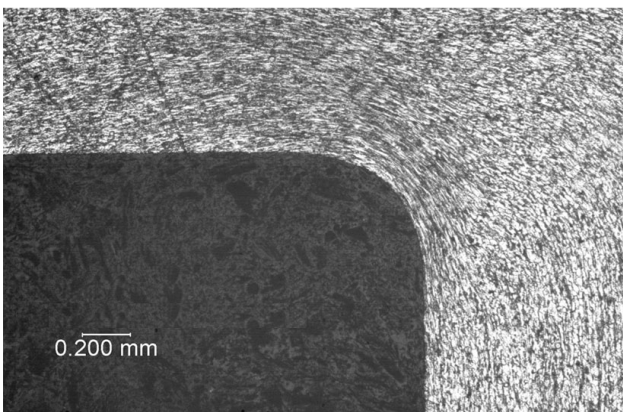


Fig. 6. Fiber flow in the area of the radius under the head – Operation III of Variant I of the technological trials

investigations, presented in Fig. 6 showed that the fiber structure was correct and was not disturbed during the forging process.

3.2. Variant II of the Technological Trials

Similar to Variant I, in Variant II the technological process was designed to include five consecutive forging operations. In Variant II, the third operation involved forming the lower flange of the head using a solid die. In the fourth operation, the shaping of the upper flange was carried out using a segmented die. The shape of the preform in Operation IV, where the segmented die was applied, as well as in the preceding operation, is shown in Fig. 7.

Variation II of the technological trials proved to be successful, the intended final shape of the bolt head was achieved. A photo of the segmented die used in this case is shown in Fig. 8. The preforms shaped in the consecutive forging stations of the press are presented in Fig. 9.

In this variation as well, measurements of radii critical to this component and an analysis of the fiber flow pattern were performed. However, the analysis of the results showed that, despite achieving the final shape of the bolt head, full compliance of the radii with the requirements of the final product was not attained (Fig. 10); the obtained profiles still lacked the required transition radius. Nevertheless, in comparison with the results of the first variation, the obtained radii satisfied the functional requirements of the product, and fiber flow remained correct (Fig. 11). It was

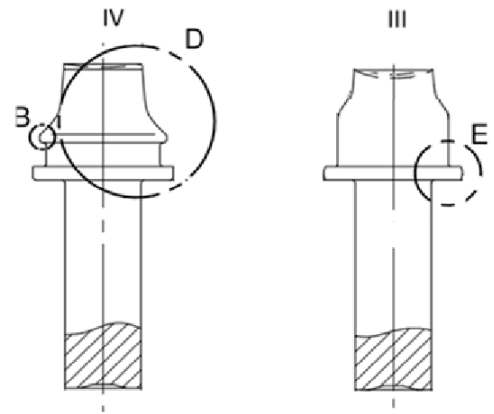


Fig. 7. Shape of the preform in Operations III and IV – Variation II of the technological trial



Fig. 8. Segmented die with the shaped preform installed in the die sleeve



Fig. 9. Preforms shaped in Variation II of the technological trials

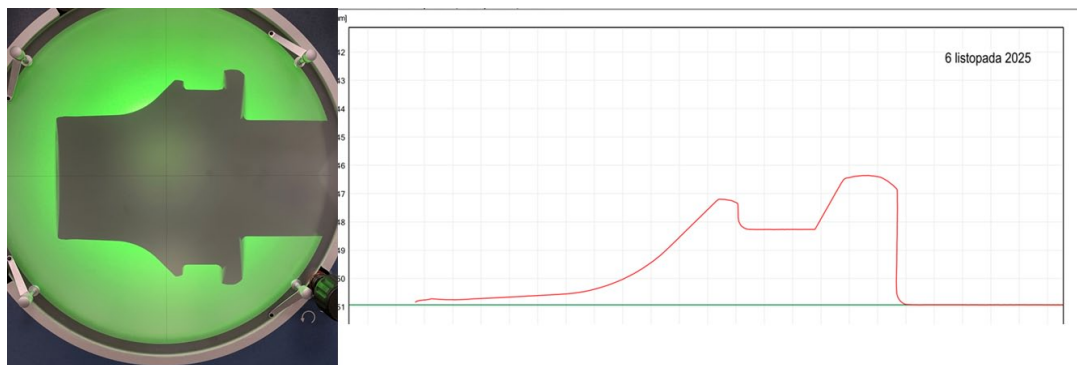


Fig. 10. Shape of the preform head after Operation IV in Variation II of the technological trials – from left: projection image; profilometer image

not disrupted during the forging process, similarly to the first variant. The correct course of material flow lines during forging constitutes an important indicator of the proper selection of process parameters and the appropriate shaping of preforms at individual stages of the technological operations. However, to prevent potential material discontinuity near the radius during vehicle operation, further optimization of strain distribution in the head was necessary.

3.3. Technological Trials of Forging with Additional Rolling of the Critical Bolt Head Radius

Several options for optimizing the bolt head radius were evaluated using a decision matrix, considering forming quality, tool durability, costs, implementation time, risk of defects, and process complexity. Weighting the criteria allowed objective comparison, identifying the variant that improved radius quality with minimal implementation difficulty. This solution, selected for further experimental verification, involved modifying the

thread rolling process by adding an extra rolling jaw to calibrate the bolt head radius precisely (Fig. 12).

This modification improved the compliance of the radius with the geometric and dimensional requirements of the final product (Fig. 13) and reduced the risk of incomplete material filling in this area, which directly decreases the likelihood of loss of integrity in the elastic material (rubber bushing) interacting with the bolt during operation.

3.4. Wear of the Tool Supporting the Preformed Bolt Head

Tool durability is a key factor in the efficiency and economics of die forging. High mechanical loads, variable contact conditions, and elevated temperatures accelerate wear, affecting product quality and production costs. In Variant II, excessive wear of the bushing supporting the bolt head in Operation IV was observed (Fig. 14). The original design allowed forging only ~100 bolts, which was uneconomical. Modifying the bush-

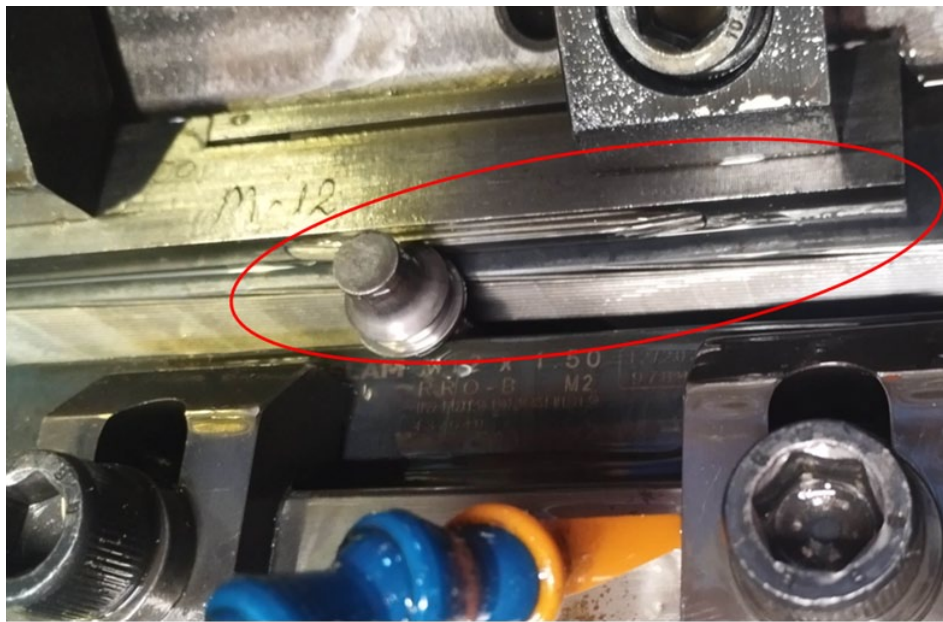


Fig. 12. Thread rolling with simultaneous calibration of the bolt head radius using an additional rolling jaw

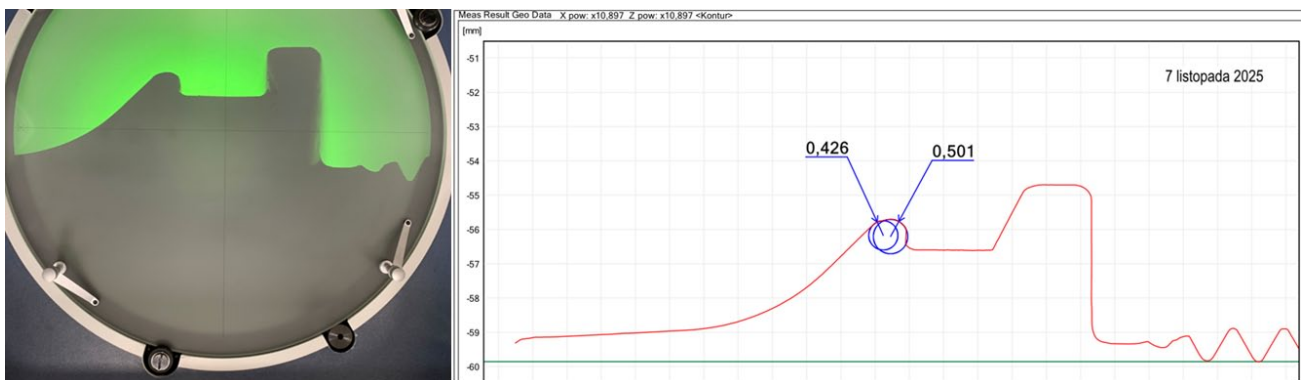


Fig. 13. Shape of the final preform head after the additional thread rolling modification – from left: projection image; radius measurement using a profilometer



Fig. 14. Modification of the bushing supporting the upper head in Operation IV of Variant II: original (100 bolts), first modification (10,000 bolts), final design (100,000 bolts)

ing shape and applying a PVD coating increased durability: ~10,000 bolts in the second iteration and ~100,000 bolts in the final version, meeting production and cost requirements.

4. Conclusions

The plastic forming of complex bolt head shapes causes numerous technological challenges during cold forging on forging machines. Obtaining products with high geometric accuracy requires the use of new die designs and changes in the forging sequence. As a result of research and technological trials, it was found that the use of segmented dies allows for the plastic formation of a corrugated (concave-convex) side surface of the bolt head.

Using segmented dies on forging machines requires numerous technological trials and adjusting the sequence of forging operations in individual work cells of processing machines.

The research concluded that the best results are achieved by using segmented dies in the fourth forging operation (for a five-operation process). Calibration of selected bolt head dimensions, such as edge rounding radii, can be performed during thread rolling by modifying the shape of the rolling segments.

Acknowledgements

The authors gratefully acknowledge the financial support of Koelner Rawlplug IP Sp. z o.o., Łańcut, which made this research possible.

REFERENCES

- [1] Z. Gronostajski, Z. Pater, L. Madej, A. Gontarz, L. Lisiecki, A. Łukaszek-Sołek, J. Łuksza, S. Mróz, Z. Muskalski, W. Muzykiewicz, M. Pietrzyk, R.E. Śliwa, J. Tomczak, S. Wiewiórowska, G. Winiarski, J. Zasadziński, S. Ziółkiewicz, Recent development trends in metal forming. *Archives of Civil and Mechanical Engineering* **19** (3), 898-941 (2019). DOI: <https://doi.org/10.1016/j.acme.2019.04.005>
- [2] S.J. Kim, T. Lee, J. Hwang, High-strength bolt manufactured by an extrusion-based forming process using twinning-induced plasticity steel. *Journal of Manufacturing Processes* **59**, 33-42, (2020). DOI: <https://doi.org/10.1016/j.jmapro.2020.09.043>
- [3] J. Sińczak, P. Skubisz, A. Łukaszek- Sołek, Modeling of forging process of a bolt. *Metallurgy and Foundry Engineering* **29**, (2), 109-115 (2003).
- [4] J. Sińczak, P. Skubisz, A. Kula, The application of finite element methods for the analysis of cold forging of screws. *Hutnik* **70**, (11), 434-438 (2003).
- [5] P. Hartley, I. Pillinger, Numerical simulation of the forging process. *Computer Methods in Applied Mechanics and Engineering* **195**, 48-49 (2005). DOI: <https://doi.org/10.1016/j.cma.2005.03.013>
- [6] Z. Pater, J. Tomczak, Innovative metal forming technologies developed at Lublin University of Technology. *Metal Forming* **26** (3), 241-254 (2015). DOI: <https://doi.org/10.4028/www.scientific.net/SSP.237.209>
- [7] T. Bulzak, A comparative analysis of hot and cold flashless forging of a stepped shaft using vertically-parted dies. *The International Journal of Advanced Manufacturing Technology* **116**, 2521-2530 (2021). DOI: <https://doi.org/10.1007/s00170-021-07542-0>
- [8] E. Doege, R. Bohnsack, Closed die technologies for hot forging. *Journal of Materials Processing Technology* **98** (2), 165-170 (2000). DOI: [https://doi.org/10.1016/S0924-0136\(99\)00194-6](https://doi.org/10.1016/S0924-0136(99)00194-6)
- [9] <https://tooling.tw/tools-segment-nut-die.html>, accessed: 26.12.2025
- [10] M. Milutinović, D. Vilotić, D. Movrin, Precision forging – Tool concepts and process design. *Journal for Technology of Plasticity* **33**, (1-2) (2008). Available at <https://ijiemjournal.uns.ac.rs/index.php/atm/article/view/jtp.2008.33.1-2.7?articlesBySameAuthorPage=3>
- [11] J. Sińczak, Advanced forging technologies for high-melting-point materials. Kraków: AGH University of Science and Technology, Faculty of Metals Engineering and Industrial Informatics (2013).
- [12] J. H. Song, Y.T. Im, Process design for closed-die forging of bevel gear by finite element analyses. *Journal of Materials Processing Technology* **192-193**, 1-7 (2007). DOI: <https://doi.org/10.1016/j.jmatprotec.2007.04.081>

- [13] B. A. Behrens, E. Doege, S. Reinsh, K. Telkamp, H. Daehndel, A. Specker, Precision forging processes for high-duty automotive components. *Journal of Materials Processing Technology* **185**, (1-3), 139-146 (2007).
DOI: <https://doi.org/10.1016/j.jmatprotec.2006.03.132>
- [14] <https://www.halfords.com/motoring/car-parts/suspension-and-steering/anti-roll-bars-and-components/>, accessed: 26.12.2025
- [15] S. Ramakrishna, B.R.H. Reddy, B. Akhil, B.P. Kumar, A review on anti-roll bar used in locomotives and vehicles. *International Journal of Current Engineering and Technology* **7** (3), (2017). Available at <http://inpressco.com/category/ijcet>
- [16] <https://www.kyb.com.au/product/stabilizer-links>, accessed: 26.12.2025
- [17] <https://warsztat.pl/artykuly/stabilizator-i-lacznik-stabilizatora-przyczyny-usz,69873>, accessed: 26.12.2025
- [18] ISO 898-1:2013, Mechanical properties of fasteners made of carbon steel and alloy steel – Part 1: Bolts, screws and studs with specified property classes – Coarse thread and fine pitch thread, International Organization for Standardization, (2013).
- [19] EN 10263-4:2017, Steel rods, bars, and wire for cold heading and cold extrusion – Part 4: Technical delivery conditions for steels for quenching and tempering, European Committee for Standardization, (2017).
- [20] Q. Yuangen, H. Y. Cho, A split die design for forging of hexagonal bolt head. *Journal of the Korean Society of Manufacturing Process Engineers* **19** (5), 91-97 (2020).
DOI: <https://doi.org/10.14775/ksmpe.2020.19.05.091>
- [21] I. Suchy, Handbook of die design, McGraw-Hill, (2006).
- [22] USCAR8 – Grain flow pattern for bolts and screws, SAE International Specification, (1998).