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Finite Element Analysis of the Transition from Multi-Station Machines to Double-Stroke Machines in the Forming Process of Ring Welded Bolts

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Research Article

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Abstract

Cold forming is a metal shaping technique that utilizes plastic deformation under high pressure with the aid of dies. This study focuses on the production of a weld bolt through cold forming, integrating the Finite Element Method (FEM) to evaluate and enhance the forming process. The conventional four-station manufacturing system was analyzed and replaced with a two-station configuration utilizing a double-stroke mechanism. FEM simulations confirmed the feasibility of this approach, demonstrating effective material flow and die filling across both stations. Subsequent experimental trials validated the dimensional accuracy of the final product and confirmed the absence of surface or internal defects. In comparison to the four-station process, the two-station system increased production speed, reduced energy consumption, and resulted in a 40% increase in annual output along with a 15% reduction in production costs. These results highlight the process efficiency and production benefits achieved through the proposed forming system.

1. Introduction

Cold forging is a highly efficient metal forming method widely employed in the production of high-strength mechanical components with tight dimensional tolerances (Kılıçaslan & İnce, 2016). The process involves plastically deforming metal materials under high pressure at room temperature, eliminating the need for preheating. Compared to other manufacturing techniques, cold forging offers significant advantages, including superior dimensional accuracy, excellent surface quality, high material utilization, and the elimination of secondary machining operations (Başdemir et al., 2018). These attributes make it an ideal method for high-volume industrial production.

In addition to its advantages in terms of dimensional accuracy and surface quality, cold forging also offers significant material-related benefits when compared to other manufacturing methods. One of the most important of these is the efficient utilization of raw material. Since cold forging shapes the material through plastic deformation without generating significant amounts of scrap, material loss is minimized, leading to higher material

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yield and reduced production costs. Furthermore, the absence of machining processes such as turning or milling, which typically produce considerable waste, further enhances this efficiency. Studies in recent years emphasize that cold forging ensures superior material flow and density distribution, resulting in components with enhanced mechanical properties and improved fatigue performance (Kim et al., 2023). These characteristics make cold forging highly suitable for the mass production of high-strength components with minimal material wastage.

In a foundational study, Vazquez and Altan (2000) reviewed cold forging applications in both academic literature and industrial practice, demonstrating the versatility and continuous advancement of the technique. Today, cold forging is extensively applied across various industries particularly in automotive, aerospace, electronics, and general manufacturing with bolt production being one of its most prevalent applications due to the method's efficiency and precision.

During the product design phase, Finite Element Method (FEM) simulations serve as a critical tool to guide the manufacturing process, enabling detailed analysis of material behavior, forming loads, and tooling performance (Vazquez & Altan, 2000). In modern die design, the integration of Computer-Aided Design (CAD) tools has become essential for reducing design errors, lowering production costs, and improving overall process reliability (Başdemir et al., 2018). FEM analyses are numerical techniques that enable a detailed examination of material behavior, stress distributions, and process parameters in complex engineering problems. Particularly in high-deformation processes such as metal forming, FEM has become an essential tool for design validation, die life prediction, and process optimization (Graça & Vincze, 2021). A typical design workflow begins with the initial geometric definition, followed by FEM-based validation, and culminates in prototype production (Hsia & Su, 2020). These simulations help assess formability, material flow, and stress distribution, ensuring that the final geometry can be achieved with minimal risk of failure.

Ring weld bolts, a widely used type of fastener, are typically produced using the cold forging method, often on four-station machines. These bolts feature a complex head geometry with multiple forming elements, which traditionally requires three to five preforming stages for complete shaping. Product designs are created to establish suitable manufacturing conditions, followed by prototype production. Although four-station machines are commonly used, the cold forging process can also be applied in systems with two, three, or five stations. The number of stations directly affects production costs and cycle times, prompting various studies that examine the influence of station count on the efficiency and feasibility of the manufacturing process.

Prior to production, forming sequences and tooling designs are finalized using FEM simulations to ensure feasibility and prevent defects such as cracking or underfilling. These simulations provide insights into die stresses, material flow, and geometrical accuracy. While previous studies have focused on optimizing multi-station configurations, the potential to reduce station count without compromising product quality remains underexplored.

In this context, the present study introduces a novel approach by demonstrating the feasibility of producing M6x25 ring weld bolts using a two-station double-stroke cold forging system—an application not previously reported in the literature. This contribution addresses both process simplification and performance enhancement, offering a new perspective for efficient fastener manufacturing.

2. Methodology

In studies conducted on the M6x25 ring weld bolt, the production process was transitioned from four-station machines to double-stroke machines. The key distinction between these machine types lies in the number of forming stages and the higher operational speed of double-stroke systems. While the four-station process includes wire cutting, preform formation, head forging, and final shaping, the double-stroke machines consolidate head formation and final shaping into two sequential cold forging steps. During this transition, FEM analyses were employed to evaluate material flow, forming behavior, and tooling design, thereby contributing to a more efficient and streamlined manufacturing process.

2.1. Product design

The M6x25 ring weld bolt is a type of fastener traditionally manufactured using four-station cold forging machines. Within the scope of process development efforts, the original tool and product designs were prepared by the design team and utilized in prototype manufacturing. In pursuit of increased efficiency and reduced production complexity, the forming process was reconfigured to operate on a double-stroke machine. The revised tooling concepts were subjected to numerical analysis using the FEM to assess their feasibility and forming performance prior to experimental validation.

2.2. Finite element method

The modeling in this study was conducted using SIMUFACT Forming software. Separate models were developed for each station, and appropriate geometries were generated accordingly. Key factors such as material flow, tool stresses, and wear behavior were analyzed to obtain valuable insights into the forming process (Joun et al., 2002). This simulation-based approach reduces process development time and allows for a broader range of design variations.

In the simulation model, all dies were assumed to be rigid, as elastic deformations occurring in the tooling do not have a significant impact on material flow. The material used in the process was defined based on its plastic deformation behavior, and its torsional properties were considered sufficient for the simulation. In the model, the fixed die was fully constrained, with all translational and rotational degrees of freedom (in the x, y, and z directions) restricted. The movable die, on the other hand, was defined to have translational movement only along the z-axis, while all other translational and rotational motions were restricted. The effect of gravity was neglected in the simulations, and the boundary conditions were defined in accordance with the structure of the actual machine and the production scenario.

The material data used as a reference in the Simufact simulation software was selected to be identical to the raw material employed in the actual production of the parts, in order to ensure consistency and reliability of the results. To accurately reflect the material behavior within the simulation environment, the yield strength of the material was experimentally determined under specified conditions prior to the simulation. As illustrated in Figure 1, the tests were conducted at 25°C (room temperature) with a strain rate of 0.01 s^{-1}, and the yield strength was measured as 322.94 MPa. In addition, the friction coefficient of the material, which was determined through experimental methods, was measured as 0.08 and incorporated into the simulation accordingly.

In this study, both experimental and numerical analyses were conducted to determine the friction coefficient between the die and the material. In the experimental procedure, the raw material used in actual production was placed in the die and compressed using a press to a defined stroke (8 mm), after which the stress value was measured via tensile testing. The same conditions were replicated in the Simufact Forming software, applying the same stroke value to obtain the corresponding simulated stress. The experimental and numerical stress values were then compared. Assuming the discrepancy arose from friction, the friction coefficient was iteratively adjusted until the simulation results aligned with the experimental data. The friction coefficient at which both results converged was considered the actual friction coefficient between the die and the material.

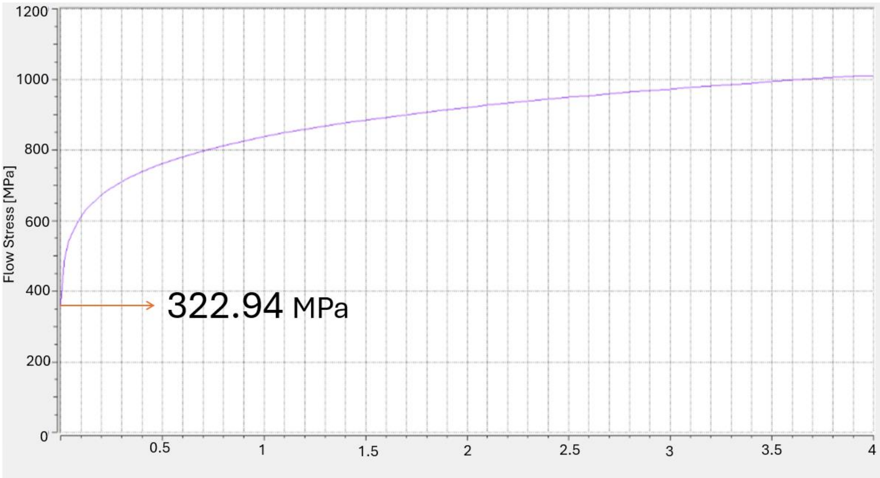

Figure 1. True flow stress–strain curve of the material used in the simulation

In order to verify the geometric accuracy of the part, 3D analyses of the selected material were performed, and the mesh structure was visually inspected. A tetrahedral mesh comprising 247 elements was employed in the simulation, as illustrated in Figure 2, and the mesh quality was checked to prevent any geometrical distortions in the analysis. These preparations were carried out as a preliminary step for ensuring reliable simulation results for the products (Zou et al., 2024).

In this study, the use of tetrahedral mesh is crucial for accurately defining the complex geometries present in the model. Tetrahedral meshing provides a more uniform and compatible distribution, particularly in structures with sharp transitions and three-dimensional free surfaces, thereby enhancing structural continuity. Given that the product and die geometries in this work likely involve intricate transitions and freeform surfaces, the use of tetrahedral mesh is considered more appropriate. Software such as Simufact can automatically generate this mesh structure in a smooth and void-free manner. This approach offers advantages in terms of visually evaluating flange formation, mesh uniformity, and material compaction.

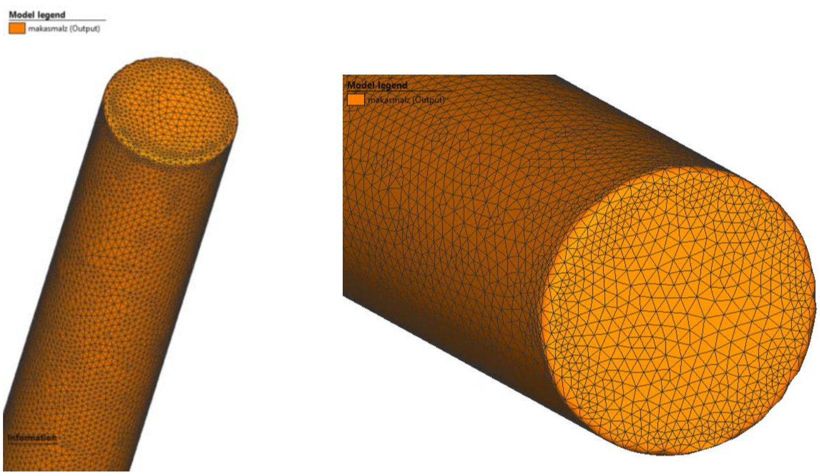

Figure 2. 3D analysis of the material to be used in production

Simulation studies were carried out for the M6x25 ring weld bolt designed for double-stroke production. The initial simulation results, illustrated in Figure 3, revealed the formation of buckling due to excessive unsupported material length. In cold forging, buckling typically occurs when the upsetting ratio (L/d) exceeds a critical value of approximately 2.5. In this case, the L/d ratio —defined by the protruding wire length (L) to wire diameter (d)— exceeded the allowable limit due to open die upsetting conditions, leading to instability during deformation.

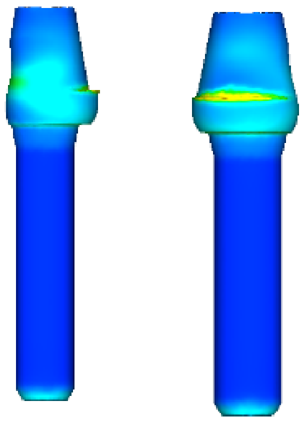

Figure 3. FEM simulation showing buckling formation due to excessive l/d ratio in open die upsetting

To address this issue, the spring-loaded preform tool design was modified to limit uncontrolled material displacement during forming. Specifically, the segment of the wire prone to buckling was enclosed within a movable die component that was preloaded with a spring, allowing contact with the fixed die at the onset of deformation. This configuration effectively shortened the unsupported material length (L) by partially constraining it within the tool, thereby reducing the **L/d ratio** below the critical buckling threshold (Craveiro et al., 2022). As illustrated in Figure 4a and 4b, the revised tooling design successfully eliminated buckling and enabled stable forming under cold forging conditions.

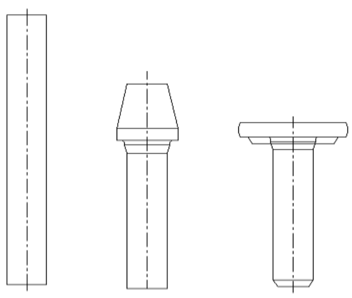

Figure 4a. Initial tooling design developed for the cold forging of M6x25 ring weld bolt

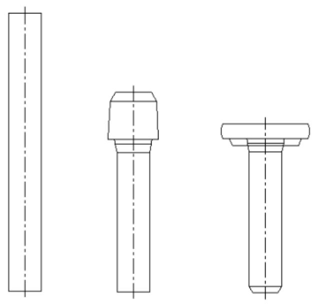

Figure 4b. Revised preform tool design incorporating a spring-loaded movable

Following the finalization of the tooling design, comprehensive analyses of material flow behavior were conducted through plastic deformation simulations under cold forging conditions, replicating actual production parameters. These simulations enabled detailed observation of material displacement, contact behavior, and die filling characteristics throughout each stage of the forming process. By examining the internal flow patterns and deformation zones within the tooling cavity, potential issues such as underfilling, excessive flash formation, or localized stress concentrations were identified and addressed prior to experimental implementation (Figure 5).

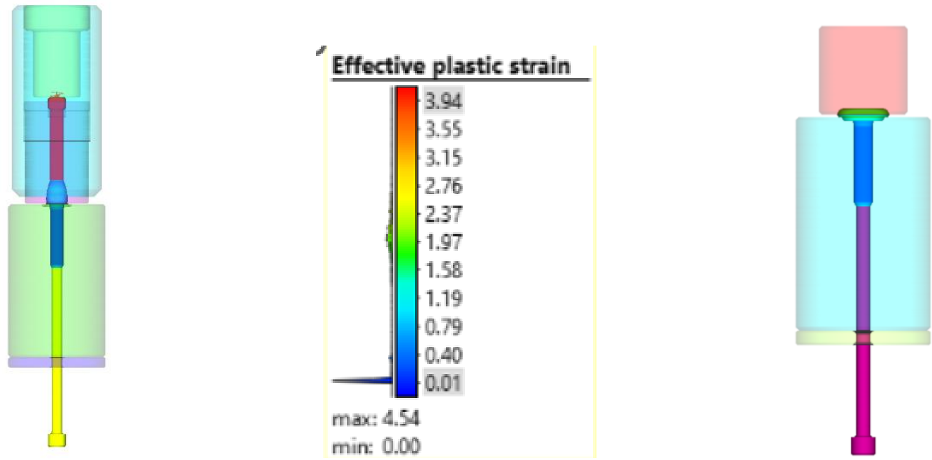

Figure 5. FEM-based representation of tooling configuration and effective plastic strain distribution during cold forging of M6x25 ring weld B

The three-dimensional simulation outputs illustrating the progression of the forming stages for the M6x25 ring weld bolt are presented in Figure 6. These visualizations provide insight into the material deformation behavior at each stage, allowing for detailed evaluation of geometry evolution, die filling, and potential surface irregularities. The sequential representation also supports verification of the forming sequence and dimensional conformity prior to experimental validation.

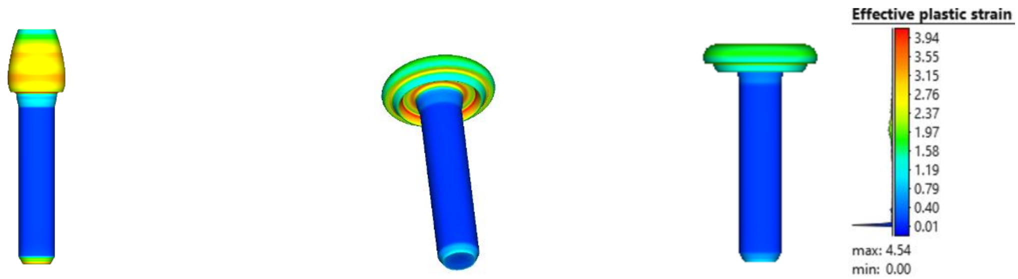

Figure 6. FEM-based simulation results showing geometrical evolution and effective plastic strain distribution of the M6x25 ring weld bolt across forming stages

Throughout the simulation process, the force–displacement relationship was systematically evaluated to assess the forming loads at each station. In the resulting graphs, the X-axis denotes the stroke length of the press in millimeters (mm), increasing as the press descends from its initial position, while the Y-axis represents the corresponding forming force in kilonewtons (kN). Variations in the slope and curvature of the graph provide insight into material resistance, deformation behavior, and tooling interaction during the forging process. Figure 7a presents the force–displacement curve obtained during the preform stage, highlighting the initial material resistance and tool engagement. Figure 7b depicts the force profile associated with the final forming stage, where higher deformation loads and geometric transitions are observed due to complex material flow and contact conditions.

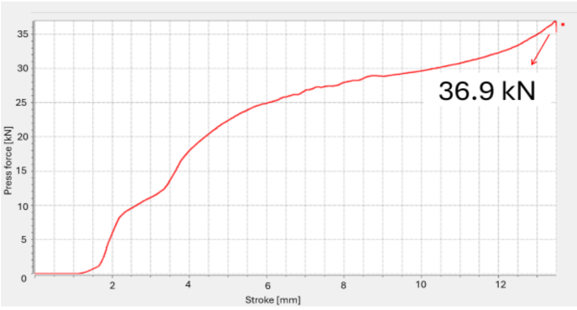

Figure 7a. Force-displacement curve for the preform in cold forging simulation

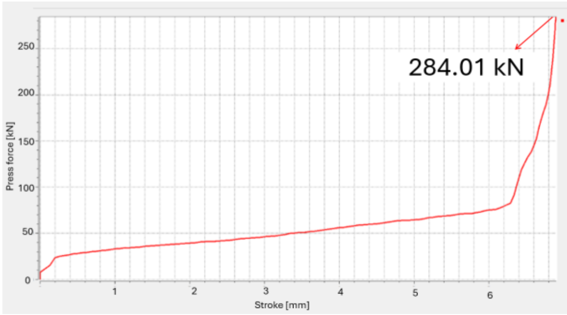

Figure 7b. Force-displacement curve for the final forming stage in cold forging simulation

3. Tests and Analyses

3.1. Metallographic analysis

The microstructural characteristics of the final product were examined to assess the quality and integrity of the material following the cold forging process. Particular attention was given to the regions exhibiting cross-sectional changes, where internal structure images were obtained from high-surface-area zones. The bolt was divided into two equal parts in the middle vertical plane and the material flow lines in the shaft region and the shaft-head joint regions were analyzed. The analysis focused on verifying the continuity and orientation of material flow lines, which are critical indicators of deformation quality. The results confirmed that the material flow was consistent with plastic forming principles, with no evidence of folding, buckling, or flow line disruption observed in the examined sections (Başdemir et al., 2018). Figure 8 presents the microscopic images of the evaluated regions.

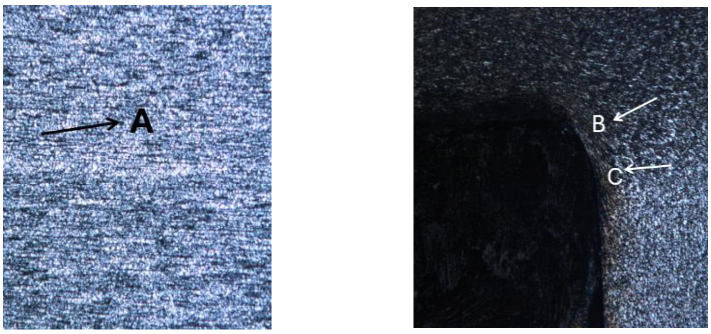

Figure 8. Optical micrographs showing flow line integrity in raw material and forged product sections

3.2. Mechanical properties

Hardness measurements were performed at specific locations on the product cross-sections, as indicated in the corresponding figure. The hardness measurements at the specified points are presented in Table 1.

Table 1. Hardness measurements at specified regions

Location	**A**	**B**	**C**
Hardness (HV)	190	220	225

Following the completion of microstructural evaluations and FEM-based design validation, prototype production was conducted using the newly developed two-station tooling system. The results demonstrated that the previously observed issues—such as material instability and geometric inconsistency—were effectively eliminated through the implemented design modifications. The final product, as presented in Figure 9, exhibited complete form fidelity and surface integrity, confirming the success of the redesigned forming process under experimental conditions.

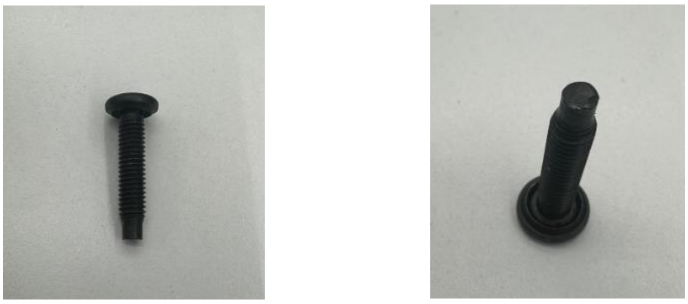

Figure 9. Final prototype of the M6x25 ring weld bolt produced using the two-station double-stroke cold forging process

4. Results and Discussions

The effectiveness of the proposed two-station double-stroke cold forging process was comprehensively evaluated through FEM simulations and subsequent prototype production. In the simulation phase, critical aspects such as forming forces, material flow, and die filling behavior were examined in detail. The analyses demonstrated that the newly designed forming sequence allowed for stable material deformation without exceeding stress limits or exhibiting failures such as buckling or underfilling.

Following simulation validation, physical prototypes were manufactured using the redesigned tooling system. The final parts showed high dimensional precision and surface quality, aligning closely with the simulation outcomes. This correlation confirmed that the numerical model accurately represented the real-world process conditions. Microstructural assessments further supported these findings by showing uninterrupted material flow lines and the absence of folding or internal discontinuities—key indicators of successful metal flow during cold forming.

The application of the two-station forming approach brought considerable gains in process efficiency. Shortened cycle durations and reduced machine operating times contributed to noticeable energy savings. Furthermore, the decreased number of tooling components led to extended die life and fewer replacement requirements, resulting in lower tooling costs. Overall, the process enabled a 40% increase in annual production capacity and a 15% reduction in manufacturing expenses. A comparison between the 4-station and 2-station (double-stroke) systems in terms of tooling components, production capacity, tool cost, and tool lifetime is presented in Table 2.

Table 2. Comparison of the 4-station and 2-station (double-stroke) systems based on tooling components, production capacity, tool cost, and tool lifetime

Parameter	4-Station System	2-Station (Double-Stroke) System
Annual Production Capacity	16 000 000	16 000 000
Number of Tooling Components	160	32
Tool Cost per Unit (€)	500	250
Tool Lifetime (Produced Units)	100 000	500 000
Total Tooling Cost (€)	80 000	8 000

The dimensional measurements obtained from the samples were evaluated against the specified nominal values and tolerance limits. As shown in Table 3, all measured values fall within the acceptable range, indicating compliance with the required specifications. These results confirm the consistency and accuracy of the manufacturing process, ensuring that the produced components meet the designated quality standards.

Table 3. Evaluation of dimensional measurement results against nominal specifications for bolt samples

Dimension	Nominal value		Measured values					OK/ NOK
	Max.	Min.	1.	2.	3.	4.	5.	
Head Thickness	2,5	2,25	2,38	2,36	2,38	2,36	2,41	OK
Total Length	25,42	24,58	25,11	25,1	25,11	25,11	25,1	OK
Seating Surface Diameter	6,8	-	5,65	5,66	5,62	5,66	5,64	OK
Unthreaded Length	1,5	-	1,42	1,4	1,44	1,44	1,46	OK
Head Diameter	15	14	14,36	14,4	14,38	14,35	14,4	OK
Major Diameter	5,97	5,79	5,88	5,85	5,86	5,85	5,86	OK
Pitch Diameter	5,32	5,21	5,26	5,25	5,27	5,25	5,27	OK

5. Conclusion

Ring weld bolts, such as the M6x25 type studied here, are conventionally produced using four-station cold forging machines due to their complex geometries. In contrast, double-stroke machines have traditionally been used for simpler fastener designs. This study marks the first successful demonstration of manufacturing ring weld bolts using a two-station double-stroke system. This advancement represents a novel contribution to the field, as it showcases the feasibility of producing geometrically demanding parts using a more compact and efficient setup. While the current study demonstrates the applicability of double-stroke forming for ring weld bolts, further research is recommended to evaluate tool wear behavior under extended production cycles and to explore the method's suitability for larger fastener sizes or alternative material grades.

The methodology developed in this work offers a practical framework that can be adapted to the manufacturing of similar fasteners. By reducing equipment requirements and simplifying production without compromising quality, this approach provides a flexible and scalable alternative for industrial cold forging operations.

Authorship Contribution Statement

Each author contributed significantly to the study. BA: study conception and design, analysis and interpretation of results; ÖÖ: data collection, analysis and interpretation of results, draft manuscript preparation; İÖ: analysis and interpretation of results. All authors have read and approved the final manuscript.

Conflict of Interest

The authors declare no conflict of interest.

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