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Simulation of roll forming for U-shaped bent profiles

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Моделювання профілювання U-подібних гнутих профілів

Abstract. Purpose. *To develop an approach for simulating the roll forming process of U-shaped bent profiles using the QForm software package.* ***Methodology.*** *The study is based on the finite element method implemented in QForm. The process was simulated in a 3D environment, accounting for elastic–plastic deformation, using a single operation of the «Sheet Bulk Forming» type. A sequential forming scheme was implemented using 12 roll stands, which incorporated the elastic–plastic properties of the material. Appropriate boundary conditions were defined to replicate real technological parameters of the roll forming process.* ***Results.*** *The simulation yielded stress and strain distributions in the blank at various stages of its passage through the roll stands. It was found that maximum plastic strains occur in the bending zones, while the edge regions are predominantly subjected to tensile stresses. The simulation results are consistent with the physical nature of the bending process and confirm the validity of the proposed approach.* ***Scientific Novelty.*** *An adaptation of the QForm software package is proposed for simulating the roll forming of bent profiles, which is not covered by its standard modules. Simulation algorithm and boundary condition setup were developed, enabling the analysis of the stress–strain state of the blank during profile formation.* ***Practical Significance.*** *The results of the study can be used to optimize technological parameters of the roll forming process, reduce the likelihood of defect formation, and expand the functional capabilities of QForm in the field of sheet metal forming simulation. The proposed approach is valuable for technologists, engineers, designers, and researchers working in the field of metal forming.*
Key words: *bent profile, deformation, simulation, roll calibration, roll stand, defect.*

Анотація. Мета. *Розробити підхід до моделювання процесу профілювання U-подібних гнутих профілів за допомогою програмного пакету QForm.* ***Методологія.*** *Дослідження базується на методі скінченних елементів, реалізованому в QForm. Процес моделювався в 3D-середовищі з урахуванням пружно-пластичної деформації, використовуючи одну операцію типу «Sheet Bulk Forming». Послідовну схему формування було реалізовано з використанням 12 вальцьових клітей, які враховували пружно-пластичні властивості матеріалу. Були визначені відповідні граничні умови для відтворення реальних технологічних параметрів процесу профілювання.* ***Результати.*** *Моделювання дало розподіл напружень та деформацій у заготовці на різних етапах її проходження через вальцьові кліті. Було виявлено, що максимальні пластичні деформації виникають у зонах згинання, тоді як крайові області переважно піддаються розтягуючим напруженням. Результати моделювання узгоджуються з фізичною природою процесу згинання та підтверджують обґрунтованість запропонованого підходу.* ***Наукова новизна.*** *Запропоновано адаптацію програмного пакету QForm для моделювання профілювання гнутих профілів, яке не охоплюється його стандартними модулями. Було розроблено алгоритм моделювання та налаштування граничних умов, що дозволило проаналізувати напружено-деформований стан заготовки під час формування профілю.* ***Практичне значення.*** *Результати дослідження можуть бути використані для оптимізації технологічних параметрів процесу профілювання, зменшення ймовірності утворення дефектів та розширення функціональних можливостей QForm у сфері моделювання формування листового металу. Запропонований підхід є цінним для технологів, інженерів, конструкторів та дослідників, що працюють у галузі обробки металу тиском.*
Ключові слова: *гнутий профіль, деформація, моделювання, калібрування валків, прокатний стан, дефект.*

Introduction. Bent profiles manufactured by progressive edge bending are widely used in the automotive, aerospace, and other industrial sectors [1]. Their production technology – cold roll forming – is characterized by high dimensional accuracy, efficient material utilization, increased structural strength, economic feasibility for mass production, and the ability to produce profiles with complex geometries and small bending radii [2].

The design of roll forming technology is a complex process that requires a high level of expertise from the process engineer. Setting up a roll forming line involves significant time and material costs, and errors made during the initial design stages may lead to repeated equipment adjustments and additional economic losses.

The application of the FEM enables simulation of the roll forming process at the profile development stage. For this purpose, general-purpose software packages such as Ansys, Abaqus, and QForm are used, as well as specialized tools like UBECO PROFIL and COPRA RF. General-purpose platforms offer broader capabilities for defining initial conditions but require deep knowledge of FEM. In contrast, specialized systems simplify model setup but have limited flexibility – for example, when simulating profiles with variable cross-sections [3].

Literature Review and Problem. Statement FEM of roll forming processes for bent profiles is a powerful tool for verifying technological and structural parameters prior to production. It enables the analysis of the material's stress–strain state, prediction of defects,

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and optimization of process parameters. The literature presents a variety of approaches to building FEM models, differing in complexity, element types, kinematic descriptions, and software platforms used.

In [4], a nonlinear finite element model is proposed using a mixed Eulerian–Lagrangian formulation based on the Kirchhoff–Love shell theory. This approach effectively accounts for contact interactions and axial material flow, providing high accuracy in simulating steady-state processes. However, the model does not consider material anisotropy, limiting its applicability to complex materials. Study [5] implements an FEM model in LS-Dyna to predict the stress–strain state of steel sheets, identify forming defects, and account for production parameters. The model is experimentally validated using strain gauges and 3D scanning. Its main limitation is the insufficient accuracy in predicting transverse deformations.

In [6], an innovative approach is introduced using non-conforming meshes with hanging nodes processed via Lagrange multipliers. This allows for local mesh refinement in bending zones without excessive model complexity, reducing computational costs while maintaining high accuracy. The method is implemented in Metafor software and tested on U-profile and tubular panel forming tasks. Its limitation lies in the use of linear elements only.

Study [7] investigates the forming of short symmetric U-profiles from AA5052-H32 aluminum alloy. A numerical model is built in UBECO PROFIL using LS-DYNA shell elements, which aligns with experimental results. The study establishes the relationship between springback and thinning with sheet thickness and forming speed. However, it does not specify whether failure criteria or geometric tolerances were considered. In [8], the influence of a support stand on longitudinal distortion during aluminum U-profile forming is examined. Two models – with and without support – are built in LS-DYNA and UBECO PROFILE. It is found that the support significantly reduces distortion, though the models do not account for friction or residual stresses.

Study [9] analyzes deformation mechanisms at profile ends after cutting. FEM and experimental methods are used to develop models linking bend curvature to residual stress distribution, enabling prediction of waviness and process optimization. The study is limited to a single profile type. In [10], the effect of the number of forming passes (6 and 10) on edge stresses during C-profile forming from low-carbon steel St24-2 is investigated using UBECO PROFIL. It is shown that six passes result in stress levels exceeding the yield strength (up to 219 %), causing defects, while ten passes ensure uniform stress distribution (up to 73 %) and high-quality forming. The study does not address springback and is limited to one profile type.

Study [11] presents a comparative analysis of four methods for forming thin-walled round tubes from high-strength steel CR700/980DP. Simulation in COPRA RF shows that the combined method yields minimal edge elongation and highest forming quality. Increasing the gap between upper and lower rollers reduces plastic strain and roller load, improving equipment durability. Only one steel type is considered. In [12], the forming of a complex asymmetric profile from stainless steel SUS301L-ST is investigated. COPRA RF simulation evaluates the influence of inter-roll distance, friction coefficient, roller diameter increment, and linear speed on longitudinal edge deformation. An optimal parameter combination is identified for high-precision forming. However, material anisotropy is not considered.

Study [13] proposes a method for controlling edge waviness during H-profile forming from high-strength steel. ABAQUS simulation shows that optimizing sheet thickness, flange height, and forming speed minimizes defects. Yet, geometric tolerances and local defects – critical for welding – are not addressed. In [14], an analytical model based on bifurcation theory and thin-shell mechanics is proposed to reduce flange waviness during forming. FEM confirms the approach's effectiveness, though simplified boundary conditions were used.

Study [15] examines the impact of discrete roller dies on aluminum profile forming accuracy. ABAQUS simulation shows that paired die arrangements yield lower shape deviations, more uniform thickness, and reduced springback. Increasing the non-contact zone worsens accuracy and causes thinning. In [16], the influence of roller gap (0,3–0,5 mm) and inter-roll distance (100–140 mm) on thin asymmetric profile forming is analyzed. ABAQUS simulation reveals that an optimal combination (0,4 mm gap, 100 mm spacing) ensures high shape accuracy without waves or cracks. Excessive gap reduction leads to local thinning and microcracks, while increased spacing causes edge flutter. The study does not consider springback and is limited to one material and simple geometry. Study [17] models FEM-based tool stiffness during roll forming. A 3D model of shafts and rollers is developed, accounting for nonlinear effects, bearing clearances, roller preloading, and support geometry. The model predicts shaft deflections under load, which is critical for precise equipment setup. Simulation results align with experimental data, demonstrating high accuracy. However, challenges remain in accounting for real tolerances, assembly errors, thermal deformation, and dynamic loads.

The literature review confirms the active use of FEM in simulation roll forming processes for bent profiles. The approaches presented cover a wide range of tasks—from constructing geometrically complex models to optimizing process parameters and controlling potential defects. However, most models have limitations and do not account for factors such as elastic recovery, thermal effects, material anisotropy, geometric tolerances, and simplified material property representation. Only a limited number of FEM-based roll forming studies have been conducted using the QForm software package. This highlights the need for further research, particularly in modeling the roll forming of U-shaped profiles, where prediction accuracy and model adaptability to real production conditions are critical.

Purpose and objectives of the research. Development of an approach to modeling the roll forming process of a U-shaped profile using the QForm software package. To achieve the stated purpose, the following objectives are envisaged: construction of the geometric model of the profile and tooling; definition of boundary conditions and technological parameters of the process; execution of numerical modeling and analysis of the obtained results.

Materials and Methods of Research. The object of simulation is a U-shaped bent profile with dimensions of 120×60×6 mm made of St3 steel, which is widely used, particularly in warehouse infrastructure. A roll forming mill of classical design was used, with an inter-stand distance of 1000 mm and a profiling speed of 30 m/min. The roll forming scheme includes 12 passes, shown in Figure 1, with the following bending angles: 0°–8°–18°–30°–42°–54°–66°–78°–88°–80°–88°–90°.

The U-shaped profile has a relatively simple design. Its height is 60 mm, which determines the height of the roll flanges, but is not a significant value and does not require a substantial increase in the number of passes. At the same time, the profile thickness of 6 mm necessitates either a reduction in profiling speed or the use of a greater number of passes when selecting the forming scheme. The profile material is carbon steel St3, which is well-suited for the roll forming process. Lubrication was not applied.

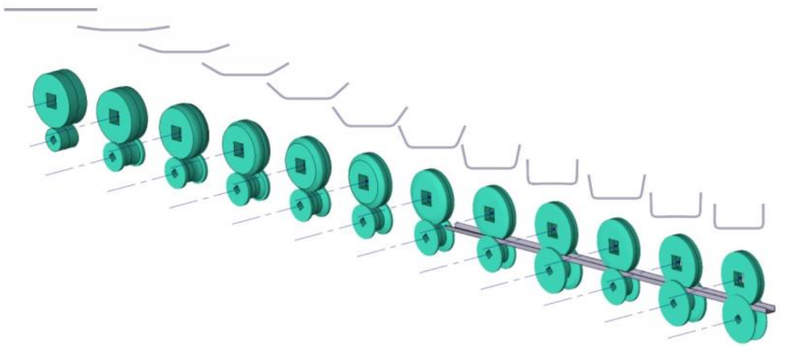

Figure 1 – Roll forming scheme of the U-shaped profile with bending angles: 0°–8°–18°–30°–42°–54°–66°–78°–88°–80°–88°–90°.

The forming of the U-shaped profile was simulated using a classical scheme [18]. The profiling axis passes through the center of the horizontal wall, and the process is considered in the single-piece forming variant with the flanges oriented upwards. Practice shows that the number of forming passes can be optimized by reduction; however, this issue is not addressed within the scope of this study.

According to the design, the set of roll forming tools used in this study can be divided into three groups. The first and second groups include bending rolls (so-called closed calibers) with a total bending angle of 30° and above, and from 30° to 85°, respectively. The third group consists of finishing rolls [18].

The blank width calculated using software (UBECO PROFIL) is 215,9 mm, while the analytical calculation yields 217,1 mm. The latter was selected for simulation. The 1,2 mm difference is due to the use of different methods for calculating blank length along bending radii and is not considered significant.

The simulation of the roll forming process for the U-shaped bent profile was performed in the CAE system QForm. This software package contains a wide range of modules for simulating various metal forming processes, but it does not include a dedicated module for roll forming of bent profiles. Nevertheless, QForm provides sufficient tools to implement this task. In this study, the forming process of the U-shaped bent profile was realized as a single operation of the «Sheet Bulk Forming» type, with a 3D task setup and consideration of elastic–plastic deformation.

The 3D models of the rolls and their arrangement scheme were created in the CAD system Fusion and exported to the CAE system QForm. Geometry verification was performed using the QShape utility. The blank itself was created using parametric geometry in QForm. The selected mesh type was hexahedral, ensuring at least three elements across the profile height during simulation. Since the roll stands are symmetrical, only half of the model was considered using a symmetry plane, which accelerated the simulation. Each roll was assigned a rotation axis.

The material selected for the profile was St3 steel. During material parameter setup, the cold forming mode was used, meaning the blank was not preheated.

The roll drive was implemented using the "Universal" drive type, with specified direction and rotation speed for each roll. During roll calibration development, the transitional shapes and their mutual arrangement must satisfy the condition that the average circumferential speed of each subsequent roll pair is not less than that of the previous one [18]. Since precise calculation is difficult in practice, the increase in circumferential speed of subsequent roll pairs was achieved by gradually increasing their base diameters. In this study, the base diameters of the rolls were increased by 0,4 % from the first to the last pair. The roll stands were made of steel grade H12MF. It should be noted that contact between the rolls and the blank occurs without lubrication, and in the «Bring into contact» parameter, the value «do not bring into contact» must be set.

The FEM simulation of the U-shaped bent profile forming process continues until the entire profile passes through all roll stands. The stop condition for the calculation is defined by the specified number of rotations of the upper roll in the first stand. Setting an additional boundary condition «Pusher» (dimensions, direction, and movement speed are specified) can be used to move the blank in the given direction and/or to fix surface nodes from shifting in planes perpendicular to that direction.

Figure 2 shows the cross-section of the final roll stand and the characteristic points used for stress–strain state analysis: Point 89 – outer side of the profile end; Point 74 – inner side of the profile section subjected to bending.

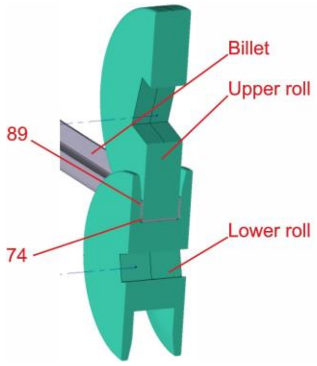

Figure 2 – Cross-section of the final roll stand and characteristic points used for stress–strain state analysis.

As a result of the FEM simulation of the forming process for the U-shaped bent profile, the data presented in Figure 3 were obtained. The figure shows the distribution of stress intensity and plastic strain along the length of the profile: a) Point 74 is located on the inner surface at the bending zones of the blank; b) Point 89 is located at the edge of the blank.

a)

b)

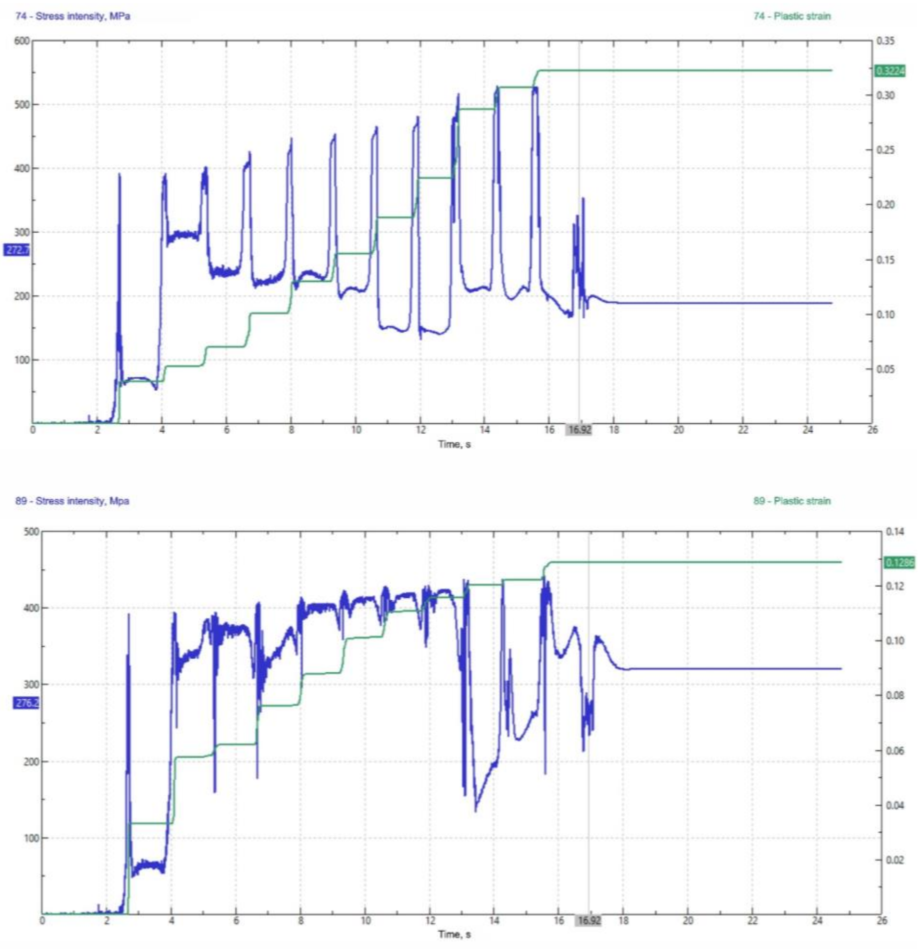

Figure 3 – Distribution of stress intensity and plastic strain along the length of the U-shaped bent profile during the roll forming process: a) Point 74 – located on the inner surface at the bending zones of the blank; b) Point 89 – located at the edge of the blank.

During the roll forming of a U-shaped bent profile, the distribution of stresses and plastic strains in the material is significantly influenced by the position of the point relative to the neutral bending axis. Analysis of the simulation results (Figure 3a, b) shows that on the inner surface of the bend (Point 74, Figure 3a), impulse-like stress spikes occur as the blank enters the roll stand, followed by partial unloading. Notably, stress accumulation begins even before the analyzed region enters the stand. The peak stress values reach 450–520 MPa, while the accumulated plastic strain is approximately 32 %. The strain increases in a stepwise manner at each forming pass, corresponding to the gradual shaping of the profile, and stabilizes at the end of the process. This indicates that the primary loading and risk of crack initiation are concentrated in the bending zones of the profile. In contrast, the stress–strain behavior at the edge of the blank (Point 89, Figure 3b) is different. Here, the stress level is higher and more uniform throughout the forming process, stabilizing within the range of 350–420 MPa, with local fluctuations and drops associated with tensile stresses. The plastic strain in this region reaches only 12–13 %, which is significantly lower than in the bending zones and indicates a smoother deformation behavior. Thus, the bending zones of the profile experience substantially higher plastic strains with a stepped accumulation pattern, whereas the edge of the blank is subjected to elevated tensile stresses but exhibits a lower degree of irreversible deformation. The obtained results are consistent with the physical nature of sheet metal bending, where the inner layers undergo compression and the outer layers are stretched, ultimately shaping the final geometry of the profile.

Conclusions

This study proposes an approach for simulating the roll forming process of a U-shaped bent profile using the QForm software package, despite the absence of a dedicated module for this type of metal forming. The core of the approach involves the use of the «Sheet Bulk Forming» operation, incorporating the elastic–plastic properties of the material to closely approximate real forming conditions. A geometric model of the profile and tooling was developed, along with a forming scheme consisting of 12 passes, enabling step-by-step simulation of the process and capturing the characteristic features of the material's stress–strain state during passage through the roll forming stands. It was shown that as the blank approaches the roll stand, stress gradually accumulates, reaching a maximum in the contact zone with the tooling, and subsequently decreases due to elastic springback after exiting the stand. The obtained results confirm the effectiveness of QForm in analyzing the roll forming of bent profiles.

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