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RESEARCH INTO TECHNOLOGIES AND EQUIPMENT FOR PROCESSING HIGH-STRENGTH MATERIALS BY THE STAMPING-ROLLING METHOD

Research on technologies and equipment for processing high-strength materials by the method of rolling stamping. The work performs a systematic analysis of the current state and prospects for the development of technologies for metal processing by pressure with a locally moving center of plastic deformation in relation to high-strength materials. The physical foundations of the rolling stamping process, the kinematics of the formation of a local center of deformation, the mechanisms of substructural strengthening and the regularities of the formation of crystallographic texture are considered. It is shown that the localization of the center of plastic deformation provides a reduction in the deformation force by 70–80% and allows processing previously heat-strengthened workpieces.

An analytical model of the stress-strain state in the deformation cell is proposed, which connects the technological parameters of the process (tool inclination angle, axial feed, degree of deformation and number of cycles) with the mechanical properties of the products. The model is supplemented with a modified Hall–Petch equation and implemented using finite element modeling in the DEFORM-3D and QForm complexes with verification by digital image correlation methods.

A comparative analysis of the increase in mechanical properties of traditional alloyed steels and modern high-strength materials (AHSS/UHSS, martensitic aging steels, aluminum and titanium alloys) was performed, which showed an increase in the tensile strength in the range of 24–47% while maintaining satisfactory plasticity. The nonlinear nature of the dependence of strengthening with saturation of the effect at degrees of deformation over 50–60% was established.

The integration of the technology into the Industry 4.0 concept using digital twins, FEM modeling, and machine learning is considered. Promising directions for implementing the technology in Ukrainian industry are substantiated, in particular for the production of seamless liners for type III hydrogen cylinders at 70 MPa and body parts for electric vehicles.

Keywords: *roll forming, high-strength materials, AHSS, UHSS, locally moving center of plastic deformation, substructural strengthening, digital twin, FEM modeling, hydrogen cylinders.*

Introduction. Modern mechanical engineering is being shaped by the European Green Deal, REPowerEU and Industry 4.0, which define the requirements for lightness, energy efficiency and digital integration of products. Reducing the mass of vehicles by 10% provides a reduction in fuel consumption by 6–8%, which leads to the widespread introduction of high-strength materials in the automotive and aircraft industry, energy and defense complex. Ukraine, in the context of war and European integration, needs to quickly master the production of components with increased performance characteristics as a strategic task of post-war restoration of the industrial base and technological sovereignty. High-strength materials include AHSS and UHSS steels (σv > 1500 MPa), martensitic aging and TRIP/TWIP steels, high-entropy alloys, titanium α+β alloys, nickel heat-resistant alloys, aluminum alloys of the 7XXX and 2XXX series. Traditional HMT methods are limited by high plastic flow stress (2–4 times higher than structural steels), low ductility (δ = 6–10%), elastic aftereffect (5–15%) and anisotropy. Hot forming destroys the martensitic structure, increases the carbon footprint and contradicts the requirements of the EU CBAM.

A promising solution is the processes with a locally moving center of plastic deformation - screw rolling, rotary drawing, rolling stamping. The latter reduces the deformation force by 70–80%, forms a nanocrystalline substructure (fragments 100–200 nm with misorientation angles ~20°), provides a metal utilization factor of 0.75–0.90, controlled anisotropy and processing of pre-heat-strengthened blanks.

The current stage of technology development is associated with Industry 4.0: digital twins, FEM modeling (DEFORM-3D, QForm, Abaqus, LS-DYNA), machine learning and CPFEM, in-situ monitoring (acoustic emission, DIC, thermal imaging), servo presses with programmable control. Heinrich Schmid and FELSS orbital presses provide forces up to 16 MN, oscillation frequency up to 250 min^{-1} and positioning accuracy ±10 μm. The Ukrainian scientific school of OMT (NTU "KhPI", KPI named after Sikorsky, DSMA, ZNTU) is integrated into Horizon Europe programs in cooperation with Poland, Lithuania, Latvia, the Czech Republic, Georgia and Kazakhstan.

The questions of rheology of new alloys, digital modeling of rolling stamping, tool durability under cyclic contact loading conditions (2500–3500 MPa), texture stability in high-pressure vessels - type III/IV hydrogen cylinders at 70 MPa, missile weapons bodies, and elements of generation IV reactors remain open.

Research objective – Systematic analysis of the current state, trends and prospects of technologies for rolling stamping of high-strength materials with justification of priority areas for Ukrainian industry.

Task: analyze trends in metal processing by pressure (MPT); substantiate the advantages of a locally moving deformation center; systematize equipment; consider digital approaches; identify promising research directions.

Research results. Rolling stamping (SHO) is performed on specialized and traditional (basic) forging and press equipment after its modernization. Localization of the center of plastic deformation is achieved by the oscillatory (rolling) motion of the tool. Effective processes for rolling stamping of labor-intensive and critical parts of a wide range have been developed. Metal savings, reduced manufacturing labor, and improved quality and operational reliability of products are ensured. Modern industrial implementations of the method - orbital presses Heinrich Schmid (Switzerland) of the T-Series series and Spiroform machines manufactured by FELSS (Germany) - provide forces up to 16 MN, rolling frequency up to 250 min^{-1} and tool positioning accuracy ±10 μm. Modernization of the existing fleet of universal crank and hydraulic presses of Ukrainian machine-building enterprises by installing oscillatory motion modules is an economically viable alternative to complete equipment replacement.

The ability to control boundary conditions, create different stress-strain patterns in local zones, change the nature of the metal flow (up to wave-like), ensure relatively low levels of residual stresses and anisotropy of mechanical properties in the longitudinal and transverse directions allow rolling stamping of workpieces, the strengthening heat treatment of which (for example, hardening and tempering) is performed in advance. The workpieces after rolling stamping fully correspond to the term "precision workpieces". Modern CAE systems DEFORM-3D, QForm UK, Simufact Forming and Forge NxT allow for detailed prediction of the distribution of accumulated deformation, temperature field, level of damage according to the Gurson–Tvergaard–Needleman models and the evolution of crystallographic texture using CPFEM (Crystal Plasticity FEM) methods. The combination of FEM analysis with Bayesian Optimization algorithms and neural network surrogate models reduces the time for selecting technological parameters from weeks to hours.

The possibilities of rolling stamping are significantly expanded by providing oscillatory motion to the punch, die or workpiece. The shape of the rolling tool can be varied: from the simplest - flat or close to it (in volumetric stamping) to covering a certain part of the surface (in processing hollow and tubular workpieces). By changing the angle at the top of a flat solid tool, for example, you can obtain a conical punch or a conical die for stamping funnel-type workpieces. The conical punch and die are easily transformed into a tool for processing hollow and tubular workpieces. A combination of different types of tools is also possible. Rolling stamping of flat workpieces, known as "spherical stamping", is a partial case of more complex processes. Depending on which part of the tool (punch or die) is given oscillatory motion, the position of the tool relative to the center of oscillations and the angles of its profile also change [1]. The expansion of the range of processed materials - from traditional alloy steels to modern AHSS/UHSS (DP1180, MS1500, 22MnB5), martensitic aging steels of class 18Ni, high-strength aluminum alloys 6061-T6, 7075-T651 and titanium α+β-alloys Ti-6Al-4V - opens up new market niches for roll-forming technologies: the production of seamless liners for type III hydrogen cylinders at 70

MPa, body parts for electric vehicles, and precision aerospace blanks.

The successful implementation of the rolling stamping technology is determined by the solution of a set of theoretical and technological problems. The first group includes the tasks of developing a scheme of contact interaction of the tool with the workpiece and the geometry of the deformation cell. Based on the analysis of the stress-strain state of the metal in the deformation cell, technological parameters are calculated.

The second group of tasks includes the study of the resulting technological indicators and their relationship with the input parameters, taking into account the solution of the problems of the first group. Controlling the shapes and sizes of the plastic deformation cells, changing the position of the tool relative to the center of oscillation and kinematic conditions on the contact surfaces provides wide possibilities for rolling stamping and allows these processes to be attributed to the most complex OMT processes. In the context of the Industry 4.0 concept, these two groups of tasks are integrated into a single cycle of the digital twin of the technological process: the model of the stress-strain state in the deformation cell is synchronized in real time with the sensor data of the physical process (forces on the slider, moments on the drive shafts, temperature of the contact zones, acoustic emission signals), and machine learning algorithms adaptively adjust the rolling parameters to ensure stable product quality regardless of fluctuations in the properties of the initial workpiece.

Let us consider the essence of rolling stamping using the example of the deposition of a cylindrical workpiece in a die (Fig. 1). The axis of symmetry of the tool is inclined to the axis of the workpiece at a small angle θ. During the rolling process, this axis moves along the surface of a circular cone with the apex lying on the processing axis, and plastic deformation at each moment of time occurs only in that part of the workpiece that is in the die. For each complete rolling cycle, the tool or workpiece is moved in the axial direction by the feed amount. It is characteristic that neither the workpiece nor the tool rotates during the processing process. Experimental confirmation of the parameters of the deformation center is performed by modern non-contact measurement methods: digital image correlation systems (Digital Image Correlation, DIC) with a resolution of up to 1 μm, thermal imaging in the spectral range of 8–14 μm, three-dimensional laser scanning of the workpiece geometry in the intervals between cycles. Comparison of measurement results with FEM model predictions provides verification of rheological models of high-strength materials.

During one cycle of volumetric rolling stamping, regardless of the trajectory of movement, the entire workpiece undergoes plastic deformation. To implement processes in the deformation zone, it is necessary to have a translational movement of the tool from the press slider (or equivalently moving the workpiece through the deformation zone) and a circular rolling movement of the tool from a separate drive. The combination of these two movements leads to a helical movement of the local center of plastic deformation along the workpiece. During circular rolling of the tool, the local contact surface of the tool with the deformed workpiece rotates with a given frequency. The interaction between the tool and the workpiece is carried out by rolling the tool along the deformed workpiece.

Volumetric stamping by rolling can be compared with the processes of rolling similar workpieces between tools with intersecting axes rotating synchronously with the workpiece. In some cases, one of the tools is made in the form of a rolling roll (roller). The main advantage of this method of deformation compared to rolling stamping is the possibility of eliminating eccentric loading of the frame by installing several rolling rolls or combining the center of pressure with the zone of local deformation with the appropriate placement of the mechanism in the working space. In this regard, when rolling stamping on universal presses equipped with devices with oscillatory movement of the tool, it is necessary to use only 75–80% of the nominal force of the press. However, when bulk stamping of relatively small workpieces with a diameter of up to 200 mm, the method of deformation in conditions of a locally moving center of plastic deformation - both with rotation of the tool and workpiece, and with oscillatory movement - are quite equivalent. In a number of cases, for example, when planting thickenings on rods, forming heads, cutting out from a sheet, stamping non-circular workpieces in plan, only a tool with oscillatory movement is used (without rotation around the processing axis). It is advisable to stamp thin-walled billets of body and pipe parts on high-speed press equipment of relatively low power.

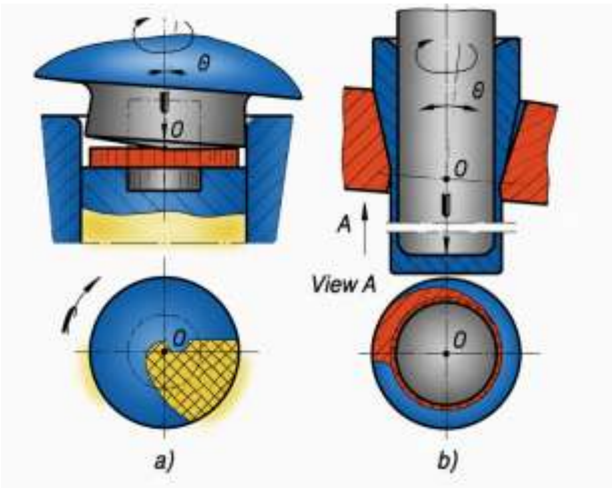

Fig. 1. Scheme of deposition by rolling a cylindrical workpiece in a die (a) and drawing with wall thinning in a rolling die (b).

The first systematic studies of roll-forming began in the mid-1960s in parallel in several scientific centers: Wrocław Polytechnic (Poland, School of Professor J. Marszalek), Heinrich Schmid AG and Schmid (Switzerland), Kramatorsk Research and Design-Technological Institute of Mechanical Engineering, Kharkiv and Kyiv Polytechnic Institutes (Ukraine), Kaunas University of Technology (Lithuania) and Riga Technical University (Latvia). Experimental and production bases created within the framework of these programs included specialized hydraulic presses with a force of 10,000 kN and long-stroke presses of vertical and horizontal execution with a force of 1000, 3000 and 4000 kN with built-in circular roll-forming mechanisms. The current stage of research is characterized by the integration of Ukrainian scientific and technical schools into the European research space through the Horizon Europe, ERA-NET programs, and bilateral agreements with Poland, Lithuania, the Czech Republic, and Georgia.

One of the most important advantages of rolling stamping is the possibility of increasing the entire range of mechanical properties, and therefore the operational reliability of products. This is achieved by grain crushing with the formation of an ultrafine-grained and fragmented substructure [2, 3]. Modern studies using electron backscatter diffraction (EBSD), high-resolution transmission electron microscopy (HR-TEM) and instrumented nanoindentation have allowed us to verify in detail the mechanisms of substructural strengthening at the nano- and meso-levels, establishing a correlation between the parameters of the rolling process (tool inclination angle θ, degree of deformation ε, number of cycles) and the characteristics of the formed substructure - fragment size, boundary misorientation angles and dislocation density.

Plastic deformation of steels was carried out in an oscillatory matrix with deformation degrees up to 60–70% depending on the initial structural state: quenching + low, medium and high tempering, then post-deformation annealing at 570 °C in order to preserve the strengthening effect, create a polygonized structure and relieve stresses. The mechanical properties and structural strength of steels 35X and 40X are given in Table 1. A separate direction of modern research is the experimental development of rolling stamping modes for modern high-strength steels AHSS/UHSS (DP1180, MS1500, 22MnB5), maraging steels 18Ni Maraging 350 and alloys of a similar class used in the production of components of electric vehicles, hydrogen cylinders of type III and elements of critical infrastructure. The tests are conducted using standardized methods ASTM E8/E8M (static tensile), ASTM E23 (Charpy impact toughness), ASTM E1820 (J-integral crack resistance), as well as specialized methods for assessing resistance to hydrogen embrittlement according to ISO 16573-1 for hydrogen infrastructure materials.

Table 1. Mechanical properties and structural strength of steels 35X and 40X

Steel grade	Strengthening scheme	σв, MPa	σт, MPa	Ψ, %	δ5, %	KCU+20, J/cm²	KCU−60, J/cm²	KCT+20, J/cm²	KCT−60, J/cm²
35X	З + В (570 °C)	800	550	65	12	165	120	32	16
35X	З + В (570 °C) + SR (ε = 30 %)	980	900	63	12	160	120	60	40
35X	З + В (570 °C) + SR (ε = 60 %)	1000	950	60	11	150	116	50	40
35X	З + В (570 °C) + SR (ε = 60 %) + ПВ (570 °C)	900	810	70	18	164	178	77	80
35X	З + В (570 °C) + SR (ε = 60 %) + ПВ (570 °C)	800	680	70	18	220	215	140	145
40X	З + В (570 °C)	900	700	55	12	100	80	20	12
40X	З + В (570 °C) + SR (ε = 60 %)	1320	1250	50	12	80	70	30	25
40X	З + В (570 °C) + SR (ε = 60 %) + ПВ (570 °C)	1050	950	55	18	110	100	70	70

Analysis of the strength and ductility characteristics (steel 40X and a number of others) of structural materials showed that this technology has a significant strengthening effect, which leads to high values of the characteristics of resistance to plastic deformation, ductility and toughness. Dynamic crack resistance tests at both room and low temperatures revealed a decrease in the susceptibility of structural steels to brittle fracture. Modern research extends these results to high-strength AHSS/UHSS steels and martensitic aging steels, for which tests are performed according to ASTM E1820 methods (determination of crack resistance by J-integral and CTOD) and ASTM E23 (impact toughness by Charpy) in the temperature range from +20 to −60 °C, which is especially important for products for cryogenic and arctic applications

The electron microscopy method has shown that in this technological process, when the tempered martensite is deformed inside the packages (rails), a fragmented substructure is formed at the nanoscale with misorientation angles of ~20° and fragment sizes of 0.1–0.2 μm (100–200 nm). The formation of a fragmented substructure inside the rails of tempered martensite at large plastic deformations leads to the formation of additional interface surfaces, which increases the work of crack propagation. Modern characterization methods - backscattered electron diffraction (EBSD), high-resolution transmission electron microscopy (HR-TEM) and automated analysis of misorientation maps - allow us to quantitatively determine the proportion of large-angle grain boundaries, which correlates with an increase in resistance to brittle fracture.

An analysis of the fractures of impact samples was carried out. It was found that the fracture of hardened steels occurs by the delamination mechanism, similar to the fracture of layered materials, which is a consequence of the features of the micro- and substructures formed in this technological process.

The method of X-ray structural analysis revealed a crystallographic texture that has a number of features in contrast to the crystallographic textures formed in other metal processing schemes. The crystallographic texture that arose during SH is close to the texture that arises during rolling. In both cases, this is the {001}{211}{110} texture. But unlike rolling, where <110> coincides with the rolling direction, during SH <110> is shifted relative to the generating cylinder by an angle of ≈10°. In addition, the texture on the outer surface of the pipe is somewhat different from the texture on the inner surface. Additionally, a texture of the {110}<110> type appears. It should be noted the extraordinary stability of the texture formed during SH: annealing at 570 °C does not change its character. Modern modeling of texture evolution by crystal-plasticity methods (CPFEM) allows predicting these features and purposefully controlling the anisotropy of the properties of finished products

In addition, it is shown that the use of final polygonization annealing in this technological process allows to reduce the level of residual stresses that arose during deformation, and optimization of the polygonization annealing temperature made it possible to implement substructural strengthening with obtaining high values of the final set of mechanical characteristics and high structural strength of finished parts. The control of the level of residual stresses is performed by non-destructive methods - X-ray strain gauges according to the EN 15305 standard and the hole drilling method according to ASTM E837. An example of the practical implementation of the technology is the production of ultra-light steel cylinders Ø 219, 232 and 254 mm from alloyed steel 30KhGSA with a mass perfection coefficient m/v = 0.7. The technology is based on the processes of cold rolling forging with a locally moving center of plastic deformation, while strengthening heat treatment is performed on the initial pipe blanks or semi-finished products. Transferring this experience to modern materials opens up the prospect of manufacturing seamless metal liners of type III composite cylinders for storing hydrogen under a pressure of 70 MPa from aluminum alloys of the 6061-T6 series or high-strength steels with control of resistance to hydrogen embrittlement according to ISO 16573-1 and compliance with the requirements of ISO 19881 and EC 79/2009. The global market for high-pressure composite cylinders is actively developing in the direction of hydrogen energy. Leading European manufacturers - Hexagon Purus (Norway), NPROXX (Netherlands/Germany), Faber Industrie (Italy), Worthington (through European divisions) - have mastered the serial production of type III and IV cylinders for hydrogen fuel cell transport. For Ukraine, which is integrating into the European hydrogen space within the framework of the REPowerEU strategy, the development of its own production of liners using the roll-forming method is a promising direction for import substitution and development of export potential.

Based on the roll-forming processes, it is possible to manufacture a wide range of modern products:

- seamless metal liners of type III hydrogen cylinders (working pressure 70 MPa) for fuel cell transport;
- high-pressure vessels for transporting liquefied CO_2 in carbon capture and storage systems (CCUS);
- modular compressed hydrogen and biomethane storage systems for distributed energy;
- body parts and protection components for electric vehicle battery modules made of AHSS/UHSS high-strength steels;
- cylinders for stationary and mobile fire extinguishing systems;
- precision and metal composite pipes with an internal diameter of 32 to 250 mm made of

aluminum alloys for the automotive and aerospace industries;

- telescopic hydraulic cylinders [4];
- body parts of special and dual-purpose products based on complex technologies;
- a wide range of precision blanks, including gears, obtained by stamping and rolling [5].

The developed effective processes of rolling stamping (extrusion, drawing, pressing, crimping, etc.) in combination with the known processes of volumetric stamping have allowed us to approach the traditionally established technologies for manufacturing blanks for body parts and other product parts in a different way. Having certain processes of rolling stamping, it is possible to successfully develop complex low-transition technological processes for manufacturing precise blanks for body parts of products with a diameter of up to 200–250 mm and a length of up to 1500 mm, which include the preparation of a semi-finished product (volumetric rolling stamping) and subsequent forming. The distinctive features of such a technology should be metal savings, less labor intensity, increased product quality, high productivity and mobility of the technology. The integration of these processes into the concept of digital production Industry 4.0 with the use of digital twins and adaptive control ensures quality stability in serial production conditions.

Along with equipping universal presses with devices with oscillating movement of the tool built into the working space, the main attention was paid to the creation of special equipment for rolling stamping. The main working body of devices for rolling stamping is a mechanism that gives the tool a complex oscillating movement. In addition, devices for rolling stamping can be equipped with nodes for changing the trajectory of the oscillating movement of the tool, changing its angle of inclination and shifting it along an inclined axis passing through the center of oscillations. A wide variety of possible design schemes necessitated the development of a classification of drive devices with oscillating movement of the tool (Fig. 2).

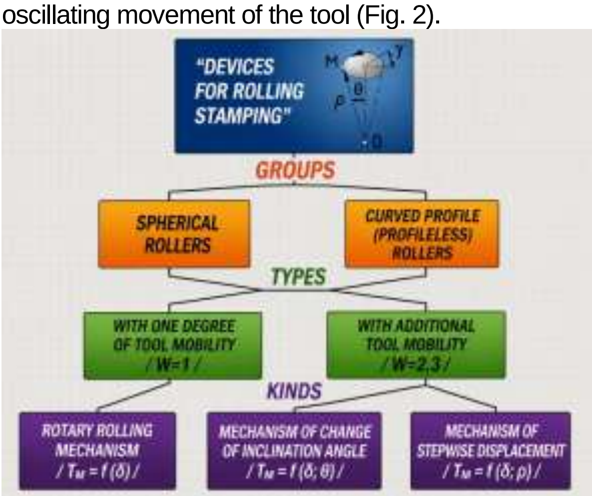

Fig. 2. Classification of devices with oscillatory movement of the tool by structural and constructive features.

Based on the operation of modernized universal presses, a specialized press with a force of 10,000 kN was developed for volumetric rolling stamping and extrusion of deep cups with a diameter of up to 400 mm. Along with the use of modernized long-stroke vertical presses, long-stroke specialized horizontal presses were created. The modern technical base of this direction is based on servo press equipment from leading European and world manufacturers - Schuler Group (Germany), AIDA (Japan), FELSS and Heinrich Schmid AG (Switzerland), which provides programmable control of the speed and force of the slider at any section of the working stroke. Unlike traditional crank presses, servo drives allow you to implement optimized laws of tool movement for a specific material - pulse, with a pause at the bottom dead center, with a controlled rate of deformation, which is especially important for processing high-strength materials with a limited plasticity resource. Orbital presses of the T-Series and Spiroform series provide forces up to 16 MN, a rolling frequency of up to 250 min^{-1} and a tool positioning accuracy of ±10 μm.

A separate engineering task for the Ukrainian industry remains the development and production of domestic specialized equipment for rolling stamping, as well as the modernization of the existing fleet of universal presses by supplementing them with built-in modules for tool oscillation. Such a solution is an economically sound alternative to a complete replacement of equipment and meets the tasks of reindustrialization and technological renewal of the machine-building industry in the conditions of post-war recovery.

The mechanisms of fiber deformation in pressings consisting of fibers of different diameters and lengths have been experimentally established. It has been shown that the deformation process is carried out due to deposition, drawing, bending and more complex schemes when metal flows into the interfiber space. The dimensions of the fibers affect the deformation mechanisms at the initial stage. Modern studies of these mechanisms are based on numerical modeling using the finite element method (DEFORM-3D, QForm, Simufact Forming) in combination with experimental verification using digital image correlation (DIC) and computer microtomography methods, which allows for detailed visualization of the three-dimensional picture of metal flow in the interfiber space and optimization of technological process parameters to obtain a defect-free structure of the finished product.

$$S_k = \frac{R \cdot s}{tan\ \theta}$$

$$\varepsilon_i = \int_0^N \left|d\varepsilon_p\right|$$

$$\varepsilon = \frac{h_0 - h}{h_0} \cdot 100\%$$

$$\sigma_{\text{т}} = \sigma_0 + \frac{k_y}{\sqrt{\lambda}}$$

$$p = n_\sigma \cdot \sigma_s$$

The integration of the above dependencies into the finite element model (DEFORM-3D, QForm) allows predicting the fields of deformations, temperatures and damageability with subsequent verification by digital image correlation (DIC) methods, which forms the basis of the digital twin of the process.

The proposed system of equations (1)–(5) forms a closed analytical apparatus that allows linking the input technological parameters of the process (tool inclination angle θ, axial feed s, number of cycles N, degree of deformation ε) with the output characteristics of the product - the level of accumulated deformation, the size of the substructure fragments and the final mechanical properties. This formulation of the problem corresponds to the modern methodology of end-to-end design of technological processes (Integrated Computational Materials Engineering, ICME), in which the behavior of the material is predicted at all scale levels - from the atomic structure to the macroscopic geometry of the finished part. This allows significantly reducing the number of expensive full-scale experiments and accelerating the introduction of new materials into production.

A feature of the mathematical model of rolling stamping is the need to take into account the cyclic nature of the load. Unlike monotonic processes of volumetric stamping, where deformation accumulates continuously, during rolling each elementary volume of the workpiece is subjected to multiple alternating loads as it passes through the local deformation center. This leads to specific strengthening mechanisms associated not only with the accumulation of dislocations, but also with their redistribution and the formation of stable dislocation structures (subgrain boundaries). Taking these phenomena into account requires the use of incremental determining relations of the theory of plasticity with kinematic strengthening according to the Armstrong–Frederick model, which is the subject of further research within the framework of the development of the proposed approach.

The numerical implementation of the proposed model is carried out by the finite element method using an explicit time integration scheme, which is optimal for modeling processes with a moving contact and significant local deformations. The workpiece is discretized with a hexahedral or tetrahedral mesh with a densification in the deformation cell zone, where the stress and strain gradients are maximal. To ensure the convergence of the solution and the correct reproduction of the helical movement of the deformation cell, adaptive mesh rezoning is used with a step consistent with the axial feed s. The rheological properties of the material are specified by flow curves obtained from the results of compression and torsion tests in a wide range of deformation rates and temperatures, with approximation by the Johnson–Cook or Zerilli–Armstrong models for high-strength steels.

Comparative analysis of mechanical properties of modern materials

To assess the effectiveness of rolling stamping in relation to modern high-strength materials, a comparative analysis of the increase in the tensile strength (Δσv) of traditional alloy steels (35X, 40X, 30XGSA) and promising materials - AHSS/UHSS steels, martensitic aging steels, high-strength aluminum and titanium alloys was performed. The generalized data are given in Table. 2. The calculated values for modern materials were obtained by extrapolating experimental dependences according to model (4) taking into account the initial structural state. For each material, the initial tensile strength, the predicted value after rolling stamping, the relative increase, the optimal degree of deformation, impact toughness and a characteristic field of application are given.

Table 2. Increase in mechanical properties of materials after rolling stamping

Material	σin ext., MPa	σin SHO, MPa	Δσв, %	ε, %	KCU, J/cm²	Application
35X	800	1000	+25	60	150	Housing parts
40X	900	1320	+47	60	80	Shafts, gears
30ХГСА	1100	1450	+32	55	90	VT cylinders
DP1180 (AHSS)	1180	1480	+25	50	95	EV bodies
MS1500 (UHSS)	1500	1920	+28	50	60	Battery protection
18Ni Mar.350	1700	2350	+38	45	45	Aerospace
6061-T6 (Al)	310	410	+32	60	–	H_2-liners
Ti-6Al-4V	950	1180	+24	40	–	Aircraft parts

Analysis of the data in Table 2 shows that rolling stamping provides an increase in the ultimate strength in the range of 24–47% for almost all studied classes of materials. The largest absolute increase is observed for maraging steel 18Ni Maraging 350 (up to 2350 MPa), which opens up the prospect of its application in the aerospace industry. For aluminum alloy 6061-T6, which is the base material for liners of type III hydrogen cylinders, an increase of 32% allows to reduce the wall thickness and, accordingly, the mass of the product while maintaining the operating pressure of 70 MPa. It should be noted that the increase in the ultimate strength during rolling stamping is accompanied by a natural decrease in the impact toughness (KCU), especially for materials with an initially high level of strength. Thus, for maraging steel 18Ni Maraging 350, the KCU value is reduced to 45 J/cm², which remains acceptable for critical aerospace applications, but requires careful control of deformation modes. For materials of hydrogen infrastructure (alloy 6061-T6), the determining factor is not so much impact strength as resistance to hydrogen embrittlement, which is estimated by the coefficient of relative narrowing in a hydrogen environment according to ISO 16573-1. Optimization of the rolling process parameters allows finding a rational compromise between strengthening and maintaining a sufficient level of plasticity and crack resistance.

A comparison of traditional alloyed steels with modern materials demonstrates the versatility of the rolling stamping technology: the method is equally effective for both medium-alloyed structural steels (35X, 40X) and new generation high-strength steels, non-ferrous alloys and titanium. This makes rolling stamping an attractive platform technology for Ukrainian machine-building enterprises seeking to diversify their product range and enter the high-tech markets of hydrogen energy, electric transport and aerospace. The economic effect is achieved by combining three factors: reduced deformation effort (and therefore capital costs for equipment), high metal utilization, and elimination or reduction of the volume of further machining.

The graphical dependence of the ultimate strength σv on the degree of deformation ε for the studied materials is shown in Fig. 3. The nonlinear shape of the curves is characteristic with a pronounced saturation of the strengthening effect for ε > 50–60%, which is explained by the stabilization of the size of the substructure fragments at the nanolevel and the achievement of an equilibrium state between the processes of accumulation and annihilation of dislocations.

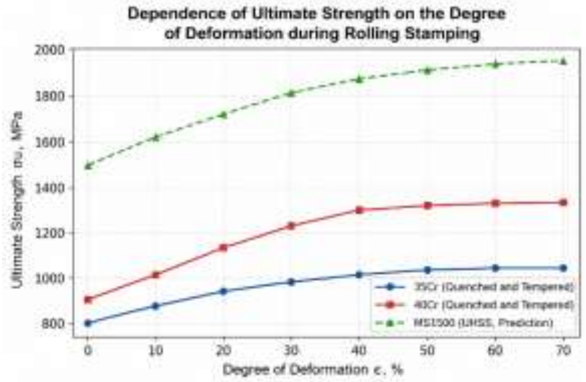

Fig. 3. Dependence of the ultimate strength σv on the degree of deformation ε during rolling stamping for steels 35X, 40X and the predicted curve for UHSS MS1500.

The obtained dependences confirm the effectiveness of controlling the mechanical properties of products by regulating the degree of deformation, a key technological parameter of the process. Further research should be directed to experimental verification of predictive curves for modern materials and integration of the obtained models into the adaptive control system for the rolling stamping process within the concept of a digital twin.

The saturation of the hardening curves for ε > 50–60%, observed in Fig. 3, has important technological significance: it indicates the inexpediency of excessive increase in the degree of deformation, since beyond the saturation limit, further increase in strength is insignificant, while the risk of exhaustion of the plasticity resource and the formation of defects increases. This justifies the choice of a rational range of degrees of deformation ε = 50–60% as optimal for most practical applications. For the predicted curve of MS1500 steel, the saturation effect occurs somewhat earlier, which is explained by the higher initial dislocation density and a more limited reserve for further crushing of the substructure.

Thus, the combination of an analytical model of the stress-strain state (formulas 1–5), a comparative analysis of mechanical properties (Table 2) and a graphical interpretation of the strengthening dependence (Fig. 3) forms a holistic methodological basis for the further development of the technology of rolling stamping of high-strength materials. The proposed approach allows us to move from empirical selection of modes to scientifically based design of technological processes with predicted properties of final products, which fully meets the modern requirements of digital engineering and the concept of Industry 4.0.

A promising direction for further research is the creation of a database of rheological and structural-mechanical characteristics of a wide range of modern materials obtained using a single testing method, which will increase the reliability of predictive models and ensure their transfer between different types of equipment. An equally important task is the development of machine learning algorithms, trained on arrays of experimental and computational data, for the prompt prediction of optimal rolling modes based on the given requirements for the geometry and properties of the product. The combination of physically based analytical models with artificial intelligence methods opens the way to the creation of full-fledged self-learning process control systems capable of compensating for deviations in the properties of the initial workpiece in real time. The implementation of such an approach at Ukrainian machine-building enterprises will contribute to increasing the competitiveness of domestic products on the European market of high-tech components and accelerating the technological renewal of the industry.

Conclusions. A systematic analysis of the current state, trends, and prospects for the development of technologies and equipment for processing high-strength materials by rolling stamping has been conducted. The following conclusions have been formulated based on the results of the study.

1. Roll-forming as a process of metal processing by pressure with a locally moving center of plastic deformation provides a reduction in deformation force by 70–80% compared to traditional volumetric forming, which makes it an effective tool for forming modern high-strength materials (AHSS/UHSS, martensitic aging steels, titanium and aluminum alloys) on press equipment of moderate power.

2. The technology provides the formation of an ultrafine-grained and fragmented substructure with a fragment size of 100–200 nm and misorientation angles of ~20°, which leads to an increase in the ultimate strength in the range of 24–47% while maintaining a satisfactory level of plasticity and crack resistance. The highest absolute strength level (up to 2350 MPa) was achieved for the maraging steel 18Ni Maraging 350, which is promising for aerospace applications.

3. The proposed analytical model of the stress-strain state (formulas 1–5), which links the technological parameters of the process (tilt angle θ, axial feed s, degree of deformation ε, number of cycles N) with the initial mechanical characteristics of the product, in combination with finite element modeling (DEFORM-3D, QForm) and the modified Hall–Petch equation, provides a transition from empirical selection of modes to scientifically based design of technological processes.

4. The nonlinear nature of the dependence of strengthening on the degree of deformation with a saturation effect for ε > 50–60% has been established, which justifies the choice of a rational range of degrees of deformation as optimal for most practical applications and allows avoiding excessive depletion of the plasticity resource.

5. The integration of technology into the Industry 4.0 concept through digital twins, sensor monitoring (DIC, acoustic emission, thermal imaging), and machine learning algorithms ensures adaptive process control and stable product quality in mass production conditions, regardless of fluctuations in the properties of the initial workpiece.

6. The technology of rolling stamping has significant potential for Ukrainian industry in the conditions of post-war reconstruction and European integration: mastering the production of seamless liners for type III hydrogen cylinders at 70 MPa, vessels for transporting CO_2, body parts for electric vehicles and dual-purpose products is a promising direction of import substitution and development of export potential. An economically justified way of implementation is the modernization of the existing fleet of universal presses with modules of oscillating tool motion.

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ДОСЛІДЖЕННЯ ТЕХНОЛОГІЙ ТА ОБЛАДНАННЯ ОБРОБКИ ВИСОКОМІЦНИХ МАТЕРІАЛІВ МЕТОДОМ ШТАМПУВАННЯ ОБКОЧУВАННЯМ

Дослідження технологій та обладнання обробки високоміцних матеріалів методом штампування обкочуванням. У роботі виконано системний аналіз сучасного стану та перспектив розвитку технологій обробки металів тиском з локально-рухомим осередком пластичної деформації стосовно високоміцних матеріалів. Розглянуто фізичні основи процесу штампування обкочуванням, кінематику формування локального осередку деформації, механізми субструктурного зміцнення та закономірності формування кристалографічної текстури. Показано, що локалізація осередку пластичної деформації забезпечує зниження зусилля деформування на 70–80 % і дозволяє обробляти попередньо термозміцнені заготовки.

Запропоновано аналітичну модель напружено-деформованого стану в осередку деформації, що пов'язує технологічні параметри процесу (кут нахилу інструмента, *осьову подачу, ступінь деформації та кількість циклів) з механічними властивостями виробів. Модель доповнено модифікованим рівнянням Холла–Петча та реалізовано засобами скінченно-елементного моделювання у комплексах DEFORM-3D і QForm з верифікацією методами цифрової кореляції зображень.*

Виконано порівняльний аналіз приросту механічних властивостей традиційних легованих сталей та сучасних високоміцних матеріалів (AHSS/UHSS, мартенситностаріючих сталей, алюмінієвих і титанових сплавів), який показав приріст межі міцності в діапазоні 24–47 % при збереженні задовільної пластичності. Встановлено нелінійний характер залежності зміцнення з насиченням ефекту за ступенів деформації понад 50–60 %.

Розглянуто інтеграцію технології у концепцію Industry 4.0 із застосуванням цифрових двійників, FEM-моделювання та машинного навчання. Обґрунтовано перспективні напрями впровадження технології в українській промисловості, зокрема для виробництва безшовних лейнерів водневих балонів типу III на 70 МПа та корпусних деталей електротранспорту.

Ключові слова: *штампування обкочуванням, високоміцні матеріали, AHSS, UHSS, локально-рухомий осередок пластичної деформації, субструктурне зміцнення, цифровий двійник, FEM-моделювання, водневі балони.*

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