

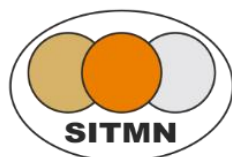
32nd International Scientific Conference

Forming 2026

September 9-12, 2026 Magnus Resort, Bystra, Poland



Book of Abstracts



COMMITTEE
OF MATERIALS ENGINEERING
AND METALLURGY



Silesian
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Book of abstracts
of the 32nd International Scientific Conference

***Forming* 2026**

September 9-12, 2026 Bystra, Poland

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Plenary lecture

3-D printing of copper powders: challenges and opportunities

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There is renewed interest in the processing and physical properties of copper alloys associated with electric vehicle production. The 3-D printing of copper alloy powders has the potential to secure a place among competing copper processing technologies.

The first stage of our research, conducted with an industrial partner, focused on proof-of-concept components fabricated via selective laser melting (SLM) of pre-alloyed Cu-4.3% Sn powder, which were heat-treated at 873 K (600°C) and 1173 K (900°C) for 1 hour. Tensile testing, conductivity measurements, and detailed microstructural characterization were performed on samples in both their as-printed and heat-treated conditions. Optimization of build parameters yielded samples with approximately 97% of theoretical density, a yield strength of 274 MPa, an electrical conductivity of 24.1% IACS, and an elongation of 5.6%. Heat treatment reduced yield strength but significantly increased ductility due to recrystallization and a decrease in dislocation density. Tensile sample geometry and surface finish also had a significant effect on the measured yield strength, but a negligible effect on the measured ductility. Microstructural characterization indicated that grains primarily grew epitaxially with a submicron cellular solidification substructure. Nanometer-scale tin dioxide particles identified via X-ray diffraction (XRD) were found throughout the structure in the tin-rich intercellular regions.

In the second stage of our research, the feasibility of printing precipitation-hardened Cu alloys was examined. The copper alloy C70250 was selectively laser melted to produce components with about 98% of theoretical density, possessing high mechanical strength and electrical conductivity. Aging heat treatments were performed at 723 K (450°C) directly on as-printed samples for up to 128 hours. Mechanical testing found that a peak yield strength of about 590 MPa could be attained with an electrical conductivity of 34.2% IACS after 8 hours of aging. Conductivity continued to increase with further aging, whereas peak strength appeared less sensitive to aging time, with a broad range of times at which near-peak properties occurred. After aging for 128 hours, the yield strength dropped to 546 MPa, while the conductivity increased to 43.2% IACS.

Electron microscopy analysis revealed nanometer-scale silicon-rich oxide particles throughout the material that persist during aging. Deformation twinning is observed in the peak-age condition after tensile testing, and several strengthening mechanisms appeared to be active to varying degrees throughout aging, accounting for the broad range of aging times at which the peak mechanical properties were nearly achieved.

Keywords: 3-D printing, copper alloy powders, selective laser melting, SLM



Plenary lecture

**Artificial Intelligence in metal forming – overview of applications, trends
and barriers on the path to industrial implementation**

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The rapid development of artificial intelligence (AI) methods, including machine learning, deep learning, computer vision, and generative data models, opens up new opportunities in metal manufacturing and processing. This presentation provides a critical review of the current state of AI applications in this field, covering both research experience and industrial implementations. Selected key application areas will be discussed, including process modelling and optimisation, where conventional Finite Element Method (FEM) models are replaced or complemented by hybrid AI models capable of predicting deformation forces, residual stresses, and microstructural evolution in real time. Other areas include predictive maintenance of machinery and tools, which reduces unplanned downtime and extends tool life through the use of conventional techniques and federated learning, as well as computer-vision-based quality control systems that automate defect detection and equipment operation. Particular attention will be paid to implementation constraints and barriers, including industrial data quality issues, the limitations of robotics in non-repetitive tasks, high implementation costs, and insufficient workforce expertise. Recommendations will be formulated regarding the conditions required for a successful transition from the pilot stage to the full-scale deployment of AI in metal-processing plants.

Keywords: artificial intelligence, machine learning, metal forming, process optimization, Industry 4.0

Semi-industrial physical simulation of the R350HT rail head hardening process by selective spray cooling

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The paper presents the results of a physical simulation of the hardening process of the head of a 60E1 railway rail made of R350HT pearlitic steel using selective spray cooling with a water–air mixture. The aim of the experiments was to investigate the influence of cooling parameters after austenitization, including different flow rates of the cooling media and different exposure times of the rail head surface to the water–air spray, on the cooling rate across the rail head cross-section, as well as on the microstructure and mechanical properties of the steel.

The experiments were carried out at Łukasiewicz – Upper-Silesian Institute of Technology using a prototype research installation designed for semi-industrial physical simulation of air–water spray cooling processes of long steel products. The cooling system used in the study consisted of six water–air nozzles with a fixed spatial orientation relative to the rail head area. The 0.75 m-long rail sections were moved through the cooling zone on a roller table in a reversing motion at a constant velocity of $v = 0.05$ m/s. The influence of the water–air mixture parameters on the temperature distribution and cooling rate across the rail head cross-section was analysed by varying the water pressure within the range of $p_w = 0.7$ – 2.4 bar, while maintaining a constant air pressure of $p_a = 3.0$ bar.

Based on the obtained results, cooling parameter values were selected and subsequently applied in experiments on the rail head hardening process. The spray cooling method and parameters developed as a result of the study enabled the formation of a fine, fully pearlitic microstructure in the rail head, with a mean interlamellar spacing of 90 nm. As a result, a running-surface hardness of 368 HBW, a proper hardness distribution across the rail head cross-section, and a tensile strength of $R_m = 1.2$ GPa were achieved, meeting the requirements of PN-EN 13674-1 for R350HT rails.

Keywords: rail head hardening, physical simulation, spray cooling, microstructure, mechanical properties

Investigation of material-related defects in automotive sheet metal stamping

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The study investigated stamped automotive sheet-metal components manufactured from advanced high-strength steels, including Dual Phase (DP) steel grades. Research conducted at the Laboratory Research Center of the Łukasiewicz Research Network – Poznań Institute of Technology focused on identifying the causes of discontinuities occurring in stamped parts and establishing a methodology for product evaluation and failure analysis. The study highlighted the challenges associated with forming modern steel sheets characterized by diverse microstructural features and enhanced mechanical properties. Based on comprehensive metallurgical and technological examinations, the root causes of various types of discontinuities and cracking defects in stampings were determined. Furthermore, the work identified opportunities for early detection of potential defects through enhanced incoming material inspection procedures and the implementation of more stringent acceptance criteria for supplied sheet materials.

Keywords: steel stamping, dual-phase (DP) steel, cracking, product defects, sheet metal forming

Effect of strain path changes on the low-cycle fatigue behavior of X10MnAl10-1 steel

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The ongoing development of advanced structural materials is focused on achieving a favorable combination of high strength, ductility, and energy absorption capacity. Manganese steels belonging to the Advanced High-Strength Steels (AHSS) group are of particular importance in this context, as their mechanical properties can be tailored through advanced strain-hardening mechanisms activated during plastic deformation. Assessing their behavior under cyclic loading is essential in view of their potential application in structural components subjected to cyclic strains exceeding the elastic range of the material.

The aim of this study was to evaluate the effect of low-cycle fatigue on the mechanical properties of X10MnAl10-1 steel and to determine its response to increasing total strain ranges. The experimental program included a static tensile test, strain-controlled low-cycle fatigue tests, analysis of hysteresis loops and fatigue characteristics, and fractographic examination using scanning electron microscopy.

Low-cycle fatigue tests were conducted at room temperature at total strain ranges of 0.6%, 0.7%, 0.8%, 1.0%, and 1.2%. The recorded stress–strain responses were used to establish relationships describing the cyclic hardening behavior and fatigue life of the material, including the Manson–Coffin relationship.

The static tensile test yielded an ultimate tensile strength (R_m), of approximately 1592 MPa and a 0.2% proof stress ($R_{p0.2}$), of approximately 433 MPa. The material also exhibited an elongation at fracture of approximately 7% and a reduction in area of approximately 23%, indicating high strength combined with moderate ductility.

The fatigue tests revealed a clear relationship between the total strain range and fatigue life. At the lowest investigated total strain range, $\Delta\epsilon_c = 0.6\%$, the number of cycles to failure was approximately 51 400, whereas at $\Delta\epsilon_c = 1.2\%$ it decreased to approximately 154 cycles. At the same time, the saturation stress increased from approximately 577 MPa to 1180 MPa. The observed changes in hysteresis-loop shape and the cyclic deformation response indicate pronounced cyclic hardening of the X10MnAl10-1 steel. The highest hardening rate occurred during the initial stage of cyclic loading, followed by a period of

relative stabilization of the material response and, subsequently, rapid failure during the final cycles of the test.

An increase in the total strain range also resulted in a marked increase in the degree of cyclic hardening. At $\Delta\epsilon_c = 0,6\%$, the stress increase associated with cyclic hardening was approximately 80 MPa, whereas at $\Delta\epsilon_c = 1,2\%$, it reached approximately 700 MPa. The Manson–Coffin relationship indicated that the strength properties played a dominant role in determining the low-cycle fatigue life of the investigated material.

Fractographic analysis revealed a characteristic zonal morphology of the fatigue fracture surfaces, comprising crack-initiation regions and a dominant final-fracture zone. The proportion of the fatigue crack-propagation zone was distinctly smaller than that of the final-fracture region, indicating a high susceptibility of the material to crack propagation following crack initiation.

The results confirm that X10MnAl10-1 steel exhibits a pronounced cyclic-hardening capacity, the intensity of which increases with increasing total strain range. At the same time, increasing the strain range leads to a rapid reduction in the fatigue life of the material. The present findings provide a basis for further investigation of the deformation and fracture mechanisms in this group of steels and for assessing their potential application in structural components subjected to large cyclic strains.

Keywords: TRIP steels, Advanced High-Strength Steels (AHSS), low-cycle fatigue (LCF), fractography

*Work carried out within the framework of the project UMO-2023/51/B/ST11/01607
“The influence of complex strain path on the microstructure, deformation mechanisms
and mechanical properties of TWIP steel” financed by the NCN.*

The influence of abrasive blasting parameters on quality of zinc and organic coatings

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The aim of the presentation is to present the results of research aimed at determining the influence of the surface topography of sheet metal produced during abrasive blasting using various abrasives on the properties of zinc and organic coatings. Thin low-carbon steel sheets were used for the tests, which were abrasive blasted, hot-dip galvanized and painted. The topography of sheet metal surface before and after coating, the quality and thickness of zinc coatings and a gloss of organic coatings were analysed.

The surface treatment of the sheets was performed using abrasives in the form of aloxite, alundum and glass balls in two diameter ranges. The surface topography was determined using 3D roughness measurements and analysis. All sheet sections were hot-dip galvanized and organic coated in industrial conditions. Then, 3D roughness measurements, gravimetric coating thickness measurements and gloss measurements of organic coatings were performed again.

The tests showed that depending on the type of abrasive used for abrasive blasting, a different appearance and thickness of zinc coatings and a similar gloss of organic coatings were obtained.

Keywords: steel sheets, surface topography, 3D roughness

Multiscale modelling of texture evolution during multi-pass asymmetric cross-rolling of copper

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A multiscale numerical model of multi-pass asymmetric cross-rolling of copper was developed to predict the evolution of crystallographic texture under different deformation paths and process asymmetry conditions. The proposed approach combines a macroscopic finite element model of the rolling process with a mesoscale crystal plasticity model describing the response of individual grains and the resulting texture evolution. This coupling enables the non-uniform deformation history generated during rolling to be transferred from the process scale to the microstructural scale.

At the macroscopic scale, the rolling process was simulated using the finite element method implemented in ABAQUS. Both symmetric and asymmetric rolling conditions were analysed. In the symmetric configuration, the work rolls had equal diameters, whereas process asymmetry was introduced by using rolls of different diameters. This resulted in an asymmetric velocity and stress distribution within the deformation zone and generated additional shear deformation, particularly in the near-surface layers of the strip.

The simulations comprised several consecutive rolling passes leading to a gradual reduction in strip thickness. After each pass, the distributions of strain, stress and deformation gradient were analysed through the strip thickness. Particular attention was paid to material points located near the upper surface, in the mid-thickness region and near the lower surface. The deformation histories extracted from the macroscopic model were subsequently used as loading conditions for the mesoscale simulations. In this way, the influence of the non-homogeneous macroscopic deformation field on the local crystallographic response of the material could be taken into account.

The mesoscale calculations were carried out using the DAMASK framework [1], which provides a finite-strain crystal plasticity formulation for the simulation of the mechanical response of polycrystalline materials. The copper microstructure was represented by a representative volume element composed of 1000 grains with assigned random initial crystallographic orientations. Each grain was treated as a face-centred cubic crystal, and plastic deformation was assumed to occur by crystallographic slip on the $\{111\}\langle 110 \rangle$ slip systems.

The multi-pass character of the process was reproduced by sequentially applying the deformation histories corresponding to successive rolling passes. The crystallographic orientations and internal state variables obtained after one pass were used as the initial state

for the next pass. This procedure allowed the cumulative effect of strain path changes, shear deformation and material hardening on texture evolution to be investigated.

The predicted textures were compared with experimental results obtained by X-ray diffraction measurements at selected positions through the strip thickness. The comparison included the location and intensity of the main orientation density maxima as well as the evolution of characteristic copper rolling texture components. A satisfactory agreement between the numerical and experimental results was obtained, confirming that the proposed multiscale approach can reproduce the main trends of texture development during symmetric and asymmetric cross-rolling.

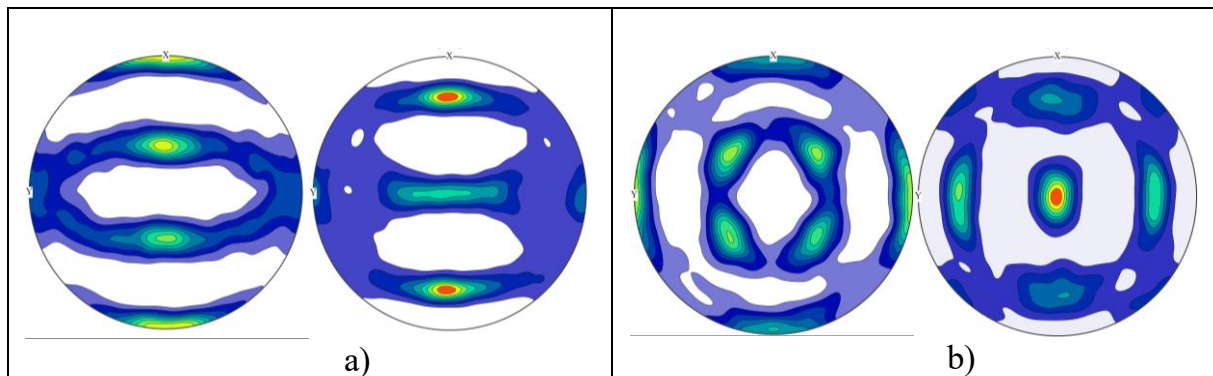


Fig. 1. Predicted mid-thickness copper textures after: a) symmetric unidirectional rolling and b) symmetric cross-rolling; (111) and (220) pole figures

Keywords: asymmetric cross rolling, crystallographic texture, crystal plasticity, multi-scale modelling

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Application of the self-piercing riveting as an alternative solution in the new technology of the special-purpose catering trolleys manufacturing – Part 1

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The key to the convenient and efficient transport of ready-made meals, tableware, and accessories is the use of stainless steel catering trolleys (Figure 1). Their design, based primarily on profiles and flat bars, must feature a specialised structure that ensures both dimensional tolerances and long-term reliability. They are most often manufactured using welding and metal forming technologies. As part of a project financed by the NCBiR in collaboration with RETECH company, the Institute of Manufacturing Technology is conducting extensive research aimed at, among other things, optimising the production technology for a selected series of such structures in two areas: modernising welding lines and developing alternative joining solutions in the form of self-piercing riveting.

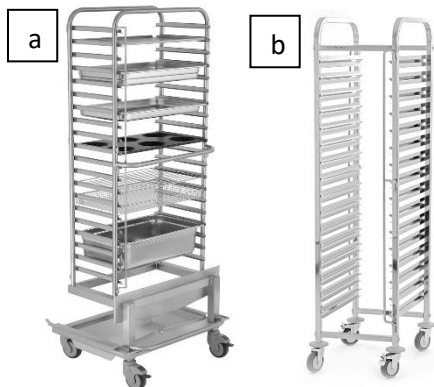


Fig. 1. Examples of transport trolley solutions: trolley with a drip tray (for use in special ovens) (a), standard solution for transport (b)

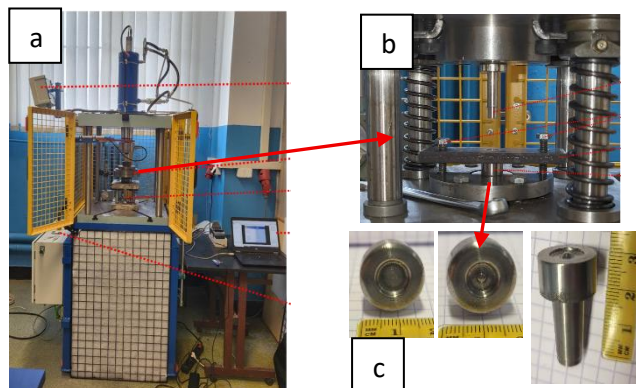


Fig. 2. Dedicated, special stand for testing mechanical joining processes (a), special tool (b) and a set of dies for preliminary experiments (c)

Self-piercing riveting is a mechanical joining technique, primarily for sheet metal, that induces large local plastic deformation in the joined elements by pressing a freely deforming rivet of a specific shape into them, which acts as an additional reinforcement element. The feasibility analysis of self-pierce riveting for stainless steel sheets used in the construction of catering carts has two scientific aspects. The first concerns the type of material being joined, which is not a standard solution (the research focuses on the 1.4301/AISI 304 grade). The second aspect concerns joining profiles to flat surfaces, which is not a currently used procedure. A special tool system was designed, which will be the subject of a future publication.

Within the project, the extensive simulations were carried out for two systems of joined sheets 1-1 and 1.5-1.5 mm thick, taking into account the variability of the die land profiles (three die variants: with a small island - MMW, without an island - Flat – MBW, and with a large island - MDW, for five types of rivets, commercially available at six hardness levels in the range of 255-580 HV, Table 1. The modelling of the joining process was supplemented with experimental verification covering the quality of the resulting joint in terms of both geometry and strength. Two basic criteria were adopted to assess the usefulness of the applied solution: no cracking in the lower layer and a shear strength of the joint above 4 kN. Computer simulations of the riveting process were performed using the commercial Simufact Forming software. The numerical models underwent a validation and verification procedure. Experimental tests are carried out on a special stand consisting of a dedicated 9T press (Figure 1a) and a specially designed set of tools (Figure 1 b-c). The displacement of the punch is controlled by setting its stroke or until the assumed force level is exceeded.

Table 1. Simulation test layout

Rivet Die	5x5	5x5,5	5x6	5x6,5	5x7
Flat					
MMW					
MDW					

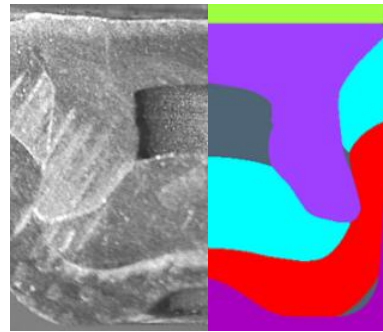


Fig. 3. Comparison of simulation and experiment results - a selected case for verification of the FEM model

Numerical simulations enabled testing of numerous combinations of rivet-sheets-die configurations. Experimental studies limited the number of tested variants to selected cases. In some of these, excessively high rivet positions, cracks, and fractures were observed, eliminating these cases from production use. Experimental results confirmed simulation findings about increased forces for dies with islands. FEM simulations predicted the appearance of the joints in cross-section (compared to the sample cross-section), as shown in Fig. 3. However, in some cases of joining 1-1 mm sheets, noticeable differences in the force curves were observed during the joining process. When joining a series of 1.5-1.5 mm sheets, almost all process parameters were comparable. The result of the research was the preparation of recommendations for verification on the production line.

Further research will include production tests, final strength tests, and the design and verification of a special device for riveting profiles and flat sections on the production line.

Keywords: self-piercing riveting, stainless steel, numerical modelling, gastronomy tray

Numerical modelling and experimental validation of thermal phenomena in the hot stamping process

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Hot stamping of manganese–boron steels is one of the key technologies used for manufacturing high-strength structural components for automotive body structures. In this process, the final properties of the stamped component depend not only on the deformation history but also on the heat transfer conditions between the heated blank and the tooling, as well as on the effectiveness of tool cooling. Reliable representation of these phenomena in numerical models is therefore essential for tool design and process parameter selection. This remains challenging due to the local nature of thermal contact and the strong dependence of the heat transfer coefficient on press contact pressure [1–5].

The aim of this study was to assess the agreement between the numerical model of the hot stamping process and the actual thermal behaviour occurring at the sheet–tool interface. The investigations were carried out for a reinforcement beam of a passenger car sill manufactured from 1.8 mm thick 22MnB5 steel. The numerical model of the process was developed using the AutoForm software. The analyses were performed for four different characteristics describing the relationship between press contact pressure and the heat transfer coefficient at the sheet–tool interface. The model was validated during technological trials conducted using the actual production tooling. Temperature was measured using thermocouples located in the die, punches and blank holder, approximately 0.5–1.0 mm below the working surface. The measured temperature histories were compared with those obtained from the numerical simulations. In addition, the quality of the stamped components was evaluated based on the forming limit diagram (FLD), thickness reduction distribution and predicted hardness. To experimentally verify the quenching conditions, hardness measurements and uniaxial tensile tests were performed on specimens extracted from 30 randomly selected stamped components.

The application of different press pressure-dependent heat transfer coefficient characteristics resulted in only minor changes in the predicted temperature distribution, not exceeding several degrees Celsius. The simulations confirmed the satisfactory formability of the analysed component. The maximum thinning did not exceed 15%, compared with the adopted limiting value of 18%, while the predicted hardness exceeded 400 HV over the entire surface of the stamped component.

Comparison of the numerical and experimental temperature histories showed good agreement in terms of the overall temperature distribution, although local differences in maximum temperature values ranged from approximately 5 to 26°C. The observed discrepancies were primarily associated with the position of the thermocouples below the working surface of the tool and with the simplified representation of the actual coolant

flow and heat removal conditions within the cooling channels. Mechanical property testing confirmed that the quenching process proceeded correctly. The minimum hardness values measured in the analysed regions of the stamped component ranged from 417 to 443 HV, while the average tensile strength in the three investigated regions was comparable and slightly exceeded 1500 MPa.

Keywords: hot stamping, reinforcement beam, 22MnB5 steel, numerical simulation, hardness, tensile strength, temperature distribution, thinning

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Processing and formation of tantalum-based core-shell metallic microparticles by mechanical alloying

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Metallic core-shell microparticles provide a versatile platform for designing heterogeneous and functionally graded materials in which chemical composition, phase constitution, porosity and mechanical response can be controlled at the particle level. In this study, a mechanically driven approach was used to produce metallic core-shell microparticles with tantalum-rich surface regions and to investigate their potential for the fabrication of hierarchically structured porous metallic materials. Ti Grade 5, 316L stainless steel and aluminum powders were used as core materials in the comparative processing stage, while a Ti-Ta system was selected for detailed analysis after consolidation and sintering.

Core-shell structures were produced by high-energy mechanical alloying, during which repeated particle deformation, surface activation and mechanical embedding of tantalum promoted the progressive development of Ta-containing outer regions. The influence of processing conditions and core material on particle morphology, shell formation and particle size distribution was evaluated using scanning electron microscopy combined with energy-dispersive X-ray spectroscopy (SEM/EDS) and laser diffraction analysis. SEM/EDS observations confirmed the formation of tantalum-enriched peripheral regions and revealed that the continuity and morphology of the shell strongly depend on the mechanical response of the core material and milling intensity. The mean particle sizes obtained for Ti Grade 5 + Ta, 316L SS + Ta and Al + Ta systems were approximately 45, 58 and 96 μm , respectively.

After consolidation and sintering, the Ti-Ta core-shell particles formed a porous bulk architecture composed of interconnected spherical and elliptical particles joined by diffusion necks. Two complementary levels of porosity were identified. Interparticle macroporosity resulted from incomplete densification and neck formation, whereas intraparticle voids developed as a consequence of unequal Ti and Ta diffusion rates and vacancy accumulation associated with the Kirkendall effect. This hierarchical porosity creates a structurally heterogeneous system combining interconnected pathways between particles with fine internal voids within individual particles.

Microstructural investigations revealed a radial diffusion-driven gradient consisting of a Ti-rich α core, an intermediate $\alpha + \beta$ Widmanstätten-type transition zone and a Ta-rich β outer region. The resulting phase distribution demonstrates that each consolidated particle can act as a microscale functionally graded unit. Nanoindentation mapping further showed that the local mechanical response follows the phase sequence, with the $\alpha + \beta$ transition region exhibiting lower Young's modulus values than the β -rich shell and α -rich

core. Such spatial modulation of stiffness provides a basis for extending microscale heterogeneity toward macroscale functionally graded architectures.

The results demonstrate that mechanical alloying can be used not only for powder homogenization but also for engineering the surface architecture of metallic microparticles prior to consolidation. Combined with diffusion-controlled phase evolution during sintering, this approach enables the fabrication of heterogeneous and hierarchically porous metallic materials with locally tailored chemistry, phase composition, porosity and mechanical properties. The developed strategy is particularly promising for advanced Ti-Ta biomaterials, where the combination of a Ta-rich corrosion-resistant surface, interconnected porosity and graded mechanical response may contribute to improved biomechanical compatibility and long-term biological integration.

Keywords: core-shell microparticles, mechanical alloying, tantalum, powder metallurgy, functionally graded materials

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Formation and prevention methods of tin whiskers in electrical engineering – a review article

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Tin whiskers are one of the key threats to the reliability of electronic devices and assemblies where current is distributed using busbars. Although the first documented cases of tin whiskers appeared as early as the 1940s, the problem has still not been resolved to this day. The elimination of lead under the RoHS (Restriction of Hazardous Substances) Directive has led to a resurgence of the problem of faults in electronic circuits as well as industrial switchgear assemblies.

This article presents a review of the literature on the origins of the phenomenon, the current state of knowledge regarding the mechanisms of tin-whiskers growth, and the environmental and technological factors influencing their growth. The sources of stress and the process factors responsible for whisker growth are discussed. The paper also provides an overview of the available techniques for limiting whisker growth and methods for preventing their formation. Furthermore, best practices for handling materials susceptible to this phenomenon are presented. The paper is supplemented by selected results from the authors' own research carried out on busbars.

Keywords: tin whiskers, Pb-free materials, electrical engineering, reliability, prevention

R&D work commissioned by ABB Sp. z o.o. Report No. 8721/G/2026:

*Preparation of a literature review on the formation of tin whiskers
and preliminary investigations of the component supplied.*

Fabrication of Al-TiC materials and semi-finished products from aluminium powders and machining chips using HIP

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The study explores the possibility of manufacturing Al-TiC composite using aluminium machining chips and ceramic TiC powder as alternative feedstock for the production of rods and wires. The proposed approach combines recycling-based material preparation with solid-state consolidation, thereby reducing the need for remelting and limiting oxidation of the aluminium feedstock. In the experimental stage, aluminium chips were cleaned, mixed with TiC powder, compacted into billets and subsequently consolidated by KOBO extrusion. These operations confirmed that secondary aluminium resources can be transformed into compact semi-finished products suitable for further processing. Particular attention is given to Hot Isostatic Pressing (HIP) as a potential extension of the developed processing route. HIP applies elevated temperature and uniform gas pressure to a material from all directions, enabling the reduction of residual porosity, improvement of interparticle bonding and enhanced consolidation of interfaces between individual aluminium chips. In Al-TiC composites, HIP may also contribute to a more homogeneous distribution of ceramic particles and improve the structural integrity of the material before final extrusion or forming. Although HIP was not experimentally applied in the present study, it is considered a promising intermediate or final consolidation stage. Its integration with chip-based recycling and KOBO extrusion could provide a technologically attractive route for producing dense, homogeneous and high-quality aluminium-matrix composite products.

Keywords: aluminium machining chips; Al-TiC composites; hot isostatic pressing; solid-state consolidation; KOBO extrusion; recycling

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Optimization of the forging process for Ti-6Al-4V ELI alloy endoprostheses

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This paper analyzes the forging process of endoprostheses made from the Ti-6Al-4V ELI titanium alloy, used in medical implantology, with particular emphasis on the influence of deformation conditions on temperature distribution, material flow, and changes in the microstructure of the forged material.

A comparison of the forging process performed on a press and a hammer is presented, taking into account the differences resulting from the operating characteristics of both devices and their impact on the technological process, as well as the changes in the material's microstructure resulting from the process kinematics. Particular attention is paid to the proper design of the preform geometry and the appropriate distribution of the material volume before the finish forging operation. Excessive material deformation and local temperature increases occur in areas corresponding to small cross-sections of the finished endoprosthesis. This can lead to local overheating of the material, affecting the microstructural transformations of the Ti-6Al-4V ELI alloy and, consequently, affecting the quality of the resulting forging.

The process was analyzed using numerical simulations using the Finite Element Method (FEM), which allowed for the assessment of temperature distribution, strain intensity, and material flow characteristics during forging. The results of the numerical analyses were compared with the results of forging tests conducted under actual production conditions. The combination of FEM simulations, microstructural studies, and industrial tests allowed for the assessment of the impact of the forging technology and preform geometry on the quality of the forgings and identified directions for optimizing the process of manufacturing endoprostheses from the Ti-6Al-4V ELI alloy.

Keywords: die forging, numerical simulation, grooved rolls, manufacturing of implants

Formability of AZ magnesium alloys assisted by pulsed electric current

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Magnesium alloys possess an exceptionally high strength to weight ratio, making them highly desirable for structural applications; however, their room-temperature ductility is severely limited due to their hexagonal close-packed (HCP) crystal structure, where a scarce number of active slip systems leads to premature failure. This limitation is traditionally overcome by forming at elevated temperatures using conventional furnace heating. The increase of temperature activates additional non-basal slip systems, thereby enhancing ductility and substantially reducing deformation resistance. Alternatively, a less common but increasingly researched method involves electrically assisted forming. Applying an electric current during deformation significantly increases material ductility, offering a faster and more economical alternative to traditional furnace heating. To date, these advantages have been demonstrated primarily under simplified laboratory setups, particularly uniaxial tensile tests, leaving the effect of current pulses under multi-axial and complex stress states largely unexplored. This study investigates the effect of pulsed electric current on the mechanical properties and microstructure of an Mg–3Al–Zn alloy subjected to torsion. The results demonstrate that electroplastic forming under a pulsed electric current not only enhances torsional ductility but also increases strength. This improvement is driven by dynamic recrystallization in the outer regions of the specimen, which suppresses surface defect propagation and eliminates surface cracks. Ultimately, these findings suggest that current pulses can be successfully integrated into advanced metalworking processes involving complex deformation states. However, this approach requires specialized equipment and introduces geometric constraints related to current distribution throughout the workpiece.

Keywords: magnesium alloys, electroplastic effect, electrically-assisted forming, recrystallization

Single-step production of NiAl alloys by MVM process for high-temperature applications

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NiAl alloys are considered as candidates to replace conventional nickel-based superalloys in aero-engine turbine blades due to their low density, high-temperature capability and excellent oxidation resistance. However, despite their favorable properties under service conditions, their high brittleness and poor machinability at low temperatures present significant challenges during the manufacturing of components. In particular, non-metallic inclusions can contribute to material embrittlement and are one of important factors to be controlled during processing. This work investigates a novel single-step approach for producing high quality NiAl alloys.

The proposed process uses an MVM technology (Metalothermic Velocity Melting) in which centrifugal force is applied during the self-propagating high-temperature synthesis (SHS) to promote the separation of slag and flux from the forming metallic phase. The main objective is to obtain high-purity and homogenous NiAl from primary and secondary raw materials in a single step and minimizing non-metallic inclusions.

The resulting NiAl samples were investigated by optical microscopy, scanning electron microscopy and energy-dispersive X-ray spectroscopy (EDX), including point analysis and elemental mapping. Porosity was also evaluated, while tensile testing is being prepared to provide further mechanical characterization.

The measured porosity is comparable to that reported for conventional industrial processing routes. Microstructural and EDX analyses revealed inclusions consisting predominantly of flux containing dissolved Al_2O_3 . Their presence highlights the flux composition and coagulating-agent content as important parameters for further process optimization and reduction of non-metallic inclusions.

Further experiments will focus on optimizing these parameters and eliminating hydrogen-related porosity. The results demonstrate the potential of MVM process to produce a NiAl alloy in a single processing step, with the reduction of non-metallic inclusions representing an important objective towards improving the machinability of NiAl material for aero-engine turbine blade applications.

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Keywords: NiAl alloy, aluminothermic reaction, centrifugal separation, single-step production, turbine blades

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From microstructure analysis to process feedback: expert AI as an assistance system for forging companies

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This article presents an AI-based assistance system for metallurgical analysis and process optimization in forging. The approach combines automated microstructure image analysis with expert knowledge and large language models to support the evaluation of material properties, defects, and process-related causes. Metallographic features such as grain size, phase fractions, decarburization, cracks, and carbide morphology can be detected and quantified automatically using deep learning methods. These results are then linked with process parameters, standards, scientific knowledge, and expert experience to generate possible explanations and recommendations for process improvement. A key element of the concept is the human-in-the-loop approach. The AI system does not replace metallurgical experts but supports them by providing structured hypotheses and decision-relevant information. Expert feedback can be incorporated into the knowledge base, enabling continuous improvement and preservation of company-specific know-how. The approach can accelerate metallographic evaluation, improve reproducibility, support systematic root-cause analysis, and reduce trial-and-error in process optimization. The authors conclude that combining image analysis, process data, and expert AI can improve the speed, consistency, and quality of metallurgical assessments and contribute to more efficient and knowledge-based process optimization in forging companies.

Keywords: artificial intelligence, metallography, microstructure analysis, forging, process optimization

A comparison of the properties of high-manganese steel subjected to compression and tension under dynamic loading conditions

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The research focuses on investigating the properties of high-manganese TWIP (twinning-induced plasticity) steel subjected to tensile and compression deformation under dynamic loading conditions. The motivation for undertaking this research stems from the growing role of advanced high-strength steels in safety-critical structural components, particularly in the automotive industry, where high energy absorption capacity must be combined with the ability to undergo large deformations [1].

In order to determine the properties of high-manganese steel under dynamic conditions, tensile tests were carried out using flywheel machine (FM) (Figure 1) and compression tests using a Split Hopkinson Pressure Bar (SHPB) (Figure 2), which is widely used in testing of high strain rate compression [2]. During the compression tests, Digital Image Correlation (DIC) method was used to measure deformations on the surface of the compressed material in order to determine the distribution of strain vectors during the process.

The FM tests were carried out at specified strain rates in the range of 300–950 s⁻¹. The experimental results indicate that the TWIP steel under investigation is sensitive to strain rate. The excellent plastic properties of the steel are confirmed by the total elongation values obtained, which ranged from 70 to 79 per cent. It was found that the yield stress values corresponding to an actual strain of 0.4 increased under dynamic conditions by approximately 25% compared with the reference static test. Furthermore, the calculated value of absorbed energy increases as the strain rate increases.

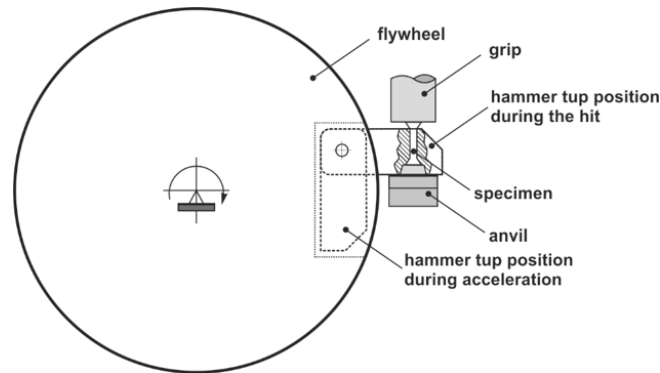


Fig. 1. Schematics of the flywheel machine used during tensile tests

The compression tests on SHPB were carried out at strain rates ranging from 450 to 3300 s⁻¹. The lower strain rates are comparable to those obtained on FM, whilst the higher rates allowed a similar level of true strain to be achieved as in the tensile tests. Analysis of the compression test results confirms the findings regarding the good combination of strength and mechanical properties obtained in the tensile tests.

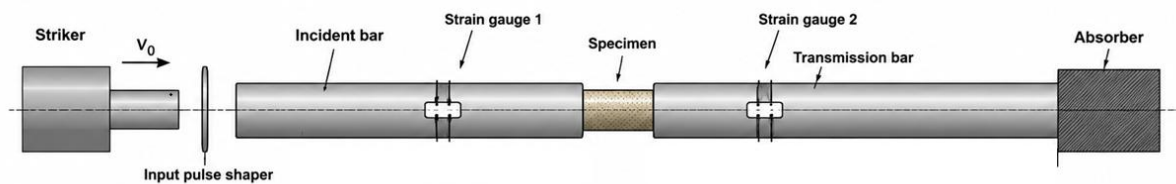


Fig. 2. Schematics of Split Hopkinson Pressure Bar used during compression tests

A comparison of the strain curves obtained for both deformation states enabled the determination of the material's basic mechanical properties and its energy absorption capacity. The results obtained provide new insights both into the methodology for obtaining results under dynamic loading conditions and into the mechanical response of TWIP steel under these conditions.

Keywords: TWIP, SHPB, flywheel-machine, deformation, dynamic loading

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Effect of DRECE processing on high-cycle fatigue response and post-fatigue deformation substructure of DC01 steel

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Dual Rolls Equal Channel Extrusion (*DRECE*) is a severe plastic deformation (*SPD*) technique capable of substantially modifying the deformation substructure of low-carbon steels through the generation and rearrangement of dislocations. Although the microstructural evolution of DC01 steel during consecutive DRECE passes has been previously characterized, it remains unclear to what extent deformation states developed at different levels of accumulated strain remain distinguishable after high-cycle fatigue (HCF) loading. The present study addresses this issue by comparing the fatigue behavior and post-fatigue deformation substructure of DC01 steel subjected to one and six DRECE passes.

Axial high-cycle fatigue tests were performed under fully reversed loading, and the fatigue behavior of the two deformation states was evaluated based on S–N characteristics. Selected specimens were subsequently examined by transmission electron microscopy using bright-field and dark-field imaging together with selected-area electron diffraction. The fatigue results revealed a clear difference between the investigated conditions, with the material subjected to six DRECE passes exhibiting higher HCF resistance than that processed by a single pass. TEM observations demonstrated that the corresponding post-fatigue deformation substructures remained distinguishable despite prolonged cyclic loading. The single-pass condition was characterized by a heterogeneous, elongated dislocation arrangement with locally developed dislocation walls, whereas the six-pass condition exhibited a more pronounced organization of dislocation walls and greater local subdivision of the deformation substructure.

The results indicate that differences associated with accumulated DRECE strain remain reflected in the dislocation organization after HCF loading. The higher fatigue resistance of the six-pass condition is accompanied by a distinct post-fatigue deformation substructure, suggesting that the deformation state introduced by DRECE remains relevant to the subsequent fatigue behavior of DC01 steel.

Keywords: SPD method, DRECE, high-cycle fatigue, deformation substructure, DC01 steel

Insight into microstructure and properties of novel bainitic tool steels

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A comparative study was conducted to evaluate two distinct isothermal heat treatment routes: above and below the martensite start (M_s) temperature, aimed at the development of

The development of new steels for warm- and hot-forging tools requires simultaneous consideration of high strength, thermal stability, resistance to tempering, sufficient ductility, and industrial feasibility of heat treatment. In the present study, an application-driven alloy design strategy was developed to combine the strengthening mechanisms characteristic of nanostructured bainite with secondary hardening used in conventional hot-work tool steels. Particular attention was given to controlling the stability and morphology of retained austenite, limiting the formation of preformed martensite, and reducing the concentration of costly carbide-forming elements.

The chemical compositions were designed using a CALPHAD-assisted approach in which the bainitic transformation kinetics, martensite start temperature, retained austenite fraction, and processing constraints were considered simultaneously. The design criteria included low-temperature bainitic transformation, sufficiently rapid transformation kinetics for potential industrial implementation, and a limited total Mo and V content while retaining the ability to generate secondary hardening. Additional thermodynamic and precipitation calculations were used to assess the expected response during high-temperature tempering. Based on the computational screening and subsequent optimization of carbon, Ni, Si, and Al contents, three experimental steels, denoted MoV, MoVNi, and MoVAlSi, were selected for validation.

The steels were austenitized at 1000 °C and subjected to isothermal transformation at 280 °C, followed by tempering at 550 °C for 1 h. Dilatometric experiments confirmed that bainitic transformation was completed within approximately 1-1.5 h, substantially faster than initially predicted by the computational approach. Microstructural characterization by SEM, EBSD and S/TEM revealed highly refined bainitic structures consisting of bainitic ferrite, retained austenite and different fractions of autotempered preformed martensite. The bainitic ferrite lath thickness remained below 100 nm for all investigated compositions.

A distinct relationship between alloy composition, preformed martensite fraction, retained austenite morphology and mechanical response was identified. The preformed martensite fraction increased from approximately 2.2% in MoV to 6.4% in MoVNi and 12.4% in MoVAISI. Higher preformed martensite fractions were accompanied by coarser blocky retained austenite and the formation of M/A constituents, resulting in a progressive reduction in ductility. Tempering at 550 °C caused partial decomposition of film-like retained austenite, destabilization of blocky austenite and precipitation of secondary carbides. S/TEM observations confirmed the increasing contribution of Mo-V-rich MC-type carbides, together with additional carbide populations, providing the microstructural origin of the pronounced secondary hardening response.

Among the investigated compositions, the MoV steel exhibited the most favorable balance of properties. After isothermal treatment, it reached an ultimate tensile strength of 1602 MPa, a yield strength of 1468 MPa and a total elongation of 16.7%. Following tempering, the strength increased to 1858 MPa and 1659 MPa, respectively, while a total elongation of 10.4% was retained. In contrast, the alloy containing the highest fraction of preformed martensite exhibited only about 2% elongation after tempering.

The results demonstrate that the successful design of thermally stable nanobainitic tool steels cannot rely solely on secondary precipitation hardening. The amount of preformed martensite and the morphology and stability of retained austenite play a crucial role governing the strength-ductility balance. The proposed CALPHAD-guided strategy therefore provides a route for integrating computational alloy development with microstructure control in steels intended for demanding warm- and hot-forging applications.

Keywords: forging tools, advanced steel, alloy design, microstructure characterization

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FEM modeling and experimental verification of the influence of FDM process parameters on the strength of polymer gears

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This paper presents an evaluation of the applicability of Fused Filament Fabrication (FFF/FDM) technology for manufacturing bevel gear components intended for rapid repair and spare part prototyping in low-power drive systems. The study involved a reverse engineering process applied to an existing gear component, encompassing geometry digitisation, CAD model development, and geometric optimization accounting for additive manufacturing constraints and material consumption minimization.

The developed model was subjected to numerical analysis using the Finite Element Method (FEM) in Forge NxT 4.1 software. Distributions of reduced (von Mises) stresses and total strains were determined for components manufactured from ABS, ASA, PET-G, and PLA filaments, as well as their modified variants reinforced with carbon fiber (CF) and metal powder (Metal). The results were compared to assess the influence of material properties on the stress-strain state of the manufactured components.

The findings confirm the technical feasibility of applying FDM/FFF technology for the production of functional gear prototypes. A significant influence of filament type on stress and strain distributions was demonstrated, providing a basis for rational material selection in the design of additively manufactured gear transmission components.

Keywords: FEM numerical analysis, 3D printing, incremental methods, , strength testing, materials

NitridAge – A novel processing strategy for Cu-containing steels combining cold forging and tailored hardness gradients achieved by nitriding

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The increasing use of steel scrap in modern steel production inevitably leads to elevated residual copper contents. Since there are currently no conventional metallurgical processing routes capable of efficiently removing copper from the melt, alternative alloy and process strategies are required to transform residual copper from a problematic impurity into a strengthening mechanism for high-performance steels. At the same time, the steel industry faces growing pressure to reduce energy consumption and CO₂ emissions associated with conventional heat treatment routes for high-strength components. In this context, the NitridAge concept was developed to investigate whether tailored hardness gradients between core and surface regions can be achieved within a single thermochemical processing route while remaining economically feasible. For this purpose, a new alloy approach in combination with tailored thermomechanical-thermochemical processing was investigated.

The presented study investigates a modified low-alloyed Q&T steel 23MnB4 with intentionally increased Cu content designed for cold heading and cold extrusion operations. Instead of relying on conventional quenching and tempering, the proposed approach combines direct patenting, cold heading and precipitation hardening during gas nitriding. Particular attention was paid to the interaction between Cu precipitation, ferritic microstructure formation and nitriding response.

Experimental processing included laboratory melting, hot rolling, controlled cooling, subsequent cold deformation trials and simulation-supported nitriding process design. Microstructural characterization was carried out using light microscopy, SEM, hardness measurements and tensile testing. The influence of alloy composition on nitriding response, microstructural evolution and cold formability was also evaluated.

The results demonstrate that controlled cooling after adjusted hot rolling enables the formation of comparatively soft ferritic-pearlitic microstructures suitable for subsequent cold forging, despite elevated copper contents. Subsequent nitriding results in a significant hardness increase at the surface and enables the development of adjustable hardness gradients between surface and core regions. Furthermore, the obtained results indicate that the combination of Cu-induced precipitation hardening and tailored nitriding treatments

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enables additional adjustment of surface and core properties, opening further possibilities for the development of energy-efficient cold-forged wear-resistant steel components with locally adapted mechanical performance.

Keywords: Cu-containing steels, recycled steel, gas nitriding, precipitation hardening, cold forging, hardness gradient, thermomechanical processing, cold formability, sustainable steel design, alloy design

Relating hot torsion testing to industrial extrusion: a microstructural study of EN AW-6060 aluminium alloy

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This work conducted a detailed metallographic analysis of samples made of EN AW-6060 aluminum alloy obtained by two different plastic deformation processes: high-temperature torsion and extrusion. Physical modelling of both processes was preceded by numerical modelling with using finite element method (FEM) and a detailed analysis of the deformation conditions occurring during both processes.

By carefully selecting thermoplastic processing parameters, ensuring comparable strain rates, strain values, and temperature profiles, materials suitable for direct microstructural comparison were obtained. Example of strain distribution in both analyzed processes are shown in Fig. 1.

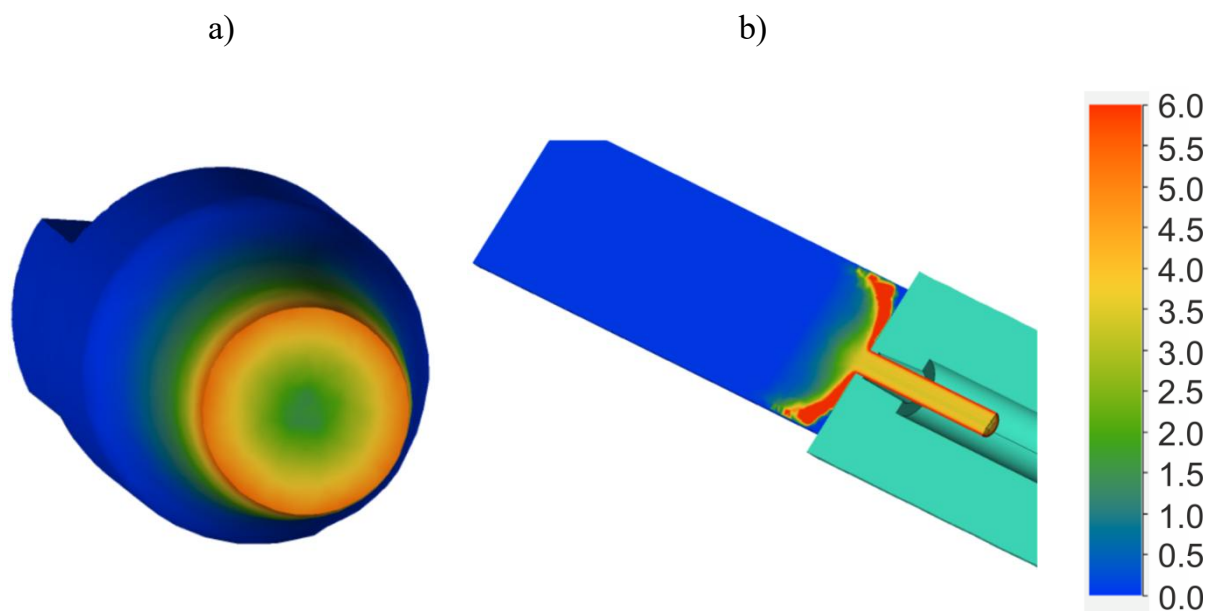


Fig. 1. Example of strain distribution obtained during numerical modelling:
a) torsion test, b) actual extrusion process

The studies presented in this paper were conducted within the temperature range characteristic for the extrusion process of the tested aluminum alloy, with various cooling rates after deformation. QForm Extrusion® commercial software was used for numerical modelling of the analyzed thermoplastic processes. Physical modelling was performed by using STD 812® torsion plastometer. The real extrusion process was carried out by using a horizontal press with 5 MN maximum extrusion force. Metallographic examination was performed by using the Barker etching method and detailed analysis by using Electron Backscatter Diffraction method (EBSD).

The main objective of this work was to investigate the effect of thermoplastic processing parameters (strain magnitude, strain rate, temperature, and a cooling rate after deformation) on the evolution of the microstructure of the tested material. The research presented in this work also examined the possibility of using the torsion test for physical modelling of the actual extrusion process of the EN AW-6060 aluminium alloy. The obtained results allow for the assessment of strain gradients and the identification of representative area, where the microstructure and resulting material properties can be reliably characterized and predicted, thus supporting the development and optimization of industrial aluminium alloy forming processes.

Numerical simulations revealed distinct strain gradients in both hot torsion and extrusion processes. Based on the numerical analysis results, regions located approximately $0.6\text{--}0.75\ r$ (where r is a radius of the sample) were identified as the most representative area for microstructural comparisons between torsion and extrusion tests. These regions exhibited comparable strain parameters and similar temperature conditions, enabling significant correlation of the resulting microstructures.

Metallographic analysis of the EN AW-6060 alloy revealed a strong dependence of grain size and degree of recrystallization on the thermoplastic processing temperature and local strain level. Increasing the deformation temperature led to grain growth, particularly in highly deformed areas, due to the combined effect of stored energy, due to plastic deformation and thermally activated recrystallization process. Higher cooling rates, especially after the deformation process at temperature of 500 and 550°C, resulted in partial inhibition of grain growth after deformation due to the limited time of exposure to high temperature. However, the applied cooling rates were insufficient to completely eliminate recrystallization process.

The obtained research results confirm that the hot torsion test, combined with the selection of representative areas determined using the finite element method can be effectively used to predict evolution of microstructure in industrial extrusion processes.

Keywords: hot torsion test; extrusion; microstructural evolution; aluminium alloy EN AW-6060

Tool wear in ceramic roof tile extrusion: influence of material and surface solutions

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This research evaluates the effect of tool material selection and surface treatment on the wear behaviour of tools used for the industrial extrusion of plastic clay in ceramic roof tile production. Tool wear affects product quality by altering material flow, increasing local stresses, and reducing process stability. Four tool material variants commonly used in industry were evaluated: Hardox 600 steel, NC11LV tool steel, nitrided NC11LV tool steel, and hardfaced C45 steel. Wear resistance was assessed using laboratory abrasion tests and subsequently evaluated under industrial production conditions by measuring material loss in critical tool regions. The results showed that the performance of the materials depended on the prevailing wear conditions. NC11LV and nitrided NC11LV exhibited the highest resistance to abrasive wear, whereas hardfaced C45 steel performed best under combined rolling–sliding conditions. Industrial tests showed higher wear in the entry area than in the exit area, with the highest material loss occurring at the inlet edge of the working surface. The nitrided NC11LV tool showed the lowest average material loss, with approximately 2.3 mm measured at the inlet edge of the working surface, compared with more than 4.8 mm for Hardox 600. Microscopic observations and numerical simulations helped explain the differences between the laboratory and industrial results by linking local stress concentrations to the observed wear mechanisms. The findings highlight the importance of considering the specific wear mechanisms and loading conditions encountered in service when selecting materials for extrusion tools.

Keywords: tool wear; abrasive resistance; numerical simulations; ceramic roof tiles

Theoretical and experimental analysis of mandrel-free bending of high-yield-strength CP and DP steel tubes on small radii

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The objective of the study was to apply steel with specific mechanical properties to mandrel-less tube bending processes at small radii. These specific properties refer to high yield strengths. Such conditions are unfavorable for bending processes.

The research problem was to determine whether the developed pipe bending method could be applied to the forming of DP and CP steels. These steels have high yield strengths, which results in relatively high springback.

Based on the available literature, it should be assumed that the springback is also significantly influenced by the internal (residual) stresses accumulated in the raw material. Internal stresses arise as early as the manufacturing stage of the feedstock. These stresses remain in the material after the external load acting on the workpiece is removed. The cause of these stresses is non-uniform changes in the shape of the body resulting from permanent deformations. As a result of an external load, parts of the crystal lattice shift relative to the rest of the structure. The phenomenon of dislocation disrupts the continuity of the lattice order, leading to the formation of a field of residual stresses. Residual stresses can be classified based on the region in which they balance each other out. Thus, they are classified as macro stresses, sub-stresses, and micro stresses. The resulting residual stresses primarily affect properties such as the material's susceptibility to corrosion, its machinability, and its mechanical properties. Most of the phenomena occurring in the material during machining take place at shallow depths (relative to the surface of the workpiece), which is why residual stresses are mainly localized in the surface layer or in adjacent layers. Typically, the absolute value of residual stresses is higher near the surface layer and decreases with depth into the workpiece. To eliminate residual stresses from sheet metal feedstock, the most commonly used processes are straightening rolling (involving repeatedly passing the sheet between rolls, which force the sheet to bend within the range of plastic deformation without changing the thickness of the feedstock), or the "temper rolling" technology (rolling with very low reduction of area, up to a maximum of 4%), which is used, among other applications, in this study. These processes significantly alter the state of residual stresses by introducing residual stresses, thereby influencing the internal ordering of defects in the crystal lattice.

Two steel grades were used in the study: DP steel grade HCT700X and CP steel grade CR800Y980T. DP steels consist of a soft ferritic matrix with islands of hard martensite. Thanks to its low initial yield strength relative to its ultimate tensile strength (R_m), this steel is highly suitable for deep drawing while maintaining a high energy

absorption capacity. This steel offers ease of forming while maintaining high ultimate strength. CP steels have a significantly more complex microstructure than DP steels, containing ferrite, bainite, and martensite, and sometimes also residual austenite; therefore, they exhibit relatively high springback while having the same strength as DP steels. For CP steels, the R_e/R_m ratio is significantly higher than in DP steels. This means that the material remains in the elastic range much longer under increasing load. Material data for computer simulations of three-point bending and sheet metal bending were obtained from the Simufact Forming database.

Springback was determined using computer simulation and laboratory tests.

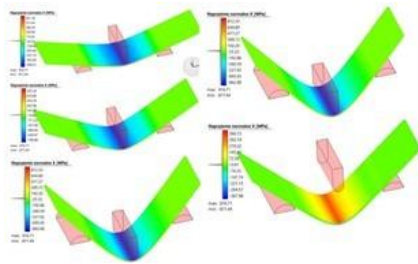


Fig. 1. Modeling of three-point bending

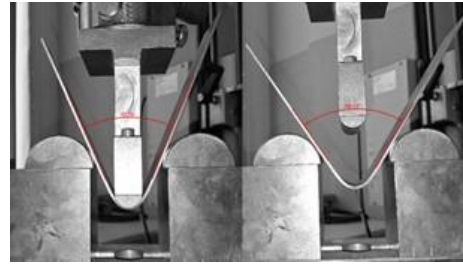


Fig. 2. Methodology for determining the springback angle

The bending processes were studied using numerical modeling in the Simufact Forming software and on a custom-built laboratory apparatus.

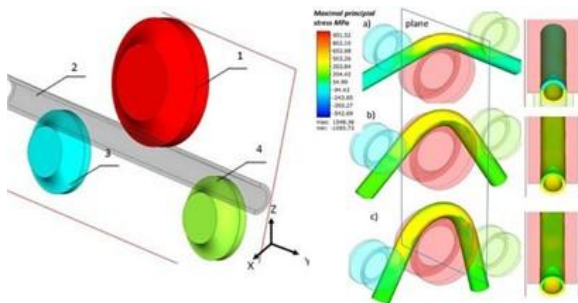


Fig. 3. Modeling of bending process

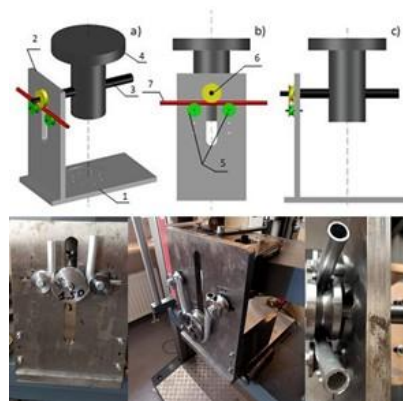


Fig. 4. Tool for bending tests

Conclusions

Experimental and theoretical studies have shown that CP steel exhibits greater elastic recovery than DP steel. Therefore, DP steel is recommended for the production of tubes using new bending processes.

Keywords: pipe bending, high-strength steels (HSS), materials with high yield strength, new pipe bending methods

Microstructure and mechanical properties of cast Al-Cu-Ni-Mg alloy for aerospace applications

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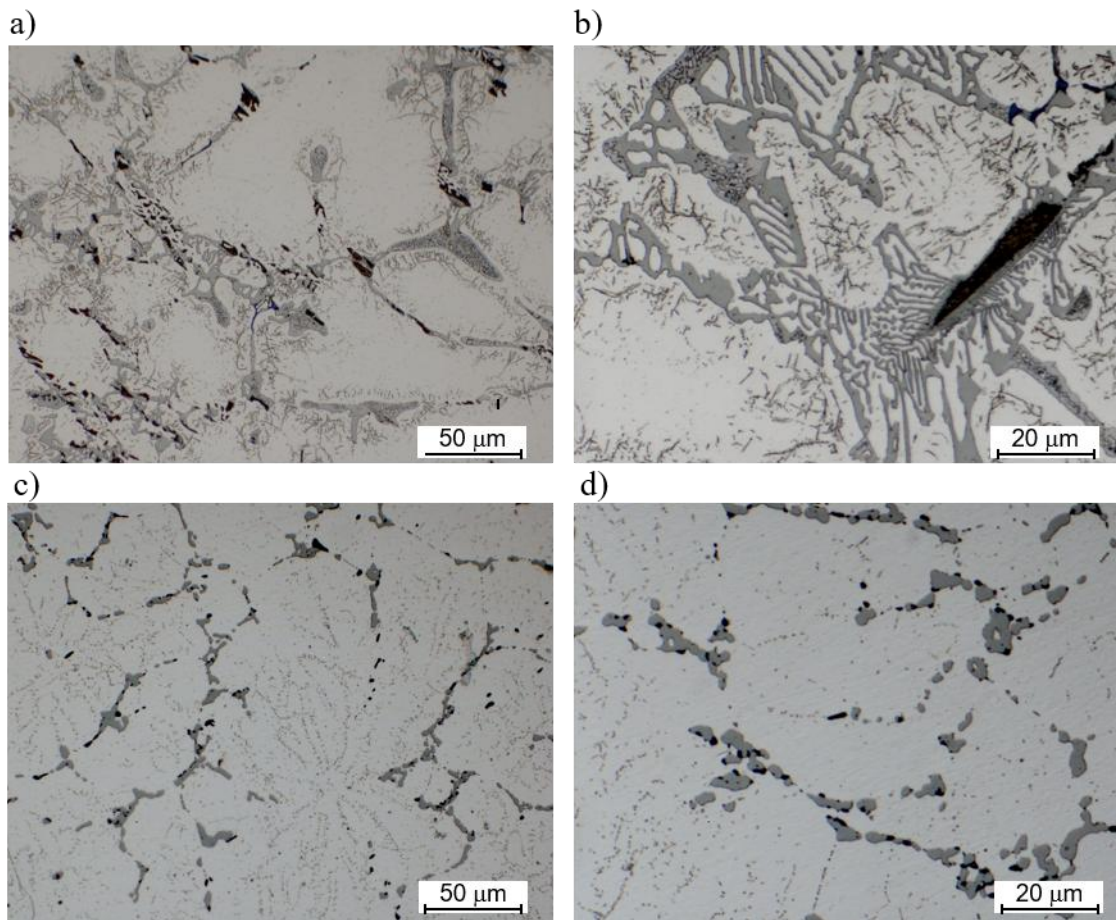
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Aluminum casting alloys are used in the aerospace industry due to their low density, high specific strength (R_m/ρ), good thermal conductivity, and beneficial technological properties. Among materials designed for use at elevated temperatures, Al-Cu-Ni-Mg alloys are of particular importance; in these alloys, the appropriate selection of alloying element content allows for a favorable combination of mechanical properties and microstructural stability. Al-Cu alloys present greater technological difficulties during casting than commonly used Al-Si alloys, partly due to their increased susceptibility to hot cracking; however, they form the basis for the production of multi-component alloys with enhanced resistance to elevated temperatures. In the AlCu4Ni2Mg2 alloy, the presence of Cu and Mg enables the use of the precipitation hardening mechanism of the α -Al matrix, while the addition of Ni promotes the formation of thermally stable intermetallic phases, which influence the retention of mechanical properties during prolonged exposure to elevated temperatures.

This study evaluated the effect of metallurgical treatments performed in the liquid state and T6 heat treatment on the microstructure and mechanical properties of the AlCu4Ni2Mg2 casting alloy. The alloy was melted in a gas furnace in a graphite crucible, then refined with argon of purity 5.0 and subjected to grain refinement using an AlTi5B1 modifier. The thermal effects associated with phase transformations occurring during heating were analyzed using differential scanning calorimetry (DSC) in the temperature range from room temperature to 800°C, at a heating rate of 5°C/min in an argon atmosphere. Microstructural studies were conducted using light microscopy and scanning electron microscopy (SEM) in the as-cast state and after heat treatment. Heat treatment included solution treatment at 520°C for 8 h, cooling with a stream of compressed air, and artificial aging at 200, 250, and 280°C. After solution treatment, the alloy exhibited a hardness of 107 HBW, a yield strength of $R_{p0.2} = 244.2$ MPa, a tensile strength of $R_m = 286.6$ MPa, and an elongation of $A_5 = 0.97\%$. The highest strength properties were achieved after aging at 250°C: $R_{p0.2} = 343$ MPa and $R_m = 387$ MPa, with $A_5 = 2.5\%$. Increasing the aging temperature to 280°C resulted in a decrease in $R_{p0.2}$ to 305 MPa and R_m to 318 MPa.

The results demonstrate that the mechanical properties of the AlCu4Ni2Mg2 casting alloy are strongly dependent on the applied heat-treatment conditions. Solution treatment followed by artificial aging resulted in a significant increase in strength compared with the solution-treated condition, confirming the effectiveness of precipitation strengthening of the α -Al matrix. Among the investigated aging conditions, aging at 250°C

provided the most favorable combination of mechanical properties, resulting in the highest values of $R_{p0.2}$ and R_m . The decrease in strength observed after aging at 280°C indicates changes in the precipitation state of the alloy associated with the progression toward overaging. These results show that appropriate control of solution treatment and aging parameters enables effective tailoring of the microstructure and mechanical properties of AlCu4Ni2Mg2 alloy, supporting its potential application in aerospace components operating under demanding thermo-mechanical conditions.



Keywords: cast aluminum alloys, AlCu4Ni2Mg2 alloy, microstructure, intermetallic phases, heat treatment

Influence of hot-rolling parameters and thermophysical properties on lateral material flow

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Designing hot-rolling technologies is a complex process that requires consideration of numerous interrelated factors influencing the material behaviour during deformation. These factors determine both the ability to obtain the desired cross-sectional shape of the product and the expected functional properties. In addition to parameters related to the product type, mill configuration, stand design and formability of the material under process conditions, an important role is also played by quantities such as reduction per pass, rolling speed, and the forces and torques acting on the rolls. Another significant aspect is the thermal conductivity of the material, as well as the heat-transfer and friction phenomena occurring at the interface between the rolled strip and the roll surface.

In this study, the influence of selected hot-rolling process parameters (such as reduction per pass, roll diameter, process temperature, rolling speed and friction coefficient) on the lateral material flow was analysed. Physical and numerical simulations were performed to study thermomechanical states during the rolling of flat bars made of materials with markedly different thermal conductivity: austenitic steel X5CrNi18-10 and copper M00B. Experimental tests were carried out using the LPS/B semi-industrial physical simulation line at Łukasiewicz Research Network – Upper Silesian Institute of Technology, while numerical analyses were conducted using the finite-element method (Forge NxT 4.1). Spread characteristics were determined as a function of the cross section shape factor, reduction per pass and roll diameter. The results were also compared with empirical relationships available in the literature. Temperature, stress and strain distribution maps were developed, enabling detailed assessment of thermomechanical states in materials with differing thermal conductivity. The results show that differences in thermal conductivity significantly affect the material flow and consequently the magnitude of strip spread.

Keywords: hot rolling, steel, copper, thermal conductivity, spread, temperature distribution, heat transfer

Effect of the modified DRECE process on the mechanical properties and microstructure of low-carbon steel

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Modified Dual Rolls Equal Channel Extrusion (MDRECE) is a severe plastic deformation (SPD) method that enables substantial plastic strain to be introduced into metallic materials while maintaining the initial cross-sectional dimensions of the processed strip. This study investigates the effect of an innovated DRECE process on the mechanical properties and microstructure of low-carbon steel. The primary objective was to achieve substantial strengthening within a minimum number of passes while retaining sufficient formability of the processed material. Low-carbon steel strips were subjected to repeated passes through the DRECE forming device. Tensile tests were performed after each pass to evaluate changes in mechanical properties, particularly yield strength and ultimate tensile strength. The effect of strip feeding speed on the resulting mechanical properties was also investigated. Microstructural changes and grain refinement induced by DRECE processing were characterised using transmission electron microscopy (TEM), scanning electron microscopy (SEM), and electron backscatter diffraction (EBSD). The results reveal the relationships between the DRECE processing parameters, mechanical properties, and microstructural evolution of low-carbon steel, demonstrating the potential of the innovated DRECE process for the effective strengthening and microstructural refinement of low-carbon steel strips while retaining sufficient formability.

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Keywords: severe plastic deformation, DRECE, low-carbon steel strip, mechanical properties, grain refinement, microstructure

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Metastable reaction zones and intermetallic layer growth in explosively welded Ti–Al and Mg–Al multilayers

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Explosive welding generates highly localized reaction zones subjected to rapid melting, mixing, solidification, and cooling. These zones may act as metastable precursors for subsequent interfacial phase transformations; however, their influence on phase selection, layer growth, and crystallographic development during post-weld heat treatment remains insufficiently understood. This study compares the evolution of reaction zones and intermetallic layers in two multilayer systems fabricated by single-shot explosive welding: a fifteen-layer Ti–Al composite consisting of alternating 1 mm sheets of Ti Grade 1 and AA1050 Al, and an eleven-layer Mg–Al composite composed of AZ31 Mg and AA1050 Al sheets. Post-weld annealing was conducted at 903 K for the Ti–Al system and 673 K for the Mg–Al system, with treatment times ranging from less than 1 h to more than 10³ h. The interfacial regions were examined using scanning electron microscopy, transmission electron microscopy, and synchrotron X-ray diffraction, while local mechanical response was assessed by microhardness and shear-strength measurements.

Solidified melt zones were formed along all interfaces in both multilayer systems. They consisted predominantly of non-equilibrium phases with ultrafine-grained or amorphous structures. During short annealing treatments, these metastable products underwent rapid transformation and promoted the development of intermetallic layers. In the Ti–Al system, continuous Al₃Ti layers formed at all interfaces. Prolonged annealing produced a Ti–Al₃Ti–Al multilayer architecture containing residual Ti and Al layers. In the Mg–Al system, annealing for less than 1 h at 673 K resulted in substantial growth of the γ -Mg₁₇Al₁₂ and β -Mg₂₈Al₄₅ phases near all interfaces. Simultaneously, the pre-existing non-equilibrium products within the reaction zones transformed into the β phase. After prolonged annealing for at least 500 h, intermediate ϵ -Mg₂₃Al₃₀ layers developed between the β and γ layers, resulting in an Al– $\gamma/\epsilon/\beta$ -Mg multilayer intermetallic architecture.

The reaction products in both systems displayed pronounced morphological and crystallographic heterogeneity. In the Ti–Al multilayers, this heterogeneity involved the coexistence of Al₃Ti-based superstructures with the conventional D0₂₂-Al₃Ti phase and the formation of distinct fibre-texture components within the interfacial regions. In the Mg–Al multilayers, the β and γ layers were composed of strongly elongated grains, whereas the ϵ phase exhibited an equiaxed grain morphology. None of the Mg–Al intermetallic phases showed a preferred crystallographic orientation. The results demonstrate that rapidly solidified reaction zones govern the initial phase-transformation pathways and

contribute to the subsequent development of compositionally, morphologically, and crystallographically heterogeneous intermetallic layer architectures.

Keywords: explosive welding, metastable reaction zones, intermetallic layer growth, phase transformations, Ti–Al and Mg–Al multilayers

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Experimental identification and numerical validation of the Archard wear model for predicting forging die wear

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Prediction of the wear of tools used in metal forming processes remains one of the major challenges in numerical modelling, particularly in the case of hot die forging. Despite the continuous development of computational methods, the reliability of the obtained results strongly depends on the appropriate selection of the wear model and the experimental identification of its parameters. One of the most commonly used approaches is the Archard wear model, which describes abrasive wear based on contact conditions. In practice, however, it is also frequently applied to represent the overall degradation of tools, including mechanisms that are not directly described by the model.

The aim of this study was to develop, parameterise, and validate an Archard-based wear model for predicting tool wear in hot die forging processes. In the first stage, ball-on-disc tribological tests were carried out to determine the wear coefficient, K . Subsequently, a numerical model of the tribological test was developed, and the calculated wear track geometry was compared with the experimental results. This enabled verification and calibration of the model parameters under controlled friction and wear conditions. The calibrated model was then applied to simulate tool wear in a selected industrial hot die forging process.

Particular attention was paid to the physical interpretation of the wear coefficient and to the limitations associated with the application of the Archard model. It was demonstrated that achieving agreement between numerical and experimental results by adjusting the value of the wear coefficient does not necessarily imply that the actual mechanisms of tool degradation have been correctly represented. The obtained results indicate that the Archard model can be used more reliably to predict forging die wear, provided that its parameters are properly calibrated and that the actual degradation mechanisms are taken into account.

Keywords: tool wear, forging, ball on disc

Microstructure and texture gradients across Al_3Ti layers in annealed Al/Ti multilayer composites

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Interfacial architecture and thermally induced phase evolution were investigated in Al–Ti multilayer plates containing an Al_3Ti reaction layer. The laminates, composed of alternating Ti Grade 1 and AA1050 sheets, were fabricated by single-shot explosive welding and subsequently annealed at 903 K for up to 10^3 h, resulting in an Al– Al_3Ti –Ti multilayer system. Scanning electron microscopy, transmission electron microscopy, and synchrotron X-ray diffraction were employed to resolve spatial variations in the reaction-layer morphology, grain structure, and crystallographic orientation.

The Al_3Ti layer exhibited a pronounced through-thickness gradient in its interfacial microstructure. The zone adjacent to Ti was characterized by substantial grain refinement, whereas the Al-facing region underwent pronounced grain coarsening. An exception was a thin, refined sublayer located directly at the Al/ Al_3Ti phase boundary. These spatial differences coincided with the redistribution and coarsening of Al–Fe(Ti,Si) precipitates, indicating a possible coupling between second-phase evolution and localized grain-growth behaviour within the reaction layer.

A corresponding orientation gradient developed across the Al_3Ti layer. Near the Al/ Al_3Ti boundary, the intermetallic phase displayed a strong [001] fibre texture, with the fibre axis parallel to the interfacial plane and perpendicular to the preferential propagation direction of the reaction layer. Toward the Ti/ Al_3Ti boundary, the orientation distribution transformed into a more complex configuration comprising $\langle 100 \rangle$ and [001] fibre components, whose axes were nearly parallel to the layer-growth direction. The results demonstrate that prolonged thermal exposure produces coupled gradients in grain structure, precipitate distribution, and crystallographic orientation across the Al_3Ti reaction layer, highlighting the role of the two dissimilar phase boundaries in its spatially nonuniform evolution.

Keywords: Al_3Ti intermetallics, Al/Ti multilayer composites, crystallographic texture, interfacial evolution, explosive welding

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under project number 2023/51/B/ST11/02937.*

The influence of the addition of rare earth metal on the strength of 7095 aluminum alloy

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This study investigates the effect of rare-earth element additions on the mechanical properties, hardness, microstructure, and corrosion resistance of high-strength AA7095 Al–Zn–Mg–Cu aluminium alloy. The base alloy was modified with cerium, erbium, and scandium additions at two concentration levels, approximately 0.1 wt.% and 0.5 wt.%. The alloys were produced by semi-continuous casting, followed by two-step homogenisation, extrusion, solution treatment, water quenching, and artificial ageing in T6 and T76 conditions. The alloy containing approximately 0.5 wt.% Sc achieved the highest ultimate tensile strength, reaching 651.94 MPa after T6 treatment and 603.59 MPa after T76 treatment. The 0.1 wt.% Sc addition also improved strength compared with cerium- and erbium-containing variants. Erbium produced a moderate strengthening effect, whereas cerium showed the weakest influence on tensile strength. In contrast, hardness was not clearly improved by rare-earth additions; the base alloy exhibited the highest hardness values in both T6 and T76 conditions. Microstructural observations confirmed the presence of MgZn₂ strengthening precipitates, while rare-earth additions affected precipitation behaviour and grain-boundary features. Corrosion testing in neutral salt spray for 96 h showed the lowest mass loss for the base alloy and a comparable result for the alloy with 0.1 wt.% Sc. Higher scandium content and 0.5 wt.% Ce reduced corrosion resistance. The results demonstrate that scandium is the most effective addition for improving tensile strength.

Keywords: supersaturation of aluminum, aluminum alloy 7095, rare earth metal

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of rare earth metal (cerium, erbium, scandium) on the microstructure, strength and stress
corrosion cracking resistance of a modern aluminum alloy 7095”).*

Analysis of the calibration process for steel rings produced by rolling and evaluation of the calibration fixture

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The calibration of steel rings (Fig. 1) is a critical stage in the manufacturing process of components used in the mechanical, automotive, aerospace, and energy industries. As the final forming operation, the calibration process is intended to minimize geometric deviations generated during preceding manufacturing stages and to achieve the required dimensional accuracy, circularity, and surface quality. Proper calibration significantly improves the dimensional stability, operational reliability, and service life of the finished components.

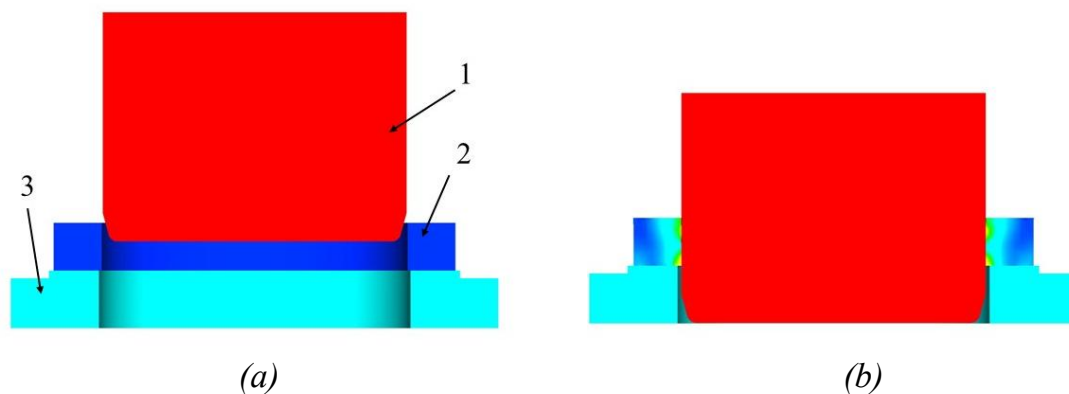


Fig. 1. Schematic diagram of the ring calibration process: (a) before calibration, (b) after calibration, 1 – punch, 2 - sized ring, 3 - lower backing plate

The objective of this thesis was to analyze the calibration process of steel rings manufactured by the ring rolling process and to evaluate the design and operational performance of a dedicated calibration fixture. The study presents the characteristics of the calibration process and discusses its role in ensuring compliance with the specified geometric tolerances of rolled rings. Particular attention is devoted to the structural analysis of the calibration fixture, including its design, operating principle, functional characteristics, and the influence of the adopted engineering solutions on process accuracy, repeatability, and operational stability.

The investigated fixture (Fig. 2) enables controlled elastic-plastic deformation of the ring by uniformly transmitting the forming load through a punch acting on the inner surface of the workpiece. The adopted structural solutions ensure adequate stiffness of the tooling system, precise guidance of the working components, and stable process conditions,

thereby minimizing the occurrence of localized deformation, instability, and material damage. In addition, the fixture design allows the calibration of rings with different wall thicknesses while maintaining high dimensional repeatability and process reliability.

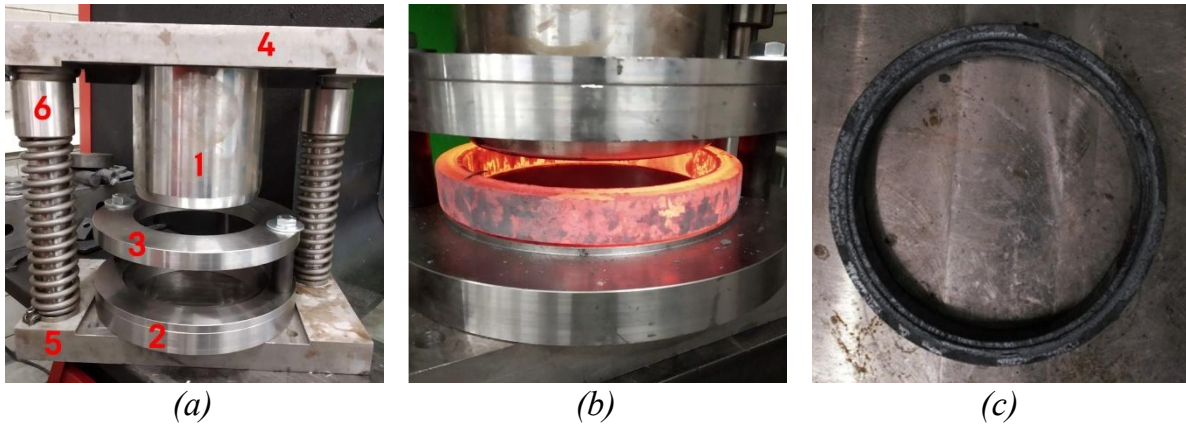


Fig. 2. Ring calibration under near-industrial conditions: (a) calibration fixture, (b) ring before calibration, (c) calibrated ring; 1 – punch, 2 - lower backing plate, 3 - upper backing plate, 4 - upper plate, 5 – lower plate, 6 - guide pillar

The conducted analysis demonstrated that the application of a dedicated calibration fixture significantly improves calibration accuracy, reduces process variability associated with manual operation, and decreases the number of non-conforming products. Furthermore, the implementation of the fixture shortens process cycle time, enhances production efficiency, and reduces manufacturing costs by limiting the need for subsequent finishing operations.

The obtained results confirm that a properly designed calibration fixture constitutes an effective technological solution supporting the production of rolled steel rings. Its application enables the achievement of high dimensional and geometric accuracy, improves the stability and repeatability of the manufacturing process, and enhances the overall quality of the finished components. In view of the increasingly stringent industrial requirements regarding the dimensional precision and geometric accuracy of machine parts, the calibration process and the appropriate design of dedicated tooling play a crucial role in ensuring product quality, process capability, and manufacturing competitiveness.

Keywords: steel rings, ring rolling, calibration, calibration fixture

Development of material and technological solutions for large-size wire bearings

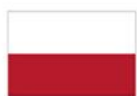
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The study presents the results of research on the development of material and technological solutions aimed at improving the performance of lightweight large-size wire bearings. The research conducted at the Łukasiewicz Research Network - Poznań Institute of Technology focused on two main areas: the development of a self-lubricating AlWS₂ composite for bearing separators and the development of guidelines for reducing flatness and roundness errors in wire bearing races. Within the composite study, the effect of WS₂ content on the tribological properties of the material was investigated. The obtained results demonstrated a significant reduction in volumetric wear for Al 431 composites containing 5% and 10% WS₂ compared with the reference Al 6063 material. The second research area focused on the influence of material properties, geometry, and different loading schemes on the possibility of permanently reducing geometrical errors in wire bearing races. The obtained results provide a basis for further development of separator manufacturing technology and an semi-automated process for reducing geometrical errors in wire bearing races.

Keywords: composite, wire bearings, bearing separators, tribological properties, geometrical error reduction, wire bearing races



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Strain-rate-dependent microstructure evolution in Fe–29Mn–3Al–0.46C TWIP steel under torsional loading

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High-manganese austenitic TWIP steels exhibit a favorable combination of strength, ductility, and energy-absorption capacity resulting from pronounced strain hardening. Their deformation response is governed by the relative contributions of dislocation glide, deformation twinning, strain localization within shear bands, and dynamic strain aging. The activation of these mechanisms depends on stacking-fault energy, chemical composition, temperature, grain size, crystallographic orientation, strain magnitude, and strain rate [1-10].

The aim of this study was to analyze the evolution and spatial variability of the microstructure in a high-manganese austenitic steel subjected to torsion-to-fracture tests at nominal strain rates spanning four orders of magnitude. The investigated material was an Fe–29Mn–3Al–0.46C steel with a calculated stacking-fault energy of approximately 47.4 mJ m⁻².

Longitudinal metallographic sections were prepared from specimens torsion-tested to fracture at strain rates of 0.001, 0.01, 1, and 10 s⁻¹. The experimental methodology included light microscopy, scanning electron microscopy using secondary-electron and backscattered-electron imaging, energy-dispersive X-ray spectroscopy (EDS), and Vickers microhardness measurements. The microstructural observations and hardness measurements were referenced to the axial distance from the fracture surface, expressed as z/L, and to the radial position relative to the specimen axis, expressed as r/R, allowing the deformation gradient generated during torsion to be assessed. Preliminary light-microscopy observations revealed distinct differences in the morphology and spatial distribution of deformation features as a function of strain rate. In the specimen deformed at 0.01 s⁻¹, clearly separated individual deformation twins were observed together with packets of twins extending from one grain boundary to another. Local configurations of intersecting deformation bands were also identified. The specimen deformed at 1 s⁻¹ exhibited a fine and extensively developed banded microstructure. In contrast, the specimen deformed at 10 s⁻¹ showed the most complex arrangements of

overlapping deformation twins and twin bands, suggesting the activation of multiple twinning systems. In the specimen deformed at 0.001 s^{-1} , numerous individual and intersecting deformation twins were also revealed; however, their detailed assessment was hindered by local metallographic preparation artifacts.

EDS analysis was additionally performed to identify the chemical nature of inclusions and localized precipitates observed during microstructural examination of the investigated steel. Because all specimens were torsion-tested to fracture, the observed differences should be interpreted as the combined effects of strain rate, the strain reached before fracture, and the local deformation level associated with the analyzed position within the specimen cross-section.

Keywords: TWIP, torsional loading, strain rate, microstructure, properties

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“The influence of complex strain path on the microstructure, deformation mechanisms
and mechanical properties of TWIP steel” financed by the NCN.*

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Rolling of circular cross-section bars from prefabricated elements obtained from the feet of scrapped railway rails

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High raw material prices on global markets drive up the core production costs of metallurgical components, which translates into their high price. This trend has been particularly visible recently, with raw material prices increasing up to several times. Consequently, new sources of cheap structural materials are being sought with increasing frequency. An alternative to metallurgical semi-finished products can be the use of decommissioned products, which can be reprocessed into other components in a relatively simple manner, bypassing energy-intensive and expensive metallurgical technologies. The railway sector is a massive supplier of decommissioned steel components, where large volumes of steel structures are sent for disposal each year.

Currently, scrapped railway rails are recycled in two ways. The first and most common method involves remelting them in steelworks. The second method relies on using selected rail fragments as feedstock for forging or rolling. In the case of traditional railway rail recycling, the total processing cost per metric ton (Mg) consists of 80-90% for the steelmaking process (which involves scrap remelting and steel reproduction) and 10-20% for the cost related to manufacturing the finished product from such steel, e.g., rolling bars, sheets, or strips. The high costs of the metallurgical process justify the search for processing methods that eliminate the steelmaking stage from rail recycling and enable the production of fully functional products directly from decommissioned rails. The properties of rail steel allow it to be used for manufacturing components such as reinforcing bars, bars used for spring production, and grinding ball stock bars for ball mills, as well as many other products and semi-finished products made of steel with enhanced strength properties.

Currently, in most cases, heads cut off from decommissioned railway rails are used for reprocessing. This is due to the highly compact shape of this rail section and its total mass share reaching up to 40%. Conversely, the remaining rail fragments, accounting for 60% of the mass, are sent to steelworks for remelting. The high mechanical parameters of rail steel combined with the relatively low sourcing cost of decommissioned railway rails justify conducting research aimed at developing effective methods for the comprehensive processing of railway scrap into fully functional semi-finished products and finished goods. For this purpose, the application of rolling processes has been proposed, which are considered among the most efficient methods of plastic working. The concept of comprehensive recycling of scrapped railway rails relies on dividing the rail into three sections (Fig. 1): the head, the web, and the foot, followed by rolling each section in grooved passes into circular cross-section bars. Subsequently, such bars can serve, among

other things, as semi-finished products for the cross-wedge rolling of balls of various diameters.

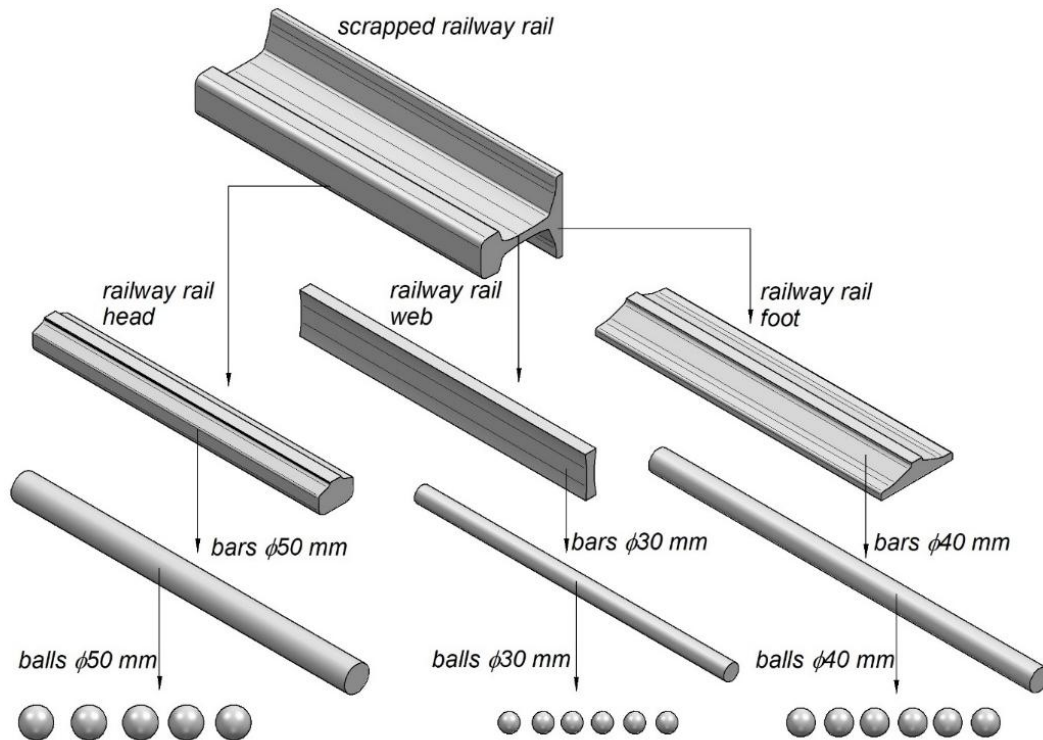


Fig. 1. The concept of comprehensive management of used railway rails, bypassing the metallurgical process

Due to the complexity of the issue, this paper focuses on discussing the most challenging process – rolling bars from the foot cut from used S60 type railway rails. As previously noted, the shape of this rail fragment is irregular, which significantly complicates the process of re-manufacturing semi-finished products from such materials. Using traditional rolling methods to roll bars with a circular cross-section would require the use of up to a dozen passes, which is associated with considerable implementation costs and significantly limits the diameter of the rolled bars. Therefore, the use of unconventional groove cutting was proposed, thanks to which the circular profile of a bar with a diameter of Ø40 mm can be achieved in just four passes. The resulting bars can serve as full-value semi-finished products for helical rolling of balls with a diameter of Ø40 mm, or, after calibration, such bars can be used as the final product.

Keywords: scrap railway rails, longitudinal rolling of bars, grooved rolls

Microstructure and properties development of clad steel plates for special applications

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The aim of this study was to develop a manufacturing technology for clad steel plates containing layers of ultra-high-strength NANOS-BA[®] steel with a nanobainitic microstructure. Physical simulations of the hot-roll bonding process followed by a two-stage heat treatment were carried out to produce a durable metallurgical bond without compromising the material properties. A comprehensive evaluation of the microstructure, bond interface quality, and hardness distribution across the plate cross-section was performed. The results demonstrated that the proposed technology provides a continuous metallurgical bond free from cracks, delamination, and other discontinuities while preserving the characteristic nanobainitic microstructure and high hardness of the NANOS-BA[®] steel layers. To evaluate their application potential, the manufactured clad plates were subjected to ballistic testing in accordance with the NATO STANAG 4569 standard, and the obtained results were compared with those of commercially available armour steels with a hardness of approximately 500 HB. The developed technology represents a promising alternative to conventional manufacturing methods for multilayer armour materials and offers the potential for designing lightweight ballistic protection systems with high bond integrity and a favourable combination of strength and penetration resistance.

Keywords: clad plates, hot roll – bonding, nanobainitic steels, armour clad plates

Properties of DC01 and DC03 low-carbon steels deformed by the DRECE severe plastic deformation process

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Steel is the most widely used structural material among metals. It is used in nearly every branch of modern industry. Its prevalence in terms of production, recycling, and processing is growing and evolving every year, both in terms of volume and the adoption of new technologies [1]. An important factor is economics, the ability to obtain the best possible material with the highest desired mechanical properties at the lowest possible cost. Therefore, the use of the latest, innovative forming techniques which are not yet widely used in industry aims to increase the productivity and efficiency of processes [2].

One of the newer, rapidly developing technologies is the severe plastic deformation (SPD) method. This technology allows, through the use of unconventional methods, for a significantly finer microstructure than that achieved with conventional plastic deformation techniques [3]. The effect that results in a highly refined microstructure is an increase in the number of dislocations and their reorganization within the material during dynamic, large-strain deformation. In certain SPD methods, the process can be repeated multiple times, making it possible to achieve different levels of deformation using a single method. Early research on SPD methods focused on non-ferrous metals with high ductility, such as copper, aluminum, and their alloys [4].

In the study, the SPD process selected for testing on steel materials was DRECE [5]. This is an experimental method in which metallic materials in the form of sheet metal or strip are processed. This process involves feeding the material onto guide rolls, which pull the material while compressing it within the elastic deformation range and feed it onto the main roll. The main roll, in turn, guides the material further, bending it in an angular channel, and discharges it from the machine [6]. This process can be repeated multiple times to achieve greater deformation resulting from the accumulation of deformation effects. The process parameters can also be influenced by changing the speed of the rolls and adjusting the element that defines the angle in the angular channel [7].

Many research groups have undertaken studies to investigate the mechanisms affecting the material in this device and its potential industrial applications. The initial experiments, as with other SPD methods, were conducted on non-ferrous materials due to

their greater ductility [8]. Later, tests were conducted on low-carbon steels, such as DC01 [10], and ultra-low-carbon steels [11].

This study involves analyzing the results of tests conducted on selected samples of DC01 and DC03 steel sheet with thicknesses of 1.5 mm and 2 mm, deformed on two versions of the DRECE machine, with an angle in the angle channel of 100° and 103°, at constant roller speeds of 10 mm/s and 100 mm/s, with up to four passes, using two different rotation methods between processes. Tests conducted included tensile strength tests, hardness tests, and metallographic examinations, which demonstrated an increase in the yield strength, where the intensity depended on the process conditions applied, an increase in microstructural refinement along with grain elongation depending on the direction of deformation, and a non-uniform increase in hardness throughout the material's volume resulting from the device's design and phenomena occurring in the angular channel during deformation. Significant differences in the material's mechanical properties were demonstrated depending on the number of passes and the rotation method used.

Keywords: SPD, DRECE, plastic deformation, low-carbon steels, the effect of plastic deformation

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Al-based matrix composites reinforced with particles, manufactured by hot forming of semi-finished products obtained from powders

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This paper presents the principles and selected examples of technologies for the production of particle-reinforced aluminium alloy matrix composites. As an initial material a fine-grained Al-Si-Fe-Cu alloy powder was used. The reinforcing phase particles were introduced into the matrix by mixing in the presence of tungsten carbide balls, which significantly facilitated the homogeneous distribution of the components in the volume of the mixture. To produce the unreinforced alloy and composite, a hot-pressing method was used. Materials with a very high relative density were produced, suitable for use as feedstock for further forming.

In order to determine favourable conditions for hot plastic deformation, plastometric tests were carried out to analyse the influence of thermo-mechanical deformation conditions on the flow behaviour of the matrix alloy. Tests on the matrix alloy were carried out at temperatures ranging from 350 to 525 °C; this approach made it possible to identify the temperature limitations for this material. These data were used to establish the range of thermomechanical parameters for the plastometric tests on the composite. The tests were carried out over a strain rate range of 0.1 to 20 s⁻¹, which made it possible to use the data obtained as a basis for designing processes under industrial conditions using a wide range of equipment operating at significantly different tool speeds.

The microstructure of the specimens after deformation was analysed; in the case of composites, the distribution of the reinforcing phase particles resulting from plastic flow was assessed. The results obtained at this stage were used to develop the manufacturing parameters for the test products.

To produce the demonstrators, the hot extrusion method was employed. A laboratory test stand designed and used for forming products from conventional materials, manufactured using casting methods, was utilized. The tests were successful, products with the correct shape and a favourable microstructure were obtained.

The study also presents the perspectives and examples of possibilities arising from the combination of powder metallurgy and plastic deformation technologies for the production of various types of particle-reinforced composites, such as layered structures or the selective placement of the reinforcing phase in strictly defined zones of the products, in response to the specified requirements.

Keywords: metal-matrix composites (MMC), powder metallurgy, hot forming, plastometric testing, microstructural analysis

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Strength analysis of a CNC machine structure for incremental forming of thin-walled components

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Thin-walled sheet metal components are widely used across numerous industrial sectors, including the automotive, aerospace, space, energy, shipbuilding, medical, and electronics industries. The increasing demand for high product quality, dimensional accuracy, and manufacturing flexibility has driven the continuous development of advanced sheet metal forming technologies. Conventional manufacturing of sheet metal components is primarily based on established metal forming processes, such as stamping, bending, deep drawing, and metal spinning.

Incremental sheet forming has emerged as a promising alternative to conventional sheet metal forming technologies for manufacturing thin-walled components. One of its key advantages is the ability to produce parts with complex geometries without the need for dedicated and expensive tooling [1]. The most widely recognized variants of this technology include Single Point Incremental Forming (SPIF), Two Point Incremental Forming (TPIF), Double Sided Incremental Forming (DSIF), as well as numerous modified process configurations [2]. Owing to their high flexibility, these methods are particularly well suited for prototype and low-volume production, where rapid design changes and short production lead times are essential [3].

Despite significant advances in incremental sheet forming technologies, the process is still predominantly performed using conventional CNC machine tools or industrial robots, while the availability of dedicated forming machines remains limited. To address this limitation, a specialized numerically controlled machine for the incremental forming of thin-walled components was designed and manufactured at Lublin University of Technology. In the proposed solution, the sheet metal blank is clamped to the machine worktable, while the forming process is carried out using two cooperating rollers—a forming roller and a support roller—located on opposite sides of the blank. Precisely programmed movements of the worktable and both rollers induce gradual, localized plastic deformation of the material, enabling the workpiece to achieve the desired geometry. The developed machine is capable of forming components with maximum dimensions of $600 \times 600 \times 100$ mm. Due to the specific loading conditions associated with the forming process and the load transfer from the working system to the machine frame, a structural analysis was required to evaluate the stiffness and load-carrying capacity of the developed machine.

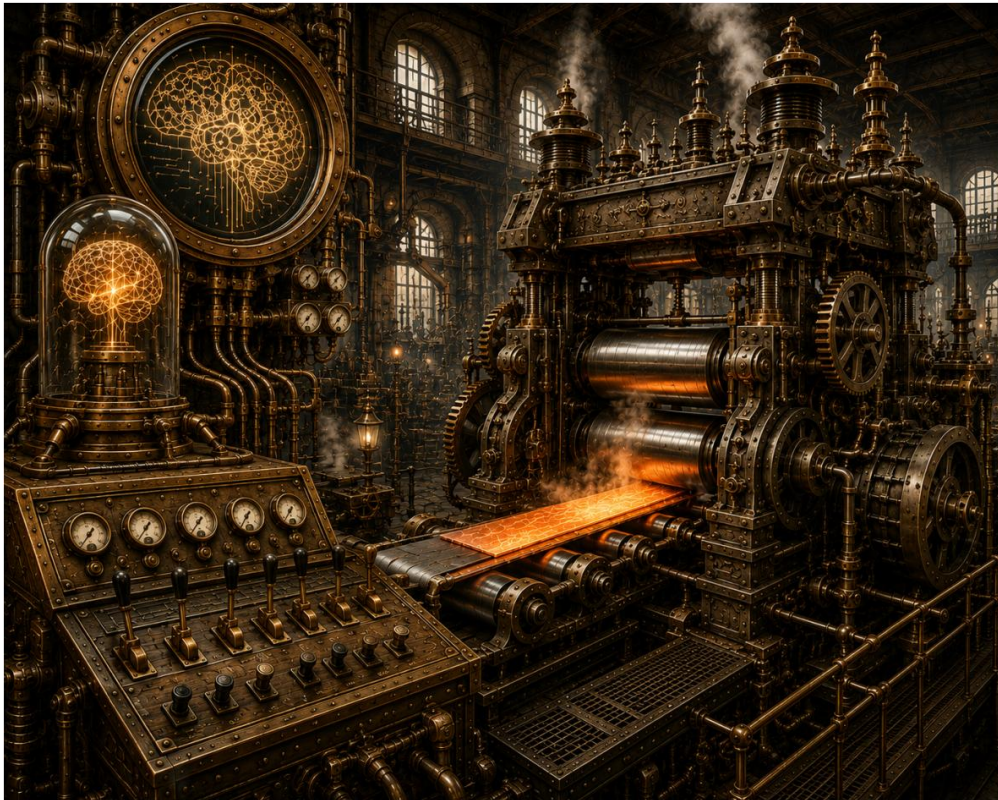
Previous investigations of the incremental forming process made it possible to determine the forces acting on the forming tools. Numerical simulations performed for an S355 steel sheet indicated a maximum forming force of 24.5 kN. To ensure

a sufficient safety margin, a significantly higher load of 50 kN was adopted for the structural analysis. The structural performance of the machine was evaluated using the Finite Element Method. The numerical model was subjected to forces representing the interaction between the formed sheet and both the forming roller and the support roller, thereby accurately reproducing the actual loading conditions of the working system. The analysis yielded the distributions of von Mises equivalent stresses and structural displacements. The obtained results provide the basis for assessing the adopted design solutions and verifying the strength and stiffness of the developed machine under loading conditions corresponding to the actual incremental sheet forming process.

Keywords: incremental forming, sheet metal forming, CNC machine, FEM

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