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Analysis of mechanical properties material during the process alternate pressing and multiaxial compression

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ABSTRACT

The paper presents the results of studies on the alternating use of countercurrent extrusion and multiaxial pressing. In the plastically formed material, this process induces the deformation states similar to those observed during channel extrusion and cyclic extrusion. According to the results of numerical studies, during extrusion, a zone of large plastic deformations is formed on the side surface of the material, which gradually disappears towards the material axis. After the multiaxial pressing stage, when the material regains its original shape, the large deformation zone moves and takes the shape of a ring in the area under the impactor. During the next extrusion operation, a significant deformation zone is again formed on the material side, while the previously deformed parts of the material are pushed out towards the material axis. On the basis of the tests carried out, it can be concluded that the alternating use of extrusion and multiaxial pressing causes the deformations to accumulate and obtains a deformation state that is particularly beneficial for grain refinement. By repeating the process multiple times, a large, uniform deformation can be obtained throughout the entire volume of the material. The paper also presents the results of material tests obtained in laboratory experiments, which confirm the increase in strength properties using the described procedure.

Keywords: plastic working processes, numerical modeling, severe plastic deformation processes, microstructures of aluminum, metallographic test.

INTRODUCTION

In recent years, many industrial sectors have experienced continuous development [1, 2]. At the same time, the level of safety requirements for the structures used has increased, which has also led to an improvement in the quality of the materials used [3, 4]. The global market, there is a growing interest in products characterized by high strength, while maintaining good plastic properties and low dead weight [5, 6]. Such products undoubtedly include products made of aluminum and its alloys. These metals are increasingly competing with commonly used steels [7, 8]. Their advantage is high strength in relation to the specific gravity and the ability to damp vibrations [9, 10]. The products made of aluminum and its alloys are characterized by worse strength properties in relation to the products made of steel [11, 12]. However, they have a lower specific gravity, with very high corrosion resistance. This results in the constant search for new light and durable materials that compete with steel products currently used in various industries. Light construction materials with specific requirements should be characterized by a highly fragmented structure, which will increase their strength properties [13]. Many studies show that the materials with an ultra-fine-grained structure [14] are characterized by the mechanical and physic – chemical properties that exceed the properties of the materials with grain structures in the micrometer scale [15, 16]. There is also a growing interest in developing a technology for producing materials with a finely divided structure and high mechanical properties of metals through the use of large plastic deformations [17, 18].

Many research institutes conduct theoretical and experimental research aimed at further developing the existing technological solutions that enable the widespread use of lightweight materials in the production of machine and device parts [19, 20]. The result of the tests should be obtaining products characterized by a highly fragmented structure, which should increase strength properties while maintaining appropriate plasticity and obtaining very good corrosion resistance [21, 22]. The most effective, known and widely used methods that allow obtaining materials with a highly fragmented structure are a group of plastic working processes with the use of large plastic deformations called SPD (severe plastic deformation). It collects a number of methods significantly different in their course, but their common feature is the impact on the material with very large deformations in strictly defined boundary conditions. Among the many SPD processes using large plastic deformations, the most popular are [23]: Equal channel angular pressing, multiaxial forging, high-pressure torsion, repetitive corrugation and straightening, cyclic extrusion compression, accumulative roll-bonding.

Most SPD methods are significantly limited by technological parameters that affect their universality in many technical and utility aspects. This is often caused by too complicated characteristics of the production process, which translates into time and costs of manufacturing the finished product. Therefore, any additional attempt to modify the classic SPD methods could significantly increase production costs, which in turn may become a low-cost solution to the assumed problem. So far, mainly aluminum and its alloys, copper alloys and Armco iron [24, 25], and in recent years also magnesium alloys [26] have been used as the feed material.

The materials with an ultrafine-grained and nanocrystalline structure are characterized by very interesting and still not fully explored physicochemical properties [17, 23, 27]. Obtaining the materials with a highly fragmented structure is currently one of the most dynamically developing areas of research in metallurgy and materials engineering [28, 29]. Such materials are characterized by much higher strength properties compared to the materials obtained using traditional methods [30, 31]. The materials with a highly fragmented structure are not only characterized by much better strength properties [17, 32, 33] but also changes in physical and chemical properties such as thermal permeability or electrical conductivity are observed [34–36].

Intensive metal forming processes have a significant impact on the structure and properties of materials [37]. Examples include grain size reduction and sublattice formation by rolling or drawing. Ultrafine-grained and nanostructured materials are characterized by unique physical and mechanical properties, such as high strength at low temperatures and exceptional superplasticity at high stress [38, 39].

The use of materials with a fine-grained structure, and thus a material with higher strength properties, can significantly improve the safety of the structure while reducing its overall weight. It is also related to economics, as a smaller amount of materials used can reduce the overall cost of building a structure or device.

Accumulation of very large deformations can lead to a strong fragmentation of the structure while maintaining the integrity of the deformed material. Most often, processes with large plastic deformations in order to fragment the structure are carried out at ambient temperature or under the conditions of plastic processing into heat, i.e. below the recrystallization temperature. The fragmentation of the structure is achieved here by introducing a large number of dislocations creating low-energy configurations in the form of high-angle grain boundaries with wide-angle boundaries. The resulting dislocation boundaries can form the so-called geometrically necessary dislocation boundaries (GNBs), taking the form of shear bands or dislocation layers, and geometrically random dislocation boundaries (IDBs), which form clusters between the former [16, 17]. The volume fraction of dislocation boundaries increases with plastic deformation and directly affects the properties of the deformed material, i.e. yield stress, plasticity or texture [23, 40]. With the increase in the value of plastic deformation, the distance between grain boundaries decreases and, at the same time, the average angle of their disorientation increases [30,38].

This article focused on the combined application of alternating countercurrent extrusion and multiaxial pressing, which was carried out on the EN AW-1050A aluminum alloy. The aim of the research was to determine how these intensive plastic processing processes affect the grain refinement of the material structure and the improvement of mechanical properties. The study presents the results of both numerical simulations and laboratory experiments. The numerical studies were used to model in detail the distribution of stresses, strains and temperatures in the deformed parts of the material, with special attention paid to the optimization of the tool geometry (impact and die angle). Laboratory experiments showed that the strength properties of the material were significantly improved by alternating cycles of extrusion and pressing, but an ultrafine-grained structure was not created without further heat treatment. The aim of the research was therefore to develop a plastic processing technology that can be used under industrial conditions and allows for a gradual improvement of the mechanical properties of the material in a cost-effective way, in particular without heat treatment. The study highlights that even small technological improvements can deliver significant industrial benefits and play a key role in product development, quality management and innovation processes.

The subject matter discussed in the paper is important in the context of managing production processes, quality and technological innovations. Modern industrial enterprises are constantly looking for the methods to increase operational efficiency while maintaining high product quality standards. The development and implementation of new plastic processing technologies, such as alternative extrusion and multiaxial compression, enables significant improvement of manufacturing processes, improvement of material properties and reduction of production costs. Managing technological innovations in this area allows not only to increase the durability and strength of products, but also to react faster to changing market and customer needs. Additionally, effective process optimization and quality control, based on the analysis of experimental and numerical research results, is the foundation for building a competitive advantage. Therefore, research on new methods of intensifying plastic deformations and their impact on the structure and properties of materials is a key element in the development of modern management systems in industry.

METHODOLOGY

The process of alternating extrusion and multi-axial compression was proposed by a team of employees of the Department of Forming and Safety Engineering of the Częstochowa University of Technology. It is characterized by the occurrence of deformation states in a plastically processed material similar to those occurring in the processes of pushing through the angle channel and cyclical compressive extrusion [41–43].

During the extrusion of the material, a distinct zone of plastic deformation is formed on the side surface of the compacted body, which gradually disappears towards the material axis. After the multiaxial pressing stage, when the material regains its original shape, the zone of greatest deformation shifts and takes the shape of a ring in the area under the impactor. During the next extrusion operation, a distinct deformation zone reappears on the side surface, while the previously deformed parts of the material move towards the material axis. By repeating the described operations, it is possible to obtain a large, uniform deformation in the entire volume of the tested material.

Numerical modeling

Numerical studies were performed using Forge NxT®, a commercially available thermomechanical analysis software that uses the finite element method. The Forge NxT program is based on the finite element method and is intended to model plastic forming processes [16]. The software allows simulation of plastic deformation processes in a state of spatial stress. The behavior of a plastically deforming medium is described by an equation based on the Norton-Hoff law:

$$S_{ij} = 2K_0(\bar{\varepsilon} + \varepsilon_0)^{n_0} \cdot \cdot e^{(-\beta_0 * T)}\left(\sqrt{3}\dot{\bar{\varepsilon}}\right)^{m_0 - 1}\dot{\varepsilon}_{ij} \tag{1}$$

where: S_{ij} – stress components of second-order tensors; $\dot{\bar{\varepsilon}}$ – strain rate intensity; $\dot{\varepsilon}_{ij}$ – strain rate components of second-order tensors; $\bar{\varepsilon}$ – strain intensity, ε_0 – base strain, T – temperature, K_0, m_0, n_0, β_0 – material constants specific to the plastically worked material.

A general form of this law is as follows:

$$\sigma = 2K\left(\sqrt{3}\dot{\varepsilon}_i\right)^{m-1}\dot{\varepsilon} \tag{2}$$

The coefficient m in Equation 2 may assume the following values: m = 1 corresponds to a

Newtonian liquid with a viscosity of η = 2K, m = 0 gives a plastic flow law for a material satisfying Huber-Mises' plasticity criterion with a yield stress of $\sigma_p = \sqrt{3}K$, that is Levy-Mises' rigid-plastic law:

$$\sigma = \frac{2}{3}\frac{\sigma_p}{\dot{\varepsilon}_i}\dot{\varepsilon} \tag{3}$$

The friction relationships between material and tools are described using the Coulomb friction model and the Treska friction model, which use specific friction coefficients and friction factors:

$$\tau_j = \mu \cdot \sigma_n \text{ for } \mu \cdot \sigma_n < \frac{\sigma_0}{\sqrt{3}} \tag{4}$$

$$\tau_j = m\frac{\sigma_0}{\sqrt{3}} \text{ for } \mu \cdot \sigma_n > m\frac{\sigma_0}{\sqrt{3}} \tag{5}$$

where: τ_j – unit friction force vector, σ_0 – base stress, σ_n – normal stress, μ – friction coefficient, m – friction factor.

The boundary conditions of the heat transfer model are assumed as the combined limiting conditions of the second and third kinds, and are described by the formula:

$$k_x \frac{\partial T_s}{\partial x} l_x + k_y \frac{\partial T_s}{\partial y} l_y + k_z \frac{\partial T_s}{\partial z} l_z + \\ + q + \alpha(T_s - T_o) = 0 \tag{6}$$

where: l_x, l_y i l_z – directional cosines of the normal to the strip surface, q – heat flow rate on the cooled strip zone, α – heat transfer coefficient, T_o – ambient temperature.

ForgeNxT software allows determining the temperature, stress, strain and strain rate fields in the tested zone of the deformed metal. The accuracy of calculations is significantly increased by the fact that the rheological properties of the ductile metal can be defined as a mathematical function or table, owing to which the actual stress-strain relationships can be reflected more accurately.

The accuracy of the results of tests based on numerical models is closely related to the applied boundary conditions. The following factors have a particular impact on the obtained results: properties of the tested materials, friction conditions and kinetic and thermal parameters of plastic deformation [42–44].

The numerical tests were carried out in two stages: the first stage included the extrusion operation, and the second stage involved the multiaxial pressing process. The raw material and tool models were created using CAD software, and then a finite element mesh was fitted to them. During mesh creation, the elements were densified in the zones of the largest deformations, which allowed obtaining high geometric accuracy after deformation.

EN AW-1050A aluminum was used as the raw material in the experiments. The height of the initial sample was 50 mm, and the diameter of the formed disk was 50 mm. The following initial conditions were assumed for both stages of the study: friction coefficient μ = 0.1 and m = 0.2; heat transfer coefficient between material and tool α = 1000 [W/Km²]; heat transfer coefficient between material and air αp = 10 [W/Km²]; initial temperature of the sample, tool and environment is 20 °C. The friction between the tools was defined as sliding friction, which corresponds to lubrication conditions. At all stages, the vertical feed rate of the tools was constant and equal to 2 mm/s. According to the nature of the cold forming process, the deformation history obtained in the first stage (extrusion) was transferred to the second stage (multiaxial pressing).

The use of thermo-mechanical models in Forge NxT software requires precise definition of boundary conditions, as they have a fundamental impact on the correctness of numerical calculations. The calculation results are particularly influenced by the properties determined during material tests, friction conditions, and kinetic and thermal parameters of plastic deformation. The geometry of the raw material and the tool were modeled using a CAD-based program, and then a finite element mesh was fitted to them. During meshing, the elements were densified in the areas that underwent the greatest deformations, which ensured the appropriate geometric accuracy after deformation.

In order to take advantage of the symmetry of the process, the theoretical analysis was limited to half of the raw material, which allowed for a significant saving of computational time.

The analysis focused on examining the geometric design of the ram and the tool, which allowed for the forming of the material without overlap. Figure 1 illustrates the distribution of strains first during extrusion and then during the multiaxial compression operation.

The strain values shown in Figure 1 can be used to predict the material flow during the extrusion process. It can be clearly seen that the largest deformations occur on the bat surface, where the formation of a crater can also be observed. In the second multi-axis pressing operation, a material overlap (sheet) is created, which gradually penetrates into the material interior.

The aim of further numerical simulations was to change the tool inclination angle to 95° and 100°. The results presented in Figure 2 show that changing the tool inclination angle can reduce or even eliminate the formation of craters in the material axis. Further studies were carried out to further reduce the risk of material overlap. To achieve this, the rocket geometry was modified. The deformation results obtained using different bat designs are shown in Figure 4.

The results of the modified bat shape shown in Figure 3 confirm that the deformation uniformity can be improved compared to the previous straight bat shown in Figure 1A. Figure 4 shows the temperature distributions obtained during the numerical simulation of the alternating extrusion and uniaxial pressing operation, which were obtained based on the variant used in the laboratory tests.

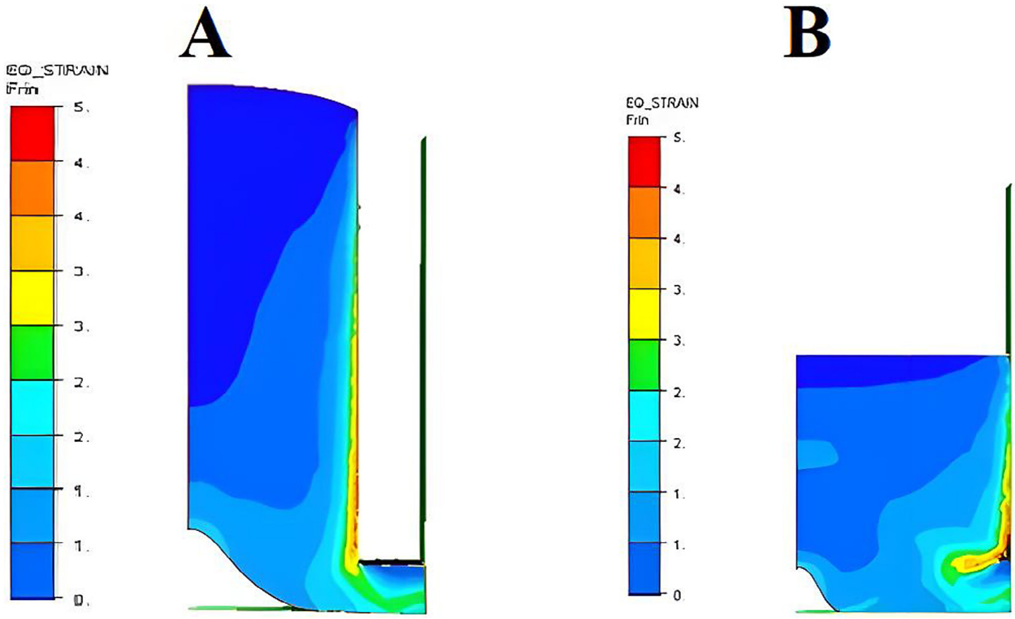

Figure 1. Strain distribution (A – extrusion operation; B – compression operation)

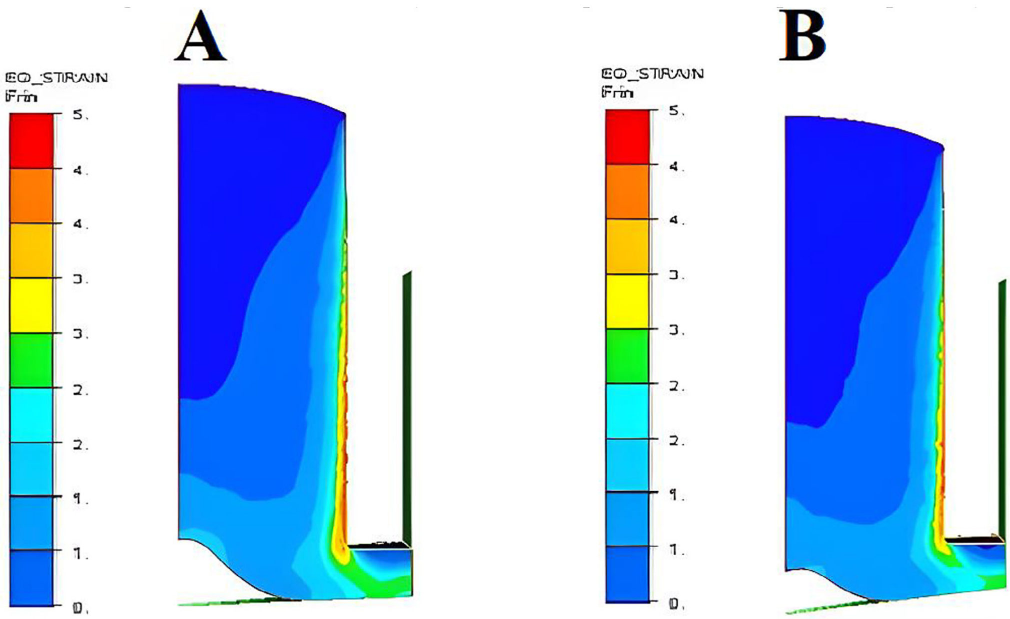

Figure 2. Strain distribution, the extrusion operation (A – 95° die; B – 100° die)

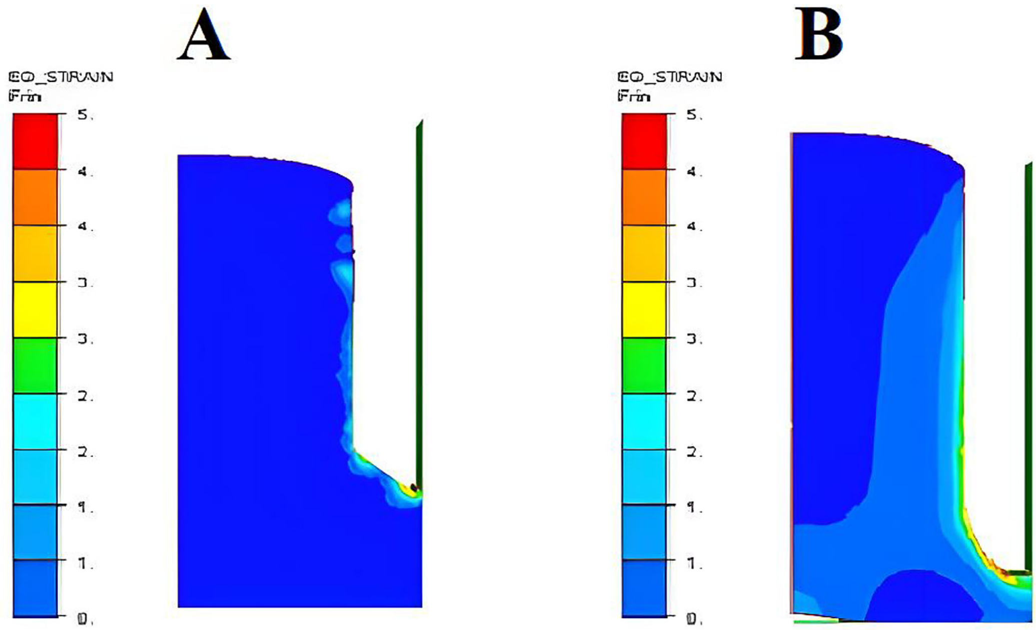

Figure 3. Strain distribution, the extrusion operation (A – 45°- angle ram; B – rounded ram)

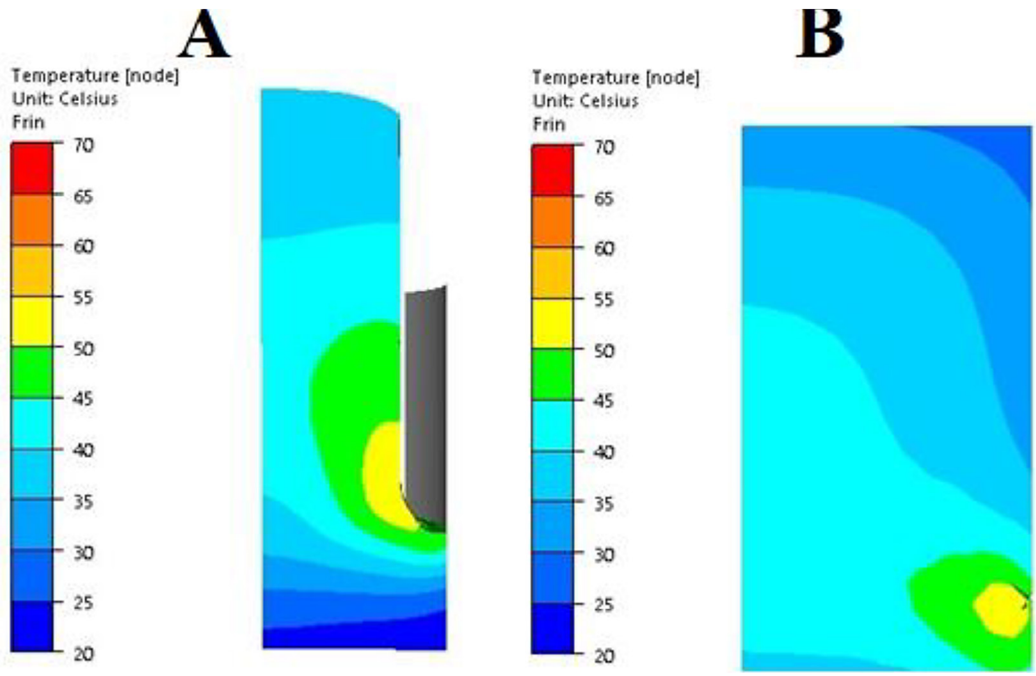

Figure 4. Temperature distributions (A – 1 step – extrusion process; B – 2 step – compression process)

From the temperature distribution shown in Figure 4, it can be seen that the largest temperature increase during the extrusion process occurs on the bat surface, but the maximum temperature does not exceed 55 °C

The results obtained in the first stage of alternating extrusion and uniaxial pressing were applied in the subsequent stages, but no significant increase in temperature was observed. On the basis of the obtained results, it can be concluded that a small increase in temperature did not significantly affect the values of stress and compressive force shown in Figure 12.

Laboratory tests

Laboratory tests were performed on the HYDRAPRESS PWH-250r vertical press. The

PWH-250r frame hydraulic press is designed to perform metal forming operations, such as extrusion, stamping, jacking, riveting, etc. The press is equipped with a slider to maintain greater rigidity and parallel movement of the upper table. This is accomplished by eight rolling, guiding blocks. The main actuator has a pressure force and distance measurement system. The initial dimensions of the sample were 50 mm diameter, 150 mm length. During the pressing process, the diameter was reduced to 42 mm. In both processes, the piston speed was 100 mm/min. The oil pressure was not analyzed.

The sets of punches and dies were mounted on the press table. Figures 5 (A, B, C, D) show photos of the bottom and top plates as well as the die and punch, as well as the assembly of the punch-die set with visible guide columns. A photograph of a sample of EN AW-1050A aluminum obtained after extrusion is shown in Figure 6.

The photograph of the samples after extrusion shown in Figure 6A confirms the formation of the compression protrusion. To ensure the stability of the sample pressing process, the protrusion was removed (Figure 6B).

In the next technological operation, i.e. compression in a closed die, the sample was expanded in such a way that it filled the entire volume between the punch and the die. The squeezed sample could be removed from the die only by disassembling it and pressing the material with a full punch, therefore such a sample was not pulled out, but squeezed again during the next technological operation of the cycle. A photo of the material obtained after the second extrusion is shown in Figure 7.

Subsequent extrusion operations increased the total pressing force from about 375 kN for the first extrusion to nearly 600 kN for the third extrusion, which confirms the strengthening of the material.

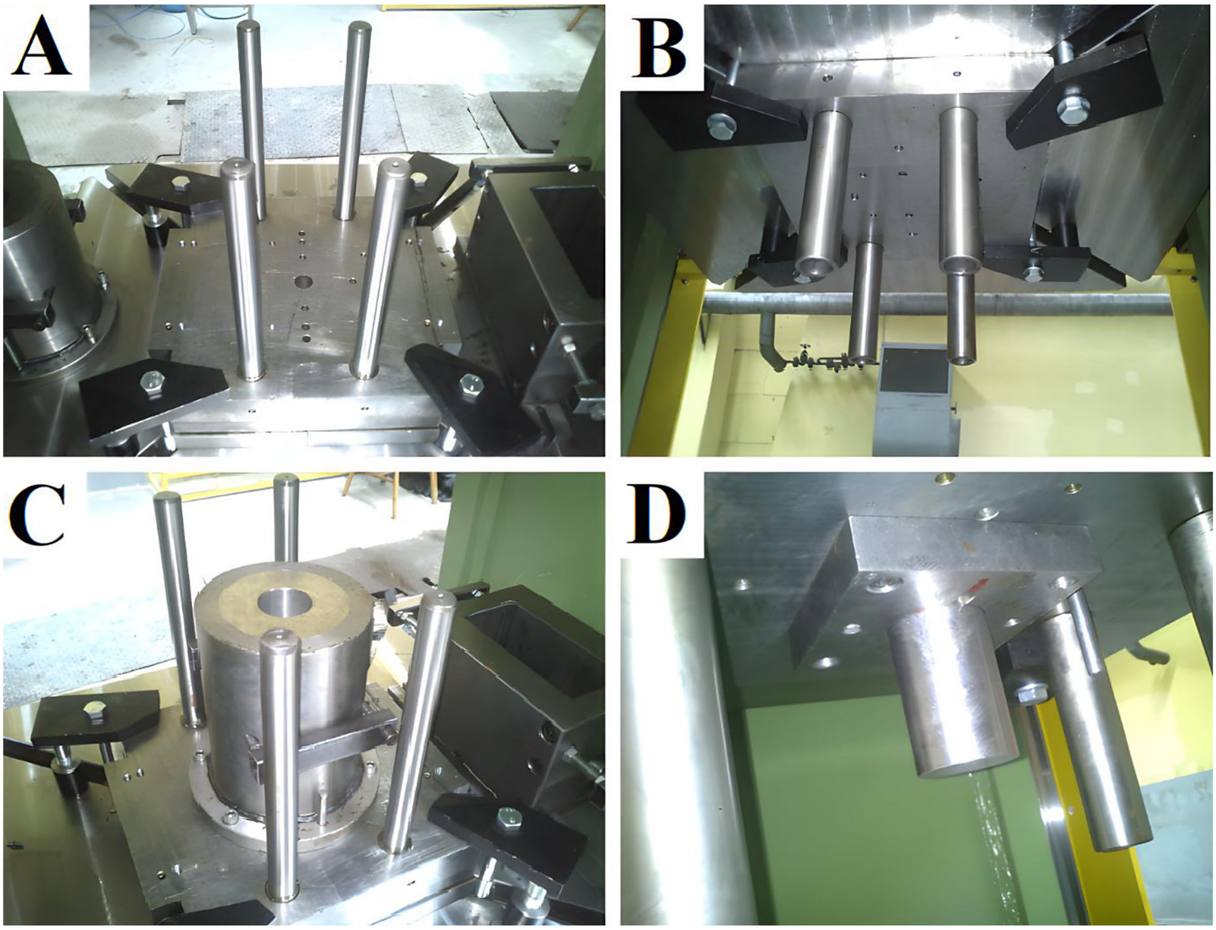

Figure 5. A – Photo of the bottom plate mounted on the working table of the hydraulic press; B – Photo of the top plate mounted on the ram of the hydraulic press; C – Photo of the die mounted on the plate of the working table of the hydraulic press; D – Photo of the punch mounted on the top plate of the hydraulic press slider

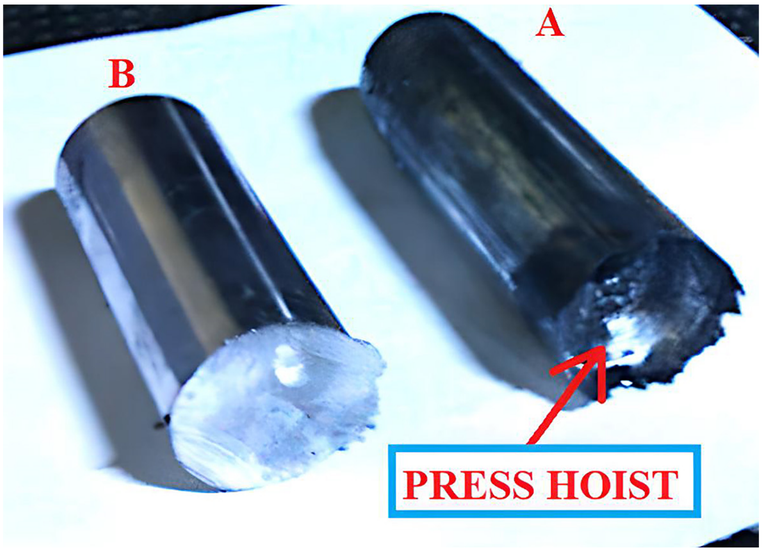

Figure 6. Photo of aluminum grade EN AW-1050A after extrusion (A – sample with the press pull marked, B – sample prepared for the next operation, i.e. compression)

Figure 7. Photograph of EN AW-1050A aluminum after first extrusion (A – first sample; B – second sample extruded immediately after the first) and second extrusions (C – sample prepared for the next operation; D – sample after removal from the punch)

Testing of materials

Selected EN AW-1050A aluminum samples obtained after successive extrusion operations were cut in half, and then vertically along the axis of symmetry, and subjected to metallographic tests on longitudinal and transverse sections, and subjected to hardness tests. The FM-700 microhardness tester by FutureTech was used for hardness testing. The hardness at a low load force of 1 kgf was determined by determining the HV1 hardness. Pictures of the samples subjected to hardness tests are shown in Figure 8 (A, B, C).

Hardness measurements were taken along the diameter of the sample at a distance of approximately 15 mm and 30 mm from the sample face, respectively. The initial hardness value HV1 was 22. The results obtained for each sample are shown in Figures 9–11.

On the basis of the hardness changes measured along the diameter of the sample, shown in Figure 9, it can be concluded that the left side of the tested cross-section was deformed more than the right side. This can probably be explained by the uneven flow of material inside the stick. At a distance of 15 mm from the front surface of the sample, the average HV1 hardness value is approximately 37. The hardness measurements taken at a distance of 30 mm did not show significant differences in the HV1 value, and a similar pattern of changes was observed along the diameter of the sample.

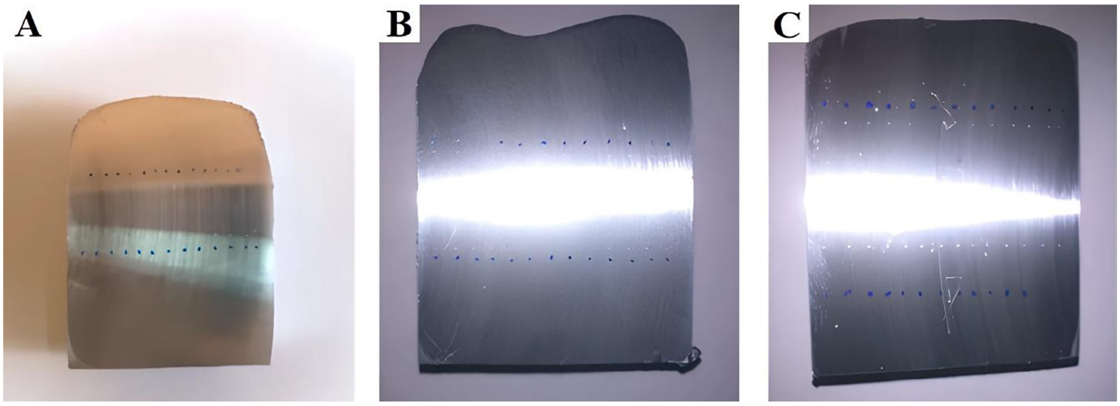

Figure 8. A – Photo of a sample with marked hardness measurement points for aluminum after 1 extrusion; B – Photo of a sample with marked hardness measurement points for aluminum after 2 extrusions; C – Photo of a sample with marked hardness measurement points for aluminum after 3 extrusions

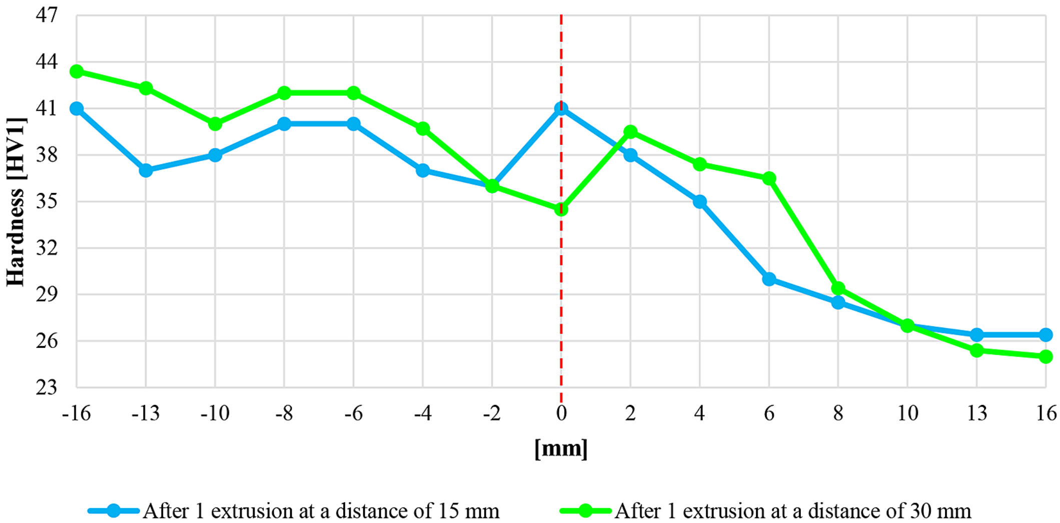

Figure 9. Graph of HV1 hardness changes for aluminum after 1 extrusion (at a distance of 15 mm from the front of the sample; at a distance of 30 mm from the front of the sample)

The graphs of hardness changes for aluminum after the second extrusion (Figure 10) along the diameter of the sample do not show such large discrepancies as in the case of the material after the first extrusion. The average HV1 hardness value along the sample diameter at a distance of 15 mm from the sample face is about 50. Hardness measurements at a distance of 30 mm from the sample face did not show significant changes in the HV1 hardness value.

Graphs of hardness changes along the diameter of the sample for aluminum after the third extrusion (Figure 11) are similar in character and values to the hardness measured for the material after the second extrusion. It can therefore be concluded that further deformation of the material will not result in a further increase in hardness. The graph of hardness changes presented in Figure 11 shows that for real deformations above 3 there is no significant increase in material hardness.

Figures 12 presents graphs of changes in the punch force during the process of alternating extrusion and uniaxial compression for the values calculated during numerical simulations and the values measured during laboratory tests.

On the basis of the graph of the change in impact force measured during the extrusion process shown in Figure 12, it can be concluded that higher force values were achieved during the laboratory tests. Also during the next stage of the process - multi-axial compression (Figure 12), higher force values were obtained in laboratory tests. The differences between the values calculated during numerical simulations and those

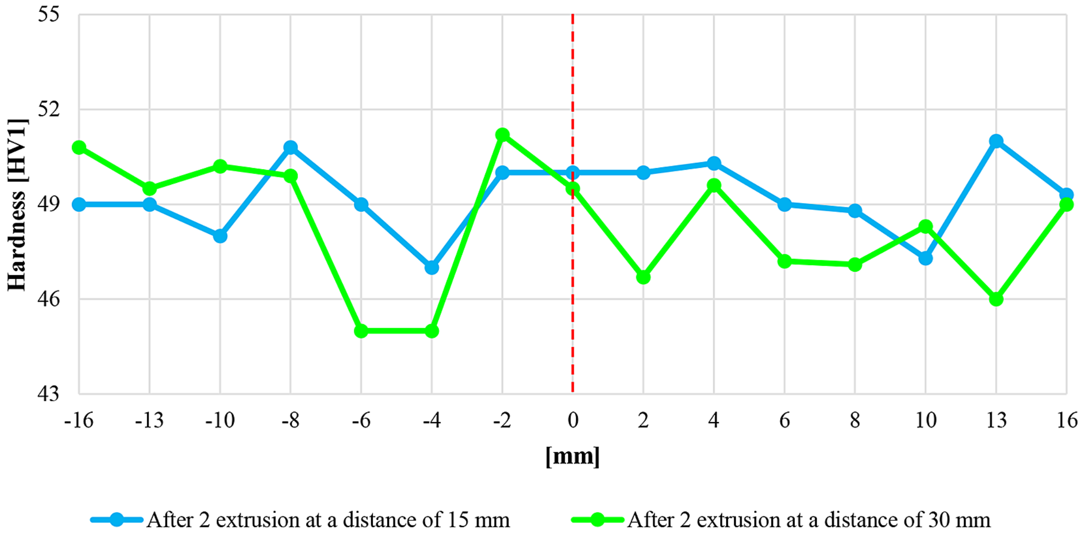

Figure 10. Graph of HV1 hardness changes for aluminum after 2 extrusion (at a distance of 15 mm from the front of the sample; at a distance of 30 mm from the front of the sample)

measured during laboratory tests did not exceed 7–10%. A difference in the force values could be expected because the numerical simulations did not take into account the resistance of the guides in the guide columns.

The significance of the improvement in the mechanical properties of the material compared to traditional plastic forming methods can be assessed from several aspects. First, the hardness values (HV1) measured after successive extrusion cycles clearly indicate the strengthening process of the material. An average value of 37 HV1 was obtained after the first extrusion, while 50 HV1 was obtained after the third, which is an increase of about 35%. This increase in hardness indicates significant mechanical strengthening without compromising the structural integrity of the material. In contrast, traditional plastic forming processes, such as cold rolling or forging often do not allow such a degree of uniformity and strain distribution throughout the volume. In addition, microstructural studies have shown gradual refinement and elongation of the grains, which is also caused by large plastic deformations. Therefore, the results show that the combination of alternative extrusion and multiaxial compression results in more efficient grain structure modification and hardening than conventional methods, without

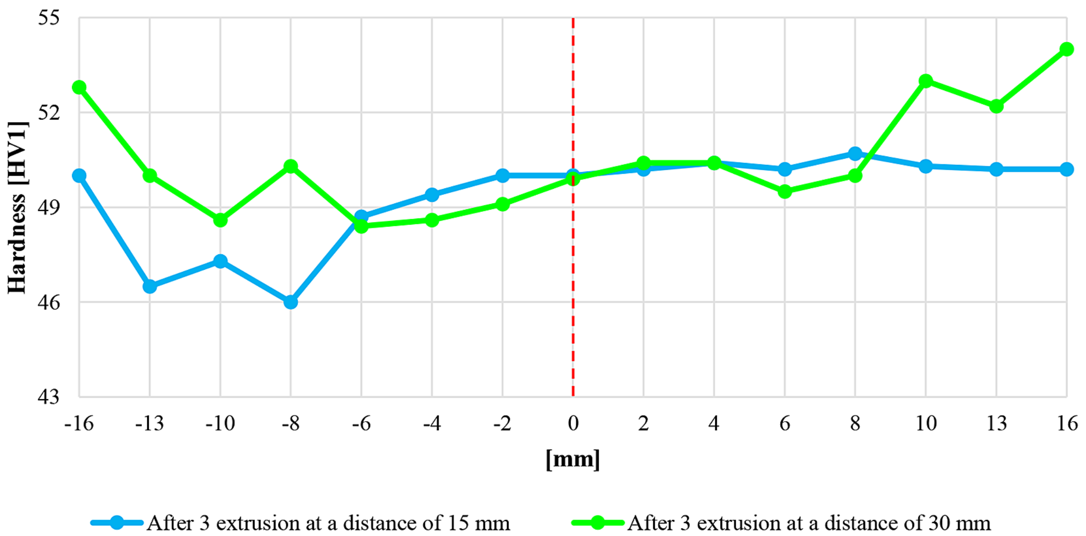

Figure 11. Graph of HV1 hardness changes for aluminum after 3 extrusion (at a distance of 15 mm rom the front of the sample, at a distance of 30 mm from the front of the sample)

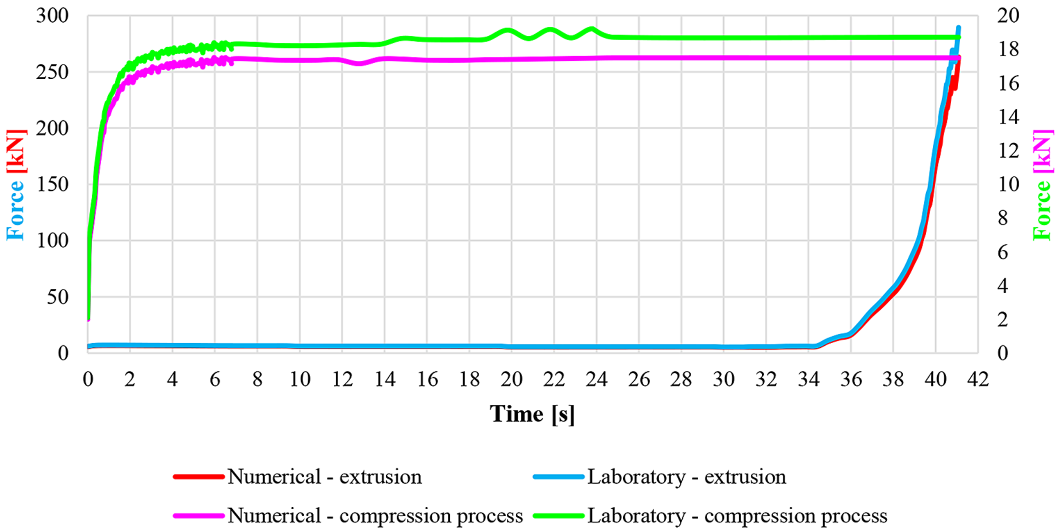

Figure 12. Graphs of changes force during 1 step – extrusion and graphs of changes force during 2 step – compression process

increasing production costs. This is particularly important for the industrial application and mechanical performance of the material.

Metallographic test

Selected EN AW-1050A aluminum samples obtained after successive extrusion operations were cut in half, and then vertically along the axis of symmetry and subjected to metallographic examination in longitudinal and transverse sections. The evaluation of the influence of deformations on the structure of the tested aluminum alloys was carried out based on tests performed using a NIKON ECLIPSE MA-200 optical microscope. The obtained images of the microstructure are shown in Figure 13.

On the basis of the microstructures of aluminum shown in Figure 13, after successive stages of the alternating extrusion process, the formation of fragmented elongated grains can be observed, which should increase the strength parameters of the material.

On the basis of the included photos of the microstructures of the tested material, it can be concluded that the fragmentation of the structure occurs with the increase of deformation.

RESULTS AND DISCUSSION

The results of the numerical simulation of the process of alternating extrusion and multiaxial compression show that by appropriately modifying the shape of the punch, it is possible to produce a material free from internal defects, such as compression marks. The studies show that to achieve the desired effect, it is necessary to apply a maximum diameter reduction of 30% during extrusion and round the lower edge of the stick.

Selecting the appropriate punch geometry significantly reduces the risk of wrinkles and internal defects during the multiaxial extrusion process. Laboratory tests of the extrusion process conducted using the HYDRAPRESS PWH-250R vertical press showed the appearance of a significant press pull at the bottom of the sample. In order to remove the extruded material from the punch, another sample was placed in the die and the part of the material of the first sample remaining under the punch was squeezed out to the zone above the calibrating part of the punch. Squeezing the two samples separately caused the upper surface of the second sample to be distorted, as the extruded material flowed into the press thread formed in the previous sample. In the next technological operation, i.e. compression in a closed die, the sample was expanded in such a way that it filled the entire volume between the punch and the die. The squeezed sample could be removed from the die only by disassembling it and pressing the material with a full punch; therefore, such a sample was not pulled out, but squeezed again during the next technological operation of the cycle. Subsequent extrusion operations increased the total pressing force from about 375 kN for the first extrusion to nearly 600 kN for the third extrusion, which confirms the strengthening of the material.

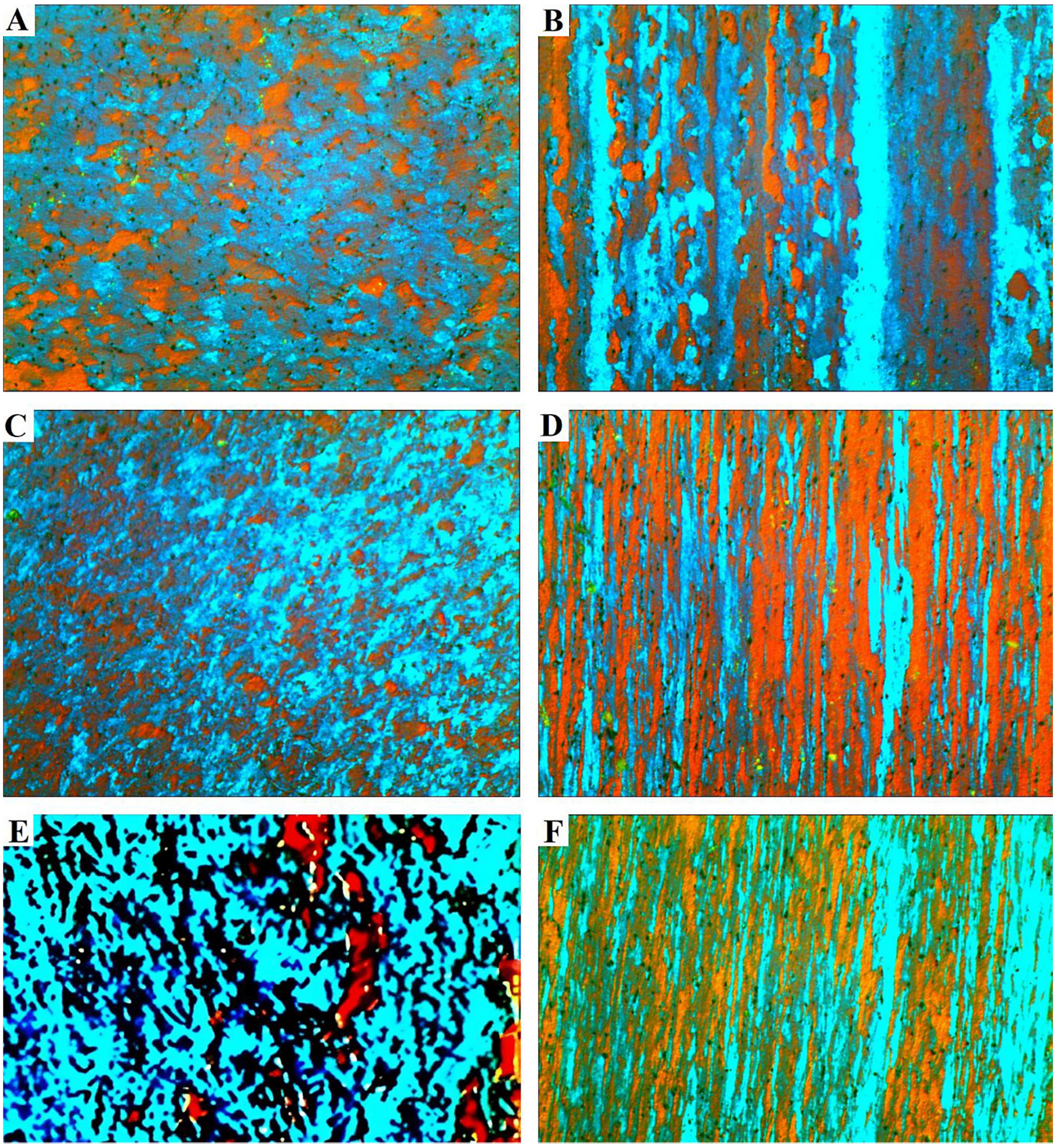

Figure 13. Microstructure of EN AW-1050A aluminum after the first extrusion (A – cross section; B – longitudinal section), after the second extrusion (C – cross section; D – longitudinal section), after the third extrusion (E – cross section; F – longitudinal section)

The next research stage of the alternating extrusion and multi-axial pressing process, aimed at developing technological guidelines, was to conduct heat treatment tests of EN AW-1050A aluminum. Recrystallization annealing was performed at 300 °C for 1 hour, and then supplemented by slow cooling in air. The results of the obtained microstructures are shown in Figure 14. In the case of the EN AW-1050A alloy, no ultrafine-grained structure was observed after heat treatment.

The detailed microstructural analysis presented in Figure 14 shows that although the grains have become more uniform compared to the as-formed condition, they are still relatively coarse-grained and only initial signs of static recrystallization can be observed. In Figure 14A, which shows the situation before heat treatment, fragmented and elongated grains can be observed, which are characterized by a high density of sub-particle boundaries and high strain. In Figure 14A, which shows the situation after recrystallization annealing, the grain boundaries have become rounded and more regular. This indicates the beginning of static recrystallization. The formed grains remain in the micrometer range and do not exhibit ultrafine-grained (UFG) properties, such as high-angle boundaries between sub-micron grains. All this confirms the fact that annealing is an effective process in restoring formability and minimizing internal stresses. However, this in itself is not

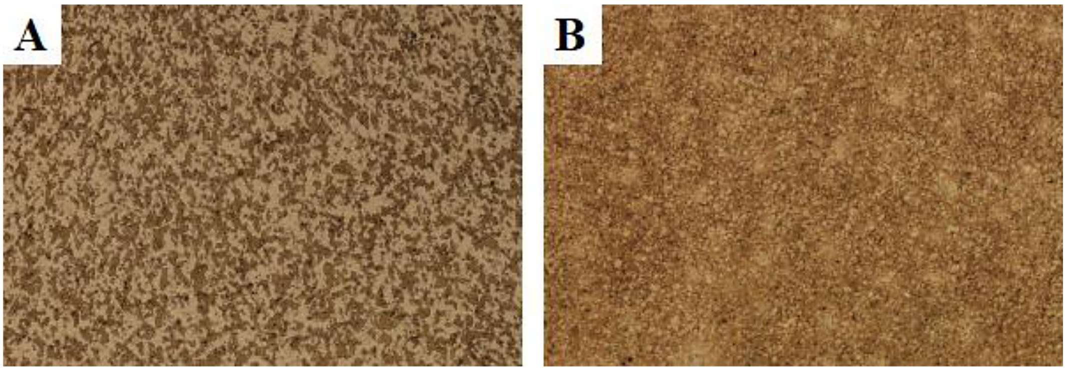

Figure 14. EN AW-1050A alloy microstructure at 50x magnification (A – before heat treatment; B – after recrystallization annealing)

sufficient to refine the grain unless thermomechanical treatment cycles or optimized forming parameters are used.

The results of numerical simulations and laboratory tests showed that the use of alternating extrusion and multiaxial pressing is an effective way to accumulate large plastic deformations in the volume of EN AW-1050A aluminum. The deformation zone formed during the process is evenly distributed over the entire cross-section of the material, which allows for a reduction in grain size without the occurrence of material defects such as wrinkling or cracking. This behavior is consistent with the results of the ARB (accumulative roll bonding) method studied by [17, 18], where a similar improvement in mechanical properties was also observed.

The tests showed that by modifying the tool geometry (especially the angle of the punch and die), the number of material defects occurring in the deformation zones can be significantly reduced. An optimal design, such as a rounded die, promotes a gradual, uniform material flow, reduces heat accumulation and results in an even hardness distribution. This is particularly important in industrial environments, where consistent quality is a key requirement during high-volume production [40, 41].

The measured total in the extrusion force in laboratory tests (increasing from 375 kN to almost 600 kN) clearly confirm the work hardening of the material. This phenomenon is well known from cold working processes, where deformation increases the number of lattice defects, such as dislocations, which leads to an increase in strength properties [30]. This phenomenon is the result of internal structural changes in the material – mainly an increase in dislocation density – which hinder the movement of new dislocations. As a result, the yield strength of the material increases, which means that a higher force is required for further plastic forming. However, it should be noted that despite the reduction in grain size, no UFG structure was formed. This confirms the conclusion from [17, 18] that in order to obtain the UFG structure, in addition to plastic deformation, a controlled heat treatment is also required. The increase in the extrusion force from 375 kN to 600 kN during successive extrusion cycles is a clear sign of increasing material hardening, which is the result of microstructural changes associated with the accumulation of plastic strains. The increasing dislocation density and grain boundary refinement increase the yield strength of the material, so that each subsequent forming step requires a higher force. This phenomenon confirms that the applied technology not only acts towards grain refinement, but also causes significant material strengthening, which can be beneficial in the production of structural elements exposed to high mechanical stresses. However, from the perspective of process control, it is important to consider the risk of a decrease in formability, especially after repeated cycles, which may require the use of intermediate heat treatments to stabilize the microstructure. The observed increase in strength and parallel increase in hardness value (HV1) are consistent with the SPD (Severe Plastic Deformation) processes known in the literature [30, 31, 34] and confirm that the industrial implementation of this technology allows not only for the improvement of design parameters but also for the optimization of manufacturing costs.

The hardness measurement results (increase in HV1 value from ~22 to ~50) clearly reflect the refinement of the grain structure and improvement of the strength properties of the material. With the increase in the number of deformation cycles, the hardness did not increase further (after the 3rd extrusion), which may indicate approaching the formability limit. Similar behavior was observed by [34], where the mechanical properties of aluminum alloys were saturated after reaching a certain deformation threshold.

In terms of industrial application, one of the most important advantages of the process is its technological simplicity and energy efficiency. Low-temperature processing (up to 55 °C) allows the processing of heat-sensitive alloys, as well as reduces energy consumption and ecological footprint. This is particularly important in the context of sustainable industrial development strategies, such as the European Green Deal [28, 29, 45].

Recrystallization heat treatment did not lead to the formation of an ultrafine-grained structure, which indicates the need for further experiments, such as optimization of holding temperature and time or testing of deformation methods combined with thermomechanical cycles. Such studies contribute to the design and introduction into industrial practice of new high-performance metal materials [27, 30].

The process of alternating extrusion and multiaxial pressing is not only important from the perspective of materials science, but also has direct industrial application. The studies confirm the fact that such plastic processing methods provide significant added value both in terms of product development and production quality management.

The presented studies were conducted primarily under laboratory conditions, but the material used (aluminum alloy EN AW-1050A) is known as a commonly used material suitable for industrial applications. The technological parameters used in the experiments (e.g. tool geometry, pressing speed, degree of deformation) were deliberately selected in such a way.

The results of the conducted research show that by applying large plastic deformations in a cyclic and targeted manner by combining multiaxial compression and alternating extrusion, the material properties can be gradually improved without the use of heat treatment. The conducted laboratory tests emphasize that the hardness and compressive strength values increased gradually after each deformation cycle. This fact indicates the gradual hardening of the material. This phenomenon suggests that with the right tool geometry and technological process parameters, structural and property improvements can be achieved without capital-intensive heat treatment processes. In turn, microstructural studies indicate that controlled heat treatment is still necessary to create an ultrafine-grained structure. Therefore, the management of strain accumulation alone can bring significant benefits, but additional processes such as heat treatment may also be required for some purposes.

The technological approach described in the study – combining alternating extrusion and multi-axis pressing – allows for achieving a balance between improving quality and reducing costs in industrial production management. During the process, owing to changes in classical plastic forming methods, it is possible to obtain material properties (e.g. increased strength, more uniform structure, fewer internal defects) that improve the quality of the final product. Additionally, the technique used does not require huge investments and energy-consuming heat treatment phases. Thus, production costs can be kept low. It is possible to reduce the number of rejects, increase production reliability by optimizing the tool geometry and repeating forming cycles. This has a direct impact on ensuring the highest quality and customer satisfaction. This approach is a new strategy in managing technological innovations, i.e. using the solutions based on incremental improvements that simultaneously maximize added value and keep costs under control.

The test results show that the alternating use of counter-extrusion and multi-axial pressing significantly contributes to the improvement of the mechanical properties of EN AW-1050A aluminum. The obtained increase in hardness (HV1 values increase from 22 to ~50) in relation to the increase in the number of deformation cycles confirms that during the process, effective grain refinement occurs, which increases the strength of the material. However, the tests also show that the improvement of mechanical properties is not linear: after the third deformation cycle, the hardness no longer increases significantly, which indicates that the saturated deformation state has been reached.

Compared to traditional plastic processing methods, such as unidirectional pressing or rolling, the advantage of the alternating extrusion and multi-axial pressing process is that a large uniform deformation can be achieved throughout the material volume, while maintaining structural integrity. This enables the production of materials with fine grain sizes, high strength, but still sufficiently ductile, which is of particular importance in such sectors as the aerospace, automotive and energy industries.

The significance of the improvement in mechanical properties can be measured not only by the increase in the hardness or strength of the material, but also by the fact that the process does not require the use of expensive heat treatments. Numerical simulations and laboratory experiments have shown in close agreement that the increase in forming forces – from 375 kN to 600 kN – is consistent with the increase in the strength of the structure, which indirectly confirms the efficiency of the process.

In addition, the experiments confirmed that the process did not lead to the formation of an ultrafine-grained structure without heat treatment, which requires further optimization of the microstructure by including an inter-operational heat treatment. This may indicate new directions of research in the combined use of plastic forming and heat treatment.

Overall, the improvement in mechanical properties of the new technology is not only measurable and reproducible, but also offers a more favorable alternative in terms of production costs compared to traditional technologies. On the basis of the combination of technological flexibility and industrial applicability, this process can be considered a potential candidate for integration into modern production systems.

CONCLUSIONS

On the basis of laboratory and numerical tests, it can be concluded that the combination of alternative countercurrent extrusion and multiaxial pressing offers an effective method for accumulating plastic strains in the EN AW-1050A aluminum alloy. The deformation zone formed during the process is evenly distributed over the cross-section of the material, which promotes grain refinement without the occurrence of significant internal material defects such as wrinkling or cracking.

A reduction in grain size is observed with the accumulation of strains. This alone does not lead to the formation of an ultrafine-grained structure. The increase in the measured hardness values (HV1) – from 22 to about 50 after the third extrusion – clearly indicates the strengthening of the material during cold forming. At the same time, the extrusion force also increased from 375 kN to almost 600 kN, which can be described as an increase in the dislocation density and grain boundary refinement.

It should be noted that the hardness increase occurring in parallel with the deformation shows saturation after the third cycle. This indicates that the material has reached its formability limit. This result is in line with other ongoing studies on severe plastic deformation (SPD) showing that the improvement of properties stops or slows down after a certain level of deformation.

The tool geometry used, and above all the embossed shape of the punch and the angle of the embossing tool, plays a fundamental role in the success of the process. Numerical simulations have shown that the appropriate tool design allows for a smooth flow of the plastically deformed material, reducing heat build-up and the risk of material defects. This is particularly important in industrial environments where constant quality and reliability are required.

The energy efficiency of the process is also remarkable: the measured temperature did not exceed 55 °C even at intense deformation. This offers the possibility of processing heat-sensitive materials while reducing energy consumption and the ecological footprint of production – in line with sustainable development strategies such as the European Green Deal.

The performed recrystallization annealing tests (300 °C, 1 h, slow air cooling) did not lead to the formation of an ultrafine-grained structure, which suggests that further parameter optimization or a different combination of heat treatment cycles of deformation is required to obtain the UFG structure.

The alternative extrusion and multiaxial pressing offer a technological approach that is not only important from the perspective of materials science, but also has industrial applications. Studies have shown that this technology can cost-effectively improve the mechanical properties of metals, reduce manufacturing defects as well as facilitate product development and quality management processes. This method offers a new opportunity for innovative, sustainable and economic development of modern production systems.

On the basis of the results of the alternating extrusion and multiaxial compression tests, the following conclusions can be drawn:

1. A combination of extrusion processes and multi-axial compression that allows the accumulation of deformation can be applied in industrial settings.

2. As the total true strain increases, the average grain size of the tested materials decreases, but this does not result in the formation of an ultra-fine-grained structure.
3. An increase in the value of the greater true strain in the cycle also causes a decrease in the average grain size.
4. For aluminum in the en aw-1050a grade, the increase in real deformation also resulted in a decrease in plasticity.
5. Skillful combination of cold plastic working with inter-operational heat treatment may allow for obtaining a greater fragmentation of the microstructure of the tested materials, which will affect the strength parameters.

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