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POSSIBILITIES TO OBTAIN PRODUCTS FROM 2024 AND 7075 CHIPS IN THE PROCESS OF CONSOLIDATION BY KOBO EXTRUSION

Basing on experimental data, the possibility of consolidating side products of turning, milling and drilling of aluminum alloys into the form and properties of solids metals using low-temperature KoBo extrusion method has been assessed. Research regarding mechanical and structural properties of the final products revealed their total consolidation and proved their compatibility with requirements for products made of bulk billets. Importantly, the chips consolidation process does not require high or even raised temperature, which significantly reduces the unfavorable phenomenon of chips oxidation and its negative influence on the structure and mechanical properties of products. A very good effect of chips compaction has been proved by KoBo method, which has been confirmed by relatively slightly different mechanical properties of the material after recycling compared with the bulk one. Among currently applied techniques of consolidation of dispersed fractions in a solid state (leaving the melting stage out), the KoBo method seems an innovative way of utilizing metallic chips, as it enables a cold deformation process.

The paper presents investigations using 2024 and 7075 aluminum alloys chips from manufacturing process, formed into briquettes and deformed under conditions of KoBo extrusion process, which enables to obtain long product by cold forming. The final product characterized by good microstructures, mechanical features and low cost of production.

Keywords: metallic chips, KoBo method, cold plastic consolidation, structural and mechanical properties of extrudate

1. Introduction

Aluminum alloys are important non-ferrous alloys that have been widely used in automotive, aerospace and construction applications due to their low density, good mechanical properties, corrosion resistance, good weldability, good machinability, high formability and relatively low cost [e.g. 1-2]. As valuable by-products of manufacturing metallic parts, aluminum alloy machining chips are normally recycled by melting which destroys their microstructure and consumes a substantial amount of energy [e.g. 3-6].

Aluminum machining chips are one of the most difficult types of scrap to recycle using traditional methods of remelting. It is characterized by elevated surface/volume ratio and it is usually oxidized and covered by different types of contaminants (i.e. lubricants used for the machining process). Due to these features, conventional consolidation by melting technologies may lead to different drawbacks and environmental issues, e.g. fumes and gas formation, energetic/economic issues, i.e. low efficiency in terms of obtained material and high energetic cost and technological issues, i.e. defectiveness in the final product. In the last years, the consolidation by melting of aluminum alloys has been deeply investigated by many researchers [e.g. 3,5,7-8]. From these studies it arises that the recovery rate of the entire process usually hardly reaches 50%. Moreover, the whole process requires several intermediate operations: cleaning, dying, compacting, etc. as well as high energy usage, causing these conventional technologies to be inadequate for the modern industrial needs.

One of the promising ways of consolidation of metallic scrap, alternative to re-melting, is the technology based on plastic working. Then appropriate high pressure, high temperature and large plastic strain are needed in order to crush the oxides layer (which covers the individual chips) and to activate diffusion as well as the bonding processes [9-10].

There are great literature reports concerning the consolidation of metallic chips based on the traditional plastic deformation processes and their combinations. In this field most of the numerous achievements in chip consolidation described in the literature are dedicated to aluminum and its alloys, which is widely reported in the general reviews by [e.g. 11-16].

Generally, based on the literature described above, it should be concluded that the processes of chips consolidation are mainly conducted via several-stage procedures. These methods (containing compacting-pressing, heating and plastic working) lead to the successful recycling process [16-19].

The research has shown that the consolidation process of plastic materials based on Al and Mg alloys is able to provide very high quality and desired properties of the output product, in some cases even better than for bulk material [20-22]. Obtaining material possessing good mechanical properties is conditioned

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by prevention of too thick oxide coatings on the chip particles' surface in the process of refinement and depletion of aluminium oxide coatings on the chip particles' surface as a result of using large plastic deformation [21-22].

The above suggested methods, which do not use melting processes and high temperature, seem to be highly attractive from the economical point of view. The use of plastic consolidation should limit the waste of metallic material almost completely, and the estimated amount of work and energy is from two up to five times lower compared with recycling by melting method [23-26]. However, conventional, high-temperature extrusion of chips does not result in their satisfactory consolidation due to the slight value of extrusion ratio λ and strong surface oxidation of chips. So far, using SPD or ECAP methods to solve this problem, given their low efficiency, have not proved to be very applicable in the industry. That is why, new methods of chip consolidation by low-temperature processes are being investigated. Such a result can be obtained by the use of KoBo extrusion method [e.g. 20,25-27].

The KoBo method is an unconventional method of metallic materials extrusion using the phenomenon of changing the path of plastic deformation by introducing a tool (die) into cyclic oscillations (around its axis) by a given angle and at a predetermined frequency (Fig. 1).

The oscillations of extrusion die enforce constant changes of the deformation path, thus increasing plasticity and allowing for relatively high diameter reduction in a single step of deformation process [28].

The KoBo extrusion differs from the conventional extrusion process by additionally implemented cyclic torsion of metal, resulting from a forced reciprocal rotations of adequately configured die (Fig. 1). Basing on the analysis of the experimental dates, the superplastic nature of metal flow subjected to KoBo extrusion has been revealed. A cyclic change of deformation path leads to shear banding and generates over-balance concentration of point defects, typically in the form of nano-dimensional clusters of interstitial atoms.

More importantly, this superplastic type of metal flow makes it possible to obtain a high quality product, even with complex shapes. Low flow stress and lack of strain hardening at high strains, which characterizes superplastic flow, allows us to deform even hard alloys at low temperatures by the KoBo extrusion method.

The KoBo method can be classified as an SPD method, but unlike most of the methods of this group,which only aim to change the material's properties by grain fragmentation, it also allows theshaping of the desired geometry products, as in conventional extrusion processes. The main advantagesof the KoBo method are the considerable reduction of the extrusion force and thus reduction in deformation work, and the possibility of implementing the process without preheating the billet and tools, with the possibility of high deformation [27,29]. As a result, a product is obtained with high plastic properties, suitable for further, direct forming operations [29].

The great advantage of the process compared to classical SPD and extrusion methods is to obtain the product in a single step [30-32], at room temperature and with properly reduced cross sections, even for hardly deformable materials. It is believed that, during process a new mechanism of deformation called visco-plastic flow occurs [33]. The axial-radial flow typical for the extrusion process is replaced by layer-like radial flow. Researchers emphasize that, during plastic flow, the relation between flow stress and strain rate is linear, where the viscosity coefficient is the proportionality factor. In the materials processed to high strains by reversible, monotonic extrusion, the generation of point defects may lead to an concentration overbalanced state, greatly exceeding equilibrium values. High contention of point defects affects the viscosity coefficient. Radial flow dominates in the deformation zone, while the zone shape is similar to a cylinder with a base diameter equal to the diameter of the batch. Therefore, during the KoBo extrusion dead zone, a region where material does not flow, is not apparent.

High plasticity of materials after KoBo is an important differentiating factor form other SPD techniques such as ECAP, as it allows further deformation and shaping of the material, without the need of annealing, which might lead to recrystallization and deterioration of mechanical properties [34].

In comparison to conventional method of metal extrusion, high extrusion ratio λ, can be realized at low temperature conditions of KoBo method, reach much higher value (up to

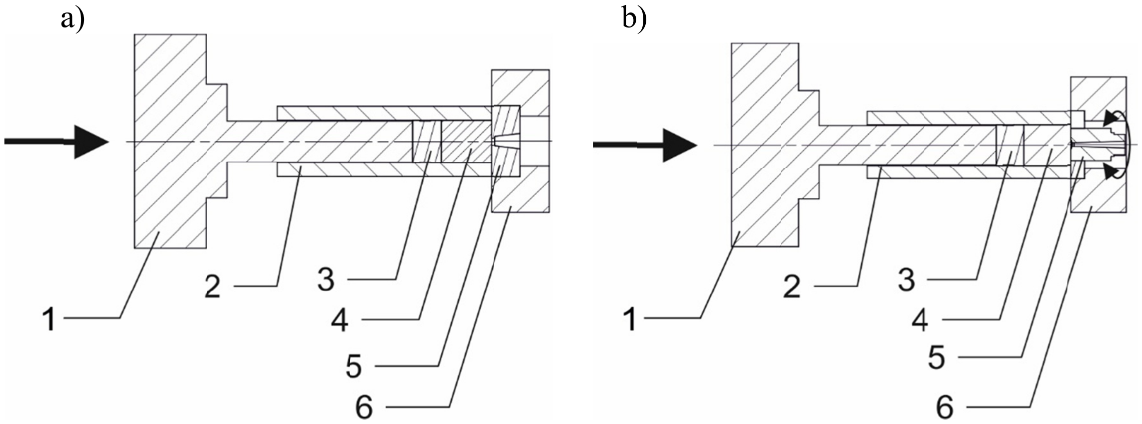

Fig. 1. Conventional extrusion pattern (a) and KoBo extrusion pattern (b), 1 – ram, 2 – cylinder, 3 – dummy block, 4 – billet, 5 – die, 6 – die backer

λ = 10 000) [20]. It results from relatively easier plastic flow in KoBo method, which is reflected by both reduced extrusion force and increased extrusion rate [20,31,33,35].

In case of extrusion of chips there are two issues: the necessity of their compaction up to solid state and recreation of joints between individual chips in order to form bulk material/product, which requires inducing a cyclic change of strain path in each of them. In particular, cyclic torsion leads to deformation in the sheared layers, and thus "exposure" of new, non-oxidized surface elements of adjacent chips. High compressive stresses provide them with good mutual adhesion and in effect their stable joint at atomic level. Concurrent extrusion by KoBo method uses the change of strain path within the whole process, and it is achieved by the cyclic, double-sided, plastic metal "torsion". It causes a strong interference with the metal structure and an increase of lattice defects concentration (the Frenkel defect) [20,31,33,35-36]. Cyclic, double-sided, extruded metal torsion changes its state into the one characteristic of liquid state, in spite of keeping solid state [20,35]. Under such conditions, plastic metal flow through the die hole is triggered by the punch force resulting from properly correlated frequency of oscillating die with extrusion rate.

In spite of similarities between the conventional method of extrusion and KoBo method regarding the forces, they are quite different in terms of values. The extrusion force in KoBo method is at least twice as low as the one needed for conventional extrusion (Fig. 2).

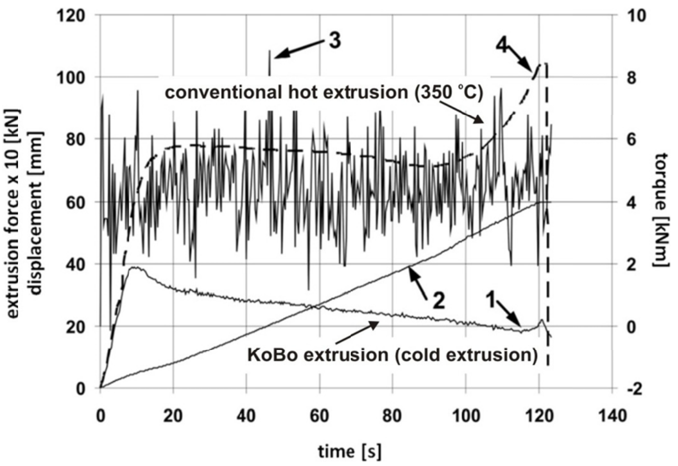

Fig. 2. Mechanical characteristics of aluminum extrusion process by KoBo method (1 – extrusion force, 2 – punch travel, 3 – torsional moment).The data for conventional extrusion are plotted by means of a dotted line (4) [37]

Also, the friction force is quite low and it stays practically at the same level, regardless of the phase of the process [20,37]. Friction forces have an essential influence on the direction of the material flow lines and the plastic strain distribution in the cross section of the deformed element. The force decrease results from the fact that the material flow is aided by frictional forces, which direction agrees with the material flow.

Considering other fixed parameters of the chips extrusion by KoBo method, the more waste is processed, the better the consolidation effect is. The problems becomes more complex under real conditions, where it is not only about recycling of chips by their consolidation, but also about giving the products the required geometry and quality (including the mechanical properties and surface quality). Another important issue is the extrusion rate, which has to be related both with the value of extrusion ratio λ, but also the angle and frequency of torsion, deciding upon the number and size of torsional deflections per one product length. The KoBo method is an efficient, low energetic method for consolidation of chips both from light metal alloys such as aluminum or magnesium, and from alloys of hardly deformable materials such as titanium.

Each of the five process parameters (temperature, extrusion ratio, extrusion rate, angle and frequency of oscillations) can exert influence on mechanical properties and microstructure. This influence should be considered in order to obtain desirable results [30-31,38].

In this work, the possibility of consolidation machining chips from aluminum alloys into products with properties of solids leaving the liquid phase out has been assessed.

For this purpose, the process of low-temperature extrusion using the KoBo method was used, enabling the control of the plastic deformation process of metallic materials, as well as an effective method of the properties of the final products.

The proposed method is based on cold compaction of chips into briquettes, and then extrusion by KoBo method without initial heating. The extruded wires were tested for mechanical properties (uniaxial tensile test and Vickers hardness test), and compared with specific mechanical properties of extrudate made of bulk material.

The consolidation of machine chips by cold processing reduces processing costs and energy requirements. This process has the potential for greatly improving material properties and energy efficiency; it uses only approximately 2% of the energy of existing recycling processes. Furthermore, the process requires only simple equipment to convert scrap directly into a material product.

2. Experimental procedures

Research regarding mechanical properties of the final products revealed their total consolidation and total proved their compatibility with requirements for products made of bulk materials.

The investigation was conducted using 2024 and 7075 alloys in the form of chips from real manufacturing process and in the form of bulk material, for the sake of comparison of the final effects of both methods.

The machining chips coming from the manufacturing processes, contained coolant and lubricant residue. They were not given any cleaning after being produced. In the first stage of the experiment, the chips were compacted. They were put into a special container and pressed on a vertical hydraulic press under pressure of 0,3 MN. The obtained metal briquettes, 59 mm in

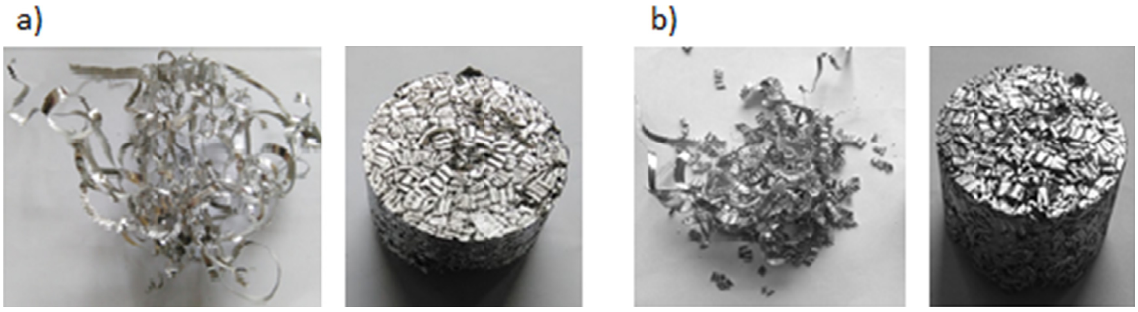

Fig. 3. Chips of 2024 (a) and 7075 alloys (b) and aluminum briquettes made of them as initial material for KoBo process (billet)

Fig. 4. Hydromet hydraulic KoBo 2,5 MN press used in the experiment

diameter (the diameter of the container was 60 mm) and 105 mm in length, were used as billets for KoBo method (Fig. 3). The process of consolidation by KoBo extrusion method at low temperature was conducted on the HYDROMET hydraulic KoBo press with the maximum load of 2,5 MN (Fig. 4).

Based on the experimental results obtained in the process of extrusion of bulk metals and alloys, the presented experiments were conducted with the amplitude of the die rotation angle equal to ±8°. The frequency of die oscillation was selected in the range of 5÷8Hz. In order to keep constant kinetics of the extrusion process (constant force and rate of extrusion) the frequency of the oscillation of die was a variable. The extrusion process was conducted at room temperature with the use of non-heated briquettes as billets. The thermal effect (an increase of temperature) mainly resulted from deformation. The speed of punch movement was in the range of 0,2-0,25 mm/s. The parameters of the extrusion process were the same for both extruded material (chips and bulk).

As a result of extrusion process ϕ10 mm wire was obtained with the extrusion ratio $\lambda = 36$. The obtained products (Fig. 5) were tested for their mechanical properties in a uniaxial tensile test and Vickers hardness test.

The process of extrusion of compacted machining chips resulted in their consolidation and it was conducted at lower force compared with the extrusion of bulk material with the same process parameters (Table 1).

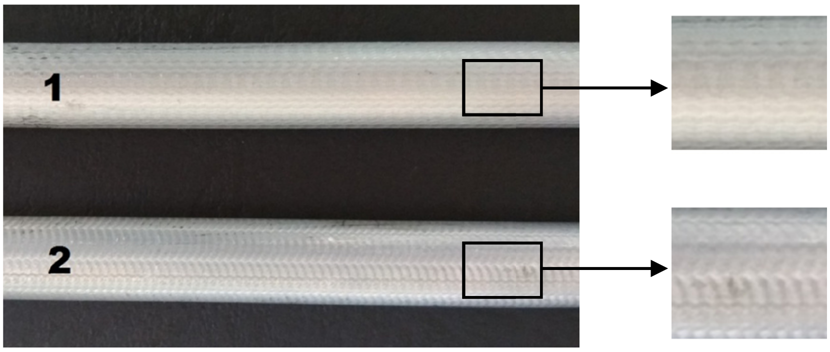

Fig. 5. Wires obtained by KoBo extrusion method: 1 – wire made of bulk billet (smooth surface quality), 2 – wire obtained from chips (smooth surface with "pattern" resulting from die rotation)

TABLE 1

Maximum extrusion force

Material	Max. extrusion force [kN]
2024 bulk billet	2300
2024 chips briquette	2100
7075 bulk billet	1700
7075 chips briquette	1370

3. Investigation of mechanical properties of KoBo extruded wires

Quality evaluation of extrudates is based on the determination of their mechanical properties and surface quality. Test pieces for a static uniaxial tensile test were taken from extruded wires, and test was conducted by means of Zwick/Roell Z100 testing machine. The test pieces were taken from the beginning, middle and end part of the extrudate. They were subjected to tensile test at constant strain rate. Diagrams showing stress-strain ($\sigma - \varepsilon$) relationship were made, and tensile strength (R_m), yield point ($R_{0,2}$) and elongation (A) were determined.

Also, Vickers hardness tests were taken according to PN-EN ISO 6507-2 by means of NEXUS 4303 hardness tester. Test pieces for hardness tests were made according with standards mentioned in PN-EN norms (e.g. PN-EN ISO 6507-1:20020).

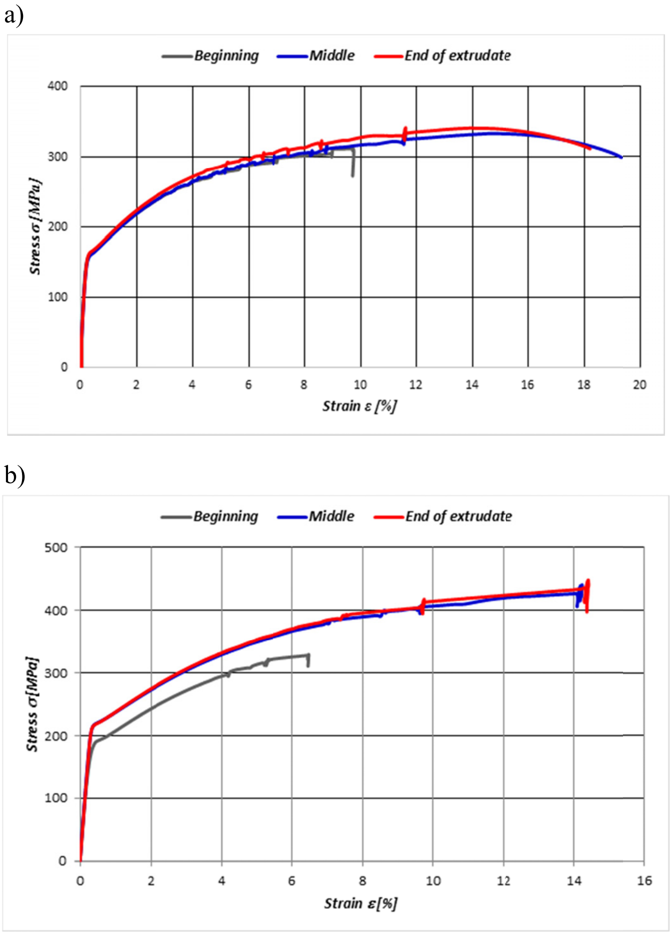

Fig. 6. An example of tensile curves of ϕ10 mm wires after 2024 (a) and 7075 (b) chips consolidation by KoBo method

Fig. 6 shows the diagram of tensile tests on wires obtained by consolidation of chips of 2024 and 7075 in the process of extrusion by Kobo method, whereas Table 2 presents determined mechanical properties.

TABLE 2

Mechanical properties of extrudates made of chips obtained after extrusion by KoBo method (average values from three test pieces)

Test piece/Properties	R_m [MPa]	$R_{0,2}$ [MPa]	A [%]
2024 – beginning of extrudate	290	161	9,2
2024– middle of extrudate	299	165	19,3
2024 – end of extrudate	306	171	18,2
7075 – beginning of extrudate	309	190	6,46
7075– middle of extrudate	385	210	14,2
7075 – end of extrudate	392	219	14,3

For comparison of the effect of KoBo extrusion of consolidated chips the results of extrusion of bulk material were given. Fig. 7 presents diagrams illustrating tension of wires from bulk material of 2024 an 7075 alloys in the process of concurrent extrusion by KoBo method, whereas Table 3 shows determined mechanical properties.

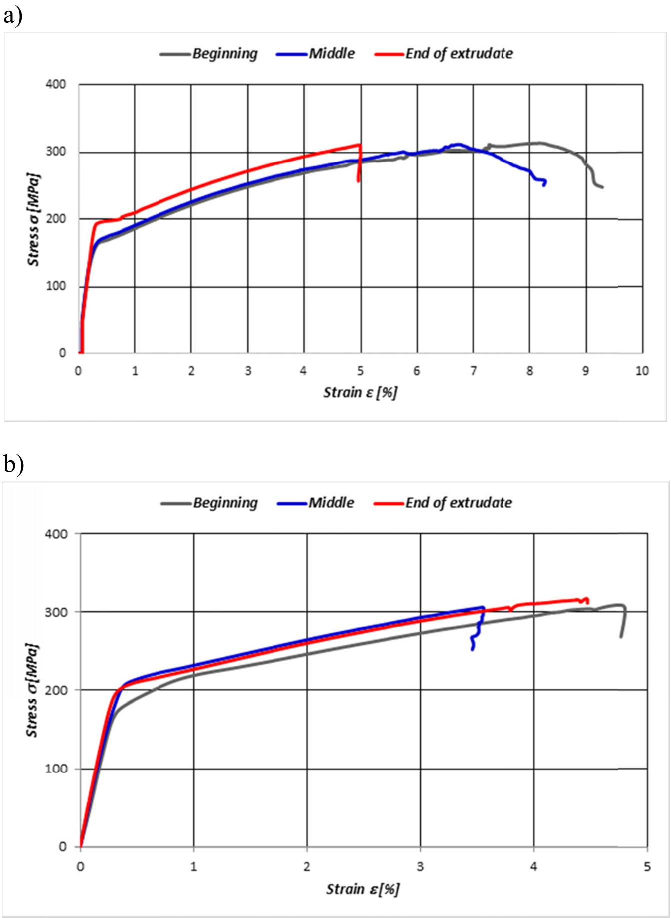

Fig. 7. An example of tensile curves of ϕ10 mm wires obtained from bulk 2024 (a) and 7075 (b) materials by KoBo method

Analyzing the properties of wire made of bulk material of 2024 and 7075 alloys it can be observed that the tensile strength

TABLE 3

Mechanical properties of extrudate made of bulk material extruded by KoBo method (average values from three test pieces)

Test piece/Properties	R_m [MPa]	$R_{0,2}$ [MPa]	*A* [%]
2024 – beginning of extrudate	286	163	9,7
2024– middle of extrudate	292	171	8,2
2024 – end of extrudate	296	196	4,9
7075 – beginning of extrudate	295	189	4,7
7075– middle of extrudate	295	214	4,4
7075 – end of extrudate	303	209	3,4

increases as the distance from the beginning of the extrudate grows. The obtained product is characterized by varied yield point with the lowest point in the beginning part of the tested piece for 2024 and 7075 alloys. The elongation in the beginning and middle the part of extrudate is considerably different from the yield point measured for the ending part, which proves that the ending part of the extruded wire is relatively brittle. The longer the process, the more flowing the extruded material becomes.

Figure 8 shows the results of Vickers hardness tests with the load of 1 N, according with ASTM E407-07 of the sample taken from the middle part of extrudate for 2024 and 7075 chips alloys.

Table 4 presents the results of hardness tests for bulk material and chips consolidated, including the average value.

The Vickers hardness tests prove that after chip consolidation by KoBo method the material has better hardness compared with hardness of bulk material.

TABLE 4

Hardness test results for bulk material and after chips consolidation

Hardness [HV 0,1] (average value)			
Bulk material		**Material made of chips**	
2024	83,89	**2024**	85,78
7075	102,96	**7075**	105,89

The oxide coating after refinement due to plastic strain in the process of extrusion constitutes the hardening phase, which has an advantageous effect on the extrudate's mechanical properties. It is proved by slightly better hardness of aluminum alloy obtained directly after chip consolidation (Table 4).

Large differences in hardness values result from the fact that the indenter most likely "hit" once in the matrix, and once in some phase (e.g. oxide). When measuring the grain size, the result could have a significant grain deformation and size.

Macro- and microstructural observations

The results of macro and microstructural observations of profiles of the extrudate produced by bulk aluminum alloy 2024 and 7075 during low-temperature KoBo extrusion is presented in Fig. 9 and Fig. 10.

Based on the observations, in the case of rods extruded from bulk material – 2024 and 7075 macro, and the microstructure is highly homogeneous.

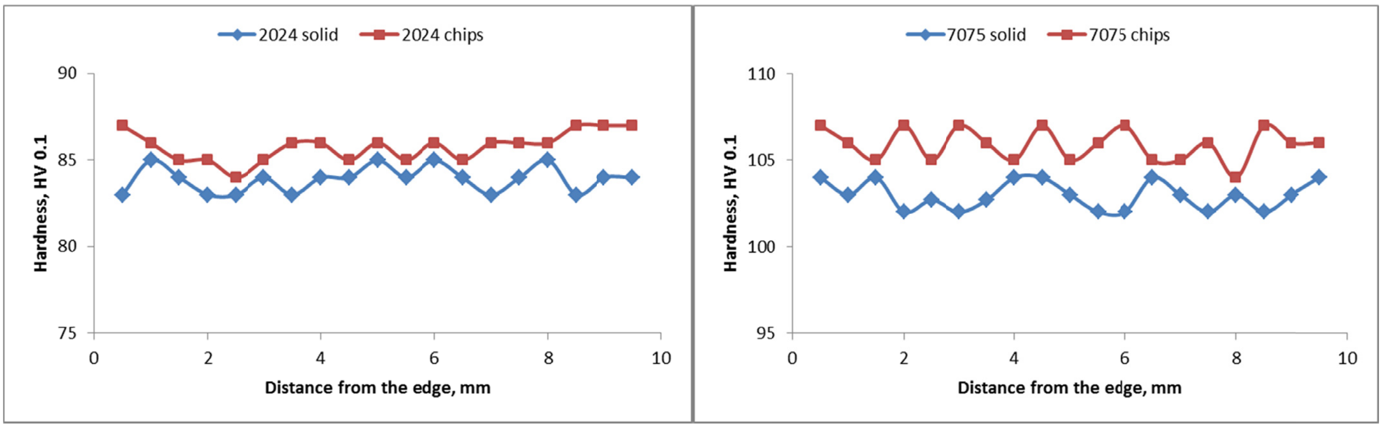

Fig. 8. Hardness distribution in the extrudate made of chips and bulk materials by KoBo method (middle part of extrudate)

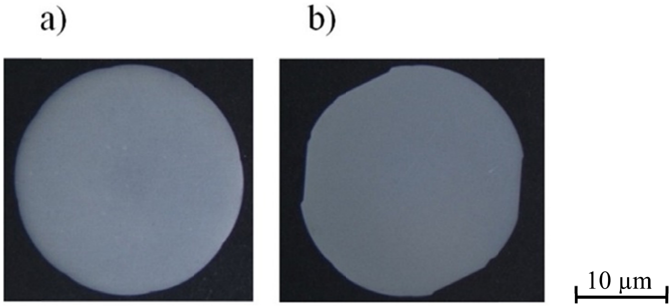

Fig. 9. Macrostructures on cross section of rod obtained from bulk 2024 (a) and 7075 (b) aluminum alloy

Carried out microstructural studies have shown that the microstructure of the alloy 2024 consists of the matrix – the grains of the solid solution α-Al and the relatively large, undissolved molecules of the intermetallic phase (Cu, Fe, Mn) Al_6 and $CuMgAl_2$ phase particles in the form of spheroidal shaped particles.

The microstructure of the 7075 alloy consists of a matrix of solid alloys in aluminum and fine precipitates of irregular $MgZn_2$ phase particles and large precipitations of the $FeAl_3$ intermetallic phase, insoluble precipitates $(Fe,Mn)Al_6$ at the grain boundaries and the Mg_2Si dispersion strengthening phase.

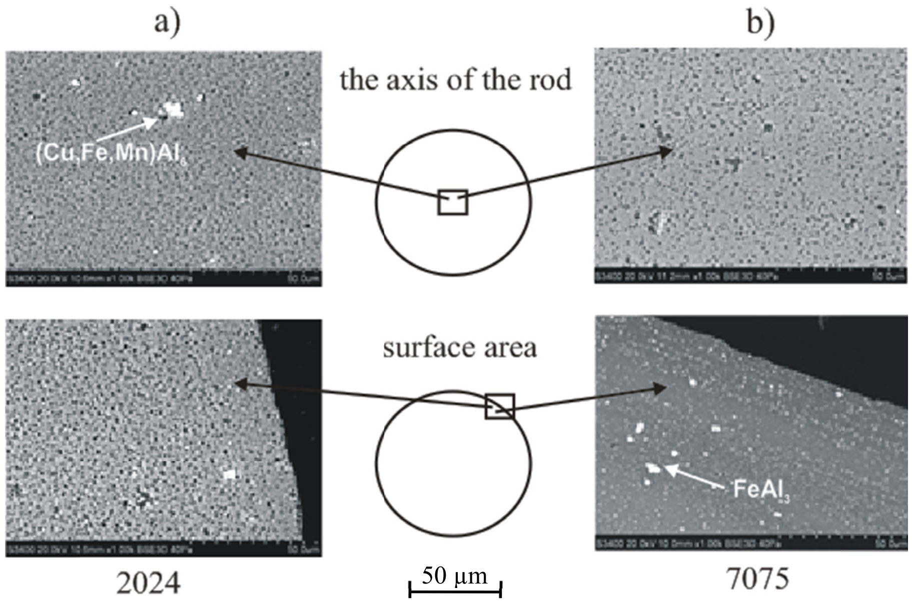

Fig. 10. Microstructures on cross section of rod obtained from bulk 2024 (a) and 7075 (b) aluminum alloy

In the area of the outside diameter, plastic strain lines are visible, typical for the extrusion process, no cracks, impurities or other discontinuities were found.The plastic forming operations applied did not cause major changes in the morphology of the alloy microstructure components.

The results of macro – and microstructural observations of profiles of the compact produced by aluminum alloy 2024 and 7075 chips consolidation during low-temperature KoBo extrusion are shown in Fig. 11.

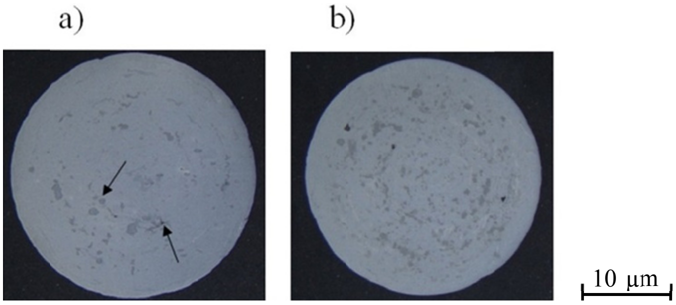

Fig. 11. Macrostructures of rod obtained from 2024 (a) and 7075 (b) aluminum alloy chips

Observations of the macrostructure showed that in the case of extruded rods from chips 2024, the heterogeneity, unevenly appearing in the cross-section is visible – the largest occur in the near-surface area, the smallest in the area of the rod axis. Some of these inhomogeneities have the appearance of small discontinuities (indicated by arrows). The 7075 structure is characterized by the presence of ring-shaped heterogeneities. In this case, there are no visible discontinuities.

Based on the observation of the microstructure of rods extruded from material from consolidated chips, it was found that in the surface areas there are heterogeneities in the form of strongly deformed, elongated bands, without a clear boundary of separation (Fig. 12).

Observations using a larger magnification allowed to state that the bands are areas constituting an integral part of the alloy, not separated by a distinct boundary and differing only in the morphology of the intermetallic phase precipitates.

These types of bands also occur, at lower or higher intensity, outside the subsurface zone (Fig. 13). These effects result from the nature of the extrusion process used.

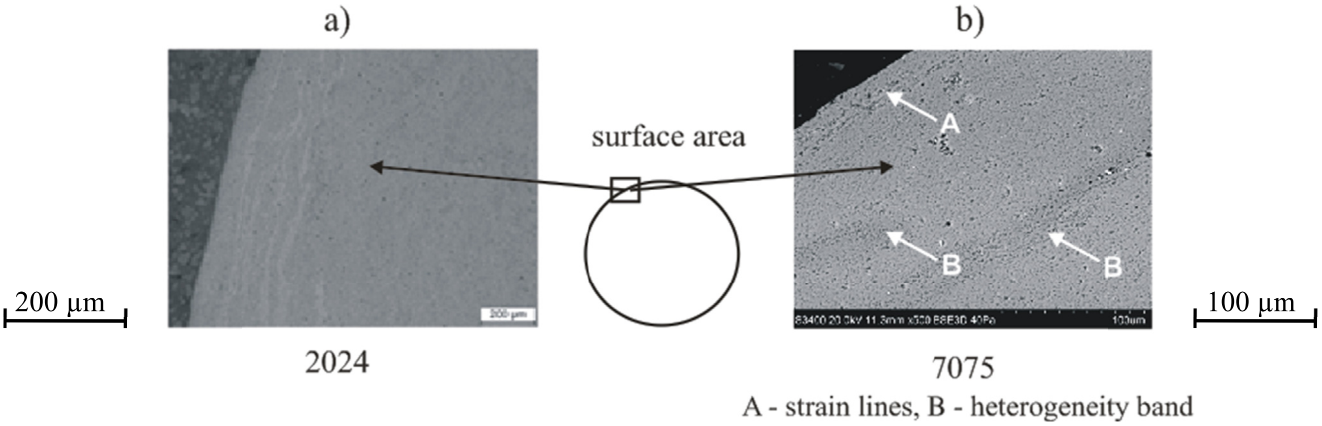

Fig. 12. Microstructures on cross section of extruded rod obtained from 2024 (a) and 7075 (b) aluminum alloy chips

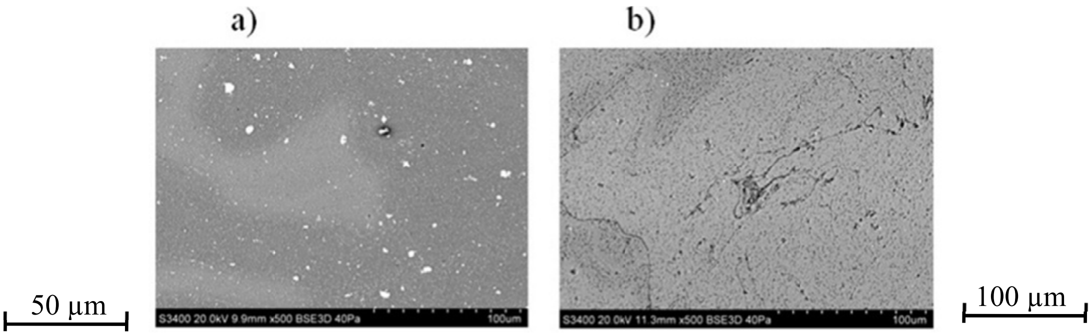

Fig. 13. Heterogeneity of the microstructure on cross section of the rod in the form of thin lines forming discontinuities, formed on the border of the chip separation a) 2024, b) 7075

In addition to the bands of heterogeneity of microstructure related to heterogeneity of alloys in the macroscopic scale, there are also areas in which discontinuities with the appearance of thin boundaries are visible. The analysis of the observation results suggests that they are oxide films present on the surface of chips that have not degraded in the extrusion process and remained in the alloy representing the shape of the chips. These films are fragmentary and make the connection of chips into a fully consolidated material difficult. In the case of alloy 2024, incidental voids were observed.

4. Summary and conclusions

The investigation of mechanical properties of billets extruded from consolidated chips, compared with the properties of a product extruded from bulk material both by KoBo method leads to the following conclusions:

1. Low temperaturing extrusion by KoBo method allows for full consolidation of dispersed chips of 2024 and 7075 aluminum alloys and for obtaining long products.
2. Product made of consolidated chips at right temperature is characterized by better strength properties compared with the one obtained from bulk material, at almost twice as high elongation measured in tensile tests (Table 2, 3).
3. The proposed method of manufacturing products is both material and energy-saving and harmless for the natural environment. Presented consolidation process of chips may be applicable not only for recycling of chip of aluminum and its alloys.
4. The presence of impurities in chips, after machining, does not pose a significant difficulty for obtaining a solid product in the process of extrusion by KoBo method, however their good purification fosters consolidation. That method has a tremendous technological potential and has an extensive range of process control options.
5. The universal character of the phenomena taking place during the deformation processes with a cyclic change of the loading scheme (substructure destabilization) is retained irrespectively of the temperature of the process. This fact is a substantial argument for the possibility of the production on industrial scale of metallic products by means of extrusion combined with torsion, using installations weaker than those employed so far, as well as conducting the process at temperatures lower than those usually applied.
6. The research has shown that the consolidation process of materials based on Al alloys obtained by KoBo extrusion method is able to provide very high quality and desired properties of the output product.

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