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BACKWARD EXTRUSION OF ALUMINUM ALLOY SECTIONS USED IN AIRCRAFT STRUCTURAL COMPONENTS

WYCISKANIE PRZECIWBIEŻNE KSZTAŁTOWNIKÓW ZE STOPÓW ALUMINIUM STOSOWANYCH NA ELEMENTY KONSTRUKCJI LOTNICZYCH

The paper presents an analysis of selected aluminum alloys as structural materials used in production of aircraft parts as well as specification of technological parameters of Al alloys extrusion on a backward press with their effect on mechanical properties, microstructure and quality of the final product. Upsetting tests with backward extrusion complex cross-sectional profile tests were conducted on aluminum alloys 7075, 2024, 2099. Based on the results, specifications of forging in the form of unit stress - effective strain relations were determined using logarithmic deformation index, allowing proper choice of extrusion parameters. The range of temperatures for hot plastic treatment along with range of extrusion rate for the analyzed thin-walled aircraft profiles were determined. Tests were also conducted on the microstructure of Al alloys in the initial state as well as after the extrusion process had been completed. It has been proved that the proper choice of parameters in the case of a specific profile extruded from Aluminum alloys 2024, 7075, 2099, allows the manufacturing of products of complex cross-sections and the quality required in aerospace industry. This has been demonstrated on the example of complex cross-sectional profiles using elements of varied wall thickness.

Keywords: backward extrusion, aluminum alloys, 7075,2024, 2099, sections

W pracy przedstawiono analizę wybranych stopów aluminium jako materiałów konstrukcyjnych z przeznaczeniem na elementy obiektów latających wraz z określeniem technologicznych parametrów wyciskania tych stopów na prasie przeciwbieżnej oraz ich wpływu na właściwości mechaniczne, mikrostrukturę i jakość finalnego wyrobu. Przedstawiono wyniki testów spęczania i wyciskania przeciwbieżnego profili o złożonym kształcie przekroju poprzecznego z wykorzystaniem stopów aluminium 7075, 2024, 2099. W oparciu o uzyskane wyniki wyznaczono charakterystyki spęczania jako wykresy zależności średnich nacisków jednostkowych od logarytmicznego wskaźnika odkształcenia, umożliwiające adekwatny dobór parametrów wyciskania. Określono przedział optymalnych temperatur przeróbki plastycznej na gorąco i prędkości wyciskania dla analizowanych cienkościennych profili lotniczych. Wykonano również badania mikrostruktury stopów Al w stanie wyjściowym i po wyciskaniu. Wykazano, że adekwatny dobór parametrów procesu do danego typu profilu wyciskanego ze stopów 2024, 7075, 2099, pozwala na uzyskanie wyrobów o złożonym kształcie przekroju poprzecznego i o wymaganych własnościach oraz wysokiej jakości pożądanej w lotnictwie, co pokazano na przykładzie profili o złożonym kształcie przekroju poprzecznego z elementami o zróżnicowanej grubości ścianki.

1. Introduction

The new generation of Al-Li alloys are modern metallic materials used in production of aircraft parts, such as: fuselage sub-assemblies or floor bearing elements (e.g. A380). These alloys are characterized by attractive mechanical properties in comparison to conventional aluminum type alloys. The Al-Cu 2xxx series alloys, characterized by high strength and low density properties, as well as Al-Zn 7xxx series alloys characterized by high corrosion resistance, are used for structural applications such as, aircraft wings. The development of light-weight materials and fabricating parts/sub-assemblies of substantially large dimensions has become a major issue for the aerospace industry, which has boosted the development of more advanced materials with high specification properties. Recent aluminum alloy developments are based on achieving superior fatigue crack growth resistance, better corrosion resistance, lower density, etc. Standard manufacturing techniques, such as: welding, casting or extrusion, ought to be developed in order to find beneficial solution allowing structural weight reduction, which is a very efficient means of improving aircraft performance.

Al alloys used in aircraft applications possess a number of extraordinary properties, which make them suitable for use in the manufacture of the structural parts of aircraft. Extrusion as a manufacturing process of these materials allows for the obtaining of the required quality of the specific geometrical parameters, macro and microstructure, properties (including

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mechanical ones) but also creating structural elements of very complex cross-sections, whose manufacture is usually impossible or more costly with the use of other techniques. Another main advantage of this process is its ability to select optimum shapes of extruded blanks used to manufacture parts maximally similar to the theoretical profile of the final part.

Taking into consideration the material requirements such as: ability to carry loads in given operation conditions with lowest possible dimensions and mass of an aircraft, susceptibility to processing (castability, plasticity, machinability, spot weldability etc.) and providing good strength, toughness and reliability of the elements and subassemblies, the selection of proper technological parameters and their current check seem to be a crucial issue. The identification of specific properties of Al alloys' mechanical response, such as: stress value causing material damage, mechanical parameters values, such as for example, elastic/plastic strength, may be implemented via upset forging. Its results may allow for the proper choice of extrusion parameters.

Aluminum and its alloys are remarkable for their specific properties in contrast to other materials. Owing to low mass density and high mechanical properties at the same time, excellent corrosion and abrasion resistance, silvery white color, good electrical and thermal conductivity, low shrinkage and high impact strength in sub-zero temperatures, aluminum alloys remain of continuing interest. Concurrently, there is a great deal of research carried out nowadays, in order to increase the product's properties through the creation of new compounds and development of manufacturing techniques.

Low-density aluminum alloys are becoming more and more attractive to the aerospace industry. The most popular Al alloys used in aircraft applications include duraluminum (2-5% Cu and to 2% Mg; alloys: 2014, 2017, 2024). Still, silicon, magnesium (6xxx series), zinc and magnesium (7xxx series, a.g. 7075) alloys have even better strength properties. These alloys are used in aircraft components which require the highest weight or corrosion resistance. Commercial aluminum-lithium alloys (e.g. 2099 alloy) are targeted as advanced materials for aerospace technology primarily because of their low density (only 0,53 mg/m3). 1% lithium content reduces alloy density by 3%, and increases the Young modulus by as much as 6%.

Nowadays, the majority of elements made of aluminum alloys are manufactured in the machining processes, whereas relatively small number of products are plastically deformed [1-5]. The principal disadvantage of the machining processes is high consumption of material, energy and equipment. Owing to this fact, the implementation of metal forming processes for products made of aluminum alloy is becoming more and more popular. The application of metal forming in the manufacturing process is not only cost-effective but it also increases product strength and fatigue properties, owing to good internal structure.

A wide range of semi-finished products made of aluminum and its alloys is manufactured through extrusion, which allows selecting optimum shapes of semi-finished products used to manufacture parts maximally similar to the theoretical profile of the final part [for example 6-8]. Aluminum is the most commonly extruded material. Examples of products include profiles for the following aircraft parts: brackets, levers, fasteners, frames, liners, window frames, rails or cargo (fig. 1).

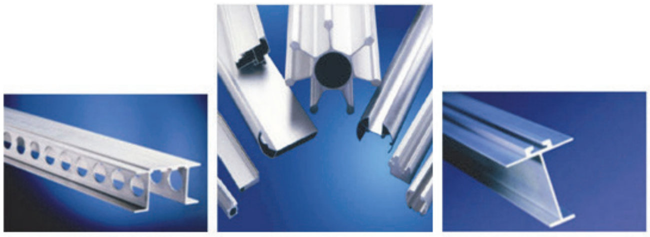


Fig. 1. Examples of sections extruded in aluminum alloys used in aerospace industry

The designing and checking of aluminum alloys bulk forming processes results from the specific properties of this group of materials. They include, to name but a few, thermal properties, relatively low plasticity and narrow range of process parameters, which make metal forming methods and achieving high quality of the product a difficult task [9-15]. Controlling and enforcing specific changes in the metal structure in the process of extrusion is vital in the case of aircraft aluminum alloys characterized by very complex cross-sections. That is the reason for which it is so important to carry out research aimed at finding such constructional and technological solutions, which might allow the manufacturing of parts of very sophisticated shapes, high dimensional accuracy, uniform structure, high mechanical properties and proper quality of the surface finish [13-22]. It is essential, owing to a number of reasons, such as: the properties of aircraft alloys, including light weight alloys such as aluminum, achieving the desired effect of precise shape mapping (e.g. edges, dimensional accuracy of walls, rectilinearity of the product or its deliberate curvilinearity), desired property distribution on the cross and longitudinal section of the product, as well as the proper microstructure.

The aim of this paper is to determine technological parameters of extrusion in the case of selected Al alloys, which have an effect on mechanical properties, microstructure and quality of the manufactured product. Furthermore, the paper justifies their application in the aerospace industry. Deformability of Al alloys in the process of extrusion may be initially determined through an upset forging test. It requires specifying the level of flow stress at a given temperature, determining the effect of the size and rate of deformation on the final product as well as specifying plastic range and deformation level leading to cracking. Determination of extrusion process conditions on the base of the test results, along with proper choice of parameters in relation to a specific profile extruded from Al alloy, allows the manufacturing of products of complex cross sections, as well as high quality and properties required in aerospace industry.

2. Experimental work

2.1. Material and investigation methods

The ability to deformation of Al alloys was conducted through upsetting test with the use of 20mm P/M compact samples. In the extrusion process the billet (preform) of 95mm in diameter was used (diameter of the extrusion container 100mm). Tables 1 and 2 demonstrate the chemical composition of Al alloys and their mechanical properties.

TABLE 1

Chemical composition of Al alloys (percent of mass)

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr	Li	Other
7075	0,40	0,50	1,2-2,0	0,30	2,1-2,9	0,2-0,3	5,1-6,1	0,20	0,25	-	0,05
2024	0,50	0,50	3,8-4,9	0,3-0,9	1,2-1,8	0,10	0,25	0,15	0,10	-	0,05
2099	0,05	0,07	2,4-3,0	0,1-0,5	0,1-0,5	-	0,4-1,0	0,1	0,05-0,12	1,6-2,0	≤0,05

TABLE 2

Mechanical properties of the tested Al alloys

Alloy	Mechanical properties		
	R0,2 [MPa]	Rm [MPa]	A [%]
7075	390-470	480-540	6-8
2024	250-290	360-435	12-14
2099	597-603	615-621	5-10

Upsetting tests were conducted on a hydraulic press of maximum rated force 1MN. In the process of forging, the force and ram displacement were recorded in time function. The tests were realized at room temperature (approximately 20 degrees C) and at higher temperatures: 300, 350, and 400 degrees C. The dimensions of the samples were as fallow : 20mm diameter and 30mm high. Before the upsetting test the samples had been annealed at 300 degrees C. The samples undergoing upset forging at higher temperatures (hot deformation) were brought up to a set temperature in a chamber-type resistance furnace. Next, they were moved to the press and upsetting was realized with the use of a heated punch on a heated die, under near-isothermal conditions (fig. 2). The hot upsetting test was conducted up to the one-third of the initial sample height. Upsetting at room temperature was conducted until the sample got damaged by cracking.

Fig. 2. The test station to perform the upset forging test – set of tools used in the process of upset forging at higher temperatures on a hydraulic press of maximum rated force 1MN

Preform dimensions	
d_0, [mm]	95
h_0, [mm]	125
State	extruded
Process parameters	
Heating temperature of the preform, [°C]	450
Heating time, [min]	~40
Extrusion temperature, [°C]	460
Extrusion rate, [mm/s]	0,25 ÷ 1
Extrusion ratio λ	20, 60
Die temperature, [°C]	450

Fig.3. PH-LR 500 - a horizontal hydraulic press - 5 MN used for backward extrusion

The process parameters were recorded automatically by a microprocessor built-in the control panel of the press. File reading and its processing allowed for determining the variability of the selected parameters of the press work in time function. Hydraulic-press capabilities allow for recording of all stages of extrusion process, beginning with the loading of the perform up until the moment when the tools go back to the initial position. In the above mentioned work, only the steady state extrusion stage was taken into consideration. Al alloys 7075, 2024 and 2099 in perform of φ95 mm in diameter (φ100mm of the container) and lengths 250 mm and 125 mm were subjected to extrusion process.

Before the extrusion process, the billets and the die were heated to the temperature of 450 degrees C. The raw material input of the ingots was extruded by applying properly selected ram rates (from 0,25 – 1 mm/s) and dies in the shape of a working hole: circular, square, triangular, T-shaped as well as two complex profiles, similar to aircraft structural profiles (fig. 4).

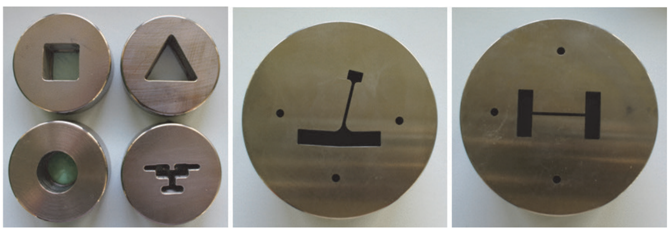


Fig. 4. Extrusion dies

Such profiles are usually characterized by the complexity of the cross-section, whereas they ought to be characterized by uniform properties of the cross- and longitudinal sections and highest possible mechanical properties.

2.2. Results

The formability of aluminum alloys under extrusion was provisionally determined by the upsetting test through specification of the flow stress in relationship to the deformation size and rate, determining the range and level of deformation leading to cracking.

The upsetting of aluminum alloys at room temperature (approximately 20 degrees C) is presented in fig. 5. The average unit pressure for a logarithmic strain ε_h=0,8 was approximately 370 MPa for the 2099 alloy sample; 350 MPa for the 2024 alloy sample and 290 MPa for the 7075 alloy sample.

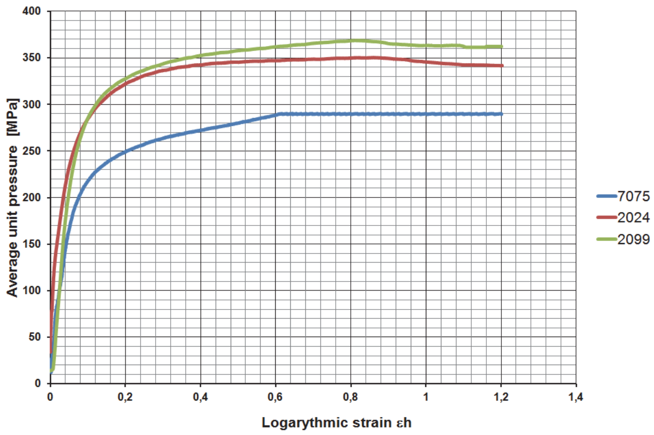
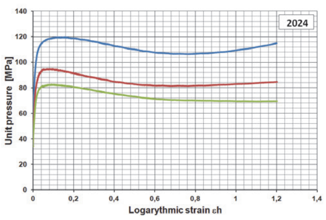
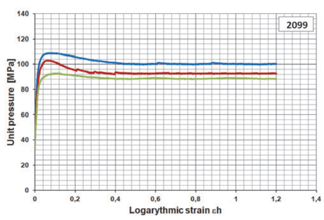


Fig. 5. Average unit pressure vs. logarithmic strain εh - curves for Al alloys : 7075, 2024, 2099 at the temperature of 20 degrees C

At higher temperatures, the upsetting test was conducted up to the one-third of the initial sample height (fig. 6.). Within all three temperature ranges, that is; 300, 350 and 400 degrees C, dynamic recrystallization of the material occurred in the process of upsetting. Initially, the unit pressure increased up to the maximum, but then it decreased and remained stable at a given level. Along with the increase of the forging temperature, maximum stress value decreased as follows: for the 2024 alloy from about 120 MPa at the temperature of 300 degrees C to about 95 MPa and 82 MPa at the temperatures 350 and 400 degrees C respectively. For the 7075 alloy from about 82 MPa at the temperature of 300 degrees C to about 74 MPa and 62 MPa at the temperature of 350 and 400 degrees C respectively. For the 2099 alloy from about 108 MPa at the temperature of 300 degrees C to about 102 MPa and 92 MPa at the temperatures of 350 and 400 degrees C respectively. Considering relatively low coefficients of elongation estimated in the extrusion process (λ = 20 and 60), the maximal extrusion temperature, that is heating up of the perform and the temperature of the press container, was set to be 450 degrees C.





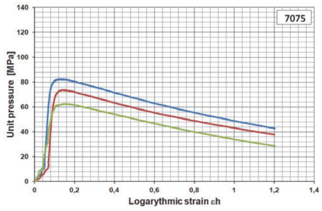


Fig. 6. Average unit pressure vs. logarithmic strain εh - curves for 2024, 7075, 2099 alloys at higher temperatures

On the basis of the results the upsetting test, 7075, 2024, 2099 alloys were subjected to extrusion. As long as the extrusion ratio was λ = 20 and λ = 60, the result were positive, that is the extrusion force was lower than the nominal force of the press, and satisfactory quality of the extrudate. A characteristic feature which was observed during the processes was the initial rapid growth of the extrusion force, connected with the forming of deformation gap, and then a drop to the minimal value followed by a slight increase in the process of extrusion (fig. 7). In order to decrease the initial extrusion force the die was extra heated to the temperature of 450 degrees C. The extrusion rates were selected not to cause any damage of the finish surface, which would prove the disturbance of the extrusion process or negative structural phenomena in the material (e.g. hot cracking). All the manufactured sections were characterized by smooth surface finish with no visible defects. Despite of increasing the extrusion ratio λ = 60, the quality of the extrudate was also good. A slightly larger force was required to extrude square, triangular and 6 profiles in comparison to other profiles.

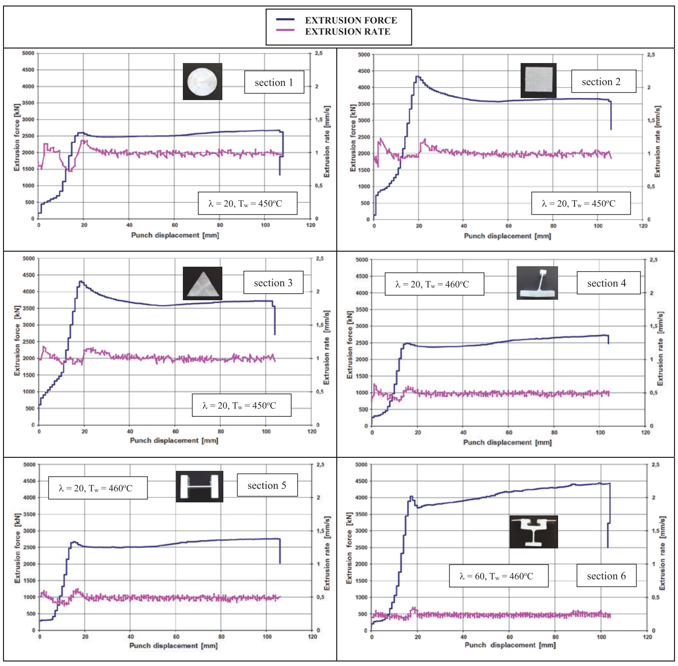


Fig. 7. Relationship the force, punch displacement and extrusion rate in the process of extrusion on the 2024 alloy profiles

The extrusion process for complex profiles 4, 5 and 6 with the use of dies shown in fig. 4, required an increase of the temperature to 460 degrees C and a decrease of the extrusion rate. In the case of profile 4 and 5 the rate was 0,5 mm/s; and for profile 6 - 0,25 mm/s. Achieved extrudates were characterized by a good quality of the finish surface and geometrical accuracy of the profile (Fig. 8).

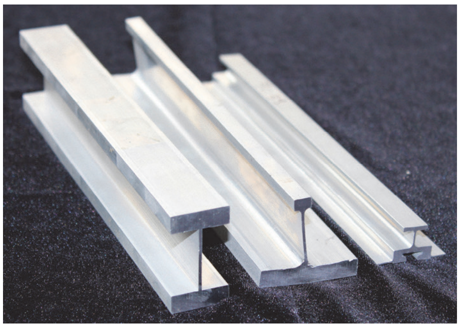


Fig. 8. Examples of extruded profiles

Metallographic tests were conducted on samples cut out from extruded profile. The cross-sections of the samples were subjected to microsections (Fig. 9, 10).

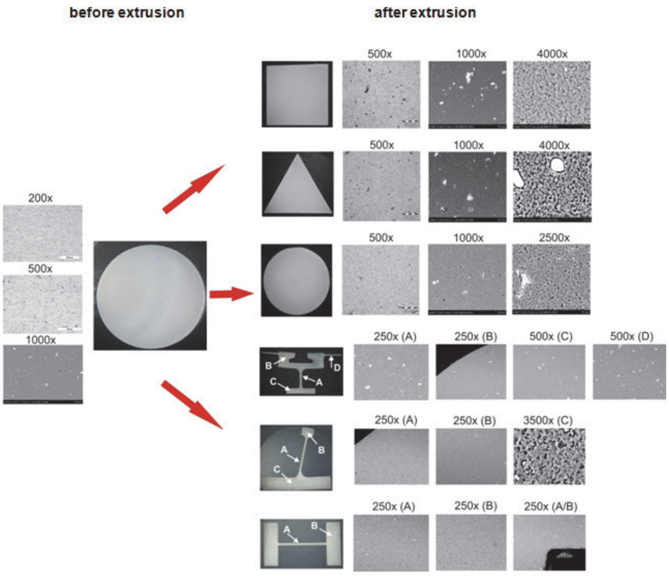


Fig. 9. Macro and microstructure of the 2024 alloy, before and after extrusion

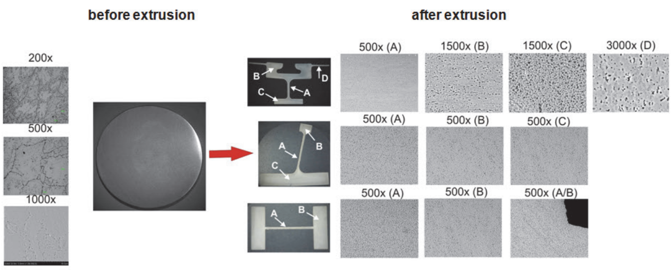


Fig. 10. Macro and microstructure of the 2099 alloy, before and after extrusion

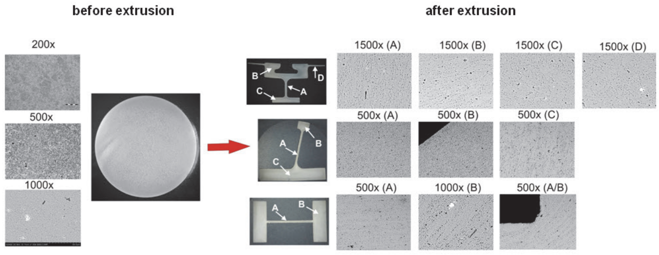


Fig. 11. Macro and microstructure of the 7075 alloy, before and after extrusion

Basing on the results of the tests of macro- and microstructure of 2024, 2099 and 7075 aluminum alloys after plastic deformation in the process of extrusion, it has been noticed that the macrostructure of the investigated alloys was subject to homogenizing – fine-grained and uniform alloys were achieved, regardless of the profile shape. The microstructure of each and every investigated alloys is typical of its type and grade. No morphology or chemical composition diversification of the phases was observed in all the investigated cross-sections. For each investigated aluminum alloy, the plastic deformation in the extrusion process caused a significant homogenization in terms of distribution and refinement of the intermetallic phases' molecules but also a slight increase of the size of hardening phases' molecules, whereas their dispersional character stayed the same. No changes in the chemical composition of intermetallic precipitation and hardening phases were observed.

After the plastic deformation , the macrostructure of the 2024 aluminum alloy underwent a significant homogenization in terms of the grain sizes. Regardless of the profile cross-section – circular, square or triangular, the alloy is characterized by fine equiaxial grain in the whole section. The microstructure of the 2024 alloys also changed significantly – refinement and homogenization of intermetallic phase precipitation (Fe,Mn)3SiAl2 and multicomponent phase (Si,Mn,Fe,Cu)Al occurred. However, the occurrence of the S−(Cu,Fe,Mg)Al5 phase, which was a component of the alloy microstructure before the plastic deformation in extrusion, was not observed. The molecules of the hardening phase Mg2Si are highly dispergated, while there was a slight increase of the θ-Al2Cu phase. The analysis of the microstructure and chemical composition showed that each investigated section was not affected by the plastic deformation in extrusion in terms of changes of chemical composition of intermetallic precipitates as well as hardening phases.

Plastic flow of 2099 alloy caused a significant granularity change – the size of grains was reduced by half. However, no changes in the microstructure were observed as it stayed the same in terms of the type, composition and distribution of the phase components. Some of the intermetallic phase molecules (e.g. (Fe,Mn)Al6 i Mn-Fe-Cu-Al) underwent partial defragmentation. The morphology of the hardening phase stayed the same.

The plastic deformation in extrusion of the 7075 alloy caused a significant refinement and homogenization of the grains. The microstructure of the alloy was considerably uniform in terms of the shape, size and intermetallic phase distribution. No vital changes of the chemical composition of individual components of the alloy micro- and macrostructure were observed.

The macro- and microstructure of all investigated alloys after extrusion was in every case highly uniform in terms of grain sizes but also the morphology of phase components, compared to the micro- and macrostructure before the process. Intermetallic phase precipitates underwent defragmentation and refinement, while hardening phases existed in the form of dispersional molecules, which slightly grew in size. Neither segregation or chemical composition changes of the matrix and intermetallic and hardening phases was observed.

The Brinell hardness test results shown in tables 3 and 4 prove the homogeneity of the structure and mechanical properties of the profile cross-section. The measurements were done with the use of hardness tester Zwick ZHU 250, the load employed was 625N and the ball of 2,5mm in diameter. The Brinell hardness was measured before and after extrusion process.

TABLE 3

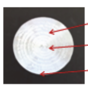
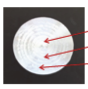
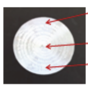
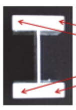
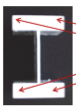
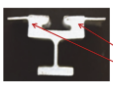
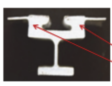
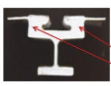
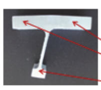
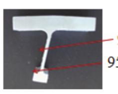
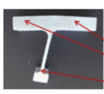
HB hardness test results of various Al alloys and extruded profiles

Alloy	HB hadrness 2.5/62.5 (average values)			
	Billet (preform)	Extruded profile 1	Extruded profile 2	Extruded profile 3
7075	164	102	102	112
2024	134	96,5	95	96,5
2099	169	72,5	72	97

The average values of the hardness measured in specific characteristic regions of the extruded profiles' cross-sections demonstrate the homogeneity of mechanical properties on the cross-section, both in the thick-wall regions and the remaining area of the section.

TABLE 4

Hardness results for Al alloys in characteristic regions of the extruded profiles sections and the billlet

2099	2024	7075
Billet (preform) Ø100  169 HB, 169 HB, 169 HB	**Billet (preform) Ø100**  135 HB, 131 HB, 135 HB	**Billet (preform) Ø100**  164 HB, 164 HB, 164 HB
Extruded profile 1  72 HB, 72 HB	**Extruded profile 1**  95 HB, 95 HB	**Extruded profile 1**  102 HB, 102 HB
Extruded profile 2  97 HB	**Extruded profile 2**  99 HB	**Extruded profile 2**  112 HB
Extruded profile 3  72 HB, 73 HB	**Extruded profile 3**  95 HB, 95 HB	**Extruded profile 3**  102 HB, 102 HB

3. Conclusions

The determination of the extrusion process conditions on the basis of the upsetting test results allowed for the proper parameters choice for a given extruded Al alloy (2024, 7075 and 2099), achieving products of complex cross-sections and required properties but also high quality required in aerospace industry. This has been demonstrated on the example of complex cross-sectional profiles using elements of varied wall thickness. The test results proved very good processability of the investigated alloys using backward extrusion. In a specified range of temperatures and extrusion rates, sections characterized by high quality finish surface, accurate shape of the cross-section and homogeneity of the structure as well as mechanical properties presented by the hardness tests, were obtained.

Metal exit speed depends on the kind of alloy, shape of extrudate and extrusion ratio. But first of all the shape of extrudate cross section decides on metal exit speed without any fracture. It is important to pay attention for ram speed and metal exit speed dealing with extrusion ratio (λ). From the point of view of good quality of extrudate the metal exit speed decides of it. To indicate parameter of the process the ram speed is needed. So the recommended levels of speed are as follow: profile 1, 2, 3 – 1 mm/s, profile 4, 5 – 0,5 mm/s, profile 6 – 0,25 mm/s.

The results allow for drawing the following conclusions:

1. The most favorable temperatures for extrusion of 2024, 7075 and 2099 alloys range from 450°C to 460°C.
2. Taking into consideration the complexity of the cross-section of the extruded profile, the force initializing the process of Al alloy extrusion (PH-LR 500 horizontal hydraulic press - 5 MN used for backward extrusion) may reach very high values, close to the nominal press force. The decrease of the force may be achieved by decreasing the extrusion rate at the stage of deformation zone formation.
3. Increasing the complexity of the cross-section of the extruded profile (profile 4, 5 and 6) requires a significant reduction of the extrusion rate as too fast extrusion rate causes extrudate to crack on the side surface and material pull in thin-walled sections.
4. Macro- and microstructure of all the investigated alloys after extrusion is, in each case, highly homogeneous in terms of the grain size and morphology of the phase components, compared to the macro- and microstructure in the initial state. This is also demonstrated in the hardness test results, which prove the homogeneity of the cross-sectional mechanical properties of the extruded section.

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