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Extrusion of Lightweight Aluminum and Magnesium Alloys Structures for Aviation Applications

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Abstract. 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 and magnesium alloys developments are based on achieving superior fatigue crack growth resistance, better corrosion resistance, lower density, etc. Standard manufacturing techniques, such as extrusion, ought to be developed in order to find a beneficial solution allowing for structural weight reduction, which is a very efficient means of improving aircraft performance. It is associated with the problem of extrusion profiles with a complex cross-section shape. In this work the formability of aluminum and magnesium alloys in the extrusion process was determined by the upsetting test through specification of the flow stress in relationship to the deformation size and rate. The results of the upsetting test of Al (7075, 2024, 8090, 2099) and Mg (AZ31, AZ61, AZ80, WE 43) alloys were used in determining the conditions of the extrusion of profiles of various cross section shape and extrusion ratio. The analysis of macro and microstructure of extruded products and their mechanical properties demonstrates strong influence of the shape of extrudate cross section on metal exit speed and extrusion force value. Macro-and microstructure of all the investigated alloys after extrusion are highly homogeneous in terms of the grain size and morphology of the phase components, compared to the macro- and microstructure in the initial state, which justifies the use of them in production of aviation profiles.

Introduction

Aviation aluminum alloy is the backbone material of aircraft and space vehicle manufacturing. With the continuous improvement of flight performance, payload, fuel consumption, service life, safety and reliability requirements of modern aircraft design and manufacturing, higher and higher requirements are put forward for the comprehensive performance and reduction effect of aluminum alloy structure. Aircraft generation is related to the generation of materials. Aviation aluminum evolved into the third generation of aluminum alloy represented by an aluminum-lithium alloy.

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 [1– 6]. 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, e.g. 7075) alloys have even better strength properties. [1,2,7–9] These alloys are used in aircraft components which require the highest weight or corrosion resistance.

A wide range of semi-finished products made of aluminum and its alloys is manufactured through extrusion, which allows for selecting optimum shapes of semi-finished products used to manufacture parts maximally similar to the theoretical profile of the final part. 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 their specific properties. Thermal properties, relatively low plasticity and narrow range of process parameters, make metal forming methods and achieving high quality of the product a difficult task [1 - 3, 7,8, 17]. 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 complex cross-sections, high dimensional accuracy, uniform structure, high mechanical properties and proper quality of the surface finish [5,6 16-23]. 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), decide of proper distribution of mechanical features on the cross and longitudinal sections of the product, as well as the proper microstructure. [3,7,8,10-16]. During extrusion, high mean compressive stresses in the deformation zone enable processing materials with limited workability [10,11].

While looking for other metals for such aviation applications magnesium alloys are considered for possible use. They are characterized by light weight, high specific strength and shock resistance, strong thermo-conductivity and electromagnetic shielding. These alloys are easy to recycle and can be regarded as "the green material" with the greatest application potential in the 21st century [22, 23, 26]. The plasticity of magnesium alloys is limited at room temperatures because of the hexagonal close-packed (HCP) crystal structure So, the plastic working of these alloys can be done at elevated temperatures. Temperatures above 200ºC permit the activation of other slip systems as well as the formation of deformation twins enabling these materials to be hot workable. The temperature range between the brittle and the plastic deformation behavior of magnesium alloys is narrow; magnesium alloy AZ61 has a limited workability at 208ºC and high ductility at 220ºC, increase of only 12ºC involves significantly better deformation properties, as it was quoted by Sauer [20,25]. During the hot deformation, some metallurgical phenomena, such as work hardening, dynamic recovery and dynamic recrystallization occur simultaneously, resulting in material structure and physical properties. Studies on AZ31 alloy showed that the deformation which occurred by twinning in low temperatures, was gradually replaced by dynamic recrystallization at temperature above 300ºC, reduction in flow stress and increase in ductility[6]. due to increased dynamic recrystallization at temperature above 360ºC. Transformation of the coarse cast structure into a fine grain elongated structure, which occurs during hot working in the extrusion process, significantly improves the mechanical properties of the magnesium alloys. Plastic working obviously improves the mechanical properties of magnesium parts compared with casting ones, but the poor ductility at room temperatures causes that plastic working of magnesium alloys should be done at elevated temperatures. The main manufacturing methods of magnesium alloy products are press forming, forging, rolling and extrusion. The extrusion processes for magnesium are performed like for aluminum alloys but the extrusion speed is much lower than for aluminum alloys, as it was emphasized by Lapovok et al. [24]. Adequate determining the formability of magnesium alloys is very important to describe proper parameters of the process e.g. extrusion, individually for the type of the magnesium alloy.

Deformability of Al and Mg alloys in the process of extrusion may be initially determined through an upsetting 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 and Mg alloys, allows the manufacturing of products of complex cross sections, as well as high quality and properties required in aerospace industry [5, 14-16].

The aim of this work is to show influence of the shape of extrudate cross section on metal exit speed and force value, basing on analysis of extrusion force, macro- and microstructure of deformed alloys, choice of parameters of extrusion in the case of selected Al alloys and magnesium alloys, which justifies their application in the aerospace industry.

Experimental Work

The formability of aluminum and magnesium alloys in the extrusion process was determined with the use of the flow stress characteristics in relation to the deformation value and rate as well as the determined range and value of deformation leading to cracking. The upsetting tests of Al (7075, 2024, 8090, 2099) and Mg (AZ31, AZ61, AZ80, WE 43) alloys were carried out to determine the conditions of the extrusion of profiles of various cross section shape and extrusion ratio. Measurements of extrusion load, analysis of macro and microstructure and testing mechanical features were carried out.

The cast and extruded aluminum alloys and magnesium alloys were investigated. In order to study feasibility of these alloys in extrusion process, the upsetting process of cylindrical specimens was carried out. The dimensions of cylindrical specimens were equal: diameter ϕ20 mm and height 25 mm.

Before upsetting Mg alloy specimens were heated in a furnace to temperatures 350 - 380oC. The tests were carried out on a 1000 kN hydraulic press and during the upsetting process the press ram displacement and the upsetting force were recorded. The specimens, after heating in a furnace to a suitable temperature, were carried to a special heating equipment mounted to the press platens, and then were upset. This equipment was designed in order to provide the uniform temperature distribution in the specimen during upsetting. It consists of an electric heating system embedded in the punch and the die, both insulated from the press bases (Fig. 2).

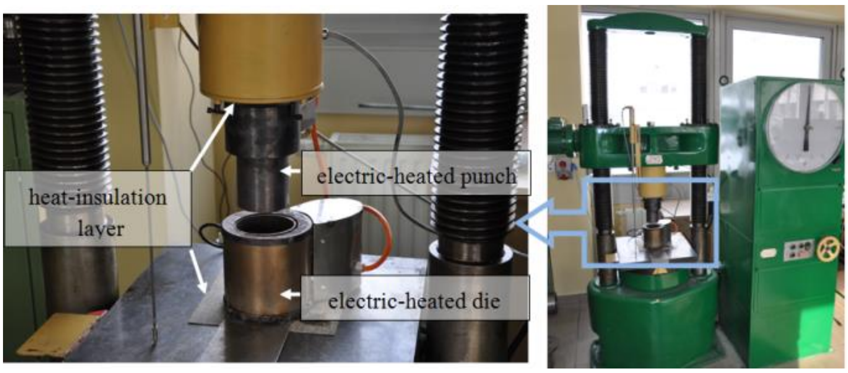

Fig. 2 Set-up of the upsetting test in high temperatures mounted on a 1000 kN hydraulic press

The upsetting of the specimens was performed to about one-third of the initial specimen height or to the moment of the material cracking. During upsetting no lubricants on specimen frontal surfaces were applied.

Upsetting Test. Results

In order to determine the mechanical behavior of the material in the extrusion process, the upsetting test was used to realize plastic deformation in various conditions and to make an adequate selection of parameters for the real extrusion process. Different types of alloys of various initial structures were used in the investigations.

Upsetting tests of aluminum alloys were conducted at room temperature (20°C) and at higher temperatures: 300, 350, and 400°C. The dimensions of the samples were as follows: 20mm diameter and 30mm high. Before the upsetting test, the samples were annealed at 300°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 performed with the use of a heated punch on a heated die, under near-isothermal conditions.

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. The results are presented in Figure 3 and Figure 4.

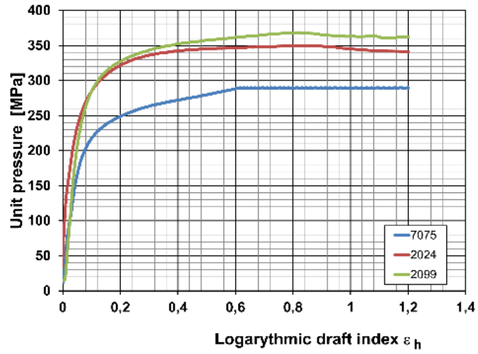

Fig.3 Average unit pressure vs. logarythmic draft index ε_h - curves for Al alloys : 7075, 2024, 2099 at the temperature of 20 degrees C in the upsetting test

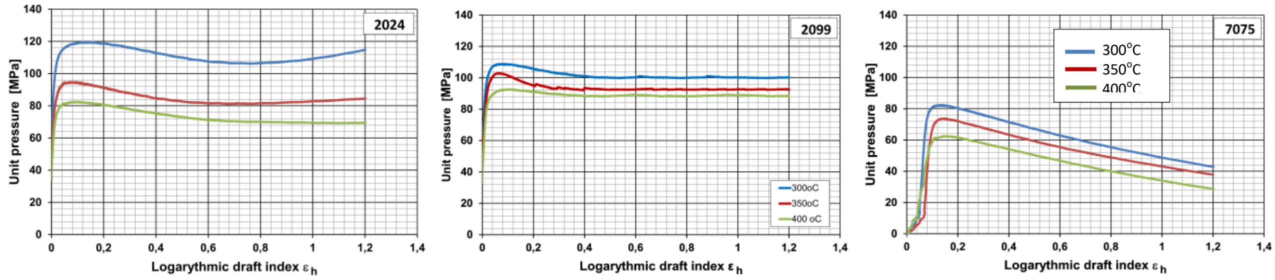

Fig.4 Average unit pressure vs. logarythmic draft index ε_h - curves for 2024, 7075, 2099 alloys at higher temperatures in the upsetting test

The stress-strain characteristics of various aluminum alloys at different temperature values allow them to be taken as a description of the mechanical behavior in the extrusion process and to predict the extrusion force.

Typical curves of the tested magnesium alloys calculated from the hot compression test results are shown in Figure 5 and Figure 6.

a) b)

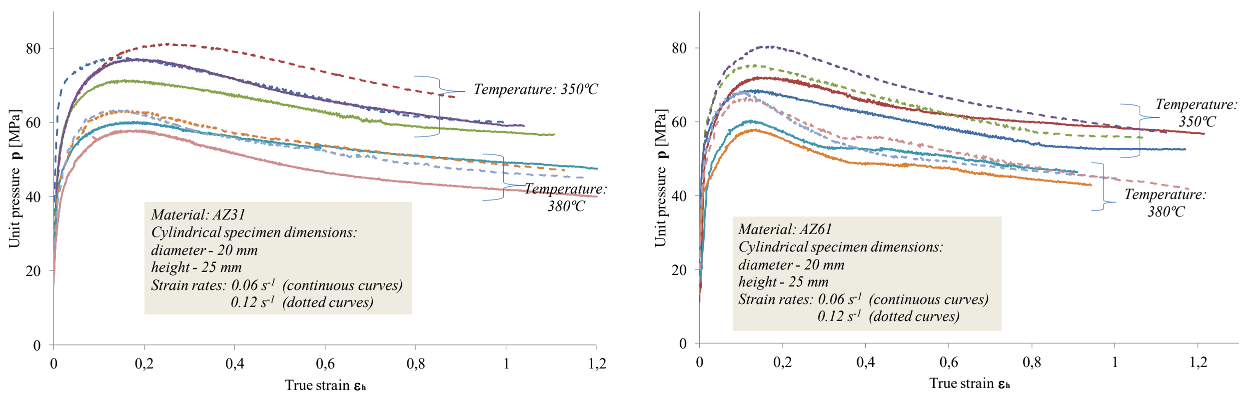

Fig. 5 Typical flow curves of AZ31(a)and AZ 61 (b) magnesium alloy determined in upsetting test

Because of the barreling effect (as a result of friction forces on the specimen pressure frontal surfaces) the curves are described as the mean unit pressure versus the logarithmic true height strain. As it can be seen, all results obtained for Mg-Al-Zn alloys are similar; all curves show the peak value of the unit pressure due to intensive work hardening at quite low strains in the initial stage of upsetting. After that point, the unit pressure decreases slowly because of softening mechanism caused by dynamic recrystallization and finally attains the steady state because of the equilibrium of work hardening and dynamic recrystallization softening. It is a normal tendency, which usually appears in metals deformed at elevated temperatures. The peak pressures are greater for lower temperature and the total deformation increases with temperature growth; these differences are related with individual alloy properties (different peak values for AZ31, AZ61 and AZ80).

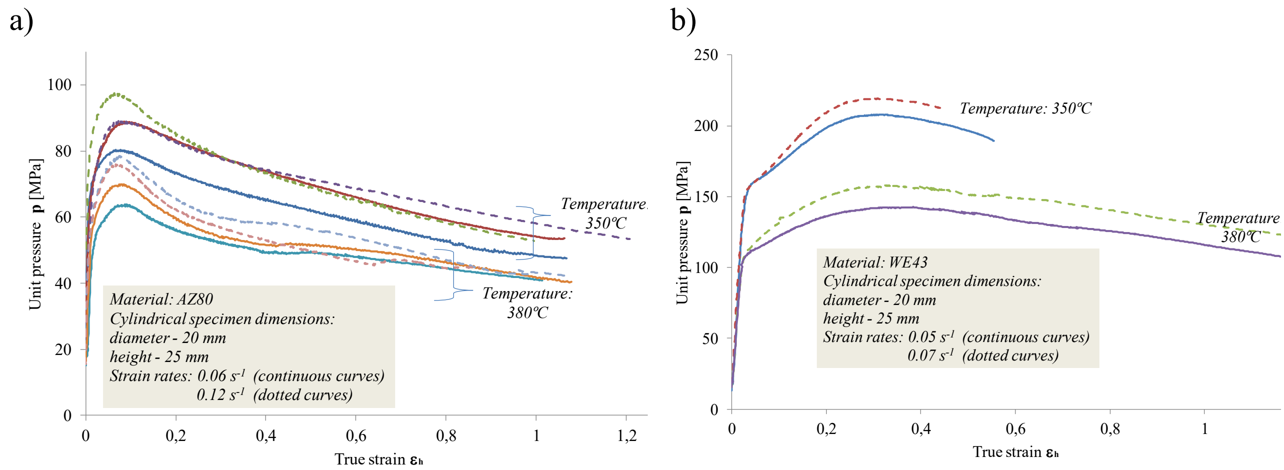

Fig. 6 Typical flow curves of AZ80 (a)and WE 43 (b) magnesium alloy determined in upsetting test

The strain rates marked in Figures 5 and 6 are the mean values calculated from the recorded data of press ram velocity and specimen height during the upsetting test.

For all the above mentioned materials the upsetting tests were finished when about one-third of initial specimen height was obtained. In case of WE43 magnesium alloy, material cracking occurred at the temperature of 350°C. Increasing the upsetting test temperature to about 380°C caused increasing the strains in the process up to one-third of initial specimen height (i.e. logarithmic strain $\varepsilon_h = \ln(h/h_o) \approx 1.1$) without cracking.

Extrusion Process

The extrusion process was carried out on the backward extrusion 5 MN capacity hydraulic press type PH-LR 500, (Fig. 7a). A set of dies (of simple shape of die orifice: round, square, triangular shape and complex shape of aviation profiles (Fig.7b) was used in the experimental work.

Before the extrusion process, the aluminum alloy billets and the dies were heated to the temperature of 450°C for 40 min. The billet was extruded by applying properly selected ram rates (from 0,25 – 1 mm/s) at the temperature of extrusion 460°C and extrusion ratio λ equal to 20 and 60. The temperature of the die was 450°C.

The backward extrusion of Mg alloy billet was conducted at the temperature of 350°C and 400°C (i.e. temperature of the extrusion press container; temperature of the billet was the same or different than container temperature). The billets were heated to extrusion temperatures and kept in a furnace for about 2 hours before extrusion.

a)

b)

Fig. 7 Backward extrusion 5 MN capacity horizontal hydraulic press (a) and extrusion dies with examples of extruded profiles (b)

Extrusion of Al Alloys. Results

The steady state extrusion stage was taken into consideration. Al alloys 7075, 2024 and 2099 (preform of 95 mm and lengths 250 mm and 125 mm) were subjected to extrusion process using 5 MN press(diameter of the press container - 100 mm). The results of extrusion of aluminum alloys were evaluated according to obtained mechanical properties of the extruded profile in comparison to features of initial material of the billet and they are presented in Table 1.

Table 1 Mechanical properties of the tested Al alloys

Alloy	Mechanical properties								
	density [g/cm^3]	before extrusion (billet)				after extrusion (extrudate)			
		$R_{0,2}$ [MPa]	R_m [MPa]	A [%]	HB	$R_{0,2}$ [MPa]	R_m [MPa]	A [%]	HB
7075	2,81	526	583	8	152	230	399	10	107
2024	2,78	311	436	14	120	211	364	11	97
2099	2,63	600	618	6	157	173	319	8	80

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.

The results of the upsetting test, 7075, 2024, 2099 alloys were used in extrusion (e.g. relationship between the force, punch displacement and extrusion rate for 2024 alloy - Fig. 8.)

As long as the extrusion ratio was $\lambda = 60$, the results were positive, that is the extrusion force was lower than the nominal force of the press, and the quality of the extrudate was satisfactory. A characteristic feature which was observed during the process 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 extrusion (Fig. 8).

In order to decrease the initial extrusion force the die was extra heated to the temperature of 450 °C. The extrusion rates were selected not to cause any damage to 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 without any defects. Despite of increasing the extrusion ratio $\lambda = 60$, the quality of the extrudate was also good.

A significant influence of the shape of the cross-section of the extruded profile on the value of the extrusion force was demonstrated, comparing the extrusion forces of these profiles with the same extrusion ratio(Fig.8).

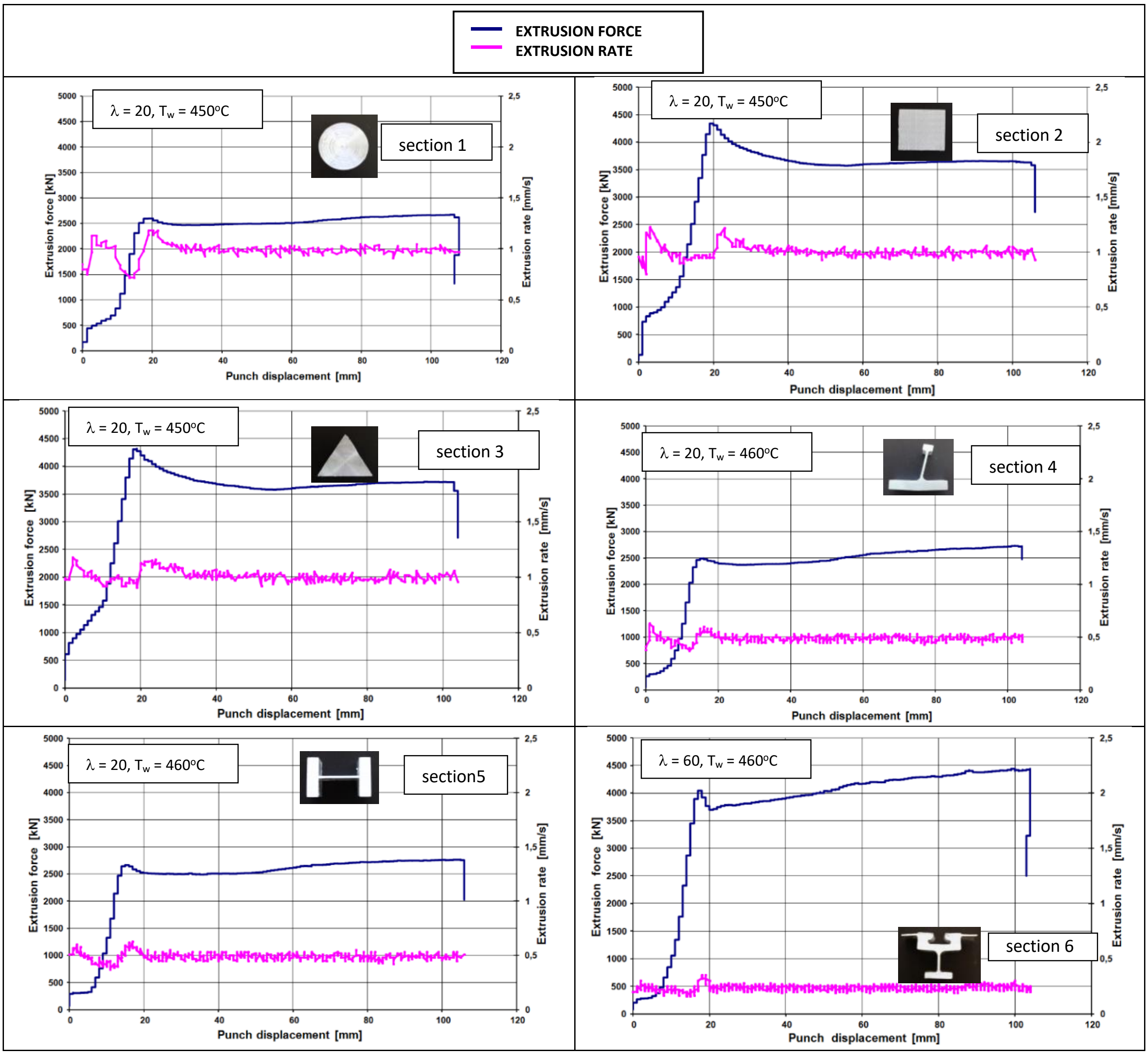

Fig.8 Relationship between the force, punch displacement and extrusion rate in the process of extrusion of the 2024 alloy various profiles

To check the required features of the extruded profile metallographic tests were conducted. The cross-sections of the samples were subjected to micro sections (Fig.9,Fig.10).Transformation of microstructure of aluminum alloys during extrusion is related to the selection of conditions of the process, i.e. temperature of the process, heating conditions, strain rate, extrusion ratio etc. as shown in Fig. 9 and Fig.10. Evaluation of microstructure was carried out basing on the results of the identification and measure 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 subjected to homogenizing – fine-grained and uniform alloys were achieved, regardless of the profile shape and testing hardness. In the first stage, the HB hardness was measured in certain areas, and then the HV hardness to demonstrate them as mechanical properties resulting from the homogeneous microstructure of the extruded profile with a complex cross-sectional shape. It is important to obtain uniform microstructure especially when the geometrical parameters of the extruded profile are very different e.g. very thin wall, thick part of the cross section, symmetrical or nonsymmetrical cross section.

It was observed that in the extrusion process a cross-section with a more complex shape favors a fine grained microstructure (Fig.9, 10a) and homogeneous microstructure on the whole area of the cross section (Fig.10 b).

a) b)

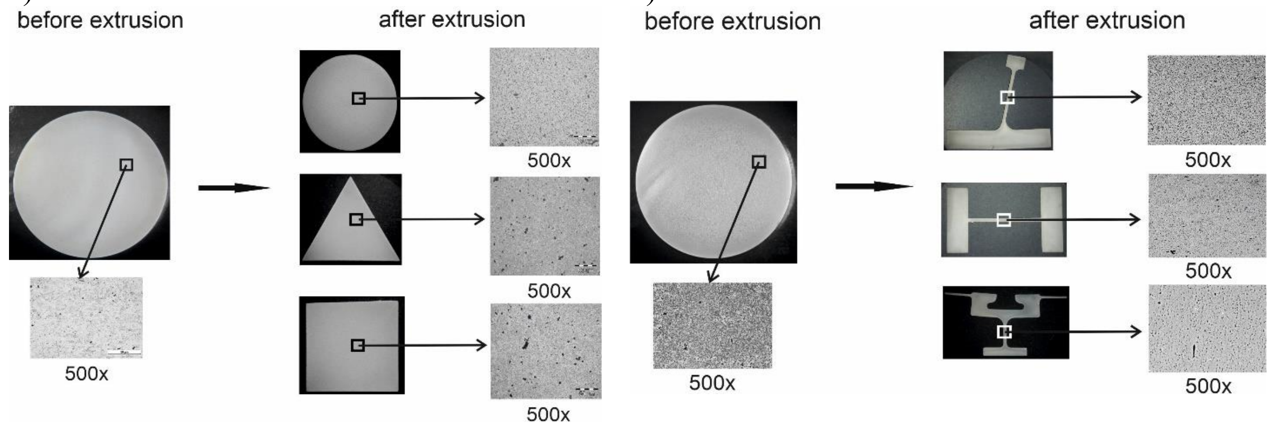

Fig. 9 Microstructure transformation during the extrusion of profiles of simple shape of cross-section of 2024 alloy (a) and microstructure transformation during the extrusion of profiles of complex shape of cross-section of 7075 alloy (b)

a) b)

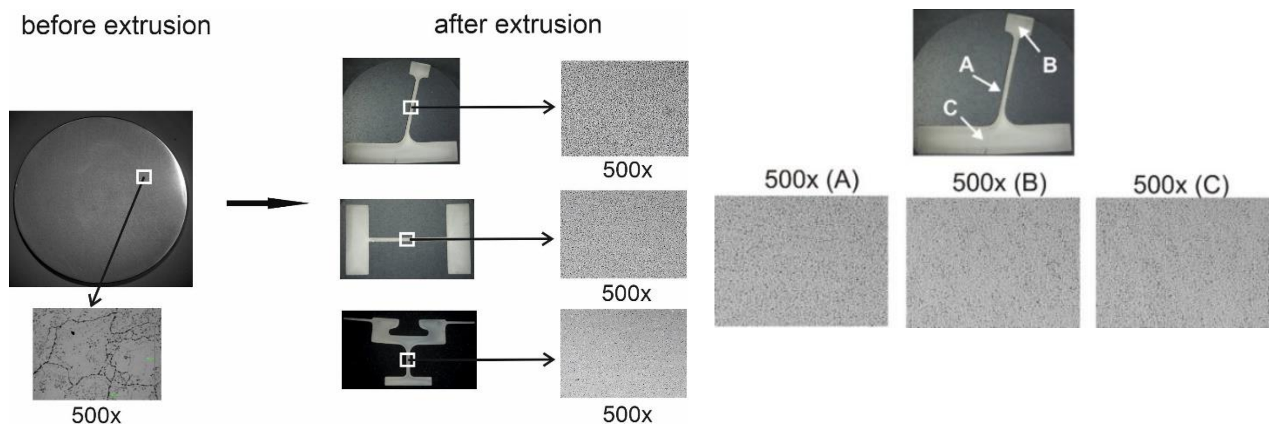

Fig. 10 Microstructure transformation during the extrusion of profiles of complex shape of cross section of 2099 alloy (a) and homogeneous microstructure of extruded profile 2099in characteristic zones of complex cross section (b)

In the extruded profiles with indicated A, B, C zones as characteristic places, the grain size was determined according to Standard ASTM E 112. The microstructure of each and every investigated alloy 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 particles but also a slight increase of the size of hardening phases' particles, 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 $(Fe,Mn)_3SiAl_2$ and multicomponent phase (Si,Mn,Fe,Cu)Al occurred. However, the occurrence of the $Si(Cu,Fe,Mg)Al_5$ phase, which was a component of the alloy microstructure before the plastic deformation in extrusion, was not observed. The particles of the hardening phase Mg_2Si are highly dispersed, while there was a slight increase of the θ-Al_2Cu phase. The analysis of the microstructure and chemical composition showed that in each of the tested cross-sections, the extrusion process did not cause any changes in the chemical composition, intermetallic phases and 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 particles (e.g. $(Fe,Mn)Al_6$ 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 particles, which slightly grew in size. Neither segregation or chemical composition changes of the matrix and intermetallic and hardening phases were observed.

The Brinell hardness test results shown in Table 2 prove the homogeneity of the structure and mechanical properties of the profile cross-section.

Table 2 HB hardness test results of various Al alloys and extruded profiles

Alloy	HB hardness 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, but the differences of the results for different shapes of the extrusion's cross sections have been identified.

Extrusion of Mg Alloys. Results

The backward extrusion processes were conducted at the temperature 350°Cand 400 °C (i.e. the temperature of the extrusion press container; the temperature of the billet was the same or different than container temperature). The billets were heated to extrusion temperatures and kept in a furnace for about 2 hours before extrusion. The diameters of billets for extrusion were 100 mm and 60 mm, the lengths 250 mm and 180 mm.

The extruded sections had diameters of ϕ60, ϕ36 and ϕ20 mm. Thus, the extrusion ratios λ were equal 2.8, 7.7 and 25 for the billets of 100 mm diameter and 2,8 and 9 for the billets of 60 mm diameter, respectively.

The recorded results of extrusion tests are shown in Fig.11 and Fig.12as an example of characteristic relationship between the extrusion load and the stem velocity versus the stem displacement.

a) b)

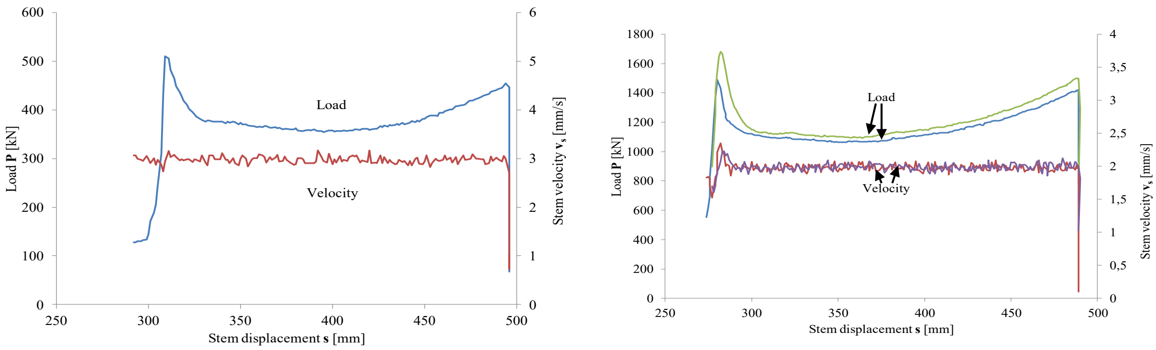

Fig. 11 The extrusion load and the stem velocity versus the stem displacement obtained for AZ31 billet, temperature 400 ºC, extrusion ratio λ = 2.8 (a) and of two billets of AZ80 alloy, temperature 350 ºC, extrusion ratio λ = 2.8(b)

a) b)

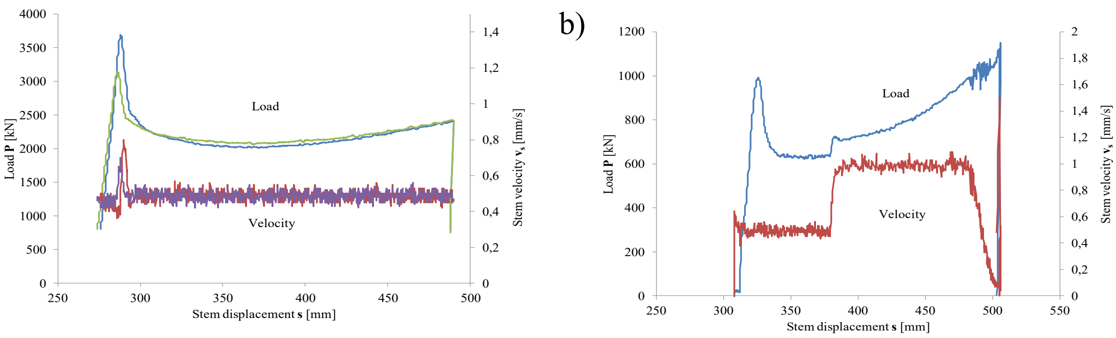

Fig. 12 The extrusion load and the stem velocity versus the stem displacement during extrusion of two AZ80 alloy billets, temperature 350 ºC, extrusion ratio λ = 25, (a) and for WE43 alloy billet extrusion ratio, temperature 400 ºC , λ = 25(b)

The plots of load and stem velocity recorded during extrusion WE43 magnesium alloy are shown in Figs 12b . For this alloy only small extrusion ratios λ = 2.8 and λ = 9 were attainable with low extrusion speed (stem velocity was equal to 0.5 mm/s).
The extrusion load, after reaching the peak value at the beginning, decreases and immediately starts to grow without any hold on the load plot. At the end of extrusion process, the press was switched from automatic control to manual, and this is visible on the load curve as decreasing of stem velocity. When the process temperature is increased to 400ºC, greater extrusion ratio is possible and the stem velocity can be increased to 1 mm/s .

The extrusion force was calculated as the difference between the product of the inner surface of the press cylinder and the pressing pressure and the double product (two actuators) of the inner surface of the cylinder and the pressure in the recipient drive system.

Some examples of characteristics extrusion load and the stem velocity versus the stem displacement for different magnesium alloys and various shape of the cross sections of extruded profiles (Figures 13 – 17) show the influence of the type of alloy and geometry of the cross section of extrudate on adequate choice of parameters of extrusion basing on the results of upsetting test.

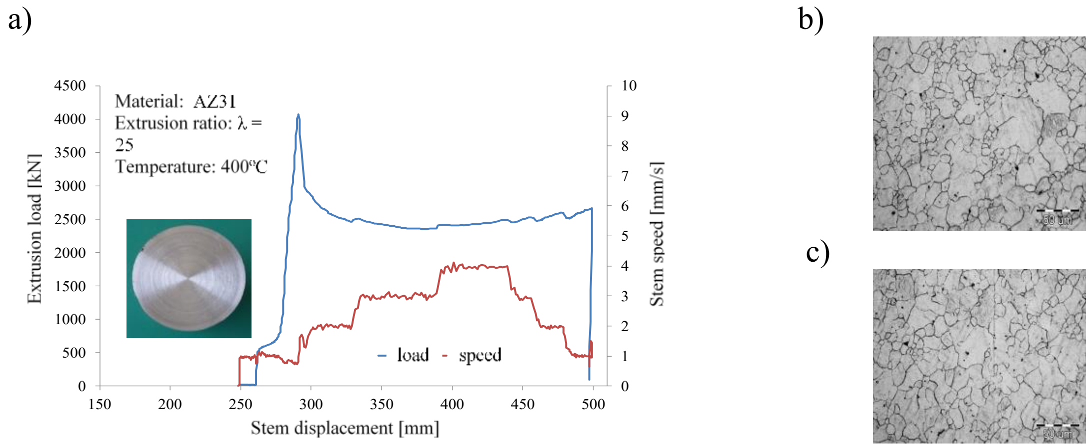

Fig. 13The extrusion load and the stem velocity versus the stem displacement obtained for AZ61 (a), Microstructure of the AZ31 alloy – cross-section, rod ϕ20 mm after extrusion, the region close to the specimen surface, magnification 500x (b), the centre of the rod, magnification 500x (c)

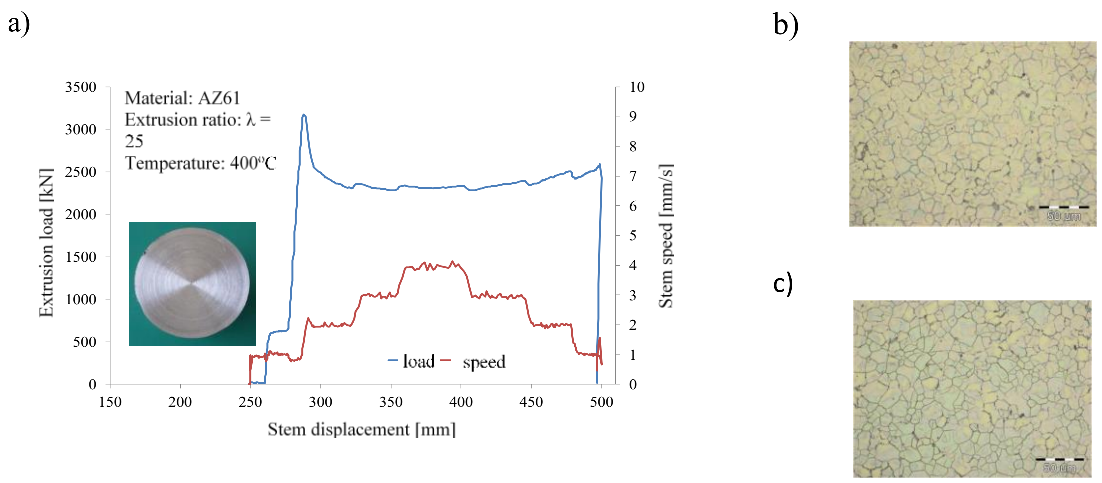

Fig. 14 The extrusion load and the stem velocity versus the stem displacement obtained for AZ61 (a), Microstructure of the AZ61 alloy – cross-section, rod ϕ20 mm after extrusion, the region close to the specimen surface, magnification 500x (b), the centre of the rod, magnification 500x (c)

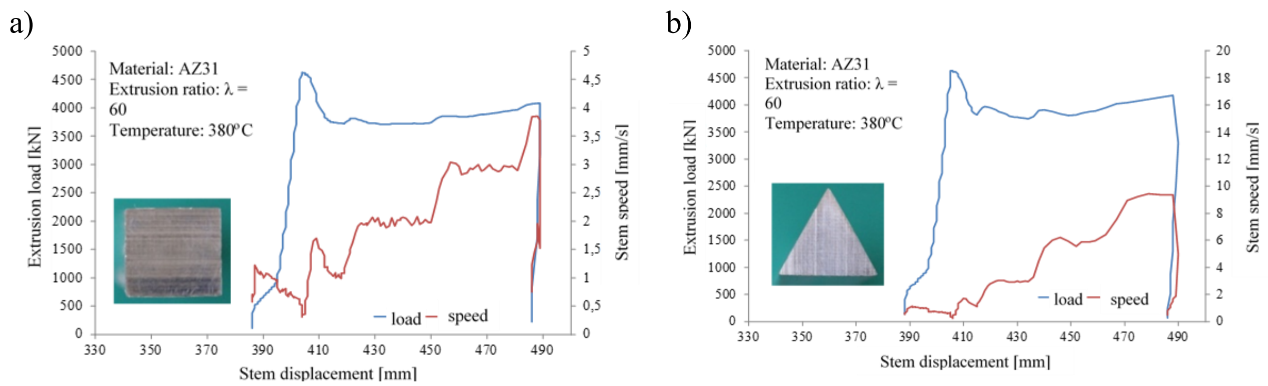

Fig. 15 The extrusion load and the stem velocity versus the stem displacement obtained for alloy AZ31, square cross section(a), triangle cross section (b)

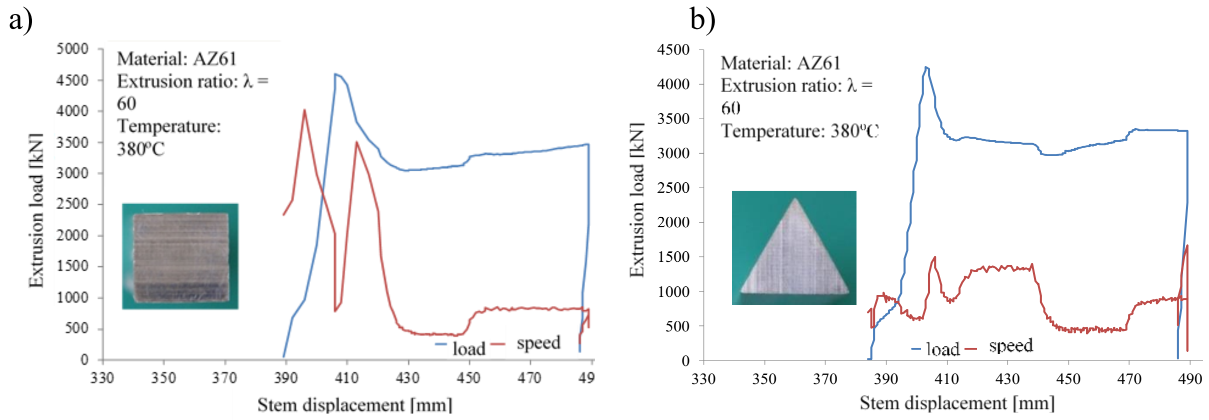

Fig. 16 The extrusion load and the stem velocity versus the stem displacement obtained for alloy AZ61, square cross section(a), triangle cross section (b)

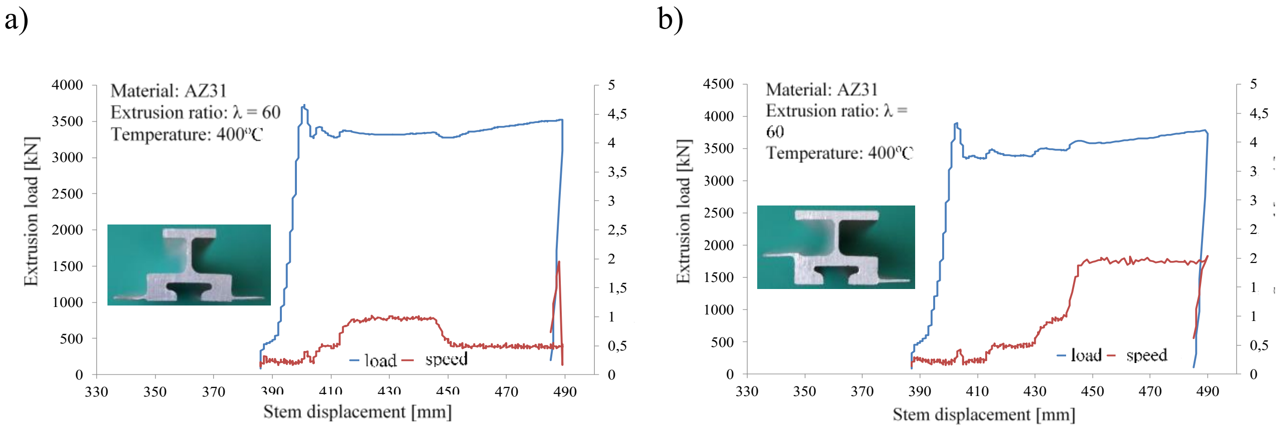

Fig. 17 The extrusion load and the stem velocity versus the stem displacement obtained for AZ31 - cross sections of 2 various aviation profiles: (a) and (b).

The obtained extrusion characteristics of the tested materials as the dependence of the extrusion force and the extrusion speed versus the position of the press stem allowed to identify the influence of the shape of cross sections on the final results of extrusion measured by extrusion load, mechanical features and internal structure.

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 with varied wall thickness, especially with a big difference of segments of the cross-section. The tests results proved very good process ability of the investigated alloys using backward extrusion. In a specified range of temperatures and extrusion rates, profiles characterized by high quality finish surface, accurate shape of the cross-section and homogeneity of microstructure as well as mechanical properties presented by the hardness tests, were obtained.

Taking into consideration the complexity of the cross-sections of the extruded profile, the force initializing the process of Al alloy backward extrusion may reach very high values, close to the nominal force of the press. The decrease of the force may be achieved by decreasing the extrusion rate at the stage of deformation zone formation. Increasing the complexity of the cross-section of the extruded profile requires a significant reduction of the extrusion rate as too fast extrusion rate causes extrusions to crack on the side surface and material pull in thin-walled part of extruded profile. The most favorable range of temperatures for extrusion of 2024, 7075 and 2099 alloys is 450ºC to 460ºC. 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.

Magnesium alloys (AZ31, AZ61, AZ80, WE 43) can be processed by backward extrusion efficiently. The maximum speed at which magnesium alloys can be extruded is relatively slow and should be carefully balanced taking into account the extrusion process temperature. To design the extrusion process for magnesium alloys, at the optimal speed and temperature, performing the upsetting tests at elevated temperatures is very useful. Comparison of the relationships between: extrusion load, stem displacement and stem velocity and true strain - unit pressure relationship in upsetting test – for different magnesium alloys allowed to choose proper parameters for a given material and conditions of the process to obtain required final product of special application. The plastic formability of magnesium alloys at ambient temperatures is low; the fracture deformation for AZ31 and AZ61 alloys is approximately ε_h = 0,2.The optimum hot forming temperatures of AZ31 and AZ61 alloys are in the range of 350 ºC – 400ºC. In the case of AZ61 alloy, at temperatures higher than 400ºC, due to the separation at the grain boundaries of the intermetallic phase Mg17Al12 with a low melting point (437ºC), hot cracking may occur. The initiating force of extrusion of the magnesium alloy can reach very high values, close to the nominal force of the press, often preventing the process from being carried out. A reduction in force can be achieved by significantly reducing the extrusion speed. The value of the maximum extrusion force is influenced by the initial temperature of the die. Its low value causes cooling of the initial material - billet, thus increasing the unit pressures necessary to plasticize the material. It is therefore justified to heat the die to the same temperature as the billet. Magnesium alloys are strongly sensitive to the extrusion speed, although the change in speed in the established process has little effect on the increase in the extrusion force due to the phenomenon of dynamic recrystallization. However, too high speed causes rapid overheating of the material, which is initially manifested by a change in the color of the extrudate surface from metallic white to intense yellow, and in the case of a significant increase in temperature, cracking (especially for alloys with an increased aluminum content, e.g. AZ61).

Basing on the results of aluminum and magnesium alloys extrusion the following main conclusions can be drawn:

- The shape of the cross-section of the extrudate mainly decides about the metal exit speed without any fractureand it has influence on extrusion load value.
- Increasing the complexity of the cross-section of the extruded profile 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 section.
- Macro-and microstructure of all the investigated alloys after extrusion are highly homogeneous in terms of the grain size and morphology of the phase components, compared to the macro- and microstructure in the initial state.

References

[1] K. Saha Pradip, Aerospace Manufacturing Processes, CRC Press (2017)

[2] K. Muller at all, Fundamentals of Extrusion Technology,, Giesel Verlag GmbH, (2004)

[3] W. Libura: Metal flow in extrusion, Metallurgy on the turn of the 20th century, Kraków, 2002, 391-412

[4] J. Piwnik, Mechanika procesów wyciskania metali, Rozprawy naukowe nr 6, Politechnika Białostocka (1991)

[5] J. Piwnik, Teoria i eksperyment w analizie procesów wyciskania, Oficyna Wydawnicza Politechniki Białostockiej (2010)

[6] Y .Yang, B. Li, Z. Zhang,. Analysis on flow stress of magnesium alloys during high temperature deformation. Trans. Nonferrous Met. Soc. China18, 2008, 180 - 184.

[7] B. Pawłowska, R.E. Śliwa, Archives of Metallurgy and Materials, v.60, 4, (2015), 2805 - 2011

[8] Boeing 747-400. Fuselage Panel. 2007. Available online: https://www.verkehrsrundschau.de/nachrichten/ups-erhaelt-erste-boeing-747-400-560172. html (accessed on 18 February 2021).

[9] D. Leśniak, M. Dziki, J. Zasadziński, W. Libura, Influence of Mg content on deformability of AlMg alloys during extrusion, Archives of Metallurgy and Materials, vol. 61, iss. 1, 2016, 86-92.

[10]W. Johnson, H.K. Kudo, The Mechanics of Metal Extrusion, 1962

[11] K. Laue , H. Stenge,. Extrusion – Process, Machinery, Tooling, ASM Internationla, Metals Park, Ohio 1981

[12] J. Chodorowski, A. Ciszewski, T. Radomski: Materiałoznawstwo lotnicze, Oficyna Wydawnicza PW, Warszawa 2003

[13] M. Hatherly, Deformation at high strains, Strength of Metals and Alloys, Proceedings of the 6th International Conference, ICSMA 6, R.C. Gifkins (ed), Pergamon Press, Oxford, 1983, 1181-1195.

[14]B. Pawłowska, R.E. Śliwa, Analiza plastycznego płynięcia materiału w procesie wyciskania płaskowników, Rudy i Metale Nieżelazne, R.44, nr 11, 1999, 607-613

[15] B. Pawłowska, R. E. Śliwa, Czynniki kształtu w określaniu siły wyciskania wyrobów o różnej geometrii przekroju poprzecznego, Rudy i Metale Nieżelazne, R.51, nr 4, 2006, 192-200

[16] B. Pawłowska, R.E. Śliwa, Wpływ czynników kształtu oraz własności wyciskanego profiluna efekt odkształcenia i poziom siły kształtowania. XIV Konferencja Sprawozdawcza "Metalurgia 2006"

[17] W.Z. Misiolek , Extrusion of Aluminum alloys , ASM Handbook, Volume 14A: Metalworking: Bulk Forming S.L. Semiatin, editor, 522-527,

[18] Pradip Saha, book chaper on Extrusion and Drawing of Aluminum Alloys. ASM HANDBOOK Aluminum Science and Technology (2018)

[19] R. Ye. Lapovok, M. R. Barnett, C. H. J. Davies,. Construction of extrusion limit diagram for AZ31 magnesium alloy by FE simulation. J. Mater. Process. Technol. 146, 2004, 408 – 414.

[20] G.Sauer, Extrusion of Semifinished Products in Magnesium Alloys. Extrusion. 2nd ed., M. Bauser, G. Sauer, K. Siegert. ASM International, Materials Park, Ohio, 2006, 203 - 207. Available online: www.asminternational.org.

[21] K. F. Zhang, D. L. Yin, D. Z.Wu,. Formability of AZ31 magnesium alloy sheets at warm working conditions. Int. J. Machine Tools and Manuf. 46, 2006, 1276 – 1280.

[22] E. Hadasik, D. Kuc, G. Niewielski, R.E. Śliwa, Rozwój stopów magnezu do przeróbkiplastycznej; Hutnik - Wiadomości Hutnicze, 76 (8), 2009, 580 - 584

[23] Z .Zeng, N. Stanford, C. H. J. Davies, J. F.Nie, N Birbilis, Magnesium extrusion alloys: a review of developments and prospects. International Materials Reviews, 64(1), 2019, 27-62.

[24] R. Ye. Lapovok, M. R Barnett, C. H. J. Davies,. Construction of extrusion limit diagram for AZ31 magnesium alloy by FE simulation. J. Mater. Process. Technol. 146, 2004,408 – 414.

[25] G. Sauer, Extrusion of Semifinished Products in Magnesium Alloys. Extrusion. 2nd ed., M. Bauser, G. Sauer, K. Siegert. ASM International, Materials Park, Ohio, 2006, 203 - 207. Available online: www.asminternational.org.

[26] E. Hadasik, D. Kuc, G. Niewielski, R.E Śliwa, Rozwój stopów magnezu do przeróbkiplastycznej; Hutnik - Wiadomości Hutnicze, 76 (8), 2009, 580 – 584