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Correlation of Temperature-speed Extrusion Parameters, Tool Design and Quality of Profiles of Magnesium Alloys

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Experimental investigation of the extrusion process of Mg-Al-Zn-Mn and Mg-Ca magnesium alloys with different tools and extrusion conditions had been carried out. The effect of pocket or porthole die design, deformation and temperature-speed extrusion parameters on temperature of the strips and tubes of alloy AZ31B, grain size, mechanical properties and stability of the geometric dimensions along the profile as well as weld quality in tubes had been investigated. The influences of calcium content, temperature conditions and extrusion ratio on the extrusion force, mechanical properties and structure of small-diameter tubes with wall thickness 0.4 to 0.7 mm of Mg-Ca alloys had been established.

Key words: EXTRUSION, MAGNESIUM ALLOY, AZ31B, MG-CA, STRIP, TUBE, POCKET DIE, PORTHOLE DIE, MANDREL

Introduction

The advantages of extruded profiles of magnesium alloys are their high specific strength, shock absorption properties, cutability and recycling. In addition, the price for magnesium in the last decade has significantly decreased what affords to expect the growth in the consumption of such profiles.

Extrusion of magnesium alloys in comparison with aluminium is considerably less covered in literature. The recommended extrusion temperature-speed conditions and mechanical properties of extruded semifinished products of Mg-Al-Zn-Mn alloys are shown [1-3 and others]. There is data [4] about using for tube extrusion both solid billet with porthole dies and hollow billets with a long mandrel. Information about the optimal ratio of billet and container temperatures are given in [4, 5].

An analysis of published data shows that Mg-Ca alloys are not enough investigated. Data on the extrusion of these alloys have not been found. Data on characteristic points of phase diagram [4, 6, etc.] is contradictory and can’t be used at choosing the billet temperature for alloys with low calcium content. At the evaluation of the optimal extrusion temperature-speed regimes as the closest can be considered technically pure magnesium and low alloyed Mg-Mn and Mg-Al-Zn-Mn systems without zirconium and rare-earth elements.

Objectives

The aim of this paper is analysis of the influence of the temperature-speed conditions and extrusion tool design on the quality of profiles of magnesium alloys. In particular, a study of extrusion of strips with different thickness through the flat and pocket dies, as well as tube extrusion through a different porthole type dies and with a long mandrel had been carried out. Let's have a detailed look at these directions.

1. Extrusion of solid profiles of Mg-Al-Zn-Mn alloy through a flat and stepped pocket dies

1.1. Experimental

The experiments were carried out on horizontal hydraulic 10 MN press of the Institute of Materials Science, Hannover University after Leibniz.

Die casted and homogenized billets were machined to length of 260 to 300 mm and 120 mm diameter. Chemical composition of alloy AZ31B according to ASTM is as follows:

Mg	Al	Mn	Zn	Zr	Si	Cu	Ni	Fe	Ca	rest
rem.	2,5…3,5	0,2…1,0	0,6…1,4	–	0,1	0,05	0,005	0,005	0,04	0,3

Billet was heated in an electric resistance furnace within 0.5-1.5 hours. The time between removal from the furnace and loading into the container was 6 to 10 sec. Billets were loaded by the bottom part to the die. The temperature of the tool before loading into the press was equal to the billet. Extrusion was realized without front tension and lubrication. Pressure in the hydraulic cylinders of the press, speed and ram position were recorded. The temperature of the strip surface was measured with hand contact thermocouple. The average temperature of the strip at the exit from the die was recalculated according to the results of measurements, adjusted to the distance from the die to the measurements point and the profile speed.

Extrusion of thick strips of 80 × 6 mm was carried out through the flat and two-stepped pocket die with extrusion ratio 25 (**Figure 1**), and thin strips 60 × 2 mm through 2 or 4 channel pocket dies with extrusion ratio of 50 or 25 respectively. Temperature and speed regimes are shown in **Table 1**. For the purpose of experiments number reducing, extrusion was carried out from high speeds to lower evaluating the quality of the surface of the strip. If it was not satisfactory then further experiments with this combination of temperature and speed were not carried out, reducing speed or temperature. The main defects are surface darkening due to oxidation and so-called "hot cracks" (**Figure 2**).

The reason of these cracks is a high temperature of the strip due to deformation heating and the non-uniform deformation in the cross section of the strip. At the same extrusion conditions, cracks in the thinner strips usually did not occur. The hot cracks are caused not only by high temperature, but also by non-uniform of deformation. This is proofed by the fact that on the strip edges first appears "orange peel" and then the cracks emerge. "Orange peel" is a defect associated with the presence of tensile stresses. They arise due to central layers of metals tend to acquire greater outflow velocity. The darkening of the surface due to oxidation indicates elevated temperature. Moreover both color and surface roughness along the section of thin bands remain practically unchanged in comparison with 6 mm thick strips, characterized by higher surface quality in the middle of the strip.

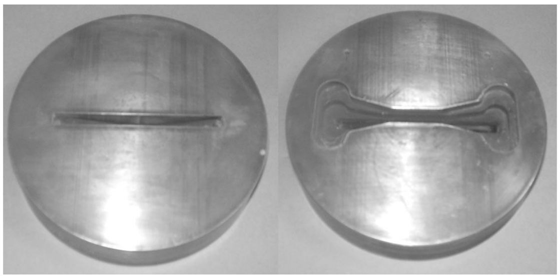


Figure 1. Flat and stepped pocket die

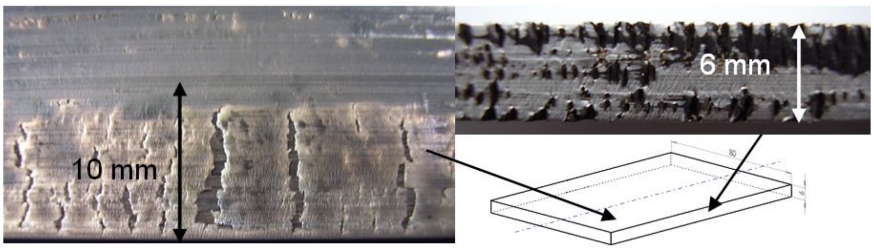


Figure 2. Cracks in the strip edge zone

Table 1. Extrusion parameters for strips of alloy AZ31

Cross section [mm]	Die type	Extrusion ratio	Billet temperature [°C]	Container temperature [°C]	Ram speed [mm/s]
80×6	F*; SP	25	360	340	4; 6; 8
80×6	F; SP	25	320	310	2; 4
60×2	SP	25	320	310	2; 4
60×2	SP	50	320	310	1; 4

* For a given temperature the flat die was used only at extrusion speed of 4 mm/s; "F" is flat die, "SP" is stepped pocket die

1.2. Influence of process parameters on the dimensional accuracy and temperature of strips

As an integral characteristic of size and accuracy of the 80 × 6 mm strips, obtained at various extrusion conditions, the mass per meter was used (**Table 2**). It was established that increasing of extrusion speed and reducing of the billet temperature lead to decline of specific profile weight due to rise of die set elastic deformation. Magnesium alloy extrusion through a flat die always leads to strip thinning not only due to elastic deformation of the die set but also as a result of out-of-contact deformation of the metal at the exit from the die bearing. Weight per meter of strip at extrusion through a flat die is 1.3% less than at extrusion through a pocket die.

Extrusion speed has a significant influence on the temperature. Thus, for thin strips with extrusion ratio ER = 25 and speed of 1 mm/s temperature increases no more than on 50° C and the temperature reaches a maximum when the distance between the press stamp and the die is approximately equal to the container diameter and then temperature begins to decline due to heat removal by the container. Increasing of the extrusion speed V_P and extrusion ratio *ER* intensify the increment of temperature ΔT. At V_P = 4 mm/s value of ΔT reaches 100 °C and 145 °C on the strip's end, for the cases *s* = 6 mm, *ER* = 25 and *s* = 2 mm, *ER* = 50 respectively.

1.3. Mechanical properties and structure of the metal of strips

The mechanical properties of extruded profiles are listed in **Table 3**. There is no clear dependence of mechanical properties from extrusion speed and billet temperature for strips with thickness 6 mm, changes do not exceed the limits of standard deviation. Elongation, at the increasing of extrusion speed in 2 times, decreased slightly (3 to 12%). Extrusion through a flat die provides insignificant higher yield strength (3.5 to 5.5%) and elongation (6 to 10%), that can be explain by increased temperature of the metal at extrusion through the pocket die. To rectify this lack the lower billet temperature (10 to 20 °C) could be recommended.

For strips with thickness 2 mm, increase in extrusion speed had led to some reduction in strength and yield stress (2 to 6% that is comparable with the value of standard deviation), elongation did not change. Increase in extrusion ratio did not lead to appreciable change in tensile strength, only yield strength slightly declined (4 to 6%) and elongation grew.

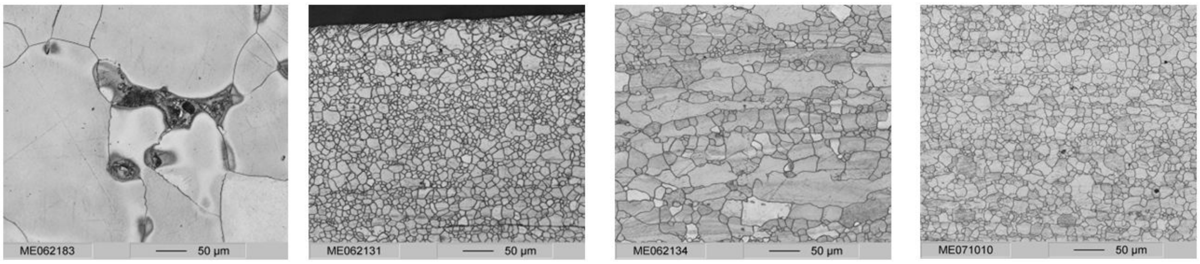
Unlike aluminium alloys, in thick strips (6 mm) of the alloy AZ31B near-surface layer with depth of about 0.3 mm with a fine-grained structure in the center strip cross section (**Figure 3b** and **3c**) was observed. The average grain size in this layer was 14 to 15 mm, in the base metal – 22 to 27 μm and in the billet was 38 μm. The average value of the grain size was less at extrusion through the flat die but the structure was much more homogeneous in comparison with the metal extruded through the pocket die. There were some elongated not recrystallized grains in the center of section in both cases.

Table 2. Weight per meter of strips of 80 × 6 mm

	Type of die and billet temperature						
	Stepped pocket die, 360°C			Stepped pocket die, 320 °C		Flat die, 320°C	
Extrusion speed [mm/s]	4	6	8	2	4	2	4
Specific mass [gr/m]	813,6	810,4	807,8	811,9	811,4	801,4	800,7

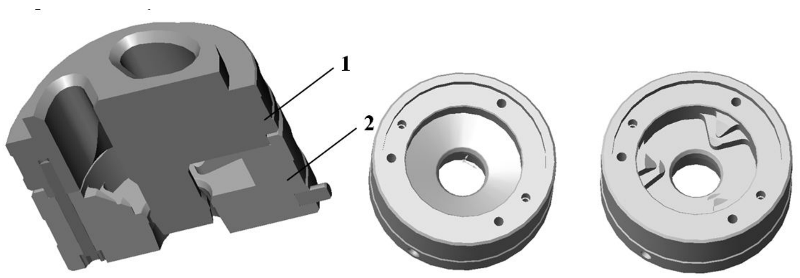
Table 3. Mechanical properties of extruded strips

Strip size, mm	Die type	T_B, [°C]	V_P, [mm/s]	*ER*	$R_{p0,2}$, [MPa]	R_m, MPa	A_5 [%]
80×6	SP	360	4	25	147,4	251,0	16,1
			6		150,0	250,2	15,8
			8		150,1	251,7	15,6
	SP	320	2		146,5	252,2	16,8
			4		146,2	250,5	15,2
	F		2		152,2	256,0	18,7
			4		154,7	255,3	16,2
60×2	SP	360	2		153,8	258,8	18,9
			4		151,4	252,6	18,2
			1	50	150,9	255,6	18,3
			4		141,4	249,8	18,1



a b c d

Figure 3. Microstructure in longitudinal direction: *a* – billet; *b* – surface layer, strip 80×6 mm; *c* – axial layer, strip 80×6 mm; *d* – strip 60×2 mm



a b c

Figure 4. Extrusion tool: *a* – porthole die set (1 – mandrel plate, 2 – die); *b* – conical die; *c* – flat-stepped die

Table 4. Plan of experiment and mechanical properties of tubes

#	Die type	T_B, [°C]	T_C, [°C]	$R_{p0.2}$, [MPa]	R_m, [MPa]	A, [%]	e_D	F/D, [N/mm]
0	with mandrel	360	340	159	257	18.3	0.098	84
1	porthole	360	340	158	248	18.1	0.114	96
2	with conical die	400	340	162	246	16.4	0.108	95
3		400	400	160	243	16.1	0.119	89
4	porthole with	360	340	160	237	17.2	0.114	95
5	flat-stepped die	400	400	159	237	18.4	0.123	102

In thin (2 mm) strips as well as in thick (6 mm) grain size at the strip edge was always smaller (**Figure 3d**). By increasing the outgoing velocity of the metal the average grain size can increase due to the higher temperature because of deformation heating. The grain size in thin strips was 12 to 16 μm at the strip edge and 14 to 18 μm in the center.

2. Effect of extrusion conditions and porthole die design on quality of tubes of magnesium alloy AZ31B

2.1. Experimental

The experimental technique was similar to that described in part 1.1. Extrusion was carried out through the porthole die. However the shape of the die was different from the traditional for aluminium alloys. Two dies in a set with the same mandrel plate were used (**Figure 4**). The first has inclined double-cone bottom. The second die has a flat bottom, where 3 pairs of steps were situated. Axis of steps coincides with the axes of the mandrel plate ports. It is assumed that this will lead to the improvement of welding under the bridges through the directing of the metal to this area.

Also the temperature of the billet T_B as well as the relationship between container T_C and billet temperature T_B were varied (**Table 4**). The extrusion speed was 2 mm/s, extrusion ratio was 50, the nominal outgoing velocity was 6 m/min. Comparison of the results was carried out not only for porthole dies of different type but with extrusion on a long mandrel (base case "0"). Tests on expansion by a cone with an angle of 60° were performed according to EN 10234.

2.2. Geometric characteristics of tubes

The values of diameter and wall thickness of tubes are shown on **Figure 5**. Elastic deformation, out-of-contact plastic deformation and thermal expansion are the main causes of uneven sizes of tubes and their deviations from the nominal. The value of outside diameter of the tube, which it must have in a cold state considering only the different thermal expansion of metal of the tubes and the tools, shown in **Figure 5** with black line. The wall thickness is defined as the difference in diameters. Diameter of the mandrel and the die as a result of elastic deformation was determined using COSMOSWorks for SolidWorks®. Reducing the gap between mandrel and die at maximum extrusion force was only 0.007 mm for a set of flat-stepped die and with a conical die – 0.016 mm.

Analysis of the results shows that the diameter and wall thickness at the end was always less than at the beginning of the tube due to a larger thermal expansion. Flat-stepped die provided a smaller tube diameter and wall thickness than the conical. The tubes extruded through the flat-stepped die had much smaller diameter expansion at the beginning that associated with the taper of extruded metal temperature. Wall thickness of tubes extruded through the conical die is always greater (0.01 to 0.08 mm) than expected due to thermal expansion and elastic deformation of the tool. Values for flat-stepped die are not very different from the expected value (less than 0.01 to 0.02 mm).

The temperature increment during extrusion at investigated extrusion ratio (50) was considerable – 130 to 160°C (lower values correspond to higher billet temperature). The main change in temperature (about 90%) was in the front part of the tube (**Figure**. **6**). At extrusion through the die with the flat-stepped bottom, tube temperature was few degrees higher.

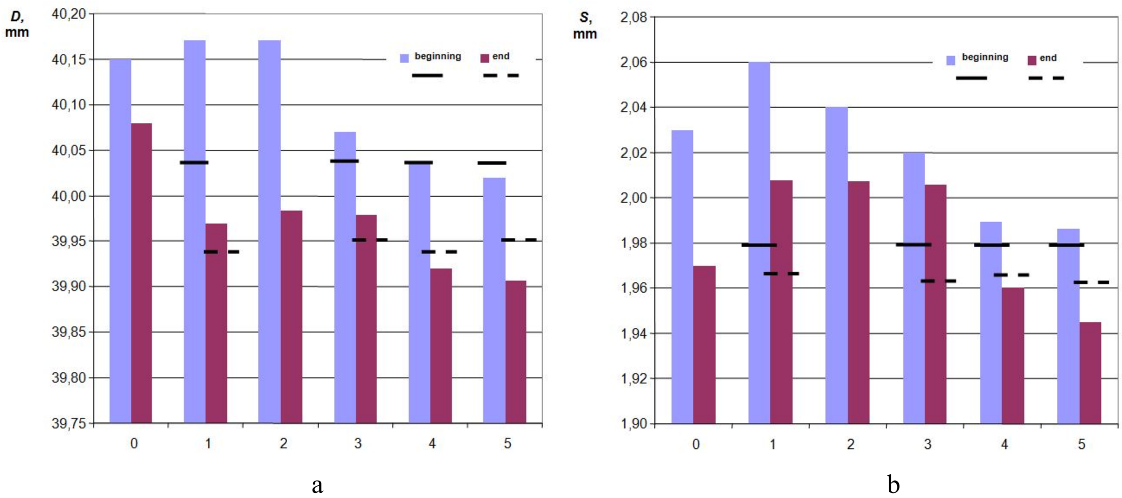


Figure 5. Sizes of the tubes: *a* – diameter; *b* – thickness

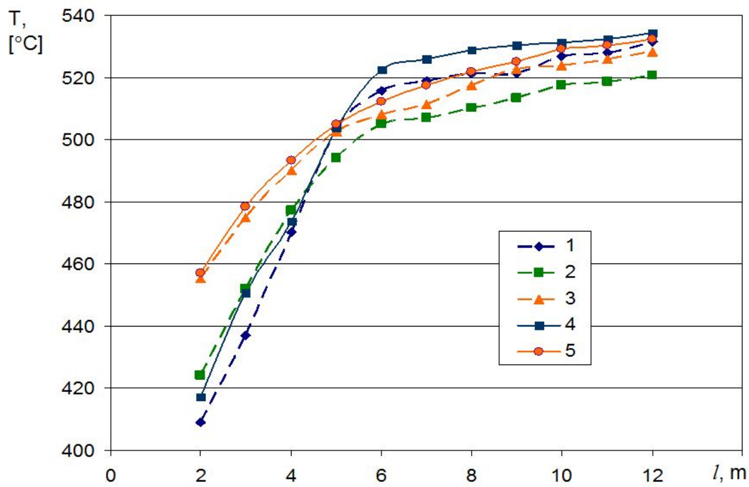


Figure 6. Temperature change along the tube length

2.3. Mechanical properties and structure of metal of tubes

Yield strength of metal of tubes, obtained under different extrusion conditions does not differ significantly and within 2.5%. With increasing of billet temperature the tensile strength of the tube reduces in the case of the conical die (in the range of 8 N/mm^2) and practically unchanged for the flat-stepped die. Tensile elongation is slightly higher for tubes extruded through the flat-stepped die. In general the tubes obtained under the above mentioned temperature-speed conditions are at the lower limit of tensile strength but significantly exceed the requirements of DIN and ASTM for tensile elongation (60 to 120%). However it should be mentioned that the tubes had been obtained without any further stretching which would lead to the strengthening of tubes and reduce the elongation. Tests on the expansion more objectively characterize the strength of the weld seam and heat affected zone than the tensile test. At the expansion tests the amount of force per tube perimeter unit and the relative perimeter increasing ($e_D = \ln(D_1/D_0)$) are in 10% to 40% greater for the tubes extruded through the flat-stepped die (maximal value of e_D is 0,124 for case #3). In general these characteristics for welded pipe are not less than for seamless.

Analysis of the cross-section of tubes shows that near the outside and inside tube surfaces there are smaller grain size layers with a depth of appr. 0.3 mm (**Figure 7**, **Table 5**). Sometimes there is a layer with coarser grain closer by outside surface with a depth of about 50 μm. Such distribution may be explained by a greater work of deformation in the near-surface layers and the friction of the surface layers with the die. Longitudinal weld was found in micro sections only at the beginning of tubes which were extruded at the higher billet temperature (400 °C) through the dies of both types (**Figure 7**). In the weld axis the grain size is bigger than in the base metal. Grain size is given in **Table 5**. The grain size is greater on 2 to 4 μm in tubes extruded through the flat-stepped dies. Extrusion through the cone die is more sensitive to temperature of the billet: with an increase of T_B from 360 to 400° C, the grain size in the main body of the tube was increased on 30% whereas at extrusion through the flat-stepped die it practically did not changed.

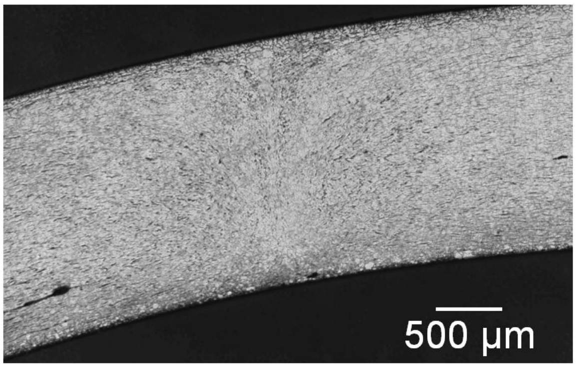


Figure 7. Example of longitudinal weld zone (cross-section)

Table 5. Average grain size in the longitudinal section for different zones of tube cross section

Layer	Variant number					
	0	1	2	3	4	5
Outer	5.3	11.9	12.9	14.1	14.6	15.7
Middle	9.3	17.9	19.1	25.3	28.7	27.5
Inner	6.6	17.4	18.9	21.3	24.9	25.3

2.4. The quality of the tube surface

The quality of the tube surface was evaluated in respect to the "color", i.e. darkening due to oxidation as well as the presence of the visible weld on the outside and inside tube surface.

It is established that:

– the beginning of the tube is always less oxidized than the end;

– at lower billet temperatures the inner surface of the tube is darker than the outer, at higher contrariwise;

– as a rule on the outer surface weld is not visible (only exception is extrusion through the cone die at high billet temperature);

– the weld on the inner surface is rarely seen and its width is less at extrusion through the flat-stepped die; for the case of extrusion at a lower billet temperature (360° C) it was not found;

– at the higher temperature of extruded metal the weld becomes wider and changes to white-gray color instead of gray ("white" is the place of appearance of fine lines, wrinkles and roughness).

3. Investigation of the extrusion process of thin-walled tubes of small diameter of alloys of Mg-Ca system with a long mandrel

The effect of chemical composition and extrusion parameters on the mechanical properties of thin-walled tubes of Mg-Ca alloys was investigated. Tubes with a diameter of about 6 mm and wall thickness 0.3 to 0.7 mm are used as a half-product for subsequent drawing of capillary tubes to the diameter of 2 to 4 mm and wall thickness of 0.2 to 0.6 mm for the manufacturing of implants for vascular surgery. To reduce the necessary wall reduction at drawing it is reasonable to get the extruded tubes with the minimum possible wall thickness.

3.1. Experimental

It is known that extrusion on the vertical tube extrusion presses provides a less deviation in wall thickness. Taking into consideration this fact and wide distribution of low-power vertical hydraulic presses the experimental studies were carried out on 800 kN press of the Institute of Materials Science, Hannover University after Leibniz. The diameter and length of container are 29 and 120 mm respectively, the extrusion speed is 1.25 mm/s.

Extrusion was carried out with a long mandrel and a conical die but not through a porthole die in order to reduce the extrusion force and produce seamless tubes. The die had double-coned design with radial taper to the bearing.

Billets were cylinders with a conical head shape obtained by upsetting the extruded rod of ∅20 mm in the container of the same press. After upsetting the billets were cooled in air and drilled. As a lubricant was used molybdenum disulfide. Ultimate tensile strength of initial extruded rods of alloys containing of 0.4 to 2.0% calcium was 290 to 316 MPa and elongation was only 1 to 6%.

The experiments were carried out in two phases by varying the following parameters:

1) calcium content: 0.4, 1.2 and 2.0 %;

- nominal wall thickness of tube: 0.3, 0.4 and 0.5 mm;
- billet temperature T_B: 350 and 410 °C;
- container temperature T_C: 380 and 410 °C.

2) billet temperature T_B: 340 to 420 ° C in increments of 20°C at the constant extrusion ratio (70);

3) nominal tube wall thickness: 0.3 to 1.0 mm.

In the second series temperature of the container and of the tool was equal to the temperature of the billets.

The main factors that limiting the possibility of the process are: maximum extrusion force, destruction of the mandrel or extruded material. At the direct extrusion of the specified alloy the maximum force at the beginning of the process was significantly greater (30%) than at quasi-steady process. Note that the section of pressure increasing was very sloping and took one third of the extrusion time. The lubricant was used to reduce the extrusion force but its heavy coating leads to a worsening in the tube appearance, i.e. darkening, especially at the beginning of the process.

Carrying out the process at extrusion ratio of more than 80 to 100 and the billet temperatures below 350 °C was practically impossible because the metal did not flow to the die channel. High billet temperatures reduced the extrusion force but can lead to “hot cracks”. The most probable place of their occurrence is a section of tube near the front end of the tube corresponding to the peak extrusion pressure.

At the extrusion process breaks of mandrels had also been noticed because of large tensile stresses due to friction on the surface of the mandrel as the metal speed greatly exceeds the mandrel.

Deviations of the geometric dimensions (diameter and wall thickness) of tubes ∅6,4×0,4 mm meet the requirements of ASTM V107/V107M-92.

3.2. The influence of calcium content in the alloy Mg-Ca and extrusion parameters on the mechanical properties and structure of the metal of tube.

The test results are given in **Table 6**. Mechanical properties of tubes obtained at extrusion ratios corresponding to the stable process are satisfactory: the tensile strength of 160 to 200 MPa, elongation 10 to 18%. Tubes have 30% lower strength compared with extruded rod-billet but several times higher elongation that is required for the subsequent drawing.

The increase in temperature had leaded to grain grows. For smaller values of T_B (340 to 370 °C) the grain size is reduced in comparison with the original structure of the extruded billet (**Figure 8**). At higher temperatures the grain size of the tube metal was approximately equal to the grain size in the billet. Increase in the extrusion ratio leads to more coarse-grained structure (**Figure 9**). At extrusion with maximum extrusion ratio sufficiently fine grain was received because of extrusion speed decreasing.

Table 6. Mechanical properties of tubes received at different temperatures of the billet (at T_C = 380° C)

Alloy	Extrusion ratio	T_B = 350 °C		T_B = 410 °C	
		R_m [MPa]	A, %	R_m [MPa]	A, %
MgCa0,4	55…57	–	–	177	15,7
	70…74	177	18,5	179	14,4
	120…130	160	12,1	199	10,3
MgCa1,2	55…57	–	–	204	14,2
	70…74	191	14,0	198	11,4
	120…130	167	6,2	252	3,6
MgCa2,0	55…57	–	–	195	12,2
	70…74	193	9,2	197	10,1
	120…130	184	4,8	266	1,2

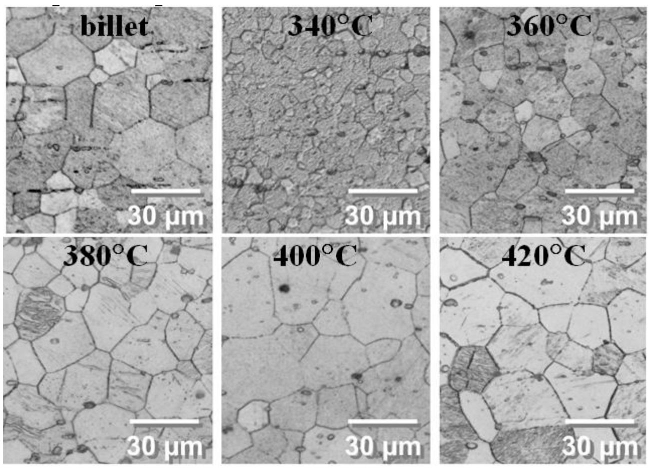


Figure 8. The microstructure of the metal of the tube ∅ 6 mm of alloy MgCa0, 8 obtained at different extrusion ratios of drawing (longitudinal section)

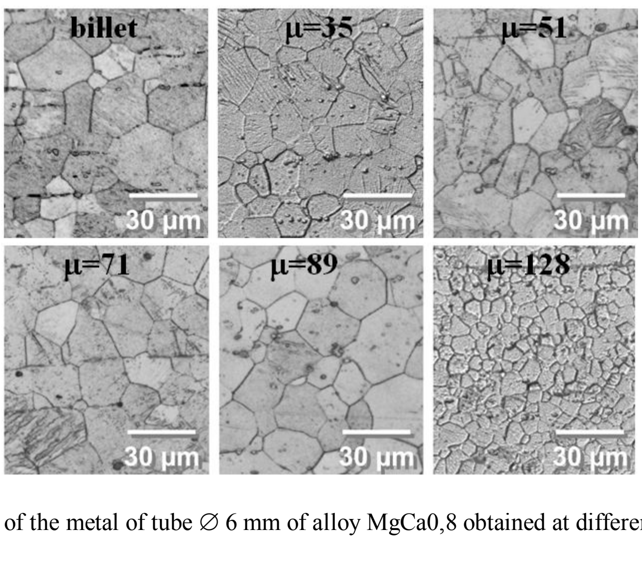


Figure 9. The microstructure of the metal of tube ∅ 6 mm of alloy MgCa0,8 obtained at different extrusion ratios of drawing (longitudinal section)

Conclusions

Experimental investigations of extrusion process of Mg-Al-Zn-Mn and Mg-Ca system‘s magnesium alloys with different extrusion tool for different temperature-speed parameters showed the following.

The using of flat die with stepped pocket or porthole die with stepped weld chamber bottom leads to a slight increase in the profile temperature and the grain size, but provides greater stability on the geometric dimensions along the profile and higher longitudinal weld quality in the extruded tube.

Unlike aluminum alloys in the magnesium bands and tubes exists the near-surface layer with lower (1.5-2 times) grain size then in base metal.

Porthole die with stepped weld chamber bottom provides greater plasticity of tubes, extrusion weld strength and surface quality.

Increase of calcium content and outgoing velocity leads to decrease in strength and plasticity of thin-walled tubes extruded on a mandrel. Elongation of tubes was several times higher than in metal of extruded billet.

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Взаимосвязь температурно-скоростных режимов прессования, конструкции инструмента и качества профилей из магниевых сплавов

Головко А. Н., Данченко В. Н., Шапер М.

Проведены экспериментальные исследования процесса прессования магниевых сплавов систем Mg-Al-Zn-Mn и Mg-Ca с использованием различного прессового инструмента при различных температурно-скоростных параметрах. Установлено влияние конструкции плоских форкамерных и комбинированных матриц, деформационных и температурно-скоростных параметров прессования на температуру полос и труб из сплава AZ31B, величину зерна, механические свойства и стабильность геометрических размеров по длине профиля, а также качество сварного шва при при прессовании труб. Экспериментально установлено влияние содержания кальция, температурных условий и коэффициента вытяжки на силовые параметры прессования, механические свойства и структуру труб малого диаметра с толщиной стенки 0,4-0,7 мм из сплавов системы Mg-Ca.