Bartłomiej **PŁONKA**
Piotr **KORCZAK**
Krzysztof **REMSAK**
Marek **RAJDA**

MODERN TECHNOLOGIES OF MANUFACTURING ADVANCED MAGNESIUM ALLOY PRODUCTS USING METHODS OF PLASTIC PROCESSING

Abstract. This paper discusses the process of direct and indirect extrusion of rods, profiles, tubes, etc. for a series of MgAlZn magnesium alloys, which are suitable for heat treatment to obtain the highest strength. These products have been manufactured at the Institute of Non-Ferrous Metals, Light Metals Division (IMN OML) in the form of billets with a 100 mm diameter. The extrusion process was performed in the temperature range between 320°C and 430°C and at the ram speed of 0.5 to 5.0 mm/s. The impact of heat treatment on the mechanical properties of magnesium alloys was also the subject of this study. The tested magnesium alloys had higher mechanical properties for temper T5 than for temper T6. In conclusion, reference is made to the possibilities of practical application of the results obtained.

Keywords: Mg alloys, extrusion, heat treatment, mechanical properties, bending.

1. INTRODUCTION

Magnesium, being an element of very low density (1.74 g/cm^3), is the lightest metal used for construction purposes. However, due to the poor mechanical properties of pure magnesium, only its alloys for casting and plastic processing are in common use. Magnesium alloys, due to their characteristics, such as low density (ca. 1.8 g/cm^3), a very high specific strength (ratio of strength to density) and relatively good electrical and thermal conductivity and machinability, their market position is continuously improving, providing the ability to create very lightweight structures of high stiffness [1]. Today, most parts produced from magnesium alloys, especially in Poland, are manufactured using casting methods: by gravity casting into metal or sand moulds or by pressure die casting. When articles made of magnesium alloys are to be used in parts subjected to higher loads, e.g. in the automotive or aviation industry, then these would require better mechanical properties. Products that meet such criteria may be obtained after plastic processing or heat treatment.

The most popular magnesium alloys are those with aluminium, zinc and manganese [1, 2]. Aluminium improves tensile strength and hardness of the alloy. Zinc in magnesium alloys is used to increase the strength of the alloy at room temperature, and manganese is used to improve corrosion resistance of the alloy. In terms of structure Mg-Al alloys comprise solid solution and eutectic. The phase equilibrium diagram of Mg-Al alloys (Fig. 1) shows that the variable increasing solubility of aluminium in magnesium reaches a maximum of 12.7% in solid state at the eutectic temperature of 437°C. These alloys, therefore, are heat treated to improve their mechanical properties by precipitation strengthening (temper T5, T6) [3, 4].

Magnesium alloys are usually subjected to plastic processing at elevated temperatures. This is due to the crystalline structure of magnesium, which crystallises in the hexagonal system. In

Bartłomiej **PŁONKA**, Piotr **KORCZAK**, Krzysztof **REMSAK**, Marek **RAJDA** - Institute of Non-Ferrous Metals in Gliwice, Light Metals Division in Skawina

this system there are only three sliding systems, which is insufficient for magnesium and its alloys to be plastic enough at room temperature [1]. It is only at elevated temperatures when two additional sliding systems are triggered, which makes plastic forming practicable. During deformation of metals at high temperatures the following processes occur: strain hardening, dynamic recovery and dynamic recrystallisation. These processes proceed in the metal simultaneously. Magnesium alloys have low stacking fault energy, and therefore dynamic recrystallisation is the leading process during high-temperature plastic processing [5]. It causes the removal of the effects of strain hardening, increases plasticity and reduces flow resistance.

Most of the magnesium produced is used as an alloying addition to aluminium. Only ca. 34% is used for the manufacture of magnesium parts, most of which are cast, and only about 1% is plastic worked. Cast parts have poorer mechanical properties (strength, elongation) as compared to parts subjected to plastic processing followed by heat treatment [6]. These differences are clearly illustrated in Fig. 2.

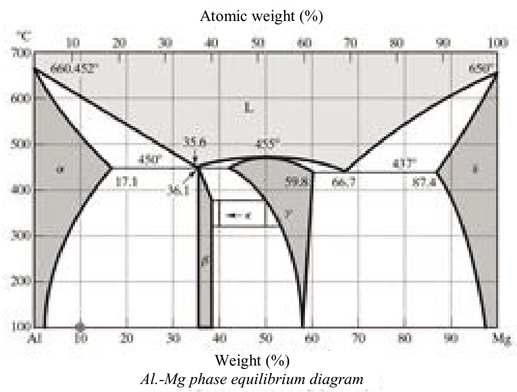


Fig. 1. Al-Mg phase diagram [4]

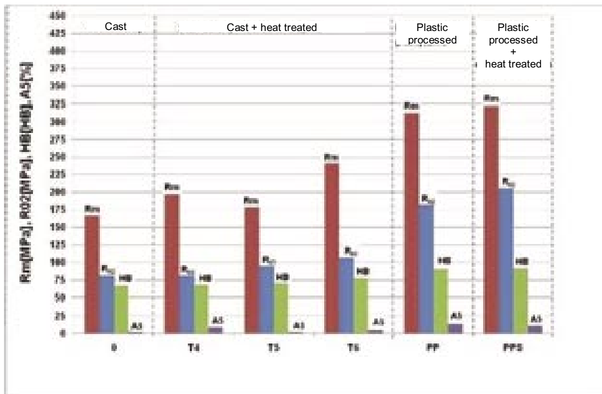


Fig. 2. Graphic representation of mechanical properties of AZ91 alloy depending on the type of processing [6]

Nevertheless mechanical properties of magnesium alloys are still much poorer than those of many aluminium alloys. Therefore efforts are made to improve the strength of parts made of magnesium alloys by selecting appropriate type and conditions of plastic forming. The best process to achieve this goal appears to be extrusion, during which the generated compressive stress provides the best conditions for plastic processing.

2. MATERIAL CHARACTERISTICS AND TESTING METHODOLOGY

As part of the presented work studies have been conducted of MgAlZn magnesium alloys (AZ80A, AZ61, AZ31). The chemical compositions of these alloys are shown in Table 1. These alloys, for the purpose of testing advanced forming processes, were cast in the form of round billets 100 mm in diameter at the Institute of Non-Ferrous Metals, Light Metals Division in Skawina, the only site in Poland and one of the few in Europe that have a facility for semi-continuous vertical casting of Mg alloy billets [7].

A fully equipped and automated stand (Fig. 3) consists of a melting foundry furnace with a capacity of 150 kg, a well with moulds and a shielding gas mixing and distribution system. It provides an excellent base for carrying out trials of obtaining materials from Mg alloys for further testing of plastic processing.

Table 1. Chemical composition of MgAlZn alloys

Alloy	Zn [%]	Al [%]	Si [%]	Cu [%]	Mn [%]	Other additions total [%]
AZ80A	0.28	8.1	0.02	0.01	0.18	< 0.3
AZ61	0.62	5.97	0.03	0.003	0.31	< 0.3
AZ31	0.72	3.2	0.02	0.001	0.37	< 0.3

Fig. 3. Line for semi-continuous casting magnesium alloy billets

Tests of direct and indirect extrusion were carried out on a horizontal press of max. capacity of 5 MN (Fig. 4). The press is fitted with a hydraulic piercer enabling the extrusion of seamless tubes, an induction heater with three heating zones for billets up to 100 mm in diameter and up to 450 mm long, a 12-metres run-out table with a puller and an extruded blank cooling system, and a 0.2 MN stretcher for bars up to 6 m long. This press enables carrying out tests on a semi-commercial scale [8,9].

Fig. 4. A 5 MN direct/indirect extrusion press with a piercer, "water wave" and run-out table

The next step was the bending test. In view of the aforementioned problems with cold forming of magnesium alloys, a special resistance heating system was developed to enable carrying out the tests also at elevated temperatures. Bending tests were carried out using a GM-38NCB mandrel bending machine (Fig. 5), which together with a specially designed set of tools allowed forming into the desired shapes. On their basis the required parameters to be met by an industrial bending machine and tooling (including heating system) for bending pipes and profiles made of magnesium alloy were determined.

Fig. 5. A GM-38NCB bending machine with tooling for bending magnesium alloy tubes

3. RESULTS

3.1.Extrusion of magnesium alloys

In general, plastic processed magnesium alloys have significantly better properties compared to those of cast alloys. This is due to the fact that plastic processed materials have finer grains as a result of dynamic recrystallisation. The extrusion temperature has a significant effect on the rate of recovery and recrystallisation processes, and on the degree of supersaturation. This is evidenced by literature data [2,4]. Properties of the products after high- and low-temperature extrusion are presented in Table 2.

Table 2. Effect of extrusion temperature on final product properties [2].

Extrusion temperature	$R_{p0.2}$ (MPa)	R_m (MPa)	A (%)	Temper after heat treatment
low	200-285	300-340	10-16	T5
high	145	280	13	T5

T5 = cooling from the temperature of plastic processing and artificial ageing 200°C/16 hours.

The billets 100 mm in diameter were peeled to 96 mm diameter and after that bars of round, square or rectangular cross section were extruded from the billets. More complex profiles and tubes were also extruded (Fig. 6).

Fig. 6. Examples of parts extruded from magnesium alloys

The tested magnesium alloys were directly extruded at an extrusion ratio λ (ratio of cross-sectional area of the billet to the cross-sectional area of the extrudate) between 8 and 30 using ram speeds (V_t) between 1 mm/s and 5 mm/s. The materials were heated to between 320°C and 430°C. Billets which were heated above 400°C were previously protected by chromating to minimise oxidation. The adopted criterion for assessing the quality of the extruded material was the condition of the surface and occurrence of cracks on the hot extrudate. Examples of the surface types of the extruded material observed depending on the temperature and rate of extrusion are shown in Fig. 7.

a) b) c)

Fig. 7. Examples of surface types of extruded products

a – proper surface T_w-320°C -420°C, V_t<3mm/s; b – transitional surface T_w-380°C -410°C, 3mm/s<V_t<4mm/s; c – cracked/bad surface T_w-400°C -430°C, 4mm/s<V_t<5mm/s.

The extrusion tests carried out show that for the tested alloys, at ram speed of up to 3 mm/s, the temperature of the extruded material can be in the range of 320°C to 400°C. Higher extrusion temperatures are advantageous in terms of reduced force and are essential in the case of solutionising of the bar in the "on-line" system on the run-out table of the press (T5 temper). At higher ram speeds, the temperature of the material to be extruded should be lowered, otherwise no proper material will be obtained. Obviously, the results presented show only a very generalised dependence between the surface quality of the extruded material and the three main parameters of the extrusion process, that is temperature, extrusion speed and extrusion ratio λ for the MgAlZn alloys. As the extrusion process is characterised by several other parameters and factors that have an impact on its outcome, these results only indicate a certain trend that could be helpful in controlling the process of extruding magnesium alloys.

3.2.Heat treatment

For magnesium alloys, both alloys for casting, as well as alloys for plastic processing, mainly the T5, T6 tempers are applied. The tested extruded parts made of magnesium alloys were heat treated to such tempers, and additionally to tempers T1 and annealed temper "0". In view of insufficient literature information on the parameters of solutionising and of ageing, a series of tests was run to determine the appropriate parameters of temperature and time. A solutionising temperature of between 420°C and 460°C was adopted for the T6 temper based on literature data, while the T5 temper was attained by solutionising on the run-out table from the plastic processing temperature. The adopted ageing temperature of 175°C was identical for all alloys.

In order to determine the optimum ageing time, precipitation strengthening curves were plotted for the option of solutionising in the furnace and from the plastic processing temperature. Fig. 8 shows selected curves of natural and artificial ageing. Selected mechanical properties of various alloys of various tempers are listed in Table 3.

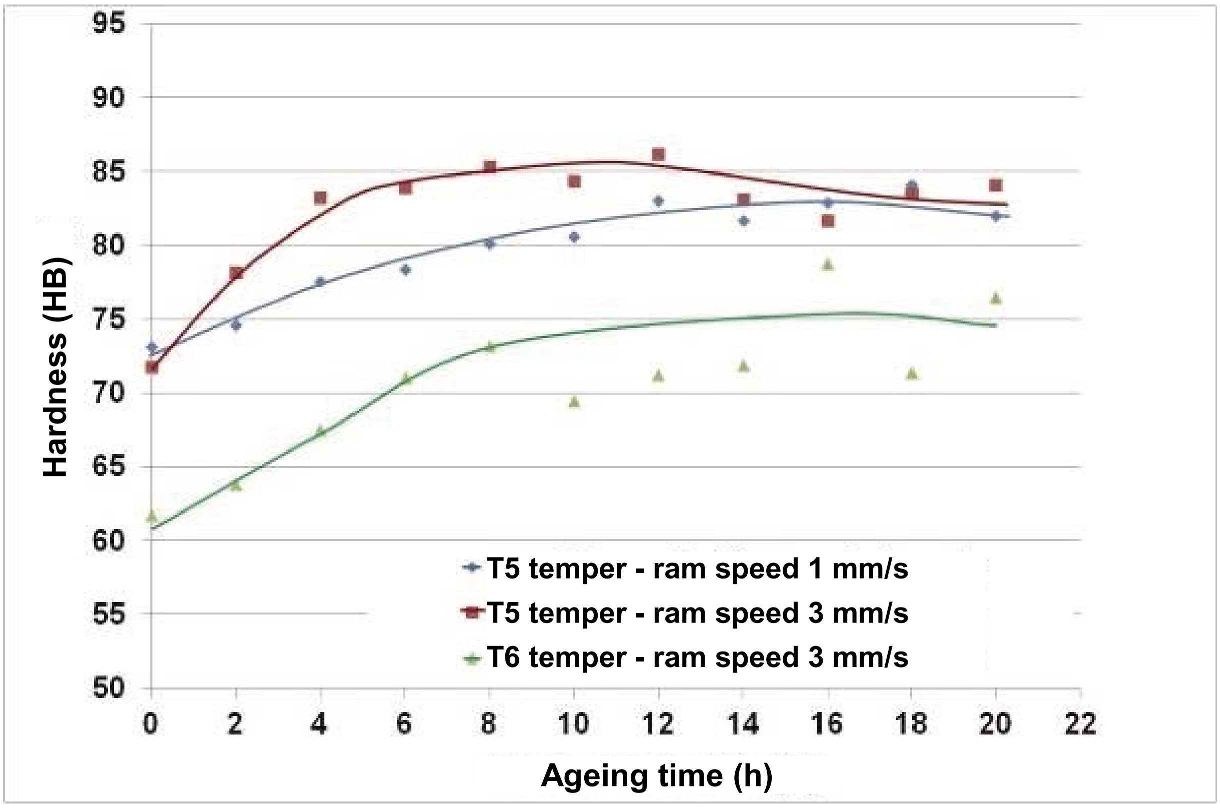


Fig. 8. Curves of natural and artificial ageing of the AZ80A magnesium alloy at 175°C

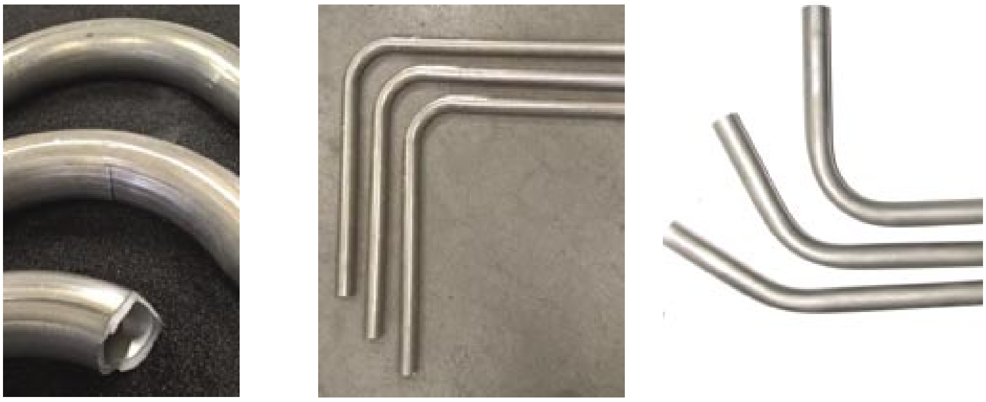
In order to attain the best economic effects, combined with the highest quality of products, heat treatment to the T5 temper should be applied, that is solutionising from the temperature of plastic processing ("online solutionising"). Artificial ageing for 10 to 12 hours is the most advantageous process. Heat treatment is more efficient in the case of alloys of higher content of alloying additions, namely the AZ80A alloy. In the case of heat treatment in a furnace after extrusion (T6 temper), alloys of lower Al content acquire worse mechanical properties than those in the extruded condition (F). This is a result of intensive grain growth during solutionising in the furnace, which is not compensated by the effect of precipitation strengthening. The extrusion temperature has a strong effect on the mechanical properties of magnesium alloys.

Table 3. Mechanical properties of extruded Mg alloys after heat treatment under various conditions

Alloy	Temper	$R_{p0.2}$ (MPa)	R_m (MPa)	A (%)	HB
AZ80A	F	237	312	10	65
	T1	210	329	13	85
	T5	275	353	9	87
	T6	226	336	10	78
	R	192	310	19	64
AZ61	F	207	316	17	64
	T5	243	338	19	70
	T6	204	311	21	58
	R	164	291	18	61
AZ31	F	249	306	11	61
	T5	265	318	19	64
	T6	165	255	25	55
	R	200	273	14	57

3.3 Bending tests

Tests were carried out on tubes of two sizes: diam. 30 x 2.5 mm and diam. 25 x 2 mm. They consisted in determining the practicable angle of bending, with the goal being an angle of at least 100°. Tests were performed at two different temperatures: room temperature of ca. 20°C and elevated temperature of ca. 200°C. Bend testing of hot parts was not conducted because of the small increase in bending susceptibility at 200°C and significant complexity of the required tooling and of the handling process. Much better results would probably be achieved at higher temperatures of about 300°C to 350°C, but according to the authors this would make the process excessively complex. The tubes subjected to bending were in the F, T5, T6 and O tempers. Examples of typical defects that occurred during the bending tests, and properly formed parts obtained after establishing the optimum machine settings are shown in Fig. 9. The most frequent defects included partial cracks on the inside of the arc, and occasionally complete ruptures of the tube. There were also cases of significant deformation of the pipe along the arc (collapse, ovalisation). The maximum angle usually attained on tubes in the F, T5 and T6 tempers was 45 to 50°. Only tubes in the "O" temper (annealed) could be bent to the angle of 100°.



a) b) c)

Fig. 9. Tube bending tests

a – defective bending; b, c - properly bent tubes

The tests the results of which are included in this paper were conducted with an intention to develop a technology of manufacturing bent magnesium pipes for constructing wheelchair frameworks. The technology generally applied so far is based on the use of aluminium alloys. The use of magnesium alloys may result in a 20% decrease in the weight of the wheelchair framework and in improved vibration damping.

4. CONCLUSIONS

1. Magnesium alloys of the MgAlZn group, at low ram speeds of up to about 3 mm/s, can be extruded in the temperature range of 350°C to 420°C, while at ram speeds greater than 3 mm/s the temperature must be reduced in proportion to the increasing extrusion ratio λ.
2. Performing extrusion at higher temperatures and at the same time at lower ram speeds is more advantageous as it reduces the extrusion force and allows solutionising immediately after extrusion. The structure obtained in this case is fine-grained and the mechanical properties are superior.
3. AZ (MgAlZn) series magnesium alloys acquire in the T5 temper better mechanical properties than in the T6 temper, that is after reheating and solutionising in a furnace.
4. With increasing content of aluminium in an AZ series magnesium alloy, the mechanical properties obtained after heat treatment are increasingly better.
5. In order to improve susceptibility to cold plastic forming, magnesium alloys should be subjected to an annealing process.
6. Mechanical properties of magnesium alloys can be adjusted by selecting appropriate parameters of plastic processing and heat treatment.
7. Properly devised technological processes enable the manufacture of products from magnesium alloys for use in many industries, e.g. in special-purpose military equipment of reduced weight.

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