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High-Strength Aluminium Alloys and Their Use in Foundry Industry of Nickel Superalloys

S. Pysz [a], M. Maj [a, b,] *, E. Czekaj [a]
[a] Foundry Research Institute, Zakopiańska 73, 30-418 Cracow, Poland
[b] Faculty of Foundry Engineering, AGH University of Science and Technology, Reymonta 23, 30-059 Cracow, Poland
*Corresponding author. E-mail address: m.maj@agh.edu.pl

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Abstract

Of great importance in the selection of materials for cast structures is keeping a proper balance between the mechanical and plastic properties, while preserving the relevant casting properties. This study has been devoted to an analysis of the choice and application of high-strength aluminium-based alloys maintaining sufficient level of casting properties. The high level of tensile strength (R_m > 500 MPa) matched with satisfactory elongation (A > 3%) is important because materials of this type are used for cast parts operating in the aerospace, automotive, and military industries. These beneficial relationships between the high tensile strength and toughness are relatively easy to obtain in the Al-Zn-Mg-Cu alloys subjected to plastic forming and proper heat treatment. In gravity cast products, on the other hand, whether poured into sand moulds or metal moulds (dies), obtaining this favourable combination of properties poses a number of research problems (mostly resulting from the alloy chemical composition) as well as technical and technological difficulties.

1. Introduction

Increasing demand for lightweight castings was witnessed not earlier than in the mid-70s of last century, mainly due to the growing requirements for fuel economy in the transport means. Depending on the type of application and compared with parts made from ferro-alloys, aluminium castings are able to reduce the weight of a vehicle by 35 to 50% by [1,2].

Future applications of light alloys are particularly interesting in all those cases where weight reduction is important. A good example is the production of land and air transport means, due to a close relationship that exists between the weight of a vehicle and fuel consumption, and also for easier handling of electronic products and home appliances. For designers and manufacturers, the lightweight structural parts made from aluminium alloys have - in addition to the reduced weight - a number of other advantages. They are characterised by high levels of functionality (material performance indeces) like individual stiffness parameters (E/ρ), strength ($R_{p0,2}/\rho$)) or toughness (K_{1c}/ρ)) - Table 1 [3-6].

Modern advances in computer hardware, software and databases provide new opportunities in the range of simulation and *ad experientiam* estimating of technological and operational properties of castings [7-9]. Increasingly, computer-assisted, thermodynamic and other models of the behaviour of materials are included in the research programmes even in early stages of the project execution (e.g. target projects for industrial applications) [8,10].

Table 1.
Some indicators of functionality (material performance indeces) for selected casting alloys (own study based on literature date [3-6])

Alloys	Density ρ, [Mg/m^3]	Young's modulus E, [GPa]	Yield strength, $R_{p0,2}$, [MPa]	Material performance indeces					
				M$_1$	M$_2$	M$_3$	M$_4$	M$_5$	M$_6$
				E/ρ	$E^{1/2}/\rho$	$E^{1/3}/\rho$	$(R_{p0.2})/\rho$	$(R_{p0.2})^{1/2}/\rho$	$(R_{p0.2})^{2/3}/\rho$
aluminium	2.70	70	300	25.93	3.10	1.53	111.11	6.42	16.60
iron	7.85	200	1100	25.48	1.80	0.74	140.13	4.22	13.57
copper	8.93	124	500	13.89	1.25	0.56	55.99	2.50	7.05
zinc	7.13	84	250	11.78	1.29	0.61	35.06	2.22	5.57

Note! The density (ρ) and Young's modulus E are given for technically pure elements, since they assume nearly the same values in alloys based on these elements. In contrast, the yield strength $R_{p0,2}$ is expressed in mean values for the whole group of alloys.

2. High-strength aluminium alloys – a brief study of literature

Analysis of domestic and foreign source materials allows dividing the casting alloys in terms of their tensile strength R_m into the following groups: 1) $R_m \geq 500$ MPa, 2) $400 < R_m < 500$ MPa, 3) $300 < R_m < 400$ MPa, 4) $R_m \leq 300$ MPa. Additionally, one can distinguish high-strength aluminium casting alloys, standardised and newly developed, based on Al-Si, Al-Cu, Al-Mg and Al-Zn systems [11]. From [12,13] it follows that in the group of aluminium alloys, the highest strength of $R_m \geq 700$ MPa have alloys from the Al-Zn-Mg-(Cu)-(Mn)-(Cr) system produced by plastic forming and subjected to optimum, as regards the method and parameters, heat treatment. The division of aluminium alloys into wrought alloys and cast alloys is nowadays of rather conventional nature. At the same time, attempts are made to increase the strength and improve the technological characteristics of similar types of aluminium alloys processed by casting technique (e.g. [10]).

Aluminium casting alloys with $R_m \geq 500$ MPa

A good example of the alloy of the highest strength at room temperature is ВАЛ10 based on Al-Cu, described in [11]. The alloy has the following chemical composition (in wt%): 4.5-5 Cu; 0,35-0,80 Mn; 0,07-0,30 Cd; 0.15-0.30 Ti, rest Al + impurities (Fe, Si, Mg and Zn). It has been experimentally demonstrated that the addition of cadmium increases the alloy resistance to corrosion, while mechanical properties are strongly dependent on the iron content (Table 2).

Table 2.
Changes in the mechanical properties of ВАЛ10 alloy as a function of the iron content [11]

Mechanical properties	Iron content, [wt %]							
	0.015	0.05	0.10	0.15	0.20	0.30	0.40	0.50
Tensile strength R_m, [MPa]	530	515	505	495	468	440	405	370
Elongation A, [%]	12.0	10.2	8.0	6.5	5.5	5.0	4.5	4.5

The results given in Table 2 show that the tensile strength R_m of more than 500 MPa is obtained in the Al-Cu casting alloys at a low iron content (≤ 0.10 ... 0.15 wt %).

Alloys from the Al-Zn-Mg-Cu system [14], both wrought and cast, belong to the group of most resistant aluminium-based alloys (particularly in the T4 or T6 condition). As a result of the conducted studies, an extra-high strength casting alloy called ВАЛ12 was developed. It has the following chemical composition (in wt %): 6.5-7.5 Zn; 2.0-2.8 Mg; 1.0-1.5 Cu; 0.05-0.25 Zr; 0.1-0.3 Ti; 0.05-0.25 Be; 0.005-0.1 B; rest Al + impurities [11]. In this alloy, the most harmful elements are iron (≤ 0.3%) and silicon (≤ 0.2%). Some mechanical properties of the ВАЛ12 alloy cast into metal moulds (dies) in the T64 state (solution heat treatment and artificial underaging) are as follows: R_m - 550 to 600 MPa; $R_{p0,2}$ - 500 to 520 MPa; A - 3 to 5%. The linear shrinkage of the alloy is 1.25%, and the range of solidification temperatures is 630-490^{o}C [11,15].

Aluminium casting alloys with $400 < R_m < 500$ MPa

Developed in the former Soviet Union, the ВАЛ10M casting alloy based on Al-Cu-Si-Mn-Cd system is through the addition of silicon a modification of ВАЛ10. In addition to high mechanical properties at room temperature (Table 3) it is also characterised by increased creep resistance, as claimed by the author of [11].

Table 3.
Chemical composition of alloy from the Al-Cu-Si-Mg-Mn-Cd system [11]

Alloy designation	Casting process[1)]	Condition	Chemical composition, [wt %]							Mechanical properties[3)]				
			Si	Cu	Mg	Mn	Cd	Ti	Al	R_m, [MPa]	$R_{p0,2}$, [MPa]	A, [%]	HB	E, [MPa]
ВАЛ10M	S	T6	0.5-2.5	4.5-6.0	–	0.3-0.8	0.05-0.30	0.1-0.3	rest[2)]	440	340	4.0	120	72 000
	K	T6								500	360	6.0	120	–

[1)] S – cast in sand moulds; K – cast in metal moulds (dies);
[2)] Fe ≤ 0,4%;
[3)] at room temperature (~20^{o}C).

Table 3 shows that higher strength and toughness have alloys with a higher rate of solidification, that is, cast into metal moulds.

According to the data presented in [12], mechanical properties of the heat-treated to T63 condition and gravity die cast AlCu4.2Mg0.4Mn0.4Zn3.0 (A249) alloy, as described by AA or ASTM, are: R_m - 476 MPa, $R_{p0,2}$ - 414 MPa and A - 6.0%.

Aluminium casting alloys with 300 < R_m < 400 MPa

In accordance with the European standard PN-EN 1706:2011, high-strength aluminium casting alloys include alloys from the Al-Cu-Mn system containing Mg as an alloying addition and Ti – as a refiner of the α_{Al} solid solution. Depending on the heat treatment type (T4, T6, T7 and T64), these alloys offer the following minimum values of mechanical properties [16]: R_m - 280 to 370 MPa, $R_{p0,2}$ - 180 to 310 MPa, A - 2 to 5%, Brinell hardness HBW - 85 to 110 units.

In the U.S., construction parts for the automotive industry are most often made from three aluminium alloys gravity cast into sand moulds and/or metal moulds (dies): A319 (AlSi6Cu3.5Mg0.3); A356 (AlSi7Mg0.35) and A357 (AlSi7Mg0.55). On the other hand, high-pressure die casting uses alloys such as: A380 (AlSi8.5Cu3.5Zn3.0) and A383 (AlSi10.5Cu2.5Zn3.0). All these silumins offer very good casting properties, but their typical strength properties do not exceed the level of $R_m \leq$ 360 MPa, $R_{p0,2} \leq$ 300 MPa, $A \leq$ 10%, Brinell hardness HBW $\leq$ 100 units [2,12].

In [17] it is shown that a relatively high tensile strength R_m is obtained in high-zinc alloyed silumins of the Al-Si8Cu3Mg0.4Zn type cast in metal moulds (dies): a) R_m - 342 MPa in the T6 condition (after solution heat treatment and artificial aging), b) R_m - 295 MPa in the T1 condition (after natural aging); with the elongation A kept at a level of 0.9 and 1.2 %, respectively. As shown by experimental studies, the tensile strength R_m of AlSi8Cu3Mg0.4Zn alloy (in the T6 condition) is a function of the zinc content, namely for 1% Zn the tensile strength R_m is 286 MPa, and for 4% Zn it is 338 MPa.

In the former Soviet Union, a high strength corrosion resistant ВАЛ11 alloy based on the Al-Mg-Zn system was developed. It has the following chemical composition (in wt %): 6.0-7.0 Mg; 2.0-2.5 Zn; 0.1-0.2 Mn; 0.005-0.15 Cr; 0.1-0.3 Ti; 0.1-0.3 Zr; 0.07-0.15 Be; rest Al. The shrinkage of this alloy is 1.3% and the solidification range is 610-475^{o}C. Its typical mechanical properties when cast into sand moulds fall within the following range of values: R_m - 320 to 360 MPa; $R_{p0,2}$ - 250 to 280 MPa; A - 4 to 7% [11].

Standardised according to GOST 1583-93, aluminium alloys from the Al-Mg system (АЛ8, АЛ13, АЛ22, АЛ23, АЛ27, АЛ27-1 and АЛ28) - containing additionally Be (0.02-0.15%, and exceptionally 0.70 % in the АЛ8 alloy), Mn (0.0-1.0%) and Si (0.0-1.3%) - exhibit variations in mechanical properties depending on the content of magnesium; the highest properties are achieved with Mg at a level of 12.4 % (in the T4 condition): R_m - 380 MPa; $R_{p0,2}$ - 200 MPa; A - 20%. Higher magnesium content in alloys promotes their embrittlement; they also have a natural tendency to aging, which results in an increased strength and reduced toughness. These alloys are generally characterised by good corrosion resistance and polishability [11].

According to the Polish standard PN-EN 1706:2011 [16], this group of aluminium casting alloys (300 < R_m <400 MPa) also includes silumins cast in metal moulds (by gravity die casting): a) EN AC-45100 (AlSi5Cu3Mg) in the T6 condition and b) EN AC-45500 (AlSi7Cu3Mg) also in the T6 condition - for which the minimum value of R_m is 320 MPa.

Aluminium casting alloys with $R_m \leq$ 300 MPa

In this group, some attention deserve the EN AC-42100 (AlSi7Mg0.3) and EN AC-42200 (AlSi7Mg0.6) silumins. In accordance with PN-EN 1706:2011, both these alloys are designed for sand mould casting, gravity die casting and investment casting. Occasionally, they are also used in low-pressure die casting. Outside the EU, their counterparts are widely known cast silumins of the A356 and A357 type, designated in accordance with the American AA or ASTM standards. In the T6 condition their tensile strength (R_m) at room temperature can reach 300 MPa (sometimes even more). Similar high levels of strength in the T6 condition are offered by the, commonly used for automotive applications, alloys such as: a) piston alloy - EN AC-48000 (AlSi12CuNiMg) and b) alloy for cylinder block bodies - EN AC-48100 (AlSi17Cu4Mg) [16].

3. Numerical calculations in the strength estimation

In [8], for various combinations of alloy composition in AK5M (AlSi5Cu1Mg) according to GOST 1583-93, the alloy castability was evaluated by modelling the mould filling process and solidification process using a computer programme. It was also decided to use the *MAGMASoft*® software module called *MAGMANonferrus* for the preliminary estimation of an impact of the chemical composition on the tensile strength and other physical-mechanical properties of alloy from the Al-Zn-Mg–Cu system. The predictions were based on the heat flow balance analysis in a metal casting-ceramic mould system leading to a distribution of temperature and/or microporosity. Due to this, the evaluation of certain elements of the microstructure was possible (e.g. SDAS), and consequently, the evaluation of mechanical properties (R_m, $R_{p0,2}$ or A) for each grid point in the virtually examined structural element. The process of simulation run on a micro-scale allowed the analysis of a solidification process at the solidification front (including the diffusion of elements depending on their local concentration) and the analysis of phase transformations occurring under these conditions.

At the current stage of development, the *MAGMASoft*® simulation programme [9] has some constraints. As regards the chemical composition and the content of basic alloying elements, they are of the following nature (in wt %): Si $\leq$ 12.5; Cu $\leq$ 3.5; Mg $\leq$ 0.6; and the sum of all other elements $\leq$ 2.0; rest is Al. In spite of these constraints, it is still possible to carry out calculations for the majority of gravity sand and metal mould cast aluminium alloys, including A356 (AlSi7Mg0.3) and A357 (AlSi7Mg0.6), which make about 70-80% of all aluminium-based castings.

In view of the fact that the currently available *MAGMASoft*® packages lack the data on the alloys with 1 to 10% Zn content included in the Al-Zn-Mg-Cu system, it has been decided to examine, as an example, the zinc casting silumins (Table 4) with a variable zinc content of 1.0 or 2.0 wt %.

The reference alloy was A356 (AlSi7Mg0.4) silumin, mainly due to the fact that its physical, mechanical and thermodynamic properties are generally known.

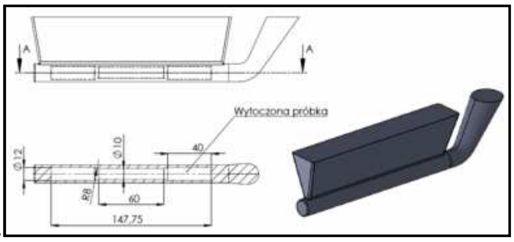
Table 4.
Chemical composition of the examined aluminium alloys

Designation by chemical composition	Numerical designation	Chemical composition [wt%]								
		Si	Cu	Mg	Fe	Mn	Ni	Ti	Zn	Al
AlSi7Mg	St-1	7.0	0.03	0.4	0.5	0.3	0,1	0.15	0.1	rest
AlSi9Cu3Zn1Mg0.3	St-2	9.0	3.0	0.3	0.59	0.3	0.3	–	1.0	rest
AlSi9Cu3Zn2Mg0.3	St-3	9.0	3.0	0.3	–	–	–	–	2.0	rest
AlSi9Cu3Zn2Mg0.6	St-4	9.0	3.0	0.55	–	–	–	–	2.0	rest
AlSi9Cu3.5Zn2Mg0.3	St-5	9.0	3.5	0.3	–	–	–	–	2.0	rest
AlSi9Cu3.5Zn2Mg0.6	St-6	9.0	3.5	0.55	–	–	–	–	2.0	rest
AlSi7Cu3Zn2Mg0.6	St-7	7.0	3.0	0.55	–	–	–	–	2.0	rest

Figure 1 shows the shape and dimensions of the cast sample used for mechanical tests and location of the control measuring point (Pkt 1).

The simulation results for the seven virtually tested aluminium casting alloys are presented in Table 5, while graphs a) and b) in Figure 2 are their graphical counterparts.

a)



b)

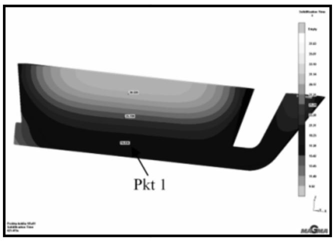
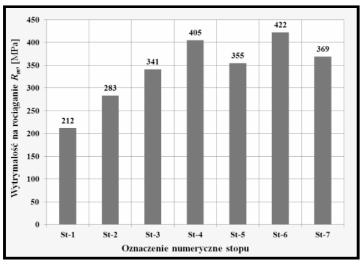


Fig. 1. a) The shape of test casting used for simulation calculations, and b) the results of simulation using *MAGMASoft*® package

Table 5.
The results of numerical calculations for the measuring point Pkt 1 in a 10 mm diameter sample cast into metal mould (die) depending on the aluminium alloy type (see Table 4)

Measured parameters	Numerical designation of alloy						
	St-1	St-2	St-3	St-4	St-5	St-6	St-7
Solidification time, [s]	25.7	36.1	96.2	109.2	100.0	111.5	102.7
SDAS, [µm]	22.6	19.2	19.9	20.7	20.1	23.1	22.73
Microporosity, [%]	1.021	1.271	1.115	1.247	1.0	1.843	2.495
R_m in T6 condition, [MPa]	212	283	341	405	355	422	369
R_m before heat treatment, [MPa]	169	223	243	262	250	269	237
A in T6 condition, [%]	2.1	1.1	2.0	3.3	1.9	3.1	3.1

a)



b)

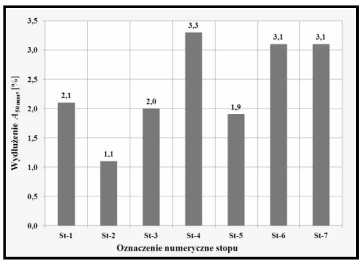


Fig. 2. Graphical presentation of the results of numerical calculations (for the measuring point Pkt 1):
a) the tensile strength R_m and b) the elongation *A* (see Table 5)

From the data given in Table 5 and Figure 2 it follows that the highest strength (R_m = 422 MPa) combined with an acceptable level of toughness (A = 3.1%) should have the St-6 (AlSi9Cu3.5 Zn2Mg0.6) alloy in the T6 condition. The simulated values of mechanical properties (R_m and A) correlate well with the literature data. The resulting calculated data show that the increase in strength will follow the increased content of zinc as well as copper and magnesium. In all the tested alloys, a very strong effect of heat treatment of the T6 type on the strength characteristics has been observed.

4. The results of own experimental studies of the Al-Zn-Mg-Cu alloy

Preliminary studies were carried out on an aluminium alloy from the Al-Zn-Mg-Cu system cast into sand and metal moulds (dies). The alloy selected for tests had the following chemical composition (in wt. %): 5.53 Zn; 2.37 Mg; 1.56 Cu; 0.2 Fe; 0.1 Si; rest Al. The test melting was performed in an electric resistance furnace of the CFM-10/10/BS type made by REMIX, Poland. The die pouring temperature (after preheating the die to approximately 200°C) was comprised in a range of 700 ÷ 720°C. The gravity die cast samples for mechanical testing had the shape and dimensions shown in Figure 1a. Rods with ø40 mm diameter were also cast in sand moulds. From these rods specimens were next prepared by turning for testing of the mechanical properties.

To select the heat treatment parameters, studies were conducted by differential scanning calorimetry (DSC), using for this purpose the DSC 404C Pegasus® calorimeter making part of the equipment available at the Foundry Research Institute in Cracow. The representative curves for heating and cooling of the tested Al-Zn-Mg-Cu alloy at rate of approximately 5K/min under an argon atmosphere are plotted in Fig. 3.

Based on the analysis of the DSC curves (Fig. 3) and literature data [11-13,15], the following heat treatment parameters (T6 type) were adopted for the tested alloy:
a) solution heat treatment: 450°C, 4 h + 470°C, 4 h,
b) aging: 110°C, 5 h + 160°C, 10 h,
Final results of the mechanical tests are compared in Table 6.

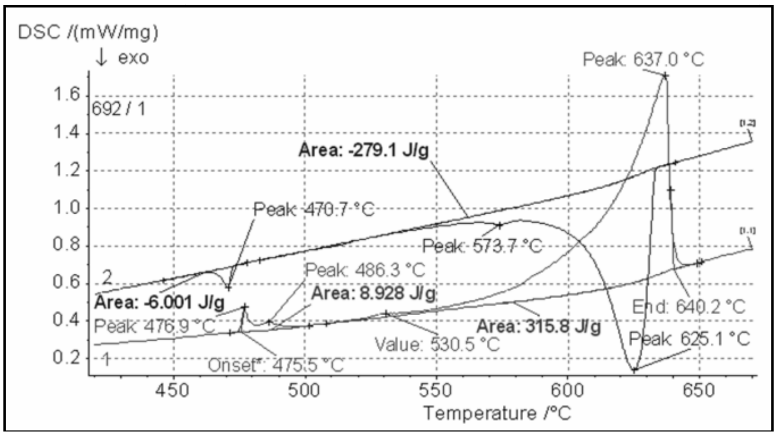


Fig. 3. The representative DSC curves plotted for the tested Al-Zn-Mg-Cu alloy showing elements of phase transformations (in the form of peaks): 1 - heating curve; 2 - cooling curve

Table 6.
The results of mechanical tests (R_m and A) carried out at room temperature (~ 20°C) on samples of the Al-Zn-Mg-Cu alloy cast into sand and metal moulds

No.	Sand mould			Metal mould (die)		
	Designation	Mechanical properties		Designation	Mechanical properties	
		R_m, [MPa]	A, [%]		R_m, [MPa]	A, [%]
1.	1-1P	320	1.1	1-1K	458	0.8
2.	1-2P	348	0.9	1-2K	393	0.9
3.	1-3P	305	1.2	1-3K	424	0.7
4.	1-4P	283	1.8	1-4K	484	0.6
5.	1-5P	318	1.1	1-5K	416	1.1
6.	1-6P	314	1.1	1-6K	440	0.7

The numerical data in Table 6 indicate that the expected tensile strength R_m of about 400 MPa can be achieved in cast alloys from the Al-Zn-Mg-Cu system, but the level of toughness (measured as A) will be highly unsatisfactory. Preliminary observations have shown that the microstructure of the cast alloy is characterised by high microporosity (Fig. 4).
The increased porosity observed in this alloy is caused by a very wide range of the solidification temperatures: T_{lik}(637.0°C) – T_{sol} (475.5°C) = 167.5°C. It probably affects the toughness levels ob-

tained, irrespective of the type of the casting process. The microphotographs in Figure 4a and b indicate that at a higher rate of solidification (in metal mould), the structure of the tested alloy is more refined, which directly translates into the corresponding values of strength (see Table 6).

a) b)

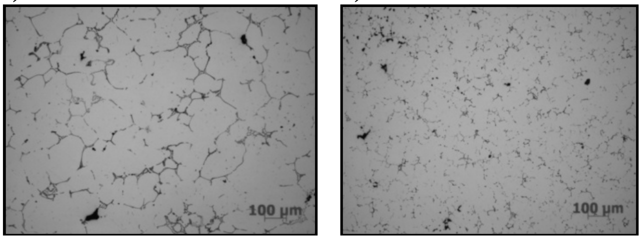


Fig. 4. Microstructure of Al-Zn-Mg-Cu alloy cast into: a) sand mould, and b) metal mould (die)

Using the initially selected Al-Zn-Mg-Cu alloy system, at the Foundry Research Institute in Cracow, the first rockers for off-road vehicles were cast in sand moulds.

a) b)

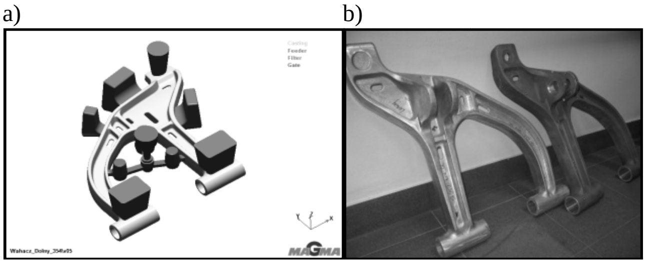


Fig. 5. a) Working drawing for computer simulation, and b) actually produced rocker for off - road vehicle

The first observations show that casting properties of the tested Al-Zn-Mg-Cu alloy are satisfactory. The only exception is the very wide range of solidification temperatures. Studies are going on to optimise the chemical composition and heat treatment parameters and to improve the technology of melt preparation and the process of casting similar construction parts (Fig. 5) (e.g. by SOPHIA® or HERO Premium Casting® technology [18]).

5. Final conclusions

1. A review of source materials indicates that, as regards mechanical properties, cast alloys from the Al-Zn-Mg-Cu system differ significantly from their wrought counterparts.
2. Studies are currently carried out in Poland and in the world to increase the mechanical properties of aluminium casting alloys (including R_m > 500 MPa and/or A > 3%) through optimising of the chemical composition, modification, the selection of best casting methods and heat treatment parameters, and also by improvement of the melt preparation technique and casting process.
3. Future studies in this field should take into account various potentials of advanced computer simulation of the solidification process, allowing also for the prediction of alloy phase composition, the analysis of diffusion process, and the impact of chemical composition on physico-mechanical and technological properties.

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