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Application of 2XXX and 7XXX series alloys as input material for the new casting-forging hybrid process

Michal Szucki[a1], Anna Dziubinska[b], Grzegorz Winiarski[b], Krzysztof Majerski[b], Krzysztof Drozdowski[c], Marcin Gorny[a], Janusz Buras[a]

[a]AGH University of Science and Technology, Faculty of Foundry Engineering, Reymonta 23 Str., 30-059 Krakow, Poland
[b]Lublin University of Technology, Faculty of Mechanical Engineering, Nadbystrzycka 36 Str., 20-618 Lublin, Poland
[c]ZOP Co. Ltd Forging Plant, Kuznicza 13 Str., 21-045 Swidnik, Poland

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The aim of the work has been to analyze the aluminum alloys for plastic working from the point of view of their usefulness in the new hybrid manufacturing process which includes gravity casting and forging. The tests have been carried out on popular aluminum alloys from the 2xxx and 7xxx series: 2017A, 2024, 7022, and 7075, respectively. The authors have focused on the problem of using these materials at the casting stage. The analyses have included verification of the technological properties of alloys, including fluidity and the tendency to create porosities. Next, the influence of the solidification rate (associated with the use of various molds) on the casting microstructure has been determined. Based on the conducted analyzes, the alloys with the best casting behavior have been indicated. At the same time, possible problems that may occur at the forging stage have been discussed.

Keywords: Aluminium, Casting, Forging, Castability, Microstructure

1 Introduction

Aluminium alloys are currently one of the most widespread engineering materials[1,2]. Due to the favorable ratio of density and strength properties, they are used in many industries, including automotive and aerospace[3-6].

Casting and forging are two of the most commonly used production methods of airplanes and car parts made of aluminium alloys. Casting is a less expensive and more efficient technology because almost the final shape of the product is obtained in the single, relatively fast process[7,8]. On the other hand, its main disadvantage is the heterogeneity of the obtained material structure and lower mechanical properties. In turn, forging allows for high dimensional accuracy and homogenization of the microstructure[9,10] which, however, are associated with the need to incur greater financial and work effort[11-14]. In this case, then the required shape is obtained by forging rectangular or cylindrical ingots. The input material (ingots) for the forging process is characterized by a fine and homogeneous structure (Fig. 1), which is associated with its good plastic properties[15]. Such a structure is obtained by high solidification rate in special continuous or semi-continuous casting techniques (as Direct chill casting or extrusion methods).

An interesting alternative seems to be the combination of mentioned above production methods (hybrid approach) so that the prefabricates can be made by casting and then used in the forging process, Then the ingot used for forging has a shape similar to the final product, which allows reducing the time, waste and costs of the manufacturing process. Previous research[16-19] in this area has mainly focused

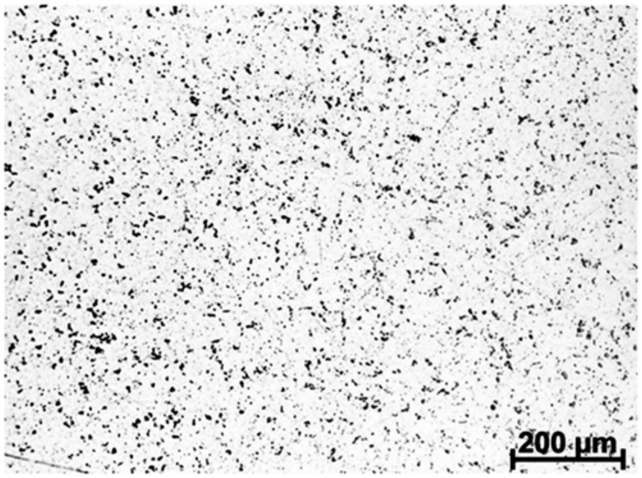

Fig. 1 — The microstructure of extruded 2017A alloy.

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*Corresponding author (E-mail: mszucki@agh.edu.pl) on making casting in the die casting process. The authors developed the idea of using in the hybrid process a much cheaper gravity casting method.

An important issue here is the selection of the right input materials for both process stages. Alloys for gravity casting should be characterized by proper castability[20]. In turn, input material for forging process must be characterized by appropriate plasticity and a small number of internal defects (e.g. the porosity which is characteristic for gravity casting)[21]. Due to the very high responsibility of aluminum parts used in the automotive and aerospace industry, the implementation of new materials is a long-term process. Hence, it seems reasonable to try to analyze the possibilities of using typical aluminum alloys of 2xxx (alloyed with copper) and 7xxx (alloyed with zinc) series for casting prefabricates for forging stage.

2 Methodology

One of the most important parameters determining the material's ability to be used in foundry engineering is mentioned above castability. It is the ability of the alloy to be cast to a given shape with a given process without the formation of casting defects[22]. The material and technological features affecting castability include, among others: fluidity, macrosegregation, hot tearing, and porosity[20]. In the work, tests were carried out on the fluidity of the analyzed alloys and their tendency to form porosity. At the same time, the analysis of the influence of the solidification time (depending on the type of used mold) on the microstructure of castings was performed.

2.1 Analyzed Materials

Two representatives of Al-Cu alloys: 2017A and 2024 and two of Al-Zn alloys: 7022 and 7075 were selected for the tests. These are representatives of the so-called aerospace materials widely used in plastic working. Normalized alloys were delivered in the form of cylindrical ingots obtained by an extrusion process. In accordance with the European Standards[23,24] the chemical composition of individual alloys shall be in conformity with the limits specified in Table 1.

In addition, for comparison purposes, a typical foundry Al-Zn-Si alloy for gravity casting in sand molds and permanent molds[25] with the trade designation: EN AC-71100 (or simply 71100) was also analyzed.

2.2 The Test of Fluidity

The fluidity defines the material's ability to completely fill the mold cavity. There are a number of methods for determining the fluidity of casting alloys[26]. In this case, the so-called spiral test in accordance with the Polish Industry Standard[27] was used. This test is dedicated to measuring fluidity of cast iron but used also in the case of Al alloys[28]. It consists in making a thin spiral casting with special reference points placed every 50 mm over the entire spiral length. The fluidity F value is the number of all correctly reconstructed reference points on the casting multiplied by the distance between them:

$$F = z \cdot 50, \qquad \ldots(1)$$

where, z – number of correctly reconstructed points,
50 – distance between points (mm).

As commonly known, the fluidity of alloys depends on the temperature of their overheating. The higher the temperature, the easier it is to fill the mold cavity (fluidity is higher), and the danger of misrun formation decrease. This is confirmed by the preliminary test results where spiral castings were made of 7075 alloy at two pouring temperatures of 700 °C and 750 °C.

As can be seen in Fig. 2, for a lower pouring temperature, the length of the cast spiral is significantly smaller. On the other hand, too high temperature value can lead to other casting defects. Hence, it was assumed that for each alloy (in all tests) the pouring temperature was 100 °C above the liquidus value. Three tests were carried out for each

Table 1 — The chemical composition of analyzed alloys in accordance with the European Standards[19,20]

Symbol	Cu	Cr	Fe	Mg	Mn	Si	Ti	Zn	Other	Al
2017A	3.5-4.5	Max 0.1	Max 0.7	0.4-1	0.4-1	0.2-0.8	Max 0.25 (Ti+Zr)	Max 0.25	0.15	Rest
2024	3.8-4.9	Max 0.1	Max 0.5	1.2-1.8	0.3-0.9	Max 0.5	Max 0.15	Max 0.25	0.15	Rest
7022	0.5-1	0.1-0.3	Max 0.5	2.6-3.7	Max 0.4	Max 0.5	Max 0.2 (Ti+Zr)	4.3-5.2	0.15	Rest
7075	1.2-2	0.18-0.28	Max 0.5	2.1-2.9	Max 0.3	Max 0.4	Max 0.2	5.1-6.1	0.15	Rest
71100	Max 0.1	-	Max 0.3	0.2-0.5	Max 0.15	7.5-9.5	Max 0.15	9-10.5	0.15	Rest

of the analyzed alloys, and then the average and rounded value of the obtained fluidity *F* was drawn.

2.3 Casting into the Sand and Permanent Molds

Gravity castings can be made in both sand and permanent molds. In order to analyze the influence of the type of mold on solidification of 2xxx and 7xxx series alloys, the castings in sand molds made of green sand with 5 wt% of water content (Fig. 3a) as well as in carbon steel permanent mold pre-heated to 150 ^{o}C were made. This temperature value of the permanent mold was dictated by the desire to achieve the highest possible cooling rate (the largest temperature gradient) while ensuring the correct filling of the mold - lower temperature values resulted in the formation of misrun. Hence, it was possible to compare the obtained microstructures for relatively long (sand mold) and short (permanent mold) solidification times.

In both cases, the castings had the shape of a cylinder with dimensions of ϕ32 mm x 75 mm. In the geometric center of the casting, a K-type thermocouple was placed (Fig. 3b), which enabled temperature measurement during the solidification and cooling process.

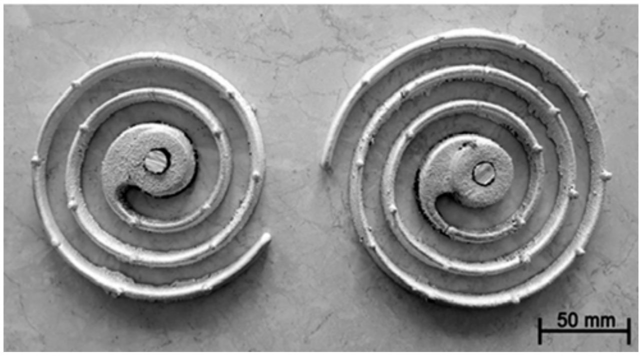

Fig. 2 — Spiral test for 7075 alloy with pouring temperature of 700 ^{o}C (left) and 750 ^{o}C (right).

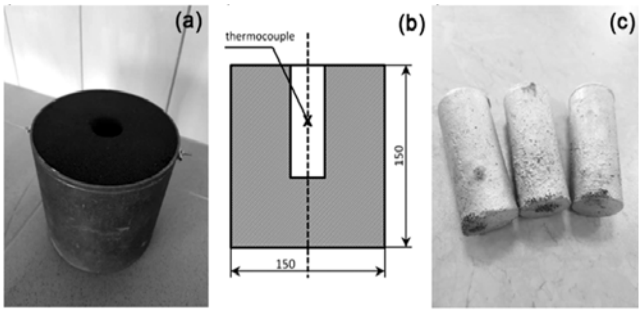

Fig. 3 —Casting process in green sand molds: (a) Sand mold before pouring, (b) Mold scheme and (c) Ready castings after shakeout.

2.4 Examination of Microstructures and Tendency to Form Porosity

From the middle part of cast cylinders (Fig 3c), cylindrical samples with a size of ϕ20 mm x 20 mm were cut. The samples after the binding and polishing were subjected to microscopic examination. This allowed determining the influence of solidification time, associated with the use of different molds, on the microstructure of the material.

In the next stage, a tendency to introduce porosity was analyzed. The macroscopic maps of the surface of the sample were created. The images obtained in this way were subjected to graphics processing to reveal casting defects. The image analysis software, in turn, allowed to determine the surface area of the porosity and compare it with the surface area of the sample. In this way, the fraction of porosity for each of the analyzed materials was obtained.

3 Compilation and Discussion of Results

3.1 The Test of Fluidity

The obtained results of fluidity test for each alloy were characterized by high repeatability, and discrepancies between individual values within a given series (3 test in each) did not exceed 2 reference points. Figure 4 presents the compiled results of the fluidity test.

As it was possible to suppose the foundry alloy 71100 is characterized by the highest fluidity. Among other analyzed materials, Al-Zn (7xxx series) alloys have the fluidity of above 1000 mm. In the case of the 2xxx series (Al-Cu) alloys, the 2017A alloy performs slightly better, while the 2024 alloy is characterized

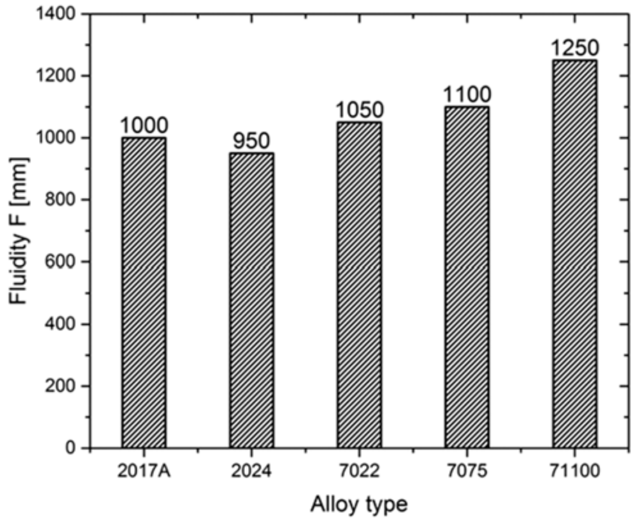

Fig. 4 — Fluidity test results.

by the worst fluidity in the entire set. It should be noted that the obtained values of fluidity do not differ significantly from the fluidity of other typical casting alloys based on aluminum[29].

3.2 Cooling Curves

As part of the tests, cooling curves were obtained for all analyzed alloys cast in both sand and permanent molds. Analysis of these curves indicates a wide range of solidification temperatures: about 140 and 160 °C in the case of 2xxx and 7xxx series alloys respectively. Such values are consistent with the literature data[30]. It should be noted that a wide range of solidification temperatures may contribute to the formation of microporosities[31]. As can be seen in Fig. 5, the process of cooling and solidification of the casting is much faster (about 20 times) in the case of the permanent mold. This can influence structural fineness of material cast in this type of mold.

The comparison of solidification times for the analyzed materials is presented in Table 2. These values were obtained in accordance with a commonly used method based on the first derivative of temperature versus time.

3.3 Analysis of Microstructures

The different solidification kinetics have a significant influence on the microstructure of the analyzed alloys (Fig. 6). All tested materials, after casting, are characterized by a dendritic structure with interdendritic, mainly eutectic, phases separations (particularly visible in the 2024 and 7075 alloys). However, in the case of permanent mold, the higher number of the primary dendrites (α-Al) was observed.

Table 2 — Approximate values of solidification times for aluminium alloys cast into the sand and permanent molds.

	2017A	2024	7022	7075	71100
Sand mold (s)	436	463	573	437	488
Permanent mold (at 150 °C) (s)	19	19	24	29	18

The higher degree of structure fineness is observed for the 2017A and 7075 alloys. On the other hand, in the case of the latter, it can be noticed that the structure is also characterized by high heterogeneity.

The microstructure of the 71100 alloy is somewhat different (due to the chemical composition). On the recorded images (Fig. 7), it is possible to find the characteristic platelet eutectics structures[32].

3.4 The Tendency to Form Porosity

During the microscopic examination practically in all cast alloys porosity was observed. In some cases (e.g. in 7022 alloy) pores were visible to the naked eye (Fig. 8a). According to the literature[33] in the aluminum alloys, both shrinkage porosity, as well as gas porosity associated with a smaller solubility of hydrogen in solid aluminum (comparing to liquid one), may occur. Due to the type of test materials used (refined and extruded alloys), the shrinkage nature of the defects is most likely to occur.

This is indicated by a detailed analysis where the observed microstructural defects have the (irregular) shape of a typical shrinkage interdendritic porosity – Fig. 9. Additionally, to confirm the nature of the defects, the 7022 alloy was remelted three times (without refining) and cast into the sand mold. In this case, the porosity on the polished samples was very clearly visible, and its character has changed to a mixed shrinkage-gas, where the shape of the pores resembles partially distorted spheres (Fig. 8b).

On the basis of the results obtained, it was also observed that castings in sand molds are more exposed to porosity formation (see Fig. 8a and 8c).

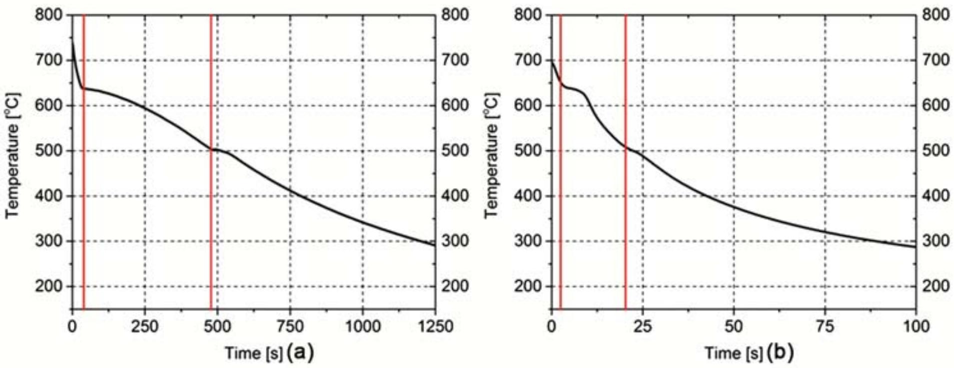

Fig. 5 — Cooling curves for 2017A alloy cast into the (a) Sand and (b) Permanent mold; red vertical lines indicate the solidification range.

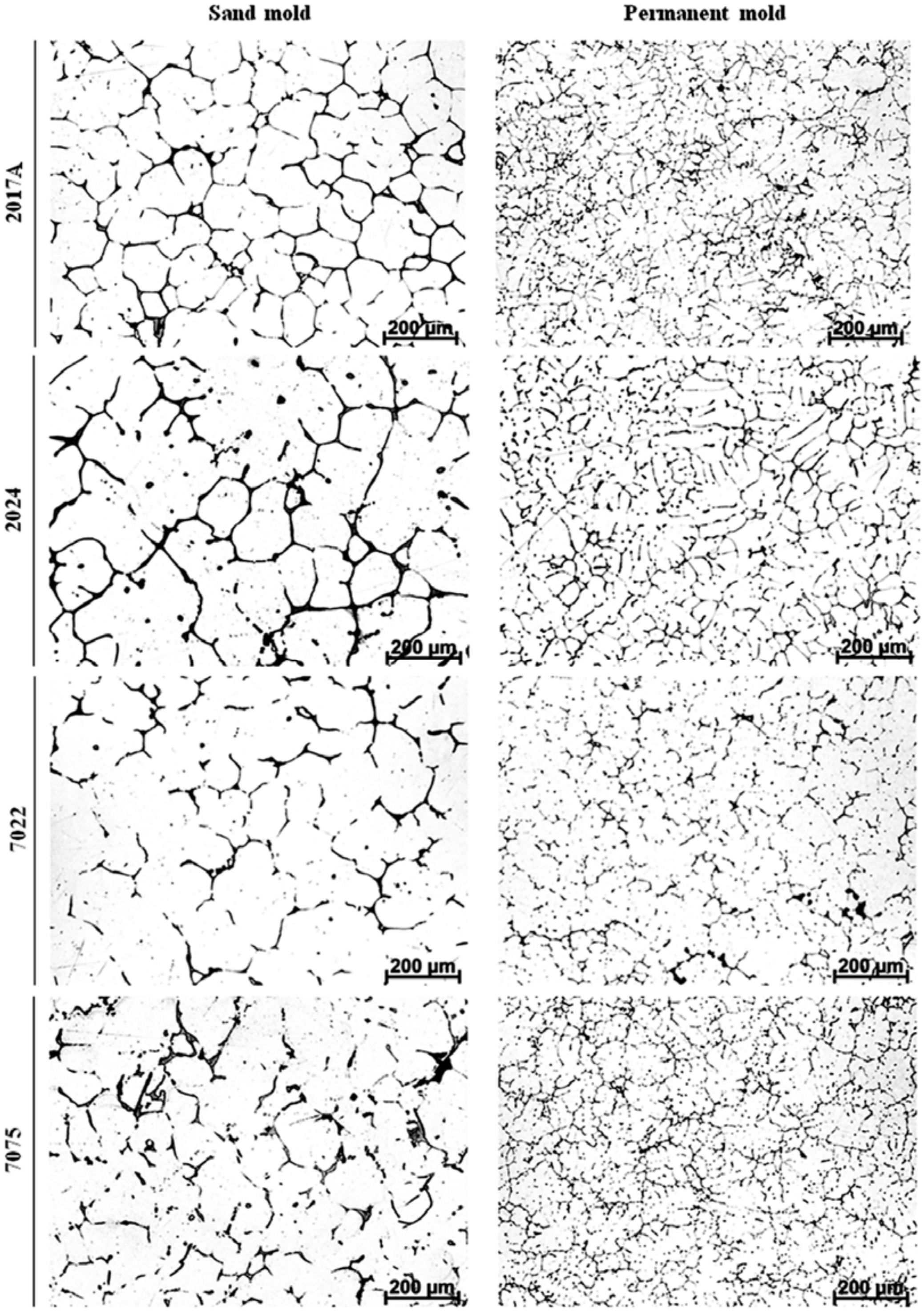

Fig. 6 — Microstructures comparison of 2xxx and 7xxx alloys cast into the sand and permanent molds.

Figure 10 shows a comparison of the percentage of porosity on the surface of the samples, obtained in accordance with the above mention procedure, for all analyzed alloys. The highest shrinkage porosity was observed in the case of alloy 7022, and in foundry alloy 71100. It can also be seen that the smallest fraction of pores occurs in 2017A and 7075 alloys. However, it should be noted that regular structural defects such as shrinkage interdendritic porosity can be relatively easily removed at the forging stage.

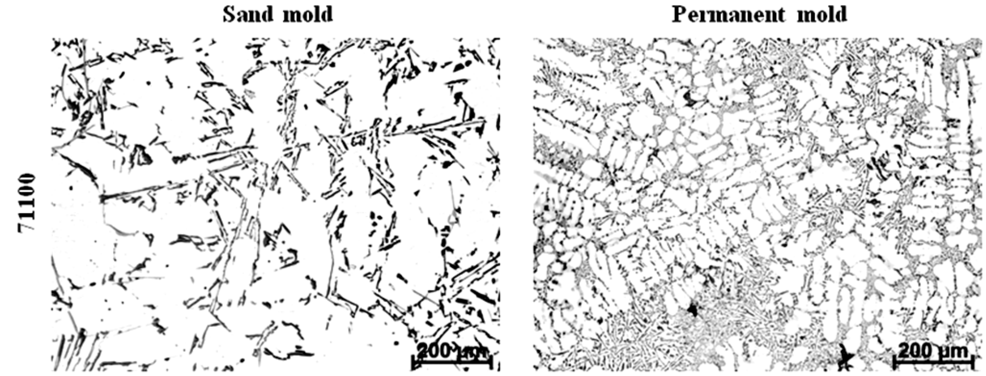

Fig. 6 — Microstructures comparison of 2xxx and 7xxx alloys cast into the sand and permanent molds.

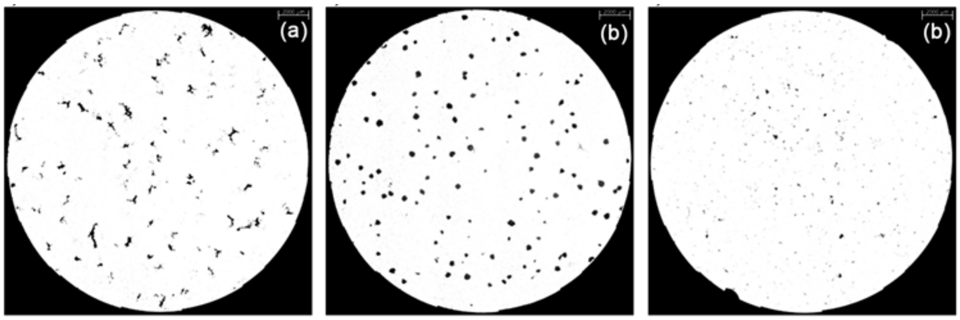

Fig. 8 — Porosity distribution in 7022 alloy: (a) Material cast into the sand mold, (b) Repeatedly melted material cast into the sand mold and (c) Material cast into the permanent mold.

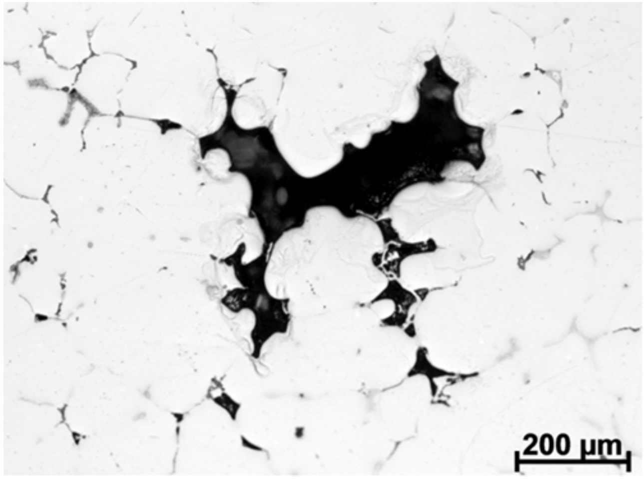

Fig. 9 — Shrinkage porosity in 7022 alloy.

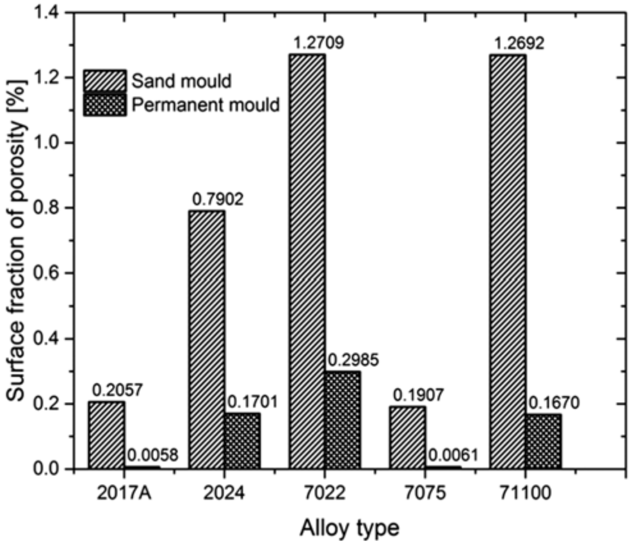

Fig. 10 — The surface fraction of porosity for Al alloys cast into the sand and permanent mold.

4 Conclusions

Obtained results indicate different casting behavior of tested alloys. Among the analyzed materials of the 2xxx series, the 2017A alloy is characterized by higher fluidity. In turn, from Al-Zn alloys (7xxx series) the best ability to recreate the mold cavity has 7075 alloy. Differences in fluidity values within a given series of alloys were amounted to 50 mm only. But at the same time in both cases, the fluidity differs significantly from the fluidity of the 71100 foundry alloy (by 150 mm for 7075 and 250 mm for 2017A alloy). This means a limited possibility of using the analyzed materials for castings with thin walls and complex shapes. The 2017A and 7075 alloys are also characterized by the lowest tendency to porosity formation. Additionally, they show a slightly higher fineness of the structure in the cast state compared to other materials. However, it should be remembered that the size of the grain is primarily affected by the heat dissipation rate, and thus the type of casting mold used. On the other hand, in the 2024 alloy, coarse, and in the case of the 7075 alloy simultaneously irregular, eutectic structures located in interdendritic regions of the primary phase grains can be observed. These phases can reduce the deformability of the material and contribute to its cracking during forging. Hence, regardless of the alloy used, it seems necessary to perform thermal homogenization treatment before forging as it was proposed by Fan *et al.*[34].

Considering the above it can be concluded that in the case of a 2xxx series, 2017A alloy could be used as a material for casting prefabricates in the forging process. For Al-Zn alloys it is necessary to analyze both the possibility of removing shrinkage defects at the forging stage (7022 alloy) and the problem of homogenization of the structure by thermal treatment (7075 alloy). Simultaneously in all cases, the use of permanent mold ensures obtaining finer structure and thus better deformability. This was confirmed by studies presented in works[35, 36].

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