Effect of pressing pressure on microstructure and selected strength properties of AlSi-C_F composite castings

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Abstract

The results of the study of the microstructure and selected strength properties (R_m, E) of an aluminum composite reinforced with chopped carbon fibers are presented. Composite castings were produced by the combined method of mechanical mixing and direct squeeze casting. Silumin EN 44300 and carbon fibers with a diameter of 6-7 μm and a length of 5-6 mm with a metallic coating - Ni (Tenax) and without a coating (Fortafil) were selected for the investigations. Experiments were carried out for 4 pressure values in the range of 20-80 MPa and their impact on the structural homogeneity of the composites as well as the strength and elasticity of the castings was assessed. The beneficial effect of the metallic coating manifests itself directly in the properties of the composites. The tensile strength of the composites reinforced with Tenax fibers is approx. 250 MPa and is 10% higher than the R_m of the reference alloy of the matrix. This level of strength is achieved by applying a pressing pressure of 60 MPa. The lack of a cohesive connection of the fibers with the matrix and a significant number of internal defects in the structure of the composite reinforced with Fortafil fiber cause a reduction in its strength both in relation to the composite with Tenax fibers and the reference alloy. As part of the strength tests, it was shown that chopped carbon fibers cause a significant increase in the elastic properties (E) of composites with an AlSi matrix, while the effect of the preparation of the surface of the reinforcing phase as well as the pressing pressure on this property are insignificant.

Keywords: chopped carbon fibers, AlSi matrix, squeeze casting, strength properties.

INTRODUCTION

Metal aluminum matrix composites (AlMMC) belong to a group of engineering materials with a wide range of mechanical and physical properties. These properties are designed by selecting the type of reinforcement (particles, fibers, nanotubes), its size and quantity, as well as the method of distribution in the matrix (local, gradient, volumetric) [1-5]. Taking into account the additive or synergistic nature of the interaction of the reinforcing phase with the matrix, it is possible to potentially optimize the set of material properties in terms of conditions and loads occurring during the operation of the composite product (cast). Obtaining the desired level of functional properties of the composite is, however, conditioned by the limitations of various technological processes. The methods of preform infiltration, spray deposition, rheocasting/thixoforming, liquid state mixing combined with gravity casting or external pressure casting (pressing, high-pressure, low-pressure and centrifugal casting) are used to produce composites [6-11]. The main priority of all composite technologies is to obtain a uniform or planned (gradient structures, local reinforcements) distribution of the reinforcing phase in the metal matrix and to minimize internal defects. The structural assessment criteria employed to optimize the process parameters include the degree of segregation (agglomeration) of the reinforcement, the degree of macro- and microporosity and the presence of slagging or undesirable inclusions resulting from chemical reactions between the liquid metal and the reinforcing phase or its preparation [3, 6, 9–13].

The occurrence of defects in the composite structure is caused by poor wettability of the reinforcing ceramic phases (SiC, Al_2O_3, B_4C, AlN, C) by liquid aluminum alloys. For this reason, during the production of composites, high temperatures of liquid metal overheating are used, and in the case of mechanical mixing methods, a relatively long time of composite suspension homogenization is applied. In addition, the conditions of the production process of aluminum composites reinforced with carbon-containing phases are conducive to the formation of harmful aluminum carbide. It exhibits strongly hygroscopic properties, causes destruction of the reinforcement and reduces the mechanical properties. Therefore, in order to avoid a reaction between the reinforcement and the matrix, as well as to improve the wetting conditions, barrier and technological coatings are used (e.g. SiO_2, $Na_2B_4O_7$, B_2O_3, Ni_3P, Na, Ni, Cu) [3, 11, 13-18].

Aluminum matrix composites reinforced with carbon fiber are characterized by good specific strength, specific stiffness, electrical and thermal conductivity, and resistance to creep and fatigue [15-21].

The properties of AlMMC composites with carbon fibers are better than polymer matrix composites, as well as non-reinforced reference aluminum alloys. Their main purpose is lightweight constructions for the automotive, aviation and military industries [1, 5]. Currently, there is greater interest in composite materials in the industrial sector and the use of various casting technologies for the serial production of composite castings. At the same time, taking into account the specificity and economics of composite production, casting methods are selected that ensure high stability and control of the technological parameters. This group of methods includes squeeze casting technology, which allows the production of castings with a fine-grained structure, high dimensional and shape accuracy, very low microporosity and low surface roughness, while ensuring a high metal yield and process efficiency [1, 21, 22].

The study carried out tests of the microstructure and selected strength properties of the composite with the EN 44300 silumin matrix reinforced with chopped carbon fiber at a volume fraction of 10%. Carbon fibers with Ni surface preparation and without a metallic coating were selected for the tests. In order to determine the optimal pressing pressures, the experiments were planned for 4 values in the range of 20-80 MPa. The results of testing the strength properties of the produced composites were compared with the properties of the reference matrix alloy.

RESEARCH MATERIAL AND METHODOLOGY

The composites were produced by the combined method of mechanical mixing and direct squeeze casting. The matrix of the composites was a standardized casting alloy EN 44300 (AlSi12(Fe) - Table 1), while the reinforcing phase was carbon fibers with a diameter of 6-7 μm and a length of 5-6 mm. Two types of fibers were selected for the tests: 1 - without a metallic coating (Fortafil) and 2 - covered with a Ni layer with a thickness of 0.25 μm (Tenax). The used fibers were in packages with the number of elementary fibers of 10,000 - Fortafil and 12,000 - Tenax. On the basis of the above-mentioned components, composites with a constant volume share of reinforcement - 10% were produced.

Table 1. Chemical composition of EN 44300 alloy

Chemical composition, wt.%						
Si	Fe	Cu	Mn	Ti	Sn	Al
12	0.8	0.1	0.55	0.15	0.15	Rest

The stage of melting the metal charge and preparing the composite suspensions was carried out in an induction furnace with a carborundum crucible. Mixing was performed in a protective atmosphere of argon, utilizing a turbine stirrer with a diameter three times smaller than the internal diameter of the crucible. The composite suspensions were homogenized at the temperature of 750°C for 300 s, using an angular speed of the stirrer of 10^{-1}s. After the mixing process, the suspensions were pressed on a hydraulic press with a nominal force of 250 tons. Before starting melting, the press was equipped with a punch and a mold for making castings in the shape of a plate with dimensions of 100×200×25 mm. The experiments were conducted using variable pressing pressure: 20, 40, 60 and 80 MPa. The temperature of the mold and the pressing time of the castings were constant and amounted to 200°C and 50 s, respectively. The selection of the process parameters was established based on the results of the authors' own research [20, 23]. For comparative purposes, castings from the non-reinforced reference alloy were also made by means of a hydraulic press. The lower part of the metal mold employed in the research and scheme of the pressing system are shown in Figure 1.

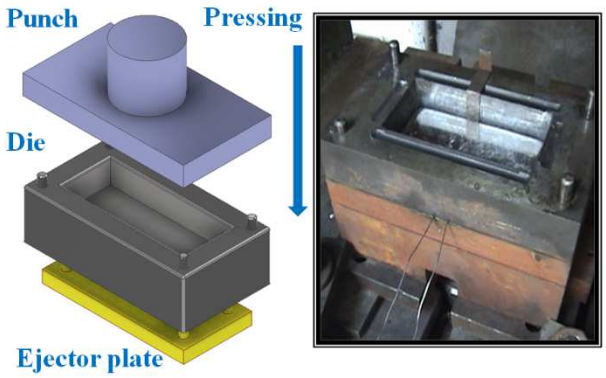

Fig. 1. Lower part of metal mold used in research and scheme of pressing system

Tests of the strength properties were carried out on standard five-fold samples in accordance with the PN-EN ISO 6892-1 standard, using a ZWICK-1488 durability testing machine. The average R_m and E values of the composites and the reference alloy were determined by making 4 measurements for each point of the experiment. The microstructure of the castings was observed by a NIKON EPIPHOT light microscope.

RESEARCH RESULTS AND THEIR DISCUSSION

Examples of the microstructures of the pressed composite castings reinforced with the Fortafil and Tenax fibers are shown in Figures 2 and 3. The presented microstructures refer to castings pressed under a pressure of 60 MPa, but they are also representative of other applied pressing pressures. The observations indicate that obtaining a composite based on the EN 44300 alloy reinforced with Fortafil fiber is technologically difficult. The lack of a metallic coating on the Fortafil fibers makes them virtually unwettable by liquid silumin. The microstructure of the composite is characterized by numerous defects in the form of local fiber segregation, intercrystalline cracks, slag inclusions, gas bubble-reinforcement discontinuities, etc. The presence of such defects in the structure results from high values of interfacial tension forces in the interfiber spaces and high work of adhesion is needed to overcome the liquid metal flow resistance during mixing of the composite suspension as well as pressing of the solidifying castings.

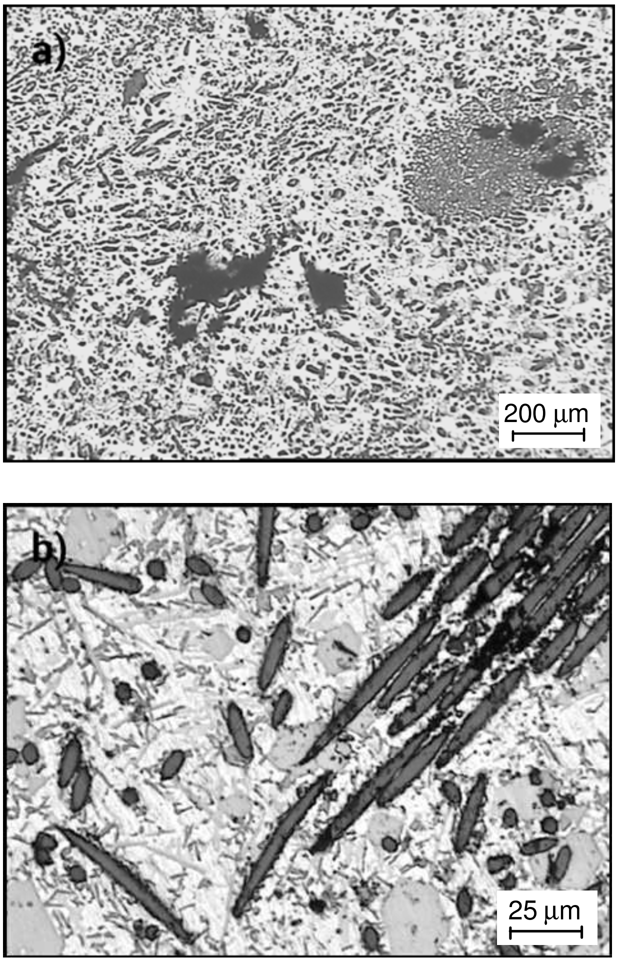

Fig. 2. Microstructure of AlSi-CF composite reinforced with Fortafil fiber (without metallic coating)

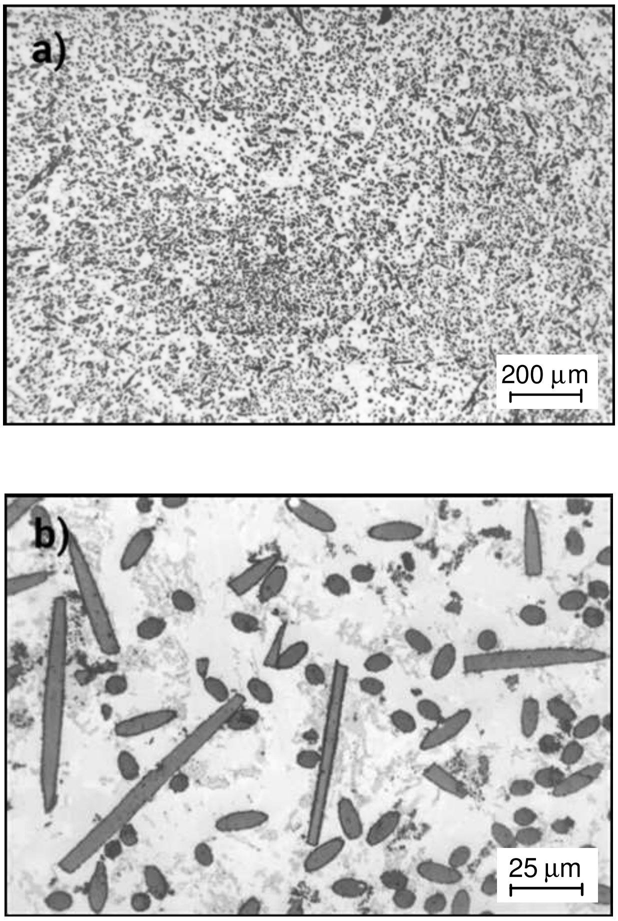

Fig. 3. Microstructure of AlSi-CF/Ni composite reinforced with Tenax fiber (with Ni preparation)

The microstructure of the composites reinforced with the Tenax fiber is different. The distribution of the reinforcing phase in the volume of the matrix alloy is relatively even, the spaces between the fibers do not have voids, local clusters of fibers are sporadic, and the microporosity was practically eliminated. The obtained microstructures indicate that the developed methodology for the production of AlSi-CF/Ni composites and the adopted process parameters are correct. During the production of this composite, the main problem is the separation of individual carbon fibers at the stage of mechanical mixing. Tenax fibers are prepared in bundles with the number of elementary fibers of 12,000 pieces and in this form they must be applied to the liquid matrix alloy. Their separation in the metal bath and their uniform redistribution is possible due to reduction of the surface tension at the fiber-matrix interface by the layer of nickel coating. Good wettability of the Ni layer by liquid aluminum also makes the time needed for proper homogenization of the composite suspension relatively short. Shortening the mixing time, in turn, reduces the risk of introducing oxide impurities and gas bubbles into the liquid metal. The applied method of direct pressing allows technological problems to be solved resulting from the poor casting properties of composite slurries. The presence of the reinforcing phases in liquid silumin reduces its fluidity. With a volume fraction of 10%, it becomes impossible to make castings using gravitational methods. In the case of squeeze casting technology, obtaining castings with high dimensional and shape accuracy is not a problem even with 20-30% shares of the reinforcing phase. In addition, as a result of the rapid solidification of the matrix alloy and elimination of the shrinkage gap between the casting and the mold, a fine-crystalline structure of the composite is obtained over the entire thickness of the casting wall. An important advantage of high pressures occurring during pressing is also the reduction in shrinkage porosity in castings and the complete removal or reduction of the dimensions of gas pores that may be introduced into the liquid matrix alloy at the mixing stage.

The impact of the pressing pressure and the type of carbon fibers on the tensile strength of the composites and the matrix alloy is shown in Figure 4. In comparing the obtained test results, it can be seen that the tensile strength of the composite reinforced with Fortafil fibers is 20-30% lower than the R_m of the composite with the Tenax fibers. This effect is visible for all the pressing pressures, especially for the range of 20-40 MPa (Fig. 4). The presence of numerous internal defects in the composite reinforced with fibers without a metallic layer, its low fluidity and the lack of a good connection between the fibers and the matrix also result in reduced strength compared to the reference matrix alloy. In the case of the composite reinforced with Tenax fibers, the beneficial effect of the nickel coating translates directly into improvement of the strength properties, with the optimum pressing pressure ensuring the greatest increase in R_m being 60 MPa. For this pressure value, the strength of the AlSi-CF/Ni composite material is greater than the R_m of the matrix alloy and amounts to approximately 250 MPa. A 10% increase in tensile strength proves that the carbon fibers bear part of the stress during the tensile test, which in turn indicates the presence of a good bond between the fibers and the metal matrix. The impact of external pressure, especially its higher values, during solidification of the castings causes the flow of liquid metal to interdendritic spaces as well as well-wettable interfiber spaces. As a result, in the final phase of matrix solidification, the efficiency of infiltration increases and a coherent connection between the composite components is created.

At pressing pressures of 80 MPa, however, there is a slight decrease in tensile strength. This may be caused, as indicated by the papers [19, 24, 25], by the formation of stresses at the fiber-matrix interface, damage to the surface of the fibers, and their cracking as a result of too high pressing pressures during solidification of the metal matrix.

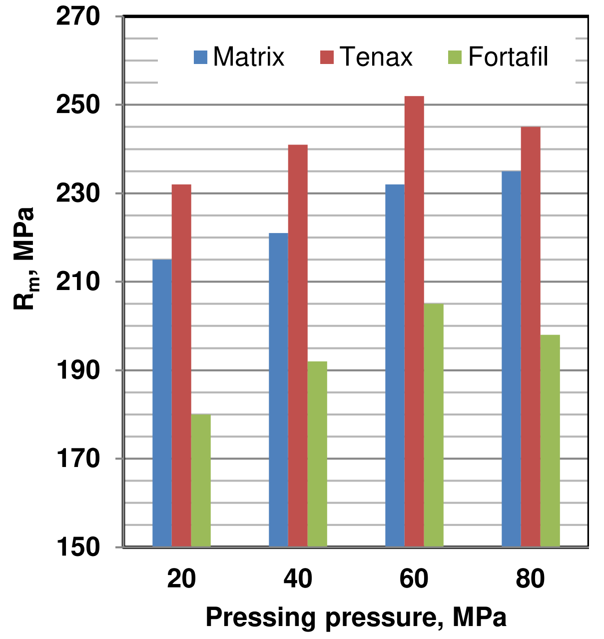

Fig. 4. Influence of pressing pressure on tensile strength of composites and reference alloy

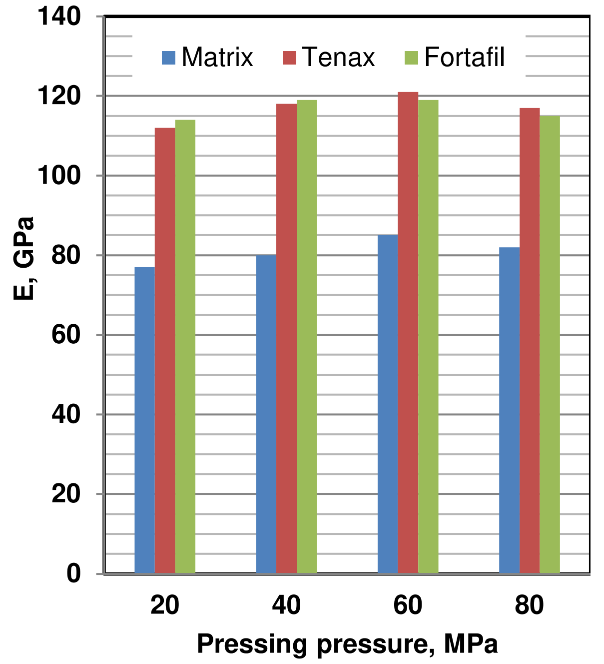

Fig. 5. Influence of pressing pressure on longitudinal modulus of elasticity *E* of composites and reference alloy

Figure 5 presents the results of the measurements of the longitudinal modulus of elasticity of the composites and the reference matrix alloy. Regarding this property, the introduction of carbon fibers into the aluminum matrix results in a significant increase in E, regardless of the presence of a metallic coating. The influence of the pressing pressure on the change of Young's modulus is also negligible. For the tested volume fraction of carbon fibers - 10%, the E modulus of the composite materials is at the level of 120 GPa, which is over 40% higher compared to the reference matrix alloy.

CONCLUSIONS

1. The nickel layer covering the surfaces of the carbon fibers ensures their good wetting by the liquid AlSi alloy and enables the production of homogeneous composite suspensions by mechanical mixing in a relatively short time.
2. The use of Fortafil carbon fibers (without a Ni coating) for the reinforcement of composites causes large structural heterogeneity of the castings and numerous internal defects.
3. The pressing pressure ensuring the highest tensile strength of the AlSi-CF/Ni composite is 60 MPa. For this pressure level, the R_m of the composite reaches a value of 250 MPa and is 10% higher than the R_m of the reference alloy.
4. The increase in the strength properties of the composites in relation to the EN AC 44300 alloy indicates a strong connection of carbon fibers with the metal matrix, which is formed as a result of the Ni layer reducing the adhesion work, as well as being the result of effective infiltration characterizing the squeeze casting process.
5. The introduction of carbon fibers into the silumin matrix causes a significant increase in elastic properties, while the effect of the preparation of the surface of the reinforcing phase as well as the pressing pressure (within the tested range of changes) is insignificant.
6. The direct pressing method allows technological difficulties related to high viscosity and low fluidity of composite suspensions to be eliminated, prevents the segregation of fibers and guarantees obtaining composite castings with high dimensional and shape accuracy.

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