Journal of Casting & Materials Engineering Vol. 6 No. 1 (2022) 8–13
https://doi.org/10.7494/jcme.2022.6.1.8

# An Analysis of the Features of Cast Composite Materials Based on Light Alloys Reinforced by Particles

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Received: 24 June 2021/Accepted: 21 December 2021/Published online: 14 January 2022.
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**Abstract**

Light alloys are widely used in industry and everyday life due to their high physical and mechanical properties, wear and corrosion resistance, as well as low cost. In this regard, the use of light alloys as a basis for composite materials is both justified and expedient. The potential of these materials has not been fully used to this day, despite the growing interest in metal matrix composites and extensive investigations aimed at the development of production technology and the introduction of advanced systems based on light matrices. The article presents a short review of the analysis of the main components of the technology of cast composite materials based on light alloys of aluminum and magnesium reinforced by particles. Particular attention is paid to the choice of the matrix alloy, the type, size and amount of reinforcing particles introduced into it, as well as the thermal-time and kinetic parameters of the process.

**Keywords:**
aluminium, magnesium, alloy, composite material, matrix, reinforcing particles

## 1. INTRORODUCTION

The successful functioning and further development of most modern industries, such as aerospace, transport, military, biomedicine, is impossible without the use of lightweight, durable and inexpensive materials in manufacturing [1–3]. Today, all these requirements are met by composite materials (CM) based on Al and Mg alloys [4–6].

Composite materials are materials containing two or more phases (matrix and reinforcing phase), significantly different in properties and having a clear interface [7]. The properties of the finished composite material are superior to those of its constituent components. Highly plastic metal matrices, for example, aluminium alloys, and high-strength, high-modulus fillers are artificially combined in CM. It is possible to obtain composites with such combination of phases with the required values of strength, elastic modulus, microhardness, crack and heat resistance as well as to create compositions with the required dielectric, magnetic, radio-absorbing and other special characteristics [8, 9].

Depending on the type of reinforcement, composites are divided into [9]: fibrous composites, particle reinforced composites, sandwich composites, hybrid composites.

The advantages of particle reinforcement are [10] significantly lower cost of the composite compared to the continuous fiber reinforcement (cheaper production of the composite; cheaper reinforcement), the possibility of producing them with metallurgical methods (casting or powder metallurgy) as well as properties similar to isotropic.

Globally, the data presented in [2] shows that primary Al production increased by approximately 1.5 times from 2009 to 2019. According to the Global Metal Matrix Composites Market Report, in the same period there has been linear growth in the production of metal matrix composites after 2012, and revenue has increased from about 220 million USD to 400 million USD [11].

The main focus when obtaining CM should be paid to the selection of both the matrix alloy and its reinforcing particles. The matrix alloy must be uniform, strong, lightweight, and inexpensive. The particles must have a high degree of hardness and be evenly distributed in the matrix, as well as reliably fixed in it. Only in this case will a positive technical and economic result be achieved.

The aim of this study is to analyze the production technologies, the influence of various characteristics of the matrix and reinforcing particles on the properties of cast composite materials (CCM) based on light (aluminium and magnesium) alloys.

## 2. ALUMINIUM AND MAGNESIUM MATRIX COMPOSITE MATERIALS

The most commonly used metals as a matrix for composites are aluminum, magnesium and titanium, with copper and zinc and their alloys less frequently employed [12]. According to [1, 2, 7, 13] composite materials based on the light alloys make up the bulk of the CCM currently produced.

Among all metal matrix composites, aluminum composites constitute a large and important group of construction materials. Since the matrix of the composite has many functions, it is important to select the appropriate alloy to ensure optimal properties and compatibility with the reinforcement. Aluminum alloys have low density, high specific strength and a relatively low price, therefore they are an attractive construction material. Magnesium and its alloys are very attractive matrix materials due to their very low density (1.74 $g/cm^3$), however they are much more susceptible to corrosion than aluminum alloys. In addition to pure magnesium, alloys of magnesium with aluminum, manganese, zinc and strontium are used in the production of composites. The above-mentioned alloy additives improve, among others, castability, strength and corrosion resistance. The most commonly used alloys are AZ91, AJ62 and AM50 [14].

Alloys based on Al and Mg have the high physical and mechanical properties, wear and corrosion resistance, as well as low cost, that's why they are widely used for purposes of industry and everyday life. At the same time, it is obvious that today's requirements for the parts of machines and mechanisms cannot be satisfied by even the whole variety of known alloys. A way out can be found by creating CM using a metal matrix on an aluminum and magnesium base.

Such materials are promising for use as thermal barrier coatings for blades of gas turbine engines, cryogenic flanges and other high-pressure elements of liquid-propellant rocket engines, lightweight pipelines in aviation and space technology, housings for electronic equipment, static and moving parts of electronic equipment [1, 15].

In addition, metal-matrix aluminium composites are currently used as radiation-shielding materials. Firstly, it is the protection of equipment and machinery operating in conditions of radiation damage. Secondly, it is a biological protection of personnel serving this equipment and machinery at nuclear facilities, as well as personnel of medical and emergency rescue services with increased requirements for biologically inert and X-ray protective properties of materials. A new class of lightweight radiation-shielding materials based on aluminium and magnesium composites with various ceramic fillers, depending on the type of ionizing radiation, is being developed. Such materials have high mechanical properties, but operating in the mode of increased ionizing radiation, they are subject to significant swelling, including due to structural changes. These structural changes can be prevented by using metals that are less susceptible to swelling and modification with various nanostructure fillers [16].

## 3. METHODS FOR OBTAINING COMPOSITE MATERIALS

All methods for obtaining composite materials are usually divided into solid-state, liquid-state and gas-state [7, 9, 13, 17, 18]. Liquid-phase methods are more technological and less expensive than solid-state (e.g., powder metallurgy methods, equi-channel angular pressing, etc.) due to the fact that most liquid-state methods are associated with the production of CM based on low-melting alloys. Methods of impregnation and casting are the most common liquid-phase methods.

The matrix metal, which is in a completely or partially molten state during the implementation of liquid-state methods, is mixed with the reinforcing material, forming a composite material that is new in its properties. In addition to other advantages, this approach to the production of CM makes it possible to effectively control the processes occurring at the interface between the solid and liquid phases.

The properties of the resulting composite material depend on a number of parameters (Fig.1).

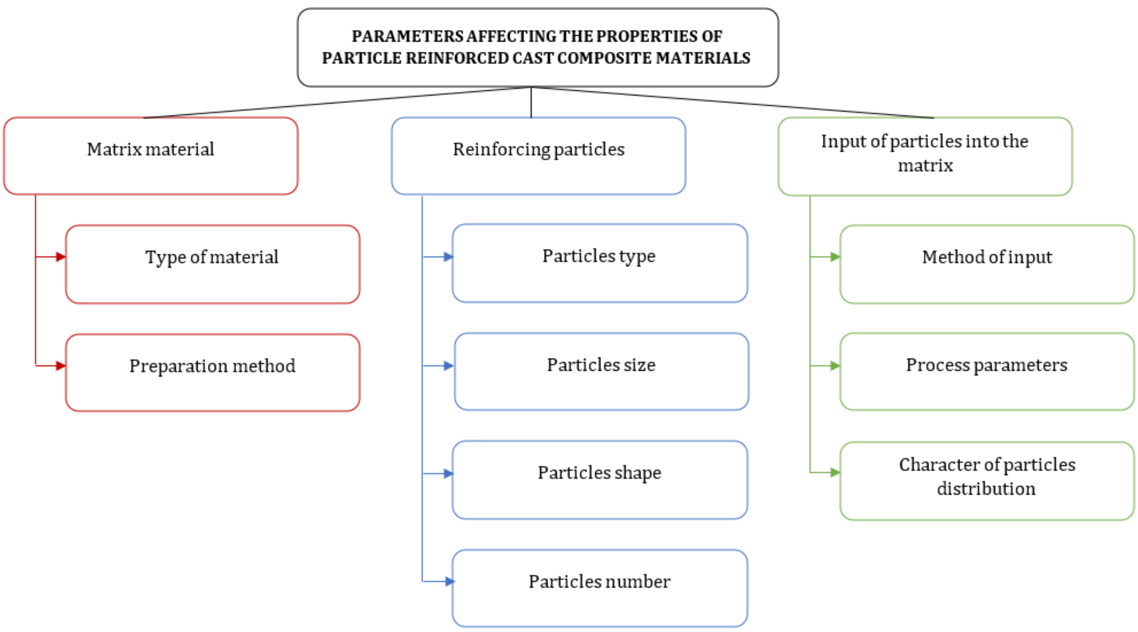


**Fig. 1.** Parameters affecting the properties of particle reinforced cast composite materials

## 4. REINFORCING PARTICLES AND THEIR INTERACTION WITH LIQUID METAL IN COMPOSITE MATERIALS

In the technology of producing CCM it is important to choose a reinforcing material and a method of introducing reinforcing particles into the melt in addition to the choice of a matrix alloy. The reinforcing particles characteristics determine the vector of properties changes of the base material. The price of the finished product is also important, given its performance characteristics.

Depending on the nature and material composition of the introduced particles, they can contribute to an increase in the strength, friction, or antifriction characteristics of the matrix alloy. The properties of CCM reinforced with solid, insoluble, refractory particles are largely determined by the nature, size, volume fraction, shape of these particles and their interaction with the matrix. Common to most production methods is the reinforcement of matrix alloys with a dispersed phase in the form of particles of oxides, nitrides, carbides, borides, and refractory metals [14, 19]. Finely dispersed materials obtained from industrial wastes are increasingly wider lately used as technologically and economically acceptable reinforcing elements for products based on matrices of aluminum alloys [20]. Slags of metallurgical production and cupola smelting, enrichment wastes, ash from thermal units, fireclay powders, broken ceramics, etc., which are ground into powder in ball or vibration mills and calcined in drying ovens or in chamber furnaces are used. There are known cases of introduction of particles of graphite and/or bronze in the form of chips to increase the antifriction properties of Al alloys [8, 21]. Particles of SiC, $Al_2O_3$, $B_4C$, cast basalt fibers, graphite flakes and mica are quite often introduced into alloys based on Al and Mg [6, 22, 23].

The micro-particles size can vary within wide limits from 0.1 to 400 μm [6, 7, 24–28]. In recent years, a too large number of studies have been devoted to the reinforcement of aluminium matrices with nanoparticles from 10 to 1000 nm [15, 18, 29–32].

Reinforcements in the form of fibres or particles can be a hardening phase only in the case of high interfacial adhesion. Typically, poor wetting is noted in the melt-solids combinations used. Improving the wetting of solid particles by liquid metal enhances their bond with the matrix metal, thereby increasing the mechanical and operational characteristics of finished products. The introduction of surface-active elements into the liquid metal reduces the surface tension at the interface between the solid and liquid phases. Heating and sometimes calcining of the reinforcing particles before being introduced into the liquid matrix alloy is necessary to remove moisture and other gases adsorbed by the surface from their surface. The positive effect of heating the particles is also reflected in the improvement of their wettability. An increase in the temperature of the melt during the introduction of dispersed particles into it has a similar effect on improving wetting.

It is possible to obtain a pure matrix metal, and to ensure its reliable contact with reinforcing particles using an inert gas or vacuum instead of an oxidizing atmosphere in the process of obtaining CM.

The amount of solid phase introduced into the melt when implementing liquid-state methods is usually less under implementing solid-state methods [13]. There are no universal recommendations in the literature on the amount of injected particles. There can be no such recommendations, since the amount of the dispersed phase, providing the greatest increase in the level of various properties, depends on the nature of the matrix alloy and solid particles, their size and the nature of their distribution in the matrix. So with the introduction of even 0.3–1.0 wt.% $WS_2$ with a fraction of ~2 μm, a noticeable increase in the ultimate strength and yield strength of the AZ91 alloy was noted [33]. The authors [34] found a positive effect on the compressive and tensile strength even with the introduction of 1.0 wt.% $B_4C$ particles into a matrix of AZ91 alloy. In study [25] it was found that for the combination AZ91/$SiC_p$ with a particle size of 20–40 μm, the optimal amount of solid phase is about 10–15 wt.% for increasing of strength properties. In [4], a significant increase in the wear resistance of the AZ91 alloy was noted when reinforcing it with 10 wt.% particles of $SiC_p$ with an average grain size of 10 μm. According to the results of investigations [35], it is recommended to introduce 5–50 vol.% solid particles into high-alloy steels in the form of carbides, titanium nitrides, tungsten and niobium in order to increase the wear resistance of cast parts.

It is shown in [36, 37] that with a high volume fraction of reinforcing particles, CM with an aluminium matrix shows high contact strength, that's why they can be used to create supporting elements of cargo roller tables, mirrors substrates for guidance systems and parts of hydraulic devices.

There is little discussion in the literature about the influence of the shape of reinforcing particles on the properties of CCM. As a rule, particles of ceramics, carbides, metal nitrides have an acute-angled, chipped shape, graphite particles are lamellar, and refractory metals are rounded [5, 7, 35]. It is obvious that the shape of dispersed particles can be a factor that determines the different characteristics of the finished CM. For considering this issue an analogue can be the form of graphite in cast iron [38]. It has been established that inclusions of lamellar graphite in gray cast iron have a notching effect on the metal matrix, in contrast to inclusions of nodular graphite in ductile iron. As a consequence, ductile iron has a much higher level of mechanical properties. It should be assumed that inclusions of rounded solid particles will be more favourable for the properties of CCMs compared to acute-angled or splintered ones.

It is necessary to consider the role of dispersed particles in crystallization processes. The rate of crystals nuclei formation as well as the rate of their growth, are two competing processes that ultimately determine the micro- and macrostructure of the solidified metal base, and, consequently, the complex of its properties. Thus, the predominance of the rate of formation of embryos over the rate of their growth leads to the appearance of a fine-grained micro- and macrostructure and a higher level of properties, in comparison with the opposite case [39].

Dispersed reinforcing particles can become heterogeneous nuclei of crystallization. At the same time, there is an opinion that the introduction of dispersed refractory fillers into aluminium melts helps to reduce the dendritic parameter of the cast structure. Ceramic particles, according to [40], are not crystallization centres, but are pushed aside by growing dendrites of α-aluminium into interdendrite spaces enriched with easy-melting phases. The modifying role of ceramic particles is due to the limitation of the volumes of the melt in which the liquation takes place. Particles of metal-like carbides and intermetallic compounds also have a modifying effect on the cast structure of CM, but already as crystallization centres. When graphite particles are added to the CM composition, the particles are located mainly in the interdendrite spaces and can also serve as a substrate for primary silicon crystals in Al-Si alloys. It was found that the refinement of the fragments of the structure increases with an increase in the content of ceramic and graphite particles in the CM.

## 5. METHODS OF INTRODUCING REINFORCING PARTICLES INTO THE MELT AND PARAMETERS OF THE INJECTION PROCESS

The next parameter of the CM manufacturing technology by liquid-state methods is that of introducing solid particles into the liquid phase. Depending on the chosen method, several variants of the distribution of particles in the matrix can be obtained. One of the following input methods can be selected depending on the expected result.

The most common is the stirring method, designed to ensure the uniform dispersion of reinforcing particles [5, 7, 29, 33, 41]. The basic principle of the method is the reinforcing particles are introduced directly into the molten matrix metal and are evenly distributed in it due to stirring. The more uniformly the hard particles are distributed in the soft matrix, the higher the level of properties in the entire volume the resulting composite acquires. Therefore, it is important to choose the right technological parameters of the process:

- stirring speed;
- stirring time;
- melt temperature;
- heating temperature of the introduced particles;
- the introduction of wetting agents into the melt.

The stirring rate is an extremely important parameter that determines the degree of turbulence of the liquid metal flow, and, consequently, the nature of the distribution of solid particles in the melt. As shown in [5, 7, 41], the movement of reinforcing particles in molten metal is directly related to the speed of its movement. In this case, the higher the mixing rate is higher the degree of flow turbulence and the less noticeable sedimentation processes, the more uniformly the particles are distributed in the liquid and then in the solidified matrix alloy. In the same works, it was shown that with an increase in the mixing rate, the surface tension at the interface between the solid and liquid phases decreases, which, as already noted, is very important for ensuring reliable fixation of particles in the matrix. In practice, high-speed mechanical with a rotation frequency of up to 4000 rpm and more and ultrasonic mixers are used for mixing reinforcing particles into liquid metal [42]. The choice of stirring speed should be based on an estimate of the melt viscosity. This parameter is known to be directly related to the composition of the liquid metal and its temperature.

Stirring time is also a critical process parameter [43]. An insufficient stirring time can lead to the uneven distribution of solid particles in the liquid metal, their concentration in some volumes and absence in others. Excessive stirring can result in deformation and destruction of the active element of the agitator due to high temperatures combined with mechanical stress. Obviously, it is necessary to empirically choose the optimal stirring time for each specific case.

The choice of the process temperature is an important element of the castings manufacturing technology from CM [44]. The function of temperature is fluidity to providing the required viscosity of the melt at the time of introducing and mixing reinforcing particles in it. The role of fluidity in filling moulds and obtaining the correct configuration of castings is widely recognized. An increase in the temperature of the melt, in addition, improves the wetting of dispersed particles by the melt.

A slightly different approach to ensuring a uniform distribution of reinforcing particles is implemented under casting by the lost-foam method. Solid particles are mixed with granules of expanded polystyrene and injected into a compression mould [45, 46]. Their uniform distribution in the model is preserved in the finished casting. This method has not yet found wide application in practice due to poor process control.

The second option is typical for obtaining functional-gradient materials. In this case, the necessary parameters of physical properties and performance characteristics (coefficients of friction, thermal expansion, wear resistance, elastic modulus, etc.) are implemented in separate specified areas of the product. Reinforcing particles in one way or another are concentrated in the most loaded section of the casting, thereby increasing its efficiency. There are several ways of such concentration. The production of composites by centrifugal casting makes it possible to obtain blanks with a differentiated distribution of reinforcing elements over the section of the casting [47]. The resulting parts have a reinforced outer or inner surface (zone), depending on the ratio of the density of particles and matrix alloy [8, 47–49]. One of the most important technological factors in centrifugal casting, affecting segregation processes, is the gravitational coefficient, showing how many times all the components of the alloy become heavier in the field of action of centrifugal forces.

During casting in stationary moulds, due to the difference in the specific gravity of the matrix metal and reinforcing particles, they can be concentrated either in the upper or in the lower part of the casting, thereby giving it the necessary properties that differ from those of the base metal.

Another group of methods for introducing reinforcing particles into a matrix alloy is based on the technology proposed by Nukami and Flemings [50]. *In-situ* technology, is based on the synthesis of the second phase as a result of the chemical interaction of the components introduced into the melt. It is characterized by a number of advantages:

- simple and relatively inexpensive equipment;
- short technological cycle;
- high purity and quality of the final alloys.

The most widespread technology option is the preparation of a master alloy consisting of ultrafine powders of titanium, carbon and aluminium as moderator in the form of pellets and the introduction of this alloy into the aluminium melt [51, 52]. TiC is formed as a result of a chain of chemical reactions at the place of introduction of the master alloy, which acts as a reinforcing phase [52–54].

The molten metal matrix solidifies after mixing, securely fixing the reinforcing particles within it. In this case, depending on the purpose of the composite material, it is possible to form a shaped casting or an ingot.

## 6. CONCLUSIONS

Cast composite materials based on aluminium, magnesium and their alloys provide a level of properties much higher than that of base metals and alloys. This makes CCM promising materials for various branches of engineering.

During obtaining CCM, such parameters of technology are important:

- the choice of the type of matrix alloy;
- the method of its preparation;
- type, size, shape and amount of reinforcing particles;
- the principle and parameters of the introduction of dispersed particles into the melt.

Only the optimal combination of all these elements can provide composite materials with a high level of physical, mechanical and operational properties.

## ACKNOWLEDGMENT

*This study was supported by the International Visegrad Fund (IVF contract No. 52010054).*

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