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Joinability of Centrifugal Composite Castings

Abstract: Centrifugal composite castings based on aluminium alloys belong to a group of materials with high potential for application in the automotive and aerospace industries. Their use is limited by the lack of a technology enabling the obtainment of a permanent joint ensuring safe operation. The article presents the results of preliminary surfacing and welding tests of a hybrid centrifugal composite casting based on the AlSi12 alloy and reinforced with silicon carbide (5% by weight) and glassy carbon (5% by weight) particles. Structural tests and the quantitative evaluation of the distribution of structural constituents indicated the possibility of the joining of such composites using the TIG welding process. It was found that overlay welds made using the filler metal having a chemical composition similar to that of the matrix could be treated as a buffer layer. The aforesaid approach should enable the joining of composite castings. The structure of the weld revealed the presence of heterogeneously distributed reinforcing phases, which was related to the gradient structure of centrifugal composite castings. The presence of the Al_4C_3 phase at the interface between the glassy carbon and the matrix could result in the reduction of corrosion resistance in a humid environment. The structural tests discussed in the article should be supplemented with the assessment of the mechanical properties of the joint. As a result, it will be possible to implement the technology for the welding of composite castings on an industrial scale.

Keywords: composite castings, centrigugal castings, alluminium alloys, weldability, mechanical properties of the joints

Introduction

The development of material manufacturing technologies has been imposed by requirements formulated by design engineers and connected, among other things, with the necessity of reducing the weight of structures as well as with the improvement of selected mechanical and physical properties of materials. Certain trends concerning the development of materials are focused on composite materials including

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light metal-based composites reinforced with ceramic particles (e.g. of oxides or carbides). Composites are defined as designed materials, made of two or more components, characterised by significantly different physical or chemical properties and structure than those of the each of the components separately [1,2].

Presently, as regards the design of highly complex structural elements, the most common technologies used in the fabrication of metallic composites include liquid-phase methods, particularly the stir-casting method [3]. One of such technologies, enabling the obtainment of cylindrically-shaped elements characterised by the gradient of properties is centrifugal casting [4]. In the above-named technology, aluminium (AlMC), magnesium (MgMC) or titanium (TiMC) alloys are used as the matrix, whereas oxides (e.g. Al_2O_3 or ZrO_2), carbides (SiC, TiC, B_4C, ZrC, Cr_3C or TaC) or nitrides, silicates and borides [1] are used as the reinforcing phase.

The use of light metals as the matrix results from their high specific strength, i.e. the proportion of immediate strength (R_m) to density (ρ), where the addition of approximately 30% of the reinforcing phase results in an increase in strength of approximately 30% [1,5]. Many machinery elements such as pistons, sleeves or belt pulleys only require the improvement of the surface layer, i.e. of the local distribution of reinforcement. Particularly in terms of reinforcement based on ceramic particles, the aforesaid distribution is favourable as it increases the abrasive wear resistance and the heat resistance of subsurface layers without compromising the high mechanical and plastic properties of the core [4]. The foregoing results in the increasingly high popularity of this group of materials in the aviation and automotive industries. However, the design of highly complex shapes of castings and the need for using various materials necessitate the development of a technology enabling the joining of composite castings by means of joining methods.

Reference publications contain little information about the joining of composite casings based on light metal alloys. Authors Ogonowski K., Wysocki J. et al. performed tests involving the TIG welding (using ER5356 (AlMg5) as the filler metal and without the use of the filler metal) of a composite based on alloy AC-44400 (AlSi9) and reinforced with silicon carbide (SiC) [6]. In the above-named publication, the authors informed that it was possible to join the above-named composite, yet the joint was characterised by numerous welding imperfections including soot present on the surface of the crater. The soot originated from the decomposition of silicon carbide particles, the heterogeneous decomposition of carbide particles and pores. The article also indicates that the filler metal should improve the wettability of the reinforcing phase, be characterised by good castability and enable the control the flowing power of metal in the weld pool [6]. The researchers also confirmed their observations in work [7], presenting results of a static tensile test involving a joint. The strength of the weld was by 20% lower than that of the base material (AlSi9+20%SiCp composite). Publication [8] presents the analysis concerning the friction welding-based joinability of AlSi9/SiC/21(p) and AlSi11/SiC/15(p) composites with alloy AlSi11. Related test results revealed the transfer of particles from the composite to the alloy, which, in the Authors' opinion, indicates the favourable stirring of welded materials and their joinability. Jitai Niu et al [9] attempted to obtain a laser joint of a composite based on alloy AW6061 and reinforced with silicon carbide. Based on metallographic test results, the Authors confirmed the laser welding-based joinability of the composite. It was found that reactions occurring at the matrix/reinforcing phase interface could be controlled by reducing beam energy and increasing the content of silicon in the pool. Similar research was conducted by Bonollo F., Tiziani A. and Penasa M. from Italy, who used a CO_2 laser [10].

Another group of scientists led by Tjahjanti, P. H. tested the gas welding-based joinability of an AlMg10-based composite reinforced with silicon carbide (15%) [11]. The researchers revealed the joinability of the above-named composite, yet they also found that the joint contained microcracks and porosity.

There are no works concerned with the joining of centrifugal composite castings based on aluminium alloys and reinforced with silicon carbide and glassy carbon. It is necessary to identify the joinability and claddability of such composites in relation to their unique properties (if compared with those of the base material) including significantly increased material strength and abrasive wear resistance (SiC addition) without compromising the relatively low friction coefficient (spherical glassy carbon).

Test material

Surfacing and welding tests involved the use of a sleeve having a diameter of 46 mm and a wall thickness of 10 mm. The sleeve was made of a composite based on aluminium alloy grade AlSi12 reinforced with silicon carbide particles and globular glassy carbon (GC). Similar to glassy carbon, the volume fraction of the SiC phase amounted to 5%. The technological casting of the composite sleeve was performed in two stages. At the first stage, in accordance with a technology discussed in publication [12], it was necessary to prepare slurry having the total fraction of the reinforcing phase amounting to 10%. At the second stage, the heated composite slurry was stirred and cast into the metal mould having a diameter of 46 mm and rotating at a rotation rate of 3000 rpm (in accordance with a technology discussed in publications [13,14]). The exemplary composite sleeve is presented in Figure 1a.

Because of the manufacturing technology, centrifugal composite castings are characterised by the variable structure along the cross-section [4,15,16,17]. The macrostructure of the casting in cross-section is presented in Figure 1b.
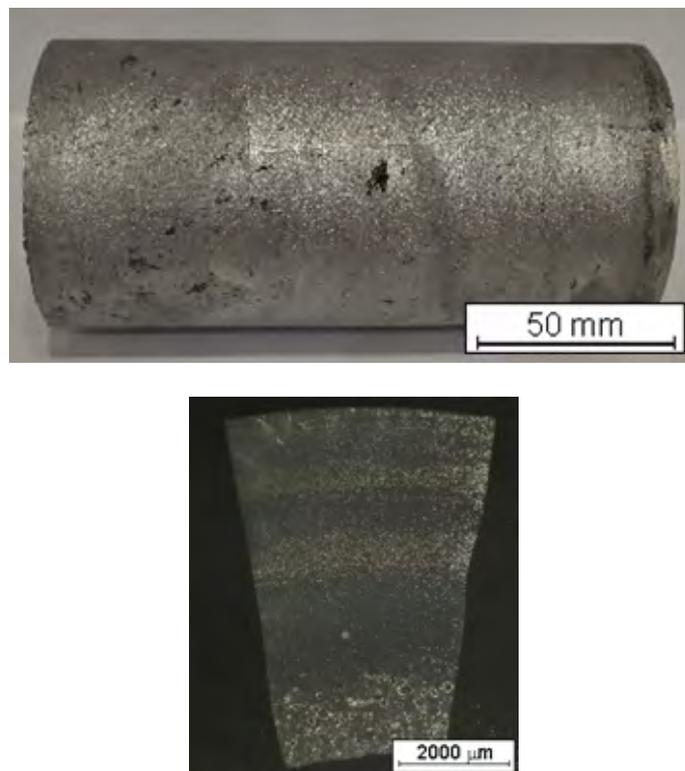
Fig. 1. Composite sleeve (AlSi12/SiC/GC): a) main view and b) macrostructure revealed in cross-section

Technological welding and surfacing tests

Technological surfacing tests involved the sampling of 10 mm thick specimens out of the composite sleeve (along its axis). Technological welding tests involved specimens sampled along the sleeve and subjected to Y-groove joint preparation (on the internal side), leaving the welding threshold having a height restricted within the range of 2 mm to 3 mm. The bevel angle on the external side of the sleeve amounted to 30°. After cleaning in acetone, the specimens were subjected to TIG surfacing and welding using parameters presented in Table 1. The filler metal used in the welding and surfacing process was in the form of wire grade AlSi12 having a dimeter of 2 mm. The argon–shielded surfacing process was performed using an AC of 120 A and the low rate of argon (99,995%) amounting to 10 l/min; the welding process was performed using an AC of 140 A (Fig. 2).

Methodology and test results

Specimens subjected to metallographic tests were sampled in perpendicular to the direction

Table 1. Parameters used during the surfacing and welding of the centrifugal AlSi12/SiC(5%)/GC (5%) composite casting

Alloy	Process	Current [A]	Arc voltage [V]	Welding rate [cm/min]	Gas flow rate [l/min]	Gas nozzle diameter [mm]
AlSi12/SiC/ GC	Surfacing	120	14	20	10	12
	Welding	140	16	20	10	12
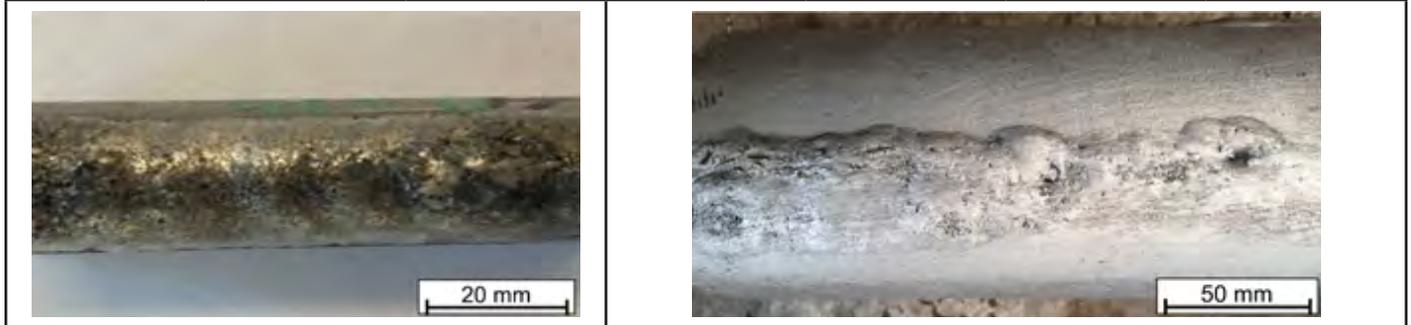
of surfacing and welding. The specimens were next ground and polished using diamond paste. Afterwards, the metallographic specimens were subjected to observations performed using a light microscope (LM) and a magnification of 500x in the bright field technique and a scanning electron microscope (SEM) in the secondary electron (SE) technique and in the backscattered electron (BSE) technique. The SE images made it possible to observe the topography of the specimen, whereas the BSE images revealed the differences in the chemical composition of individual structural components. Exemplary structures of the centrifugal AlSi12/SiC/GC composite casting are presented in Figure 3. In turn, Figures 4 and 5 present the structure of the overlay weld and that of the welded joint respectively. The structural tests were supplemented with the EDS-based microanalysis of the chemical composition of revealed structural components (Fig. 6).
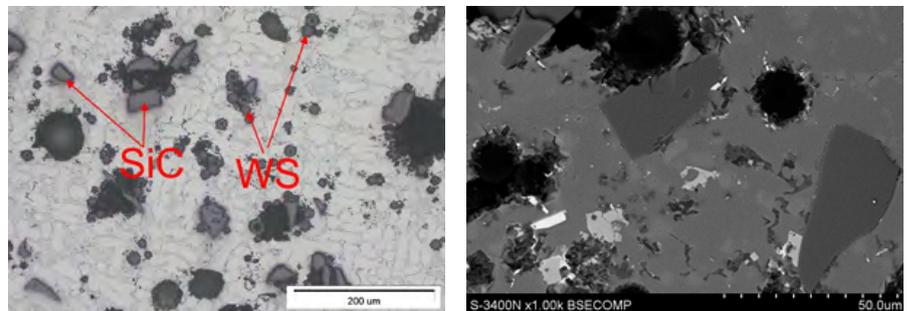
Fig. 3. Microstructure of the centrifugal AlSi12/SiC/GC composite casting: a) structure of the composite with visible reinforcing phases and numerous pores (LM), b) SiC, GC and the remaining phases revealed in the structure
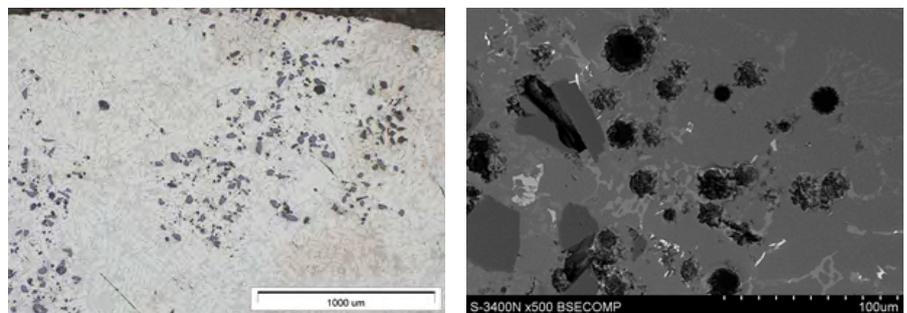
Fig. 4. Microstructure of the AlSi12/SiC/GC overlay weld: a) structure of the overlay weld with the visible heterogeneously distributed reinforcing phases (LM) and b) structure of the overlay weld in the area of glassy carbon concentration (SEM)
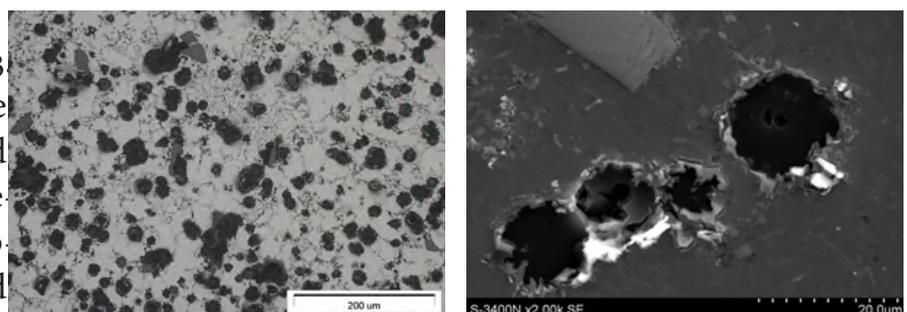
Fig. 5. Structure of the AlSi12/SiC/GC composite weld: a) area of the uniform distribution of the reinforcing phases in the weld (LM) and b) glassy carbon and silicon carbide in the weld (SEM)

Fig. 6. Results of the microanalysis of the chemical composition of the phases revealed in the AlSi12/SiC/GC composite structure
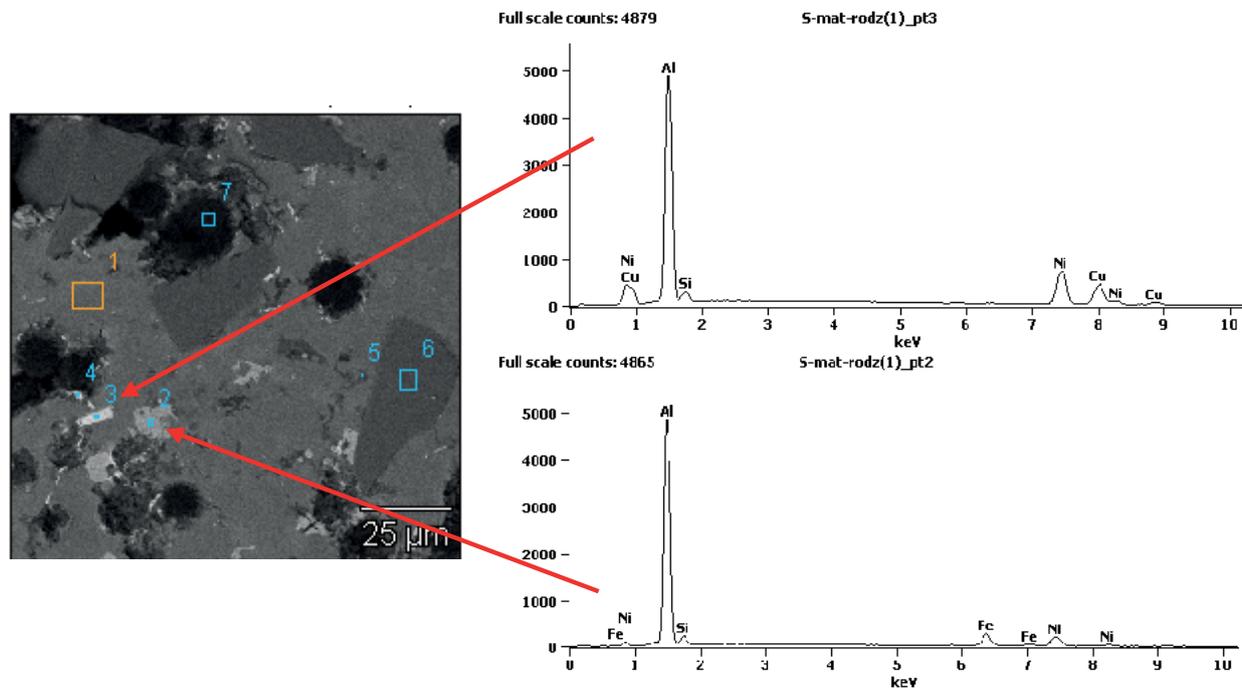
Wt%	C-K	Mg-K	Al-K	Si-K	Fe-K	Ni-K	Cu-K
W-base-mat.(1)_pt1		0.3	91.3	6.5			2.0
W-base-mat. (1)_pt2			54.1	2.8	17.5	25.6	
W-base-mat. (1)_pt3			29.2	1.5		38.3	31.1
W-base-mat. (1)_pt4		0.2	31.0	0.4		37.4	31.0
W-base-mat. (1)_pt5		35.7	19.2	45.1			
W-base-mat. (1)_pt6	30.0S			70.0			
W-base-mat. (1)_pt7			43.4	56.6			
At. %	C-K	Mg-K	Al-K	Si-K	Fe-K	Ni-K	Cu-K
W-base-mat. (1)_pt1		0.3	92.5	6.3			0.8
W-base-mat. (1)_pt2			70.3	3.5	11.0	15.3	
W-base-mat. (1)_pt3			47.5	2.3		28.7	21.5
W-base-mat. (1)_pt4		0.4	50.0	0.6		27.7	21.3
W-base-mat. (1)_pt5		38.8	18.8	42.4			
W-base-mat. (1)_pt6	50.0			50.0			
W-base-mat. (1)_pt7			44.4	55.6			

The structure of the centrifugal metal matrix-based composite reinforced with silicon carbide and glassy carbon was heterogeneous. For this reason, to evaluate the effect of the welding process on the structure of the joint it was necessary to perform the quantitative assessment of the surface content of individual phases. The tests involved the preparation of five specimens sampled along the axis of the sleeve and weld cross-sections corresponding to the aforesaid specimens (Fig. 7a). The tests involved the cross-sections being unetched metallographic specimens. The analysis of the structure was performed using the METILO software programme, developed at the Faculty of Materials Engineering of the Silesian University of Technology [18]. The methodology of transformations from the grey image into the binary measurement image is presented in Figure 7b. The results are presented in Figure 8.
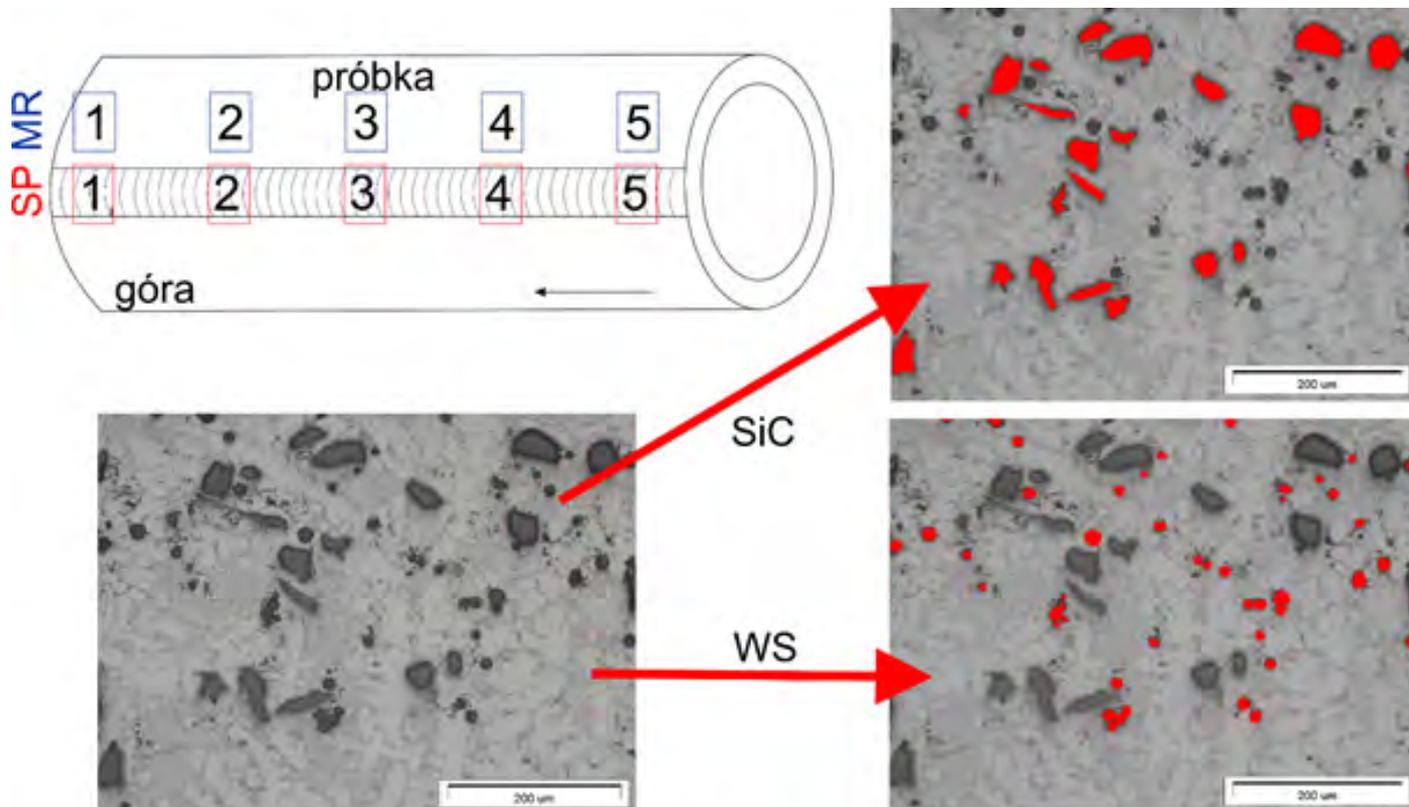
Fig. 7. Methodology of the assessment of the surface content of individual phases in the joint structure: a) sampling area and b) exemplary images after transformations in the METILO analyser
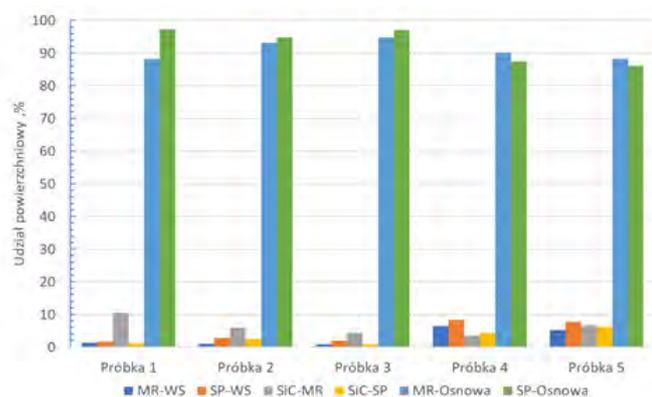
Fig. 8. Comparison of the surface composition of the primary phases in the structure of the base material (BM) and in the structure of the weld (WS) in the joint of the centrifugal AlSi12/SiC/GC casting

Analysis of test results and conclusions

Aluminium alloy-based metal composites belong to the group of the most advanced materials applied, among other things, in structures and elements used in the automotive and aviation industries. The increasingly high interest in the aforesaid materials is connected with their unique properties combined with light weight. Such composites are usually cast, which limits their application potential and, consequently,

necessitates the development of technologies enabling the joining of these materials and increasing their scope of application, among other things, by joining individual castings or joining castings with other elements.

Because of the system of their fabrication [4, 5], centrifugal composite castings based on aluminium alloys and reinforced with silicon carbide particles and glassy carbon are characterised by the heterogonous complex structure both of the matrix and of reinforcing phases. Such materials of the inhomogenous chemical composition and complex structure are difficult to weld. The research work involved the surfacing and welding of the AlSi12 alloy-based centrifugal composite casting containing silicon carbide (5% by volume) and glassy carbon (5% by volume). The composite having the form of a sleeve (ø46 mm) was cast at the Faculty of Materials Engineering of the Silesian University of Technology (Fig. 1). The argon-shielded surfacing and welding processes were performed using the TIG method (141), AC and the filler metal in the form of a AlSi12 wire having a diameter of 2 mm (Table 1). The visual tests of the

overlay weld face revealed the proper and uniform face containing reinforcing phases on the surface (having reached the surface of the liquid metal pool (Fig. 2a)). The welded joint was characterised by the non-uniform face with single pores and discontinuities, which was connected with the heterogeneity of the welded material (Fig. 2b). The analysis of the base material structure revealed the presence of numerous voids, particularly between reinforcing particles (Fig. 1b and Fig. 3a), responsible for the formation of pores in the overlay weld and in the weld. The detailed analysis of the number and the arrangement of the voids in the base material (Fig. 3b), overlay weld (Fig. 4) and in the weld (Fig. 5) indicated the partial degassing of the welding area during the welding process. The number and the size of the voids in the overlay weld and in the weld were smaller, which indicated the more favourable filling of the space between the reinforcing phases and, consequently, the continuity of the joint. The foregoing was also confirmed by SEM-based observations (Fig. 3b, Fig 4b and Fig. 5b). It was noticed that, both during surfacing and welding, despite the significant amount of gases coming from the casting, the joint between the reinforcing particles and the matrix material in the pool was proper and sufficient for the obtainment of structural continuity. However, further research (necessary to identify the mechanical properties of the joints) is needed in order to practically apply the welding technology for the joining of composites.

The EDS-based tests of the chemical composition of the individual phases revealed, in addition to the primary reinforcing phases (silicon carbide and spherical glassy carbon), also the presence of phases containing iron as well as phases containing nickel and copper (Fig. 6). These phases were observed in the composite structure [4,19] and passed to the weld in the molten base material. Both in the structure of the base material as well as in the structure of the overlay weld and of the weld it was possible to observe the significant amount of the phase containing carbon and aluminium (probably Al_4C_3 carbide) [19]. The above-named phase, located primarily between the glassy carbon and the matrix, was brittle and unstable in a humid environment. The presence of such a phase could be responsible for low corrosion resistance.

The overlay weld structure revealed locally heterogeneous distributions of reinforcing phases (Fig. 4a), primarily silicon carbide, whereas glassy carbon was observed primarily on the surface of the overlay weld face. This fact was connected with the mixing of the material in the liquid metal pool. The aforesaid phenomenon could be used when developing a technology enabling the joining of castings with other aluminium alloys, where an overlay weld could be treated as a buffer layer. The weld was characterised by the higher homogenisation of the material (Fig. 5a). However, the results of quantitative tests revealed the inhomogenous surface content of the primary reinforcing phases in the structure (Fig. 8). The welding process resulted in a decrease in the content of silicon carbide and an increase in the content of glassy carbon in the weld (Fig. 8). This fact resulted from the heterogonous distribution of silicon carbide in the casting and the filler metal not containing reinforcing phases. The increased surface content of glassy carbon resulted from the passing of globular particles to the pool and their movement towards the face (because of lower density (1.5 g/cm^3) in relation to the matrix).

The above-presented test results and their analysis justified the formulation of the following conclusions:

– It is possible to perform the surfacing and welding of composite castings based on aluminium alloys reinforced with silicon carbide particles and glassy carbon. The initial technological tests indicated the necessity of following the guidelines concerning the welding of the matrix material.

- The layers surfaced using the filler metal, the chemical composition of which was similar to that of the matrix could be treated as buffer layers constituting the substrate for joints of two castings or of a casting with another structural element.
- Similar to the base material, the weld structure contained reinforcing phases as well as phases containing iron or phases containing copper and nickel. A dangerous phase revealed at the interface of glassy carbon and the matrix was the phase of Al_4C_3, brittle and unstable under humid conditions.
- The above-presented tests constitute the reason for the performance of technological welding tests. Such tests will enable the determination of mechanical properties of joints and will constitute the basis for the use of elements made of centrifugal composite castings in the automotive and aviation industries.

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