Joining of composite materials based on Al-Si alloys by using the GMAW process

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Keywords

Aluminium matrix composite, GMAW, macroscopic analyses, weld microstructure.

1. Introduction

Composite materials are increasingly used because of their physical, mechanical and tribological properties that are better compared to the properties of the matrix material. Within the group of composite materials with a metallic matrix, are composites based on light metals aluminium, magnesium and zinc. These composites have been used in many industries primarily because of its low density. Lightweight alloys usage in various industries reduce weight and hence energy consumption and greenhouse emissions. Composites based on aluminium are the most common, while the two mostly used reinforcements are silicon carbide (SiC) and alumina (Al_2O_3) [1-3].

The A356 Al-Si alloy is a casting alloy consisting of aluminium, silicon and magnesium. It is distinguished by good mechanical characteristics and high ductility, as well as excellent casting characteristics and high corrosion resistance [4]. The A356 alloy has low density (approximately 2.7 g/cm^3) and belongs to the class of alloys whose mechanical properties can significantly be improved by the heat treatment, especially using T6 heat treatment regime [5]. It has been widely used as a matrix for the composites with ceramic particles and fibres such as SiC, Al_2O_3 etc. [6-8].

Despite the intense effort put into the development of high performance aluminium composites, relatively little work has been directed towards joining these materials. A good overview of the possible methods, available for joining aluminium matrix composites, is presented by Ellis et al. [9].

Most of the conventional fusion welding processes used for joining unreinforced aluminium alloys (GTAW, GMAW, laser, and electron beam) produce important microstructural alterations when they are applied to composites [10]. Furthermore, conventional fusion welding produces a weld pool that has poor fluidity and that solidifies with large volumes of porosity in both the weld and the heat-affected zone (HAZ) because of the release of hydrogen emanating from the aluminium powder used to fabricate many aluminium matrix composites [11]. Nevertheless, there are few successful attempts of welding aluminium matrix composites by using GMAW [12], and GTAW [10, 13] processes.

In recent years, some joining processes proved to be good for connecting these composites (e.g. friction welding [14-16]), but the typical limitations of these procedures as regards production capacity and equipment costs make it necessary to reconsider the possibility of the application of more productive welding processes [10]. There are also successful attempts of using non-conventional processes like plasma spray joining [11], or X-ray welding [17] of aluminium matrix composites.

Main aim of this experiment was to find the optimal parameters for welding of the A356 Al-Si alloy base composite (with Al_2O_3 reinforcing particles) by GTAW process, with argon as a protective gas.

2. Materials and welding parameters

Hypoeutectic A356 aluminium alloy (referred to as A356) modified with the addition of 0.03 wt. % Sr was used as the matrix for obtaining composite. Its chemical composition is given in Table 1. The amount of infiltrated reinforcing Al_2O_3 particles was 10 wt. %. The particles were approximately equal, with the average size of 35 μm.

Table 1. Chemical composition (wt. %) of the matrix alloy.

Element [%]									
Si	**Cu**	**Mg**	**Mn**	**Fe**	**Zn**	**Ni**	**Ti**	**Sr**	**Al**
7.20	0.02	0.29	0.01	0.18	0.01	0.02	0.11	0.03	Balance

The composites were produced by compocasting process, using the laboratory equipment described previously [18]. Experimental procedure used for the compocasting processing are described and discussed elsewhere [4]. Specimens of the composites were thermally processed applying T6 heat treatment regime, which consists of solution annealing at 540 °C for 4 hours, water quenching and artificial aging at 160 °C for 4.5 hours, also with quenching in water. The T6 heat treatment regime, which has been applying to improve the mechanical and tribological characteristics of the composite, is part of the overall technology of commercial production of A356 alloy castings. Obtained composite material has enhanced mechanical and tribological properties in comparison to the basic A356 alloy and its basic mechanical properties are presented elsewhere [4, 19].

The specimens supplied for welding were processed into prismatic plates with a size of 30 x 15 x 5 mm. Three different types of supplementary materials, in the wire form, were used like filler materials: AlMg4.5Zr, AlMg5 and AlSi5. Preparation of the specimens supplied for welding is performed on a planer metalworking machine tool, with the double-V joint design at 60° (Figure 1a). Prior to the welding, surfaces are cleaned with the stainless brush and grinded with the grinding machine designed for aluminium preparation.

The welding of the specimens is done using the GMAW process, with argon as a protective gas. Welding was performed by pulsed arc program. (Figure 1b).

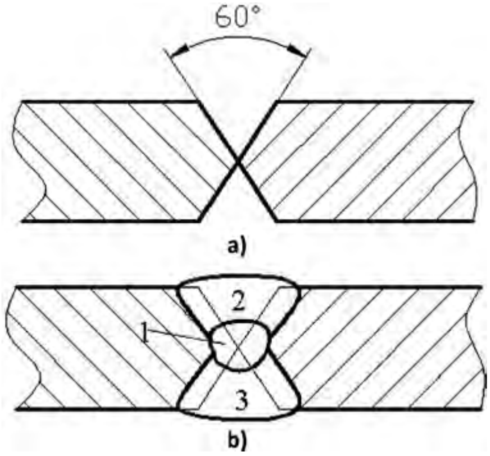

Figure 1. The schematic drawing of: (a) weld preparation (double-V joint design) and (b) sequence of welds.

The macrostructures and microstructures of the welded samples were analyzed. Cutting of the samples to analyse the structure was carried out by the water jet on the plane perpendicular to the surface of specimen. Structural tests were carried out on polished and etched (with sodium hydroxide) samples with the optical microscope. Polishing and etching were done following the standard procedure.

3. Results and discussion

The composite samples were obtained in the laboratory conditions, and as such, are not ideal. Imperfections that occurred during the welding are mainly caused by the poor structure of the composite material. Samples were very small, with a high level of porosity and impurities, which further aggravated the used GMAW process.

3.1. Macroscopic analysis

The macrostructures of welded joint are shown on Figures 2-4. In the first case, the filler material was wire with the nominal mark: AlMg4.5Zr (Fig. 2). During the analysis, imperfections were found in the base material such as high porosity, oxides and cracks. In the HAZ, imperfections were also present, such as porosity and oxides, but in the weld metal, there is less porosity.

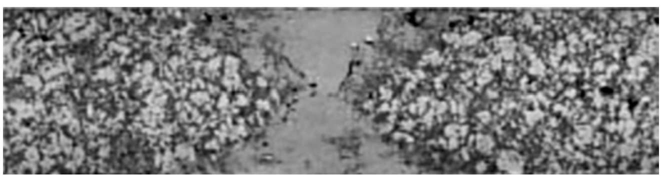

Figure 2. Macroscopic view (filer material: AlMg4.5Zr).

The welded joint where the filler material was wire with the nominal mark AlMg5 is shown in Figure 3. Base material was the same A356 alloy like in the previous case. The presence of the same type of imperfections are noticed, i.e. presence of high porosity, oxides and cracks. In the HAZ, imperfections such as presence of big pores and oxide inclusions were noticed. At the fusion line of the weld metal, presence of the lower porosity was noticed.

The welded joint where the filler material was wire with the nominal mark AlSi5 is shown in Figure 4. As in the previous two cases, it is the same base material, so the same imperfections

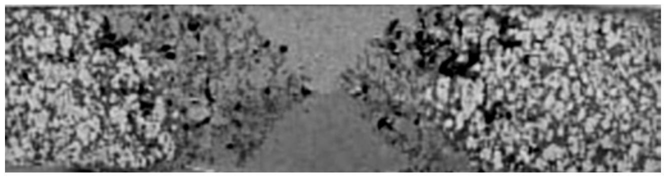

Figure 3. Macroscopic view (filer material: AlMg5).

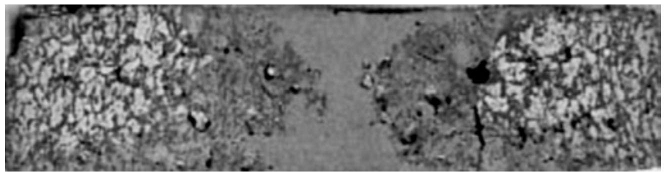

Figure 4. Macroscopic view (filer material: AlSi5).

are noticed in the composite. In the HAZ, imperfections such as error type porosity and oxide inclusions were noticed. At the fusion line of the weld metal, presence of the lower porosity was noticed.

3.2. Microstructure

Microscopic examination was performed on previously prepared samples, grounded and polished for microstructure analysis, and etched with a solution of sodium hydroxide in order to clearly delineate their structures. Examination was carried on an optical microscope at the magnification of 500 times. Microstructure analysis was carried out in three distinctive zones for each sample: base material, HAZ and weld metal.

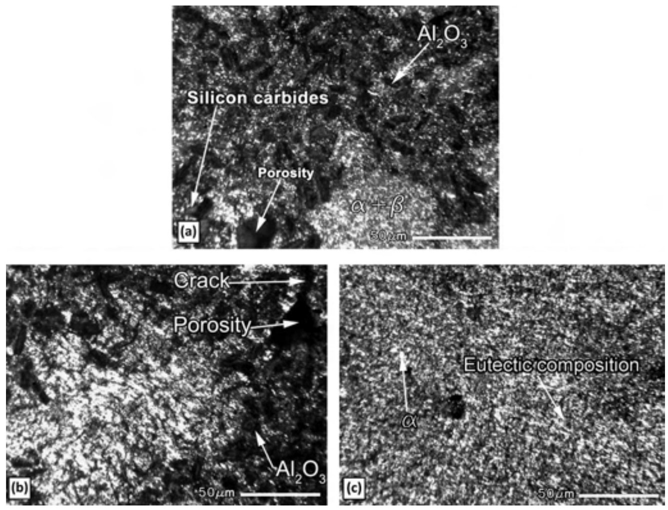

Figure 5. Microstructure of the: (a) base material, (b) HAZ and (c) weld metal (filer material: AlMg4.5Zr).

The microstructure of the welded joint where the filler material was AlMg4.5Zr is shown in Figure 5. The microstructure of base material consists of $\alpha + \beta$ phases (Fig. 5a). Presences of big pores, crystals of silicon and bigger amount of aluminium oxide are noticed. Figure 5b shows the microstructure of HAZ, where big pores, cracks and inhomogeneous structure rich in aluminium oxide are present. Figure 5c shows the microstructure of weld metal, which is fine-grained homogeneous structure (α solid solution crystal with eutectic separated by grain boundaries).

The microstructure of the welded joint where the filler material was AlMg5 is shown in Figure 6. The structure of base material is the same like in the previous case, while the microstructures of HAZ and weld metal differ. Figure 6a shows the microstructure of HAZ, where detected big pores, cracks and dendritic structures rich in aluminium oxide are present.

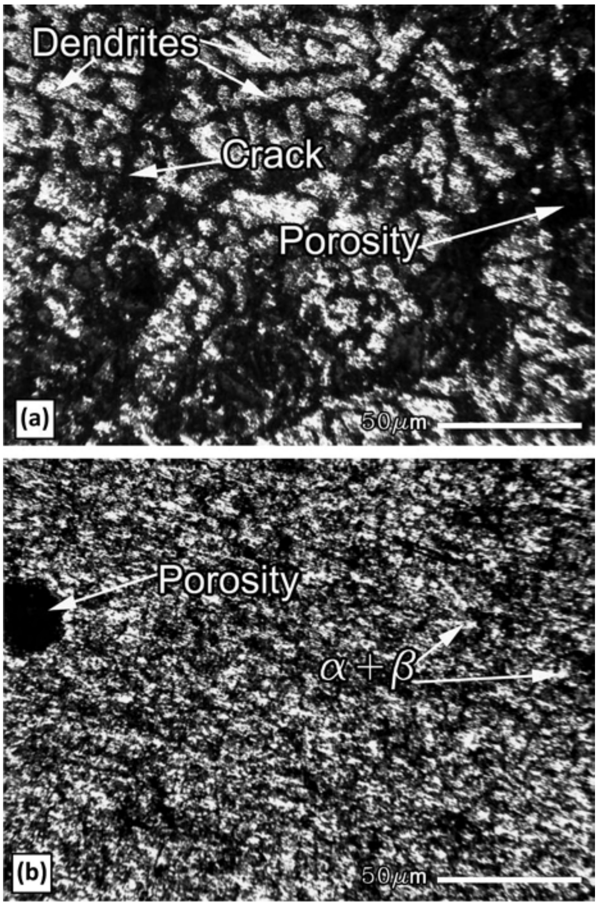

Figure 6. Microstructure of the: (a) base material, (b) HAZ and (c) weld metal (filer material: AlMg5).

Figure 6b shows the microstructure of weld metal, which has the form of fine-grained structure of the α + β phases.

The microstructure of the welded joint where the filler material was AlSi5 is shown in Figure 7. The structure of base material is the same like in the previous two cases. Figure 7a shows the microstructure of HAZ, where detected big pores, cracks, isolated β phase and oxides of aluminium are present. Figure 7b shows the microstructure of weld metal, which has a dendritic structure with contains α + β phase.

Analyzing the obtained results, it may be concluded that in all three cases the microstructure of HAZ show presence of big pores, cracks and inhomogeneous structure rich in aluminium oxide. This is a consequence of the presence of Al_2O_3 reinforcing particles in the composite, and the difference between the melting temperature of Al_2O_3 oxide and matrix alloy. Since the melting temperature of the Al_2O_3 oxide is significantly higher than the melting temperature of the matrix alloy, due to its higher specific gravity, these oxides remain unchanged and trapped in the joint. The Al_2O_3 oxide is also responsible for the presence of porosity in the joint. This oxide readily absorbs moisture from the air and reacts with hydrogen producing pores. The occurrence of cracks is the result of different coefficient of thermal expansion of the matrix alloy and reinforcing particles. This difference cause internal stress and segregation during solidification.

The weld metal is mainly composed of fine-grained and homogeneous structure in all three cases. This structure is the result of a multi-layer welding. With multi-layer welding there

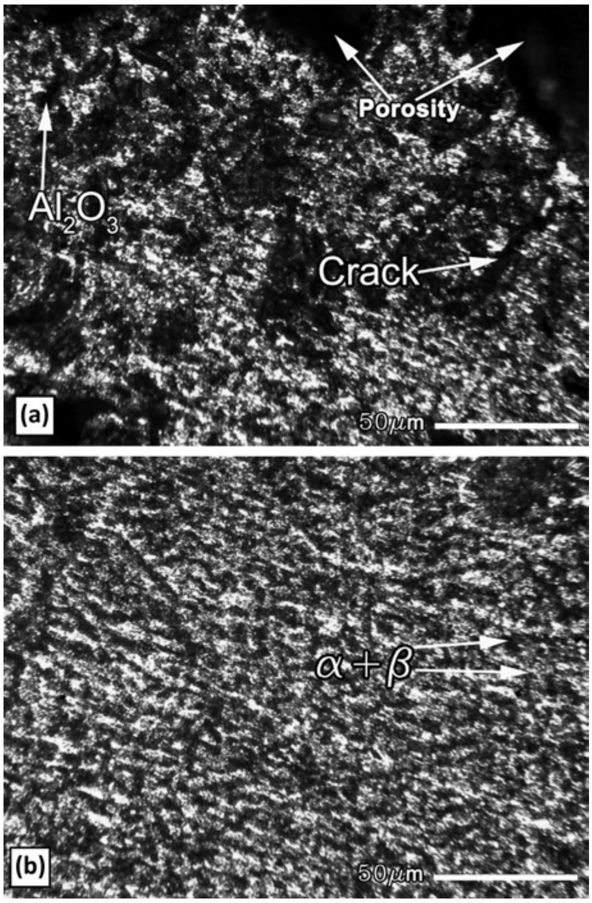

Figure 7. Microstructure of the: (a) base material, (b) HAZ and (c) weld metal (filer material: AlSi5).

is a possibility for impurities and non-metallic inclusions to emerge to the surface during the process. Multi-layer welding also provides a heat treatment of welded joints, which results in fragmentation and finer structure of the weld metal.

The observed errors in the investigated joints are the result of the composite composition and the presence of the Al_2O_3 oxide, which supports further formation of the oxides and thus adversely affect the process of welding. Since the composite samples were obtained in the laboratory conditions, and as such not ideal, and taking into account the dimensions of the samples, which were small, it is not possible to avoid these types of errors. Usage of the larger size samples would give the possibility for the preheating of samples, and thus minimised the possibility for the error occurrence. Larger size samples provide easier and faster heat dissipation, which reduces heat input and thus significantly simplifies welding process. In addition, larger size samples create the possibility of using other welding processes, e.g. GTAW process. With the application of the alternating current during the GTAW process, the oxides are removed from the weld zone and thus the possibility of the formation of defects is reduces. Nevertheless, this type of composite, regardless of the noticed errors, showed good weldability.

4. Conclusion

Experimental results indicate that the composite materials with the Al-Si alloy matrix can be successfully welded by using the GMAW process. The main problem which occurs during the welding was aluminium oxide (Al_2O_3), which had negative influence on the welding process by creating porosity, non-metallic inclusions and cracks in the weld joint. Using of the appropriate welding process and filler material can successfully resolve these problems.

Comparing the obtained results of the macro and micro analysis, the most favourable results were obtained by using the AlSi5 wire as a filler material. The microstructure of HAZ in this case contains porosity and cracks, which was also noticed in the microstructure of HAZ in other two cases, but do not contain dendritic structure, as it was noticed when filler material was AlMg5 wire (second case). On the other hand the microstructure of weld metal was homogeneous containing $\alpha + \beta$ phase without the presence of eutectic composition, as it was noticed when filler material was AlMg4.5Zr (first case).

Considering that welded material is a composite with Al-Si base, it is expected that AlSi5 wire gives the best results, since its chemical composition and other properties are the most similar to the base material. Increased silicon content provides good weldability due to its good castability, with minimal reduction in mechanical properties and negligible tendency to cracking. Multilayer welding had a positive influence on the weld joint. With the application of the multilayer welding, the heat treatment of the weld joint occurred. This phenomenon helped in reducing errors like pores or oxide inclusions residual in previous layers.

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References

[1]. K.U. Kainer, *Basics of metal matrix composites*, in: K.U. Kainer (Ed.), Metal Matrix Composites: Custom-made Materials for Automotive and Aerospace Engineering, Wiley-VCH, Weinheim, 2006, pp. 1-54.

[2]. A. Vencl, A. Rac, I. Bobić, *Tribological behaviour of Al-based MMCs and their application in automotive industry*, Tribology in Industry, 26, 3-4, 2004, pp. 31-38.

[3]. A. Vencl, *Tribology of the Al-Si alloy based MMCs and their application in automotive industry*, in: L. Magagnin (Ed.), Engineered Metal Matrix Composites: Forming Methods, Material Properties and Industrial Applications, Nova Science Publishers, New York, 2012, pp. 127-166.

[4]. A. Vencl, I. Bobić, S. Arostegui, B. Bobić, A. Marinković, M. Babić, *Structural, mechanical and tribological properties of A356 aluminium alloy reinforced with Al_2O_3, SiC and SiC + graphite particles*, Journal of Alloys and Compounds, 506, 2, 2010, pp. 631-639.

[5]. A. Kearney, E.L. Rooy, *ASM Handbook*, Vol. 2, ASM International, Metals Park, 1990, pp. 123-151.

[6]. P. Rohatgi, *Cast aluminum-matrix composites for automotive applications*, JOM, 43, 4, 1991, pp. 10-15.

[7]. H. Ribes, M. Suéry, *Effect of particle oxidation on age hardening of Al-Si-Mg/SiC composites*, Scripta Metallurgica, 23, 5, 1989, pp. 705-709.

[8]. A. Daoud, W. Reif, *Influence of Al_2O_3 particulate on the aging response of A356 Al-based composites*, Journal of Materials Processing Technology, 123, 2, 2002, pp. 313-318.

[9]. M.B.D. Ellis, M.F. Gottos, P.D. Threadgill, *Joining aluminium based MMCs*, Materials World, 2, 8, 1994, pp. 415-417.

[10]. A. Ureña, M.D. Escalera, L. Gil, *Influence of interface reactions on fracture mechanisms in TIG arc-welded aluminium matrix composites*, Composites Science and Technology, 60, 4, 2000, pp. 613-622.

[11]. T. Itsukaichi, T.W. Eagar, M. Umemoto, I. Okane, *Plasma spray joining of Al-matrix particulate reinforced composites*, Welding Journal, 75, 9, 1996, pp. 285-296.

[12]. R. García, A. Manzano, V.H. López, E. Bedolla, *Comparative welding study of metal matrix composites with the MIG welding process, using direct and indirect electric arc*, Metallurgical and Materials Transactions B, 33, 6, 2002, pp. 932-937.

[13]. J. Wysocki, K. Gawdzińska, S. Lenart, *Weld microstructure in cast AlSi9/SiC(p) metal matrix composites*, Archives of Foundry Engineering, 9, 2, 2009, pp. 173-176.

[14]. I. Boromei, L. Ceschini, A. Morri, G.L. Garagnani, *Friction stir welding of aluminium based composites reinforced with Al_2O_3 particles: Effects on microstructure and Charpy impact energy*, Metallurgical Science and Technology, 24, 1, 2006, pp. 12-21.

[15]. D. Storjohann, O.M. Barabash, S.A. David, P.S. Sklad, E.E. Bloom, S.S. Babu, *Fusion and friction stir welding of aluminum-metal-matrix composites*, Metallurgical and Materials Transactions A, 36, 11, 2005, pp. 3237-3247.

[16]. Y. Zhou, J. Zhang, T.H. North, Z. Wang, *The mechanical properties of friction welded aluminium-based metal-matrix composite materials*, Journal of Materials Science, 32, 14, 1997, pp. 3883-3889.

[17]. R.A. Rosenberg, Q. Ma, W. Farrell, M. Keefe, D.C. Mancini, *X-ray welding of metal-matrix composites*, Review of Scientific Instruments, 68, 6, 1997, pp. 2550-2553.

[18]. A. Vencl, I. Bobić, M.T. Jovanović, M. Babić, S. Mitrović, *Microstructural and tribological properties of A356 Al-Si alloy reinforced with Al_2O_3 particles*, Tribology Letters, 32, 3, 2008, pp. 159-170.

[19]. A. Vencl, I. Bobić, B. Stojanovic, *Tribological properties of A356 Al-Si alloy composites under dry sliding conditions*, Industrial Lubrication and Tribology, 66, 1, 2014, pp. 66-74.

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Joining of composite materials based on Al-Si alloys by using the GMAW process

Îmbinarea materialelor compozite cu matrice din aliaje Al-Si folosind procedeele de sudare GMAW

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Abstract

The aim of this paper is to presents a procedure of joining composite materials on aluminium base by using the GMAW process. The experiment included welding of the aluminium base composite with three different types of filler materials in the form of wire: AlMg4.5Zr, AlMg5 and AlSi5, and comparative analysis of the macroscopic and microscopic examination results. Base material was A356 Al-Si alloy composite containing 10 wt. % Al_2O_3. Average size of Al_2O_3 particles was 35 μm. The A356 matrix alloy was modified with the addition of 0.03 wt. % Sr. Composite was produced by the compocasting process. The results show that composite material with Al-Si matrix can be successfully welded by using the GMAW process. Results of macro and micro analysis show that the most favourable results were obtained by using the AlSi5 wire as filler material.

Keywords

Aluminium matrix composite, GMAW, macroscopic analyses, weld microstructure.