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JOINING OF THE AMC COMPOSITES REINFORCED WITH Ti_3Al INTERMETALLIC PARTICLES BY RESISTANCE BUTT WELDING

The introduction of new reinforcing materials continues to be investigated to improve the final behaviour of AMCs as well as to avoid some drawbacks of using ceramics as reinforcement. The present work investigates the structure, properties and ability of joining aluminium EN-AW 6061 matrix composite materials reinforced with Ti_3Al particles by resistance butt welding as well as composite materials produced by mechanical milling, powder metallurgy and hot extrusion techniques. Mechanically milled and extruded composites show finer and better distribution of reinforcement particles, which leads to better mechanical properties of the obtained products. Finer microstructure improves mechanical properties of obtained composites. The hardness increases twice in the case of mechanically milled composites also, a higher reinforcement content results in higher particle dispersion hardening, for 15 wt.% of intermetallics reinforcement concentration composites reach about 400 MPa UTS. Investigation results of joints show that best hardness and tensile properties of joints can be achieved by altering soft conditions of butt welding process e.g. current flow time 1.2 s and current 1400 A. To improve mechanical properties of butt welding joints age hardening techniques can also be used.

Keywords: composite materials, intermetallics, Ti_3Al, resistance butt welding, mechanical properties

1. Introduction

Metal matrix composites (MMCs) exhibit unique properties when compared to conventional materials as well as a possess the potential for new applications. They were designed with the aim to conjugate the desired characteristics of two or more materials and constitute one of the most important research fields in materials science and engineering since the beginning of 1960s. The applicability of MMCs is based on the improvement of both mechanical properties at high temperatures and wear resistance, principally when compared with conventional alloys without reinforcement. The aluminium matrix composites, especially, the hardenable aluminium alloys matrix, such as AA2XXX, AA6XXX and AA7XXX series, are used in applications where good mechanical characteristics and low specific weight are required. As the transportation industry and consumers pay more attention to fuel efficiency and reducing greenhouse gases emissions, aluminium matrix composites are beginning to play a very important role in modern automotive production [1-5].

Among all methods that have been developed to improve the material properties of aluminium and its composites, mechanical alloying (MA) has received much attention. The mechanical alloying process consists of repeated welding, fracturing and rewelding of a mixture of powders usually in a high-energy ball mill. The primary issue is that the powder particles are trapped between the colliding balls during mechanical alloying undergoing repeated deformation and fracture. In ball milling of at least one ductile powder, there is an initial stage in which plastic deformation is the dominant process, followed by a stage in which welding predominates. After the first period of mechanical alloying the powder is hard and brittle enough to begin fracturing processes. At the end of the process, the powder reaches a steady state characterised by an equilibrium between welding and fracture [6,7]. Currently, this technique is being used to provide various materials and alloys, including intermetallic compounds, amorphous materials, supersaturated solid solutions, and finally metal matrix composites. Powder metallurgy (PM) methods combined with mechanical alloying gives many advantages over casting methods, making possible not only improvement of the existing properties but also conferring completely new, sometimes unexpected properties. The consolidation temperatures needed during the bulk material production by powder metallurgy are much lower which promotes less interaction between the materials, reducing interfacial reactions and allows for superior mechanical properties. The use of PM and MA methods to manufacture metal matrix composites allows a uniform distribution of the reinforcement and better control of the volumetric fraction in a relatively broad range to be obtained [8-10].

Alumina and silicon carbide in the form of short/long fibers or particles are usually added to the composite materials as reinforcement because of their thermal stability, hardness and relatively low density. Recently new reinforcement

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candidates such as carbonates, borates, nitrates, and other oxides have appeared, however, materials as intermetallic compounds with outstanding mechanical properties and good thermal stability were developed making them an essential material to be used as a reinforcement in these kinds of composites [11-14].

One of the restrictions of using high performance metal matrix composites is the scarcity of proven joining methods. The most recommended method of joining in the case of metal matrix composites is the formation of disjunctive joints, riveting and cold gluing. It is important to note that these are methods which do not introduce heat into the joining zone. However in the case of equipment made of composites, where it is required to have good sealing and high level of service it is necessary to explore other joining methods. Some conventional joining techniques are welding, butt welding, soldering and specialized gluing. The formation of a durable joint between two composite materials depends on the ability of the materials to create a common structure at the joint. The basic phenomena that take place during the welding processes of composite materials are wettability, reactivity, sintering and diffusion. The standard specifications for welding processes of composites materials are:

- maintenance of the continuity arrangement reinforcements in the joining zone,
- limit of the diffusion interaction between matrix and reinforcement in the process temperature – time condition,
- reduction of local thermal stress between reinforcement and matrix materials
- It can be achieved by:
- minimizing the melting zone and simultaneous exchange of components in the joined materials,
- reducing the time of the joining process, in order to decrease the presence of high temperatures,
- use of low welding pressures,
- precise control of the chemical composition of additional materials (like electrodes, solders) to control the eventual reactivity during the joining process.

Analysing the above facts, one can conclude that to join composites the optimal operation would be the one, which takes place at low temperature, in shortest possible time and with minimum possible compression [15-20].

2. Experimental procedure

Aluminium matrix composites were produced employing the atomized aluminium alloy AA6061 produced by the Aluminium Powder Co Ltd. (UK) as a metal matrix, when as reinforcement Ti_3Al intermetallic particles produced by SE-JONG Materials Ltd. (Korea) were used. The chemical composition of powders used is given in Table 1 and 2.

TABLE 1
Chemical composition of the atomized aluminium alloy powder

	Elements' concentration, weight %						
	Fe	Si	Cu	Mg	Cr	Others	Al
AA6061	0.03	0.63	0.24	0.97	0.24	<0.3	Bal

TABLE 2
Chemical composition of the titanium aluminide powder

	Elements' concentration, weight %						
	Ti	Al	V	Fe	N_2	O_2	H_2
Ti_3Al	Max. 83.36	Max. 15.35	0.55	0.025	0.06	Max. 0.59	Max. 0.15

The particle size of aluminium alloy powder was less than 75 μm and less than 50 mm for Ti_3Al titanium aluminide. Morphology of initial powder particles used in the experiment is given in Figure 1.

a) b)

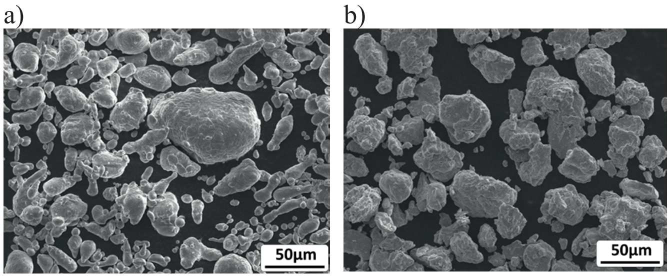

Fig. 1. Morphology of as-received powder particles used in the experiments SEM, AA6061 aluminium alloy – left, Ti_3Al intermetallic – right

To evaluate the effect of mechanical milling a high energy - eccentric ball mill was used. The composite powders were fabricated by high-energy ball milling. The planetary (eccentric) ball mill was used with the following parameters, weight ball to powder ratio 6:1, ball diameter 20 mm, ball material quenched stainless steel AISI 420, milling time 18 hours, process control agent Microwax (1 wt%). To analyse the structural evolution of powders subjected to mechanical alloying the flow rate for 50g of powder and the apparent density according to MPIF Standard 28, as well as the morphological and metallographic examination was done. Three sets of specimens with 5, 10 and 15 wt% of reinforcement concentration were prepared. The powders were cold pressed in the 25 mm in diameter cylindrical matrix with 300 MPa pressure and then extruded at 500-510°C with graphite as the lubricant without degassing and caning. In order to avoid the excessive aluminium grain growth due to a high level of stored energy, the annealing process of milled powders was performed at 400°C for 1 hour. Extruded bars of 5 mm diameter and near theoretical density were obtained.

Welding process of extruded bars was made on resistance butt welding machine. Welding currents were 1200, 1400 and 1600 A, welding time 1.2 and 0.3 s respectively, pressure force 225 N and jaw distance 3 mm. Samples were bevelled and mechanically polished before the joining process. To examine the ultimate tensile strength (UTS) of joints, tensile tests were performed on samples with 50 mm measuring length. To determine the hardness of joints, heat affected zones and base materials micro Vickers tests were performed. Microstructure observations were made by light and scanning electron microscopy.

3. Results and discussion

In contrary to conventional casting processes, the PM route of composite materials production makes possible to obtain a wide range of reinforcement particles percentage addition without typical segregation. A mechanical alloying process has improved the reinforcing particles distribution throughout the whole mixture (Figure 2). However, after 10 hours of mechanical alloying, the particles are predominantly laminar. It can be observed using microstructural analysis that the intermetallic particles have undergone plastic deformation, as well as the ductile aluminium powder. As has already been mentioned, deformation predominates at the initial stage of mechanical alloying, followed by a stage when welding predominates. After 10 hours of milling, the observed morphology indicates that the milling process is still at the initial stage. Whenever the intermetallic particles are placed between the deformed aluminium particles during the ball collision, they are integrated into the resulting welded particle, forming a composite powder. With the work hardening due to the deformation and cold welding process that the particles undergo, the tendency to fracture increase and approach the equilibrium with welding. At this stage, the equiaxial particles are formed. It can be observed that the longer milling time has improved the reinforcement distributions throughout the whole particle, and has produced equiaxial morphology. Intermetallic particles have undergone plastic deformation as well as fragmentation.

a) b)

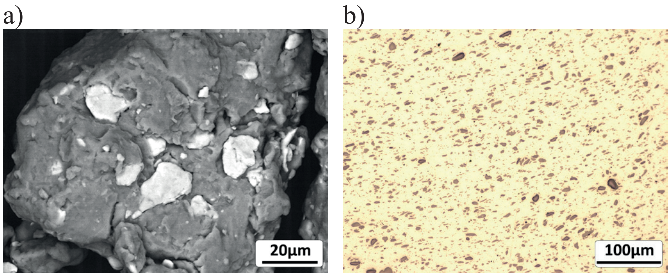

Fig. 2. Morphology of composite powder particles of AA6061+15% Ti_3Al after 18h of mechanical milling – a), microstructure of AA6061+15% Ti_3Al composite material, section parallel to the extrusion direction – b)

Depending on the reinforcement size and shape, the density difference, and type of matrix material, reinforcing particle agglomeration can occur in the final product. Despite that the extrusion processes tend to minimize this problem reinforcement particles agglomeration are the most designated cause of low performance of this type of composite materials. In order to avoid this, mechanical alloying can be used to develop the uniform distribution of the reinforcement particles in the matrix. In mechanically milled composite powders a very fine distribution of small reinforcement particles and absence of agglomerates can be observed along with a fraction of particles with an oblong or flattened shape. Mechanical alloying is characterized by high degree of deformation, high density of dislocation, oxides and reinforcing particle dispersion in the matrix, causing an increase in hardness while finer microstructure increase mechanical properties of composites materials (Table 3). An increase in the mechanical properties due to the mechanical milling process is observed. Hardness and UTS for AA 6061 aluminium alloy extruded without reinforcement particles achieve about 50 HV1 and about 200 MPa, respectively.

TABLE 3

Results of hardness and ultimate tensile strength measurements for investigated samples

Type of materials	Hardness HV	Ultimate tensile strength UTS, [MPa]
EN AW6061	49	206
EN AW6061 +5%Ti_3Al	103	375
EN AW6061 +10%Ti_3Al	112	388
EN AW6061 +15%Ti_3Al	120	408

In the case of composites after mechanical milling hardness, is observed to be more than twice that of aluminium alloy. The same can be said for observed for tensile properties; mechanical milling changes almost the ultimate tensile strength of investigated composites twofold. Moreover until 15 wt% of reinforcement particles contents UTS is growing indicating to good interfacial bonding between matrix and reinforcement particles.

MMCs, as a class, are remarkably adaptable materials, allowing the designers to combine the properties of various metals and non-metals in one product. One of their disadvantages is the difficulty of connecting such parts to themselves or bulk metals – it has become obvious, that the joining process can reduce the properties of the MMCs to the level of the matrix material or even lower. Al alloys are not especially well adjusted for bonding because of a natural tendency of stable surface oxides formation, however, by careful process control, suitable results can be achieved. Based on macroscopic observation of resistance butt welds it was found that the smallest and most regular flash was obtained for current 1400 A, Fig. 3. Microstructural investigation of welds allows to revealing the heat affected zone and changes of reinforcing particles orientation (initially compound parallel to extrusion direction) by flash materials flow. Additionally, in the central zone of welds, one can see the presence of small crevice indicating the deficiency of the joints, Figure 4.

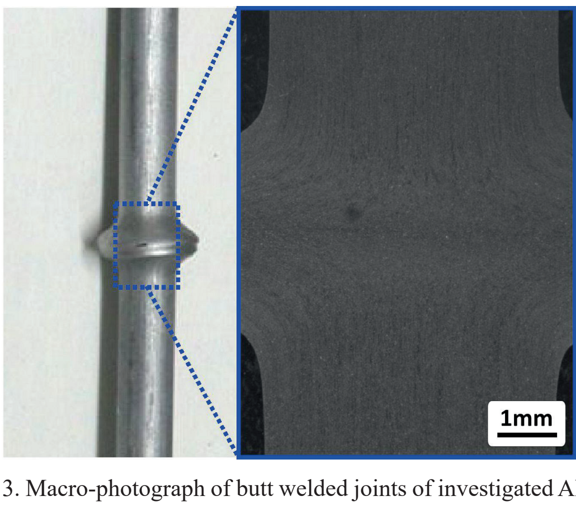

Fig. 3. Macro-photograph of butt welded joints of investigated AMCs reinforced with 15 % of Ti_3Al

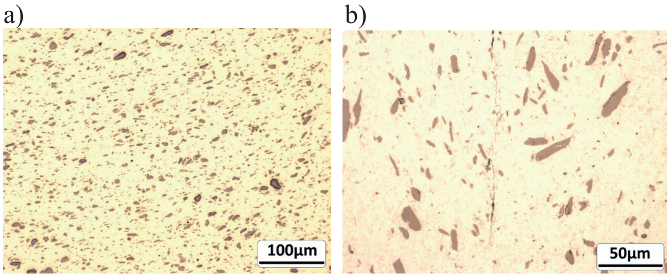

Fig. 4. Microstructure of composite material, changes of reinforcing particles orientation in the heat affected zone by flash materials flow, of small crevice in the central zone of weld, AMCs reinforced with 15 % of Ti_3Al

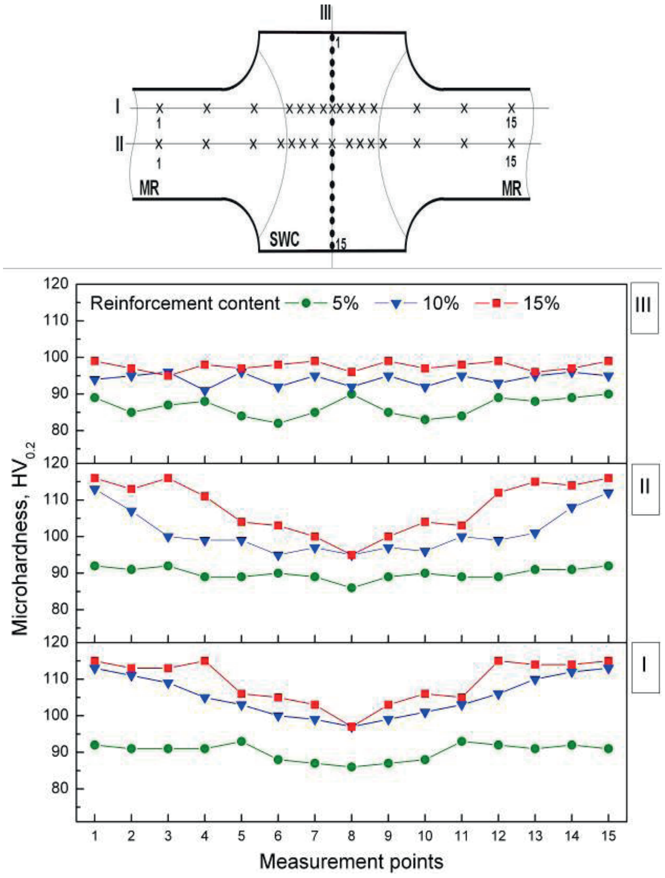

Fig. 5. Microhardness change along the joint of investigated AMCs

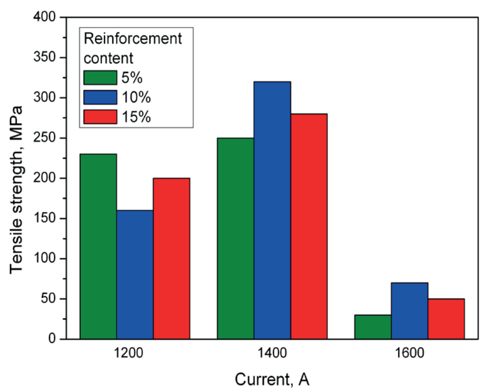

Fig. 6. Ultimate tensile strength of investigated AMCs welded in different conditions

Microhardness measured along a line perpendicular to the joint revealed their decrease in the central part of the weld (Figure 5). Mechanical properties examinations carried out in the static tensile test showing that for the applied conditions of butt welding process highest ultimate tensile strength was obtained for current 1400A, lower for 1200A and approximately lack of strength for 1600 A (Figure 6). Fractographic investigation of tensile test fracture surface confirms the presence of small areas covered with oxide layers in which the joint was not obtained as well as typical for matrix materials ductile fractures (Figure 7).

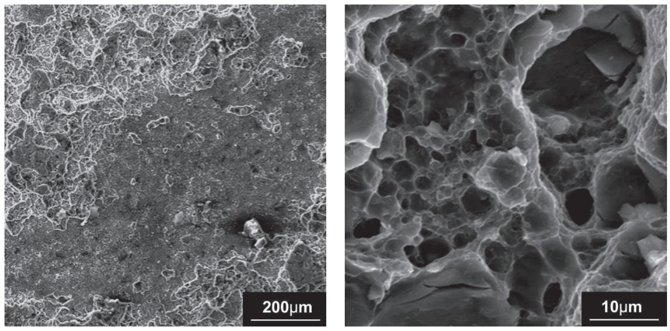

Fig. 7. Tensile test fracture topography of butt welded joint of investigated AMCs reinforced with 5 % of Ti_3Al

4. Conclusions

Based on the structural analysis carried out that the mechanical alloying can provide composites powders with the homogeneous distribution of reinforcement particles. The mechanically milled and extruded composites show finer and better distribution of reinforcement particles which leads to better mechanical properties of obtained products. However, the directed structure oriented corresponding to the extrusion direction was developed during the extrusion process. The addition of the Ti_3Al particles of the reinforcing materials to the aluminium matrix increased the hardness of the composite materials obtained. The significant hardness increases in comparison with unreinforced aluminium alloy (more than twice) were observed in the case of mechanically milled composites. Similarly, in the case of mechanically milled composites the finer microstructure and dispersion hardening increase mechanical properties of composite materials. The higher intermetallic content results in higher particles dispersion hardening. Composite materials reinforced with 15% of Ti_3Al reach about 400 MPa UTS.

In the case of AA 6061 matrix composite materials reinforced with 5-15 wt% of Ti_3Al intermetallic particles, it is possible to obtain joints by using the resistance butt welding techniques and applying soft parameters of the welding process. In certain conditions, the tensile strength of butt welded joints reaches 90% of composite material's tensile strength. The decrease of tensile properties can be explained based on the optical and scanning electron microscopy analyses. It is revealed that inside the butt welding joint one could observe incomplete fusion areas most probably due to the oxidation of the raw material. Also, hardness measurement reveals that butt welding joints have a lower hardness compared to the composite materials themselves. When matrix material is heat treatable, temperature cycle of butt resistance welding could promote over ageing of raw material (solution heat treatment could be made during extrusion) leading to decrease in hardness. To improve tensile properties and hardness of butt welding joints age hardening is necessary. Another important factor affecting the tensile properties is the change of reinforcement particle's orientation within the joints caused by the flash of materials during weld pressing.

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REFERENCES

[1] K.K. Chawla, K. Krishan, Composite Materials Science and Engineering, Springer, New York, 2012.
[2] L.A. Dobrzański, A. Włodarczyk, M. Adamiak, Mater. Sci. Forum, **530-531**, 243-248 (2006).
[3] R. Flores-Campos, I. Estruda-Guel, M. Miki-Yoshida, R. Martinez-Sanchez, J.M. Herrera-Ramirez, Mater. Charact. **63**, 39-46 (2012).
[4] D. Janicki, Sol. St. Phen. **199,** 587-592 (2013).
[5] A. Lisiecki, Metals. **5**, (1) 54-69 (2015).
[6] M. Adamiak, Arch. Mater. Sci. Eng. **58** (2) 55-79 (2012).
[7] Y.B. Liu, S. C. Lim, L. Lu, M. O. Lai, J. Mat. Sci. **29** 1999-2007 (1994).
[8] J.M. Torralba, C.E. da Costa, F. Velasco, J. Mat. Proc. Tech. **133**, 203-206 (2003).
[9] J.B. Fogagnolo, E. M. Pallone, D.R. Martin, C.S. Kiminami, C. Bolfarini, W.J. Botta, J. Alloys Compd. **471**, (1-2) 448-452 (2009).
[10] L.A. Dobrzański, B. Tomiczek, G. Matula, K. Gołombek, Adv. Mat. Res. **939**, 84-89 (2014).
[11] J.M. Torralba, F. Velasco, C.E. da Costa, I. Vergara, D. Caceres, Composites Part A **33**, (3), 427-434 (2002).
[12] M. Adamiak, J.B. Fogagnolo, E.M. Ruiz Navas, L.A. Dobrzański, J.M. Torralba, J. Mat. Proc. Tech. **155-156**, 2002-2006 (2004).
[13] S. Boncel, J. Górka, M. Shafer, K. Koziol, Mater. Lett. **116**, 53-56 (2014).
[14] J.W. Kaczmar, K. Pietrzak, W. Włosiński, J. Mat. Proc. Tech., **106**, (1-3), 58-67 (1999).
[15] T.K. Pal, Mater. Manuf. Processes **20**, (4) 717-726 (2005).
[16] B.D. Ellis, Int. Mater. Rev. **41**, (2), 41-58 (1996).
[17] Engineers handbook – Welding technology. WNT Warszawa (2003), (in Polish).
[18] X.R. Li, W.B. Tang, J.T. Niu, Mater. Sci. Forum, **704-705**, 1399-1405 (2012).
[19] M. Bonek, G. Matula, L.A. Dobrzanski, Adv. Mat. Res. **291-294**, 1365-1368 (2011).
[20] M.B.D. Ellis, M.F. Gittos, P. L. Threadgill, Materials World, August 1994, 415-417.