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Manufacturing and Friction Welding of Aluminium Matrix Composites – Review of Current Status and Future Directions

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Abstract:

Advancements in the manufacturing industries particularly in key areas such as new materials development, cost optimization of manufacturing methods and recycling methods of waste materials have been very important, significantly impactful and rapid. In the same direction, research efforts on metal matrix composites (MMC) such as aluminium matrix composites (AMC) are on the rise because of the fact that AMCs are widely used across various industries. The use of AMCs is limited by the type of fabrication methods followed, for example welding methods. AMCs have limitations towards fusion type welding processes. Solid-state welding (SSW) processes join dissimilar materials conveniently and may therefore overcome these limitations over fusion welding process. SSW processes have greater advantages such as effective joining, fumeless, reduced preparation time, environment friendly, etc. Friction welding (FW) is one of the SSW methods which work on the principle of generating thermal energy for welding operation by mechanical friction between a moving part and a stationary one. Friction stir welding (FSW) is another SSW process which is widely used for making dissimilar joints. FW process has proven to be more prospective and capable method than FSW for joining AMCs. Parameters such as mechanical strength, microstructure of the joint area, the behavior of the reinforcements during joining and more especially suitable production process for the preparation of MMC are very much important for consideration. In this paper, a comprehensive review of the research works done in the past on manufacturing of AMCs, alternate materials for constituent phases and use of FW for AMCs is discussed and findings analyzed to relate with the proposed research work. This review effort is very useful in order to carry out the research in the right direction after addressing the gap areas identified in the review.

***Keywords:** Friction welding, Aluminium matrix composites, Reinforcements, Microstructures, Mechanical properties, Stir squeeze casting process.*

I. INTRODUCTION

Welding methods suitable for joining parts made up of advanced materials such as aluminium matrix composites (AMCs) are still at infancy because of the low temperature and low strength materials involved in comparison with the conventional steel materials. Interestingly, applications of AMS are widespread

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because of their excellent mechanical properties with low density values. However, the potential applications of AMCs are limited if a proper welding process is not developed. AMCs joined through conventional fusion welding methods unveils several short comes in terms of quality of joints. A solid state welding process such as friction stir welding (FSW) in which the coalescence takes place below the melting point of the materials, shows a prominence for welding AMCs. This statement is justified with a detailed study on microstructure evolutions and degradations of AMCs during fusion welding and comparison with that of FSW. Successfully FSW welded same composites showed a significant reorientation of SiC whiskers close to the boundary. This study firmly established that the FSW processes have more potential for joining AMCs comfortably. However, further study on joining AMCs using a FSW process posed a number of challenges in terms of macrostructure and microstructure of AMC joints, evaluation of mechanical properties of joints along with the wear rate phenomenon of the rotating tool used in FSW [1].

Other arc welding processes for joining AMCs have led to one or other complications either during welding process or post-weld aging treatment processes. All fusion welding processes led to the formation of brittle secondary phases in the weld pool due to the interaction of reinforcement with molten aluminium or decomposition of reinforcement to harmful phases causes excessive heat, cracking, distortion and porosity. Many other key points in joining AMCs with FSW were presented further in terms of microstructure of the joint and the behavior of the reinforcements during joining, the friction stir weld properties etc. in similar line, the different values of thermal expansion coefficients between the aluminum and the reinforcement caused high residual stresses leading to distortion in the weld zone [2]. To avoid all defects related to melting and solidification in AMCs, the researchers went on to explore alternative methods among which the most notable method called frictional welding (FW) which is also as a solid state joining process.

Meanwhile a parallel study on use of friction welding (FW) process was carried on and FW was found to be one of the most economical and highly productive methods in joining similar and dissimilar metals [3]. Application of FW for AMC is one of the potential alternate method for welding AMCs other than fusion and FSW is FW process. The principle of FW is very easy to understand and employs frictional energy created at the joint to weld two pieces of AMCs. It is a solid state joining process which produces coalescence of materials under compressive strength when one part of the parent metal rotates relative to other (fixed) and they produce high amount of thermal energy when brought into contact with each other. There is no electrical or heat energy used from other sources. This paper presented a lot more on the mechanism of friction welding, types of relative motions of the process, influence of parameters, heat generation in the process, understanding the deformation, microstructure and the properties of similar and dissimilar welded materials. It was reported that the primary advantages of FW are (i) narrow heat effected zone (HAZ), (ii) dissimilar metals can be joined, (iii) no fusion zone, (iv) can be used under water, (v) very high reproducibility, (vi) excellent weld quality, with none of the porosity that can arise in fusion welding and (vii) environmentally friendly [4].

Proposed research work of the authors is to make AMC using LM 6 aluminum alloy. New type of reinforcements such as marble waste materials and graphene nanoparticles will be used in this effort. The current review study on use of FW for joining dissimilar metals is discussed and presented in the following order. Initially, principle of FW and potential types of FW machines used in various attempts of the researchers, followed by various types of aluminum being used in the AMCs and recent trends on the type of reinforcements used in making the AMCs. Later, types of composite manufacturing methods are analyzed and inference is drawn suitably for the proposed research work.

II. ALUMINIUM MATRIX COMPOSITES

Aluminium is one of the most plentiful metals available on the earth's crust. There are several grades of aluminium alloys frequently used as the matrix material for the production of AMCs and the most commonly used matrix phase materials used by researchers are discussed in this section along with their properties and applications.

LM2 type of aluminum is used in the research experiment with the configuration of Al-Si10Cu_2Fe.

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It was found through the experiments that it was difficult to machine the composite since the high silicon content caused rapid tool wear. However, there was good resistance to corrosion at atmospheric condition and the density is slightly lower. Recommended highly for the marine use [5].

LM4 type of a`luminum was used to make the composite (Al-Si_5Cu_3) which contained no elements of ferrous as compare to the LM2 type. It possessed fairly good machinability, resistance to corrosion which is recommended for cylinder-heads, crank cases, junction boxes, gearboxes, clutch cases, switch gear covers, instrument cases, tool handles [6].

LM5 type was found to be used in making the composite material which is coded as Al-Mg_5SiAlMg_6 and recommended for decorative finishing, manufacture of foodstuffs, cooking utensils and chemical plants because of excellent polish, high resistance to corrosion [7].

LM6 type of aluminum (Al-Si_2; Al-Si_2Fe) was used in another case to make it as commonly used alloy for automotive as well as aeronautical applications. These composite materials are good at ductility, workability and corrosion resistance [8].

In another research [9], LM13 type of Aluminium is used in the composites (Al-Si1_2Cu; Al-Si1_2CuFe) which is having high resistance to corrosion under atmospheric conditions, good resistance to wear, good bearing properties and a low coefficient of thermal expansion. These properties are suitable for applications in internal combustion engine parts such as pistons, pulleys etc.

Finally, LM25, which is rich in silicon and magnesium (Al-Si7Mg), exhibits fairly good machining properties, light weight, excellent castability, wear resistance. Applications include food, chemical, marine, electrical and transport vehicles - cylinder blocks and heads [10].

III. REINFORCEMENT TYPES AND PROPOERTIES

The various forms of inorganic reinforcements such as oxides (Aluminium oxide, Titanium oxides, Zirconium oxides), carbides (Silicon carbide, Titanium carbide), Nitrides (Titanium nitride), Borides (Titanium boride, Zirconium boride) are widely used to produce MMCs but they are relatively expensive. The organic reinforcements such as fly ash and red mud improve the strength of the composite reasonably, and the cost is less. This review includes a range of industrial waste materials being used as reinforced phase materials for the development of AMCs after discussing their salient properties and microstructural analysis.

Refinery Waste (Spent Alumina Catalyst-SAC): In oil refineries, catalysts are used for cracking of petroleum product in hydro-processing units. Over the period of time, the catalysts are rejected from the units in the form a solid waste. Disposal of spent catalysts requires severe environmental regulations due to their hazardous nature and toxic chemicals content [11]. Therefore an attempt is made to produce AMC using Scrap Aluminium Alloy Wheel (SAAW) as a matrix material and oil refinery waste such as Spent Alumina Catalyst (SAC) as reinforcement. Microstructural analysis shows clearly that the addition of spent alumina catalyst to the matrix produced porosity in the samples.

Red Mud: The red mud is an industrial waste material that is obtained during production of aluminum from the bauxite ore. This waste material is released to the waste land leading to soil, water and atmospheric pollution. Therefore in the paper, red mud was used as an alternative reinforcement since it is relatively cheap, sustainable and available in large quantity. The authors of [12] have fabricated aluminum 2024 matrix hybrid composites reinforced with SiC (5%, mass fraction) and red mud (5%−20%, mass fraction) particles using stir casting technique. In their research the mechanical properties such as tensile strength of the composites increased with the increase in the red mud content. In the microstructure analysis, the red mud particles were homogeneously distributed in the hybrid composites.

Fly Ash: It is one of the residues generated from the flue gas during the combustion of coal solid and turns in to waste byproduct. It is least expensive and low-density reinforcement available in large quantities. Authors of the paper [13] fabricated the metal matrix composite by using LM6 as matrix and two different types (fly ash type-A and type-B) as the reinforcement phases to produce the composite material by stir casting. Type B fly ash gave more enhanced mechanical properties compared to type A fly ash. In the microstructure analysis, the fly ash particles are mixed uniformly with the matrix material. Type B fly ash gave more enhanced mechanical properties such as the impact strength, tensile strength and hardness compared to type A fly ash.

Industrial Arc Furnace Dust (EAFD): Electric arc furnace dust is a solid waste generated during steel making processes. The utilization of the dust from

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these industries can avoid disposing to the waste landfills hence can save costs [14].

Slag: It is a waste matter separated from the steel production industries. Slag is regularly generated in a huge volume throughout the year. Stringent environmental regulations have prompted industry to search for alternative method of treating their waste byproducts. In paper [15] the authors synthesized aluminium slag composites using powder metallurgy techniques. The result showed that addition of 5% slag into aluminum matrix resulted in increased compressive strength values up to 372 MPa.

Waste Glass: It is prevalent across the world, both in terms of health risk and quantity. Authors of paper [16] fabricated Aluminium reinforced glass matrix composites via cold-pressing and viscous flow sintering. Fracture toughness has been conducted on the waste glass and Aluminium matrix composites, which had revealed the maximum bending strength increase in relation to the unreinforced matrix and a very low standard deviation. Mines Waste: It is shown in the paper [17] that composite developed using Aluminium matrix and mines waste-colliery shale (CS) material as reinforcement has got improved mechanical properties.

IV. COMPOSITE MANUFACTURING PROCESSES

Fabrication of composites is conventionally done using continuous stir casting process. In this process, the matrix phase material is in the melted state and continuously spun in a barrel while the reinforcement phase material is introduced into the kiln. The temperature of operation, the rotational speed of the kiln and volume rate of reinforcement phase materials introduced into the kiln will determine the distribution of the structure and quality of the composites. However, due to increased advantages, stir squeeze casting process is being used in recent time. Stir squeeze casting is a combination of casting and stirring the molten metal and hydraulic forging as schematically shown in Figure 3. In this process the solid metal is heated above to its melting point and the molten metal is then stirred to obtain homogeneous mixture and then poured in to the die and immediately forged using hydraulic press under the action of a relatively high external pressure.

The runway is connected between bottom pouring and the mould to transfer molten metal from the furnace to the die. The stir squeeze casting method is mostly developed for the commercial applications.

Major advantages of this process are: (1) capability of mass production, (2) improvements in the wettability between reinforcement and matrix material (3) good metallurgical quality of MMCs due to solidification under relatively high external pressure[19].

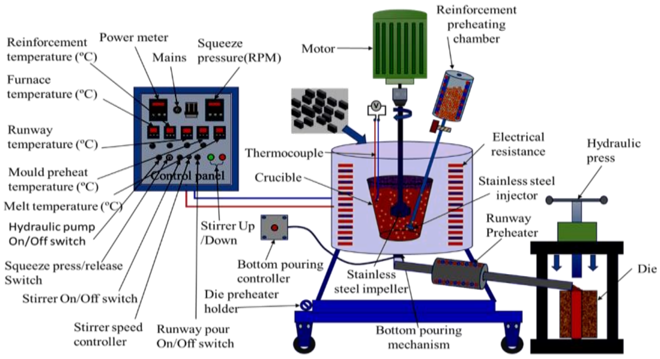

Fig 1. Stir squeeze casting setup [18]

Using stir squeeze casting techniques, a sample, fabricated by authors [20] of for their study, which was made up of AA7050 Aluminium alloy reinforced with graphene nanoparticles. 0.3% graphene particles with Aluminium matrix showed uniform distribution of particles. Maximum tensile strength of 255 MPa observed at 0.3wt% of graphene particles. Fabricated LM6 Al-fly ash composite and studied the influence of the different process parameters of squeeze casting processes. The produced composite shows an improved wear resistance, hardness and reasonable uniform distribution of reinforcement in the matrix without any casting defects [21].

V. PRINCIPLE OF COMPOSITES FRICTION WELDING

Basically there are two broad classifications of welding methods namely fusion and non-fusion welding. Fusion produces coalescence (at temperatures above the melting points of the parent metals) between the two pieces of metals being joined due to electrical spark or gaseous flames. Complete change in the microstructures of the parent metals at the joint interface is the key change in this welding process. However, non-fusion welding produce coalescence at below melting point temperatures which is called solid-state welding process. The heat energy is generated through mechanical friction between work pieces in relative motion to one another, with the addition of a lateral force called *upset* to plastically displace and fuse the materials. Because no melting occurs, friction welding is not a fusion welding process in the

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traditional sense, but more of a forge welding technique. Friction welding is used with metals and thermoplastics in a wide variety of aviation and automotive applications.

Rotary Friction Welding (RFW): The principle of RFW is illustrated in figure 1 in which the frictional energy is created between one rotating parts with the other stationary part. When the part is held in a motor driven chuck at an appropriate rotational speed, axial pressure may be applied to bring the second stationary part together as shown in step 2 of the figure 2. Friction at the interface generates heat between the abutting surfaces which initiates welding temperature as shown in step 3. Finally, the rotation is stopped and the pressure is maintained to complete the weld.

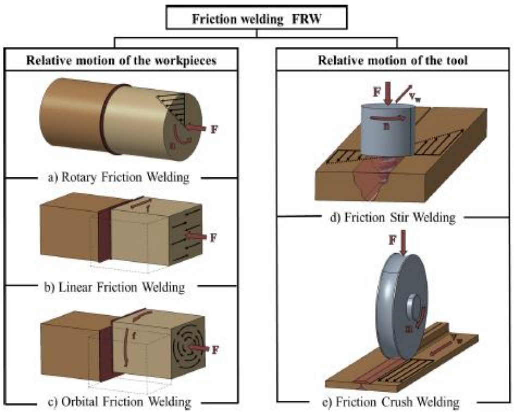

Fig. 2 Basic principle of RFW [22]

Therefore, it is evident from the principle of FW that it is a process of converting the rotational mechanical energy into thermal energy at the interface [23]. There are two other types of RFW: Inertia Friction Welding (IFW) and Continuous Drive Friction Welding (CDFW) [24]. IFW is a modified form of RFW, where the moving part is attached to a rotating flywheel while, the stationary part is forced into contact with the rotating one under hydraulic pressure. The kinetic energy in the rotating flywheel is then converted into frictional heat at the interface of the two work pieces [25]. CDFW: the work pieces are press against each other under axial pressure force. When reached to frictional heat, the moving component is stopped quickly and axial force is stay at the same value of pressure or is increased for a short period of time [26].

The authors of [27] developed and used dissimilar Rotational Friction Welding (RFW) machine for welding Al_20_3P/6061 with 5052Al alloy. The rotational speed was at 340 rpm; Friction pressure: 50 MPa; Friction time: 2-5 sec; Upset pressure: 100 MPa; Upset time: 5 sec; Hardness Slightly higher in welding region compare HAZ and base metal. It was found that the tensile strength showed nearly the same level of values AMCs. The impact value of the weld joints was reduced, to about 70% of the AMC base metal. In the year 2002, another research work [28] used RFW to weld 7005 Al / SiC and 7005 Al / Al_2O_3 composites with a rotational speed at 730 rpm. The friction pressure was 3.4 N/mm^2 and the friction time was 7 sec. The upset pressure was 3.4 N/mm^2 while the upset time was 0 sec. Aging treatment gives more hardness to particles and thus AMCs, but give poor welding properties because increase in the stress concentration of SiC particulates has led to SiC particulate could be broken [29].

Linear Friction Welding (LFW) is a solid-state joining process similar to that of RFW but the movement is replaced by a reciprocating movement allowing non-cylindrical parts to create welded joint[30].

In the year 2010 [31],a linear friction welding was used to weld dissimilar materials. The materials are 2124Al/SiC and 2124Al/SiC. The compressing axial load of 100 KN was delivered to ensure the strength of the weld. The pressure value used was: 185 N/mm^2. The frequency was set at 50Hz with the amplitude of 2 mm. Burn-off value was set at 2 mm. it was observed that the hardness decrease 10% in the welded zone. Severe plastic deformation, recrystallization and coarsening of the intermetallic phases in the Al alloy matrix. UTS value was decreased approximately to 20 % in the welded zone.

Orbital friction welding (OFW) - OFW is similar to RFW but both welded parts are rotated in the same direction and at the same speed, on non-axially symmetric components. OFW is used in manufacturing of blades in turbines [32]. However, this process is not used in joining AMCs.

Friction Stir Welding (FSW) - The method of FSW is one of the most famous solid state joining process used to join AMCs. The main advantage is that it does not need special high-cost machines. FSW works by using a non-consumable tool, which is rotated into the interface of two parts to produce friction heat that enough to weld the two work pieces together [33].

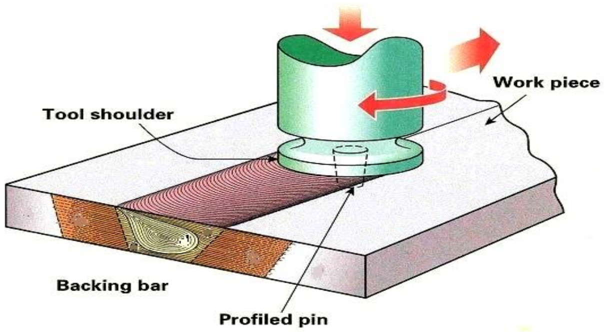

Fig. 3 Basic principle of FSW[16]

Friction Crush Welding (FCW) - FCW is a modern method of welding and similar to FSW, but depends on crushing two similar sheet edges by using hard cylindrical tool. The welding between two edges occurs due to relative motion between work pieces and rotating cylindrical tool. This process is used to weld similar sheet metals of Aluminium, Copper, Steel and Stainless steel without filler materials. However, literature reports that this process is never used to join AMCs [34].

VI. CHALLENGES AND FUTURE DIRECTIONS

In summary, this review paper comprises of 4 key topics from the past research works and correlated each one of them to the proposed research work of the authors. They include: (i) type of Aluminium alloy used, (ii) type of reinforcement phase materials used (ii) type of manufacturing process used for making the composite and finally (iv) the type of friction welding machine used. While dealing each key topic from the past research, gap areas for the proposed research work are identified and correlated as to how to address the issues raised from each of the past work. The review of the literature has helped the authors to discover the research gaps and how these gaps can be addressed in the presently proposed work. One of the reasons for choosing waste materials from the marble industry is to recycle the wastes generated from the industry which would otherwise be a harmful landfill. The characterization of the reinforcement phase materials would be carried out to find out the degree of affinity towards the matrix phase materials. The microstructures obtained from the past research works for various composite materials will be used as reference and compared with that of presently proposed work. There are several grades of LM Aluminium alloys commonly used as the matrix material for the production of MMCs and selecting particular matrix alloy is most depend on its properties and applications. Among various alloys this review recommends LM6 grade Aluminium alloy due to some of its main advantages such as ductility, recyclability, workability and resistance to corrosion, and cheap. This type of Aluminum used in military and aerospace application due to its excellent joining characteristics.

Many researchers have studied different forms of inorganic, organic reinforcements. Most of them are inorganic reinforcements. But they are relatively expensive. This literature review helped the authors to find a novel reinforcement material i.e. industrial waste material as reinforcement is still an open-ended area in which much independent research could be carried out for the development of MMC's. Two new types, which are not used thus far, have been proposed to be used into Aluminum matrix phase. The first one is marble wastes, which is abundant in the marble industries in Oman, where the stone is cut into small pieces that match the size of the walls of houses. These stones are cut by an automatic saw that produces a marble powder. One important reason to choose this type of reinforcement is to promote the recycling of wastes and to reduce the environmental contamination. The second one is graphene oxides powders which is one type of carbon-rich powder. This is not used as an aluminum reinforcement so far in the composites, which we expect will give good mechanical properties of the composites.

The review illustrated clearly that a simple bottom pouring stir casting is commonly used process for MMCs, but they contain some limitations such as non-uniform distribution of reinforcement particles, poor wettability between reinforcement and matrix material, porosity in the produced composite. These drawbacks pose challenges in the production of composites. Therefore, an alternate method called stir squeeze casting is proposed in our work to overcome those limitations. The squeeze casting attachment in the stir casting setup provides appropriate squeeze pressure once the molten metal fills the die cavity and removes air gaps. This ultimately reduces the porosity level and improves the mechanical properties of the composite material.

Joining of AMC is another challenging area as most researchers relied on the use of FSW method for the ease and availability of equipment. However, very limited or no mention of the use of FW for joining AMC is reported in the literature. This is due to fact that the bonding temperature, boding strength and challenges posed in setting up the process itself.

Therefore, authors would be facing a great deal of challenges in this aspect. However, already experience gained in designing a FW machine for joining dissimilar materials would help overcome the constructional challenges of a FW machine for the currently proposed work. In our proposed work, we will intend to use particularly RFW method for joining the AMC which brings a lot of advantages on the quality of weld produced as well as the cost elements associated within the welding process.

VII. CONCLUSION

Finally, more than 50 literature papers published in peer reviewed journals were collected and segregated into major topics as follows: type of matrix phase and type of reinforcement phase materials used. Also, the type of friction welding machine used along with the types of manufacturing process used for making the composite were of immense use to understand the conventional methods of production and recent trends in making AMCs. Type of laboratory tests to be done before and after welding of AMCs is established from the literature review. Testing facilities and equipment are available in the university and materials for matrix and fiber phases will be collected from the local industries. Clear understanding and way forward to undertake the proposed research work is the ultimate outcome of this extensive review work. Key stages the proposed work included characterization of the reinforcing phase materials. Investigative study on the wettability of the reinforcement phase with the matrix phase will also be undertaken during the course of time. Following ASME standards for preparation of specimen materials and testing procedures before and after the welding processes.

Authors strongly feel that the literature review process has helped a lot to understand the processes, identify the gap areas in each phase of the work so as to apply the knowledge gained into their research work proposed and hence to contribute to the literature and new knowledge in to the research topics.

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