Aluminium friction-stir welding with nanoparticles

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Welding is a widely used and critical joining process in fabrication industries and consumes a lot of energy and materials. Friction stir welding process is most commonly and emerging process in solid state processes. In FSW, heat for welding is generated with pressure applied between the rotational tool and base metal, leading to plastic deformation without melting of the base metal and without change in the primary microstructure of the base metal. Aluminium and its alloys have been seen to be a viable and, in some cases, superior alternative to steel. the FSW process occurs below the melting temperature of the Al alloys, resulting in avoidance of metal solidification defects, less deformation, porosity and cracks, and improved mechanical integrity of the joints. For improving mechanical properties, nanoparticles have commonly been used as reinforcement particles, as their size leads to uniform dispersion, grain refinement and reducing joint flaws.

Keywords: nanomaterials ; microstructures ; friction stir welding ; aluminum alloys

1. Introduction

Efficient production and reduced energy consumption have become a top priority of government policies aimed at promoting sustainable development. In efforts to achieve environmental and economic sustainability, industries aim to implement solutions that use minimum resources, improve production processes, and develop enhanced materials. The requirement for minimal resource utilization means that fabrication designs are tending towards joints with complicated structures and joints of similar and dissimilar metals [1].

Welding is a widely used and critical joining process in fabrication industries and consumes a lot of energy and materials [2]. Conventional fusion welding processes use phase regulator transistorized type power sources that have high energy consumptions and require large cooling units. There are limited arc manipulation features and improving such technology is expensive [3]. Moreover, conventional fusion welding can result in occlusion of gases, porosity, slag inclusions, solidification cracks and other distortions, causing expensive reworks and usage of more materials [4]. Advancements in welding processes have, however, made it possible to produce sound joints using techniques such as solid-state welding, adaptive welding, robotic welding, cold metal transfer, spray arc, the use of flux cored welding wire, weld seam sensors and inverter-based power supplies. These and other improvements have resulted in a reduction in distortion and joint defects and consequently a reduction in material and energy usage [5]. However, the nature of conventional fusion welding processes restricts their usage in dissimilar welding and welding of heat sensitive Al alloys by the high heat input. As aluminum and its alloys have high thermal and electrical conductivities, the use of fusion welding processes has resulted in hot cracking and hydrogen embrittlement along the joint [5][6]. For instance, Da Silva and Scotti [7] showed that welding heat sensitive Al alloy AA5082 using pulsed gas metal arc welding process (GMAW) showed numerous porosity formations. Moreover, the usage of the double pulsed GMAW process tends to reduce the porosity formation compared to pulsed GMAW. However, the process cannot avoid porous formation. For the case of dissimilar welding, a study showed that welding of AA5083 to AA6061 using tungsten inert gas welding (TIG), metal inert gas welding (MIG) and FSW resulted in better properties in FSW joints compared to fusion welding processes. Moreover, the FSW joint had fine grain structures unlike joints made with fusion welding processes [8].

2. Aluminium friction-stir welding with nanoparticles

As no melting is involved in solid state welding, solid state techniques can overcome the shortcomings of fusion welding in production of similar and dissimilar weld joints [9]. The friction stir welding process is a more common and emerging process in solid state processes. In FSW, heat for welding is generated with pressure applied between the rotational tool and base metal, leading to plastic deformation without melting of the base metal and without change in the primary microstructure of the base metal. Moreover, welding by fusion welding processes results in eminent microstructural transformation and mechanical properties, which can be avoided in the FSW process. An experimental study of AA6061 with Al_2O_3 reinforcement using fusion and friction stir welding revealed that the high heat input of the fusion welding process led to dissociation of the Al_2O_3 composite, leading to brittle Al_4C_3 formation through the reaction between molten liquid and SiC. However, in the case of the friction stir welding process, there were no significant changes except that the Al_2O_3 particle size decreased and number of particles per unit area in the thermo-mechanically affected zone (TMAZ) region increased. This could be due to the agglomeration of Al_2O_3 particles and the inability of particles to orient with semisolid metal flow. In terms of mechanical properties, the hardness shown in the fusion zone was 70 HV, highlighting a softening effect in comparison to the hardness of the base metal (120 HV). On the other hand, the FSW joint showed that the hardness was similar to the base metal 100–140 HV in the stir zone; however, hardness increased in the TMAZ due to clustering of Al_2O_3 particles [10][11]. A schematic of FSW is shown in Figure 1. For increasing heat input, increasing the rotation speed or decreasing the travelling speed of the tool leads to better plastic material flow and the formation of a wider weld nugget (WN) [12][13].

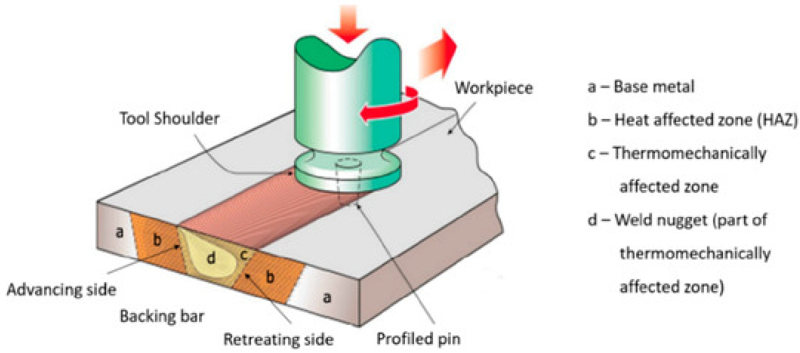

Figure 1. Schematic of the friction stir welding process.

Demanding applications such as those found in the marine, railway, automobile and aerospace industries demand a compatible material with desirable properties such as a good strength-to-weight ratio, high fatigue strength, and superior wear and corrosion resistance. Due to its inherent properties of good strength-to-weight and good corrosion resistance, aluminum and its alloys have been shown to be a viable and, in some cases, superior alternatives to steel. For instance, increasing concerns about resource usage have led to demands for improvement in fuel economy, triggering efforts to reduce the weight of vehicles. As a rule of thumb, in automotive industries, a 10% reduction in weight improves fuel economy by approximately 5.5%, and consequently usage of structural lightweight materials is highly desirable. Al has been one of the candidates used to provide good strength-to-weight ratios, so some of the engine parts have been fabricated by using Al alloys [14]. The 5x and 6x series of aluminum alloys have been employed for external structures and closure panels of vehicles and, as can be seen from Figure 2, have better density ratios than steel alternatives. Research is being carried out on 7x series Al alloys with the additions of scandium and zirconium for usage in engine cylinders to lower fuel consumption [15]. Corresponding with the automobile industry, the aerospace and the shipbuilding industries are also attempting to reduce pollutant emissions and structural costs through the use of Al alloy components in aircrafts and ship hulls [16]. For example, ferries produced using Al alloys have strengths equal to ferries made with steels for approximately half the weight, which increases fuel economy [17][18]. In recent years, various advanced Al alloys such as Al-Cu-Li, Al-Zn-Mn alloys, Al 7x series, Al 8x series and Al composites have been developed. These alloys exceed the requirements of current and foreseeable future demands [19]. For instance, the Al alloy Al-Cu-Li has been used in aeronautic applications, such as in aircraft wings, for its density ratio to mechanical resistance [20]. Although Al alloys have desirable characteristics, reduction in material usage of fabricated structures also requires welding of complex joints and joining of similar and dissimilar Al alloys.

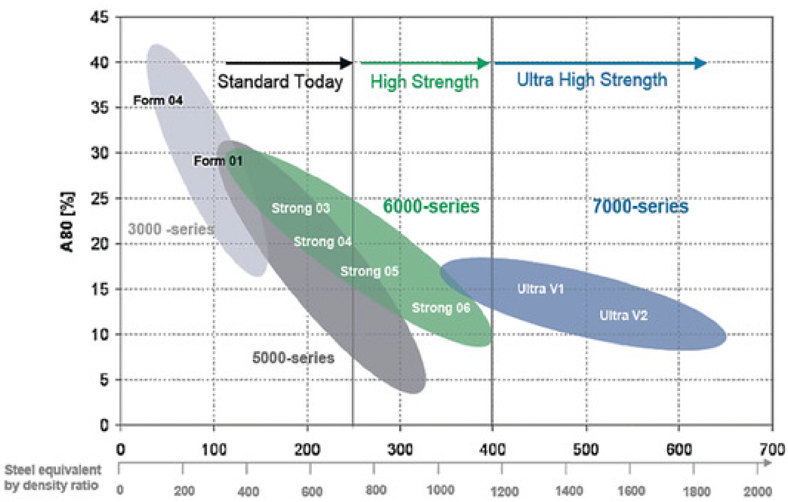

Figure 2. High strength aluminum sheets used for body structures in automotive industries [15].

Employment of fusion welding processes in welding of similar and dissimilar Al alloys results in poor weldability and can encounter problems such as weld solidification cracking, porosity, microstructural segregation from low melting eutectic formation, liquid cracking and brittle intermetallic formations. In addition, the mechanical properties of the joints can be reduced by coarse grain microstructural formations [21][22][23]. Studies suggest that welding of Al alloys using the GTAW process causes porosity formation and reduction in tensile strength, due to a decrease in dislocation density and porosity formation leading to joint fractures [24]. However, the FSW process occurs below the melting temperature of the Al alloys, resulting in avoidance of metal solidification defects, less deformation, porosity and cracks, and improved mechanical integrity of the joints [25]. For example, a study showed that welding of Al-Cu-Li alloys using GTAW and FSW had joint formation with no defects. However, considering the mechanical joint strength, the FSW joint had better hardness properties (i.e., 120–130 HV from stir zone (SZ) to base metal) compared to GTAW joint (i.e., fusion zone −70 HV and base metal −130 HV). Moreover, the softening effect (i.e., reduction in hardness value) along the Heat-Affected Zone (HAZ) region in the GTAW joint has been compared to the FSW joint [20].

As aerospace industries focus on implementing lightweight structures in wing panels, FSW of 7x aluminum alloys is being evaluated for implementation. FSW 7x Al series showed that the tensile strength of the joint improved 5.33% of the parent metal [26]. Moreover, the marine industries require storage tanks and pipelines in ferries with lightweight materials such as Al alloys. The Al alloy AA6061, which joins with low heat input, was selected, where FSW was opted for as the fusion welding process uses filler material that increases the weights of the structures [27]. The study showed the FSW of AA6061 increased in ultimate tensile strength (160 MPa) with increased tool rotational speed, welding speed and tool axial force [28]. In recent decades, studies have been conducted on FSW of similar and dissimilar Al alloys with the aim of optimizing the welding parameters and improving weld properties. Welding of 7x series in Al alloys has been used for high stress components. The joints produced by FSW of Al alloys had minor reductions in strength compared to the base metal [26]. Moreover, another study also indicates that 7x series of Al alloys have reductions in mechanical strength due to the temperature variation in weld produced by the tool geometry and tool size. This temperature difference caused variation in grain size, precipitation size as well as distribution of particles, resulting in decrement in ductility, tensile strength as well as yield strength [10]. Research showed that the FSW welding parameters such as pin size, tool rotational speed and tool traverse speed has adverse effects on the formation of the microstructure and properties of the joint. With a low rotational speed and constant traverse speed, the small sized pin had better mechanical properties compared to the large sized pin [26]. Apart from the tool geometry and welding parameters, studies also suggest that using various reinforcement materials in the stir zone can prevent abnormal grain growth and lead to grain refinement, as well as enhancement of the mechanical properties of Al joints [29][30].

Nanoparticles have commonly been used as reinforcement particles, as their size leads to uniform dispersion, grain refinement and improved joint properties. For example, nanoparticles coated on base metals and coated on electrodes in fusion welding (i.e., gas metal arc welding and gas tungsten arc welding) produced joints with improved microstructural formations by grain refinement as well as and improved mechanical properties [31]. In addition to fusion welding processes, nanoparticles have also been incorporated in FSW of Al alloys [22][23]. The incorporation of nanoparticles in FSW joints improved the weld mechanical properties and microstructures by grain refinement [8]. To incorporate nanoparticles, ethanol was mixed with the reinforcing nanoparticles in a slurry and the specimens were machined with half grooves at the joining face plate. An example groove is shown in Figure 3. To prevent reinforcing nanoparticles being ejected out of the groove during welding, a pin-less tool was passed along the groove [32][33]. Another reason for incorporation of nanoparticles in the stir zone (SZ) is to aid stiffness and improve wear resistance in Al alloys [34].

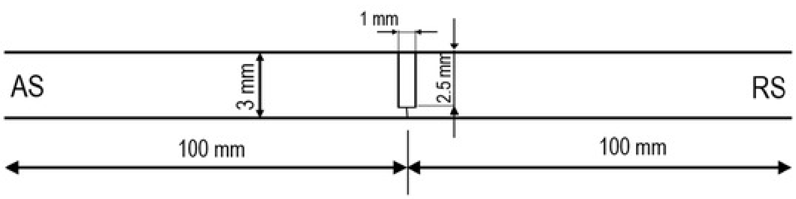

Figure 3. Example schematics of groove formation for usage in reinforcing nanoparticles.

As recent studies focus on application of nanoparticles in the FSW process and composite matrix formation and its effects on mechanical properties, they do not provide the correlation of nanoparticle selection with its effect in terms of the improvement of microstructure and properties. Moreover, only limited research has been conducted on dissimilar aluminum joints with nanoparticle reinforcement.

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