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# Combination of nano-particle deposition system and friction stir spot welding for fabrication of carbon/aluminum metal matrix composite joints of dissimilar aluminum alloys

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ABSTRACT

A nano-particle deposition system is combined with friction stir spot welding (FSSW) of dissimilar aluminum alloys to fabricate a carbon/aluminum metal matrix composite (MMC) joint. Carbon materials in the form of graphite powder are deposited on an aluminum sheet at room temperature. Lap joints of dissimilar aluminum alloys are fabricated via FSSW using the carbon-deposited aluminum sheet as the upper sheet of the joint. The Raman spectroscopy confirms that carbon/aluminum MMC is successfully fabricated in the joint. The strength and toughness of the joint are clearly enhanced by fabricating the MMC, as shown in the result of mechanical tests.

## 1. Introduction

The use of aluminum alloys is rapidly increasing in automotive structures as part of efforts to improve fuel efficiency via weight reduction in automobiles. Given that more than 2000 spot welds or joints are used in a typical automobile, it is obvious that the performance of automotive structures is significantly affected by the mechanical properties of the joints between the structural components, as well as the mechanical properties of the material used for the components. Unfortunately, aluminum alloys have poor weldability with conventional joining processes such as resistance spot welding (RSW) [1–3], which diminishes the benefits of their use in automotive structural components.

It has been proven that friction stir spot welding (FSSW), a derivative of friction stir welding (FSW), is readily applicable to the production of aluminum alloy spot joints [2–4]. Due to the nature of solid-state FSSW, this joining technique can provide several technical advantages, including the elimination of liquidation-related welding defects [5] and the capability of joining dissimilar metal alloys [6,7]. One additional advantage of FSSW (and FSW) is that solid state stirring of candidate materials during the process may be used to selectively induce metal-matrix composites (MMC) in the stir zone by adding micro- or even nano-sized particles as reinforcements [8–12]. With the induction of MMC in the stir zone, the mechanical properties of the FSSW/FSW joints may be further improved, in addition to the well-known benefits of dynamic recrystallization within the stir zone. Unfortunately, previous methods used to supply fine reinforcing particles during FSW/FSSW are time-consuming [8–10] or the amount of reinforcing particles added to the MMC may not be predictable [10–12].

Recently, a nano-particle deposition system (NPDS) has been developed as an easy-to-implement and versatile dry spray process with low energy consumption [13,14]. The NPDS can deposit various types of materials, including metals and ceramics. Specific materials such as tin, nickel, $Al_2O_3$, and $TiO_2$, are viable. The amount of these reinforcing particles can be easily controlled by changing the deposited film thickness with variations in the process parameters [14–18]. Graphite deposition on a metal substrate at room temperature conditions was recently reported [19,20], and this process is suitable for graphite coating of FSSW joining applications without thermal damage or changes to the material properties of the substrate.

In the present study, we combine an NPDS with FSSW of dissimilar aluminum alloys to fabricate a carbon/aluminum MMC (simply, C/Al MMC) joint. We will first examine the fabrication of C/Al MMC in the FSSW joint. The mechanical properties of the MMC joint will then be compared with those of conventional FSSW joints. Finally, the technical advantages of the NPDS/FSSW combination will be briefly discussed.

## 2. Experimental

Carbon reinforcements for MMC joints were prepared in the form of graphite powder (MGF 10, Samjung CNG, South Korea) with an average particle size of 10 μm. The Raman spectrum of the graphite was measured using a confocal micro-Raman apparatus (alpha 300R, WITec, Germany) from 500 to 3500 $cm^{-1}$ with an incident laser light at a wavelength of 532 nm. The Raman spectrum of the graphite shows an intense G-band peak position at ~1580.51 $cm^{-1}$ and a 2D band peak position at ~2717.51 $cm^{-1}$, as

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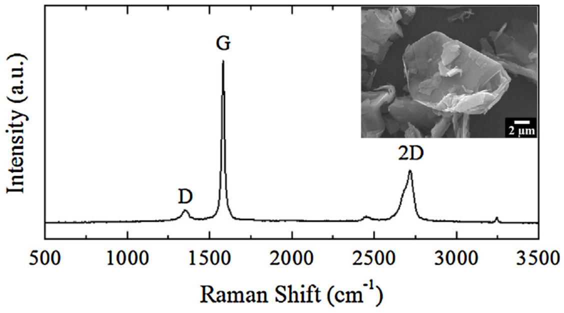

**Fig. 1.** Raman spectrum and SEM image of graphite powder.

shown in Fig. 1. The graphite also has a D band peak position at ~1352.75 $cm^{-1}$; the low intensity of this D band suggests a crystalline structure with almost no disorder. The positions of all peaks represent typical graphitic bands [21]. A scanning electron microscope (SEM, JSM 7600F, JEOL, Japan) image of the graphite is also shown as an insert in Fig. 1.

Two dissimilar aluminum alloys, 5052-H32 and 6061-T4, each with 3 mm thickness, were selected as the matrix metals for the MMC. The chemical composition of these aluminum alloys differs somewhat, particularly in magnesium (Mg), as listed in Table 1. In the present study, a combination of dissimilar aluminum alloys is considered to characterize the material mixing that occurs during FSSW using elemental mapping of Mg. For the sake of simplicity, only the combination having the aluminum 6061-T4 alloy sheet on top and the aluminum 5052-H32 alloy sheet on the bottom of the joint.

For FSSW, the 5052-H32 and 6061-T4 alloy sheets were prepared to a length of 120 mm and a width of 50 mm. The FSSW lap joint was designed to have an overlap length of 50 mm (Fig. 2). The carbon reinforcement was coated on the surface of the aluminum 6061-T4 alloy sheet (the upper sheet of the dissimilar lap joint) using the NPDS system prior to FSSW.

The NPDS used in the present study consists of an air compressor, powder feeder, nozzle, deposition chamber, vacuum pump, and translation stage. Graphite powder from the powder feeder was carried via compressed air to the nozzle. A slit converging nozzle with a nozzle exit measuring 0.4 mm × 50 mm was used to accelerate the powders via the pressure difference between the nozzle inlet and outlet. The accelerated powders entered the deposition chamber under low vacuum room temperature conditions. The accelerated graphite powders then made impact with the surface of the substrate (the aluminum 6061-T4 alloy sheet) for deposition. During deposition, the substrate was moved linearly for area deposition with a scanning speed of 0.28 mm/s. The compressed air pressure and chamber pressure were maintained at 0.3 MPa and 0.034 MPa, respectively. The stand-off distance, the distance between the nozzle and substrate, was fixed at 2 mm.

Using a thin circular polymer mask, the graphite layer was deposited on the surface of the aluminum 6061-T4 alloy sheet in a circular shape with a diameter of 20 mm, as shown in Fig. 3(a). Fig. 3(b) shows the microstructure of the coated surface. Note that the grain size of the graphite on the substrate is smaller than that of the original powder. The mass of deposited graphite in the circular shape was approximately 1 mg. The diameter of the graphite coating was designed to be slightly smaller than the diameter of the FSSW tool shoulder, and the center of the circular graphite coating layer coincides with the center of the overlap area of the joint, which is the initial contact point between the upper sheet and the tool pin. Therefore, it is assumed that the graphite coating was fully entrapped between the shoulder of the rotating tool and the upper sheet during FSSW.

**Table 1**
Chemical composition (wt%) of the base aluminum alloys.

| Alloys | Cr | Cu | Fe | Mg | Mn | Si |
|---|---|---|---|---|---|---|
| 5052-H32 | 0.15 | ≤0.10 | ≤0.40 | 2.4 | ≤0.10 | ≤0.25 |
| 6061-T4 | 0.17 | 0.22 | 0.44 | 0.68 | 0.11 | 0.65 |

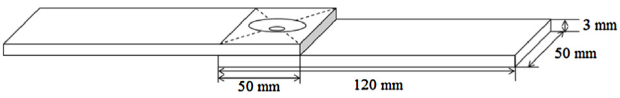

**Fig. 2.** A schematic of FSSW specimen.

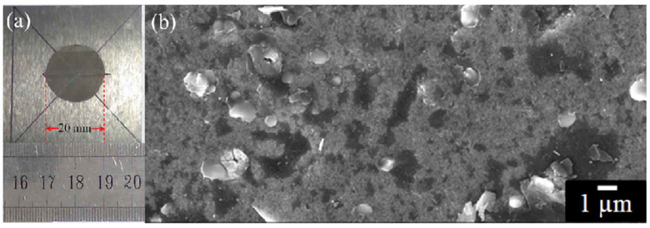

**Fig. 3.** Images of the graphite coating on the surface of the aluminum 6061-T4 substrate: (a) optical image and (b) SEM image.

**Table 2**
Process parameters of friction stir spot welding.

| Rotation speed (RPM) | Plunging speed (mm/min) | Plunging depth (mm) | Dwell time (s) | Control mode |
|---|---|---|---|---|
| 1500 | 30 | 5 | 2 | Displacement |

FSSW was conducted using a custom-built FSSW/FSW machine (RM-1, TTI, USA) and a typical concave shoulder tool with a cylindrical pin (shoulder diameter of 21 mm, pin diameter of 6.1 mm, and pin length of 4.65 mm). The process parameters, which were selected via a separate preliminary study, are listed in Table 2. In addition to the FSSW joints with an NPDS graphite coating (simply, FSSW with NPDS), FSSW joints without an NPDS graphite coating (simply, FSSW without NPDS) were also fabricated for comparison.

After FSSW, optical microscopy, elemental mapping, and Raman spectroscopy were conducted on the cross sections of the joints. Optical microscopy was conducted first to confirm the successful fabrication of joints for both FSSW with NPDS and FSSW without NPDS. Elemental mapping of Mg in the joint was then conducted to confirm the mixing of dissimilar aluminum alloys in the stir zone. Finally, Raman spectra were obtained for FSSW with NPDS to confirm the successful generation of MMC in the stir zone.

The mechanical properties of the FSSW joint with NPDS are compared with those of the FSSW joint without NPDS via quasi-static lap shear testing and hardness measurements in the stir zone. The lap shear test was conducted using a tensile testing machine (DTU-900MHN, Daekyung Tech & Tester, South Korea). A constant displacement rate of 2.5 mm/min was used during the shear test. Note that spacers were attached to both ends of the joint to align the loading axis to the center of the joint. The hardness profile in the stir zone was measured using a Vickers indenter (HM-100, Mitutoyo, Japan) with 981 mN load for 10 s.

## 3. Result and discussion

Macrographs of the cross sections for the FSSW joints, both with (Fig. 4(a)) and without NPDS (Fig. 4(b)), clearly show that the dissimilar combination of aluminum alloys selected in the present study was successfully joined, regardless of the existence of a graphite layer deposited on the upper sheet of the joint. No visible macroscopic defects have been observed. While the joining was successfully conducted for both cases (with/without NPDS), the graphite layer deposited via NPDS affected the material mixing in the stir zone. As shown in Fig. 4(a), the C-ring patterns in the FSSW with NPDS are not evident in the stir zone, while the C-ring patterns can clearly be identified in the stir zone of the FSSW without NPDS. The insignificant C-ring pattern in the FSSW with NPDS suggests that the dissimilar aluminum alloys were more evenly mixed in the stir zone with NPDS. The elemental mapping results of Mg confirm that the stir zone is a mixture of the two dissimilar aluminum alloys in the upper and lower sheets (Table 3).

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