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Erratum

Cold formability of friction stir processed aluminum composites containing carbon nanotubes and boron carbide particles

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ABSTRACT

Cold formability of friction stir processed aluminum composites was evaluated by bend-ductility test. Composites containing carbon nanotubes fractured during bending while those containing boron carbide particles survived; hybrid composites showed cracking but less than those containing solely nanotubes. Weak interfacial nanotube/aluminum bonding and inadequate nanotube distribution were found to be the possible reasons.

1. Introduction

Friction stir processing (FSP) is a novel solid state surface composite manufacturing technique derived from friction stir welding (FSW) [1]. FSP involves microstructural modification of the processed material by mechanically induced sliding motion of a rotating tool [2]. The microstructural evolution due to severe plastic deformation [3] and intense heat generation improves the mechanical properties [4] while the elimination of microstructural defects like porosity enable FSP materials more resistant to mechanical loading [5].

A range of particles, both at micrometer [6] and nanometer scale [7], have been introduced to prepare surface composites by FSP. Ceramic reinforcements include aluminum oxide [8], boron carbide [9], silicon carbide [10] and cerium oxide [11] while carbonaceous nanoreinforcements comprise carbon nanotubes (CNTs) [7] and graphene nanoplatelets (GNPs) [12]. Significant improvements in mechanical properties have been reported [13], which relate to grain size refinement and uniform distribution of reinforcement. FSP is therefore a promising technique for the automotive and aerospace industries where improved toughness [14,15] and damage tolerance is required [16]. Specially FSP eliminates inherent defects of casting techniques [17] and it has proven to be a useful technique for better dispersion of reinforcements than existing composite manufacturing processes such as stir casting [18], powder metallurgy [19], roll bonding [20].

The combined effect of chemically and morphologically different reinforcements has been less investigated to explore their synergic effect on the properties of hybrid surface composites processed by FSP. In a study [21] better hardness and wear properties of Al-5083 composites were reported by incorporating silicon carbide and molybdenum disulphide particles. In a different study [11], CNTs were used in combination with cerium oxide and improved mechanical properties and corrosion resistance were observed. Generally studies focus on strength and hardness without emphasizing the formability of surface composites. To the best of authors' knowledge, no such report is available in literature that focuses on formability together with hardness and strength of FSP surface composites containing dual reinforcements.

In this study, surface composites were developed by FSP on aluminum alloy 5083 (Al-5083) plate containing multiwall carbon nanotubes (MWCNTs) and boron carbide (B_4C) particles. For comparison, individually reinforced MWCNTs and B_4C composites were also prepared along with a reference FSP surface without reinforcement. Al-5083 was especially chosen as it possesses good corrosion resistance, moderate strength and desirable welding characteristics [22]. The two reinforcements of different chemical, mechanical and morphological attributes were selected: extremely hard B_4C particles [23] were reinforced with exceptionally strong and stiff MWCNTs [24] to study their synergic effect on mechanical properties of the composites.

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Table 1
Nominal chemical composition of base metal Al-5083.

Element	Mn	Fe	Cu	Mg	Si	Zn	Cr	Other	Al
wt%	0.4–1	≥ 0.4	≥ 0.1	4–4.9	0–0.4	0–0.1	0.05–0.25	0–0.05	Balance

2. Experimental

2.1. Materials

Al-5083 rolled plate of thickness 8 mm was used for surface composite preparation with the composition shown in Table 1. B_4C particles with average size of 10 µm and MWCNTs with average length and diameter of 1 µm and 20–30 nm, respectively, were purchased from Hongwu International Group, China. FSP tool was made of H-13 steel with final dimensions of 16 mm collect diameter, 20 mm shoulder diameter and 4.5–6.0 mm conical threaded pin diameter. The height of the pin was 4.5 mm and an angle of 5° was made from shoulder to pin root to accumulate the possible spreading of reinforcement from cavities; the tool had the hardness value of 550 ± 2.5 HV.

2.2. Manufacturing

Aluminum plate was drilled for preparing cavities of 2.0 mm diameter and 3.0 mm depth with in-between spacing of 8 mm. MWCNTs and B_4C particles were manually introduced in cavities and the compaction was performed by 1.8 mm diameter punch. For the combined reinforcement, MWCNTs and B_4C particles were introduced in equal volumes. Fig. 1 shows the schematic of FSP for producing surface composites.

A single pass of FSP at a rotational speed of 750 rpm, traverse speed of 16 mm/min and tilt angle of 2° was performed to prepare composites. The surface composites containing individually reinforced MWCNTs and B_4C particles were prepared along with the hybrid composite containing both reinforcements. For reference, a specimen was prepared by FSP without reinforcement.

2.3. Characterization

A metallurgical microscope IMM 901, Metkon Instruments, Turkey, was used for optical microscopy. The electron microscopy of the composites was performed on scanning electron microscope (SEM) TESCAN, MIRA-III, FEG-SEM, Czech Republic. Hardness testing was performed in accordance with ASTM E-384 on Karl Frank, GMBH Type 38505 micro-hardness tester at 550 g load and dwell time of 30 s. Tensile testing was performed in accordance with ASTM E8, on a universal tensile testing machine (WDW-30, Jinan Precision Testing Equipment, China) at a strain rate of 2 mm/min. The dimensions of the tensile test samples were 30 × 5 × 3 mm with gauge length of 15 mm, traverse to the FSP line. Bend-ductility test was performed as per ASTM E190 standard; a custom made U-shaped die was prepared. The specimens were loaded at crosshead speed of 2 mm/min with a plunger transverse to FSP line (Fig. 1). The convex surfaces were examined with naked eyes, and optical and electron microscopy.

3. Results and discussion

3.1. Microstructure

Fig. 2 shows SEM images of specimens at two magnifications from stir zone (SZ). Uniform dispersion of reinforcements can be seen in individual and hybrid composites. B_4C particles are visible, which are separated from other particles without forming agglomerates. Similarly no MWCNT clusters were witnessed in SZ. Occasional MWCNTs pull-outs were noted on polished surfaces of Al-CNT and Al-CNT/B_4C composites (Fig. 2). XRD (not shown here) was performed to detect the presence of any interfacial reactions between aluminum and reinforcements and the absence of aluminum carbide and aluminum borocarbide was detected indicating that no reaction of aluminum tool place with MWCNTs and B_4C particles, respectively.

3.2. Tensile properties

Fig. 3(a) represents stress-strain curves of composites and reference specimens while tensile strength, fracture strain and toughness values are plotted in Fig. 3(b) and available in Table 2. Toughness values were calculated from the area underneath the stress-strain curves [25]. The reference specimen showed the minimum tensile strength value of 272 ± 10 MPa but the maximum fracture strain of ~ 11%. A possible reason may be the ductility enhancement due to FSP [26]. After adding MWCNTs, the fracture strain decreased severely (50%). However, slight increase in tensile strength was observed. A similar trend has been reported elsewhere [27]. The presence of MWCNT clusters create voids, which result in stress concentration sites and cause crack nucleation, thus lowering the fracture strain. The toughness followed the fracture strain behavior, as also observed in aluminum alloys [28]. In contrast, the addition of B_4C particles improved tensile strength by 28% with a minor reduction in fracture strain of ~ 8% [29]. Single pass FSP effectively contributed in uniform distribution of micrometer size B_4C particles unlike MWCNTs. The combined effect of MWCNTs and B_4C particles came in increased tensile strength (300 ± 10 MPa) while the fracture strain was comparable to Al-B_4C composite though showing a slight decrease conforming to the presence of MWCNTs in hybrid composite. The toughness data reveals a comparative trend of ductility with reference and Al-B_4C composite specimens. The increase in hardness and tensile strength in hybrid composite with decrease in ductility

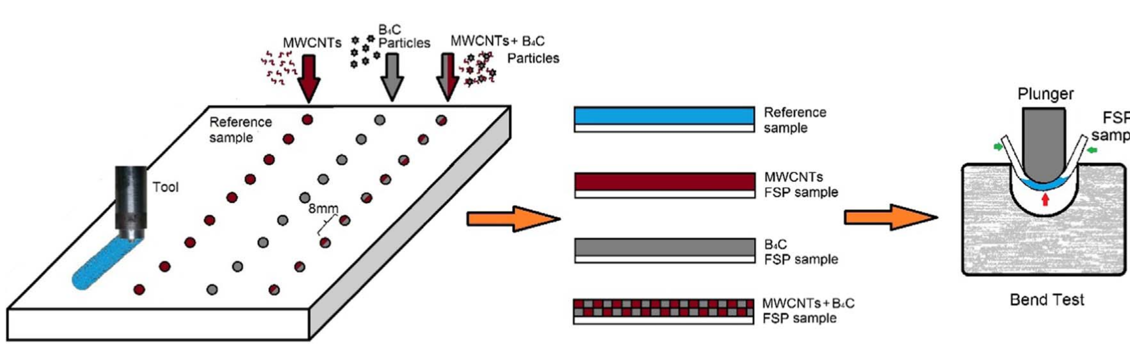

Fig. 1. Schematics of the friction stir processing for preparing surfaces composites and bend-ductility test.