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EFFECT OF HEAT TREATMENT ON THE HARDNESS AND ELECTRICAL CONNECTIVITY OF AN ALUMINUM COMPOSITE REINFORCED WITH Al_2O_3 NANOPARTICLES

Md Jalal Uddin Rumi¹ and Muhammad Muzibur Rahman²

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The effect of heat treatment modes on the microstructure, microhardness and electrical conductivity of an aluminum metal matrix composite (MMC) reinforced with Al_2O_3 nanoparticles in an amount of 2.5 wt.% is studied. The MMC is treated by quenching from 510, 530 or 550°C and subsequent artificial aging at 140, 160, 180, 200 or 220°C. The cast composite has a Vickers microhardness of 36 *HV* and an electrical conductivity of 45% IACS. The heat treatment raises the hardness and the conductivity of the composite. Quenching from 530°C and aging at 200°C produce the highest microhardness (46 *HV*); quenching from 530°C and aging at 180°C produce the highest conductivity (50% IACS).

Key words: aluminum metal matrix composite, stir casting, heat treatment, microstructure, hardness, electrical conductivity.

INTRODUCTION

There is a trend for widening the application and improving the electro-mechanical properties of aluminum metal matrix composites (MMCs) by different heat treatment processes. The Aluminum Association has standardized various heat treatment processes with different combinations of temperatures and times [1]. Precipitation hardening is a widely used heat treatment for improving the electro-mechanical properties of aluminum MMCs. It is well known that the temperature and the duration of the heating for quenching and of the aging play a determining role in variation of the properties of aluminum MMCs. However, researches aimed at optimization of the cost of heat treatment of composites without worsening their properties remain quite important.

Dynamic aging (integration of thermomechanical treatment and aging) of aluminum MMCs has been studied in [2]. As a result, the authors have suggested a treatment mode raising the strength of the composites at a shorter duration of

the process than in conventional aging. The effect of heat treatments T5 and T6 on the wear resistance of alloy AA6063 has been studied in [3]. The authors have suggested the most effective temperatures of heating for quenching (412 and 520°C with a hold for 1 h) and the mode of subsequent artificial aging (181°C, 2 h). The authors of [4] have optimized heat treatment T6 for a thixoformed aluminum alloy LM4 using the response surface method. The quenching was conducted from 510, 520 and 530°C after a hold for 0.5, 1 and 2 h and the aging was conducted at 160, 170 and 180°C for 2, 4 and 6 h. The results obtained showed that 30-min quenching from 530°C followed by 2-h aging at 180°C provided maximum hardness in alloy LM4. The effect of heat treatment on the mechanical properties of an aluminum — fly ash composite after quenching from 490°C with 8-h hold and subsequent artificial aging for 6 h at 130, 150, 170, 200 and 240°C has been studied in [5]. The increase of the aging temperature increased progressively the mechanical properties of the composite, but the best combination of the electrical and mechanical properties was obtained when the artificial aging was combined with natural one.

The aim of the present work was to study the effect of the temperature of heating for quenching and of subsequent aging on the microhardness and the electrical conductivity of

¹ Department of Aeronautical Engineering, Military Institute of Science and Technology, Mirpur Cantonment, Dhaka, Bangladesh (e-mail: jalal.uddin_rumi@yahoo.com).

² Bangabandhu Sheikh Mujibur Rahman Maritime University, Dhaka, Bangladesh.

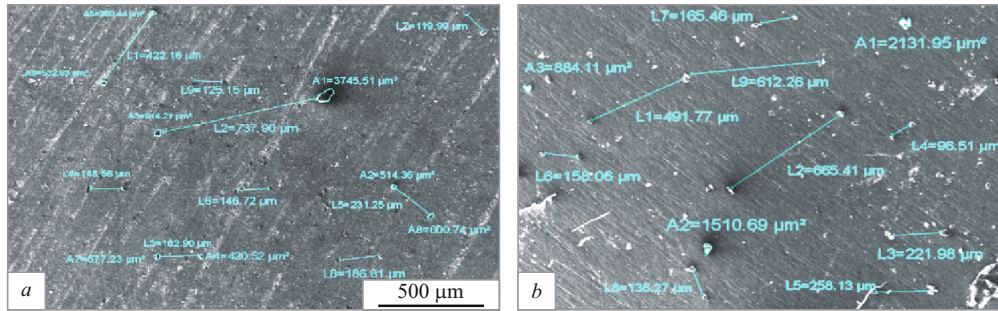


Fig. 1. Microstructure of the Al – 2.5 wt.% composite in cast condition (a) and after quenching from 530°C followed by artificial aging at 180°C (b): A1 – A8) regions of accumulation of particles of Al₂O₃; L1 – L9) distances between the particles (measured with the help of SEM).

an aluminum matrix composite reinforced with 2.5 wt.% Al₂O₃ and fabricated by multistage stir casting with various process parameters.

METHODS OF STUDY

We studied an aluminum MMC reinforced with 2.5 wt.% Al₂O₃. An Olympus XRF-analyzer (Model: Vanta C Series) was used to determine the chemical composition of the aluminum used for the production of the MMC (in wt.%): 99.052 Al, 0.614 Si, 0.323 Fe, 0.008 Zn, 0.002 Cu, 0.0009 Pb, and 0.0007 Zr.

Aluminum oxide Al₂O₃ possesses the best interfacial affinity among various reinforcing materials and is decomposable chemically under the action of molten aluminum alloys [6]. It also promotes growth of the hardness of the material [7, 8].

The composite was fabricated by the method of multistage stir casting. This is a comparatively simple and low-cost process of making aluminum MMCs [9 – 12]. Stir casting provides composites with an up to 30% volume fraction of the reinforcement [13]. The main disadvantage of the process is a nonuniform distribution of the reinforcing material in the matrix and formation of porosity lowering the properties of the composite [14]. This can be avoided or reduced to a minimum if the stir casting is performed in two stages [15 – 17]. Taking all these factors into account, we turned to two-stage stir casting with parameters chosen after analyzing the reported data, i.e., the stirring speed of 500 rpm, the stirring time of 5 min in a two-stage mode, preliminary heating of the metallic aluminum in a furnace at 500°C for 60 min, heating of the reinforcing particles in another furnace at 300°C for 120 min, melting at 800°C, reinforcing Al₂O₃ particles 20 nm in size. Total melting of the metal took 60 min. Then the melt was stirred for 5 min at the rate of rotation of the stirrer 500 rpm in two stages for attaining a uniform distribution of the Al₂O₃ reinforcement and cast into a sand mold.

To diminish the roughness, the surfaces of the fabricated aluminum MMCs were treated with a 12-mm end mill cutter with a bronze coating using a standard CNC of Model VF-2.

The samples for measuring the Vickers microhardness and the electrical conductivity by the eddy current method were prepared according to ASTM E92-17 and ASTM E1004-17 respectively. All the samples had a size of 20 × 20 × 0.8 mm. The microhardness was measured using a TMHV-10MDT Vickers hardness tester at a load of 500 g on the indenter for 10 sec. We took the *HV* value averaged after ten measurements. The electrical conductivity was determined using a 12Z Zappitec Pty Ltd (Australia) eddy current meter of electrical conductivity. The measurement was made in % IACS units (percent of the International Annealed Copper Standard). We took the value of % IACS averaged after ten measurements.

The microstructure was studied on specimens with a size of 5 × 5 × 5 mm under a TESCAN VEGA 4 scanning electron microscope.

The composite was heat treated in a Carbolite CWT 13/13 chamber electric furnace (Great Britain) with maximum operating temperature 1300°C. The rate of heating in the furnace was 16.66 K/min. The treatment modes were chosen after analyzing the reported data. The samples were heated at 510, 530 or 550°C with a hold for 1 h and cooled in room-temperature water of 26°C. After the quenching, the samples were subjected to natural aging for 72 h at room temperature. After the natural aging, they were subjected to artificial aging at 140, 160, 180, 200 or 220°C with a hold for 1 h. Then they were aged naturally again for 72 h at 26°C. We measured the microhardness and the electrical conductivity of the samples after each treatment mode.

RESULTS AND DISCUSSION

The study of the microstructure of the MMCs in cast condition and after the heat treatment showed that the particles of the reinforcing material were distributed uniformly in the aluminum matrix (Fig. 1). This proves efficiency of the method of two-stage stir casting of aluminum MMCs and agrees with the results of [16, 18].

It can be seen from Fig. 1a that the morphology of the Al₂O₃ particles in the cast composite is chiefly irregular or

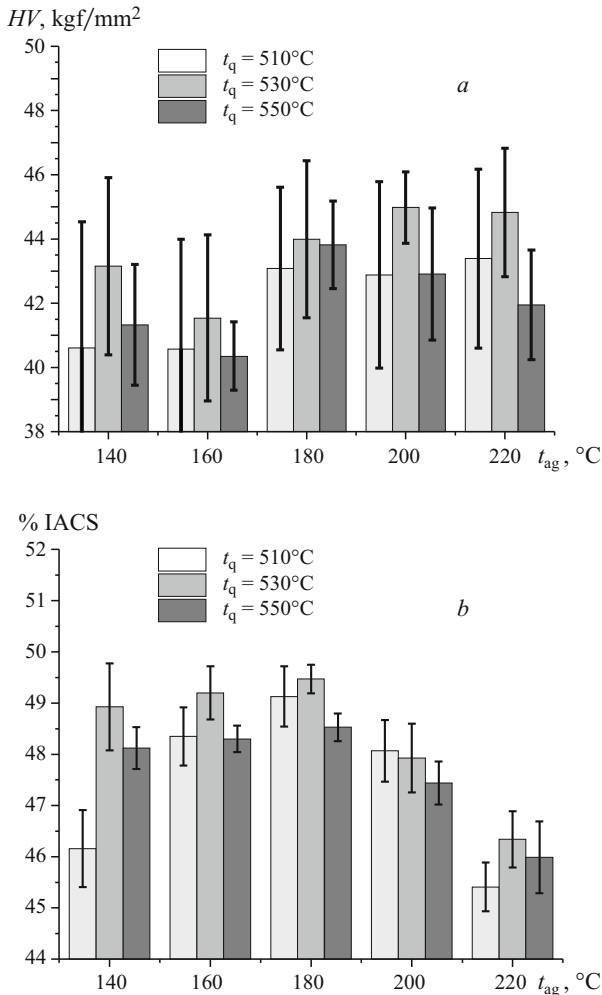


Fig. 2. Microhardness HV (a) and electrical conductivity % IACS (b) of the Al – 2.5 wt.% Al_2O_3 composite after quenching from $t_q = 510, 530$ or 550°C (with 1-h hold) and aging at $t_{ag} = 140 - 220^\circ\text{C}$ for 1 h.

close to elliptical; the particles are distributed in the matrix uniformly. After quenching from 530°C and aging at 180°C , the morphology of the Al_2O_3 particles is also irregular or almost elliptical (Fig. 1b). It should be noted that the distribution of the reinforcing particles in the matrix after the heat treatment is more uniform than after the casting. By the data of the metallographic analysis, the distance between the reinforcing particles of Al_2O_3 after the heat treatment is also greater than in the cast condition (Fig. 1). Since the arrangement of the reinforcing Al_2O_3 particles in the matrix is more uniform after the heat treatment, we may expect that this should raise the hardness and the electrical conductivity of the composite [19].

The measurements of the microhardness of the composite show that it is $36 HV$ in the cast condition, while the microhardness of pure aluminum is $26 HV$ [20]. Thus, the introduction of 2.5 wt.% Al_2O_3 into aluminum raises the microhardness of the aluminum MMC by 38%.

The effect of the temperature of heating for quenching on the microhardness after aging at different temperatures is presented in Fig. 2a. It can be seen that the hardness is the highest ($45 HV$) after the quenching from 530°C followed by aging at 200°C . After any treatment mode, the hardness of the composite is higher than in the cast condition. This result agrees with the data of [3, 19] on the effect of heat treatment on the microhardness of alloy Al6063.

The electrical conductivity of the aluminum MMC in the cast condition is 45.2% IACS at a standard deviation of 1.3% IACS. The conductivity of pure aluminum is 61% IACS [21]. Therefore, we may infer that the reinforcement of aluminum with 2.5 wt.% Al_2O_3 lowers the electrical conductivity of the composite, which agrees with the data of [22]. Figure 2b presents the conductivity of the MMC after various heat treatments. We studied the effect of the temperature of heating for quenching ($510, 530, 550^\circ\text{C}$) on the electrical conductivity. The highest value of the conductivity was obtained after quenching the composite from 530°C whatever the mode of the subsequent aging within $140 - 220^\circ\text{C}$ except for the aging at 200°C , after which the electrical conductivity was the highest after the quenching from 510°C (Fig. 2b). However, in all the cases, the electrical conductivity of the MMC after the heat treatment exceeded that after the casting. The maximum value of the conductivity (49.5% IACS) was observed when the composite was quenched from 530°C and aged at 180°C . The detected increase in the conductivity after quenching and artificial aging of aluminum alloys agrees with the data of [23].

CONCLUSIONS

1. We have studied the effect of heat treatments (quenching from $510, 530$ or 550°C followed by artificial aging at $140, 160, 180, 200$ or 220°C) on the microhardness and the electrical conductivity of an aluminum metal matrix composite reinforced with 2.5 wt.% Al_2O_3 and produced by the method of two-stage stir casting.
2. Two-stage stir casting provides a homogeneous structure in the aluminum metal matrix composite with uniform distribution of the Al_2O_3 filler. The heat treatment consisting of quenching and subsequent aging improves the structure of the composite.
3. In the cast condition, the aluminum composite has a microhardness of $36 HV$ and an electrical conductivity of 45.2% IACS.
4. The highest microhardness ($42 - 45 HV$) is obtained in the composite aged at $140 - 220^\circ\text{C}$ after a preliminary quenching from 530°C . Such quenching followed by aging raises the microhardness by 17 – 25% as compared to the cast condition.
5. The composite aged at $140 - 220^\circ\text{C}$ exhibits the highest electrical conductivity (46.3 – 49.5% IACS) after preliminary quenching from 530°C . Such quenching fol-

lowed by aging raises the electrical conductivity of the composite by 2.4 – 9.5% as compared to the cast condition.

6. Quenching of the composite from 530°C followed by aging at 200°C provides the highest microhardness (45 HV); quenching from 530°C and aging at 180°C provides the highest electrical conductivity (49.5% IACS).

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