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Investigation of Mechanical Properties of Recycled Aluminum-Fly Ash Composite

Ahmed Rabeea Hayyawi, MSc. Student in Metallurgical Engineering, ahmed.rabeea21@gmail.com[1]
Haydar A. H. Al-Ethari, Prof. (PhD) in Metallurgical Engineering, draletharihah@yahoo.com[2]
Ali Hubi Haleem, Assist. Prof. (PhD) in Metallurgical Engineering, alialihhhobi@yahoo.com[3]

Abstract

There has been an increasing interest in composites containing low density and low cost reinforcements. Among various reinforced materials used, fly ash is one of the most inexpensive and low-density reinforcement available in large quantities as waste product during combustion of fuel in thermal power plants. Hence, composite with fly ash, as reinforcement, and recycled aluminum, as matrix, are likely to overcome the cost barrier, as well as, the different physical and mechanical properties for widely used in many engineering applications. In this study, recycled aluminum reinforced by fly ash with different percentage (0, 3, 6 and 9wt%) were prepared by two step stir casting method. The composites were tested for physical and mechanical properties. The results observed that fly ash could be successfully added to recycled aluminum to produce cheap, lightweight composite with superior mechanical properties. The optical microscopic images indicate a uniform distribution of fly ash particles in the recycled aluminum matrix. The Brinell hardness number was increased by (128%) for (Al-2%Mg-9%Fly ash) compared with base alloy. Also, it was found that ultimate tensile strength was increased by (21%) for (Al-2%Mg-6%Fly ash) and decreased by (15%) for (Al-2%Mg-9%Fly ash) compared with base alloy. Wear resistance was significantly increased with increasing fly ash percentage even under high loads. So, lightweight-low cost composite with good mechanical properties can be produced by adding suitable amount of fly ash particles as reinforcement in recycled aluminum matrix.

Keywords: Recycling, Aluminum, Fly ash, Stir casting, Composite.

[1] University of Babylon- College of Material's Engineering- Dept. of Metallurgical Engineering, Babylon/Iraq, +9647802558477.
[2] University of Babylon- College of Material's Engineering- Dept. of Metallurgical Engineering, Babylon/Iraq, +9647801313567.
[3] University of Babylon- College of Material's Engineering- Dept. of Metallurgical Engineering, Babylon/Iraq, +9647803414178.

1. INTRODUCTION

Metal matrix composites (MMCs) are metals reinforced with other metal, ceramic or organic compounds. Aluminum and its alloys have attracted most attention as base metal in metal matrix composites because of its low density, low weight, high strength, superior malleability, easy machining, excellent corrosion resistance and good thermal and electrical conductivity [1]. Reinforcement of aluminum and its alloys with ceramic particles, results in advanced metal-matrix composites with precise balances of mechanical, physical and tribological characteristics. The resulted aluminum matrix composites offer superior combination of properties in such manner that today no existing monolithic material can rival [2].

There has been an increasing interest in composites containing low density and low cost reinforcements.

Among various reinforced ceramic materials used, fly ash is one of the most inexpensive and low density reinforcement available in large quantities as waste product during combustion of fuel in thermal power plants. Composite with fly ash, as reinforcement, and recycled aluminum, as matrix, are likely to overcome the cost barrier, as well as, the different physical and mechanical properties for widely used in many engineering applications. So, many papers focusing on such composites had been published. J. Babu Rao et al. (2010) [3] developed a light weight Al-Fly ash composites prepared by stir casting route, H.C. Anilkumar et al. (2011) [4] investigated mechanical properties of fly ash reinforced aluminum alloy (Al6061) composite prepared by stir casting method, Pradeep Kumar J et al. (2015) [5] studied characterization and production of Al-Cu alloy reinforced with fly ash and silicon carbide, Liang-Jing Fan et al. (2016) [6] discussed reaction effect of fly ash with Al–3Mg melt on the microstructure and hardness of aluminum matrix composites. There are little attempts to use recycled aluminum instead of pure aluminum as a matrix to produce composite; certainly, the recycled aluminum-fly ash composite is more economical than other one. In addition, the fly ash used in these papers represents a product of coal combustion that differs in its chemical composition and properties from fuel combustion fly ash. So, the aluminum used to produce Al-MMC in this study is recycled aluminum from used beverage cans (UBCs), while the reinforcement is fly ash as a powder residue generated at Al-Musayab power plant-Babylon/Iraq.

2. MATERIALS

2.1. MATRIX MATERIAL

The matrix material used in this experimental investigation was recycled aluminum from used beverage cans (UBCs) whose chemical composition (wt%) is listed in Table 1.

TABLE 1- Chemical Composition of Recycled Aluminum from Used Beverage Cans (UBCs)

Si%	Fe%	Cu%	Mn%	Mg%	Cr%
0.224	0.503	0.160	0.761	1.230	0.019
Ni%	**Zn%**	**Ti%**	**Pb%**	**V%**	**Al%**
0.004	0.067	0.022	0.009	0.011	Bal.

The recycling of aluminum generally produces significant cost savings over the production of new aluminum, even when the cost of collection, separation and recycling are taken into account. Recycled aluminum uses 5% of the energy that would be needed to create a comparable amount from raw materials. This means energy savings as well an environmental savings duo to the reduction in the emission of polluting gasses through aluminum extraction processes [7].

2.2. REINFORCEMENT MATERIAL

Reinforcement material used in current study is fly ash. Fly ash is a powdery residue generated by plants that use oil as the source of fuel. In Iraq, heavy and crude fuel oil are used in thermal power plants, where the used fuel is heavy oil, crude oil or mixed of them. Physical properties of fly ash mainly depend on the type of fuel being burned and the burning conditions.

The chemical composition of fly ash vary considerably depending upon the source and makeup of the fuel being burned. Chemical composition of fly ash resulted from burning mixture of heavy and crude oil (from Al-Musayyib thermal power plant-Babylon/Iraq) is shown in Table 2.

The presence of oxides and metals in fly ash makes it favorable as strong and light-weight reinforcement to the metal matrix composites. Fly ash was milled for (1) hour to eliminate from all particle segregation. Particle size analysis of fly ash was carried out using laser particle size analyzer, the average particle size of milled fly ash was (3.702) µm according to the report shown in Fig. 1.

TABLE 2- Chemical Composition of Fly Ash

Na2O	0.057	**CuO**	0.00825	**Ga**	0.00123
MgO	0.11	**ZnO**	0.01542	**Mo**	0.0091
Al2O3	0.31	**As2O3**	0.00058	**Na**	0.42
SiO2	0.15	**Rb2O**	0.00023	**Mg**	0.066
P2O5	0.0303	**SrO**	0.00967	**Al**	0.016
SO3	12.54	**SnO2**	0.00066	**K**	0.1484
K2O	0.1864	**BaO**	0.00447	**Ni**	0.7651
CaO	0.932	**WO3**	0.0037	**V**	3.001
TiO2	0.2165	**PbO**	0.00452	**Fe**	10.04
V2O5	5.416	**CoO**	0.0056	**Ca**	0.6511
Cr2O3	0.073	**NiO**	1.002	**Zn**	0.01181
MnO	0.0756	**Si**	0.0071	**W**	0.003
Fe2O3	14.63	**S**	4.947	**C**	41.1

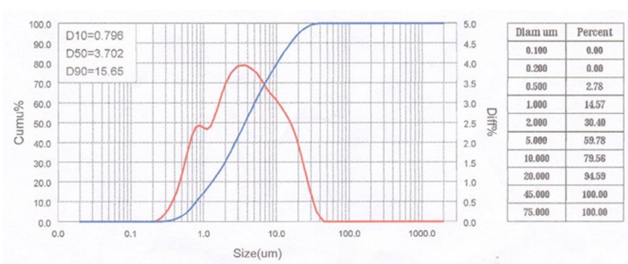

Fig. 1 Particle size analysis report

3. EXPERIMENTAL PROCEDURE

3.1. MELTING OF UBCS

More than 500 used beverage cans (UBCs) are collected, and cleaned with water, as an initial step. The cans were cut into small, equal, pieces to reduce the size and facilitate placed in a pressing machine, then, the pieces were pressed, using computer control electronic pressing device, to obtain a small compacts as shown in Fig. 2. The compacts were put in graphite crucible for melting inside an open gas furnace. Temperature development inside the crucible was monitor using thermocouple type-K, the compacts were completely melted in temperature range between (680-700)^{0}C. An argon stream was applied on molten metal to eject the slags on surface, then, remove the slags using alumina spoon. Subsequently, molten aluminum alloy was poured in a preheated metallic mold. The process was repeated many times to ensure that all slags and impurities were eliminated.

3.2. FABRICATION OF RECYCLED ALUMINUM- FLY ASH COMPOSITE

Four samples with different weight percentage of reinforcement were prepared by two-step stir casting method. The composition of each sample are shown in Table 3.

Fig. 2 UBCs compacts

TABLE 3- Samples Prepared in the Present Study

Sample Code	Recycled wt %Al	Magnesium (wt%)	Fly Ash (wt%)
S0	98	2	0
S1	95	2	3
S2	92	2	6
S3	89	2	9

The recycled aluminum rods were cut to small pieces in order to facilitate its melting in the furnace. Each of recycled aluminum pieces, magnesium, and, fly ash were weighted in desired amount (weight percentage wt%). The weighted fly ash particles were divided to many groups, each group have about (0.5 g) in weight, then, each group was covered with aluminum foil and preheated to (300^{0}C) for 2 hours in dry oven to remove the moisture content and improve the wettability.

Recycled aluminum pieces were charged in to the graphite crucible, and the furnace temperature was raised up to liquidus temperature (750^{0}C) in order to melt aluminum completely. An argon stream was entered inside the molten metal through a brass tube in order to float slags on the surface. Then, slags were removed using alumina spoon, and further the melt temperature was dropped to just below the liquidus temperature (620^{0}C) to attain the semi solid state. The magnesium ribbon were rolled and covered by thick aluminum foil, and then immersed inside the melted to reduce its combustion.

The molten aluminum slurry was stirred with mechanical mild steel stirrer with stirrer speed (870 rpm) for (10 min) and the preheated, covered, fly ash particles were slowly added to the molten metal during stirring. The design of the stirrer blade is very important factor, which affect the particle distribution and strength of the composite. For comparison, the operation is carried out two times by using two different stirrer blades design as shown in Fig. 3. The result of microstructure analysis showed non homogeneous particle distribution and segregation for the composite stirred with three-blades stirrer (Fig. 3 A), while optimum particle distribution for composite prepared with four-blades stirrer (Fig. 3 B). Thus, 4-blades stirrer was used for stirring in this work.

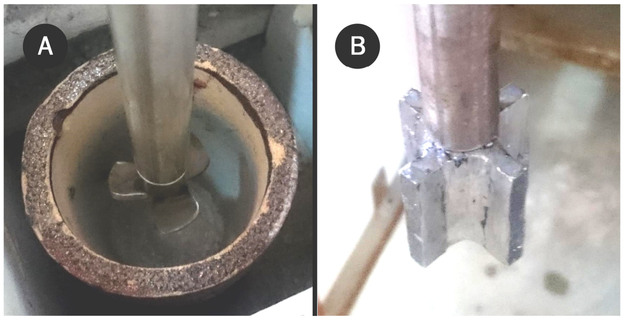

Fig. 3 Stirrer blades design

The temperature during stirring was observed, using thermocouple type-K, to be (610-620)^{0}C. Then, the temperature was raised above the liquidus temperature (750^{0}C) again. The molten composite was stirred at this temperature for the same speed and time. Finally, the molten composite was poured in preheated steel mold to solidify. The operation was repeated for each fly ash percentage. For comparison, Al-Mg was casted in the same procedure without adding fly ash. The prepared stir casting system is shown in Fig. 4.

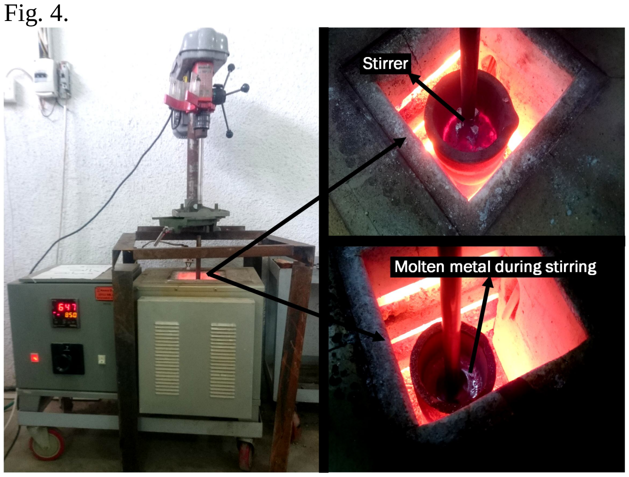

Fig. 4 Stir casting process

All prepared samples were put in an electrical furnace at (300^{0}C) for (3 hours) and cooled inside the furnace to remove all thermal and mechanical stresses. Then, the composite samples are ready to prepare for mechanical and physical tests.

3.3. Mechanical & Physical Tests

Many of mechanical and physical properties were tested for all samples. It
.includes tensile strength, Brinell hardness, wear resistance, as well microstructure analysis.

3.3.1.Microstructure Test

Specimens with (20mm) in diameter, were cut from each samples. These specimens were flattened using SiC grinding papers having different roughness (180, 220, 320, 400, 600, 800, 1000, 1200, 1500, 2000, 2500 grit size). Then, the specimens were polished using diamond paste to produce flat, scratch free, mirror like surface. The specimens were etched by (0.5% HF, 99.5% Distilled H_2O) for (15 second) at room temperature, then the specimens were washed with distilled water, and dried by electric dryer. An optical microscope with suitable magnification was used to capture the microstructure of each samples.

3.3.2. Brinell Hardness

This test was carried out according to ASTM (E10-15a) [8], with a ball indenter diameter of (5mm), and load of (31.25g) for (10 second). The hardness was recorded as an average of three hardness measurements for each specimen.

3.3.3. Tensile Test

Standard specimens were prepared with dimensions shown in Fig. 5 for each sample, according to ASTM (B557m-15) [9] The test was carried out via universal testing machine with tensile speed rate (0.1 mm/min) at room temperature.

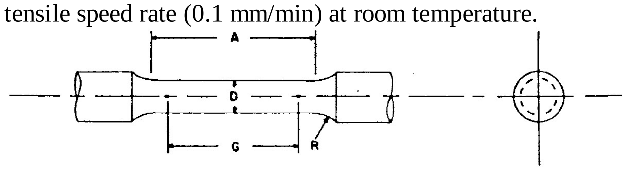

Fig. 5 Standard Round Tension Test Specimen [108].

Where: Gage length (G): (25.0 $\pm$ 0.10) mm; Diameter (D): (6.25 $\pm$ 0.12) mm; Radius of fillet (R): 5 mm; Length of reduced section (A): 32 mm.

3.3.4.Pin on Disk Wear Test

In wear test, specimen of (10mm) in diameter and (8mm) in height were prepared for each composite samples, according to ASTM (G99-04) [10]. Prior testing, the specimens were ground with SiC papers until the average surface roughness reached (0.8 µm). Then, the specimens were weighted using sensitive electric balance with +0.0001 accuracy. Pin on disk concept was used to study dry wear as shown in Fig.6 via wear test device. The tested specimens were set as a pin against standard rotating steel disk with hardness of (850 HV). The test was carried out under these conditions: normal force on the pin (F): (10, 15, and 20) N, wear track radius (R): 5 mm, rotating speed of the disk (V): 300 rpm. The specimen was weighted after (5, 10, 15, and 20 min) to determine the weight lost. Then, weight loss was converted to volume loss according to following equation:

$$\text{Volume loss mm}^3 = (\text{weight loss g/density g/mm}^3) \qquad (1)$$

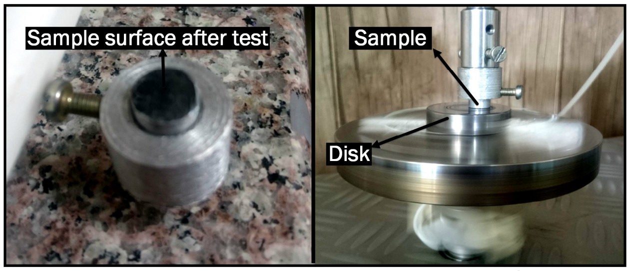

Fig. 6: Pin on disk concept and sample during and after testing

4. Results and Discussion

4.1. Microstructure Test

Fig. 7 shows the microstructures of recycled aluminum-fly ash composites. A uniform distribution of fly ash particles without voids and discontinuities can be observed from these micrographs. It was also found that there was good bonding between matrix material and fly ash particles; however no gap is observed between the particle and matrix. It is clearly shown that the use of stir casting during preparation of these composites induced an acceptable distribution of the reinforcing fly ash particles.

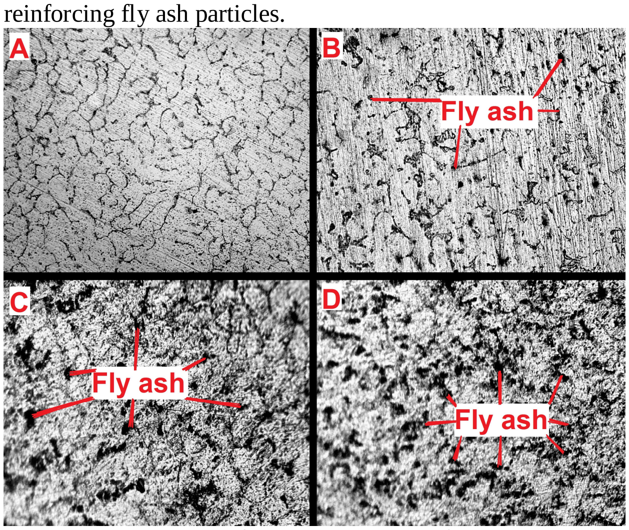

Fig. 7 Microstructures of recycled aluminum-fly ash composites: (A): S0; (B): S1; (C): S2; (D): S3

4.2. Mechanical Tests

The results of Brinell hardness and ultimate tensile strength for prepared samples are shown in Table 4. it was concluded that hardness was increased with increasing of fly ash percentage, and the maximum value was recorded for S3 sample with maximum fly ash percentage (9%). These increment could be attributed to the relatively high hardness of particles itself which acting as barriers to dislocations motion. The relation between Brinell hardness and fly ash percentage in aluminum matrix is shown in Fig. 8.

TABLE 4- Mechanical Properties of Prepared Samples

Sample Code	Brinell Hardness (Kg/mm^2)	Ultimate Tensile Strength (Mpa)
S0	41.89	100.108
S1	59.60	107.807
S2	83.41	120.352
S3	95.36	103.038

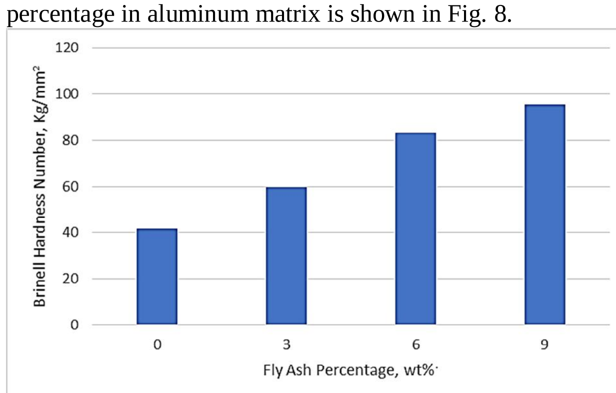

Fig. 8 Variation of ultimate tensile strength with fly ash percentage (wt%)

Tensile strength also increased with increasing fly ash percentage for the same reason above, but until to a certain amount of fly ash (6%). Tensile strength was significantly dropped due to clustering of the reinforcement particles in the composite that has high fly ash percentage (9%). This behavior is clearly shown in Fig. 9.

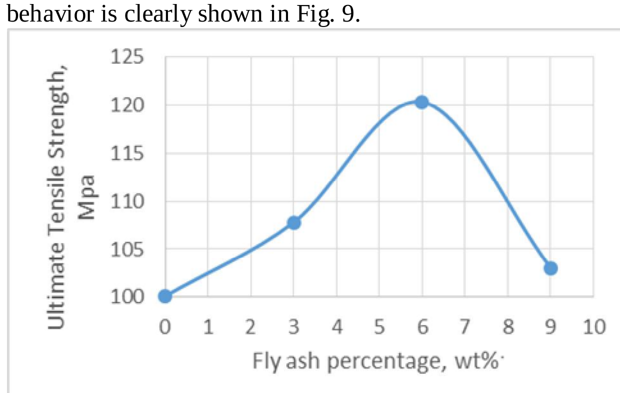

Fig. 9 Variation of ultimate tensile strength with fly ash percentage (wt%)

From Fig. 10 to Fig. 12, it can be noticed that volume loss was decreased with increasing fly ash percentage, this may be due to the role of fly ash particles in blocking dislocation motion, so hardness was increased and subsequently wear resistance was also increased.

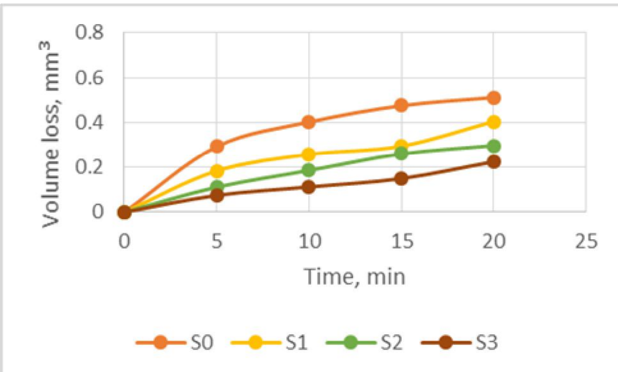

Fig. 10 Wear rate at (300 rpm) rotation speed and 10N load

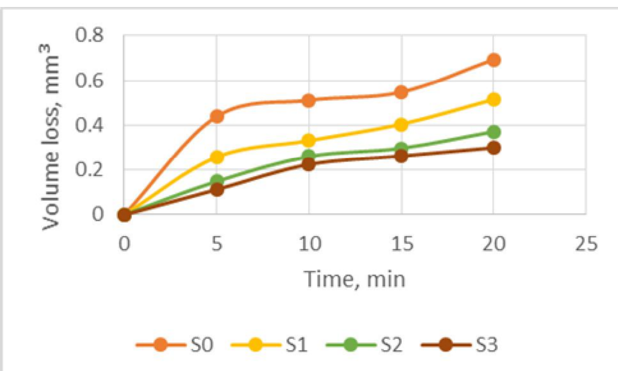

Fig. 11 Wear rate at (300 rpm) rotation speed and 15N load

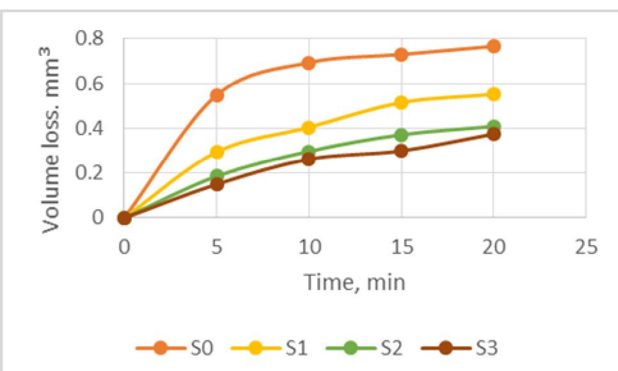

Fig. 12 Wear rate at (300 rpm) rotation speed and 20N load

5. CONCLUSIONS

The recycled aluminum-fly ash composites were successfully fabricated by using two-step stir casting technique with proper distribution of fly ash particles all over the specimen. Also, an appropriate amount of magnesium was added, in order to improve the wettability of fly ash particles by reducing its surface tension. We have drawn various conclusions from the various calculations based on the different experimental testes:

(1) Brinell hardness increases gradually with increment of fly ash percentage due to the role of fly ash particles, which act as barriers to the dislocations motion. The height increment percentage was (128%) for S3 sample.

(2) Tensile strength was gradually increased with increasing of fly ash percentage due to the same reason above, but until to a certain level (S2 sample) after this it diminishes due to the agglomeration of reinforcement particles at higher fly ash percentage. The highest recorded value of tensile strength belongs to S2 sample with increment percentage approximately (21%).

(3) Wear resistance was also increased with increasing of fly ash percentage as a results of high hardness value of reinforcement itself, and the obstruction of movement dislocations by these particles.

Briefly, fly ash along with other reinforcement as Al_2O_3 and SiC, improves the mechanical properties in large amount with keeping densities low. Thus, lightweight-low cost composite with good mechanical properties can be produced by using fly ash as reinforcement in suitable matrix as aluminum.

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