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Evaluating the Microstructure and Residual Stresses of Hybrid Aluminum Composite Formed by Equal Channel Angular Pressing

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by

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Abstract

Hybrid aluminum has drawn much attention from various engineers due to its excellent physical and mechanical properties, like high strength compared to weight and low cost. In this study, hybrid aluminum composites (Al1050/B_4C/FA), consisting of 93% aluminum, 2% boron carbide, and 5% fly ash, are manufactured by the stir-casting process. The manufactured rods are subjected to several cycles (passes) using equal channel angular pressing (ECAP) at room temperature. Channel die angles of 120° and 135° with passes number of 1P, 2P, 3P, 4P, 5P, and 6P are conducted with pressing force from (61 to 88 KN) for 120° die angle while (58 to 79 KN) for 135° die angle. The microstructure of the Al1050/B_4C/FA composite rods was investigated before and after the severe plastic deformation process during ECAP. A destructive method based on the cutting technique (CT) is applied to evaluate the induced residual stresses (IRS) in the axial direction for the initial and the extruded rods at 1P, 2P, 4P, and 6P. Furthermore, the mechanical behavior of the Al1050/B_4C/FA rods is checked before and after ECAP cycles in terms of yield stress, ultimate tensile stress, and hardness. Finally, porosity before and after severe plastic deformation by ECAP is shown. Microstructure results obtained by the OM and SEM revealed that severe plastic deformation significantly affects grain size. The smallest grain size and the best microstructure in terms of homogeneity and the elimination of defects such as voids and cracks were observed at the 120º channel angle in the sixth pass, compared to the 135º. The grain size reached 1-8 µm, while the initial rod was 4-15 µm. The residual stress values for passes 1P, 2P, 4P, and 6P tend to increase due to the effects of SPD compared to the initial rods. As the ECAP cycles increase, the magnitudes of residual stresses start to change; the compressive state of residual stresses is near the rod surface, while the stresses are in tensile state near the center of the composite rod. Regarding the mechanical properties before and after forming for passes 2P, 4P, and 6P,

the results showed an increase in the yield stress, ultimate tensile stress, and micro Vickers hardness with increasing number of passes up to the sixth pass for both angles (120° and 135°). However, the 120° die angle showed higher values for mechanicals properties compared to the 135°. The results of the porosity evaluation for passes 2P, 4P, and 6P revealed a slight increase with increasing number of passes compared to the initial Al1050/B_4C/FA rods. The porosity value at the 120° die angle was higher than at the 135° die angle.

CHAPTER ONE

INTRODUCTION

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1.1 Introduction

The Mesopotamian and Pharaonic civilizations were the first to use composite materials to make clay mixtures for construction 1500 years ago. The Mongols later used composite materials to make war bows 1,200 years ago. The use of composites made of fibers or polymers in military weapons evolved, specifically during World War II, due to their high strength relative to their lightweight, ease of manufacture, corrosion resistance, and low cost compared to ferrous alloys such as steel and heavy metals. In the 1970s, the Japanese developed composite materials for use in the automotive sector to reduce the weight of the vehicle body, which helps reduce fuel costs by increasing the vehicle speed. Furthermore, their use in various vehicle components has increased due to their impact on reducing environmental pollution, as they reduce fuel consumption and are biodegradable materials. Composite materials produce products with superior and unique properties in terms of strength, lightweight, and resistance to various environmental influences, especially in the aerospace industry[1, 2]. This depends on the materials used, such as alumina, boron and silicon carbide, graphite, nitrides, and others. By replacing heavy materials with composites composed of an aluminum matrix reinforced with various types of ceramic materials, industrial waste, and various organic wastes, these reinforcements aim to improve the properties of the resulting composite in terms of chemical composition, mechanical, thermal, frictional, and other behaviors[3]. Recently, researchers' interest has grown in the production and development of composites with reinforced aluminum matrix using more than one type of reinforcement instead of using a single one to produce higher-quality products[4]. A lack of understanding of the importance of these materials can limit their scope of use, so researchers must continue to focus on it. There are many different and varied methods for producing HAMC, and each method has specific production costs, benefits, and limitations. It is divided into two types, firstly liquid state processes include (centrifugal casting, vertex casting, squeeze casting, gas pressure casting, injection molding, spontaneous infiltration, and stir casting). While second one is solid state includes (vapor deposition, friction stir process, diffusion bonding, spark plasma sintering, and powder metallurgy). Among these various technologies stir casting are most common way to produce HAMC due to its simplicity and cost-effectiveness. To overcome the disadvantages of mechanical agitation casting, such as poor dispersion, clumps, and voids, researchers conduct subsequent improvement processes, for example, using severe plastic deformation such as ECAP to improve the quality of the final product[5].

1.2 Materials

1.2.1 Aluminum alloys

In the nineteenth century, precisely in 1888s, aluminum was isolated as an element for the first time, years after its discovery. Aluminum is characterized by its low density, which is equivalent to one-third that of steel (2.69 g/cm^3). In the late 1920s, aluminum began replacing wood in aircraft structures. Its importance lies in its corrosion resistance, ease of manufacturing, low cost, lightweight, high formability, and ability for heat treatment. On the other hand, aluminum has some potential drawbacks, such as its low capability to withstand high temperatures, low modulus of elasticity, and susceptibility to corrosion. However, researchers have been able to overcome these problems through significant improvements by adding various alloying elements and controlling impurities through the study and analysis of their chemical composition. Although aluminum use is likely to decline in the future due to the dominance of composite materials in modern industries, aluminum remains an essential and indispensable element, especially in the aviation and military industries. Aluminum alloys are divided into different series, according to the nomenclature proposed by the Aluminum Association, which are represented by four numbers ranging from 1xxx to 9xxx. Each of these series has specific properties and different alloying elements, resulting in a wide variety of uses for various applications. For example, the first series of aluminum alloys represented by 1xxx, including 1100, 1200, and 1050, establishes exceptional formability and surface finish, and superior corrosion resistance compared to all other aluminum alloys. They are popular for their use in thermal conduction and license plates [6, 7]

1.2.2 Boron carbide

Boron carbide, after diamond and boron nitride, is the third hardest known compound on Earth's crust. It is also the easiest to produce and more economical. The lattice structure of boron carbide is rhombohedral. It is characterized by its low density (2.51 g/cm^3), high wear resistance, and high hardness, making it preferred for various technical and advanced applications requiring high wear resistance. Furthermore, it is used as a reinforcing material in various alloys to improve their mechanical and tribological properties. Compared to other ceramic reinforcements such as silicon nitride, zirconia, silicon carbide, and alumina, boron carbide is lighter in weight and has higher strength. It is also characterized by its chemical inertness and stability at high temperatures. Therefore, it is preferred for usage in the manufacture of abrasive materials that require superior properties. Boron carbide has a high Young's modulus (441- 450 GPa), is widely used as armor or other protective materials against bullets and thermal shocks, as well as in advanced vehicles such as fighter aircraft and helicopters. It is also used in the manufacture of weapons such as explosive devices and nuclear reactors. Furthermore, it is used in electronic applications due to its high thermal resistance, such as sensors for environmental changes, radiation, and pollution. B_4C has a superior ability to absorb neutrons, so it can be used for cancer treatment [8-12]

1.2.3 Fly ash

Fly ash is the industrial waste produced by coal combustion in thermal power plants and is one of the biggest causes of environmental pollution. These power plants generate approximately 500 million tons of waste annually worldwide, with only a small percentage, ranging from 25 to 30%, being recycled and reused in various applications. In recent years, interest in these materials has increased to overcome concerns about environmental pollution and reduce their toxic effects on animals and humans. Fly ash particles are collected from duct gas using mechanical or electrostatic precipitators. The molten drops in the coal solidify at a temperature of 1500°C and form hollow irregular particle sizes of 10 to 50 μm with a low density of approximately 0.54–0.86 g/cm³. The chemical composition varies according to the ambient conditions, cooling system, combustion method, and the type of burned coal. One of the most prominent uses of fly ash is to remove environmental pollutants, as it acts as an absorbent for heavy metals and petroleum pollutants, stains, and other harmful pollutants found in wastewater. Further to prevent soil degradation and eliminate toxic materials in it, the construction sector, which is mixed with cement and concrete to improve its mechanical properties, and with composite metals or polymer matrix material to produce high-strength with low-weight ratio components. Moreover, fly ash is utilized in thermal spray coating techniques [13-18].

1.3 Stir Casting Technique

The basic concept of stir casting is to incorporate the reinforcing materials directly into the matrix and use a mechanical stirrer to dispersive them within the molten mixture. The mixture is then poured into designated molds and left to cool. The mixing process must be carried out thoroughly to ensure even distribution of the reinforcements, as their density is usually different from that of the matrix. If not mixed completely, they will settle to the bottom of the crucible, affecting wettability and uniform distribution. This method is one of the most economical and easy-to-perform methods for producing a hybrid aluminum composite. It must be carried out in an inert atmosphere to ensure that the molten material does not react with atmospheric elements, which could affect the product's quality and mechanical properties [19].

1.3.1 Parameters effect on stir casting

1.3.1.1 The stirring speed

One of the most important factors affecting pouring is the stirring speed, as it controls the formation of the vortex through which the reinforcement additives are distributed in the matrix and influences the wettability and homogeneity. The speed must be appropriate, and because it depends on the design of the stirring blade, it is impossible to specify a certain value [20, 21].

1.3.1.2 Proper mixing time

Contributes to homogeneous particle distribution to improve mechanical properties. A short stirring time results in uneven particle dispersion and agglomeration, while a long stirring time can lead to blade distortion. As with stirring speed, a specific value cannot be determined because it depends on the design of the stirrer blades [20, 22].

1.3.1.3 Melting and pouring temperature

The pouring temperature and the distance between the crucible and the die casting affect the quality of the final product to avoid clustering or porosity. The temperature must be appropriate; high temperatures reduce viscosity, while low temperatures cause agglomeration [20, 23].

1.3.1.4 The blade's design

The design of the stirrer blades plays a crucial role in enhancing mixing quality and creating a vortex. Blades made of stainless steel or coated with materials that can withstand high temperatures and prevent unwanted interaction with the molten material [22, 24].

1.3.1.5 Preheating of mold

Preheating the casting die to a high temperature can have negative effects on the product and reduce the mold's lifetime. Also, if the casting die is too cold, it leads to a reduction in the mechanical properties [20, 22]

1.4 Severe Plastic Deformation

The field of severe plastic deformation (SPD) has a long history spanning centuries, and over time, its popularity has grown and its application has expanded across various fields. Initially, (SPD) processes have been a fundamental and important part of human life since the Bronze Age, when basic tools for food preparation and primitive weapons such as swords were manufactured. One of the first scientists to discover the importance of this method was physicist W. Bridgman, who won the Nobel Prize in 1946 for his work on the effects of severe plastic deformation on various metals, polymers, organics, inorganics, and other materials. SPD differs from traditional forming methods in that it maintains the dimensions of the workpiece despite exposing it to severe cumulative stress. The high shear stress generated by this process on the processed material results in the production of materials with an ultra-fine microstructure, reaching submicron, along with excellent mechanical properties [25]. Furthermore, it is used in the solid state for polymer modification, cold metal production, chip reworking, and various advanced engineering applications. There are a wide range of SPD techniques approximately thirteen methods, the most distinguished among those, involve (ECAP) Equal channel angular pressing, (TE) twist extrusion, (SMAT)surface mechanical attrition treatment, (HPTT)high pressure torsion twisting, (MDF) multi directional forging, (HPT) high pressure torsion, (ARB) accumulative roll bonding. Figure 1.1 represents the types of SPD.

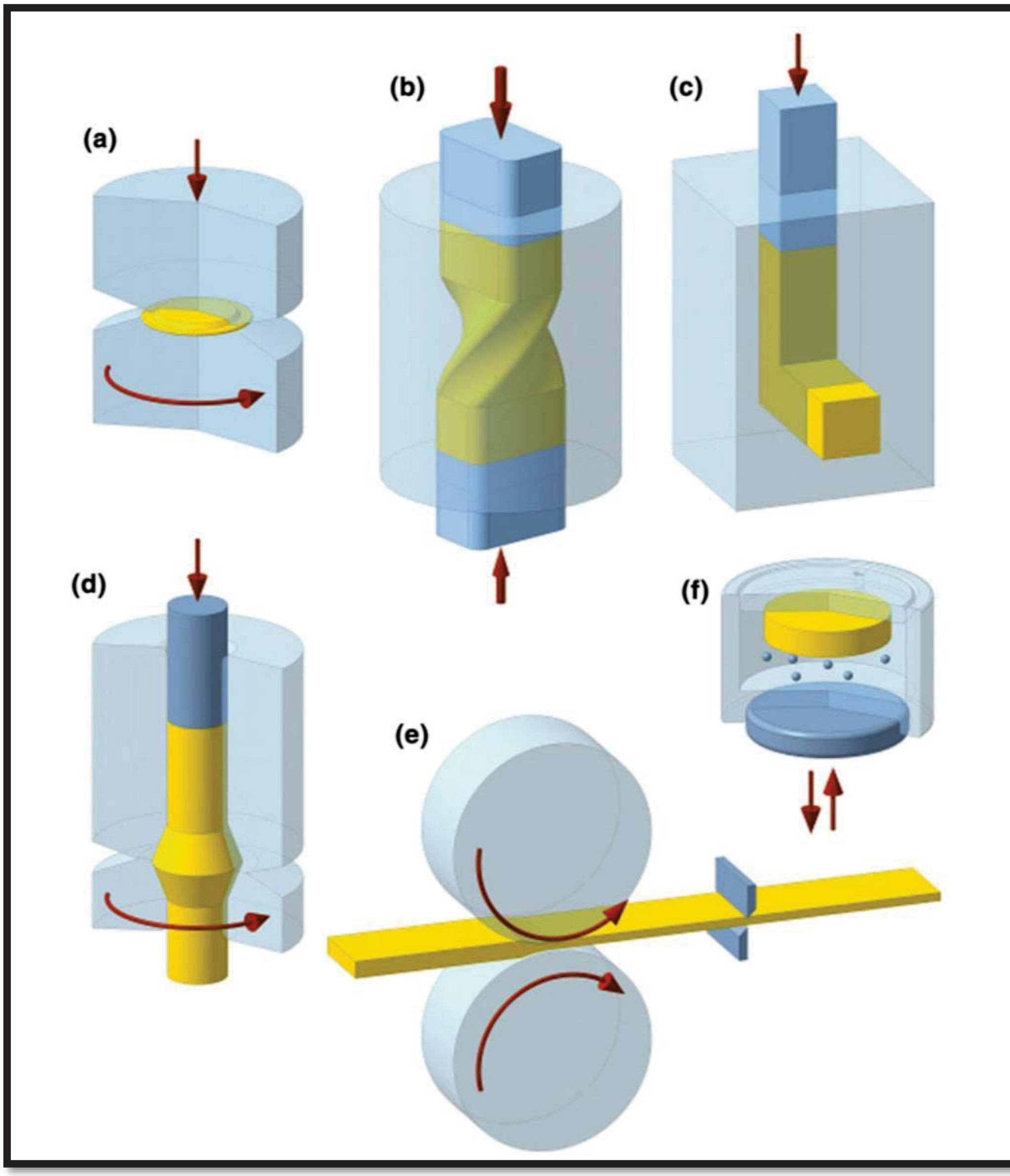

Figure 1.1 Sever plastic deformation types: a(HPT) – b(TE) – c(ECAP) – d (HPTE)– e(ARB)- f (SMAT) [26].

1.5 Equal channel angular pressing (ECAP)

Equal channel angular pressing is one of the most important methods of severe plastic deformation. It produces ultrafine-grained materials by subjecting the sample to high shear stress as it passes through an angle of the channel of the ECAP die without any change of its cross sectional area. Undergoing the sample to subsequent passes leads to higher stresses and, consequently, greater deformation, improving the material's properties, and enhancing its mechanical and microstructural efficiency and biocompatibility, while taking into account factors affecting process quality [27].

1.5.1 Parameters influence on (ECAP)

1.5.1.1 Channel angle

The effect of the ECAP channel angle is one of the most important factors that affect the deformation, controlling mechanical behavior, material flow, microstructure, and strain hardening effects. Experimental results have shown that increasing the channel angle results in a decrease in the amount of deformation. This is due to increasing the inner corner radius, which reduces the deformation area and results in nonuniform stress distribution[28].

1.5.1.2 Pressing speed

Pressing speed has a significant impact on the mechanical and chemical properties of the ECAPed material, especially its effect on wear resistance, as high extrusion speeds lead to surface deterioration, which leads to a decrease in hardness, in contrast to lower speeds[29] .

1.5.1.3 ECAP temperature

The temperature used during the extrusion process by ECAP can influence changes in mechanical properties, workability, and microstructure. The effect of temperature varies depending on the materials and alloys used. Higher temperatures increase the formability of brittle materials to prevent crack formation, while in other materials, higher temperatures can lead to increased cracking and grain growth [30].

1.5.1.4 Material properties

The initial properties and microstructure of the material before extrusion by ECAP determine the behavior of the material after ECAP. For example, if the initial billet is homogeneous and fine-grained before pressing, the results are significantly better than those of materials with larger grains[31].

1.5.1.5 Number of passes

Increasing the number of ECAP passes of the sample leads to an improvement in the microstructure and grain refinement, thus enhancing the mechanical properties such as hardness and tensile strength, but to a certain number of passes, as the material may deteriorate when the number of passes increases[32].

1.5.1.6 Back pressure

Backpressure can enhance the workability of some forming or less ductile materials, and it inhibits porosity, improves grain refinement, and increases the dislocation movement within the material [33] .

1.5.1.7 Lubrication effects

The lubrication has great importance in reducing friction; it acts as an insulating layer between the sample and the channel die walls of ECAP, which leads to uniform stress distribution throughout the sample, preventing damage to the sample and die channel walls [34] .

1.6 Residual stresses

Interest in the optimization of residual stresses began in the 1930s due to its significant importance in the industrial field. Residual stresses are generated during each step of manufacturing processes, such as heat treatments, welding, phase transformations, chemical reactions, and machining and forming processes, as a result of elastic and plastic deformations. They are defined as hidden, difficult-to-predict stresses that are generated within a material and remain effective after the absence of external loads or their cause. Recently, the study and evaluation of residual stresses have become a focus of current research. This is because the presence of residual stresses can affect the fatigue life and expected lifespan of materials. RS causes cracks, deformations, dimensional instability, degradation, or corrosion of the material over time, thus affecting its mechanical properties and leading to catastrophic failure if not properly evaluated [35, 36].

1.7 Porosity

One of the defects resulting from interfacial interactions is porosity, which causes a decrease in the mechanical properties of composite materials through creating potential areas for crack initiation or failure. Porosity formed during the stir casting process due to rapid mixing and differences between the reinforcements and the metal density, entrapment of gases and air bubbles in the melt. Porosity can also be caused by inhomogeneous or rapid cooling due to shrinkage during the solidification process. They take several forms, including longitudinal, branched, circular, or small ramified pores [37]. It is well known that through metal forming processes involving high plastic deformation, such as forging, rolling, and other processes, porosity is reduced or eliminated through deformation, as hydrostatic pressure and shear stress promote the collapse and closure of pores and enhance microstructural bonding. However, it has also been discovered that existing pores can also form or expand when subjected to high stress during processing. This means that severe plastic deformation has two opposing effects on porosity that are difficult to predict[37, 38] .

1.8 Aims and Objectives

This study aims to fabricate Al1050/B_4C/FA rods using the stir casting process, then ECAP at two channel angle (120º and 135º) with different forming cycles is used to improve the microstructure, mechanical properties and to evaluate the residual stresses based on the cutting technique as well as to assess the porosity of final rod. The objectives of this study can be included:

1.Study the effect of reinforcements on the microstructure of Al1050/B_4C/FA (as casting).

2. Evaluate the effect of reinforcements on the yield strength, ultimate strength, and hardness of Al1050/B_4C/FA (as casting).

3. Assess the effect of reinforcements on the porosity of Al1050/B_4C/FA (as casting).

4. Investigate the effect of ECAP passes on the microstructure of Al1050/B_4C/FA at channel angles (120º and 135º).

5. Illustrated the effect of ECAP passes on the residual stresses of Al1050/B_4C/FA at channel angles (120º and 135º).

6. Explain the effect of ECAP passes on the yield strength, ultimate strength, and hardness of Al1050/B_4CFA at channel angles (120º and 135º).

7. Clarify the effect of ECAP passes on the porosity of Al1050/B_4C/FA at channel angles (120º and 135º).