Research Progress on Aluminum-based Composites and Applications

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Abstract. People propose higher and higher demands for lightweight materials due to the increasing shortage of metals and energy sources. Since traditional aluminum alloy materials cannot meet demands any more, aluminum-based composites attracted high research attentions in recent years because of the excellent mechanical properties and low density. Silicon carbide (SiC) reinforced aluminum-based composite and carbon nanomaterial reinforced aluminum-based composite are two aluminum-based composites which are used mostly in existing associated studies. The former one has a long research history and it has been applied to aerospace, war industry and automobile field to some extent. The later one is an emerging material that is hardly applied yet. This study is going to introduce research progresses and applications of SiC reinforced aluminum-based composite and carbon nanomaterial reinforced aluminum-based composite.

1 Introduction

Since the development of fused salt electrolysis process in 1866, Al enters into the stage of industrialized mass production. The Al output in China has increased from 7.866 million tons in 2005 to 35.93 million tons in 2019. The development of modern society advocates green economy, energy conservation and emission reduction, which propose many new requirements on materials, including low density, high strength, high rigidity, high tenacity, and adaptation to very tough environments such as strong corrosion, high temperature or ultra-low temperature and high radiation. Although Al alloy material has an application history of more than 100 years, it still has limitations as a metal. On contrast, Al-based composites are superior for the higher strength, higher rigidity, stronger friction resistance and low expansion rate in addition to some excellent properties of Al alloy. This study mainly introduces research progresses and applications of the current mainstream fibers or whisker reinforced Al-based composites as well as the particle reinforced Al-based composites.

2 Research progresses and applications

2.1.SiC particle reinforced Al-based composites

As by-product from industrial production, SiC particles incur significantly lower manufacturing costs compared to silicon carbide fiber (SiCF), whisker, monofilament, etc. Moreover, SiCp /Al can also maintain good mechanical properties under unidirectional stress and present isotropic mechanical properties under bidirectional or three-dimensional stresses. With the increase of SiC particle content, rigidity, wearing resistance and tensile strength of SiCp/Al material are improved significantly, while plasticity declines evidently. Currently, powder metallurgy, squeeze casting, high-energy ultrasonic semi-solid composite technology [1], microwave sintering and heat extrusion technology [2] are common methods to prepare SiCp/Al material. However, these methods all face a problem of interface energy between SiC particles and Al base. Xu Jincheng et al. [3] found that copper plating on SiC particles could improve bonding energy of interface effectively, thus enabling to strengthen comprehensive mechanical properties of materials. Dong Cuige et al. [4] coated Titanium onto SiC particles, which improved uniformity and density of composites significantly and increased mechanical performances, while maintaining certain plasticity. Some foreign researchers [5] also applied ultrasonic wave technology to strengthen binding between SiC particles and Al base to further increase volume fraction of SiC particles. At present [6], SiCp/Al is used to skin of airplane in addition to engine piston and brake disc in the automobile field. Due to the low expansion rate and good shaping performance, SiCp/Al is also extensively applied to tube of satellite T/R component or high-power carrier structure [7]. In recent years, SiC particles can be used as a kind of functional material by mixing other elements. Elkady et al. [8] pointed out that that the composite which was formed by adding SiC particles coated with nano Ni particles and Ni powder into the Al-based metals could adsorb electromagnetic wave and it could be used as a microwave absorber to replace Iron-based or carbon-based materials of the same type. Since hardness of SiC is extremely large and Al alloy is relatively soft, surface quality of materials during precise processing is relatively low. If it uses hard alloy cutter, the cutter may suffer fast abrasion. If ceramic cutter, SCD or

PCD cutter is applied, blades are easy to fall off due to the long-term alternating loads. Moreover, carbon elements can accelerate wearing of the diamond cutter [9]. At present, some studies chose zone laser melting technology to process parts. The zone laser melting technology is mainly applied to aerospace field and it can not only lower R&D cost and period of parts effectively, but also achieve relatively good surface quality [10].

2.2. SiC whisker reinforced Al-based composite

Compared with SiC particle reinforced Al-based composite, SiC whisker reinforced Al-based composite has better flexural behaviors, tensile performances, elasticity modulus and thermal conductivity. Yue Shanmi et al. [11] prepared SiC whisker on the carbon base by using hydrogen silicon oil as the raw material, which lowered the preparation cost of whisker and increased safety. Nowadays, SiC whisker reinforced Al-based composite attracts increasing attentions from the public, but the SiC whisker often is mixed into Al-based materials as reinforcement materials together with other ceramic materials, such as aluminum oxide, graphene and carbon nanotubes. Currently, there are single means to prepare SiC reinforced Al-based composites, mainly using powder metallurgic method. Due to the relatively low Van Der Waals' (VDW) force among whiskers [12-13], SiC whiskers can scatter better in Al-based materials than carbon nanotubes and thereby gain better mechanical properties. As the same with SiC particle reinforced Al-based composite, SiC whisker reinforced materials are difficult to be processed. Geng Lin et al. gained workpieces with good surface quality by using diamond cutters and special technological parameters. [14] whisker reinforced Al-based composites which are prepared through casting and powder metallurgic technology often have pores, thus declining mechanical properties (e.g. fatigue strength) of materials. The incremental constraint multidirectional forging method [15] proposed by Xu Wencheng et al. avoided cracking problem in the forging process, forged pores, loose structures and other defects effectively, and refined crystals to achieve uniform composition and improve mechanical properties of the material. Therefore, the processed materials could be used to manufacture key bearing parts in aerospace or weapon vehicles.

2.3. Carbon nanotube reinforced Al-based materials

Carbon nanotube (CNT) is divided into multiwalled carbon nanotube and single-walled carbon nanotube. The later one is hardly studied due to difficulties in preparation and insignificant reinforcement of Al-based materials [16]. CNT reinforced Al-based composite is the nanocarbon reinforced Al-based composite which is studied firstly. Nowadays, powder metallurgic method is the main method to prepare CNT reinforced Al-based composite. CNTs are easy to form clusters because of VDW force, thus resulting in uneven composition of the base and declined properties of materials. In the recent decades, several technologies have been developed, such as high-energy ball milling, flake powder metallurgy, polymer pyrolytic chemical vapor deposition, slurry blending, stirring friction processing. These technologies are beneficial for uniform scattering of CNTs in Al base.

For instance, Wang Lei et al. prepared a composite with uniform distribution of CNTs by assuring uniform growth of CNTs on flake Al alloy powder by using the chemical vapor deposition (CVD) technology and pressing sintering. The elasticity modulus and tensile strength of the 3%CNT/Al composite were increased by 74.1% and 31.4%, while the elongation at break declined to 1.5%, which was significantly lower than the base material. [17] Existing studies on CNT reinforced Al-based composites mainly focus on how to improve plasticity of materials. After preparing 2% (mass fraction) CNT/Al through the fake powder metallurgic method, N.Y.Li et al. compacted materials through heat extrusion with high extrusion ratio. CNT and Al base reacted to form Al4C3 to reinforce interface bonding between CNT and Al base. Moreover, CNT generated bridge joint along the extrusion direction, which increased tensile strength of the materials while maintaining plasticity. [18] Finally, elongation of materials was 30%, accompanied with equivalent plasticity of base material. However, quantity and distribution of Al4C3 are difficult to be controlled. Some researchers implemented electroplating or chemical deposition of silver [19], copper [20] or Ni [21] on CNT surfaces to reinforce bonding between base material and CNT, thus enabling to transfer stress from base materials to reinforcement materials. However, none of them are easy to get uniform and complete cladding layer. X.Q.Liu[22] formed CNTs with TiC through sintering and used it to prepare CNT reinforced Al-based composite. Ti which is a buffer medium forms the TiC-TiAl3-Al structure at the interface, which strengthened the bonding between base and CNTs and increased plasticity and strength of materials. Moreover, smaller size of Ti particles is more beneficial for load transmission efficiency among interface layers [23]. Electric and thermal conductivities of CNT reinforced Al-based materials are also research hotspots. High-strength Al conductor is in favor of long-distance power transmission. High-strength Al-based materials can consider electric conductivity while manufacturing structural components, such as some parts in new energy vehicles. At present, agglomeration of CNTs, interface bonding with bases and anistropism of arrangement are main factors that influence thermal and electric conductivities of CNT reinforced Al-based materials [24-25]. Chen Liang et al. proposed a preparation technique for sandwich-shaped CNT reinforced Al-based composite, which improved both strength and electric conductivity of materials [26].

2.4. Graphene reinforced Al-based composite

Graphene is one of the most potential materials in the 21st Century and there are many preparation methods, including liquid-phase stripping method, redox process, CVD and epitaxial growth method [27]. At present, power metallurgic method, stirring casting method, in-situ growth method, pressure penetration method and 3D printing technology [28] are applied to prepare graphene reinforced Al-based composite. The micro-nano laminated powder metallurgic technology [29-30] which was developed by Zhang Di and Li Zhiqiang has built up a production line with annual output of 20 tons. In future, existing Al alloy material could be replaced to decrease weights by 10%~30%. Compared with CNT reinforced Al-based composite, graphene reinforced Al-based composite shows better tensile strength, plasticity and heat and electric conductivities [31-32]. Similar with CNTs, dispersion degree of graphene in base materials and interface bonding with base material are main factors that influence mechanical properties and heat and electric conductivities of graphene Al-based composite. At present, graphene and base metal powder are mixed evenly through ball milling. although ball milling is easy to damage graphene structures, it is the most economic and the simplest method and becomes the first choice of people. The research team of Han Tielong modified graphene surface with low-temperature ball milling technology [33] and nano metallic powder[34], and found that ball milling after coating copper or Ni nano powder on graphene layer can increase dispersion degree of graphene and improve interface bonding effectively compared to direct ball milling under room temperature. MahmoodKhan performed in-situ synthesis of titanium carbide coating on the graphene surface [35], which was cleaner and easier to be controlled than direct coating of a metal layer on graphene surface. Moreover, the interface strength between graphene and the base was improved accordingly. In addition to be a structural component, graphene reinforced Al-based composite can develop new functions by mixing with other elements, such as preparation of antibacterial materials [36] and hydrogen manufacturing material [37].

3 Conclusions

The fast development of modern industry proposes higher requirements on materials. Industrial development can break bottlenecks as long as breakthroughs in material performance are achieved. In addition to SiC reinforced Al-based composite, ceramic particle reinforced Al-based composite also includes basalt reinforced Al-based composite [38-39]. Some researchers added CNTs or graphene and ceramic materials together into Al-based composite [40]. Al-based composite materials have to overcome following problems to realize large-scaled applications: 1. Preparation of raw materials, especially, mass production of graphene, CNTs and other carbon fibers. 2) Preparation of composite, including synthesis of metal sheets with stable mechanical properties. 3) Processing of finished products. Existing studies on Al-based materials mainly focus on synthesis of materials, and only few studies discussed processing techniques of finished products. Applications of Al-based composite mainly concentrate in aerospace and war industry. The high processing cost restricts Al-based composite within the civil field. With continuous progresses in R&D, Al-based composite enjoys a promising application prospects and it is beneficial to lower consumptions of metals and energy resources.

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