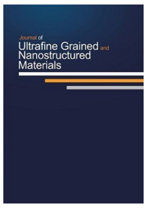

Journal of Ultrafine Grained and Nanostructured Materials
https://jufgnsm.ut.ac.ir
Vol. 52, No.2, December 2019, pp. 188-196
Print ISSN: 2423-6845 Online ISSN: 2423-6837
DOI: 10.22059/jufgnsm.2019.02.07

New-emerging approach for fabrication of near net shape aluminum matrix composites/nanocomposites: Ultrasonic additive manufacturing

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Recieved: 1 October 2019; Accepted: 27 November 2019

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ABSTRACT

Recently, high-performance lightweight materials with outstanding mechanical properties have opened up their way to some sophisticated industrial applications. As one of these systems, aluminum matrix composites/nanocomposites (AMCs) offer an outstanding combination of relative density, hardness, wear resistance, and mechanical strength. Until now, several additive manufacturing methods have been developed for fabrication of 3D metallic components among them, selective laser melting (SLM), electron beam melting (EBM), laser metal deposition (LMD), Wire+Arc additive manufacturing (WAAM), and ultrasonic additive manufacturing (UAM) are of prime significance. Unlike other methods, in ultrasonic additive manufacturing, the ultrasonic waves are used instead of applying the sintering process. This technique is well-known for its ability to produce 3D components by repeating the alternative welding and machining procedures at low temperatures. This is why it can overcome the technological issues arisen from the high-temperature sintering. The present review strives to provide an inclusive introduction to the principles of ultrasonic additive manufacturing method and recent advances in ultrasonic additive manufacturing of aluminum matrix composites/nanocomposites. Also, the challenges of this new emerging technique, i.e. its dependence to the applied weld power, is addressed in the paper. The authors attempt to give some perspectives to the researchers for further investigations in this new-emerging field.

Keywords: *3D printing, ultrasonic additive manufacturing, metal matrix composites, microstructural features, mechanical properties, microstructure evolution.*

1. Introduction

A literature review on fabrication methods of AMCs reveals that a wide variety of techniques are developed to distribute the ex-situ and in-situ reinforcing agents within the bulk structure [1-3] including stir casting [4-6], ultrasonic cavitation based solidification [7], infiltration process [8, 9], centrifugal casting [10-12], powder metallurgy [13-16], mechanical alloying [17-19], and spark plasma sintering (SPS) [20-23] or incorporate the reinforcements into the surface layer of the substrate by plasma spraying [24], laser surface engineering (LSE) [25, 26], and friction stir processing (FSP) [27-29]. The selection of these fabrication methods generally shares a common limitation on the production capability of these routes. It means that from a technical standpoint, it is difficult (and sometimes impossible) to obtain components with a high geometrical complexity through these methods. To overcome this challenge, additive manufacturing (AM) technology has been developed for the fabrication of three-dimensional (3D) components. This new-emerging technology owes its rapid growth to its capability in producing components with almost any geometry and any degree of complexity. In this technology, a final net-shape component is fabricated through the deposition of material in a layer-by-layer or point-by-point manner. To do so, AM utilizes a computer-aided design (CAD) and becomes capable of developing intricate geometries such as topologically optimized components and lattice structures. Earliest attempts to develop the layer manufacturing of 3D geometries via CAD dates back to late 1980s, when the main attempt was focused on the production of prototype parts and their modeling [30, 31]. In 1987, the rapid prototyping was carried out by the stereolithography of the UV light-sensitive polymer layers using a laser beam for the first time [32]. However, the modification of rapid prototyping processes paved the way for the emergence of novel and efficient techniques by which the final net-shape 3D components can be easily produced [33, 34]. This is why the demand for AM technology is progressively growing in the sophisticated industries such as aerospace, biomaterials and architecture [35-38]. A variety of classifications are proposed for the AM techniques. One way of classification is based on the material feedstock, energy source, shape or build volume, and other processing parameters [39]. Another standard categorizes the AM methods based on the physical state of used material systems before or during the deposition process. In this classification, the AM techniques are categorized into (i) liquid-based, (ii) solid-based, (iii) powder-based, and (iv) wire-based ones. Another classification divides the AM systems into two major categories given the building shape: (i) 2D and (ii) 3D techniques [40]. However, the ASTM F2792 standard has classified AM methods into: (i) binder jetting (BJ), (ii) directed energy deposition (DED), (iii) material extrusion (ME), (iv) material jetting (MJ), (v) powder bed fusion (PBF), (vi) sheet lamination (SL), and (vii) vat polymerization (VP). Fig. 1 summarizes the binding mechanisms involved in each AM technique in conjunction with a rough approximation of the final properties for the produced components.

Just two decades after the primary concept of AM technology emerged, ultrasonic additive manufacturing (UAM) was introduced [41-45]. Solidica Company disclosed some technical details about UAM in May 2001, as a technique combining the computer numerical control (CNC) machining with ultrasonic welding. Albeit it was employed for the fabrication of Al foams at early years, it was extended to other materials and structures with the development of its technological and scientific aspects [46, 47]. In fact, UAM is a hybrid additive-subtractive process wherein the sheets or strips of similar and/or dissimilar metals are ultrasonically

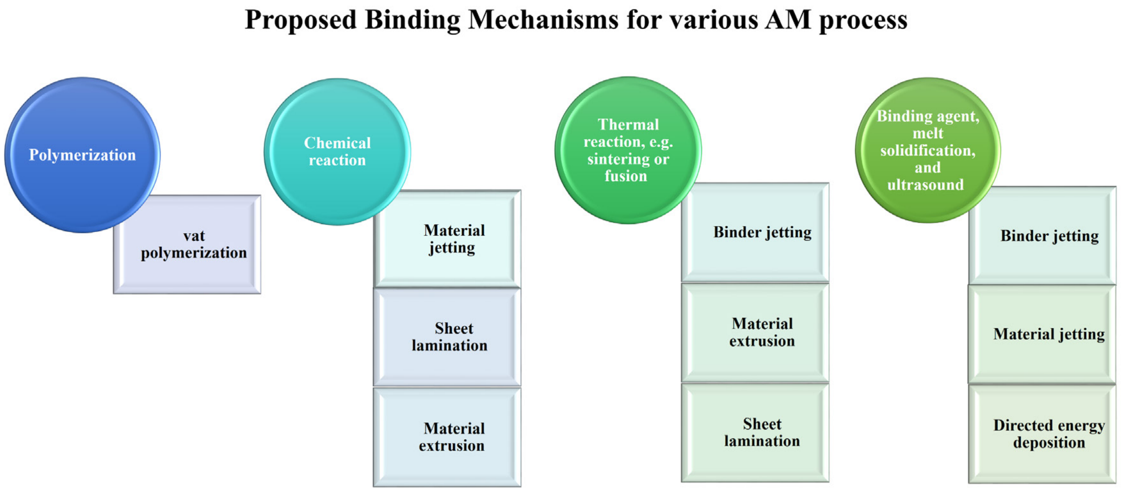

Fig. 1- Binding mechanisms of various AM processes and an approximate estimation of final properties for the parts produced.

welded to the stack using a sonotrode [48-50]. A CNC machine is often used to shape the produced parts into a favorable geometry [41, 51]. This process is characterized by a shear deformation at the interface of layers, facilitating the removal of metallic oxides from sheets' surfaces and their subsequent desirable contact [52]. Indeed, utilization of UAM method, may reduce defects as a result of its solid-state nature and low operating temperature [53, 54].

During UAM, 3D components are formed by repeating the alternative welding and machining procedures. These components can be composed of pure metals, alloys, and MMCs [55, 56]. Recently, a variety of reinforcements has been successfully incorporated into the UAMed Al and its alloys among which NiTi [57], Ti [58], magnetostrictive Galfenol [59], Yttria-stabilized zirconia layers [60],and electroactive polyvinylidene fluoride (PVDF) [61] are the most significant. Compared with conventional composite fabrication methods, UAM takes advantage of comparatively low processing temperature, wherein the final properties of the material system is highly sensitive to the processing temperature. This is the case for NiTi shape memory alloys or the metallic systems in which a chemically active brittle particulate reinforcement is dispersed [62, 63]. Such an intrinsic characteristic provides UAM with some advantages including: (i) the ability to fabricate MMCs with tailorable coefficients of thermal expansion (CTEs), provided that shape memory alloy particles are incorporated [64]; and (ii) the decreased probability for the formation of adverse intermetallic compounds due to the low temperatures nature of the process. If these advantages are fully exploited, MMCs with tunable and well-controlled properties can be successfully developed through UAM [65].

Similar to ultrasonic metal welding, UAM is based on the bonding between successive layers of pre-determined materials. Fig. 2 schematically illustrates the UAM process for Al-NiTi systems.

The frequently used UAM devices include a sonotrode, two boosters, and a transducer. The inclusion of reinforcements into the matrix or the welding of similar or dissimilar materials with UAM is accompanied by the exertion of a mechanical force at the interface of layers, wherein a sonotrode (horn) supplies the normal force. During the UAM process, the ultrasonic vibrations generated by piezoelectric ultrasonic transducers can be longitudinally propagated from the transducer to the sonotrode and subsequently supplied to different parts of the specimen using the rolling sonotrode. The vibrations transmitted to the weld interface can deform it and result in the formation of solid-state bonding between the layers. Thus, it is possible to create large bulk specimens by UAM of successive layers [59, 66].

Although several mechanisms have been suggested for the formation of bonds between metallic layers during UAM, the recrystallization in the interfacial regions of layers is the major phenomenon [67, 68]. In addition, the interfacial adhesion and mechanical interlocking may also affect the bonding performance [69].

To exploit the full potential of UAM, one should deeply understand the relationship between the processing parameters and final properties, because the bond strength of UAMed components is dramatically altered with variations in ultrasonic oscillation amplitude, weld speed (i.e. travel speed of sonotrode), applied normal force, substrate preheat temperature, and sonotrode texture [52, 70]. Thanks to the recent developments in UAM devices now providing ultrasonic powers as high as 9 kW (i.e. 9 times higher than that for the conventional UAM equipment), stronger interfacial adhesion can be generated between the layers [71]. Moreover, when combined with CNC machining system, UAM is capable of producing 3D components with unique shapes and geometries [64].

Depending on the shape and size of the reinforcement, two different approaches exist

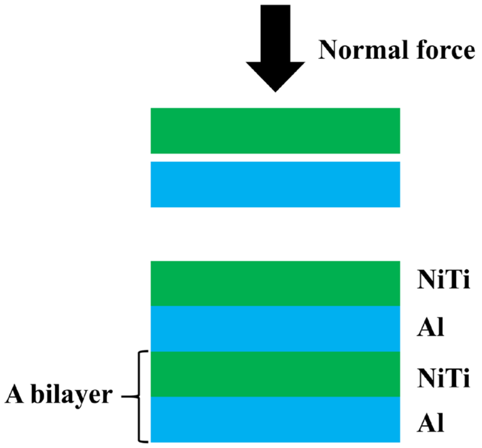

Fig. 2- A schematic view of the UAM process employed for fabricating parts with successive layers of Al and Ti.

for the incorporation of reinforcements into the Al matrix: (i) orientation of reinforcements along the desired directions followed by welding subsequent layers. This is a simple approach often used to incorporate ribbon-like reinforcements and relatively small wires into the Al matrix; and (ii) creation of pockets by machining the formerly consolidated layer followed by their filling with the reinforcements. The second approach provides the incorporation of larger reinforcements with irregular shapes into the Al matrix. This is why it is extensively used for fabricating intricate electronic components and sensors [72].

Despite the aforementioned advantages, UAM suffers from a troublesome challenge: It is strongly dependent on the applied weld power, so that a large number of voids can form when employing relatively low powers. These defects can remarkably degrade the mechanical properties of UAMed composites [64, 73].

2. Microstructural evolution

In UAM, there is no technical restriction for using regular or irregular reinforcements, so that each kind of fibrous, ribbon-like, sheet-like or equiaxed particles can be employed to mechanically strengthen the metallic matrices. For this reason, UAMed composites are often laminar in which the reinforcements are embedded between the matrix sheets. Besides, in-situ synthesized compounds may form as a result of the normal force acting at the interface of sheets. To the best of our knowledge, the literature suffers from a lack of experimental data characterizing the intermetallic compounds, where there is no profound study investigating the possibility for their formation along the inter-plane interfaces. For instance, Hopkins et al. [58] have demonstrated that no intermetallic compound forms at the interface of layers even after the heat treatment post-processing.

Overall, the interfacial adhesion between the matrix and reinforcements, processing parameters, hardness of reinforcements, and thermal and blocking stresses are the determining parameters affecting the microstructure-related properties of UAMed Al-based composites. In this section, these variables are briefly reviewed.

2.1. Interfacial adhesion & Ultrasonic vibrations

As generally believed, the reinforcements may be easily separated from the Al matrix if there is a weak interfacial bonding between them. As shown in Fig. 5-a for UAMed Al-NiTi composite systems [64], NiTi ribbons are completely separated from the Al matrix even before subjecting a mechanical load to the composite. Unlike NiTi ribbons, the intimate contact between galfenol particles and the Al matrix introduces these particles as effective reinforcements in UAMed Al-based composites [59].

The ultrasonic vibrations significantly affect the microstructural features and reinforcement/matrix interfacial bonding in UAMed composites. When in rod-like shape, the reinforcements are more likely to move along the direction of ultrasonic vibrations during the UAM process. This orientation may interrupt the matrix flow and hinder the generation of suitable coupling between the Al matrix and embedded rods. Therefore, it seems essential to consider an optimal value for inter-rod spacing. This leads to a desirable interfacial coupling and minimizes the potential destructive interactions between the incorporated rod-like reinforcements during UAM [59].

2.2. Hardness of reinforcements

Usually, in MMCs, the softer component flows around the surface topology of harder one. In the case of UAMed Al-Ti composites, for example, the superficial asperities of Ti sheets undergo no intense plastic deformation, because Ti is harder than Al. Accordingly, the Al matrix adapts itself to the superficial roughness of Ti sheets. This phenomenon can subsequently result in the generation of mechanical interlocking between the layers and reduce the possibility for the formation of inter-layer metallurgical bonds. In addition, the exposure of sheets surfaces to the sonotrode makes them rough [58].

2.3. Thermal and blocking stress

Thermal and blocking stresses may be generated during the UAM process of Al-based composites, especially for Al-NiTi systems. These stresses arise from the difference between CTEs of the matrix and reinforcements, as well as the blocking behavior of embedded NiTi reinforcements. To further explain, the blocking force or stress is defined as the maximum stress the material or one of its components generates against a steric hindrance or any external limitation [74]. Also, the blocking behavior refers to the total response of a system against the blocking stresses. In case of UAMed Al-NiTi systems, a phase transformation-induced stress may be developed due to the wrapping of incorporated NiTi reinforcements by the Al matrix, where the martensitic phase is thermally transformed to austenite. The generated stresses can drastically degrade the interfacial strength and ultimately lead to the interfacial failure [57, 64, 73]. In a recent study, Chen et al. [75] have tried to minimize the great disparity between CTEs of Al and NiTi by using an experimental-simulation approach. They proved that this difference can be minimized, if the evolving austenite phase is oriented along the $<001>_{B2}$ crystallographic direction. Such a growth minimizes this variable at 25-100 °C. As for tubular reinforcements, the fiber aspect ratio is also another key factor in decreasing the CTEs difference. In general, an aspect ratio higher than 10 is essential to achieve UAMed Al-based composites with appropriate interfacial coherency. As an interesting point, the volume fraction of incorporated NiTi alters CTE of finished composites. Therefore, due to the lower CTE of NiTi than Al, composites containing higher NiTi contents are associated with lower CTEs [57].

3. Mechanical properties

Overall, the mechanical behavior of UAMed Al-based composites strongly depends on the processing parameters, preheating temperature and characteristics of reinforcements. Any small variation in these parameters may greatly affect the stiffness, fracture mode, response to stress and strain, and dynamic behavior of fabricated composites [58, 59]. The following describes the effects of these parameters on mechanical properties of UAMed composites.

3.1. Processing parameters

A review on the literature confirms that the main processing parameters including applied normal force, oscillation amplitude, weld speed, and number of bilayers can significantly affect the mechanical properties of UAMed composites, especially ultimate shear strength (USS) and ultimate transverse tensile strength (UTTS).

3.1.1. Normal force

An increment in normal force increases USS and UTTS of UAMed Al-based composites. However, further increase may slightly degrade them. The reason is not clarified yet, and the exact mechanism is unknown. However, some studies have attributed this phenomenon to the induction of excessive interfacial stresses which can break the bonds existing along the matrix-reinforcement interfaces [58]. In addition, application of a large normal force component may give rise to uneven oscillation of the horn which can significantly reduce the efficiency of the UAM process and degrade the mechanical properties [76].

3.1.2. Oscillation amplitude

There is a linear relation between the oscillation amplitude and mechanical properties, e.g. USS and UTTS. The higher vibratory energy induced by application of higher oscillation amplitude can enhance the USS. Higher oscillation amplitude can satisfactorily remove the present impurities and contaminants on the surface of layers and improve the physicochemical contact between the faying surfaces. In most cases, this favorable phenomenon can intensify the atomic diffusion along the interface [58, 70].

3.1.3. Welding speed

In general, there is an inverse relation between the welding speed and mechanical properties, so that the composites with higher USS and UTTS can be fabricated by using lower weld speeds. Since the welding speed controls the amount of energy input during the UAM process, the slower horn movement across the layers provides sufficient time for direct exposure of the horn to sheets and consequently leads to increased total energy input in the layers. This is obvious that shorter processing times caused by faster welding speeds may lead to insufficient contamination removal and poor plastic deformation at the interfaces [58, 76].

3.1.4. Number of bilayers

An increase in the number of bilayers linearly reduces USS and UTTS of UAMed Al-based composites. In fact, when using higher numbers of bilayers, the division of energy imparted by the horn leads to lower amount of energy received by each interface. This can consequently weaken the interfacial bonding strength formed between the layers [58]. Table 1 summarizes the processing parameters reported recently for fabricating UAMed Al-based composites.

3.2. Operating temperature

The operating temperature can remarkably change the stiffness and dynamic behavior of composites. In case of UAMed Al-based systems, the

Table 1- Processing window employed for fabricating UAMed Al-based composites.

Composite system	Normal force (N)	Oscillation amplitude (µm)	Weld speed (mm/s)	Number of bilayers	Ref.
Al-Ti	500-2000	15-30	21-85	2-8	[58]
Al-NiTi	6600	32.76	84.6	---	[73]

stiffness is degraded with increase in temperature. The insufficient quality of bonding between the matrix and reinforcements is responsible for this degradation [59]. Hahnlen et al. [59] have suggested the following model to predict the influence of temperature on the overall strain value of UAMed Al-NiTi composites [57]:

$$\epsilon_{\mathrm{comp}} = \epsilon_{\mathrm{NiTi}} = \frac{1}{E_{\mathrm{NiTi}}}\left[\frac{(\alpha_{\mathrm{Al}} - \alpha_{\mathrm{NiTi}})(\Delta T)}{\frac{1}{E_{\mathrm{NiTi}}} + \frac{1}{E_{\mathrm{Al}}}\frac{1}{(1-\nu)}} - \frac{\epsilon_L(\xi_s - \xi_{so})}{\frac{1}{E_{\mathrm{NiTi}}} + \frac{1}{E_{\mathrm{Al}}}\frac{\nu}{(1-\nu)}}\right] + \alpha_{\mathrm{NiTi}}(\Delta T) + \epsilon_L(\xi_s - \xi_{so}) \quad \text{(eq. 1)}$$

where E is the elastic modulus, represents the volume fraction of NiTi fiber, α is CTE, is the maximum recoverable strain of NiTi, ξ_s signifies the volume fraction of stress-induced martensite, and ξ_{so} is the volume fraction of initial stress-induced martensite [57]. This model considers the effects of matrix modulus, reinforcement modulus, and operating temperature variation on the strain value of UAMed Al-NiTi composites.

The dynamic behavior of composites (e.g. damping ratio) can be promoted by the temperature rise. The mechanism existing behind this enhancement is not elucidated yet [57].

3.3. Characteristics of reinforcements

The most frequently investigated features of reinforcements closely controlling the mechanical properties of UAMed Al-based composites include the relative content, geometrical aspects, pre-heat treatment and surface treatment.

3.3.1. Reinforcement content

The stiffness and dynamic behavior of UAMed Al-based composites is a direct function of the reinforcement volume fraction [57, 59]. As a general rule, the higher the reinforcement content, the higher the stiffness [59]. Additionally, the natural frequency of pure Al is shown to decline with increase in temperature. This is while the incorporation of NiTi reinforcement into the Al matrix may lead to an improvement in its natural frequency. This enhancement is originated from lower CTE of UAMed Al-NiTi composites than pure Al. The composites containing higher amounts of NiTi reinforcements are associated with higher natural frequencies [57].

3.3.2. Surface treatment

The surface treatment of reinforcements prior to their incorporation into the system can highly remold the bonding mechanisms. Such a treatment can be carried out through common surface treatment processes including electrophoretic, electrodeposition, oxidation, mechanical polishing, and etc. [77-83]. Hehr et al. [73] have studied the influence of four types of surface treatments (i.e. the surface oxidation, roughening, chemical etching, and mechanical polishing) on bonding mechanism and mechanical properties of UAMed Al-NiTi composites. Fiber pull-out test for oxide-treated sample revealed the remaining of Al on the surface of fibers after pull-out. This was attributed to much higher shear strength of NiTi fibers than Al matrix. In oxide-treated composite systems, the pullout force and average shear strength are both affected by the employed surface treatment methods. For example, the composites containing roughened fibers exhibit higher shear strengths [73].

3.3.3. Aspect ratio & fiber length

For a given temperature, the increase in aspect ratio of reinforcing fibers enhances the elongation of composites. Chen et al. [75] suggested a model to study the thermal dependency of strain in UAMed Al-NiTi composites. Due to the reduced axial stress at the fibers ends, the composites containing fibers with lower aspect ratios benefit from higher strains.

Since the shear stress is generated as a result of the blocking force, it directly depends on the pure length of reinforcements. In other words, the importance of fibers length lies behind their key role in the generation of blocking force [64]. Hahnlen et al. [64] have developed a model to evaluate the interface failure temperature as a function of incorporated fibers length. The failure temperature rises with increased fiber length.

3.3.4. Pre-heat treatment

The intrinsic properties of reinforcements are key factors paying role in the mechanical behavior of composites. Whenever the pre-heat treatment of reinforcements can affect their characteristics, it can manipulate the overall properties of composites. This has been reported for UAMed NiTi-Al composites, where the pre-heat treatment of NiTi wires removes the previously induced de-twinned martensite prior to incorporating, and changes the resultant properties [57, 59].

4. Conclusions and future prospect

The UAM technology competes with conventional manufacturing methods in design freedom, part quality and accuracy, fabrication cost, and processing time. Compared to its similar counterparts, UAM benefits from the following advantages in fabricating MMCs:

(i) The high degree of freedom which enables the fabrication of near-net shape components.

(ii) The great potential in low-volume production.

(iii) The possibility of the rapid fabrication of AMCs in a single step.

The future research areas in the field of MMCs production using the UAM technology are believed to span:

(i) Applying UAM technology to a wider variety of MMCs systems with potential applications in industrial sections

(ii) Optimizing the process parameters and finding appropriate process windows for each AMC system

(iii) Producing high-quality parts by minimizing the defects, improving the surface quality and enhancing the part accuracy

(iv) Improving the mechanical properties (i.e. hardness, strength and ductility)

(v) Integrating the UAM technique with nano-materials science and engineering in order to produce AMCs with outstanding physical and mechanical properties

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