Ultrasonic Additive Manufacturing of Dissimilar Material Systems: Method, Post-processing and Properties

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Abstract

Growing number of applications require combination of dissimilar materials in one complex-shape part with gradient of properties. Manufacturing of such smart-designed components has to be based on in-depth fundamental understanding of interactions between materials of different types and the correlation between microstructural features and properties. This knowledge may be applied in the innovative fabricating approach- ultrasonic additive manufacturing, for production of highly-complex parts and devices that could not be fabricated using conventional manufacturing methods, or other additive manufacturing techniques.

Fundamental research of ultrasonic additive manufacturing of dissimilar-material systems and development of their subsequent post-treatment is the major objective of the present work. Spark plasma sintering (SPS) was used as a post-treatment method to enhance the properties of these material systems. Interfaces in the printed and post-treated dissimilar-material systems and their effect on the properties of the fabricated components are discussed.

1. Introduction

1.1. Ultrasonic Additive Manufacturing

Ultrasonic additive manufacturing (UAM) is an innovative method for fabricating 3D products by adding thin layers (as thin as ~0.125 mm) one on top of the other and joining them using ultrasonic vibration, directly from the computer aided design (CAD).

Dimensions of the fabricated parts vary from small to very large (as large as 1.8 x 1.8 x 0.9 m). The heart of the UAM system contains two transducers, which convert electrical power into high frequency vibrations (both horizontal and orthogonal), and a sonotrode horn (Figure 1). The UAM machines are hybrid including both an additive weld head and a subtractive computer numerical controlled (CNC) mill. The quality of the fabricated part directly correlates with many process parameters. It should be noted that the optimal processing conditions are different for each material having its own set of optimal processing parameters.

Amongst the most important parameters are the ultrasonic amplitude (~ 5-50 µm), the applied normal force (~500-8000 N) and the sonotrode horn travel speed (up to 105 $mm \cdot s^{-1}$) [1].

The two piezoelectric transducers convert the electrical power into high frequency ultrasonic vibrations on each side of the sonotrode assembly. Those vibrations are transferred to the rolling sonotrode horn which applies the necessary normal force and side to side ultrasonic vibrations on the thin foil. The scrubbing action removes surface oxides and contaminants and exposes new surfaces. Under a sufficient normal force these nascent surfaces bond and form a joint.

The machine prints series of layers, which are printed in small increments of material, similar to a traditional printer placing ink layers only in specific areas. The final shape of the part forms through placement of series of many layers. By selective printing only at the location of interest at any given layer, internal hollow spaces can be created.

The main advantages of UAM over conventional manufacturing methods, such as casting and forging, are reduced manufacturing costs, the ability to fabricate sophisticated and complex geometries and joining dissimilar metals (Figure 2). Compared to other main metal additive manufacturing methods, such as selective laser sintering (SLS) and electron beam melting (EBM), UAM works at temperatures much lower than the melting temperature of the raw materials ($0.3\text{-}0.5T_m$), avoiding melting and formation of defects associated with high temperature processing. Thus, UAM may be used for additive manufacturing of parts combining dissimilar materials [2,3]. Importantly, due to the low temperatures involved in the process, it enables embedding of electronics, sensors, ceramic reinforcements, manufacturing of metal matrix composites, and more. This important advantage poses UAM as a promising technology for fabricating of full systems having complex geometries and incorporating various dissimilar metals as structural and functional parts, electronics and sensors and other relevant components- in one part and one print job.

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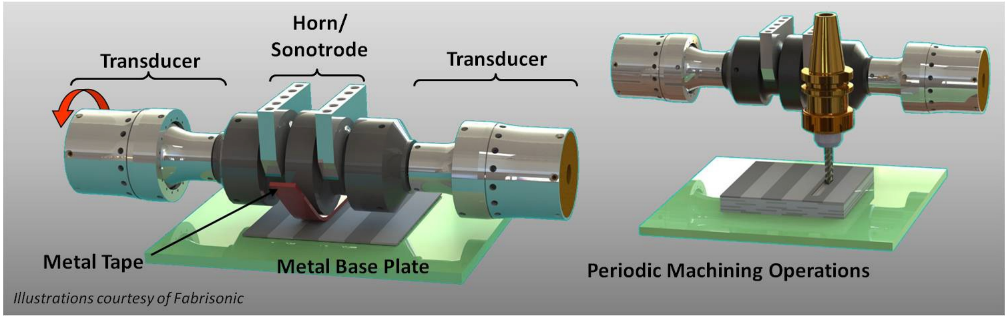

Figure 1: Main components of the UAM machine and the modes of operation (additive and subtractive) [14].

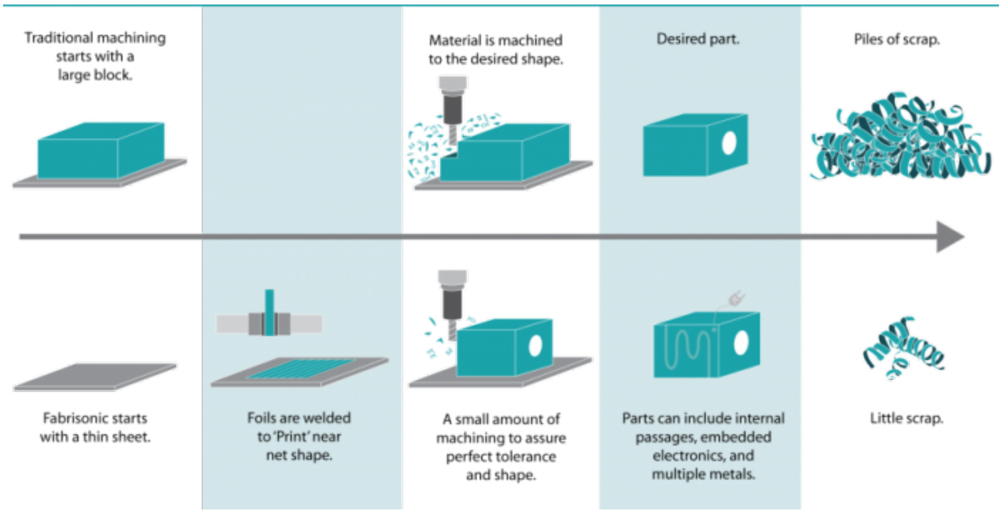

Figure 2: Schematic comparison of traditional machining method with ultrasonic additive manufacturing (UAM) [14].

Previous works on UAM can be divided into three main categories. The first category includes studies of the processing parameters effect and their optimization, the second includes characterization of microstructure at the interface region and the third one includes studies of mechanical properties of the printed materials. The main studied material systems are Al 3003, Al 6061, Al 1100, Ni-Al-Ti composites, FeGa-Al composites and PVDF-Al composites [1-8]. The most common methods for evaluating the mechanical properties of the UAM parts include shear and tensile strength tests, micro/nano hardness and push-pin test [3,4].

1.2. Post-processing

Despite the low temperature involved in the UAM process, printing dissimilar material structures may require post-processing to improve the properties of the fabricated parts, such as mechanical strength along x, y and/or z axes.
As UAM is a solid state process, the post-treatment methods for dissimilar materials should be chosen wisely to ensure compatibility of the treatment parameters, mainly temperature, with all the components in the printed multi-material system. The properties of the lowest-melting-temperature component should be taken into account.
Induction heating furnace is the conventional tool for heat treatment of metallic parts. However, it may only provide elevated temperature, while another important parameter of the solid-state joining, namely pressure, is not applied. Hot press (HP) and hot isostatic press (HIP) combine both heating and pressure and may be used as a post treatment process for similar and dissimilar materials. Recently, spark plasma sintering (SPS) has proven as an appropriate technique for joining similar and dissimilar materials [9-12]. SPS technique utilizes very high electric current and pressure. The electric current heats the conductive metallic samples and the pressure provides their intimate contact at elevated temperature. Remarkable advantages of SPS joining compared to HP and HIP were reported [10]. SPS was reported to overcome these techniques due to higher heating/cooling rates and heating samples

from inside. The SPS technique is fast and efficient in sintering and solid state joining and can be easily controlled. The main disadvantage of the SPS technique is that special design and support structures should be used in fabricating/treating parts with complex geometry.

Recently, UAM-fabricating of multilayered Al 1100/CP-Ti structures was conducted [13] (Figure 3). Conventional induction heating furnace as well as SPS apparatus were used for post-treatment of the fabricated multilayer parts. It was established that the treated samples show increase in mechanical strength as compared to the as-printed (non-treated) ones.

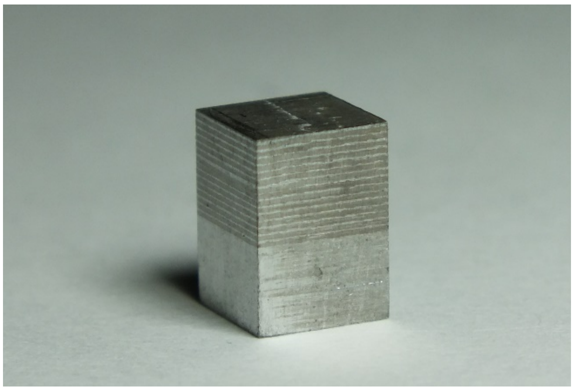

Figure 3: Al1100/CP-Ti sample (5x5x10 mm) fabricated using UAM. Al/Ti laminated structure was printed on the Al 1100 substrate for shear test experiment.

Microstructural evaluations showed no indications of voids or intermetallic formations in the as-printed samples. In the treated samples, a tiny continuous $TiAl_3$ intermetallic layer was formed between titanium and aluminum layers (Figure 4). It was suggested that the intermetallic layer is responsible for the increase in mechanical strength of the treated samples.

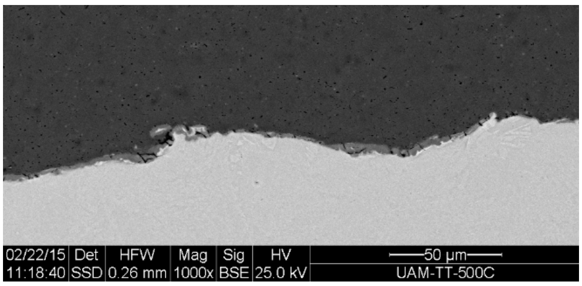

Figure 4: SEM (BSE) image showing the tiny intermetallic layer at the interface between Ti (lower) and Al (upper part) in the SPS-treated UAM part.

Adding chemical bonding effect via the intermetallic layer to the mechanical interlocking effect (forming during the UAM process) turns the post-treated UAM- printed laminates into significantly mechanically-sustainable parts. However, the intermetallic phases are brittle and are known to decrease the mechanical properties of the dissimilar materials joints [9]. Additional investigation of the Al/Ti interaction during post-treatment processing was required.

2. Experimental

Samples (12.7 mm diameter) were diamond-disc-cut from CP-Al (99.0%) and CP-Ti (99.5%), received in the form of 4 mm thick sheet and 12.7 mm diameter rod, respectively.

The mating surfaces of the samples were prepared by conventional metallographic technique with 1 µm diamond paste finish, cleaned with acetone, and dried in air. Each sample was placed in a graphite die with 12.7 mm inner and 40 mm outer diameter, and was inserted in the SPS machine equipped with a 50 kN uniaxial press, type HP D5/1 (FCT System, Rauenstein, Germany). Bonding process was carried out at 500°C for 10-240 min. under argon atmosphere (10^{-2} torr) and uniaxial pressure of 15 MPa. The rate of cooling after joining was about 0.2 deg/s. Four samples were joined for each process parameter. The parameters of the SPS joining regime are presented in Figure 5. SPS-joining imitates the SPS-post-processing conditions of the Al/Ti UAM samples.

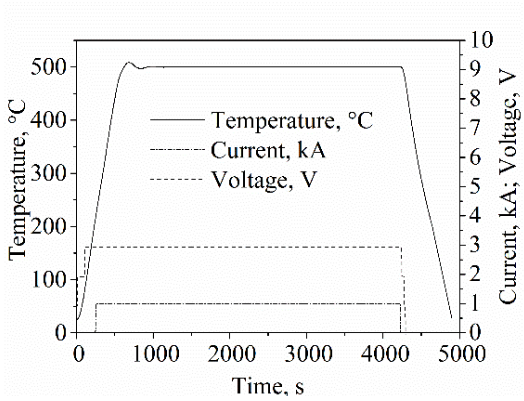

Figure 5: Parameters of the SPS joining regime of 60 min. at 500°C.

The bonded specimens were cross-sectioned and prepared by conventional grinding and polishing techniques for microstructural analysis using an optical microscope (Zeiss, Aalen, Germany) and

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High Resolution Scanning Electron Microscope (HRSEM, JEOL JSM 7400F) equipped with energy dispersive spectrometry (EDS) analyzer. Phase composition was determined by X-ray diffraction (XRD) using a Rigaku RINT 2100 (Tokyo, Japan) diffractometer with Cu Kα radiation (λ= 0.1542 nm). The operating parameters were 40 kV and 40 mA, with a 2θ step size of 0.033. The XRD patterns were analyzed using a whole pattern fitting approach with the MDI Jade 2010 software (MDI, Livermore, CA). The mechanical properties of the joints were determined using shear strength test on an LRX Plus apparatus (Lloyd Instruments, Fareham Hants, UK). Four specimens were examined for each joining regime. The shear test specimen and tools are shown in Figure 6. The test tools consist of the static part, into which the specimen is mounted, and the moving part. When mounted into the testing apparatus prior to testing, the static tool part is placed on the bottom (static) part of the apparatus, while the upper (moving) block of the instrument is adjusted to the dynamic part of the tool.

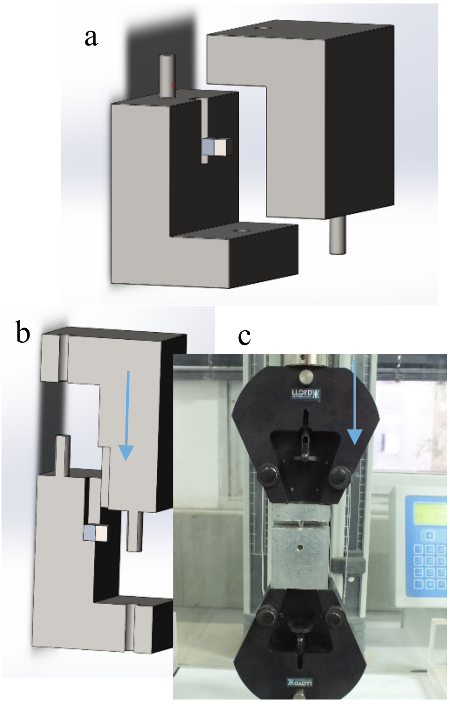

Figure 6: Shear test tools and instrument. a) two identical tool parts and a specimen; b) cross-sectional view of the shear test showing movement of the upper part down towards the specimen mounted on the static part; c) tool mounted into the testing instrument during the shear test.

3. Results and discussion

In dissimilar material joints, behavior of the tiny interface region determines properties pf the whole joint. This effect is multiplied in the laminar systems incorporating many interface regions. Previously discussed increase in the mechanical properties of the post-treated Al 1100/CP-Ti UAM parts shows positive contribution of the intermetallic layer on the properties of the final part.

In the present study the effect of the SPS treatment on the properties of the pure Al/Ti joining couples was investigated. Bulk Al/Ti specimens were joined in the SPS apparatus for various joining times at 500°C in order to examine the effect of the SPS-treatment time on the mechanical properties of the joints.

SEM images of the interface area cross-section of the joints are shown in Figure 7. The interlayer was determined by EDS analysis as $TiAl_3$. The longer was the joining time, the larger was the interlayer thickness: about 0.2 µm after 10 min., about 0.7 µm after 60 min. and about 1 µm after 240 min.

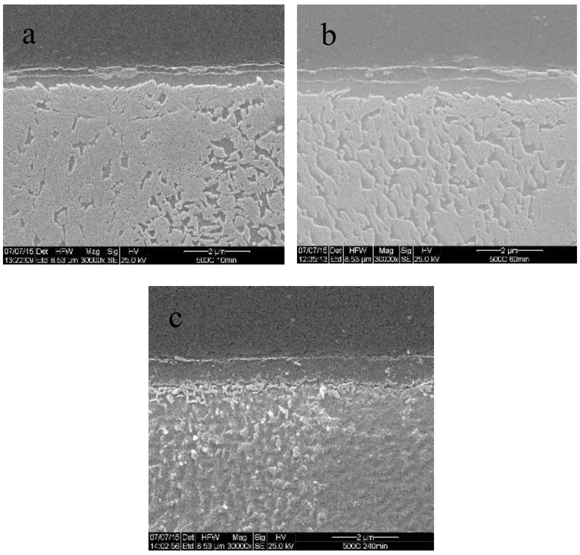

Figure 7: SEM (SE) images of the Al/Ti interface showing interfacial layer with thicknesses varying with SPS processing time. a) 10 min. at 500°C; b) 60 min. at 500°C; c) 240 min. at 500°C (bar equals 2 microns). Al is in the upper part of the images.

Mechanical properties of the joints were evaluated using shear strength test. The results showed almost equal load to failure values of about 1500 N (Figure 8). This value corresponds to the load to failure of pure aluminum. These results show that there is no effect of the SPS joining time on the load to failure in shear test.

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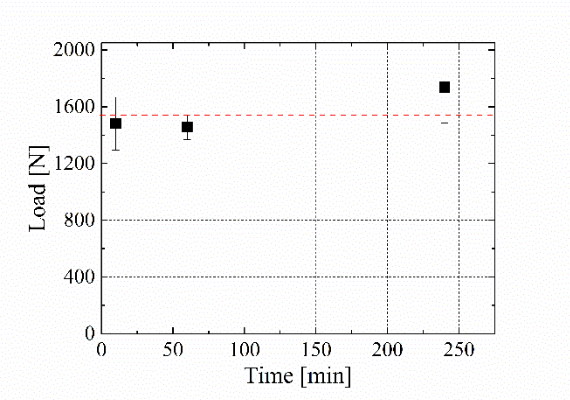

Figure 8: Load to failure as a function of the SPS joining time for the specimens joined at 500°C. Red dashed line corresponds to the characteristic value for pure Al.

XRD analysis of the fracture surfaces was conducted and it was found that the $TiAl_3$ intermetallic phase exists only on the Ti-side of the failed joint, while no intermetallic phase was detected on the Al-side of all the joints (Figure 9).

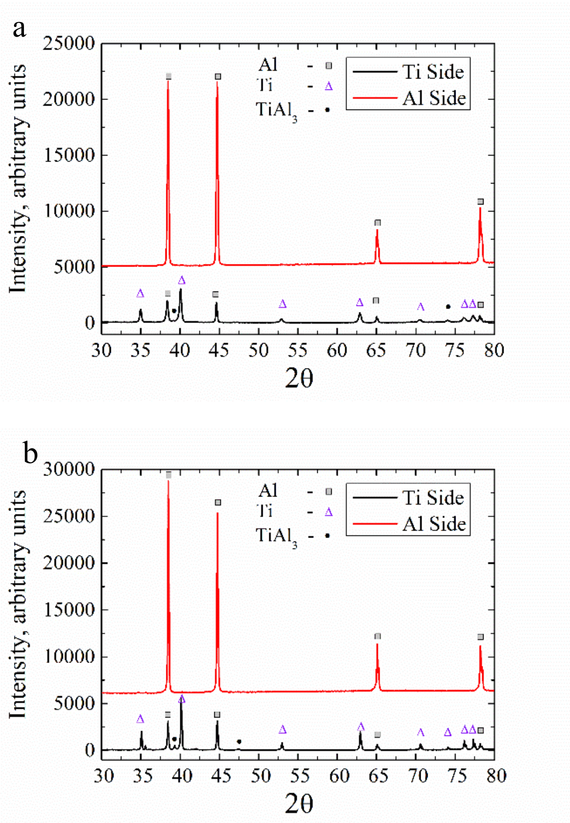

Figure 9: X-ray diffraction from the fracture surface of the specimens joined in SPS at 500°C for 10 min. (a) and for 60 min. (b).

Fracture surface investigation along with the XRD analysis show that the fracture occurred through the Al part and not along the intermetallic layer. The fracture starts at the Al/Ti interface and then continues to the Al part that undergoes significant plastic deformation as the ductile fracture occurs through it (Figure 10).

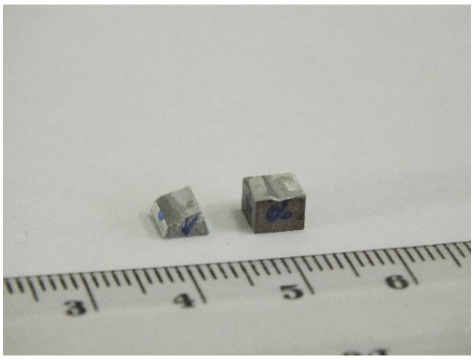

Figure 10: Al/Ti specimen after fracture in the shear test. Left part is Al.

The results show that for the pure Al/Ti couple, even very short SPS treatment (about 10 min.) results in a joint with a thin (less than 1 µm) continuous intermetallic layer. The joint exhibits failure through the Al part, while the intermetallic phase does not participate in the failure. It may be summarized that for the Al/Ti materials system joined in SPS at 500°C, very strong chemical bonds are formed and prevent failure along the interface. No effect of the joining time on the mechanical properties was observed. Joints with intermetallic phase with thickness varying from 0.2 to 1 µm showed the same load to failure value and the same failure behavior.

4. Conclusions

SPS-joining of the pure Al/Ti system resulted in formation of the $TiAl_3$ intermetallic phase with thickness of 0.2 µm (10 min.) - 1 µm (240 min.). The intermetallic layer exhibited strong bonds with both Al and Ti, and prevented brittle failure of the specimens through the interface region. The failure occurred through the joined material (Al) showing excellent mechanical properties of the joints. No effect of the joining time on the mechanical properties of the joints was observed. Thus, SPS may serve as an appropriate and very fast Al/Ti solid state joining method, as well as post-treatment method for the UAM-printed Al/Ti specimens.

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