WIRE ELECTRON BEAM ADDITIVE MANUFACTURING OF SHAPE MEMORY ALLOY

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Introduction

As regards welding technologies, three groups of methods can be used for the additive manufacturing (AM) of metallic elements. The three aforementioned technologies utilise the following sources of heat: welding electric arc (WAAM – wire arc additive manufacturing), laser beam (WLAM – wire laser additive manufacturing) and finally electron beam (EBAM – electron beam additive manufacturing). The thickness of a single layer and the rate of deposition in the wire-based AM are significantly greater in comparison with powder-based prototyping methods. The dimensional accuracy of elements made using a wire is lower than that of products made using powder-based technologies. In addition, the surface roughness (corrugation) of the final part is higher. In turn, methods involving the deposition of a wire provide higher process efficiency. The most commonly used AM methods involving the use of a wire and welding electric arc include TIG, MIG/MAG and plasma arc. Laser wire AM can be performed using both CO2 lasers and solid-state lasers. However, it should be noted, that the AM components may be structurally different from those manufactured from the workpieces obtained via commonly used processes such as casting, rolling, forging, etc. In connection with this, there is a necessity of characterizing them for structural, physico-mechanical and chemical properties.

On the other hand, the increasing demand for lighter, stronger and functional materials spawned active materials. Shape memory alloys such as nitinol (Nickel Titanium Naval Ordinance Laboratory) has found numerous applications in the medical field including neurology, orthopaedics, interventional radiology and cardiology. Nitinol was discovered in 1959 by Buehler W.J. of the Naval Ordinance Laboratory while trying to develop an impact-, fatigue- and heat-resistant alloy to use as the nose cone of a navy missile. Fatigue and kink resistance, good damping properties and superelasticity have ensured an increased application of nitinol alloy in surgical applications. Another major factor involves its biocompatibility with research showing it to have similar or better biocompatibility than stainless steel or Ti6Al4V. However, the Young modulus of Ni-Ti alloys (about 50 GPa) is slightly higher than that of a human bone (10-20 GPa), which can result in stress concentration at the connection of the implant with the bone.

Simultaneously, it should be noted that due to the extreme small melt pool during AM process, followed by extreme fast cooling but in a next layer followed by partial remelting and reheating, uncommon microstructures are obtained. Those microstructures control the mechanical properties such as strength, ductility, toughness and high residual stresses and, in case of shape memory alloys, also the quality of the functional properties.

Experimental procedure

The wire 1 mm in diameter (50.97 at% Ni, 0.22 at% max C, Ti balance), delivered by SMATEC company, Belgium, was used for EBAM process. The wire was delivered after heat treatment to modify transformation temperatures. The composition of the sheet substrate delivered also by SMATEC Company, was 50.74 at% Ni, 0.12 at% max C, 0.11 at% O, Ti balance. The AM process was conducted using a 30 kW CVE EBAM and welding machine at the Łukasiewicz - Institute of Welding (Figure 1a). Operating the EBAM system with real-time computer control, the process parameters, including the voltage, current, wire-feed rate and translation in the X and Z directions were programmed to deposit the NiTi wire as a single bead onto the NiTi substrate so as to build layer by layer a straight wall to target dimensions of 5×10×45 mm (Figure 1b). Based on preliminary studies the set of following parameters was applied during the fabrication process: accelerating voltage 60 kV, beam current 15 mA, feeding angle 30°, wire feed speed 1000 mm/min and travelling speed 2000 mm/min.

The microstructural observations of fabricated samples were conducted using a scanning electron microscope (SEM) FEI Versa 3D and a Leica DMIRM optical microscope, on previously etched samples using a Kroll's reagent. EBSD analysis was performed with EDAX Hikari CCD-based detector and a TSL OIM Data collection software version 7.0. The detailed microstructural studies were performed using a transmission electron microscope (TEM) Tecnai FEG G2 F20 Super Twin, equipped with an integrated EDAX Apollo XP energy dispersive X-ray spectrometer (EDS). The thin foils for TEM observations were prepared by electropolishing 100 µm thick discs in an electrolyte containing 10 mol% HClO4 in methanol (voltage 20 V, temperature -20°C). The compression tests were performed at a Shimadzu Autograph AG-X plus testing machine at strain rate 10-3 1/s. The samples for mechanical tests, in the form of cylinders with the diameter of 4 mm and the height of 6 mm, were prepared using an electrical discharge machine. The Differential Scanning Calorimetry (DSC, Q1000 TA Instruments) method was used in order to determine the temperatures of phase transformations. The applied heating/cooling rate was 20°C/min.

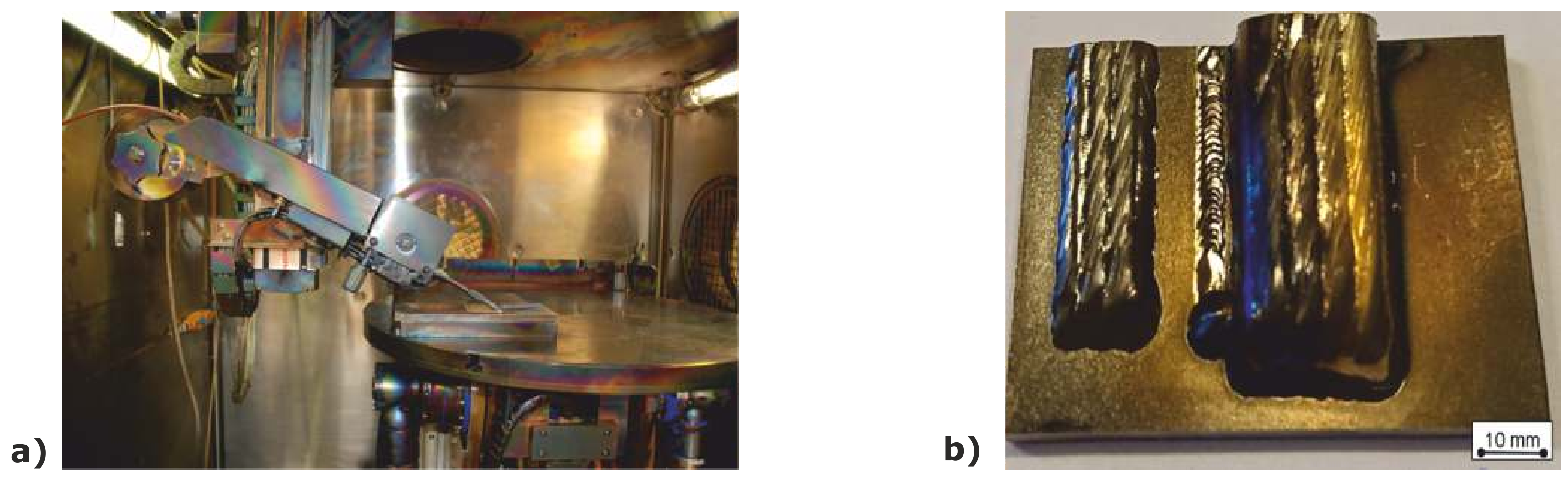

Figure 1. a) general view of chamber of XW150:30/756 EBAM machine, b) EBAM part of NiTi alloy

Results and discussion

Figure 2 shows light micrographs of the microstructure of NiTi elements manufactured using EBAM method. The EBAM allows to manufacture the final part from NiTi shape memory alloy without any defect such as cracks or porosity. The stability of the EBAM process was assured. The microstructures of the interface between the deposited material and the substrate were analysed. The elongated grains, perpendicular to the surface of substrate were observed. Their morphology indicates that, an epitaxial grain growth in the building direction takes place during the deposition. It is typical of the AM process that the penetration depth of an electron beam is larger than the thickness of the deposited layer, therefore part of the beam energy is used to re-melt the surface layer of the element. Due to a high thermal gradient in the created melt pool, conditions for the epitaxial growth of the columnar layer appear at the bottom of the pool. The EBSD analysis was conducted in order to determine the crystallographic texture, grain size of the deposited elements and the orientation dependence between the grains in the substrate and the deposited layers.

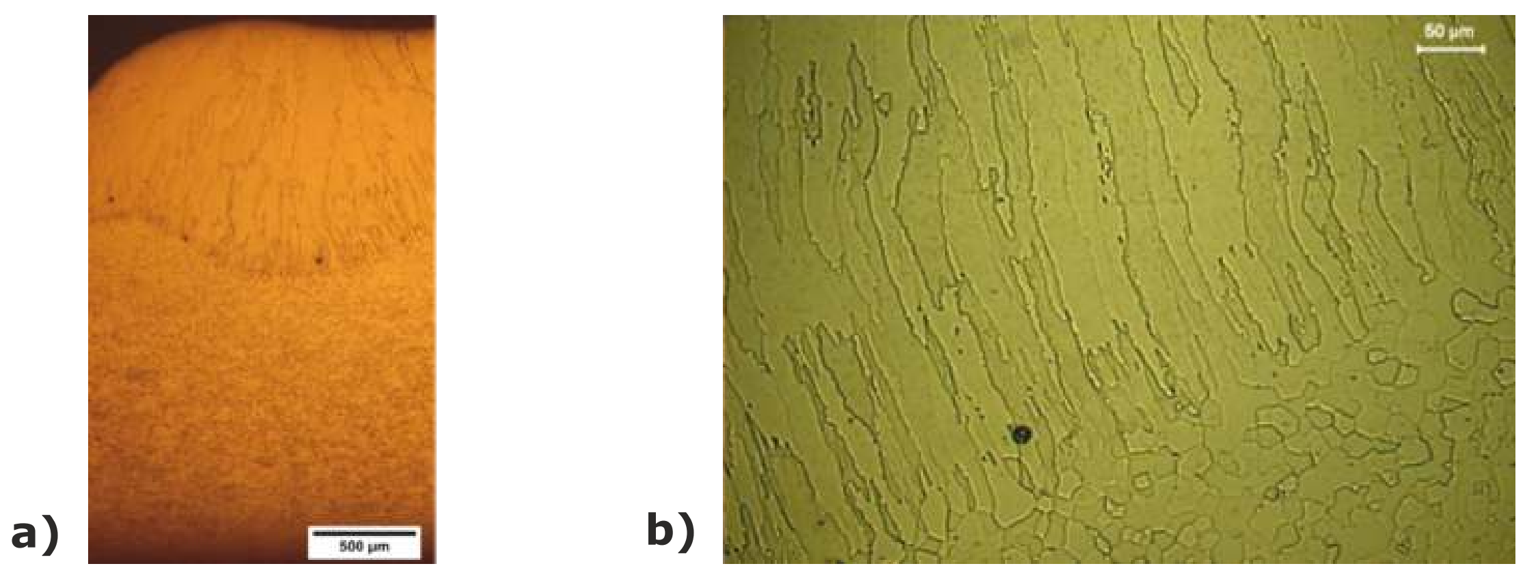

Figure 2. Light microscope micrograph of cross section of EBAM deposited sample in the plane parallel to the growth direction, a) general view, b) higher magnification

Figure 3a shows SEM micrograph of EBAM deposited sample. At the grain boundary misorientation map a red lines misorientation respond to 2-5°, green line 5-15°, and blue >15°, respectively. A Figure 3b shows grains with colours marked according to the inverse pole figure (IPF) coded map. The IPF maps of NiTi fabricated using the EBAM method, taken of the area just above the interface between the substrate and deposited layers. It should be noted that, the width of the columnar grain is controlled by the size of the equiaxed grains in the substrate near 100 mm. The results confirmed that during the deposition process, the epitaxial crystallization of columnar grains, proceeds in the heat flux direction. Figure 4a shows the texture measured on a plane parallel to the direction of growth of the lateral plane is similar to the direction [001] of the beta phase. Visible increase of beta phase orientation in a direction close to [100]. A small deviation from ideal orientation is related to movement during EB deposition process. Figure 4b shows a TEM micrograph of the sample deposited on the NiTi substrate using EBAM method with the interface between the B2 austenite and B19' martensite. TEM microstructure from deposited rectangular shape NiTi by EBAM method and SADP (Selected Area Electron Diffraction Pattern) from the central martensitic needle of [001] zone axis orientation showing small number of twins, and a low dislocation density within the austenite. The analysis of DSC curves of the EBAM deposited material in the as-deposited and aged states revealed that for the sample in the as-deposited state, a broad diffuse peak is observed, with maximum at -19.2 °C, which is a result of non-homogeneity of the deposited sample with respect to the chemical composition, as well as the grain size. Aging at 500°C for 2h caused the shift of the temperatures of martensitic and reverse transformations towards higher temperatures – Mp from -19.2°C to -15.4°C and Ap from 12.2°C to 31.7°C.

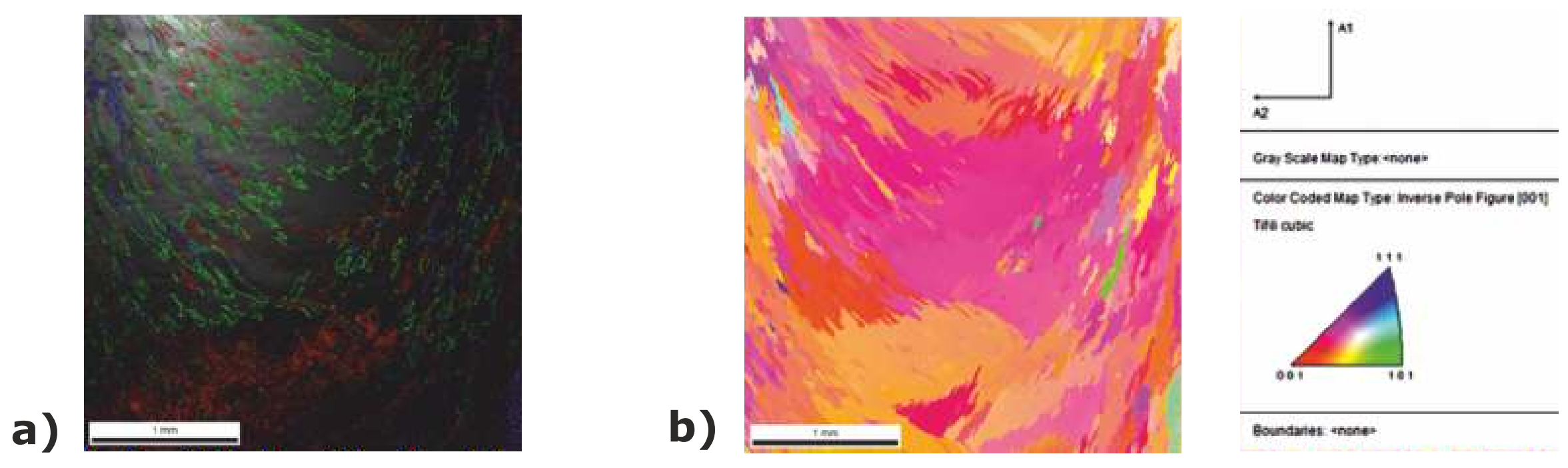

Figure 3. SEM micrograph of EBAM deposited sample,
a) grain boundary misorientation map; red lines misorientation 2-5°, green 5-15°, blue >15°
b) grains with colours marked according to inverse pole figure coded map.

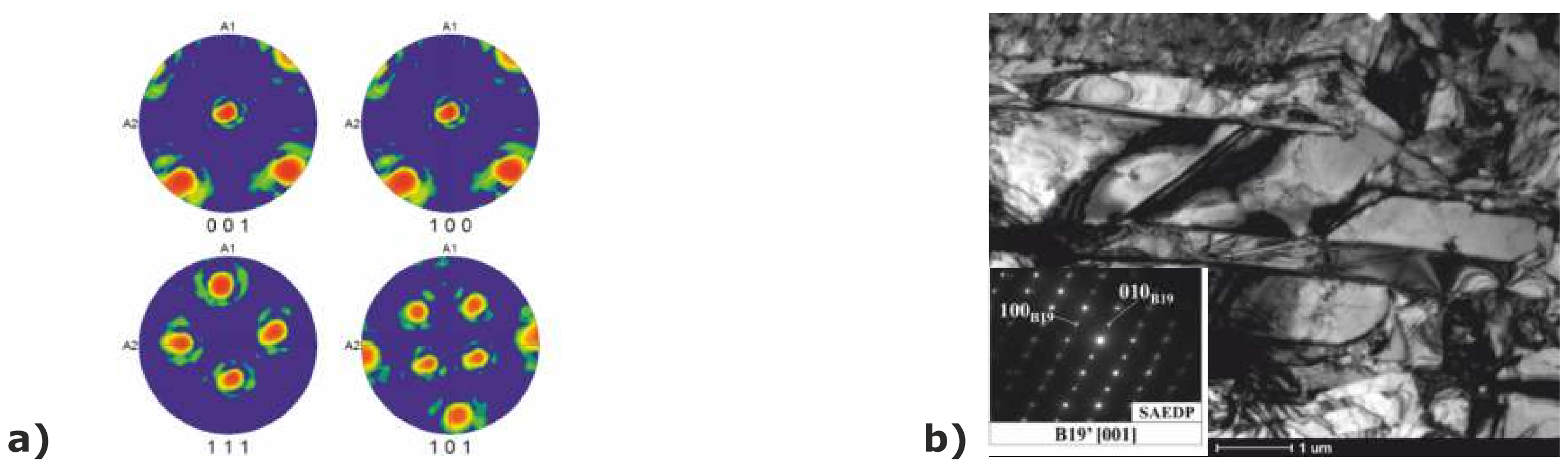

Figure 4. a) Inverse pole figure map of NiTi fabricated using EBAM technique,
texture measured on a plane parallel to the build direction,
b) TEM microstructure and electron diffraction pattern of EBAM deposited sample

Conclusion

Based on the results of the present research on developing a EBAM with wire feeding of a NiTi shape memory alloy, the following conclusions can be drawn:

- the process of additive manufacturing using an electron beam with filler material in the form of solid wire enables the fabrication of test components with strictly defined technological parameters without any defects,
- the microstructure of the deposit exhibited typical solidification features of columnar grains of austenite, due to epitaxial growth mechanism, resulting from heat transfer direction. EBSD investigations revealed that the preferential grain orientation in [001] is a result of the adopted material layer deposition,
- TEM studies from deposited rectangular shape NiTi alloy by EBAM method have shown presence of martensitic needles partially twinned within austenitic matrix, and a low dislocation density within austenite confirming ability of the EBAM manufactured sample to pseudoelastic deformation at room temperature.

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