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Freeform Fabrication Method of Alloys and Intermetallic Compounds by 3D Micro Welding†

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Abstract

A novel rapid prototyping method for metals named 3D micro welding (3DMW) was demonstrated. It is a combined process of a micro-TIG welding and a layered manufacturing method. Small metal beads with ~1 mm diameter are formed by applying a micro arc to the top of a metal wire of 200 μm in diameter. A fused bead is welded to a metal substrate or previously formed beads. By continuing this process and stacking beads layer by layer under the control of a computer system, 3D objects of various metals and alloys can be formed. The system consists of four sections; a forming stage, an arc control unit, system control computers, and a video monitoring device. A 3D model is designed on CAD software and sliced into thin layers by using commercial slicing software. After the slicing process, the arrangement of beads in a layer is calculated by in-house developed software. In this study, freeform fabrication of Inconel alloy 600 and Ti-Al based intermetallic alloy were demonstrated. The mechanical properties of formed samples with Inconel alloy 600 were measured and the phase composition of samples of Ti-Al based intermetallics alloy were analyzed. The yield strength, density and Vickers hardness of Inconel 600 objects show comparable values to the commercial alloys. These superior properties suggest that actual micro components or tools of metals with high strength, high wear, heat and oxidation resistances can be formed without molds by 3DMW.

KEY WORDS: (3D micro welding), (Rapid prototyping), (Micro TIG welding), (Inconel alloy 600), (Titanium aluminides)

1. Introduction

Rapid prototyping, also known as solid freeform fabrication, is used to form near net shape objects of resin, ceramics, metals and their composites directly from computer aided design (CAD) data sources. This technique was originally developed for fabrication of prototype samples. Nowadays, it is being used to fabricate real parts. While there are various freeform fabrication methods such as stereo-lithography, fused deposition modeling, selective laser sintering and 3D printing [1-3)], many objects formed with these methods can not achieve mechanical properties required in actual products, especially for metal products. Additionally, the methods of rapid prototyping for metals are few and the metallic materials for fabrications are limited.

3D micro welding (3DMW) is a novel rapid prototyping method for metals, which we have recently developed [4-6)]. It is possible to form objects with many kinds of metals, alloys and intermetallic alloys, and the formed objects have practical strength. The system combines micro tungsten inert gas (TIG) welding with a layered manufacturing technique. A thin metal wire is melted by the arc of a micro-TIG welder and a metal bead is formed. Near net shape objects can be formed by stacking these metal beads. Due to the complete melting of a supplied metal wire, the produced parts have practical strength and the formed structures are fully dense. Additionally, it is possible to fabricate intermetallic objects by mixing two metal wires on the forming stage and the distribution of composition can be controlled.

In this study, freeform fabrication of Inconel alloy 600 and a Ti-Al based intermetallic alloy were demonstrated. The mechanical properties of formed samples with Inconel alloy 600 were measured. The samples with Ti-Al based intermetallics alloy were analyzed by XRD and EDS.

2. System components of 3D micro welder (3DMW)

A photo of the 3DMW apparatus is shown in Fig. 1. The system consists of four sections; a forming station, an arc control unit, system control computers, and a video monitoring device. There are an X-Y-Z stage, a welding

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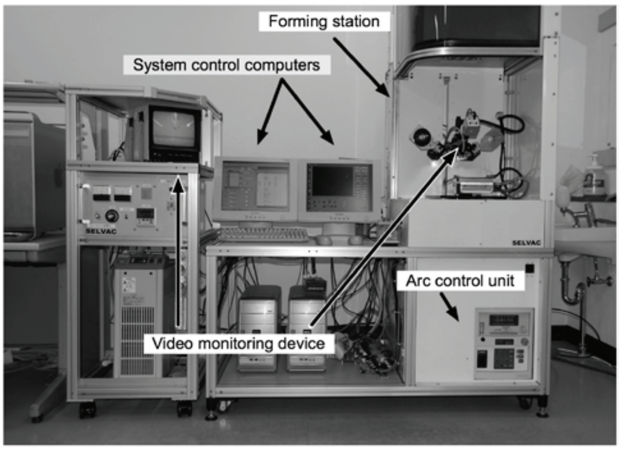

Fig. 1 A photo of 3D Micro Welding (3DMW) system.

torch and two wire feeders in the forming station. The arc control unit contains a micro TIG welder (PC-PAS 301 HMAX Corporation). All these components are controlled by the computer system. The schematic illustration of the forming station and process are shown in Fig. 2. A metal substrate is placed on the x-y stage under a tungsten electrode for arc welding. A small metal bead of ~1mm in diameter is formed by a micro arc applied to the tip of a thin metal wire of 200 μm in diameter. A fused bead is welded to the metal substrate or to previously formed beads. By continuing this process and building up beads layer by layer under the control of computer system, a 3D metal object can be produced.

A 3D model is designed by 3D computer aided design (CAD) software and it is sliced into a set of thin layers by commercial software (Magics Ver. 10.0,

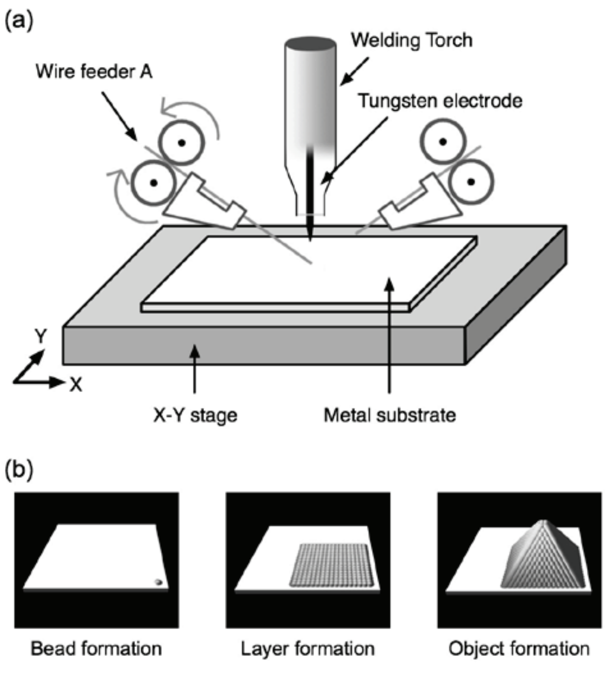

Fig. 2 A schematic illustrations of forming station (a), and elemental process of 3DMW (b).

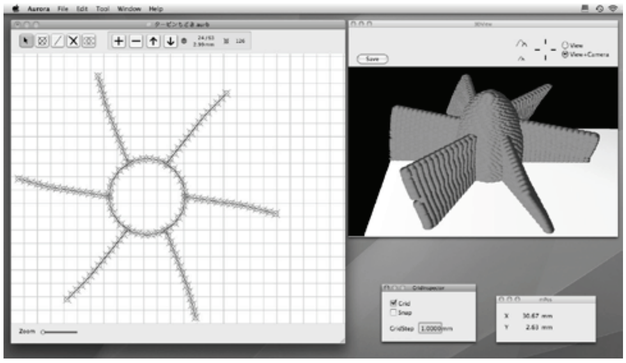

Fig. 3 A screen shot of in-house developed software for bead arrangements.

Materialise Software, Belgium). After the slicing process, the layout of beads in a layer is arranged. The original software was developed to calculate the beads arrangement (see Fig. 3) and export point data of beads with the motion control script (MCS) code that is in the system control program of 3DMW. A 3D object can be fabricated through the exported MCS code. The space of adjacent beads and the distribution of two different materials can be controlled by our in-house developed software.

3. Experimental procedure

3.1 Process conditions

The arc electrode used was a tungsten rod (2 vol.% CeO_2) of 1 mm in diameter. The tip of the electrode was ground with the angle of 45°. The distance between the electrode and the substrate was adjusted to be 1.2 mm in this study. The micro arc was discharged in a shielding

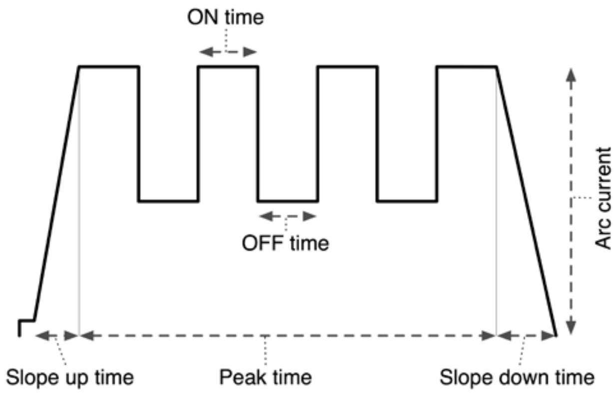

Fig. 4 A schematic diagram of pulsed arc current.

Table 1 Arc welding conditions.

Arc discharge		Shielding gas	
Arc current	:30 A	Gas	:Ar-4%H_2
Peak time	:100 ms	Gas flow	:5 l/min
Slope up time	:0 ms		
Slope down time	:5 ms		
ON time	:4 ms		
OFF time	:4 ms		

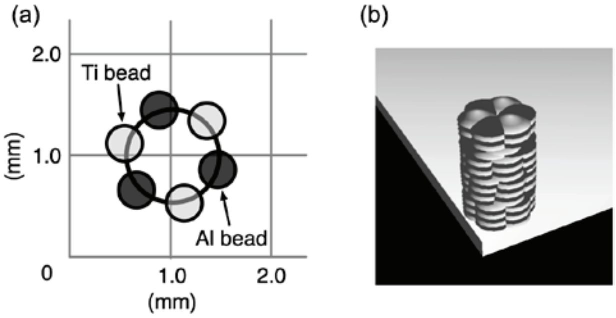

Fig. 5 The bead arrangement of a sample with Ti:Al = 4:2 (a) and its 3D image (b).

gas flow of Ar-4%H_2. The sequence of the pulse of arc current is illustrated in Fig. 4. The arc current and peak time were set to 30A and 100 ms, respectively. Other welding parameters are shown in Table 1.

3.2 Freeforming of practical alloys

Inconel alloy 600 is a nickel-based superalloy that has high strength and oxidization resistance at high temperatures. It is widely used to various components of nuclear reactors, turbines, jet engines, and others [7].

A simple cup object of Inconel alloy 600 was formed to demonstrate freeform fabrication of practical alloys and a simple pin object was formed to observe the microstructure. The cross sectional surface was mirror-polished and etched for 120 s with an acid solution of 10 ml of HCl, 10 ml of ethanol, 10 ml of water and 2 g of $CuSO_4$. The microstructure was observed by scanning electron microscopy (SEM, JEOL JSM-6060, Japan). A bar sample was fabricated to measure the mechanical properties. The test pieces of tensile tests were cut out using an electric discharge machine. The dimension of the specimens were 1 mm in thickness and 3 mm in width, with a 9 mm gauge length. The tensile test was performed using an Instron 5500R (USA) with the cross head speed of 1 mm/min. The density by the Archimedes method and Micro-Vickers hardness with a load of 980 mN (AAV-500, Akashi, Japan) were also measured.

3.3 Freeforming of intermetallics

Intermetallics are compounds of two or more metals in definite compositions and they have superior physical, mechanical, and chemical properties. In particular the Ti-Al system has high specific strength and lightness. However, due to their low ductility, the machining process is hard.

Simple pin objects were formed to establish the fabrication technique by using Ti and Al wires. When a Ti bead was formed and an Al bead was welded on the Ti bead formed previously, a Ti-Al based intermetallic alloy was produced accompanying the exothermic reaction. The height and diameter of the pin objects were 2.9 mm and 2.0 mm, respectively. One layer contained six beads, and 24 layers were stacked. Three samples were formed with different compositions. The ratios of Ti and Al beads were set to 5:1, 4:2, and 3:3. Figure 5 shows an example of the bead arrangement on a layer of the pin object with Ti:Al=3:3 and its 3D image on a computer. The phase

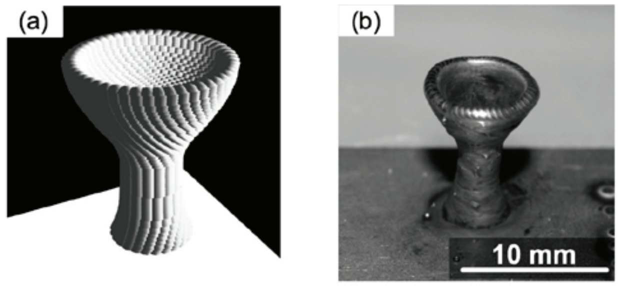

Fig. 6 Demonstration of freeform fabrication with Inconel alloy 600. (a) A CAD image of the simple cup object. (b) Formed object.

compositions were identified by using X-ray diffraction (XRD, D8 Discover with GADDS, Bruker AXS GmbH, Germany) and analyzed by energy dispersive X-ray spectroscopy (EDS, Phoenix, EDAX Inc, USA). The cross sections were mirror polished and etched for 15s with an acid solution (hydrofluoric acid (40 wt.%) : nitric acid (65 wt.%) : distilled water = 1:2:50). The microstructure was observed by the SEM.

A compositionally graded sample was formed in the Ti-Al system. The similar pin object was formed with 24 layers, and six beads in a layer. The sample was designed to be pure Ti and Al rich at the bottom and the top side, respectively. First six layers from the bottom side were formed of only Ti beads. The beads arrangement ratio of the second, third and last six layers were set to Ti: Al = 5:1, 4:2 and 3:3, respectively.

4. Results and discussion

4.1 Freeforming of practical alloys

A simple cup object with Inconel alloy 600 was fabricated. The CAD image of the cup object and formed samples are shown in Fig. 6. The distance of adjacent beads and the layer thickness were set to be 0.5 mm and 0.12 mm, respectively. The total number of beads was

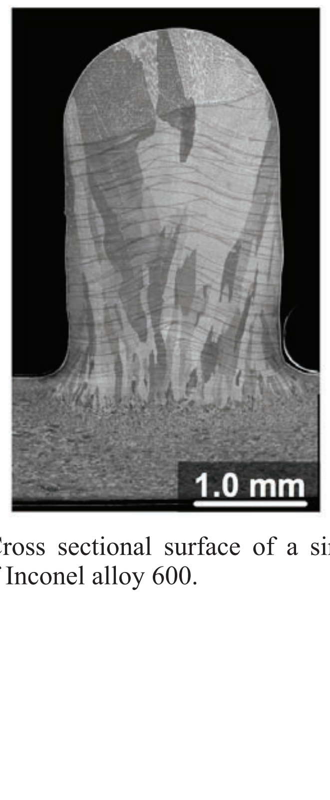

Fig. 7 Cross sectional surface of a simple pin object of Inconel alloy 600.

Table 2 Mechanical properties of the formed objects with Inconel alloy 600 [8].

	Measured	JIS G4902	
Density	8.4	8.4	g/cm^3
Hardness	158	<182	HV
Yield strength	690	>550	N/mm^2
Elongation	42	>30	%

3002 and the number of layers was 97. The cross sectional surface of a pin object observed by SEM is shown in Fig. 7. The interfaces between adjacent beads were joined well and the formed object had neither cracks nor pores. This microstructure showed that the sample was fully dense and crystals grew continuously from the bottom to the top. There were horizontal stripes except at the top area. These stripes were traces of boundary lines between the depositing melted part and the solidified part. This line was not seen in the area of about 0.8 mm below the top. It shows that the upper 5~6 layers were remelted as the several repetitions of hot bead deposition and arc discharge occurred. This remelting process for pre-deposited layers seems to produce dense objects and large grain growth.

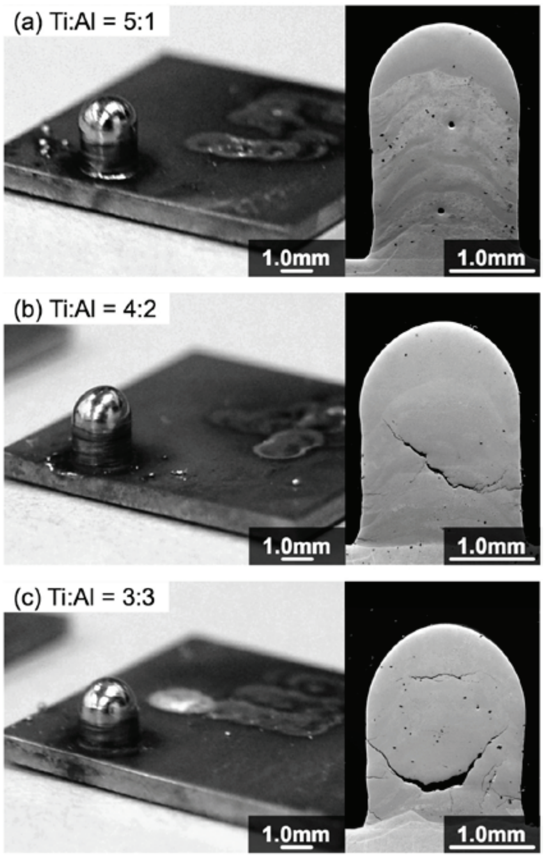

Fig. 8 Formed pin samples and their cross-sectional surface. (a) Ti:Al = 5:1 <Al = 11 at.%> (b) Ti:Al = 4:2 <Al = 21 at.%> (c) Ti:Al = 3:3 <Al = 29 at.%>

Table 3 Measured Al content and the nominal value of each sample.

	Ti:Al = 5:1	Ti:Al = 4:2	Ti:Al = 3:3
Measured (at% Al)	11%	21%	29%
Nominal (at% Al)	18%	35%	52%

A bar sample with a dimension of 45×20×1 mm was formed. The specimen for tensile test was cut out from the bar sample. The tensile experiment was performed along the layer stacking direction. The tensile strength and elongation reached 690 MPa and 43%, respectively. The hardness of Vickers and density were 158 HV and 8.4g/cm^3, respectively. These measured mechanical properties of the formed samples are compared with the Japanese industrial standard (JIS G4902) in Table 2 [8]. The density was a similar value as JIS G4902, and the hardness did not exceed the standard value. The yield strength and elongation met the industrial standard. These results suggest that actual micro components or tools of Inconel alloy 600 can be free formed by 3DMW.

4.2 Freeforming of Ti-Al based intermetallic alloy

The photos of formed pin samples and their etched cross-sectional surfaces are shown in Fig. 8. The segregation of Ti or Al was not observed. When the arc current was discharged at the top of the object, the upper five or six layers were remelted and the composition was mixed homogeneously. Some cracks appeared with increasing Al due to the thermal expansion mismatch between the pure Ti substrate and the Ti-Al alloy. The coefficient of thermal expansion (CTE) of pure Ti is 8.6 × 10-6 K^{-1} at room temperature [9] and that of Ti_3Al is 10.3 × 10-6 K^{-1} [10]. The compositional analysis by EDS against the nominal value of each sample is listed in Table 3. The Al contents of the samples with Ti:Al = 5:1, 4:2, and 3:3 were 11 at. %, 21 at. %, and 29 at. %, respectively. These values were lower than the calculated ones from the bead ratio, and this was attributed to the loss of about 40 at. % Al as welding spatter. The results of XRD analysis are

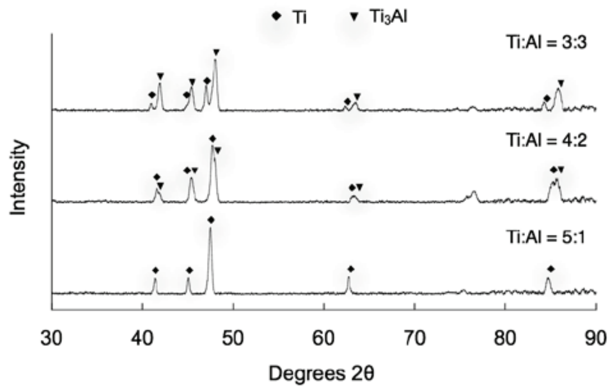

Fig. 9 XRD analysis of pin samples with different Al contents.

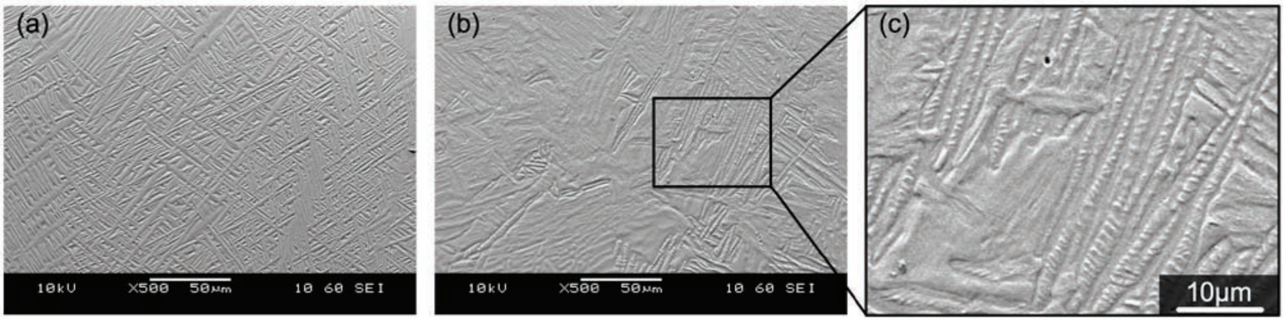

Fig. 10 The microstructure of the sample with 21 at. % Al. (a) Rapidly cooled area. (b) Heat affected area. (c) Magnified view of precipitated Ti_3Al in α-Ti grains.

shown in Fig. 9. The sample of 11 at. % Al showed only Ti peaks, but they were slightly shifted toward lower angles. This means that the sample is composed of the Ti based Al alloy. On the other hand, that of 21 at. % Al had Ti and Ti_3Al peaks. In the sample of 29 at. % Al, they were clearly separated into Ti and Ti_3Al.

A formed sample by 3DMW consisted of a rapidly cooled area and a heat affected area. The rapidly cooled area existed in the upper 5~6 layers. This upper part was remelted and rapidly solidified, when the last arc was discharged to the top of the sample. The lower part beneath these upper 5~6 layers was affected by the heat of several arc discharging. The microstructure of the sample 21 at. % Al is shown in Fig. 10. We can observe the acicular structure of α and β-Ti in the rapidly cooled area (Fig. 10a). The phase diagram (Fig. 11 [11]) suggests that the microstructure consists of α-Ti and Ti_3Al. However, we could not observe the Ti_3Al peaks in this area by spot analysis of XRD. The precipitation temperature of Ti_3Al at around 1020 °C [12] is too low to precipitate in such a rapid cooling condition. In the heat affected area, the needle likeα-Ti grains were grown and Ti_3Al phase was precipitated in α-Ti grains (Fig. 10c). The grain growth of α-Ti and the precipitation of Ti_3Al were caused by the heat of cyclic arc discharging. In the sample of 29 at. % Al, a higher content of Ti_3Al phase was observed. However, there was no precipitated Ti_3Al in the sample of 11 at. % Al. In this composition, the precipitation temperature of Ti_3Al is lower than that of the 21 at. % Al sample and the Ti_3Al phase could not be precipitated. These results agreed with the XRD analysis. A micro rotor model was formed with the bead ratio of Ti:Al = 5:1 as a demonstration of freeform fabrication. A computer graphics of bead arrangement and a photo of the formed object are shown in Fig. 12. This model contained 5516 beads in 65 layers. It was designed to have a height of 7.8 mm and a diameter of 20.5 mm. The height and diameter of the formed object were 7.7 mm and 20.0 mm, respectively.

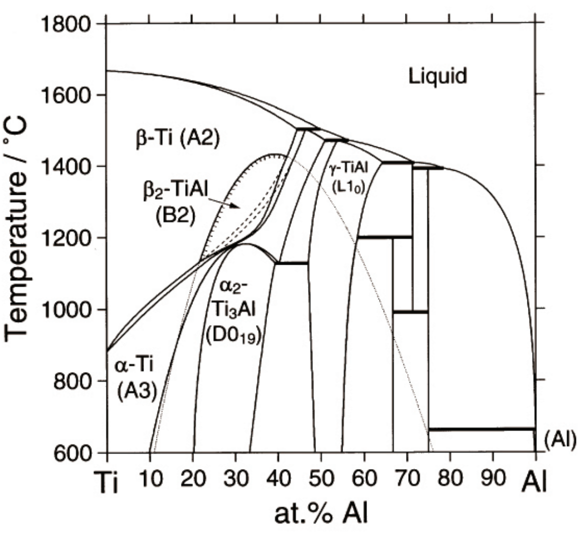

Fig. 11 Phase diagrams of the Ti-Al binary system [11].

The cross-section and microstructure of a compositionally graded sample is shown in Fig. 13 and the result of Al content analysis by EDS is shown in Fig. 14. The Al content of the top area was around 20 at. %. It decreased continuously toward the bottom. We can observe the stepwise change in microstructure. The bottom side was pure Ti (Fig. 13d), and the middle part consisted of a binary phase of α-Ti and β-Ti (Fig. 13c). Precipitated Ti_3Al phase was observed near the top (Fig. 13b), and the acicular structure of α-Ti and β-Ti appeared in the rapidly cooled area (Fig. 13a). There were no large cracks in the cross-sectional surface. The relaxation of thermal stress by the compositional gradient might prevent cracks.

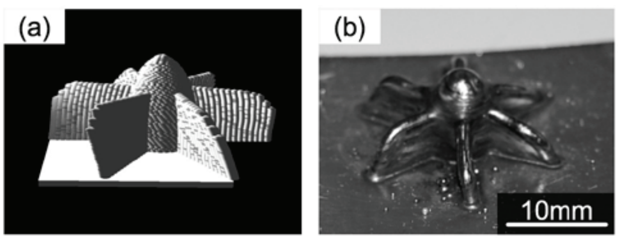

Fig. 12 Demonstration of Freeforming with Ti-Al based intermetallics alloy. (a) A image of bead arrangement. (b) Formed object.

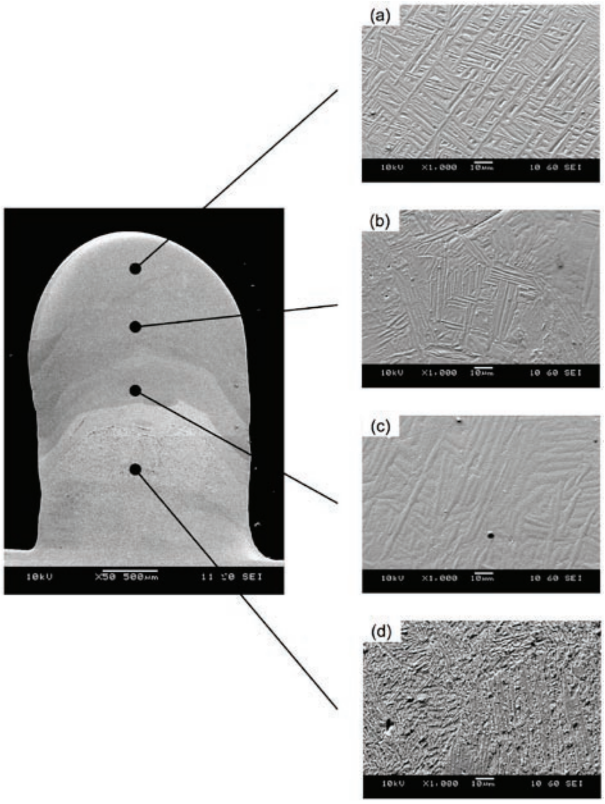

Fig. 13 The cross-section and microstructure of a compositionally graded sample. (a) Acicular structure region of α and β Ti. (b) Precipitated Ti_3Al phase region. (c) Binary phase region of α and β-Ti. (d) Pure Ti region.

5. Conclusion

A novel welding based rapid prototyping method for metals and intermetallics, named 3D micro welding is proposed. The freeform fabrication of Inconel alloy 600 was demonstrated, and the mechanical properties and microstructure of the formed objects were evaluated. The obtained objects were fully dense and there were no cracks or pores. The tensile strength, elongation, density and Vickers hardness were 690 MPa, 43%, 8.4 g/cm^3 and 158 HV, respectively. The mechanical properties of formed objects had comparable values to the commercial alloys.

Freeform fabrication of Ti-Al based intermetallic alloys was demonstrated, which accompanied the synthesis of alloys with pure Ti and Al wires. Three samples with different configurations of beads were formed and their phase compositions were analyzed. A micro rotor model was formed with the bead ratio of

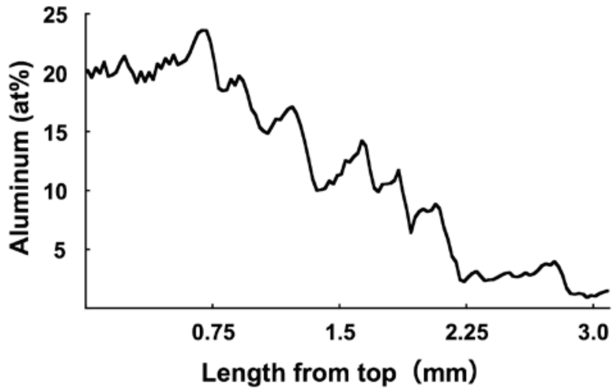

Fig. 14 Al content analysis by EDS.

Ti:Al = 5:1 as a demonstration of this freeform fabrication technique. A simple compositionally graded object was formed and it showed gradual changes in composition and microstructure. The obtained result showed that both shape and composition of objects could be controlled by 3DMW.

References

1) K. Zhang, W. Liu, X: Optics Laser Technol. 39 (2007) 549-557.
2) M.W. Khaing, J.Y.H. Fuh, L. Lu: Mater. Process Technol. 113 (2001) 269-272.
3) S. Das, J. Josepin, Beaman, M. Wohlert, L. David: Rapid Prototyping J. 4 (1998) 112-117.
4) M. Terakubo, Janghwan Oh, S. Kirihara, Y. Miyamoto, K. Matsuura, M. Kudoh: Mater. Sci. Eng. A 402 (2005) 84-91.
5) T. Horii, S. Kirihara, Y. Miyamoto: Intermetallics 16 (2008) 1245-1249.
6) T. Horii, S. Kirihara, Y. Miyamoto: Mater. Design 30 (2009) 1093-1097.
7) K.S. Al-Rubaie, L.B. Godefroid, J.A.M. Lopes: J Fatigue 29 (2007) 931-40.
8) Japanese industrial standard, JIS G4902, 1991.
9) R. Boyer, G. Welsch, E. W. Collings: Materials Properties Handbook: Titanium Alloys, first ed., ASM International, 1994.
10) H. D. Shashikala, S. V. Suryanarayana, K. S. N. Murthy, S. V. Nagender Naidu: J. Less Common Metals 155 (1989) 23-29.
11) I. Ohnuma, Y. Fujita, H. Mitsui, K. Ishikawa, R. Kainuma, K. Ishida: Acta Mater 48 (2000) 3113-3123.
12) J.C. Schuster, M. Palm: J. Phase Equilibria and Diffusion 27 (2006) 255-277.