Freeform Fabrication of Titanium by 3D Micro Welding

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Abstract

A novel freeform fabrication method for metals, named 3D Micro Welding (3DMW), has been developed. It is a combined process of the freeform fabrication system with TIG (Tungsten Inert Gas) welding. The formation of titanium micro beads was investigated with respect to the diameter, height, and contact angle on the titanium substrate as functions of arc discharge current and two different shielding gases. The Ar-4%H_2 gas was more effective in preventing oxidation of beads than Ar gas. Simple 3D titanium objects with arch, number and pyramidal shapes were formed. Needle form crystals of β- phase titanium precipitated in the α- phase titanium matrix doing bead formation by rapid cooling. The interface between a titanium bead and titanium substrate were joined well without cracks or pores.

KEY WORDS: (Freeform fabrication) (3D micro welding) (Titanium) (3D objects)

1. Introduction

Titanium has superior properties among metals such as high specific strength, chemical inertness, and low thermal conductivity [1-5]. However, its real application is still limited compared with other light metals, such as aluminum and magnesium, due to the high cost of raw materials and difficult processing. In order to overcome these shortcomings, several near net shape manufacturing techniques such as super plastic forming, isothermal forging, diffusion bonding, investment casting, and powder metallurgy have been developed [6,7].

In the present study, a new freeform fabrication technique which we named 3D micro welding (3DMW) is proposed. In this technique, net shapes of titanium are formed directly from its thin metal wire and a CAD/CAM system without using molds or dies. Significant reductions in manufacturing and time to market production as well as savings of energy and materials are expected when 3DMW system is further developed.

The principle and preliminary experiments to form titanium beads and simple 3D objects are described in this paper. The product's microstructure and composition are also analyzed.

Principle of 3D Micro Welding

The idea of 3DMW consists of a combination of two different techniques; freeform fabrication, also called rapid prototyping, and TIG (Tungsten Inert Gas) welding. The principle of 3DMW is schematically illustrated in **Fig.1**.

A metal substrate is placed under the tungsten electrode for arc discharge. When pulsed micro-arcs are emitted, the tip of a thin metal wire with a diameter of 0.1 to 0.3 mm is fused and a micro titanium bead is formed instantaneously. A fused bead is welded to a metal substrate or previously formed beads. By continuing this process and building up hot beads layer by layer under the control of CAD/CAM system, 3D metal objects can be produced. The 3DMW can be applied not only to titanium, but to other refractory metals such as nickel, steel,tantalum, tungsten due to the highly dense energy beam of the micro arc.

Experimental

The arc electrode used is a tungsten rod of 7 mm length and 1mm diameter. The tip of the electrode was ground with a tip angle of 45° . The distance between the electrode and the substrate is adjusted to be 1.2 mm. A titanium wire (Nirako Co. Ltd., 99.6% purity, 0.2 mm diameter) was fed automatically onto a titanium substrate with 0.5mm thick by computer controlled rotation of capstans. The substrate is attached on to an X-Y stage and electrically grounded. Pulsed arc current is discharged at the tip of the wire and a micro bead of titanium is formed on the substrate. The pulsed current was controlled from 5A to 30A. Two different shielding gases of Ar and Ar - 4%H_2 flowing down around the electrode were tested to prevent oxidation of metal beads. The diameter and

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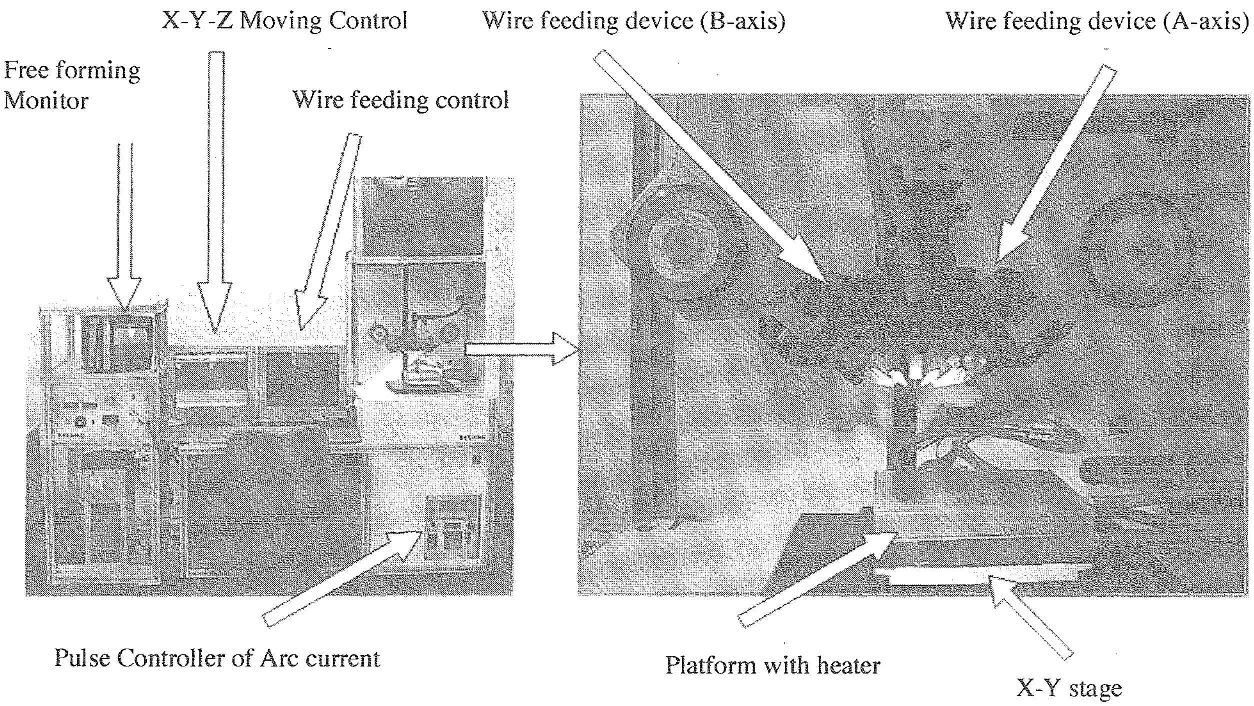

Fig.1 (a)A 3DMW system, (b) freeforming station

height of each bead formed and its contact angle with the substrate were measured. These formed positions were compared with the programmed positions to know the error range and probability of the bead formation.

The microstructure of titanium beads formed were observed by using 3D-SEM (Elionix ERA-8800FE, Tokyo, Japan). The cross section of a bead was observed by using OM. The chemical composition at the bead joint was analyzed by means of X-ray microanalysis (EPMA, JXA-8600, JEOL Co. Ltd) with the ZAF correction method. Hardness measurement on the cross section of a titanium bead and object was carried out by using a Vickers Hardness tester (AVKC-d, Akashi Co.Ltd.). The applied indentation load was 200g and the dwell time was 30 s.

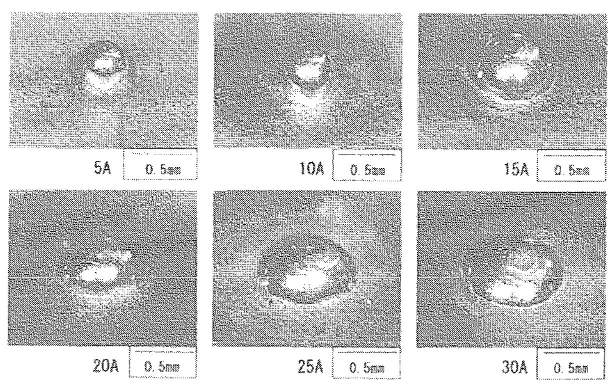

Fig.2 Photo images of titanium beads formed under Ar-4%H_2 gas.

Results and Discussion

In the formation of titanium beads by 3DMW, the size, shape, and microstructure depends on the arc peak current and shielding gas. **Figure 2** shows the appearance of titanium beads formed under the Ar shielding gas flow as a function of the arc peak current. An oxidized area with a dark green or pale color was observed around each titanium bead welded on the titanium substrate. The oxidized area increased as the arc peak current increased. However, such oxidation was remarkably reduced when the Ar-4%H_2 shielding gas was flown(See **Fig.3**).

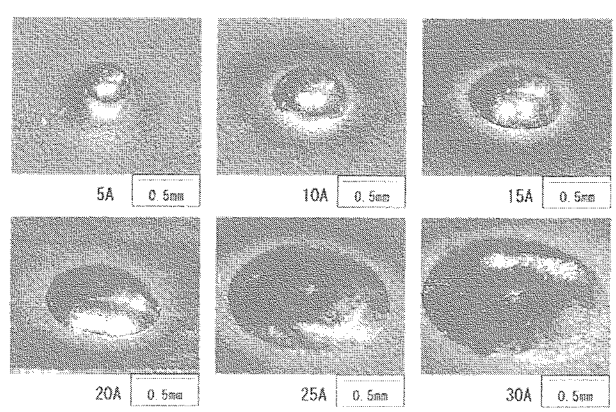

Fig.3 Photo images of titanium beads under Ar-4%H_2.

Figure 4 shows the microstructure of a titanium bead formed on the titanium substrate at 20A under Ar gas flow. The joint interface is indicated with a white line. The needle form phase was developed in the bead. We consider that the β- phase titanium precipitated in the molten titanium and quenched by rapid cooling, resulting in formation of the α - β mixed texture. Vickers hardness measured on the cross section of a bead on the substrate was 2.6GPa at the joint interface, and 4.3GPa at the central part of a bead. **Figure 5** shows the microstructure of a titanium bead formed under the Ar-4%H_2 gas flow. The titanium bead penetrated into the substrate suggesting a higher heat transfer to the bead and substrate compared with the use of Ar. The hardness at the joint interface was 1.7 GPa, and 3.3GPa at the central part. Vickers hardness of the titanium substrate itself was 1.2GPa. The influence of oxidation may give higher hardness of titanium beads formed under Ar gas flow. Although some micro pores (5-10 μm) were found near the joint interface, there were no cracks and large pores.

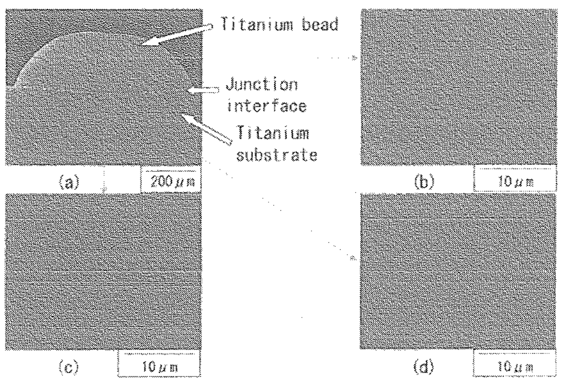

Fig.4 SEM images of a titanium bead formed under Ar gas ; (a) Cross section of a titanium bead welded on the substrate. Microphotograph of (b) a titanium bead, (c) a titanium substrate, and (d) at the junction interface of bead/ substrate.

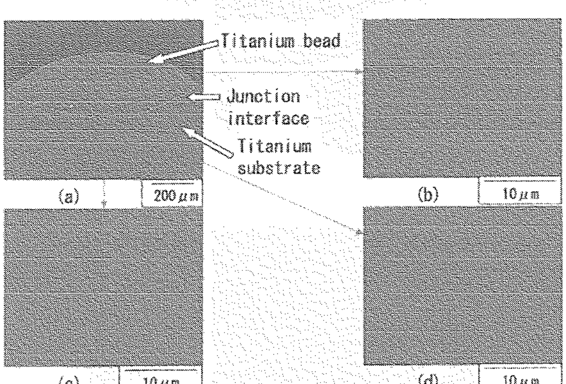

Fig.5 SEM images of titanium bead formed under Ar-4%H_2; (a) Cross section of a titanium bead welded on the substrate. Microphotograph of (b) a titanium bead, (c) a titanium substrate, and (d) at the junction interface of bead/ substrate.

Figure 6 shows nine standing pin objects of titanium. Thirty titanium beads were stacked on a fixed Z-axis by successive micro-arc discharging, where samples (a) and (b) were prepared under the Ar gas and the Ar-4%H_2 gas, respectively. **Figure 7** shows the diameter, height and contact angle of each pin. When the pins were formed under Ar gas, the diameter ranged from 1.02mm to 1.38mm. Mean height and contact angle of each pin were 1.56 mm and 109° , respectively. However, when they were formed under Ar-4%H_2 gas, the diameter expanded to 1.26mm~1.53mm. And the mean height and contact angle were 1.40 mm and 98° , respectively. The mean thickness of one layer was calculated to be 52 μm when formed under Ar gas, and 47 μm under Ar-4%H_2 gas. High heat transfer of the Ar-4%H_2 gas might form thicker titanium pins, but thin bead layers.

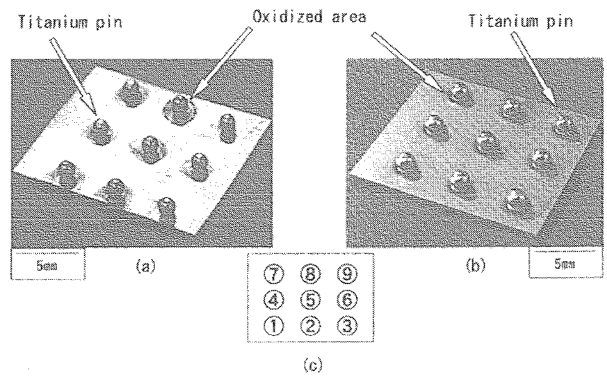

Fig.6 Feature of titanium pin objects. Grid pattern of 9 titanium pins formed under (a) Ar gas, (b) Ar-4%H_2. (c) Formation order of titanium pins objects.

The microstructures of titanium pin objects formed under Ar gas and Ar-4%H_2 gas are shown in **Fig. 8** and **Fig.9**, respectively. There were no cracks or pores at the joint interface in both coses. The welding between neighboring beads was successful. Both microstructures were quite homogeneous. These results suggest that the titanium wire was entirely melted and welded by the micro-arc. Some small pores about 50 μm in diameter sometimes existed in a pin object, however no crack was observed. As show in Fig. 4 and Fig. 5, needle form precipitates increased from the titanium substrate to the center of a titanium pin object. However they were homogeneous in the upper part of a titanium pin.

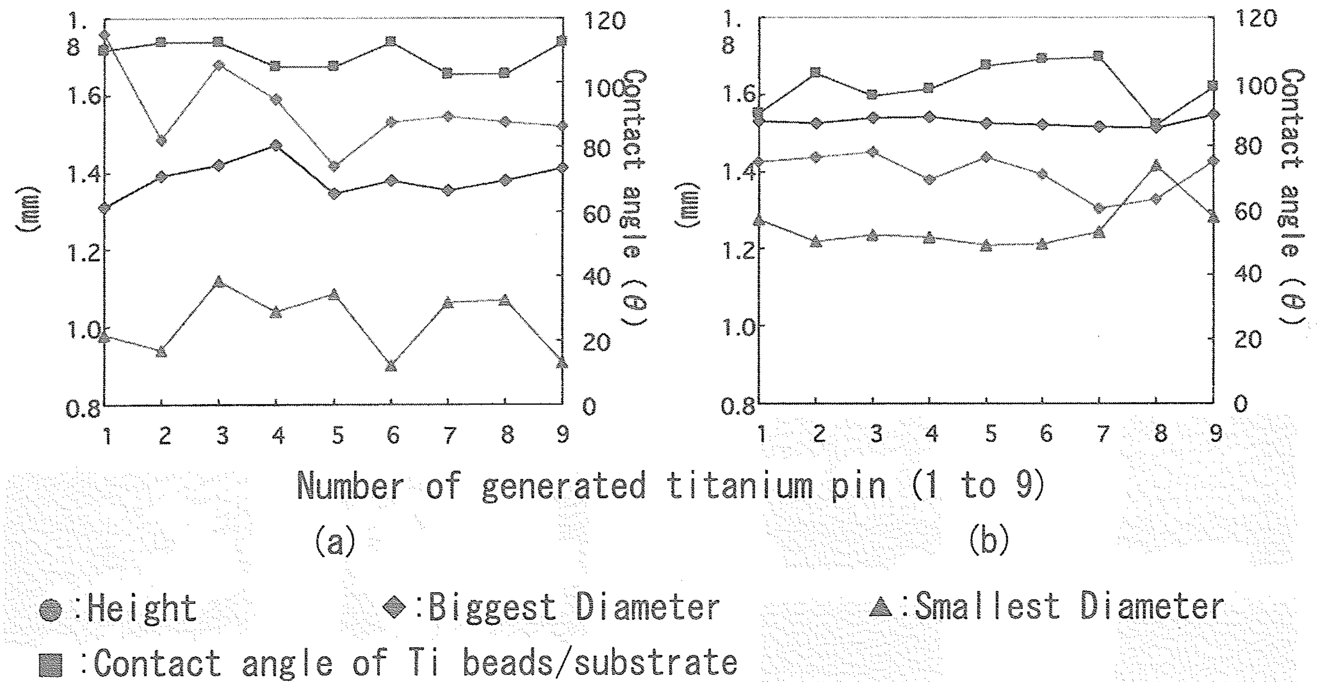

Fig.7 Geometry and contact angle of titanium pin object welded under (a) Ar gas, (b) Ar-4%H_2.

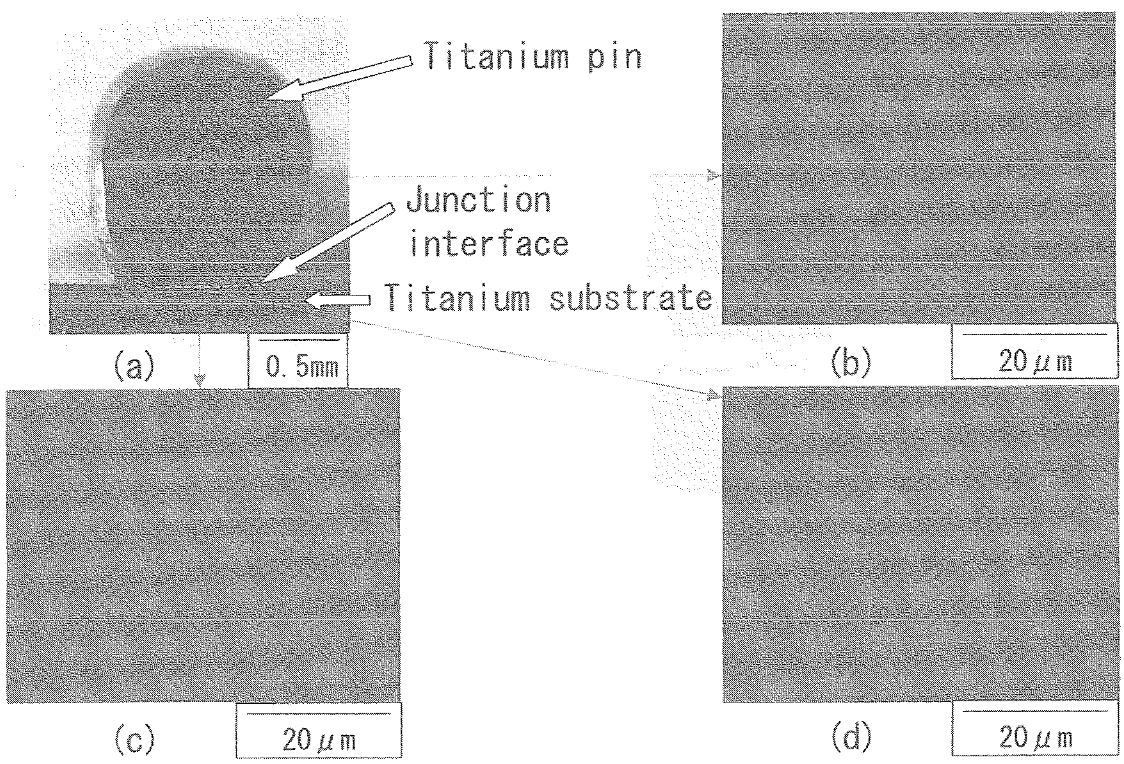

Fig.8. OM and SEM images of a titanium pin object welded on the substrate. (a) Cross section of a titanium pin object welded on the substrate. Microphotographs of (b) a titanium bead, (c) a titanium substrate, and (d) at the junction interface of pin/substrate.

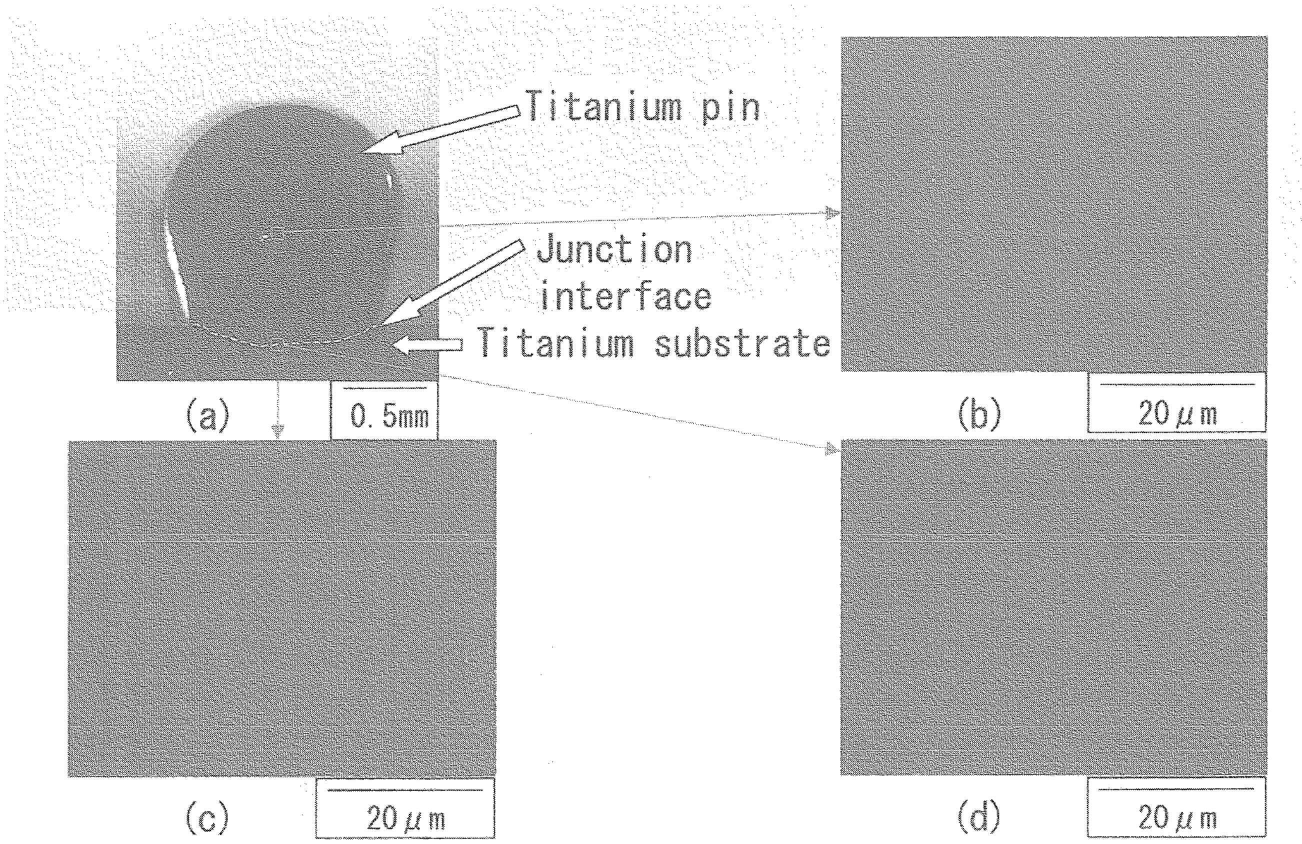

Fig.9 OM and SEM images of a titanium pin object under Ar-4%H_2 gas; (a) Cross section of a titanium pin object welded on the substrate. Microphotograph of (b) a titanium bead, (c) a titanium substrate, and (d) at the junction interface of pin/substrate.

Vickers hardness profile across a titanium pin object from the bottom to the top is shown in **Fig.10**. In both cases of titanium pin formation under the Ar gas and the Ar-4%H_2 gas, the hardness showed broad maxima at 200-500 μ m from the interface with substrate. There are some pores, 1-5 μ m in diameter, at the upper part of a pin. But no pore was found at the center. When molten titanium beads are dropped on the top of a pin, unfilled parts would remain and form pores at the upper part. However, such dispersed pores are filled by successive dropping of molten beads. It is considered, therefore, that the pin formation may always produce pores at the upper part leaving behind the dense structure, resulting in the broad maximum of hardness.

Figure 11 shows some simple 3D titanium objects which were formed by continuous stacking and welding of titanium beads. Figure 11 (a) is an arch-shaped object. This was formed by bridging two titanium pins of 30 layers. Figure 11 (b) shows titanium numbers formed of about 250 titanium beads. Figure 11 (c) is a small titanium pyramid which was formed by decreasing the pulsed current from 30A to 10A from the bottom to the top layer.

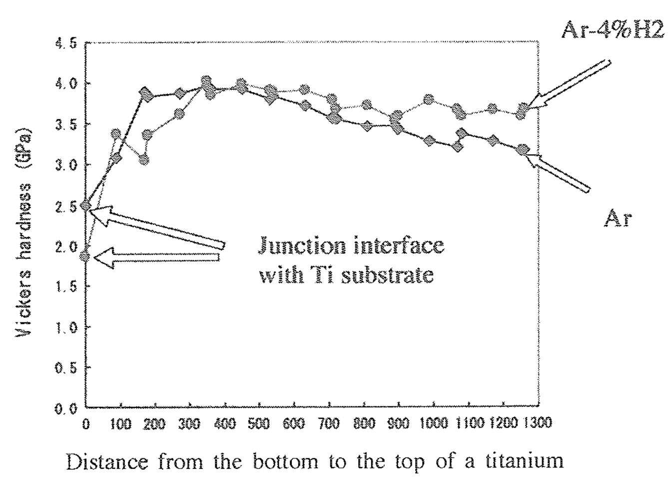

Fig.10 Vickers hardness profile of a titanium pin object

Conclusions

A novel freeform fabrication method named 3D micro welding (3DMW) has been developed using an idea to combine freeform fabrication technology with TIG welding. The optimization of forming parameters such as arc current, bead diameter and contact angle were investigated. Two kinds of shielding gas (Ar and Ar-4%H_2) were compared and the Ar-4%H_2 was found to be

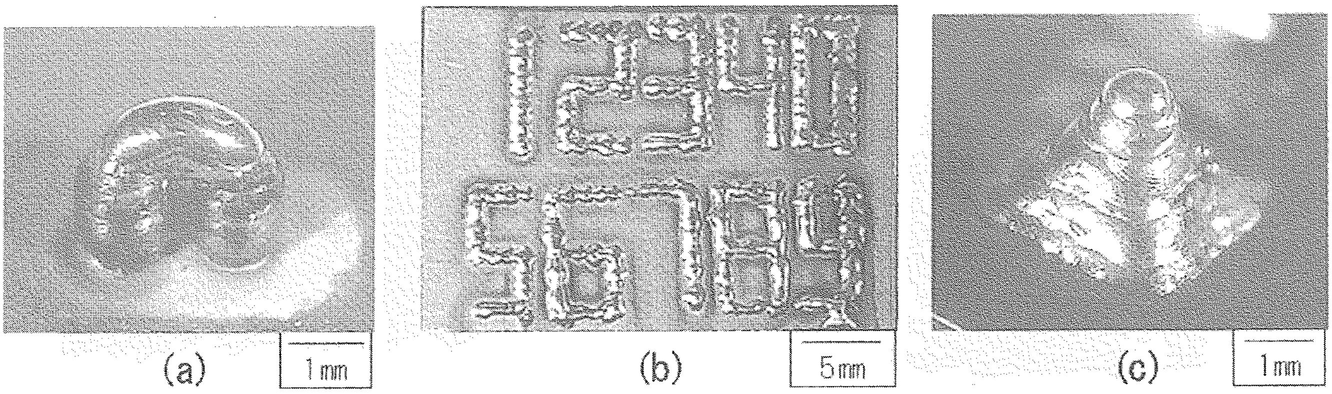

Fig.11 Photo images of titanium objects formed; (a) An arch shape, (b) Numbers, (c) A titanium pyramid.

useful to prevent oxidation of beads. The titanium bead formed showed the complex texture of needle form β-titanium precipitates in the α-titanium matrix, which increased the hardness of the titanium objects. Simple 3D titanium objects were formed by continuous stacking and welding of titanium beads under computer control. There are some pores in a titanium bead and a object, but the interface between beads or bead and substrate were jointed well without cracks. Further improvements in machine control and matching with CAD program are under investigation.

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