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Spray Forming of a Ti Alloy by a Low Pressure Plasma Spraying Method

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The authors prepared sheets of the alloy of Ti-6Al-4V by a low pressure plasma spraying method. The mechanical properties of the plasma formed sheets including hardness are measured before and after the formed sheets are subjected to various heat treatment cycles. Effects of the heat treatment cycles on the mechanical properties and potential applications of the plasma forming method are discussed.

Key words: low pressure plasma spray(LPPS), spray forming, Ti6Al-4V alloy, tensile strength, heat treatment

1. INTRODUCTION

Titanium alloys have been utilized in many important applications because of their high melting points, high specific strength, and high corrosion resistance. Gas turbine engines for utility power generation plants and for airplane utilize titanium alloys of the amount of approximately 23 % of the total weight of the engines. However, titanium alloys are chemically very active, and thus, molten titanium alloys react with most refractory materials easily, and tend to react with oxygen and nitrogen in the atmosphere. Therefore, special melting furnaces are employed for melting titanium and its alloys. Thus, higher production cost and longer production period are needed for producing titanium alloys compared to conventional melting and casting processes.

This investigation aims to solve these problems through applying a spray forming method based on a low pressure plasma spraying method. The spray forming method is applicable for forming products and parts that have very fine and rapidly solidified crystal grains to be produced directly from powder raw materials under shorter production processes without exposing molten titanium alloys to the ambient atmosphere.

The spray forming process based on a low pressure plasma forming process, namely, the LPPS process, is utilized for preparing sheets of the Ti-6Al-4V in the present investigation[1]. The mechanical properties of the sheets including microhardness, elongation, and tensile strength are evaluated. Furthermore, effects of heat treatment cycles of the sheets of Ti-6Al-4V for improving the ductility are investigated.

2. EXPERIMENTAL METHODS

2.1 A Spraying Method and Fabrication of Test Specimens

The alloy sheets of Ti-6Al-4V of 5 mm thick are deposited on substrate sheets of SUS304 stainless steel of the size of 100 mm × 100 mm by the LPPS method. Flat sheets of the size of 100 mm ×100 mm × 5 mm are obtained after being stripped from the substrates.

JIS-type standard tensile test specimens of the Class No.7 that corresponds to JIS Z 2201-1968 are prepared with two specimen sizes of 2 × 4 mm and 3 × 5 mm by cutting from the spray deposited sheets with a wire cut electric spark machine. Three types of heat treatment cycles are conducted on the specimens for improving the mechanical properties. These heat treatment cycles are (1) annealing at 940 ℃ for 2 hours, (2) recrystallization annealing at 950 ℃ for 0.5 hour, and (3) β annealing at 1030 ℃ for 0.3 hour. The sheet specimens are evaluated with respect to the following tests and observation.

2.2 Evaluation Test Methods of the Spray Deposited Sheets

The following methods were employed to evaluate the heat treatment cycles.

(1) Microhardness tests

Vickers microhardness of the heat-treated specimens were measured on mirror-like polished cross-sections of the samples with the indentation load of 0.3 kg.

(2) Microstructure observation

Optical microscopic observation under the magnification of 2000 was made on the cross-sections of the test specimens before and after being heat treated.

(3) X-ray diffraction analyses

X-ray diffraction analyses were made on cross-sections of the test samples of the size of 16 × 13 mm that were machined from the test specimens before and after being heat treated. Cu-kα radiation with 40 kVp and 100 mA is used.

(4) Electron-probe microanalyses (EPMA)

EPMA linear analyses were conducted for measuring the distribution of Ti, Al, V, and oxygen on mirror-like finished cross-sections of the test specimens. The measurement sensitivity for oxygen was increased to 5 times higher than for the other elements.

(5) Tensile tests

Tensile tests were conducted on the tensile specimens before and after being heat treated by a desktop-type high precision tensile testing machine. The crosshead speed was set to be 0.5 mm/min and tested at room temperature.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Changes of Hardness and Microstructure in Heat Treatment

Figs.1 and 2 show the Vickers microhardness and micrographs of the test specimens before and after being heat treated respectively.

The micrograph of the as-sprayed specimen shows the fine-grained microstructure that is characteristic to spray formed alloys. The microhardness of the as-sprayed specimen is in the range between HV=300 to 350 that is lower than that of Ti-6Al-4V powder.

All heat treatment cycles, namely the annealing, recrystallization and β annealing, increase the hardness above Hv=360. The recrystallization heat treatment produced colonies of acicular microstructure. The β annealed specimen shows the acicular structure in larger areas.

3.2 Changes of X-ray Diffraction Patterns

Fig.3 shows the changes of the X-ray diffraction patterns according to the heat treatment cycles applied.

The X-ray diffraction peaks corresponding to the α-phase have been identified to be present in the powder material and all the sprayed sheets before and after being heat treated, and the diffraction peak corresponding to the β-phase at 2θ=88.48° as well.

The widths of the diffraction peaks in the as-sprayed specimen are broadened, suggesting the presence of the very fine grained structure. The diffraction peaks present in the heat treated specimens have higher maximum values and narrower widths suggesting the microstructure to be relatively uniform and the grains to have grown ranging from a few μm to 20 μm.

3.3 EPMA Analyses

Fig.4 shows the EPMA linear analysis results of the sprayed sheets before and after being heat treated.

No appreciable change of the distribution of Ti and oxygen is observed in the EPMA linear analysis result on the cross-section of the as-sprayed specimen. However, the annealing heat treatment at 940 ℃ for 2 hours gives a slight change of the V distribution with an increase of the Ti content accompanied by the reduction of the V content. Furthermore, a certain periodic distance is observed in the changes of the V content, suggesting the enrichment of V at grain boundaries to be brought by the heat treatment cycle. The distribution of oxygen is not effected by the heat treatment cycle.

3.4 Tensile Tests

The tensile test results are shown in **Fig.5**. The annealing heat treatment reduced the tensile strength of the as-sprayed specimens of the size of the parallel parts of 15 mm^2 as well as that of 8 mm^2. A probable reason for the lower strength in the specimen of 8 mm^2 may be the effects of the machining method and the area of the parallel part on the strength of the deposited sheets.

The tensile strength of all heat-treated specimens is equivalent or lower than that of the as-sprayed specimen. The reason for the reduction is believed to be the embrittlement effect of the precipitates of the metastable ω-phase that is formed at grain boundaries based on the EPMA results of the enrichment of V. The formation of the ω-phase is accelerated by the slow cooling rate after the annealing treatment is finished.

The load-displacement curve obtained on the recrystallization heat treatment specimen in **Fig.6** shows a presence of a plastic region as well as in the β annealed specimen. These heat treatment cycles are believed to precipitate the ω-phase because the cooling rates from the annealing temperatures are of the same order to the annealing heat treatment.

4. CONCLUSIONS

Following conclusions are obtained in the present investigation.

(1) The reduced pressure plasma spraying with SUS304 stainless steel substrates is proved to be a high-quality production method of sheets of the alloy of Ti-6Al-4V.

(2) Annealing heat treatment cycles have resulted in increasing the crystallinity, and consequently in increasing the tensile elongation and hardness.

ACKNOWLEDGMENTS

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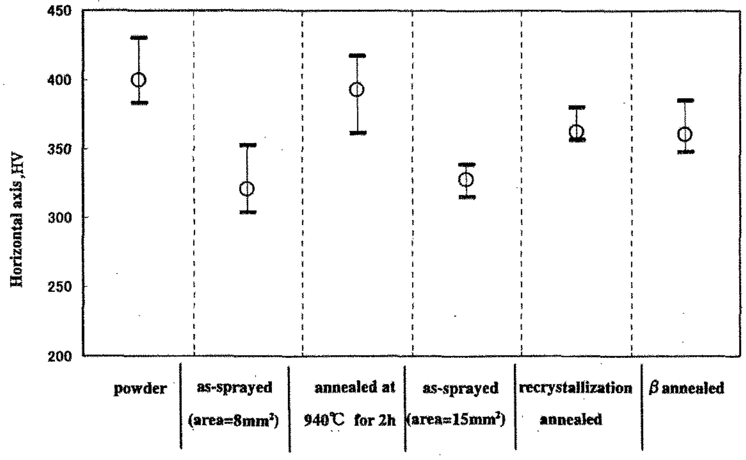


Fig. 1 Hardness of Ti-6Al-4V

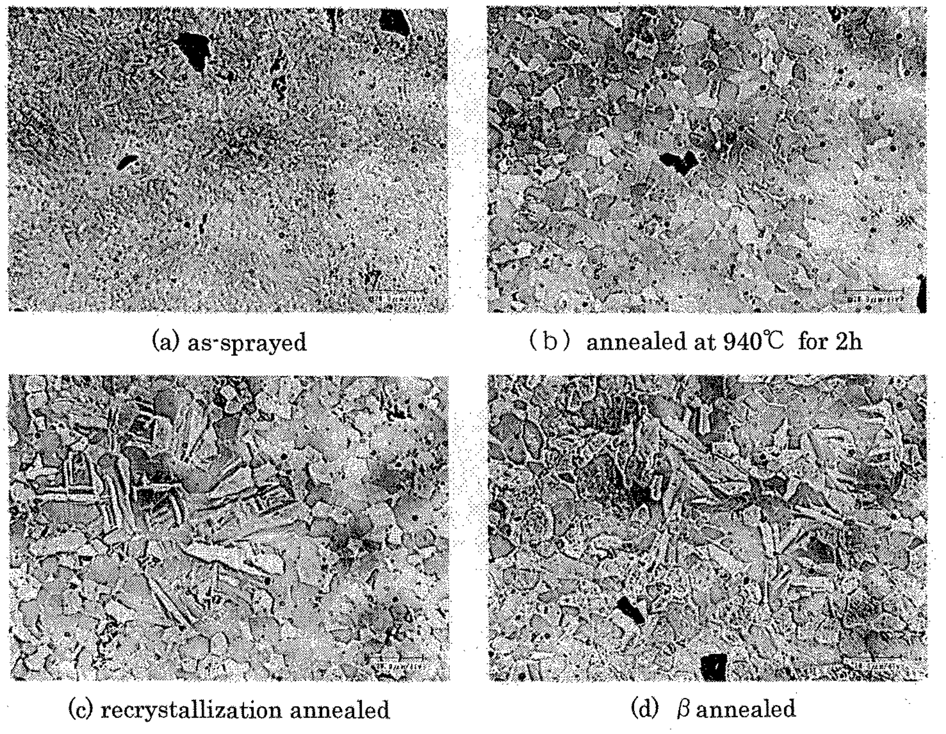


Fig. 2 Micrographs of sprayed sheets of Ti-6Al-4V before and after being heat-treated

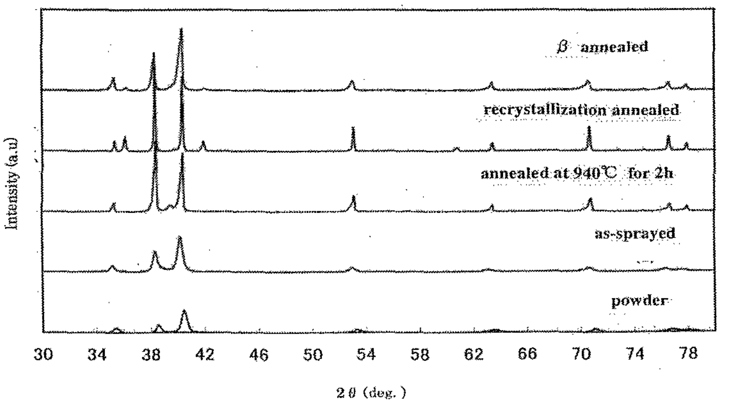
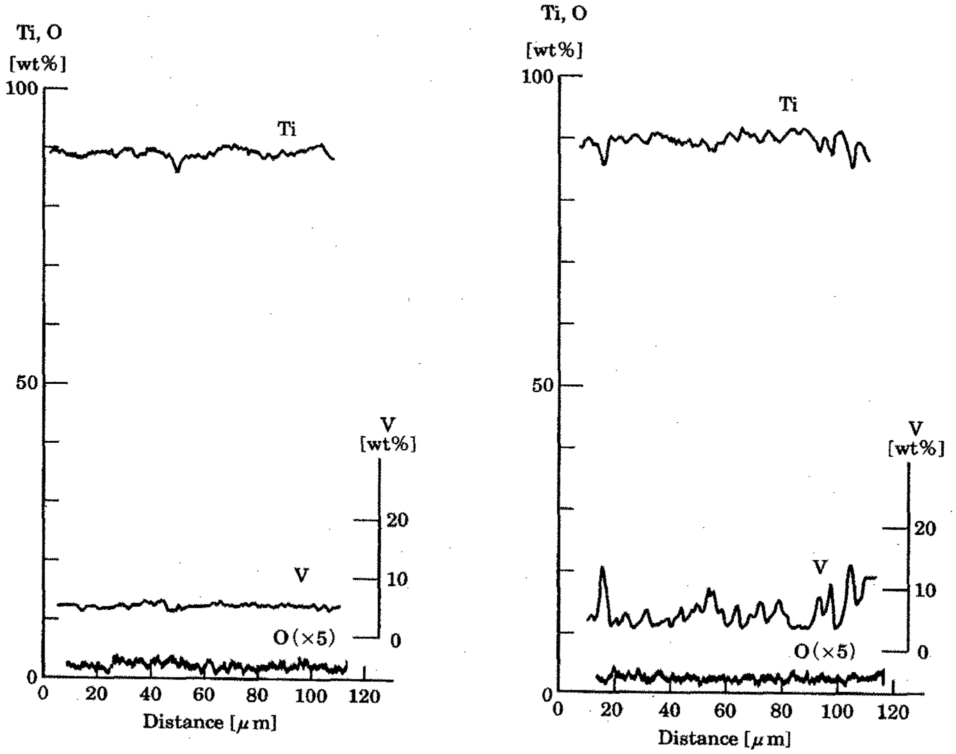


Fig. 3 X-ray diffraction patterns of sprayed sheets of Ti-6Al-4V



(a) as sprayed

(b) annealed at 940℃ for 2h

Fig. 4 EPMA line analysis results on cross-sections of sprayed sheets of Ti-&Al-4V

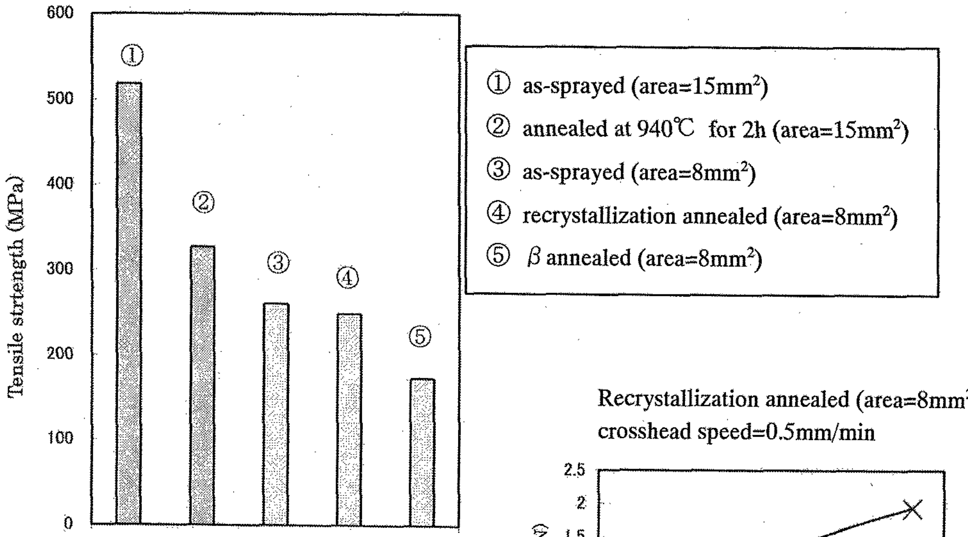


Fig. 5 Tensile strength of sprayed sheets of Ti-6Al-4V before and after being heat-treated

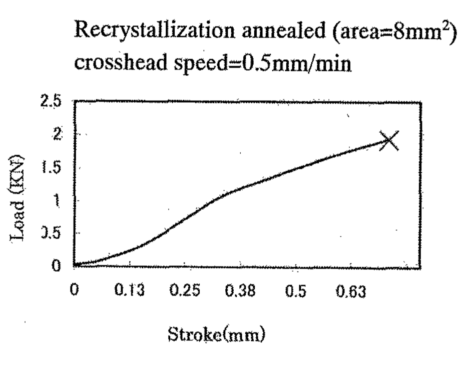


Fig. 6 Load-displacement curve

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