Effect of Post-heat Treatment on Mechanical Properties of Additively Manufactured 17-4PH Stainless Steel Lattice Structures

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Porous metals with numerous internal pores are lighter than bulk materials, and exhibit excellent energy absorption properties. In particular, energy absorption of porous stainless steels is high among porous metals due to deformation-induced martensitic transformation of the residual austenitic phase. They are expected to be used as a new shock-absorbing materials and are being studied now. The authors found that an increase of in the percentage of residual austenitic phase in porous 17-4PH stainless steel improves the energy absorption. On the other hand, the volume fraction of the residual austenitic phase in 17-4PH stainless steel can be controlled by post-heat treatment. Therefore, further improvement of energy absorption can be expected with a higher volume fraction of the residual austenitic phase through heat treatment. The objective of this study is to clarify the post-heat treatment that maximizes the compressive properties of porous 17-4PH stainless steel fabricated by additive manufacturing. The samples used in this study were 30 mm cubes. Their unit cell were obtained by Voronoi-division taking the fcc lattice as seed points (fcc-Voronoi [001]). The diameter of the strut was 1 mm. Their porosity were approximately 90 %. The specimens were fabricated from 17-4PH stainless steel by using a 3D additive manufacturing system (3D Systems ProX300). Here, solution treatment was performed on these samples at 1040 °C for 8 hours and then cooled by air. Subsequently, several samples were subjected to different heat treatments to investigate the effects of heat treatments on the microstructure. EBSD observation of the microstructure was performed using FE-SEM (JSM-IT800). Also, quasi-static compression tests were performed on each heat-treated sample. The compressive properties of the samples were evaluated from the stress-strain curves obtained from the compression tests. EBSD observations of the microstructure of the samples after the compression test were also performed. We discussed the relationship between energy absorption and the microstructure before and after the compression.

Keywords: *stainless steel, lattice structure, additive manufacturing, post-heat treatment*

1. Introduction

Porous metals[1)] with numerous internal pores are lighter than bulk materials, and exhibit excellent energy absorption properties. In particular, energy absorption of porous stainless steels is high among porous metals due to deformation-induced martensitic transformation of the residual austenitic phase[2)]. They are expected to be used as a new shock-absorbing materials and are being studied now. The authors found that an increase of in the percentage of residual austenitic phase in porous 17-4PH stainless steel[3)] improves the energy absorption[4)]. On the other hand, the volume fraction of the residual austenitic phase in 17-4PH stainless steel can be controlled by post-heat treatment. Therefore, further improvement of energy absorption can be expected with a higher volume fraction of the residual austenitic phase through heat treatment. The objective of this study is to clarify the post-heat treatment that maximizes the compressive properties of porous 17-4PH stainless steel fabricated by additive manufacturing.

2. Experimental procedure

The samples used in this study were 30 mm cubes. Their unit cell were obtained by Voronoi-division taking the fcc lattice as seed points (fcc-Voronoi [001]). The diameter of the strut was 1 mm. Their porosity were approximately 90 %. The specimens were fabricated from 17-4PH stainless steel by using a 3D additive manufacturing system (3D Systems ProX300). Table 1 shows composition of 17-4PH stainless steel. Here, solution treatment was performed on those samples at 1040 °C for 8 hours and then cooled by air. Subsequently, several samples were subjected to different heat treatments to investigate the effects of heat treatments on the microstructure. In this study, the samples were heat treated with H1150M and H1150D. Fig. 1 shows heat treatment diagram. All of the heat treatments was performed with an electric furnace(FULL-TECH FT-01VAC-50) in vacuum. Antioxidant was applied to the surface to minimize the effect of oxidation. Vickers hardness test was performed. EBSD observation of the microstructure was performed using FE-SEM(JEOL JSM-IT800).

Quasi-static compression test was performed with Universal testing machine(SHIMADZU AGX-V). The compressive properties of the samples were evaluated from the stress-strain curves obtained from the compression tests. EBSD observations of the microstructure of the samples after the compression test were also performed.

Table 1 Composition of 17-4PH stainless steel (mass%).

Cr	Ni	Cu	Si	Mn	Nb	Mo	N	O	P	C	S	Fe
16.4	4.23	3.91	0.67	0.65	0.23	0.16	0.084	0.052	0.021	0.02	0.007	Bal.

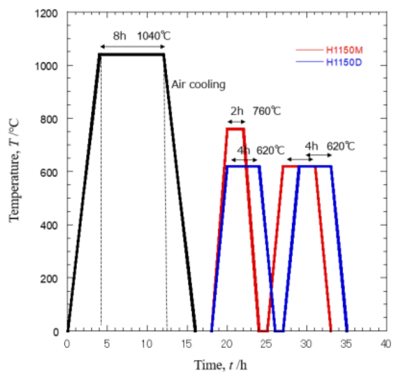

Fig. 1 Post-heat treatment procedure.

3. Results

Fig. 2 shows the phase map obtained from the microstructural observation and the results of the hardness testing of the As-built and heat-treated specimens. The Phase Map shows the distribution of phases in the microstructure. Here, red indicates the austenitic phase and green indicates the martensitic phase. The proportion of As-built specimen and specimen heat-treated with H1150M is almost same. The proportion of residual austenitic phase of specimen heat-treated with H1150D is a little higher than others. Hardness of As-built specimen and specimen heat-treated with H1150M are almost the same. Hardness of specimen heat-treated with H1150D is also a high value that sets it apart from the others.

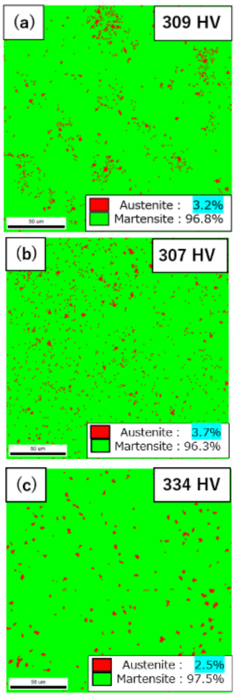

Fig. 2 Results of hardness testing and phase map of (a)As-built specimen, and specimen heat-treated with (b)H1150M and (c)H1150D.

Fig. 3 shows the results of the compression test. stresses in heat-treated specimens increased rapidly to higher values and decreased deeply compared to As-built. After 30% compression, there is no significant difference in compressive behavior among the three conditions.

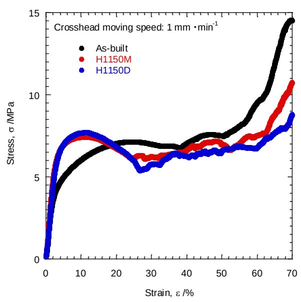

Fig. 3 Compressive stress strain curves of porous 17-4PH stainless steels after different heat-treatments.

4. Discussion

The hardness of the specimens heat-treated with H1150D increased, but the results of the microstructure observation suggest that this is due to an increase in the proportion of martensitic phase, which is a harder microstructure than austenitic phase.

The values used to evaluate energy absorption properties obtained from compression tests are initial maximum stress and energy absorption. Energy absorption is defined as in Eq.1

$$W = \int_0^{50} \sigma d\varepsilon \qquad (1)$$

Fig. 4(a) shows the initial peak stress. As the initial peak stress increases, the strength increases. The initial peak stress is increased by post-heat treatment. This means the structure is superior. Post-heat treatment produced precipitates that reduced toughness. While the strength increased, the material became more susceptible to fracture, resulting in fracture and a large reduction in stress. Fig. 4(b) shows energy absorption. Energy absorption is almost the same, though energy absorption of specimen heat-treated with H1150D was slightly decreased. The heat-treated specimens had a smaller plateau stress than As-built specimens. But energy absorption is about the same due to the larger initial peak stress.

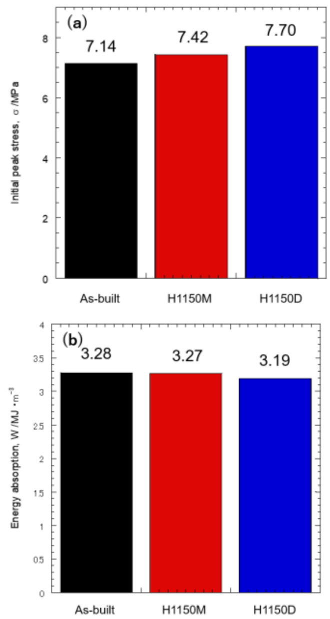

Fig. 4 (a)Initial peak stress and (b)Energy absorption.

From the experiments, it can be seen that the more residual austenite phase, the greater the energy absorption. On the other hand, the results for the as-formed samples are not in line with this. It is thought that not only phase transformation but also other factors such as crystal grains and residual stresses are involved here.

5. Conclusions

Compression testing and microstructural observation of lattice-structured 17-4PH stainless steels with post-heat treatments led to the following findings.

(1) Energy absorption becomes higher as the residual austenitic phase increases. However, it is necessary to consider the reason why the As-built specimen has better energy absorption than the heat-treated specimens.

(2) By performing post-heat treatment, the initial peak stress was increased while maintaining the same amount of energy absorption as in the As-built condition.

(3) The post-heat treatment of H1150M should be performed when using 17-4PH stainless steel as a shock absorber.

References

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