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Characterization of 3D Printed Functionally Graded Material for Nuclear Reactor

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1. Introduction

Since various parts of a nuclear reactor are manufactured with different steel types depending on the purpose of use and environment, there are inevitably many dissimilar metal welding parts in the reactor. There is a high possibility of PWSCC(Primary Water Stress Corrosion Cracking) damage attributed to residual stress caused by the difference in material properties in the dissimilar metal welded part. A number of accidents such as leakage of radioactive coolant due to PWSCC have been reported around the world, posing a great threat to nuclear safety [1]. A variety of methods have been tried to relieve the residual stress of dissimilar metal welds, but there is no fundamental solution so far.

As competition to lead the era of the 4th industrial revolution is intensifying internationally, 3D printing technology, one of the core technologies of the 4th industrial revolution, is making remarkable progress. In the nuclear industry, the development of nuclear-grade parts using 3D printing technology is being actively carried out in several countries including the United States, and a technological environment that can improve the safety of existing nuclear reactors by utilizing the advantages of 3D printing parts is rapidly being created [2].

The dissimilar metal welds in the most of the reactor are connections between low alloy steel parts and stainless steel piping. Therefore, we tried to develop a technology that can fundamentally remove dissimilar metal welds by connecting existing dissimilar metal parts by manufacturing low-alloy steel/stainless steel functionally graded material (FGM) using 3D printing technique.

2. 3D Printing of FGM

2.1 Production of Alloy Powder for 3D Printing

To fabricate a FGM in which low-alloy steel and austenitic stainless steel are additively manufactured using a 3D printer, alloy powder was prepared. The prepared alloys are SA533B low alloy steel and Type 316L stainless steel, which are mainly used for pressure vessels and piping of nuclear reactors respectively. In the case of Type 316L, commercial powder is easily available, but low alloy steel powder of the same type as that used in nuclear reactors is not available commercially. Therefore, in this study, blocks taken from SA533B low alloy steel, which is an archival material for a pressure vessel in the Kori Unit 2 nuclear reactor, and spherical powder with an average particle size of about 100 μm was produced through high temperature atomizing.

2.2 Manufacturing of FGM

The FGM was manufactured using powder mixed in such a way that the fraction of low alloy steel was reduced by 25% in 4 steps from 100% to 0%. A DED (Direct Energy Deposition) type 3D printer manufactured by a domestic company was used for 3D printing. Under DED conditions, the output was 380-450 W, the speed was 14.1 mm/s, and the stacking was performed at a hatch interval of 400 μm. As shown in Figure 1, a prototype was fabricated by the orthogonal scanning method.

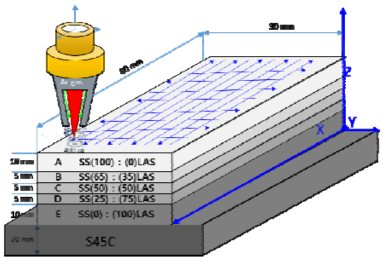

Fig. 1. Schematic of additive manufacturing process for low alloy steel-austenitic stainless steel FGM using DED type 3D printing technique.

3. Characteristics of FGM

3.1 Microstructure

The chemical composition was analyzed for layer A, which is Type 316L, to layer E, which is low alloy steel, through a scanning electron microscope(SEM-EDS). As shown in Fig. 2, the content of Cr, Ni, and Mo decreased linearly as the ratio of low alloy steel decreased, confirming that the intended gradient composition material was obtained.

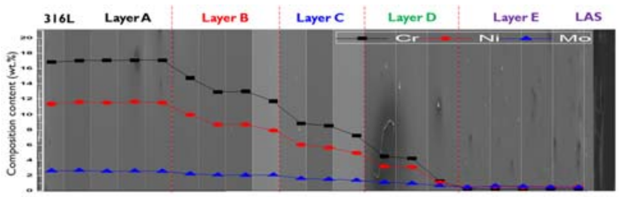

Fig. 2. Compositional profile for low alloy steel-austenitic stainless steel FGM.

3.2 Mechanical Properties

The tensile tests in the Y and Z directions of the FGM were performed in order to evaluate the mechanical properties.

As shown in Fig. 3, in the Y-direction with respect to the build-up axis, the tensile strength of layers A and B, which have a high austenite fraction, compared to layers C, D, and E, having a high ferrite fraction (655 MPa and 868 MPa, respectively) and yield strength (518 MPa and 504 MPa, respectively) were low. On the other hand, the elongation (56.5% and 82.8%, respectively) was very high. These tensile properties are attributed to work hardening that occurs in general austenitic stainless steels.

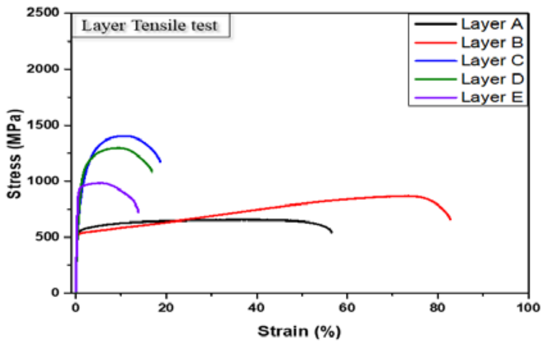

Fig. 3. Stress-strain curves for layers of ferrite-austenite FGM.

3.3 Thermal Expansion

The thermal expansion coefficient up to 800°C was measured for each layer of FGM using TMA (Thermomechanical Analysis). As shown in Fig. 4, thermal expansion coefficient tended to increase as the austenite content increased.

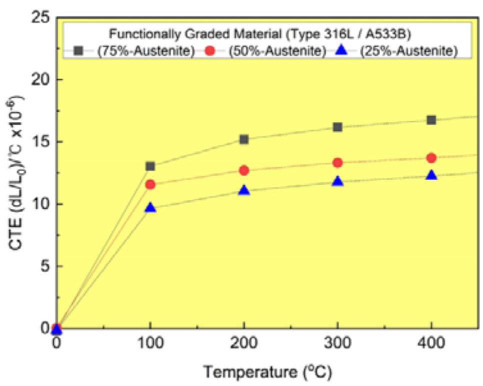

Fig. 4. Thermal expansion coefficient for each layer of FGM

3.4 Residual Stress Distribution

The residual stress generated in the circumferential direction of the pipe-type FGM manufactured in 1/3 size to simulate the welding of the actual surge line in a nuclear reactor was measured by the contour method.

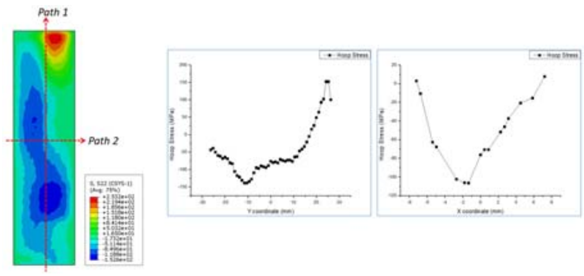

Fig. 4 Residual stress distribution in low alloy steel-austenitic stainless steel FGM manufactured using 3D printer.

As shown in Figure 4, the residual stress of the low-alloy steel-stainless steel FGM manufacture using a 3D printer was measured to be relatively low even in the as-received state.

4. Summary

A low-alloy steel-stainless steel FGM was manufactured using 3D printing technique and characterized to prevent damage to the PWSCC of the dissimilar metal welding part of the reactor. Powder production, mixing ratio calculation, and process optimization were performed to fabricate the low alloy steel-stainless steel FGM, and microstructure analysis, mechanical properties, thermal expansion coefficient measurement, and residual stress distribution analysis of the FGM were performed. The mechanical properties and residual stress of the FGM were equal to or higher than those of the existing dissimilar metal welded parts. Testing for PWSCC characterization is currently in progress.

Acknowledgement

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