Magnetostrictive Property and Energy Harvesting Performance of Additive Manufactured Fe-Co Alloys

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論文内容要約

As the use of IoT and big data progresses, the number of different sensors, including biosensors, will increase explosively. Thus, powering the sensors will be a social and economic issue. Therefore, energy harvesting, which converts unused kinetic energy into electrical energy, is attracting attention. Research on piezoelectric ceramics, magnetostrictive alloys, and their composite materials is being actively conducted to improve the performance of materials and devices used in energy harvesting. Piezoelectric ceramics and composites, particularly, have numerous applications, and various studies have been conducted. Research on the developments and property improvements of magnetostrictive materials has also been conducted. Energy harvesting devices that use magnetostrictive effects have been actively investigated; however, most of them focus on Fe–Dy–Tb (Terfenol-D) and Fe–Ga (Galfenol) alloys. Terfenol-D alloys are expensive and have the disadvantage of brittleness. In addition, Galfenol alloys have drawbacks in terms of mass productivity and processing cost. However, Fe–Co alloys have low magnetostrictive characteristics but are inexpensive and easy to process into wires. Therefore, research and development of Fe–Co alloys are critical. As previously mentioned, magnetostrictive materials are generally brittle, which limits the design of complex structures. The magnetostrictive properties of Fe–Co alloys can be improved by changing the alloy's structure. It was found that the leakage flux obtained from Fe–Co alloys could be increased by inserting a stress concentration point, or so-called notch, in the material in advance. The problem is that the structure becomes more and more complicated as one considers a structure with a larger leakage flux, and it becomes difficult to fabricate the material using conventional methods.

A series of technologies, called 3D printers or additive manufacturing (AM), are attracting attention as innovative manufacturing technologies. They enable significant time reduction from design to production, and mass customization for the mass production of components with different sizes and shapes. In addition, manufacturing time and cost are not dependent on the component shape complexity. AM technology can form shapes that are impossible or extremely difficult to form using conventional forming and processing technologies such as casting, cutting, and plastic forming. Moreover, the material consumption yield is high even if the same shape as before is produced. Furthermore, the AM strength and functionality are often superior to those obtained by conventional manufacturing methods. It is expected that superior materials can be obtained by taking advantage of the unique microstructural formation of the AM process. It is necessary to accumulate knowledge on the correlation between fabrication conditions and microstructure properties and establish guidelines for guaranteeing the properties to fully demonstrate the potential of AM. Therefore, it is essential to correctly understand the basic principles of the

current metal AM processes and the physical phenomena occurring in the process. Recently, laser metal deposition (LMD) and powder bed fusion (PBF) processes have become the mainstream metal AM technologies.

In the LMD process, a high-energy beam is irradiated while supplying the material for modeling to the area where the material is to be added by feeding a wire or injecting powder into the area, and depositing the material to form the modeled object. This can be done by moving the material supply device and beam source relative to the substrate. So, the material deposition position moves continuously along the modeled object shape to obtain a three-dimensional modeled object. In most LMD processes, a laser is used as the beam and the material is delivered as a powder. An inert gas flux transports the powder. In most LMD processes, the substrate is irradiated with a beam to form a molten pool, into which the metal powder or wire is injected to add material. These LMD processes are based on laser cladding, a technique that has been used to repair high-value-added metal parts such as turbine blades and molds. Some of the powder is added in a molten state by laser irradiation in the air. Compared to the PBF described below, the LMD has a wider acceptable powder range. Furthermore, since multiple powder types can be mixed during the powder transfer process, it is possible to produce materials with tilted functions by changing the mixing ratio.

In PBF, the raw powder is spread on a flat metal plate called the build platform to form a layer of powder called the powder bed. By irradiating the layer with a laser or electron beam while scanning it along the two-dimensional slice shape of the object, the powder particles are melted to form a densified material layer. The laser-based method is called laser power bed fusion (LPBF), and the electron beam-based method is called electron beam melting. The LPBF process is the most common metal lithography type. The gas-atomized powder is usually used as the raw material powder in PBF. This is because high fluidity is required in the powder-feeding process and in forming a flat and uniform powder layer. Gas-atomized powders are more spherical and fluid than powders obtained by water atomization, milling, or chemical reaction, and are suitable for PBF. The melt is produced by re-melting the already melted and solidified areas that have been irradiated by the beam and flows and fuses with the sides and lower layers. If the beam power and scanning speed are appropriate, a molten pool is formed with a width several to several tens of times wider than the powder particles in the scanning direction. If the beam power or scanning speed is inappropriate, defects such as pores and cracks are formed. The heat input energy density per unit volume (beam power/scanning speed/scanning line spacing/building thickness) is used as an appropriate condition indicator. Crystal orientation is another feature. In lamination molding, the temperature gradient in the lamination direction is basically large, and the solidification interface movement becomes dominant in that direction, and crystal orientation is likely to occur, reflecting the gradient. No previous studies have been on Fe–Co alloys using the AM method, and it is necessary to examine the optimum conditions for the AM method. It is also essential to examine which of the representative metal AM techniques described so far, the LMD or LPBF methods, is best suited for Fe–Co alloys.

In this paper, we fabricated Fe–Co alloys using two representative methods of metal AM technology and investigated the optimal AM conditions for each by evaluating the magnetostrictive properties. Firstly, the magnetostrictive properties of Fe_{30}–Co_{70} alloys were evaluated by AM using the LMD method in Chapter 2. Secondly, we produced and compared the performance of additively manufactured Fe_{53}–Co_{47} alloys by the LPBF method with commercial materials in Chapter 3. The results were also compared with samples produced using the LMD process. In addition, the influence on magnetostrictive properties was evaluated by crystal structure analysis. Furthermore, impact and vibration tests were conducted to evaluate the power amount generated to evaluate the power generation characteristics. In addition, complex structures were fabricated, and their power generation performances were evaluated.

In the LMD method, samples with various energy densities was fabricated using Fe_{30}–Co_{70} alloy powder, and its crystal structure and magnetostrictive properties were evaluated. The optimal laser power and scanning speed were used to reduce the porosity. Crystals tended to grow in the building direction. In terms of magnetostrictive properties, the values were almost the same as those of the rolled material. Moreover, there is a need for further clarification of the relationship between magnetostriction and porosity so as to develop a better sensor. Samples with different scanning speeds were also prepared in this study. Our findings showed that the higher the laser power and the smaller the scanning speed, the smaller is the porosity. The samples fabricated at a scanning speed of 500 mm/min exhibited increasing magnetostrictive properties with the increase in laser power. The internal strain and fcc phase were removed via annealing; this resulted in the improvement of magnetic and magnetostrictive properties. This improvement could be because of the reduction of defects inside the sample and the disappearance of the fcc phase, leaving only the bcc phase. The orientation of the samples prepared by the AM method is smaller than that of the rolled and wire samples, but this can be improved by heat treatment. It is important to perform heat treatment instead of as-AM material when mounting the material in a device. Thus, additive-manufactured Fe–Co samples could be used in, for example, sensors with complex shapes since the piezomagnetic performance increased according to property measurements. If the structures of the additive-manufactured samples are controlled in one direction, similar to a single-crystal, then the properties can be further improved.

We produced and compared the performance of additively manufactured Fe_{53}–Co_{47} alloys with commercial materials. The results were also compared with samples produced using the laser metal deposition (LMD) process. To determine the optimum conditions, samples on cubic were fabricated by changing the laser power and scanning speed. We optimized the process parameters to obtain a homogeneous microstructure, low porosity, and no cracks. Regardless of the manufacturing parameters, the relative density of each Fe_{53}–Co_{47} alloy cube exceeded 99.5%. Except for the case with 300 W of power, where a keyhole regime is expected, the densities of the cubes tended to increase with the volume energy density. Cracks were found in various Fe_{53}–Co_{47} alloy cubes. The cross-sectional observation revealed many cracks in the samples fabricated at low laser power and low scanning speed. The cracks tended to decrease as laser power increased. However, there was no crack in the one fabricated with the power of 250 W and the scanning speed of 1000 mm/s. The magnetic and magnetostrictive properties were evaluated, and those fabricated using the LPBF process had higher values than those fabricated using the LMD process. This could be because the internal defects in the samples were smaller than those in the LMD process. Because of the heat treatment, annealing at 750 °C for 1 h significantly improved the magnetostrictive properties. The heat treatment also significantly improved the magnetostrictive properties of the samples fabricated using the AM process. The LPBF process is considered to be located in the region where columnar crystals grown in the stacking direction and polycrystals are mixed, based on the results of EBSD analysis. The obtained crystals were small, and it is thought that ideal crystals (i.e. single crystals, columnar) can be obtained by further reducing the scanning speed. In the LMD process, the crystal grains were very small and polycrystalline, even though the scanning speed was slow. It is difficult to apply this to the solidification map, and it is thought that the cooling rate increased during the solidification process. One possible reason for this is the powder feed rate, which is thought to have increased the cooling rate due to the large powder feed rate, resulting in polycrystallization. In addition, if the powder feed rate is not appropriate, the porosity may increase. These results revealed that the LPBF process is more suitable than the LMD process for fabricating Fe–Co alloys.

Honeycomb structures with complex geometries were fabricated to reduce the amount of Fe–Co alloy powder used while maintaining the mechanical properties. The presence of porosity varied by structure, with honeycomb structures having a greater porosity because of the number of cells that make up these structures. We evaluated the vibration and impact energy-harvesting performance for fully dense, notch, and honeycomb structures. the fully dense and notch sample showed very high power generation near the resonance frequency, whereas the honeycomb material showed a large resonance frequency shift to the lower frequency side. This is an important result for device design because the vibration around us is on the low-frequency side. Furthermore, the notch plate demonstrated power densities that were 10 times larger than fully dense ones. In addition, the impact power generation results showed that the honeycomb material generated nearly five times more power than the fully dense material. Thus, the honeycomb structure is attractive for generating electricity effectively. This study enabled us to propose the optimal AM process conditions for Fe–Co magnetostrictive alloys and the optimal geometry for power generation performance.