Inverse magnetostrictive properties of twisted Fe–Co alloy wire

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Abstract
In this study, the inverse magnetostrictive properties of twisted Fe–Co alloy wires and the twisted Fe–Co alloy wire integrated epoxy resin matrix composites were evaluated using free and forced vibration and compressive tests. The inverse magnetostrictive properties of the twisted Fe–Co alloy wires were higher than those of the untwisted wires, with the highest values obtained for the 8-times-twisted Fe–Co alloy wires. However, no clear relationship was observed between the output voltage values and the number of twists. These findings suggested that twisting the Fe–Co alloy wire resulted in residual stress, which may have improved the inverse magnetostrictive properties.

Keywords: Fe–Co alloy; polymer matrix composite; inverse magnetostrictive effect; compressive test

1. Introduction
The Internet of Things (IoT), in which every object connects to the internet to collect big data and improve our quality of life, has recently gained popularity. To realize the IoT society, many devices, including sensors, must be prepared. However, fabricating numerous batteries for IoT devices is unrealistic. Therefore, battery-free devices should be developed using energy harvesting materials to power the devices. The conversion of unused energy, such as human movement, vibration, heat, and light, into electrical energy is known as energy harvesting. However, the low power generation performance of energy harvesting materials prevents its application.

One type of energy harvesting material is a magnetostrictive material. Because of the inverse magnetostrictive effect (Viralli effect), magnetostrictive materials generate electricity. The super magnetostrictive materials such as Terfenol-D and Galfenol have higher magnetostrictive properties than Fe–Co alloy (~150 ppm). However, they are oxidizable and expensive; hence, they cannot be used on industrial scale. The Fe–Co alloy is a promising magnetostrictive alloy with excellent mechanical properties, high saturation magnetization, high Curie temperature, and low cost. Previously, we have proposed the fabrication of Fe–Co alloy and Nickel clad plate [1,2], the notching [2,3], the nitriding [4], additive manufacturing of Fe–Co alloy [5,6], and Fe–Co alloy wire integrated or particle distributed polymer matrix composites [7,8].

We hypothesized that twisting promotes easy movement of the magnetic wall during the magnetization process and improves the magnetostrictive properties of Fe–Co alloy wire [9]. Therefore, the inverse magnetostrictive properties of twisted Fe–Co alloy wires under free and forced vibrations and that of twisted Fe–Co alloy wires integrated with epoxy resin composites under compressive stress, were investigated in this study.

2. Experimental procedure

2.1. Inverse magnetostrictive properties of twisted Fe–Co alloy wires under free and forced vibrations

Twisted Fe–Co wires, length = 50 mm, were obtained by bending Fe–Co alloy wire (diameter of 0.5 mm, TOHOKU STEEL, Co., Ltd) at the center and rotating it with a constant speed drill (see Fig.1). The twist rate varied between 3 and 9 times/cm. Further, untwisted Fe–Co alloy wire (diameter of 1.0 mm, TOHOKU STEEL, Co., Ltd) was obtained for comparison.

The free vibration test setup is shown in Fig. 2. A string was used to suspend an 8/16 g weight from the twisted Fe–Co alloy wire, which was fixed inside the coil. The data loggers (NR-500 and NR-ST04, Keyence Corporation), with an internal resistance of 4.5 kΩ, measured the output voltage by dropping of the weight.

The schematic illustration of the forced vibration test setup is shown in Fig. 3. A shaker (ET-132, Labworks Inc.) and function generator (FG-281, Kenwood Corporation), which was fixed inside the coil, are used to vibrate the twisted Fe–Co alloy wire. The output voltage was measured using the same data loggers (NR-500 and NR-ST04, Keyence Corporation), which had an internal resistance of 4.5 kΩ. The acceleration was calculated by

$$a = (2\pi f)^2 \times \frac{D}{2} \quad (1)$$

where f is the frequency and D is the total amplitude, respectively.

2.2. Inverse magnetostrictive properties of twisted Fe–Co alloy wires integrated epoxy resin composites under compressive stress

To test the inverse magnetostrictive properties of twisted Fe–Co alloy wires under compressive stress, the wires were embedded in epoxy resin. A bisphenol-F and curing agent (ST-12, Mitsubishi Chemical Corporation) were mixed in a 100:55 ratio, stirred for 10 min, and degassed for 15 min. The mixed solution was poured into a cylindrical mold with twisted Fe–Co alloy wires oriented longitudinally. The twisted Fe–Co alloy wire integrated epoxy resin composites (ϕ= 10 × 20 mm^3) were obtained after curing at 20 °C for 24 hours and at 80 °C for 180 min.

The inverse magnetic flux density measurement test is shown in Fig. 4. Using a universal testing machine (AG-5 kN XD, Shimadzu Corporation), with a testing speed of 0.08 MPa/s and the bias magnetic field of 0, 215, or 485 mT by sandwiching two permanent magnets, compressive stress was applied along the longitudinal direction of twisted Fe–Co alloy wire integrated epoxy resin composite until 50 MPa. The magnetic flux density vibration at the center of twisted Fe–Co alloy wire integrated epoxy resin composites was measured using a Tesla meter (TM-801, Kanetec Co. Ltd.).

The output voltage measurement test is depicted in Fig. 5. Using a universal testing machine (AG-5 kN XD, Shimadzu Corporation) at a testing speed of 2.0 mm/s, cyclic compressive loads of 200 and 1200 N were applied 6 times along the longitudinal direction of twisted Fe–Co alloy wire integrated epoxy resin composite sandwiched by an aluminum plate and covered with a coil. The magnetic flux density due to vibrations at the center of twisted Fe–Co alloy wire integrated epoxy resin composites was measured using a Tesla meter (TM-801, Kanetec Co. Ltd.).

3. Results and discussion

3.1. Inverse magnetostrictive properties of twisted Fe–Co alloy wires under free and forced vibrations

The output voltage density of twisted Fe–Co alloy wires increased proportionally to the number of twists (Fig. 6). However, no clear relationship could be found between the output voltage values and the number of twists. The stress applied to Fe–Co alloy wire oriented the magnetic domain and increased its magnetostrictive properties. The output voltage density of twisted Fe–Co alloy wires under forced vibrations was nearly identical regardless of the number of twists; however, it was low for untwisted wires (Fig.7).

3.2 Inverse magnetostrictive properties of twisted Fe–Co alloy wires integrated epoxy resin composites under compressive stress

Figure 8 depicts the variation in the magnetic flux density of an 8-times-twisted Fe–Co alloy wire integrated epoxy resin composite under compressive stress with different bias magnetic fields. The variations were greater with the 215-mT bias magnetic field than that with the 0-mT bias magnetic field. However, the magnetic flux density decreased with a bias magnetic field of 485 mT due to the complete orientation of magnetic domains, and a high bias magnetic field (485 mT) decreased the free rotational degrees of a magnetic moment.

The difference in magnetic flux density change between 5-and 8-times-twisted Fe–Co alloy wire integrated epoxy resin composites under compressive stress is shown in Fig. 9. The magnetic flux density of the 5-times-twisted Fe–Co alloy wire integrated epoxy resin composite remained the same, whereas that of the 8-times-twisted one increased proportionally. The magnetic flux density change between untwisted, 5-times-twisted, and 8-times-twisted Fe–Co alloy wire integrated epoxy resin composites under compressive stress is depicted in Fig. 10. The magnetic flux density of an 8-times-twisted

Fe–Co alloy wire integrated epoxy resin composite was ~28 times compared to that of the untwisted Fe–Co alloy wire integrated epoxy resin composite.

4. Conclusion

The inverse magnetostrictive properties of twisted Fe–Co alloy wires under free and forced vibrations and that of twisted Fe–Co alloy wires integrated with epoxy resin composites under compressive stress were investigated in this study. Twisted Fe–Co alloy wires had higher inverse magnetostrictive properties than untwisted wires, with the inverse magnetostrictive properties of 8-times-twisted Fe–Co alloy wire having the highest values. However, no clear relationship could be found between the output voltage values and the twisting number. The residual stress in Fe–Co alloy wire due to twisting appears to have increased its inverse magnetostrictive properties. However, more research is needed to determine the mechanism of enhancement of Fe–Co alloy wire by twisting.

Acknowledgments

We would like to express our gratitude to Naoki Takehara for his experiments. The Japan Society for the Promotion of Science (JSPS) funded this study with a Grant-in-Aid for Scientific Research (A), 19H00733.

Author statement

Conceptualization, Wang, Narita; methodology, Wang; formal analysis, Kurita; investigation, Wang; resources, Kurita; writing—original draft preparation, Kurita; writing—review and editing, Narita; visualization, Kurita; supervision, Narita; project administration, Narita; funding acquisition, Narita. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Yang Z, Kurita H, Onodera R, Tayama T, Chiba D, Narita F, Evaluation of Vibration Energy Harvesting Using a Magnetostrictive Iron-Cobalt/Nickel-Clad Plate, Smart Materials and Structure, 28(3), 034001, 2019

[2] Yang Z, Kurita H, Takeuchi H, Nakajima K, Narita F, Effect of Notches on Magnetic Induction Variation for Magnetostrictive Clad Plate, Sensors and Materials, 31(11), 3681–3690, 2019

[3] Nakajima K, Kurita H, Narita F, Performance Boost Of Co-rich Fe-Co Based Alloy Magnetostrictive Sensors via Nitrogen Treatment, Sensors and Actuators, A: Physical, 295, 75–83, 2019

[4] Yang Z, Kurita H, Takeuchi H, Katabira K, Narita F, Enhancement of Inverse Magnetostrictive Effect through Stress Concentration for a Notch-Introduced FeCo Alloy, Advanced Engineering Materials, 1800811, 2018

[5] Kurita H, Lohmuller P, Laheurte P, Nakajima K, Narita F, Additive Manufacturing and Energy-Harvesting Performance of Honeycomb-Structured Magnetostrictive Fe52–Co48 Alloys, Additive Manufacturing, 54, 102741, 2022

[6] Nakajima K, Leparoux M, Kurita H, Lanfant B, Cui D, Watanabe M, Sato T, Narita F, Additive Manufacturing of Magnetostrictive Fe–Co Alloys, Materials, 15(3), 709, 2022

[7] Kurita H, Keino T, Senzaki T, Narita F, Direct and Inverse Magnetostrictive Properties of Fe–Co–V Alloy Particle-dispersed Polyurethane Matrix Soft Composite Sheets, Sensors and Actuators A: Physical, 337, 113427, 2022

[8] Kurita H, Katabira K, Yoshida Y, Narita F, Footstep Energy Harvesting with the Magnetostrictive Fiber Integrated Shoes, Materials, 12(13), 2055, 2019

[9] Yang Z, Nakajima K, Jiang L, Kurita H, Murasawa G, Narita F, Design, Fabrication and Evaluation of Metal-Matrix Lightweight Magnetostrictive Fiber Composites, Materials and Design, 175, 107803, 2019

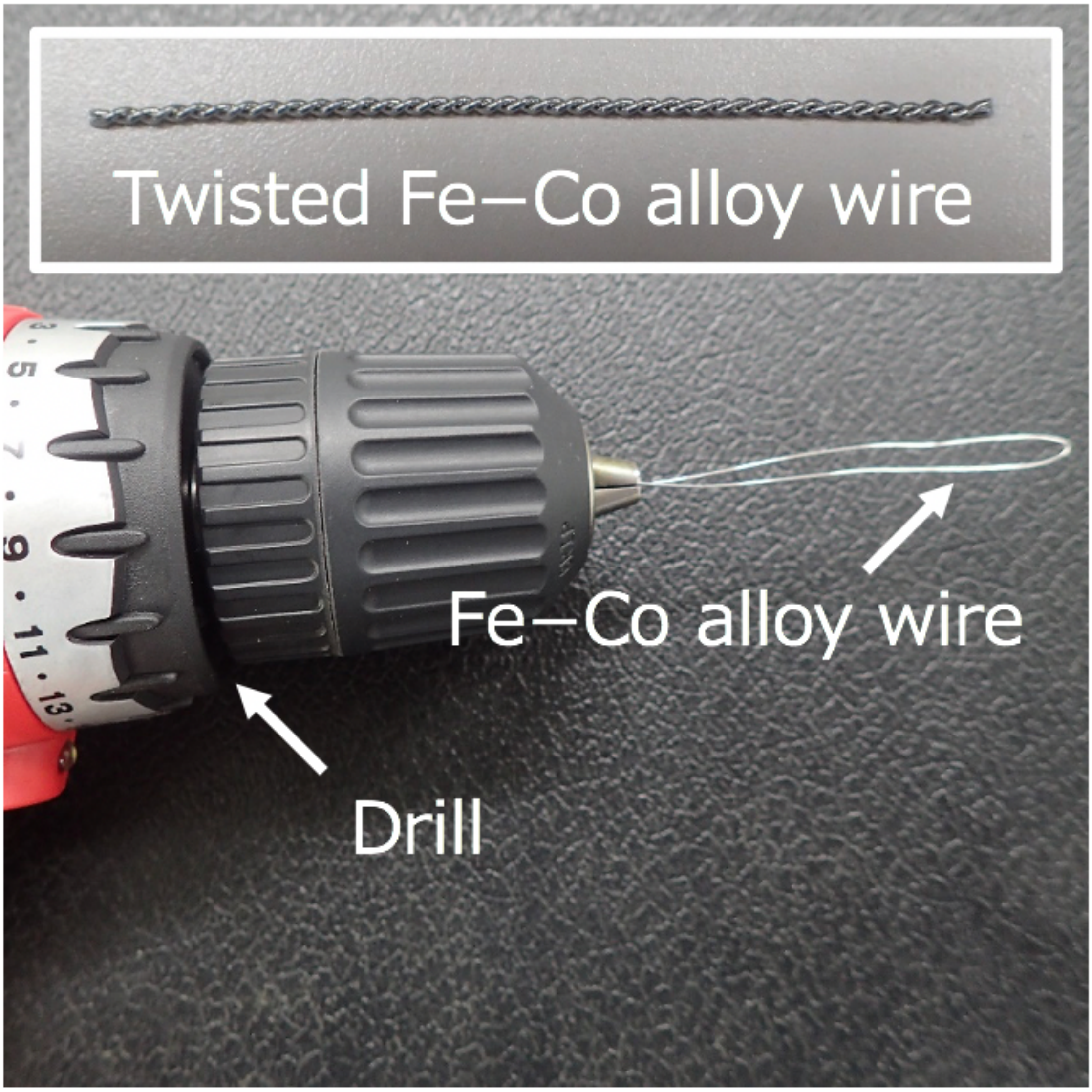


Figure 1 Twisting Fe–Co wires using a drill.

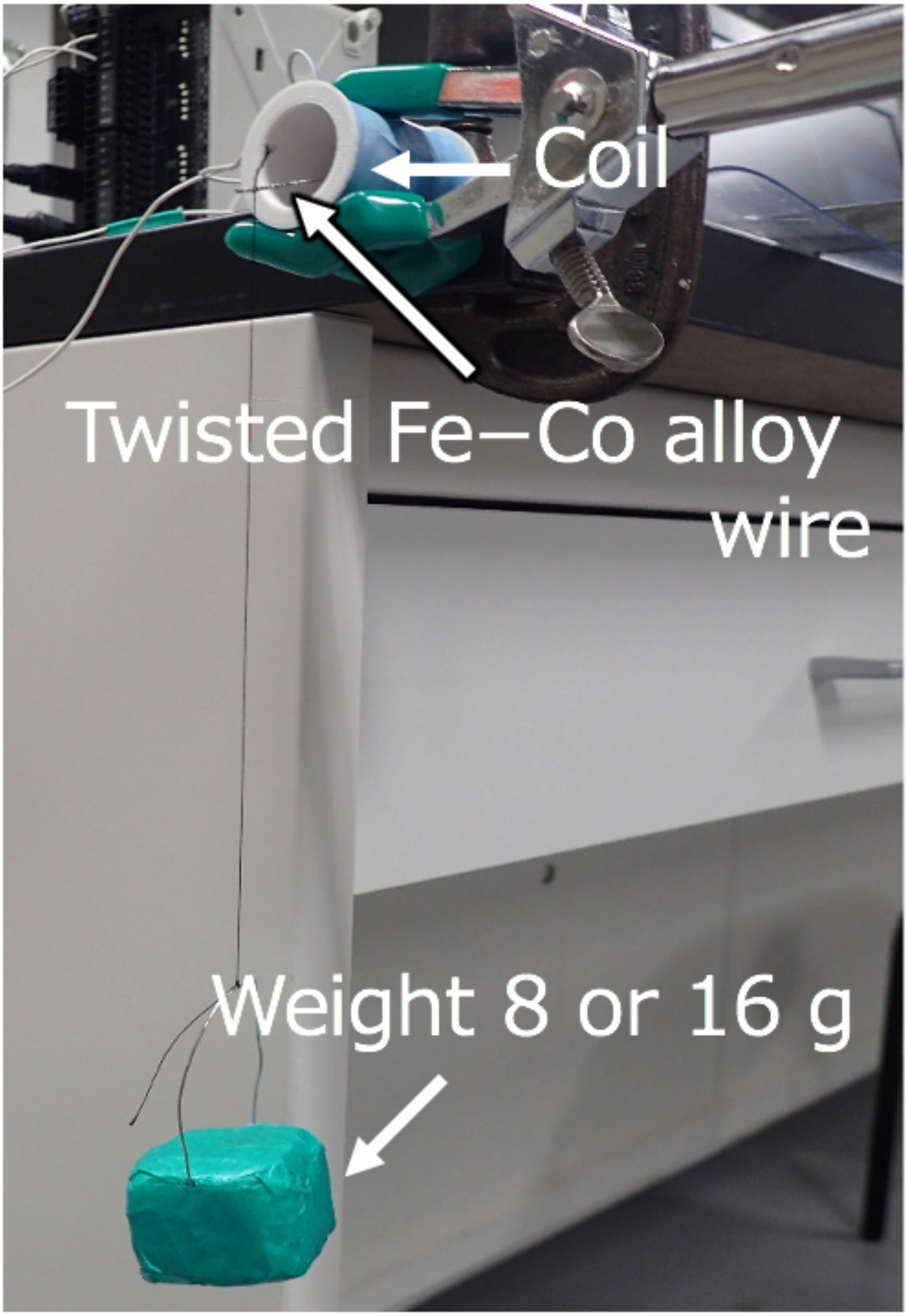


Figure 2 Setup for free vibration test.

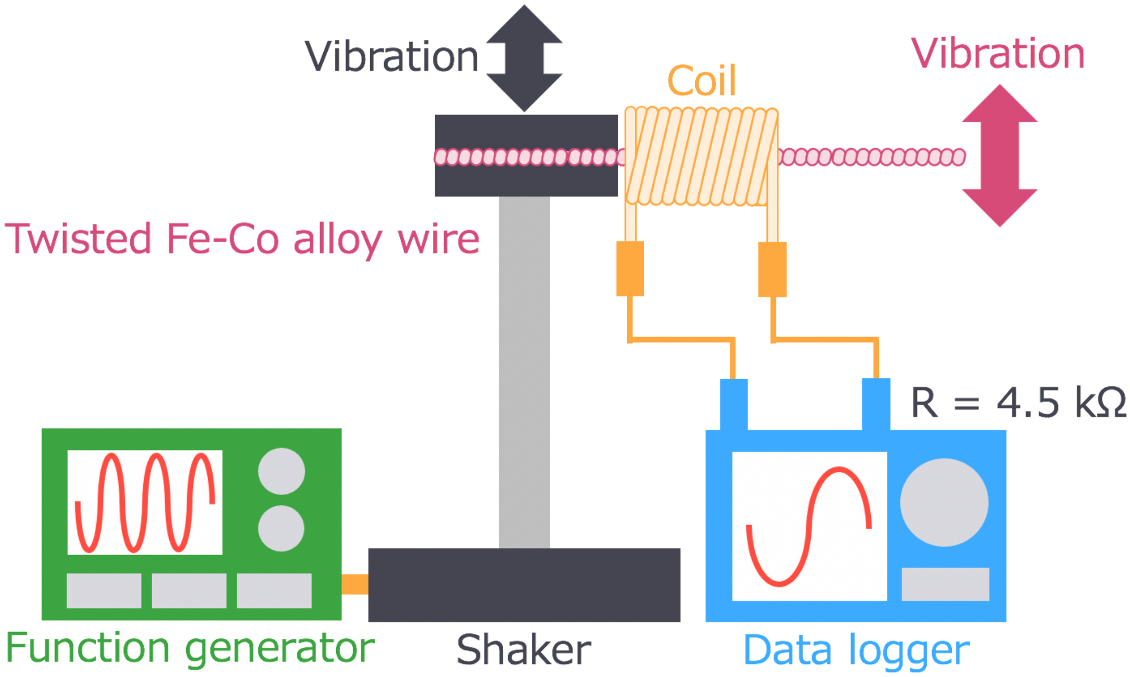


Figure 3 Schematic of the forced vibration test setup.

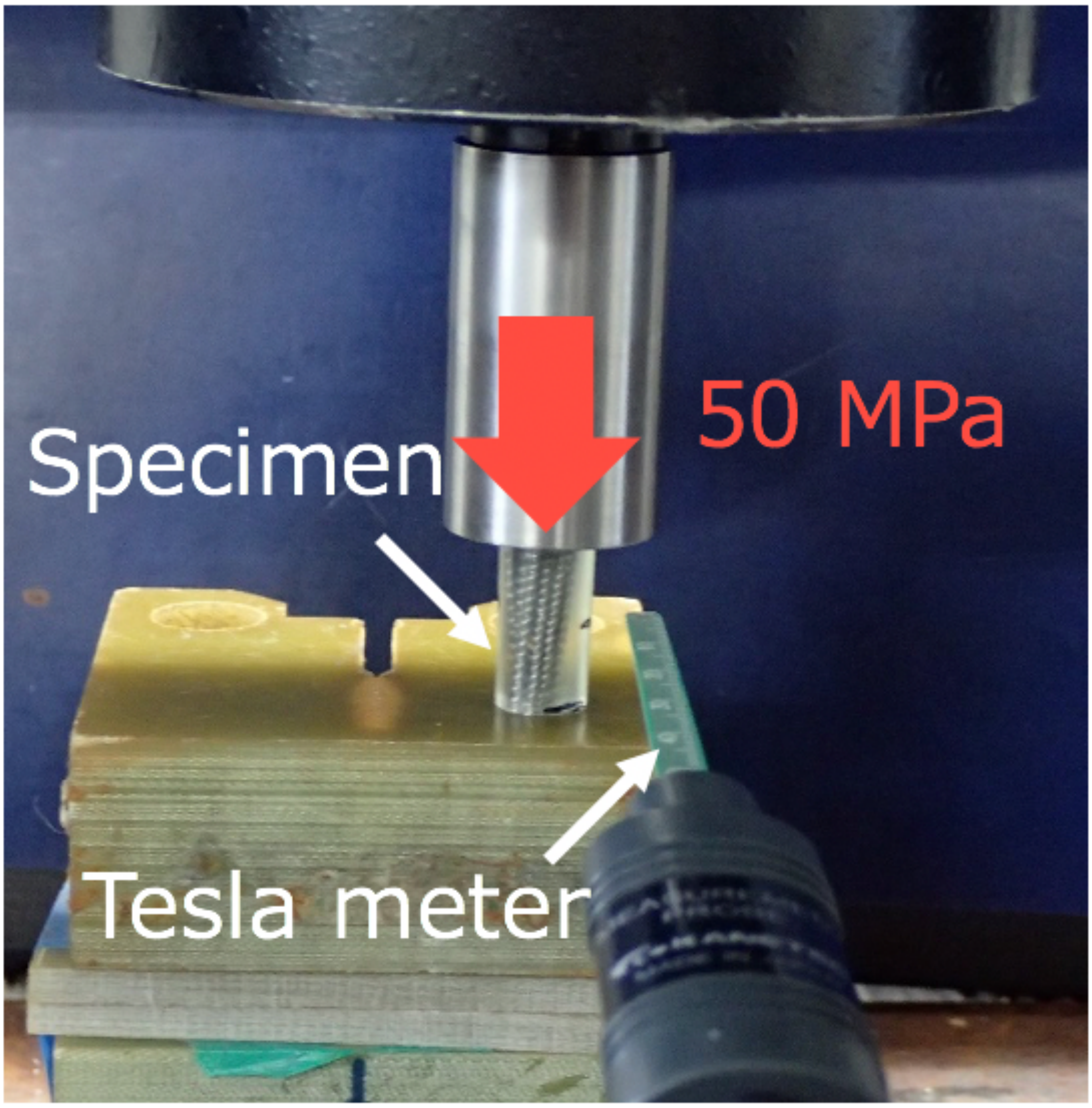
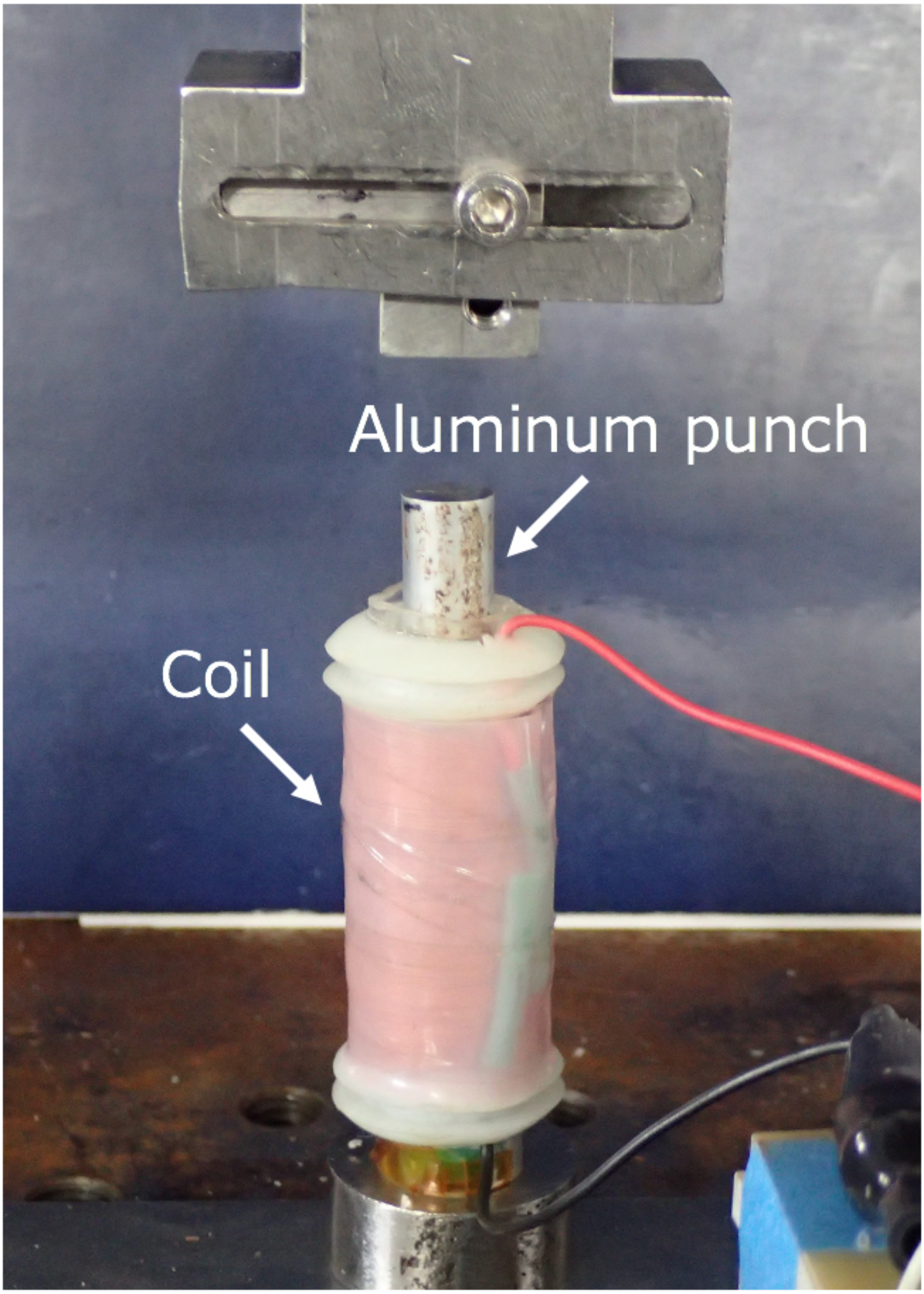


Figure 4 Inverse magnetic flux density measurement test setup.



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189 Figure 5 Output voltage measurement test setup.

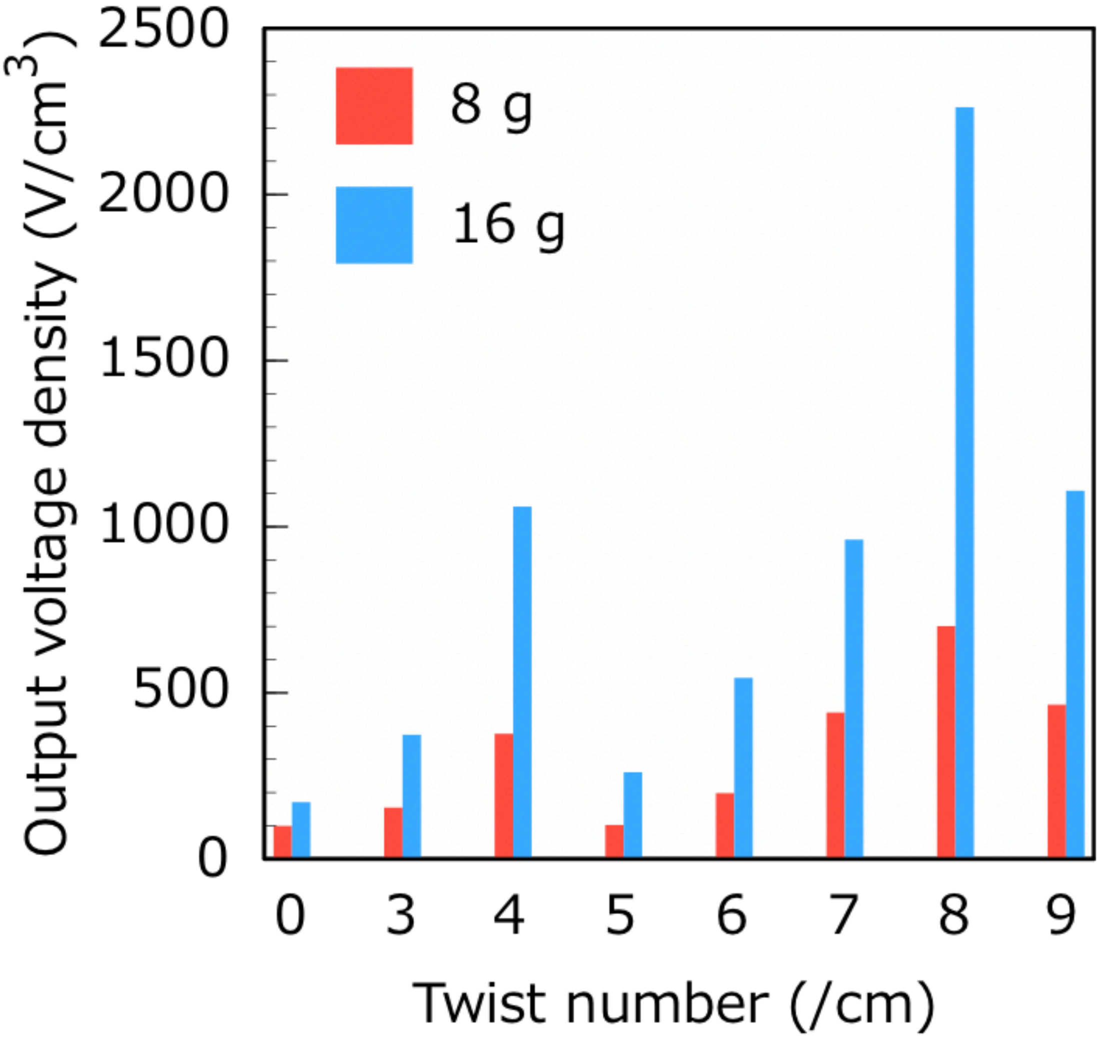

Figure 6 Output voltage density of twisted Fe–Co alloy wires under free vibration.

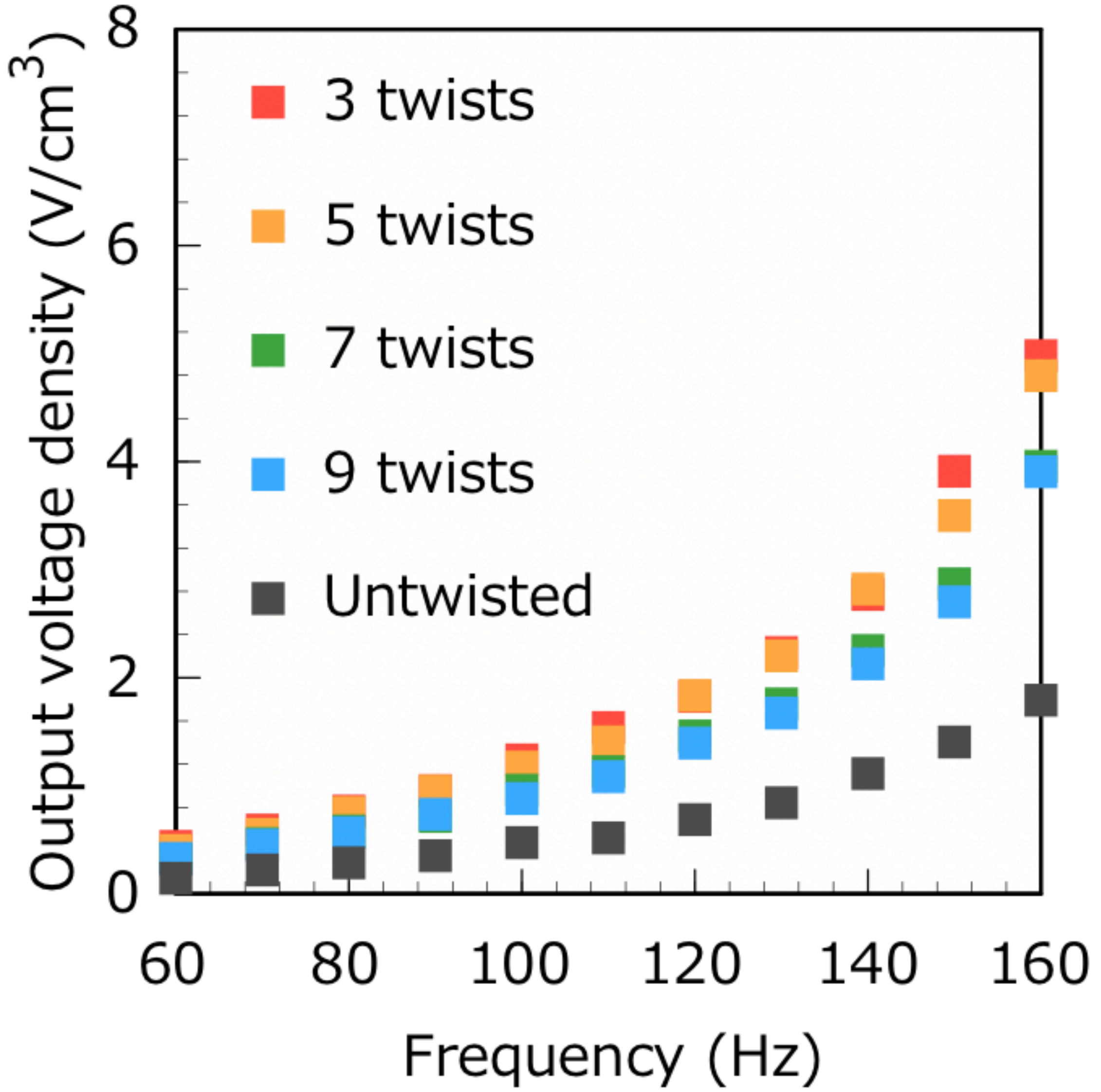

Figure7 Output voltage density of twisted Fe–Co alloy wires under forced vibration.

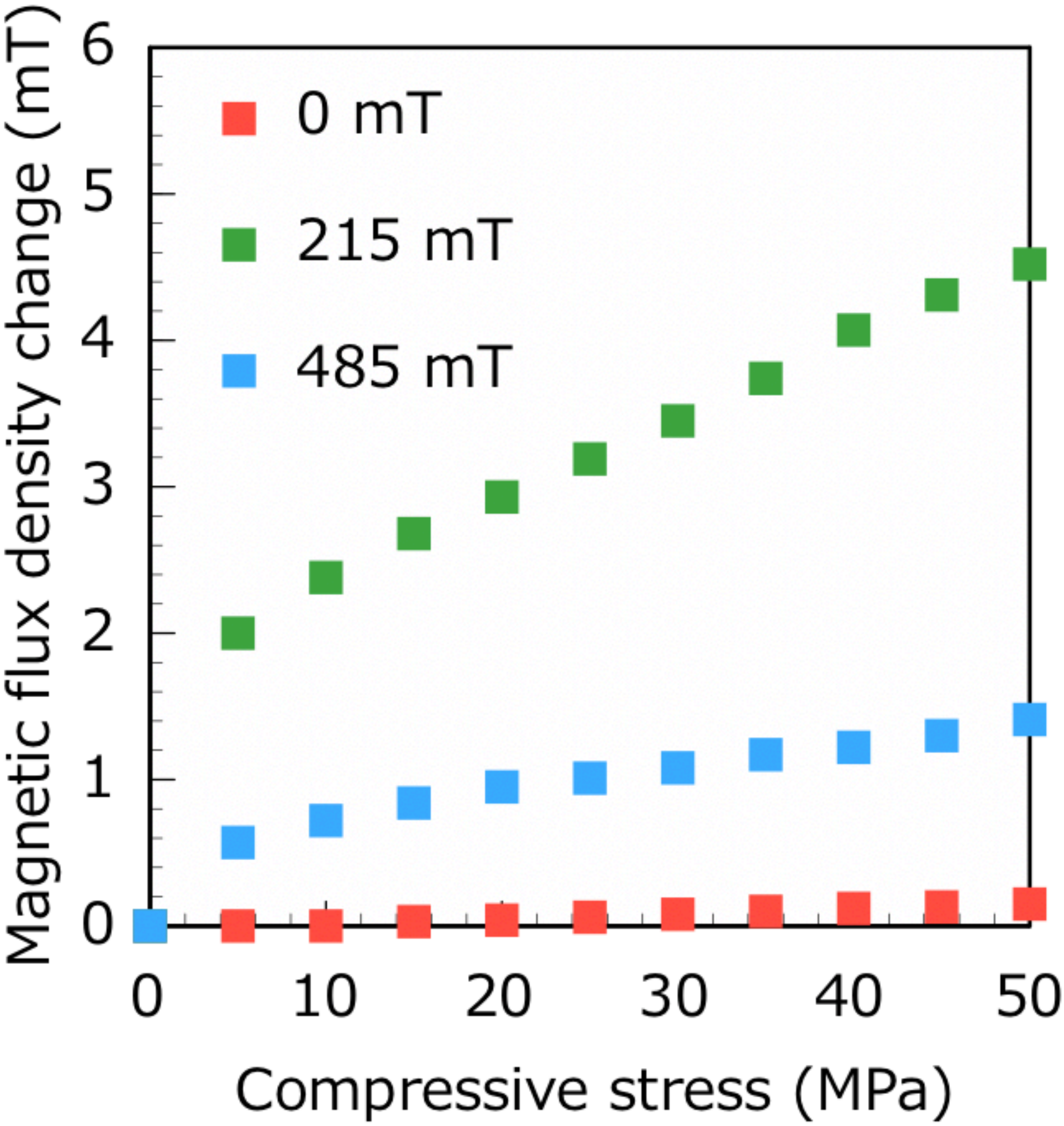

Figure 8 Magnetic flux density change of an 8-times-twisted Fe–Co alloy wire integrated epoxy resin composite under compressive stress with different bias magnetic fields.

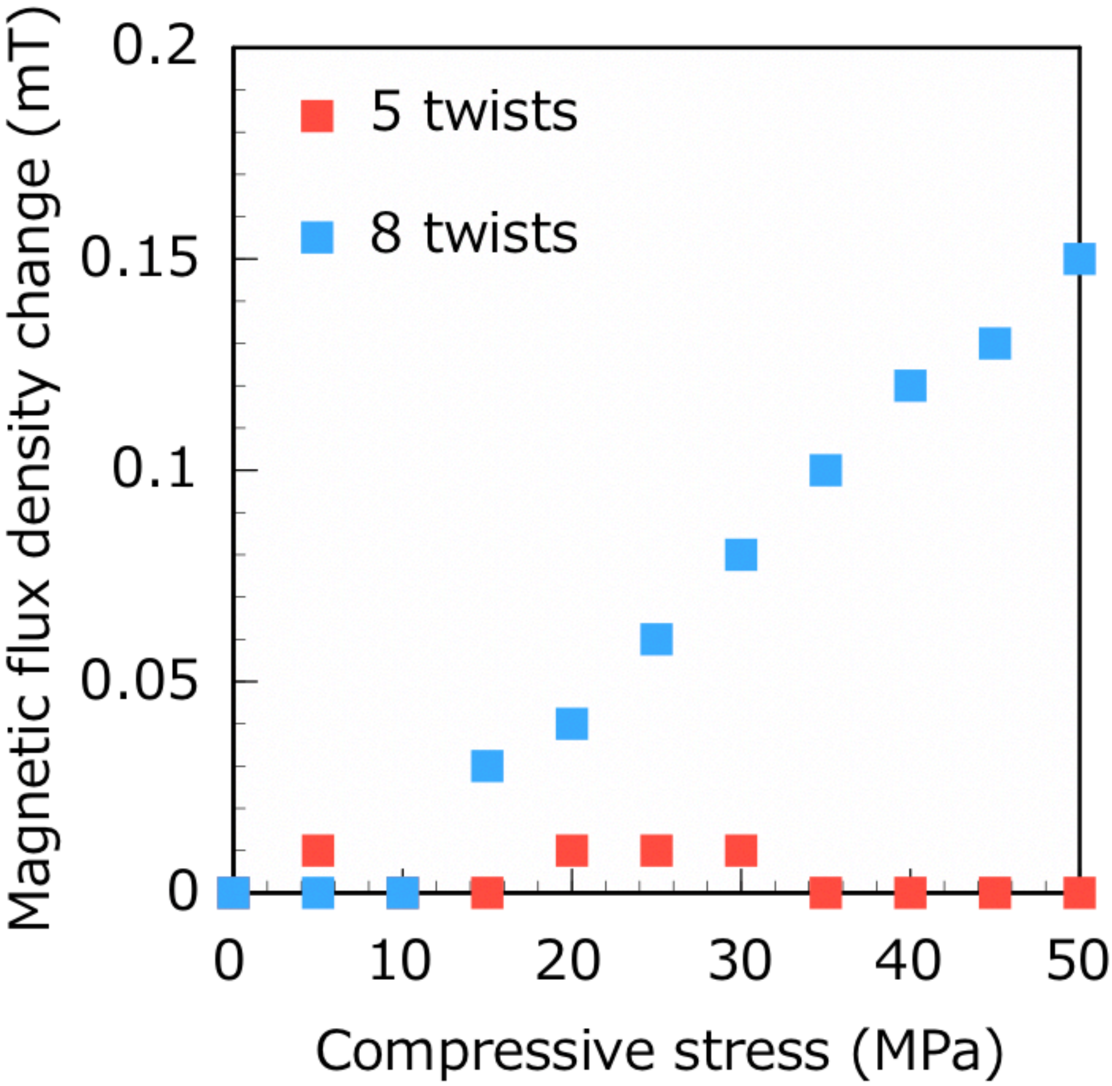

Figure 9 Difference in magnetic flux density change between 5-times- and 8-times-twisted Fe–Co alloy wire integrated epoxy resin composites under compressive stress.

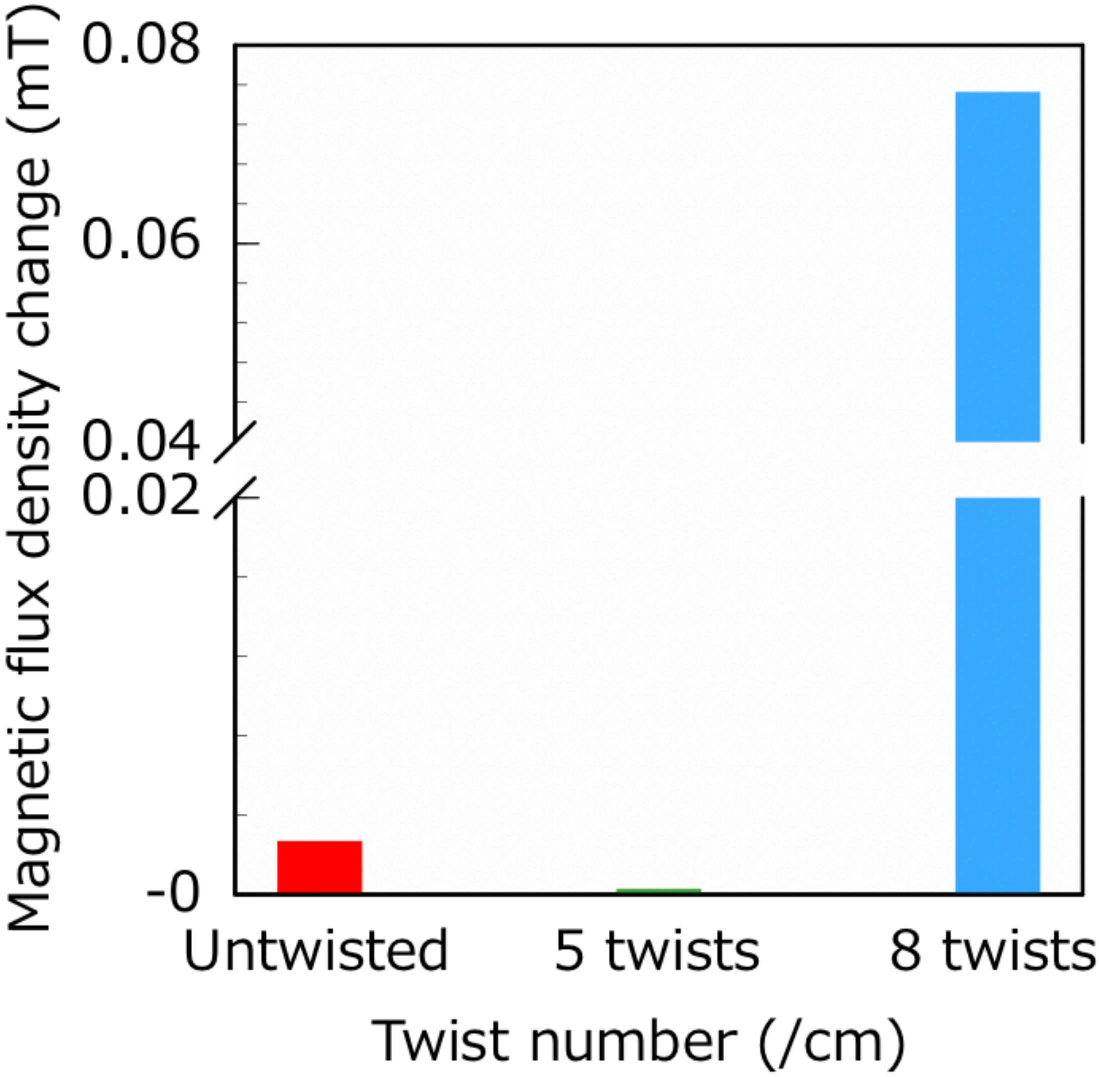

Figure 10 Magnetic flux density changes in untwisted, 5-times-twisted, and 8-times-twisted Fe–Co alloy wire integrated epoxy resin composites under compressive stress.