Short Communication

Electric polarization and crystal orientation of lead zirconate titanate under mechanical stress due to embedding in a metal matrix

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Abstract
The mechanical characteristics of piezoelectric ceramic fibers can be improved by embedding the fibers in a metal matrix. The compressive stress generated during the embedding process, however, limits the polarization of piezoelectric ceramic composites. To study and determine the relationship between the mechanical and piezoelectric properties of piezoelectric ceramics, we analyzed the crystallographic orientation of piezoelectric ceramics embedded in an aluminum matrix via electron backscatter diffraction. The orientation of the crystals before and after the polarization of the piezoelectric fibers, in which residual stresses were generated during embedding, was evaluated. Furthermore, the residual stresses were reduced by heat treatment, and the resultant angle of orientation was evaluated before and after polarization. Results showed that, as the residual stresses were relieved, the orientation of the piezoelectric ceramic crystals changed to reveal increased polarization. Our analysis shows that the crystal orientation of piezoelectric ceramics is impacted by the residual compressive stress that arises from embedding the piezoelectric fiber in the aluminum matrix; it also illustrates the hindering effect of residual stress on the polarization of piezoelectric ceramics.

Keywords Piezoelectric ceramic fiber · Compressive stress · Residual stress · Crystallographic orientation analysis · Aluminum matrix

1 Introduction

Piezoelectrics are materials in which electric charges are generated by the application of pressure; they also exhibit the inverse piezoelectric effect, wherein the application of electric field results in deformation. Owing to their unique behavior, these materials are often used in sensor applications [1, 2]. Piezoelectric ceramics, such as lead zirconate titanate ($Pb(Zr_x, Ti_{1-x})O_3$; PZT), are used in a wide range of applications owing to their excellent piezoelectric properties and thermal stability [3, 4]. However, these ceramics are brittle; therefore, it is necessary to expand

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their operating range by applying a compressive stress, as observed in bolt-clamped Langevin transducers [5].

To overcome the brittleness of piezoelectric ceramics, metal-core piezoelectric fiber/aluminum composites (PZT/Al) have been developed [6, 7], wherein PZT fibers with a platinum core [8, 9] are embedded into an aluminum matrix using the interphase forming/bonding (IF/B) method [10]. The resultant composite exhibits output voltage anisotropy (owing to its electrode structure with radial electric field consisting of metal-core and matrix [11]) and high strength (because of the metal matrix with excellent mechanical properties). Typically, metal matrix composites are reinforced with high-strength ceramics (such as SiC and Al_2O_3) to increase their mechanical strength [12–18]; however, in the developed composite, piezoelectric ceramics are reinforced by metal because the metal matrix has higher mechanical properties than the piezoelectric ceramics. In addition, the thermal stress caused by the difference in the thermal expansion coefficients between the piezoelectric ceramics and the metal is expected to improve the strength of the piezoelectric ceramics by acting as a prestress on the piezoelectric ceramics. These properties are utilized in applications such as impact detection [19] and viscosity sensor [20, 21]. The robustness of PZT/Al composites is attributed to the presence of a metal matrix and the extremely high compressive stresses generated during the embedding process [22, 23]. These stresses originate from the difference in thermal expansion coefficients of the piezoelectric ceramic fibers and metal. However, the effect of such compressive stresses on the polarization characteristics, which determine the piezoelectric performance of these composites, has not been investigated in detail. The evaluation of the polarization of piezoelectric ceramics under such triaxial stress is very important for the compatibility of piezoelectric and mechanical properties of PZT/Al, the purpose of this study is to evaluate the polarization under triaxial stress by EBSD.

The manifestation of piezoelectric effect in a material is closely related to its crystal structure. PZT has a perovskite structure, and, due to lattice vibration, a dipole moment is generated by the displacement of the ions constituting the crystal structure, which is the origin of piezoelectricity [24]. It also has a domain structure containing regions with different spontaneous polarization directions. However, the magnitude of spontaneous polarization affects the piezoelectric constant. If unpolarized piezoelectric ceramics are polarized under an applied compressive stress, the degree of polarization may decrease because the compressive stress prevents the crystal from elongating along the polarization direction. In general, when compressive stress is applied in the polarization direction of piezoelectric ceramics, especially soft piezoelectric ceramics, spontaneous depolarization occurs and the piezoelectric constant decreases [25, 26]. Several studies on the application of compressive stress to polarized ceramics have been reported [27–29]; however, most of these studies reported the change in piezoelectric properties and polarization under uniaxial compressive stress [30, 31]. Few studies have been conducted on the polarization state and the piezoelectric properties under extremely high triaxial stress (about 1 GPa [22, 23]), such as the PZT embedded in aluminum.

The degree of orientation in piezoelectric ceramics was previously evaluated using electron backscatter diffraction (EBSD) by inverting the domain structure of piezoelectric ceramics and evaluating the resultant spontaneous polarization [32–34]. The residual stress was relaxed by heat treating the fabricated composites, and changes in the polarization behavior with respect to the residual stress were evaluated. It was inferred that the polarization behavior of ceramic composite materials, such as PZT/Al, could be determined by subjecting them to crystal orientation analysis. In this study, crystal orientation analysis was conducted on piezoelectric fibers of PZT/Al, and the effect of the magnitude of compressive stress on the crystal orientation due to the polarization of fiber under compressive stress was investigated using EBSD.

The specimens were prepared by embedding a metal-core piezoelectric fiber in an aluminum matrix via the IF/B method. Initially, an aluminum plate (A1050P-O, thickness: 1.5 mm) and a copper foil (C1220, thickness: 0.01 mm) were cut into pieces with dimensions of 15 mm × 30 mm. To remove the oxide film, the surfaces of the cut aluminum plate and copper foil were polished with a water-resistant abrasive paper and washed with acetone in an ultrasonic cleaner. The aluminum plate and copper foil were stacked and a stainless steel wire (SUS304; diameter: 0.25 mm) was pressed into the center of the stack using a hydraulic press machine to form a U-groove; subsequently, the metal-core piezoelectric fiber (Nagamine Manufacturing Co., Ltd., outer diameter: 0.2 mm, core diameter: 0.05 mm, non-poled) was placed in this groove. An aluminum plate of the same size was placed above this stack and finally, the entire stacked structure was hot-pressed at a temperature and pressure of 873 K and 2.2 MPa, respectively, for a holding time of 2.4 ks. After hot pressing, the specimen was cooled to 573 K in the furnace; when the temperature of the specimen reached below 573 K, it was taken out of the furnace and air-cooled. The average cooling rate was approximately 10 K/min. For comparison, a metal-core piezoelectric fiber/epoxy composite (PZT/Ep) with a conductive epoxy (6 wt% carbon mixed) matrix was also fabricated.

The fabricated PZT/Al and PZT/Ep composites were cut along the transverse direction (TD), and the fiber cross-sections were roughly polished with a water-resistant abrasive paper, followed by fine polishing with an alumina abrasive and colloidal silica/nitric acid mixed solution. The polarization treatment was induced using a high-voltage power supply (Kepco, A100603) between the Pt core and the aluminum matrix (ground) at 300 V for 1.8 ks. The polished surface was evaluated by EBSD. However, deformation of the PZT due to the polarization and heat treatments resulted in surface irregularities, which made the EBSD analysis difficult. Therefore, in this study, the surface was polished only after performing the polarization and heat treatments. The resultant crystal orientation and its dependence on the polarization were analyzed using EBSD in conjunction with scanning electron microscopy (SEM; JEOL, JSM-6510A). The direction of spontaneous polarization in piezoelectric ceramics depends on their crystal structure, which, in turn, depends on their composition and temperature [35]. Therefore, energy-dispersive X-ray spectroscopy was conducted on the PZT fibers to evaluate their composition. The PZT fibers had a tetragonal crystal structure with a composition of $Pb(Zr_{0.35}, Ti_{0.65})O_3$. In the case of a tetragonal perovskite structure, the spontaneous polarization direction is <001> [36, 37], which implies that the B site ion of the perovskite crystal structure of ABO_3 moves in the <001> direction. Therefore, a crystal orientation analysis was performed along the (001) plane. In addition, owing to its morphology, the polarization direction of the piezoelectric fiber is radial from the center, as shown in Fig. 1, which varies depending on the location inside the fiber. Therefore, to maintain a constant polarization direction for the crystal orientation analysis, the polarization direction of the specimen was matched with the analytical TD (Fig. 1). As shown in Fig. 1, the analysis area was 10 μm along the rolling direction (RD) and 40 μm along the TD. The obtained data were analyzed using the EBSD software OIM Analysis (version 6.1, TSL Solutions Co., Ltd.). As the polarization direction in this composite was radial, the polarization occurred along the RD; however, to reduce this effect along RD, a high-aspect analysis area was set along the TD.

Figure 2 shows the pole figures of the PZT/Al and PZT/Ep composites before and after the polarization with EBSD maps that use an inverse pole figure (IPF) coloring. Compared to that of PZT/Ep, extremely strong spots are observed along the ND in the PZT/Al pole figure before the polarization, which is indicative of a strong existing crystalline texture along the ND. Because the embedding temperature (873 K) of the piezoelectric fiber was higher than its Curie point (~558 K [38]), it transformed into a cubic structure and its spontaneous polarization disappeared. During the cooling process, compressive stresses were generated owing to the difference in the coefficients of thermal expansion of the matrix and piezoelectric

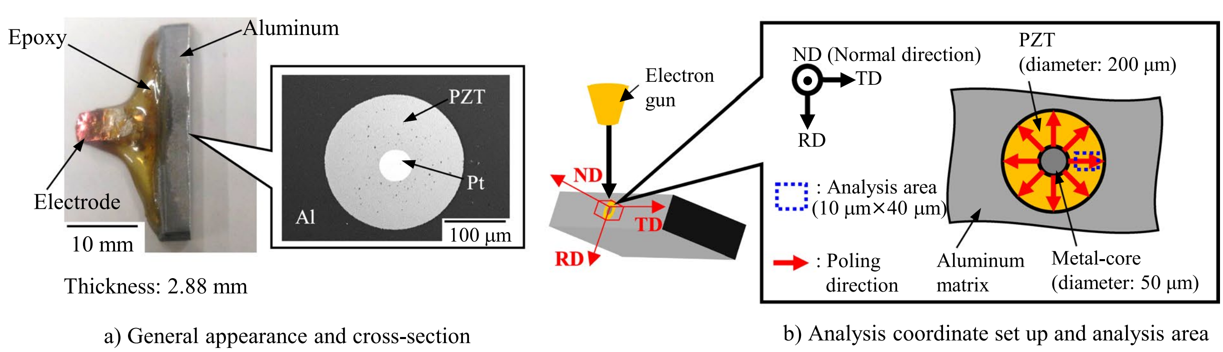

Fig. 1 Crystal orientation analysis of metal-core piezoelectric fibers embedded in aluminum. **a** General appearance and cross-section of the fabricated PZT/Al composite (cut and polished for crystal orientation analysis) and **b** Cartesian coordinate system showing the normal direction (ND), rolling direction (RD), transverse direction (TD), and analysis area

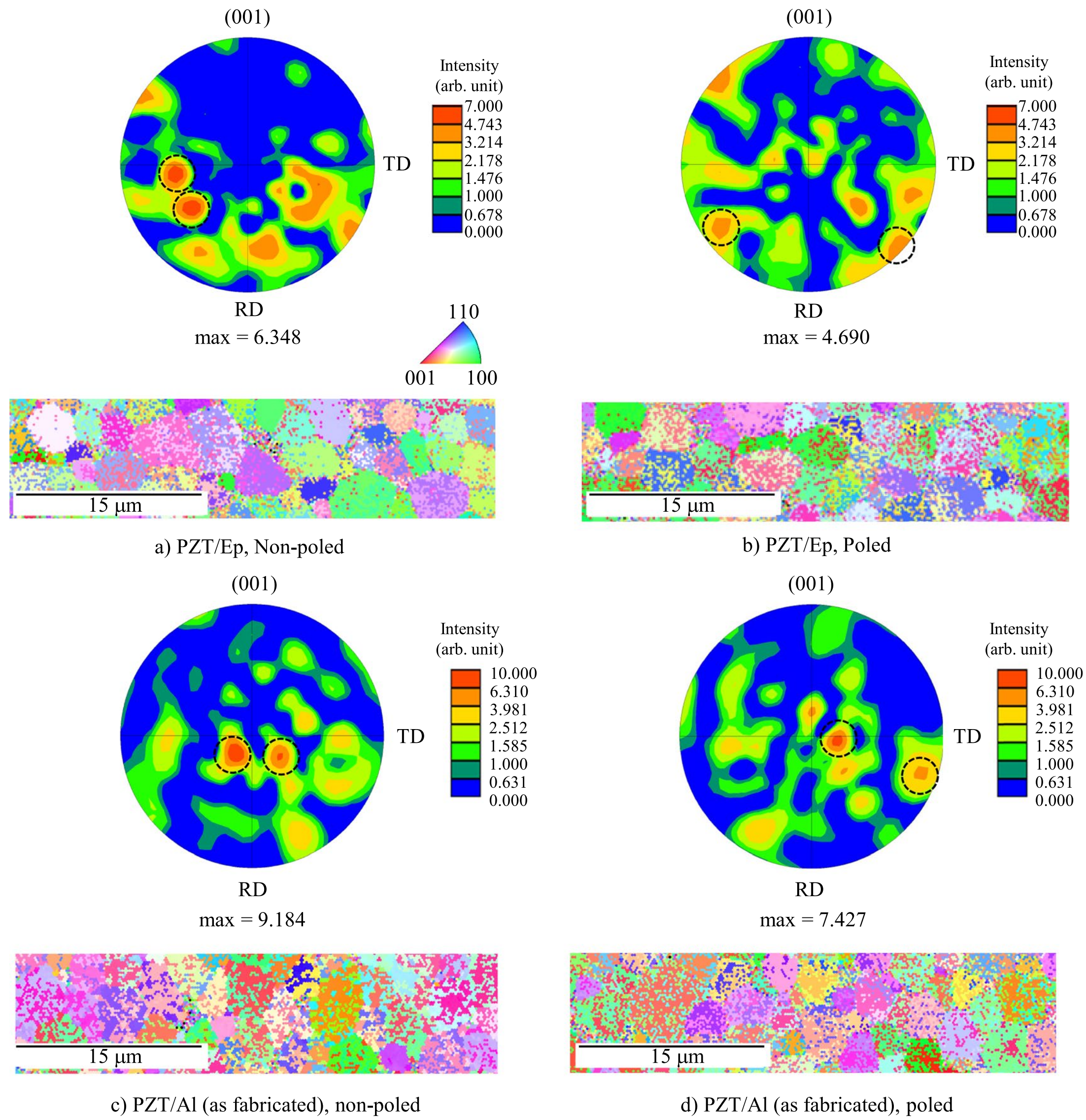

Fig. 2 Pole figures of PZT/Ep and PZT/Al with EBSD maps that use an IPF coloring. **a** PZT/Ep, non-poled, **b** PZT/Ep, poled, **c** PZT/Al, non-poled, and **d** PZT/Al, poled. In non-polarized PZT/Al, an extremely strong orientation is observed because of the residual compressive stress along the ND. After polarization, the crystal orientation transitions to TD in both the specimens

fibers (Coefficients of thermal expansion, aluminum: 23.5×10^{-6}/K [39], PZT: 4.8×10^{-6}/K [40], and platinum: 9.9×10^{-6}/K [40]).

As cooling progressed, the temperature fell below the Curie point, resulting in a phase transformation to a tetragonal structure with the crystals oriented along the ND direction because of the compressive stress, and the polarization axis reoriented randomly. This is because the crystal stretches along the <001> direction during the phase transformation from cubic to tetragonal, whereas the compressive stress inhibits it. After the polarization, the spot shifted along the polarization direction (i.e., TD) in both the PZT/Al and PZT/Ep composites. In other words, the initial strong texture along the ND transitioned toward the TD, and the maximum intensity of pole figure decreased. Furthermore, the transition toward TD was larger in the case of PZT/Ep. This may be attributed to the strong orientation along the ND due to the residual stresses in PZT/Al. The stress hinders orientation along the TD due to polarization.

To investigate the effect of compressive residual stresses on polarization in PZT/Al, the composites were stress relieved by heat treatment at 423, 473, and 523 K for a holding time of 3.6 ks, and crystal orientation analyses were carried out before and after the polarization at each temperature. The experimental procedure included heat treatment, crystal orientation analysis, polarization treatment, and a subsequent crystal orientation analysis. The pole figures of the heat treated PZT/Al before and after the polarization with EBSD maps that use an IPF coloring are shown in Fig. 3. In the pole figures before the polarization, the strong spot transitions slightly towards the TD at all the heat-treatment temperatures, and the maximum value in the pole figure decreases as the heat-treatment temperature increases. Since the Curie point of the PZT used in this study was 573 K, it was difficult to completely eliminate the polarization before the heat treatment because the resultant crystal orientation remained intact. It was also observed that the maximum value in the pole figure decreased as the heat-treatment temperature increased because the residual stress relaxation intensifies at higher temperatures. Furthermore, the crystal orientation due to residual stress was decreased by stress relaxation, and depolarization was accelerated in the piezoelectric fiber, resulting in a decrease in orientation due to polarization.

After the polarization, strong spots appeared near the ND at 473 K, whereas as the heat-treatment temperature increased, the red spots transitioned toward the TD. This is because the residual stress was reduced by the heat treatment and the polarization treatment that facilitated crystal orientation. The degrees of orientation calculated with respect to TD from the pole figures in Figs. 2 and 3 are presented in Fig. 4.

The degree of orientation with respect to TD (D) was calculated from the intensity of each spot I, angle ϕ between the TD–RD plane and ND, and angle θ between -the TD–ND plane and RD, and the average value obtained from 10 spots under each condition was used as the representative value. From Fig. 4, by comparing the degrees of orientation of PZT/Ep and PZT/Al before the polarization, it is clear that the value of the former is higher. This is because the residual compressive stress in PZT/Al promotes orientation along the ND. After the polarization, the degree of orientation of PZT/Al was lower than that of PZT/Ep, which can be attributed to the inhibition of polarization by residual stresses. The degree of orientation before the polarization in the heat-treated specimens decreased as the heat-treatment temperature increased. This is because depolarization increased with an increase in the heat-treatment temperature, resulting in a more random orientation. The poled as-fabricated specimen and non-polarized specimen heat treated at 423 K exhibited similar degrees of orientation indicating that depolarization did not occur at 423 K. This observation implies that a heat-treatment temperature of at least 473 K is required for stress relaxation to improve the degree of orientation by polarization. In the current study, the highest degree of orientation was observed at 523 K. This is the temperature at which the residual stress was most relaxed in the previous study [23]. Such an increase in the degree of orientation may be attributed to the repetition of polarization treatment on the same specimen that underwent depolarization by the relaxation of residual stresses.

Herein, the crystallographic textures of PZT/Ep, PZT/Al, and heat treated PZT/Al were analyzed, and the results suggest that the crystalline structures of the piezoelectric fibers were oriented along the ND because of residual stresses. The (001) spot transitioned more strongly toward the TD as the compressive residual stresses were relaxed by the heat treatment,

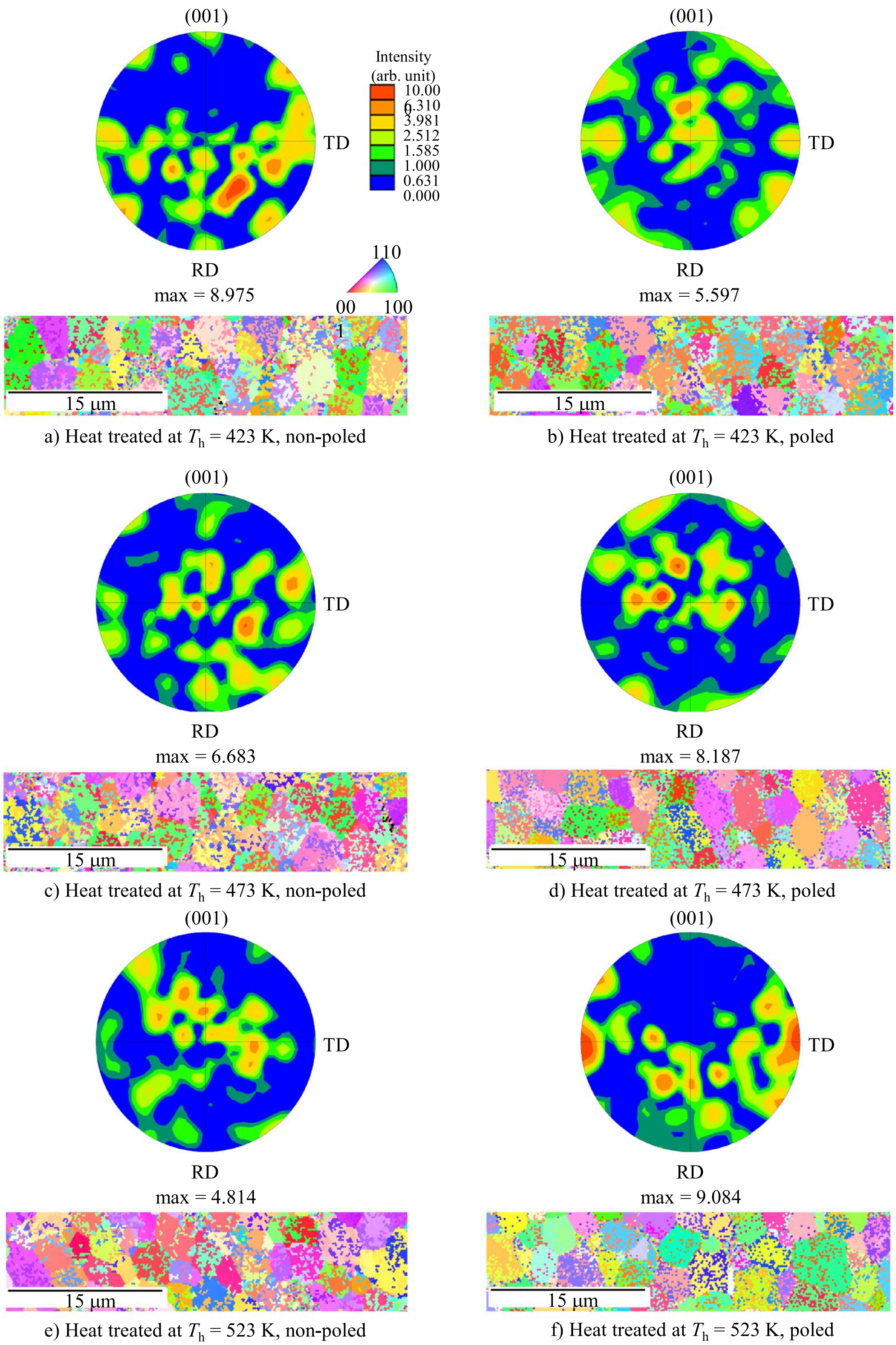

Fig. 3 Pole figures of heat-treated PZT/Al with EBSD maps that use an IPF coloring. **a** Th = 423 K, non-poled, **b** Th = 423 K, poled, **c** Th = 473 K, non-poled, **d** Th = 473 K, poled, **e** Th = 523 K, non-poled, and **f** Th = 523 K, poled. Before polarization, depolarization occurs as the heat-treatment temperature increases, and any strong orientation in the crystal disappeared. After polarization, orientation along the TD increases as the heat-treatment temperature increases

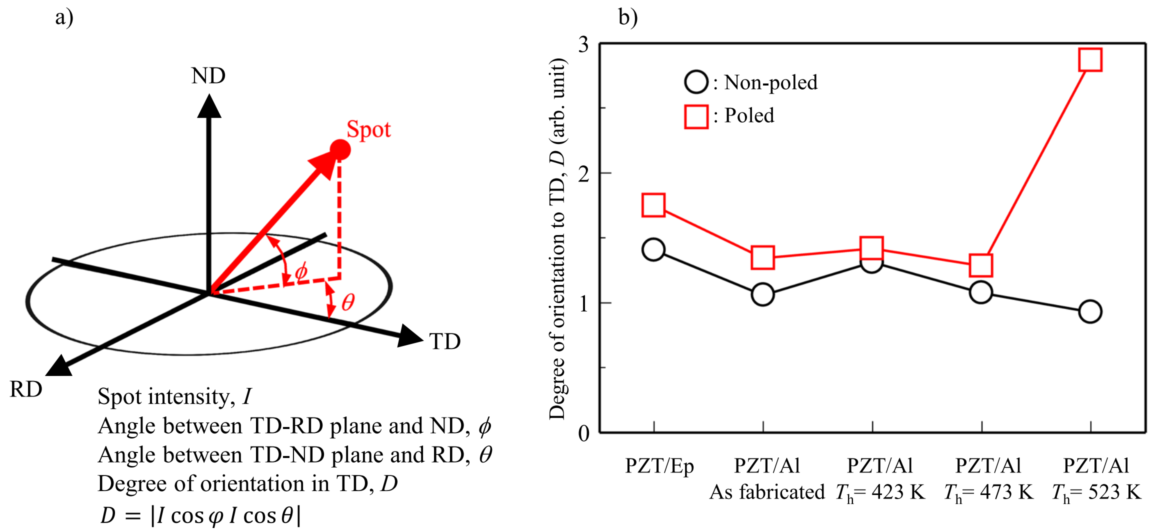

Fig. 4 Evaluation of polarization using the degree of orientation with respect to TD. **a** Calculation of the degree of orientation and **b** degree of orientation in each specimen. The difference in the degrees of orientation of PZT/Ep and PZT/Al may be attributed to crystalline orientation along the ND due to residual stress. When heat-treated, the degree of orientation decreased in the specimens before polarization treatment (because of depolarization). The degree of orientation to TD of the specimen heat-treated at 523 K exhibited the highest value

indicating that polarization was hindered by the compressive residual stresses applied to the piezoelectric fiber. This means that the movement of the central ion at the B site in an ABO_3-type material with a perovskite crystal structure, as well as polarization in the crystalline system, are hindered by the compressive stress. Therefore, the piezoelectric properties of PZT/Al are degraded by the presence of compressive residual stress. Hence, it is desirable to relax the residual stresses for preserving the piezoelectric properties of ceramics. Conversely, the mechanical properties of piezoelectric ceramics are generally improved by the application of compressive stresses. This shows that the mechanical and piezoelectric properties of piezoelectric ceramics are in a trade-off relationship. Hence, the piezoelectric and mechanical properties of ceramic materials can be balanced by an optimized heat treatment for the intended application.

Data availability The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Declaration

Conflict of interest The authors declare that they do not have any conflict of interest.

References

1. Tressler JF, Alkoy S, Newnham RE (1998) Piezoelectric sensors and sensor materials. J Electroceram 2:257–272. https://doi.org/10.1023/A:1009926623551
2. Wei H, Wang H, Xia Y, Cui D, Shi Y, Dong M, Liu C, Ding T, Zhang J, Ma Y, Wang N, Wang Z, Sun Y, Wei R, Guo Z (2018) An overview of lead-free piezoelectric materials and devices. J Mater Chem C 6:12446–12467. https://doi.org/10.1039/C8TC04515A
3. Haertling GH (1999) Ferroelectric ceramics: history and technology. J Am Ceram Soc 82(4):797–818. https://doi.org/10.1111/j.1151-2916.1999.tb01840.x
4. Panda PK, Sahoo B (2015) PZT to lead free piezo ceramics: a review. Ferroelectrics 474(1):128–143

5. Adachi K, Ogasawara I, Tamura Y, Makino M, Kato N (1998) Influence of static prestress on the characteristics of bolt-clamped langevin-type transducers. Jpn J Appl Phys 37:2982–2987
6. Yanaseko T, Asanuma H, Sato H (2014) Output voltage characteristics of piezoelectric fiber/aluminum composites fabricated by interphase forming/bonding method. Trans Mater Res Soc Jpn 39:325–329
7. Yanaseko T, Asanuma H, Sato H (2015) Characterization of a metal-core piezoelectric ceramics fiber/aluminum composite. Mech Eng J 2:14–00357
8. Sato H, Shimojo Y, Sekiya T (2005) Lead zirconate titanate fiber, smart board using lead zirconate titanate fiber, actuator utilizing smart board, and sensor utilizing smart board. US Patent No. 6,963,157. Accessed on 8 Nov 2005
9. Sato H, Sekiya T, Nagamine M (2004) Design of the metal-core piezoelectric fiber. SPIE: Smart Structures and Materials 2004; Smart Structures and Integrated Systems: San Diego, USA, 5390
10. Asanuma H (2000) Development of metal-based smart composites. JOM 52:21–25
11. Yanaseko T, Sato H, Kuboki I, Asanuma H (2018) Effect of microstructure of metal-core piezoelectric fiber/aluminum composites on output voltage characteristics. Mech Eng J 5:17–00565
12. Garg P, Jamwal A, Kumar D, Sadasivuni KK, Hussain CM, Gupta P (2019) Advance research progresses in aluminium matrix composites: manufacturing and applications. J Mater Res Technol 8(5):4924–4939
13. Jamwal A, Prakash P, Kumar D, Singh N, Sadasivuni KK, Harshit K, Gupta S, Gupta P (2019) Microstructure, wear and corrosion characteristics of Cu matrix reinforced SiC-graphite hybrid composites. J Comp Mater 53(18):2545–2553
14. Jamwal A, Mittal P, Agrawal R, Gupta S, Kumar D, Sadasivuni KK, Gupta P (2020) Towards sustainable copper matrix composites: manufacturing routes with structural, mechanical, electrical and corrosion behaviour. J Comp Mater 54(19):2635–2649
15. Jamwal A, Seth PP, Kumar D, Agrawal R, Sadasivuni KK, Gupta P (2020) Microstructural, tribological and compression behavior of copper matrix reinforced with graphite-SiC hybrid composites. Mater Chem Phys 251:123090
16. Ahamad N, Mohammad A, Sadasivuni KK, Gupta P (2020) Phase, microstructure and tensile strength of Al-Al_2O_3-C hybrid metal matrix composites. Proc Inst Mech Eng C J Mech Eng Sci 234(13):2681–2693
17. Ahamad N, Mohammad A, Sadasivuni K, Gupta P (2020) Structural and mechanical characterization of stir cast Al-Al_2O_3-TiO_2 hybrid metal matrix composites. J Comp Mater 54(21):2985–2997
18. Ahamad N, Mohammad A, Sadasivuni K, Gupta P (2021) Wear, optimization and surface analysis of Al-Al_2O_3-TiO_2 hybrid metal matrix composites. Proc Inst Mech Eng J J Eng Tribol 235(1):93–102
19. Yanaseko T, Sato H, Narita F, Kuboki I, Asanuma H (2019) Improvement estimation accuracy of impact detection using metal-core piezoelectric fiber/aluminum composites. Adv Eng Mater. https://doi.org/10.1002/adem.201900550
20. Yanaseko T, Sato H, Kuboki I, Mossi K, Asanuma H (2019) Vibration viscosity sensor for engine oil monitoring using metal matrix piezoelectric composite. Materials. https://doi.org/10.3390/ma12203415
21. Yanaseko T, Sato H, Mossi K, Asanuma H (2021) Viscosity sensor with temperature measurement function based on multifunctional metal matrix composite. Sens Actuat A Phys 331:112518
22. Wang Y, Yanaseko T, Kurita H, Sato H, Asanuma H, Narita F (2020) Electromechanical response and residual thermal stress of metal-core piezoelectric fiber/Al matrix composites. Sensors 20(20):5799
23. Yanaseko T (2015) Chracterization and improvement performance of metal matrix piezoelectric composite (Doctoral dissertation). Chiba University Repository (TLA-0196). (In Japanese)
24. Govorukha V, Kamlah M, Loboda V, Lapusta Y (2017) Fracture mechanics of piezoelectric solids with interface cracks. Springer, Berlin
25. Uchino K (1985) Piezoelectric/electrostrictive actuators. Morikita Pub. Co., Tokyo
26. Nakajima Y, Hayashi T, Hayashi I, Uchino K (1985) Electrostrictive properties of a PMN stacked actuator. Jpn J Appl Phys 24(2):235
27. Ji DW, Kim SJ (2016) Compressive stress-induced depolarization in ferroelectric ceramics at room and high temperatures: experiment and prediction. J Ceram Soc Jpn 124(10):1132–1140
28. Zhou D, Kamlah M, Munz D (2004) Uniaxial compressive stress dependence of the high-field dielectric and piezoelectric performance of soft PZT piezoceramics. J Mater Res 19(3):834–842
29. Zhang QM, Zhao J, Uchino K, Zheng J (1997) Change of the weak-field properties of $Pb(ZrTi)O_3$ piezoceramics with compressive uniaxial stress and its links to the effect of dopants on the stability of the polarizations in the materials. J Mater Res 12(1):226–234
30. Sakai T, Ogawa S, Kawamoto H, Yanagida H (1999) Fatigue behavior of piezoelectric ceramics under an applied electric field and stress. J Ceram Soc Jpn 107(8):743–747
31. Shindo Y, Narita F, Hirama M (2009) Electromechanical field concentrations near the electrode tip in partially poled multilayer piezo-film actuators. Smart Mater Struct 18:8
32. Kimachi H, Tsunekawa T, Shirakihara K, Tanaka K (2008) Observation of crystal orientation, domain and domain switching in ferroelectric ceramics by EBSP method. Trans Jpn Soc Mech Eng A 74(739):335–341
33. Reichmanna A, Mitschea S, Zankela A, Poelta P, Reichmann K (2014) In situ mechanical compression of polycrystalline $BaTiO_3$ in the ESEM. J Eur Ceram Soc 34:2211–2215
34. Yan L, Dumler I, Wayman CM (1994) Studies of herringbone domain structures in lead titanate by electron back-scattering patterns. Mater Chem Phys 36:282–288
35. Jaffe B, Jaffe H, Cook WR (1971) Piezoelectric ceramics. Academic Press, London
36. Du XH, Zheng J, Belegundu U, Uchino K (1998) Crystal orientation dependence of piezoelectric properties of lead zirconate titanate near the morphotropic phase boundary. Appl Phys Lett. https://doi.org/10.1063/1.121373
37. Ledermann N (2003) {1 0 0}-Textured, piezoelectric Pb (Zrx, Ti_{1-x}) O_3 thin films for MEMS: integration, deposition and properties. Sens Actuat A. https://doi.org/10.1016/S0924-4247(03)00090-6
38. Sato H, Nagamine M (2005) Mechanical properties of metal-core piezoelectric fiber. SPIE: In Smart Structures and Materials 2005; Smart Structures and Integrated Systems: San Diego, USA, p 5764. doi:https://doi.org/10.1117/12.601109.
39. Warlimont H, Martienssen W (2018) Springer handbook of materials data, 2nd edn. Springer, Berlin, p 181
40. Hsueh CH, Luttrell CR, Cui T (2006) Thermal stress analyses of multilayered films on substrates and cantilever beams for micro sensors and actuators. J Micromech Microeng 16:2509–2515