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Anisotropic magnetostriction for low-frequency energy harvesting applications.

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In the framework of energy conversion devices for energy harvesting, magnetostrictive materials are an attractive alternative solution to the brittleness and geometrical limitations of piezoelectric materials. So far, the anisotropy of magnetostriction has never been studied to improve an energy harvesting system's performance. In this work, we investigated the performances of an oriented grain electrical steel material in an energy harvesting context. Well-known magnetic properties, including low magnetostriction and significant anisotropy, characterize this material. We combined experimental and predictive simulation results and discussed the possibility of increasing the energy level by playing with the orientation of both the magnetic and the mechanical stimuli.

Index Terms—Ericsson cycle, multiscale model, energy prediction

I. INTRODUCTION

With the fast development of the Internet of Things, the number of wireless sensors and sensor networks is increasing. Most of these devices rely on batteries characterized by a limited lifespan, and manufacturers are looking for alternatives. Amongst limited possibilities, energy harvesting systems constitute a feasible option [1].

A complete energy harvesting system includes three main parts: an active material, a structure (mechanical, thermal, etc.), and an electrical interface. Regarding the conversion material, magnetostrictive or piezoelectric materials can be equally used for vibrational sources, while photovoltaic cells are limited to solar sources. Vibrations are an attractive energy source for their ubiquity, availability even in confined environments, and good power densities.

Most of the existing vibrational energy harvesters rely on piezoelectric, magneto-dynamic, or magnetostrictive coupling. Piezoelectric materials are brittle and have high impedances. Magneto-dynamic systems are impossible to be used in the low frequencies range. Thus, in this study, we opted for the magnetostriction conversion. Magnetostriction changes a specimen's shape when subjected to a magnetic field. The inverse effect (magnetization variation due to a mechanical stimulus) is called the Villari effect. All energy harvesting systems based on magnetostriction exploit the Villari effect. They convert the variation of the mechanical excitation due to natural vibrations into a change of magnetization state, magnetic flux density, and voltage in the associated electrical interface.

The magnetization process in a ferromagnetic material is schematically illustrated in Fig. 1. It involves multiple mechanisms:

First, the magnetic domains with a magnetization oriented favorably with respect to the applied magnetic field grow, while the domains unfavorably oriented decline in proportion.

Then, the magnetization of the resulting domain, initially oriented along an easy axis, coherently rotates toward the direction of the applied magnetic field.

Bulk specimens comprise a vast quantity of magnetic domains. Thus, during a magnetization cycle, the magnetization mechanisms are naturally overlapping.

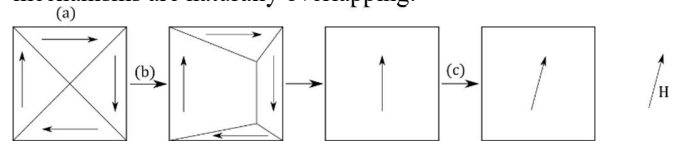


Fig. 1 – Schematic illustration of the magnetization process. (a) Unmagnetized state, (b) domain wall motion, (c) magnetization rotation.

Both the magnetic domains' kinetic and the magnetic moments' rotation induce energy variations inside the ferromagnetic medium. This process is anisotropic (direction-dependent). Suppose a magnetic field is applied to the material at an angle to an easy axis of magnetization. In that case, the material will tend to rearrange its structure so that the magnetization is aligned with the field to minimize the system's free energy. Since different magnetization orientations are associated with different lengths, this effect induces a strain in the material.

Therefore, magnetostriction is strongly anisotropic, and the coupling property can be maximized according to the direction and orientation of both magnetic and mechanical quantities. Still, as far as we know, this property has never been exploited in the context of energy harvesting systems.

This work investigates the performances of an oriented grain electrical steel material in an energy harvesting context. Well-known magnetic properties, including low magnetostriction and significant anisotropy, characterize this material. We combined experimental and predictive simulation results and discussed the possibility of increasing the energy level by playing with the orientation of both the magnetic and the mechanical stimuli.

II. EXPERIMENTAL SETUP

A. Experimental setup

The evolution of the magnetic flux density B when applying an excitation magnetic field H and mechanical stress σ (tension and compression) was measured with a dedicated test bench. The picture of this setup is shown in Fig. 2. The magnetization circuit was composed of two U-shaped yokes and a 110 turns coil. The excitation coil was wrapped around the two yokes separately and equally (55 turns each), ensuring the magnetic excitation generation from the electrical energy source. A sinus excitation voltage was generated by a waveform generator KEYSIGHT 33500B (Santa Rosa, California, U.S.) and amplified through a KEPCO BOP 100-4M Amplifier (Kepco, Flushing, NY). A 5Ω resistance was plugged in series with the coil to monitor the electrical current in the excitation coil. A 500 turns sensor coil was wrapped around the tested specimens to measure the induced magnetic flux density.

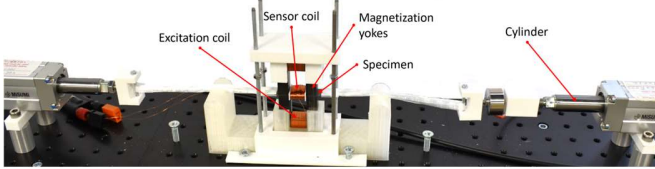


Fig. 2 – Illustration of the tested specimens.

Tension tests were done with two Misumi (Tokyo, Japan) cylinders (Fig. 2) and compression with a Shimadzu (Kyoto, Japan) tension/compression bench. All signals were monitored with a Dewesoft (Trbovlje, Slovenia) acquisition card.

B. Tested specimens

The tested material was FeSi 3% oriented grain electrical steel referenced 30TG130 from JFE steel (Tokyo, Japan). A $290 \times 150 \text{ mm}^2$ plate was cut (electro erosion) to provide specimens with different angles vs. the easy magnetization axis (Fig. 3).

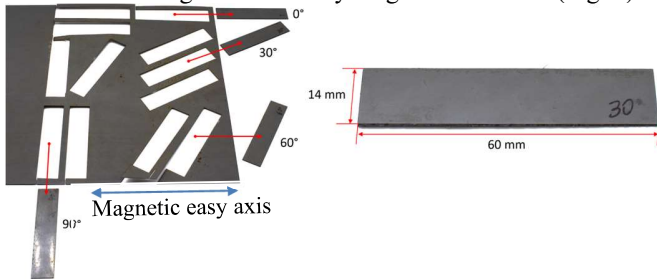


Fig. 3 – Illustration of the tested specimens.

C. Ericsson cycles

The low-frequency energy harvesting was performed assuming a thermodynamic cycle close to the equivalent Ericsson cycle and consisting of two processes at constant stress and two others under constant magnetic excitation (see Fig. 4 in [2] for illustration). During the first step, the magnetic excitation increases while the stress is constant at a maximal value (σ_{max}). During the second step, the excitation field is kept constant, and the stress is reduced up to a minimal value (σ_{min}). In this stage, B decreases. During the third step, the excitation drops to zero while the stress remains constant at σ_{min} . In the last step, the stress increases up to σ_{max} as the magnetic excitation is null.

The resulting closed-loop area in the $B_a(H_{surf})$ diagram corresponds to the energy converted from mechanical to magnetic energy.

III. SIMULATION METHOD: THE MULTISCALE MODEL

The MultiScale Model (MSM) has been developed to predict the anhysteretic magnetic behavior of a ferromagnetic materials [3]. It relies on a statistical description of the distribution of the ferromagnetic domains. MSM provides vector information, and the anisotropy effects are naturally taken into account. A polycrystalline ferromagnetic specimen is considered as an aggregate of single crystals (grains). Each grain is supposed to be divided into a finite number of magnetic domain families [3]. Each domain family is characterized by its magnetic orientation α and potential energy W_α . The volume fraction f_α of a domain family is calculated from the knowledge of the potential energy of all domain families. Once f_α is calculated for all magnetic domain families, a volume average defines the magneto-elastic response at the grain scale. An orientation distribution function (crystallographic orientations) obtained from X-ray diffraction or Electron Back Scattering Diffraction (EBSD) measurements can be used to describe the crystallographic texture of the material and return the behavior at the polycrystalline scale.

IV. FIRST RESULTS AND CONCLUSIONS

Fig. 4 shows some first experimental results. Compressive tests up to $\sigma = -25 \text{ MPa}$ were performed on the 0° and 60° specimens, and the related hysteresis cycles were plotted. The hatched part represents the potentially harvested energy. Clear distinction is visible according to the magnetization angle.

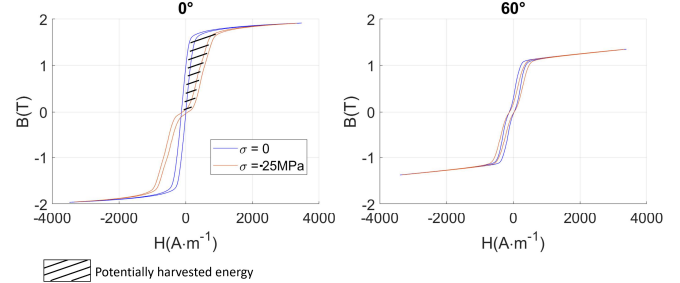


Fig. 4 – $B(H)$ cycles for $\sigma = 0$ and 25 Mpa and for the 0° and 60° specimens.

In the extended version of this abstract, we will fully use both the experimental setup and the multiscale model for assessing the material response to draw optimal conditions for enhancing energy harvesting capabilities. The predictive feature of MSM will be exploited, including stress and magnetic excitation in distinct directions. Eventually, conclusions will be provided regarding the best configuration for energy harvesting.

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