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Grain scale Hysteresis Model embedded in a Multi-scale Material Model.

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Reliable and accurate models of ferromagnetic materials are essential for designers of electrical machines and transformers to maximize the efficiency and power density, as well as for material-science engineers engaged in the optimization of morphological properties of electrical steels such as texture and grain size. These models have to consider magnetic as well as mechanical influences and their interdependence.

Energy based models such as the Armstrong model [1] or the multi-scale model [2], account for magneto-mechanical coupling. The Armstrong model uses an incremental hysteresis model for a single domain material [3], which allows the prediction of losses and shape of the hysteresis curve in this idealized case.

However, modelling non-oriented soft magnetic materials requires to consider the poly-crystalline nature. This could be done using a multi-scale technique treating the poly-crystal as a conglomerate of elementary units behaving as single domain particles [2]. Recently, magnetic hysteresis was introduced in the multi-scale model using the energy based hysteresis model proposed by Hauser [4, 5]. This way magnetic hysteresis is considered in a phenomenological way and hence requires a tedious parameter identification work which is not based on fundamental physical parameters as used in the other energy contributions.

This paper proposes an alternative energy based material model where the hysteresis effect is embedded at the grain scale. The material model is merely based on physical constants which are available using standard references.

The hysteresis phenomenon is taken into account using a new energy function in addition to the three standard energy functions: (i) the Zeeman energy W_H based on the saturation magnetization M_S, (ii) the magneto-crystalline anisotropy energy W_{an} based on the crystal anisotropy constants K_1 and K_2 and (iii) the stress induced anisotropy energy W_σ based on saturation magnetostrictions λ_{100} and λ_{111}. The new energy function is similar to the Zeeman energy and based on the saturation magnetization M_S, the simulated initial grain-scaled magnetic susceptibility χ_0 and the simulated grain-scaled magnetization M_{hys} in the previous time step. The energy function describes the effect of the demagnetization field which keeps the magnetization in a specific orientation. This means that the demagnetization field is not determined in the localization scheme, as in [2], and that the localization scheme only requires solving the Eshelby inclusion problem.

A poly-crystalline material consists of multiple grains, which can be considered as different inclusions [2,6,7]. The macroscopic crystallographic texture of the poly-crystalline aggregate can be included in the model in two different ways: (i) using the measured orientation distribution function of the crystals or (ii) a model order reduction technique assigning weights to the grains. In order to model a perfectly isotropic material a uniform grain distribution is required.

As mentioned in [8], not all grain orientations are needed to model an isotropic material. When assuming a grain to consist of perfectly aligned crystals, only a small section must be taken into consideration. As shown in Fig. 1, one single cubic crystal contains a fixed number of easy, medium and hard axes. It is clear that all magnetic directions occurring in the red triangle will also occur at other places. Using this knowledge, all directions between an easy axis, a medium axis and a hard axis are approximated by mapping these directions in a triangle. Depending on the level, a smaller or a larger number of equilateral triangles (e.g. 1, 4 or 16 equilateral triangle(s)) are used for respectively levels 1, 2, 3. The vertexes, the middle faces and the centroids of all triangles are used as possible grain orientations. If desired, a macroscopic anisotropy can be obtained using weights for all grains in the poly-crystalline scale. This approach increases the speed and the accuracy of the material model.

Using this method, the effect of a mechanical stress on the hysteresis curve has been modelled for non-oriented FeSi 3wt%. Preliminary simulated hysteresis curves, as shown in Fig. 2a, reveal that the poly-crystalline FeSi 3wt% material behaves like a material having a positive magnetostriction. When applying a tension, the hysteresis curve approximates a square loop which decreases the hysteresis losses. When applying a pressure, the remanent magnetization decreases but the coercive magnetic field increases leading to higher hysteresis losses. Fig. 2b shows minor loops of the FeSi 3wt% material. These simulation results will be verified by measurements, according to the IEC standard, performed using a single sheet tester which is equipped with a setup to apply uniaxial mechanical stress. This allows to verify the accuracy as well as the reliability of the material model.

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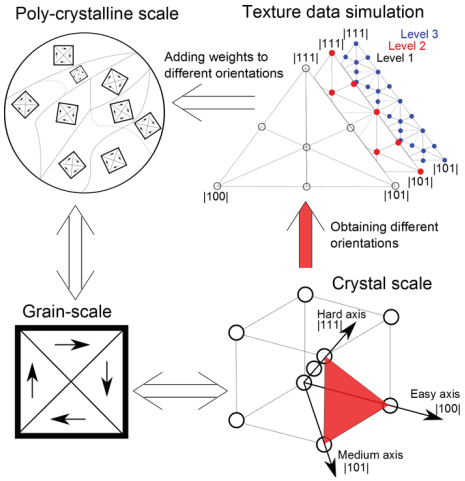

Fig1. Simulation scheme for the texture data

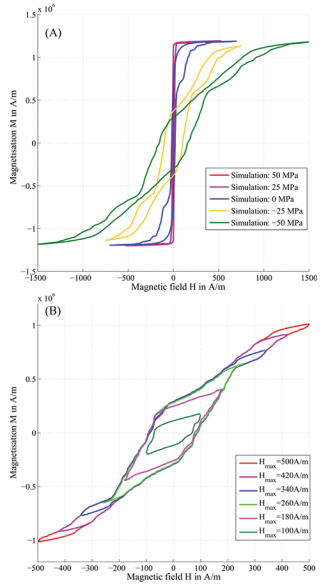

Fig2. Preliminary simulated hysteresis results: (A) major hysteresis loops (B) minor loops