Texture Development in Polycrystalline Fe-Ga Magnetostrictive Materials

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ABSTRACT
Magnetostrictive Galfenol (Fe-Ga) is a promising and mechanically robust actuator material. Single crystals of Galfenol have been shown to exhibit up to 400 ppm magnetostrictive strains with saturating fields of several hundred oersteds. However, due to the high conductivity of Galfenol, device operation will require it to be laminated, or in thin sheet form, in order to avoid eddy current losses. One of the main challenges in producing engineering components from these materials is shaping of these materials while retaining a preferred crystallographic texture to optimize the magnetostrictive performance of the polycrystals. To produce large quantities of thin sheet Galfenol for future device applications, we are investigating the effects of rolling on texture evolution and magnetostrictive properties of polycrystalline Galfenol. This work includes experimental rolling, theoretical modeling, and studies of high temperature polycrystalline plasticity. The purpose of this paper is to provide a brief description on the goals of the project, the planned research work, and the results from preliminary experiments.

1. INTRODUCTION
Alloys of iron substituted with non-magnetic gallium, Fe$_{1-x}$Ga$_x$, can produce large magnetostrictions and offer promise as mechanically robust actuator and sensor materials. Single crystals of Fe-Ga (Galfenol) have been shown to exhibit up to 400 ppm magnetostrictive strains with saturating fields of several hundred oersteds.$^{1,2}$ However, due to the high conductivity of Galfenol, device operation will require it to be laminated, or in thin sheet form, in order to avoid eddy current losses. Current lamination techniques are costly, time consuming, and can only produce a small number of laminates at a time. One of the main challenges in producing engineering components from Galfenol is shaping of these materials while retaining a preferred crystallographic texture to optimize the magnetostrictive performance of the polycrystals. Full realization of the potential of these materials requires that they can be economically produced in thin, appropriately textured, sheets, or perhaps wires, with reasonable toughness and actuation properties. In an effort to produce large quantities of thin sheet Galfenol for future device applications, DRDC Atlantic is investigating the effects of rolling on texture evolution and magnetostriction of polycrystalline Galfenol. In this paper, the goals and research plans for the project will be briefly described, followed by a discussion on the results from preliminary experiments.

2. OBJECTIVES
The objective of the current work is to develop a science-based approach to produce Galfenol (or its derivatives) in thin, appropriately textured, sheets with reasonable robustness and magnetostrictive properties. By using a combination of experimental rolling, theoretical modelling of microstructure evolution and studies of high temperature polycrystalline plasticity, our goal is to provide a complete picture of the deformation mechanisms during forming processes.
3. ROLLING OF GALFENOL

A systematic approach, combining theoretical and experimental works, is being adopted to investigate the effects of rolling on texture evolution and magnetostrictive properties of polycrystalline Galfenol. The work includes: i) experimental rolling to develop and to optimize the rolling process, ii) theoretical modelling of microstructure evolution and texture development during deformation and iii) experimental and theoretical work to understand polycrystalline plasticity in Galfenol.

Rolling of Galfenol is being explored by investigating the effects of composition, starting material structure, temperatures, processing parameters and post-deformation annealing on texture and quality (physical, mechanical and magnetic) of rolled material. Deformation and recrystallization mechanisms and mechanical behavior at high temperature are also being investigated. Investigation will be carried out to explore the influence of various annealing temperatures, thermal cycles and furnace atmospheres on recrystallization and the evolution of recrystallization texture in an effort to promote development of \{100\} texture, the preferred magnetic easy-axis in this material system. Preliminary investigation will be carried out to explore the influence of additional alloying elements on workability and texture development during thermomechanical treatments. Their effects on grain boundary migration and recrystallization, which will have strong influence on grain size and texture development, will also be investigated. Effort will also be made to conduct a preliminary investigation on the strengthening effects of the alloying additions. The findings from this work will aid in texture development during rolling, directional solidification and other fabrication methods.

Efforts are also being made in this work to develop models for the microstructure evolution and texture development as the deformation process proceeds. Initially, a combination of theoretical and semi-empirical modelling techniques will be applied. Modelling of texture development will be based on a modified Taylor’s full constraints model by assuming all grains undergo the same shape change as the overall polycrystal and taking into account the constraints imposed by neighboring grains on slip systems. A Johnson-Mehl-Avrami-Kolmogorov (JMAK)-type phenomenological modeling approach is being adopted for the modelling of the recrystallization kinetics.

Moreover, this investigation will take into account the relations among imposed deformation strain, constraints between neighboring grains and operating slip systems using in-situ neutron diffraction. The goals for the in-situ neutron diffraction are to attain quantitative information on the high temperature, plane strain deformation of Galfenol; and to identify preferential slip systems and thermomechanical treatments that will enhance/minimize lattice rotation during deformation. A specialized setup for hot-channel die compression is being developed in order to perform in-situ channel die (plane strain) compression at high temperature (Figures 1 and 2). The in-situ experiments could be able to provide extensive quantitative information on the nature and kinetics of dynamic recovery, recrystallization and precipitation reactions under simulated rolling conditions and on the influence of temperature on these processes. The data obtained will serve as inputs for modelling and analysis of Galfenol plastic deformation in polycrystalline aggregates subjected to complex states of stress, or to validate the predictions made by such models. These experiments should provide unique insights into texture evolution, deformation processes, including their kinetics, as well as information on damage accumulation.

4. PRELIMINARY RESULTS

Preliminary experiments have been carried out to determine the flow stress – flow strain behaviour of Galfenol at high temperature (Figure 3). The specimens used in these tests were about 6.35mm in diameter and 10mm in length; and were machined from directly solidified rods obtained from Etrema Products Inc. The specimens had a nominal composition of either 18.4at% Ga or 19.5at% Ga. The direction of compression was parallel to the growing direction. Compression tests were conducted at different temperatures (900°C to 1100°C) in Ar using a Gleeble 1500 thermomechanical simulator at a nominal strain rate of about $2 \times 10^{-2}$ s$^{-1}$. The curves in Figure 3 show the softening of the material as temperature increases. Moreover, the result shows very little evidence of work hardening during compression at these temperatures. The difference between the curves for 18.4at% Ga and 19.5at% Ga at 1000°C suggests that there is a composition dependence on flow stress, however, further investigation is needed. In order to study the mechanical behaviour of the material during rolling, interrupted
compression test was also carried out at 1000°C. During the test, the sample was unloaded and was hold at the test temperature for 2 minutes after each deformation of about 0.4mm. The true stress – true strain curve is shown in Figure 4. Compared the result to a simple compression at the same temperature, there is no evidence of any significant static recrystallization or recovery.

Figure 1. Channel-die-compression rig designed for plain strain compression during in-situ neutron diffraction.

Figure 2. Load frame (a) with and (b) without the environment chamber for in-situ neutron diffraction. The arrow indicates the location of the channel-die-compression rig.

Preliminary experiments have also been carried out to develop an optimized rolling process in order to produce thin sheets of polycrystalline Galfenol with preferred texture. Figure 5 shows a Galfenol arc-melted button which was used as the starting material for one of the rolling experiments. The arc-melted button has a nominal composition of
18.4 at% Ga, a diameter of about 60mm and a thickness of about 10mm. A strip with a width of about 20mm was cut from the button for rolling (Figure 5). Figure 6 shows the specimen after hot rolling to a thickness of 2.4 mm.

**Figure 3.** True stress vs. true strain during compression of Galfenol at different temperature.

**Figure 4.** True stress vs. true strain curves of Galfenol (Fe-18.4 at% Ga) at 1000°C. Blue curve: interrupted compression; red curve: simple compression.
Figure 5. Galfenol arc-melted button (18.4at% Ga) used as starting material for hot rolling. The rolling direction (RD) is indicated by the arrow.

Figure 6. Hot rolled Galfenol specimen with about 75% reduction.

Metallographic examinations showed that the as-received specimen had an average grain size of about 200 – 300 µm (Figure 7(a)) while the average grain size of the specimen after hot rolling was about 1 mm (Figure 7(b)). Preliminary results suggested that significant grain growth occurred after recrystallization during reheating of the specimens. Investigations are being carried out to determine the optimum reheating conditions. EBSD was also conducted on the specimen to examine the texture of the specimen after hot rolling. However, due to the small specimen size and large grain size, there were not enough grains to provide statistically accurate information on the distribution of grain orientation.
Figure 7. Micrograph of Galfenol arc-melted specimen: (a) as-received, (b) hot rolled with about 75% reduction.

5. SUMMARY

DRDC Atlantic is currently investigating the effects of rolling on texture evolution and magnetostrictive properties of polycrystalline Galfenol. The objective of this work is to develop a science-based approach to produce Galfenol (or its derivatives) in thin, appropriately textured, sheets with reasonable robustness and magnetostrictive properties. By using a combination of experimental rolling, theoretical modelling of microstructure evolution and studies of high temperature polycrystalline plasticity, one of the goals is to provide a complete picture of the deformation mechanisms which can be applied to other compositions and forming processes. The planned research work and the results from preliminary experiments are briefly discussed in this paper.

Preliminary results suggested that these materials show very little evidence of work hardening during compression at temperatures above 900°C. Moreover, results from interrupted compression experiments at these temperatures showed no evidence of any significant static recrystallization or recovery. However, results from metallographical analyses of hot rolled specimens suggested that significant grain growth occurred after recrystallization during reheating of the specimens. Further investigation is being carried out to clarify this.

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7. REFERENCES