# 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, it needs to be in thin sheet form for many device applications to avoid eddy current loses. 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. In this work, the effects of rolling on texture evolution of polycrystalline Galfenol are being investigated. Results from hot rolling experiments showed that careful control of rolling conditions can minimize the formation of cracks. They also suggested that significant dynamic recovery and recrystallization occurred during the deformation process, resulting in a large number of grain orientations with very little texture. Preliminary results also showed that the specimens can be successfully warm rolled to a thickness of less than 0.5 mm.

## Introduction

Magnetostriction is a phenomenon wherein a material exhibits reversible mechanical strain under the influence of a magnetic field and change in magnetization under the application of stress. Magnetostrictive materials are widely used in various applications such as actuators, sensors, damping devices, linear motors and positioning devices [1,2]. Rare earth-transition metal alloys usually exhibit the largest values of magnetostriction. For example, Terfenol-D, a compound of Tb, Dy and Fe, exhibits large magnetostriction (~ $2000 \times 10^{-6}$) at room temperature and is commercially available. However, these alloys require high magnetic field to achieve saturation, are brittle and expensive due to the high cost of Tb and Dy. Magnetostrictive materials that have adequate magnetostriction and can overcome the drawbacks of Terfenol are currently of interest.

It has long been noted that the addition of certain substitutional elements to Fe can increase the magnetostriction along certain crystallographic directions [3]. Recently, it has been shown that the magnetostriction of Fe increases significantly when non-magnetic Ga were substituted for Fe in the bcc α-Fe structure [4-8]. With ~19% substitution, single crystals of Fe-Ga (Galfenol) have been shown to exhibit up to $400 \times 10^{-6}$ magnetostrictive strains along the [100] crystallographic direction [4,5] (more than 10 times that of bcc α-Fe) with saturating fields of several hundred oersteds. In addition to their high magnetostriction, they can be machined, welded, and are mechanically strong. Moreover, annealing these alloys under a compressive stress (stress annealing) can generate a built-in uniaxial anisotropy that obviates the need for a compressive pre-stress and makes the materials active under tensile stresses [9,10]. The attractive magnetostrictive properties of Galfenol at low saturation fields and high imposed stress, associated with low magnetic hysteresis, high mechanical strength and moderately high elastic constants, makes these materials very advantageous as low cost materials for actuator and sensor applications, particularly for devices requiring mechanical strength and durability.

While single crystals of Galfenol can provide large magnetostriction along the [100] directions, growth of single crystals is an expensive process. It is thus desirable to obtain [100] textured polycrystalline Galfenol using a relatively low-cost processing approach. Polycrystal Galfenol materials (of a $Fe_{81.6}Ga_{18.4}$ composition) prepared by the free-standing zone melt (FSZM) technique [11] exhibit magnetostriction of up to about $220 \times 10^{-6}$. Single crystal Galfenol of a similar composition had a measured magnetostriction of $\sim 290 \times 10^{-6}$, with no post-growth heat treatments. However, due to the high conductivity of Galfenol, many device operations will require it to be laminated, or in thin sheet form, in order to avoid eddy current loses. Current lamination techniques require cutting of solid Galfenol (prepared by FSZM) into thin sheets and are costly and time consuming. Conventional thermomechanical processing approach, such as rolling, may provide a more economical means to produce large quantities of thin Galfenol sheets, while retaining the preferred [100] crystallographic texture to optimize the magnetostrictive performance of the polycrystals [12,13].

The objective of the current work is to develop a science-based approach to produce Galfenol in thin, appropriately textured, sheets with reasonable robustness and magnetostrictive properties. By using a combination of experimental rolling, theoretical modeling 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. In this paper, preliminary results from rolling experiments are discussed.

## Experiments

The Galfenol specimens used in this work were obtained from Etrema Products and had a nominal composition of 18.4at% Ga. The specimens used for rolling were in the form of arc-melted buttons with a dimension of about 50 mm diameter × 7 mm thick. The deformation process was carried out on a laboratory two-high, reversing rolling mill with 5 in. diameter × 8 in. wide heated work rolls. The mill was connected to a furnace in series by a delivery table. Specimens were subjected to diverse hot rolling conditions and parameters, such as temperature, reduction/pass, reheat time and roll speed, to evaluate the influence of these conditions on the formability and crystallographic texture. Similar test procedures but different processing conditions were applied for each experiment.

Preliminary experiments have been carried out to determine the flow stress – flow strain behavior of Galfenol at high temperature. The specimens used in these tests were about 6.35 mm diameter × 10 mm length; and were machined from directly solidified rods. 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 rate of about 0.2 mm/s. During the tests, the specimens were heated to the test temperature at a heating rate of 5°C/s and were held at the test temperature for 1 minute before compression. In order to study the mechanical behavior of the material during rolling, interrupted compression testing was also carried out at 1000°C. During the test, the sample was unloaded and was held at the test temperature for 2 minutes after each deformation of about 0.4 mm.

The microstructures of the arc-melted and rolled specimens were examined using optical microscopy and scanning electron microscopy. Pole figures, texture component map and orientation distribution function plots were obtained by electron backscattering diffraction (EBSD) analysis using a Nordlys II EBSD detector (HKL Technology) operating at an accelerating voltage of 20kV.

## Results and Discussion

The true stress – true strain curves during compression at different temperature are shown in Fig. 1(a). The curves show the softening of the material as temperature increases. The results show very little evidence of work hardening during compression at these temperatures. The true stress – true strain curve for the interrupted compression test carried out at 1000°C is shown in Fig. 1(b). Comparing the result of the interrupted test to that of the simple compression at the same temperature (Fig. 1(a)), there is no evidence of any significant static recrystallization or recovery during the 2-minute annealing at 1000°C.

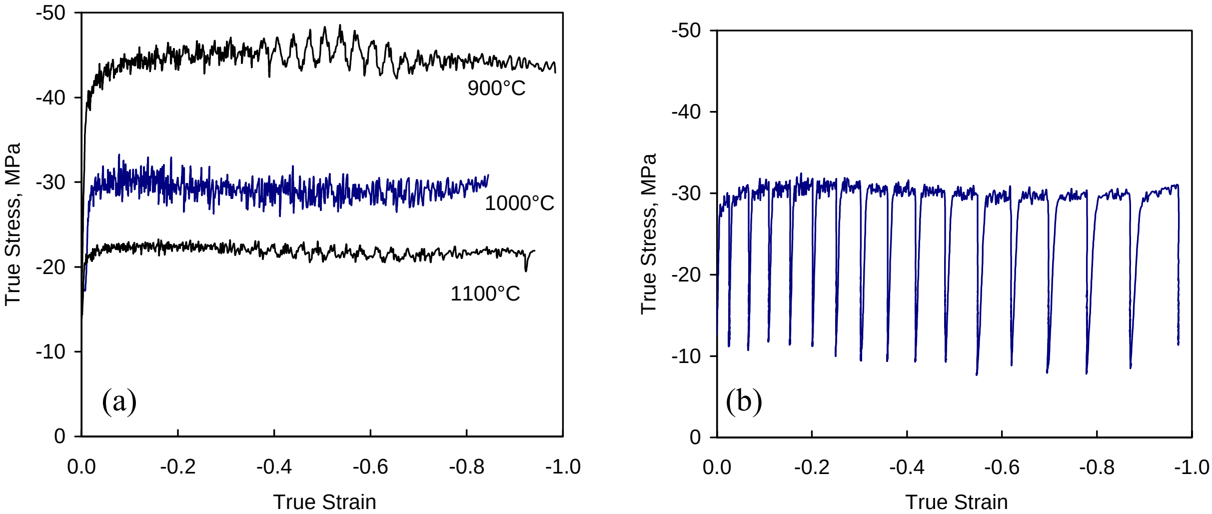


Fig. 1. True stress *vs.* true strain during compression of Galfenol (Fe-18.4at% Ga): (a) at different temperature; (b) interrupted compression at 1000°C.

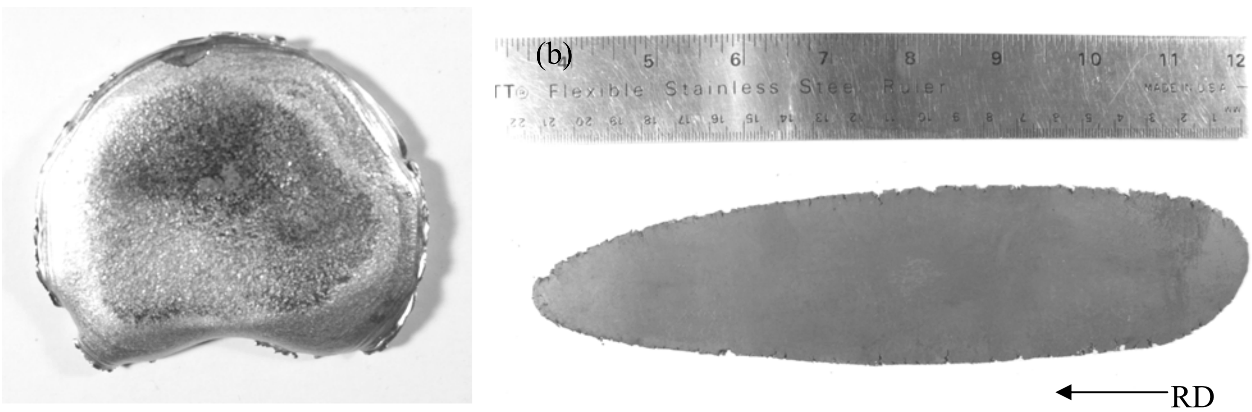


Fig. 2. (a) Galfenol arc-melted button (18.4at% Ga) used as starting material for hot rolling, (b) same specimen after hot rolling with about 80% reduction.

Fig. 2(a) shows a Galfenol arc-melted button which was used as the starting material for one of the rolling experiments. Fig. 2(b) shows the specimen after hot rolling with a total reduction of about

80%. Edge cracking, such as that shown in Fig. 3(a), can be found after similar amounts of total reduction under almost all hot rolling conditions tested in the current work. However, in some cases only minimal edge cracking occurred. Moreover, some specimens also showed extensive surface cracking, even at relatively high temperature. Analysis of the as-rolled samples showed that such cracks were intergranular in nature (Fig. 3(b)). Although it has been shown that addition of small amount of B seems to improve the ductility by suppressing grain boundary fracture [13], it is not clear what the effect of B addition is on the magnetostrictive properties of Fe-Ga alloys. Therefore, as a first step in developing a rolling procedure for Galfenol, only binary Fe-Ga is being considered in the current work. Under some rolling conditions, Galfenol specimens can be successfully hot rolled to give a reduction of 80% or more with only minimal edge or surface cracking.

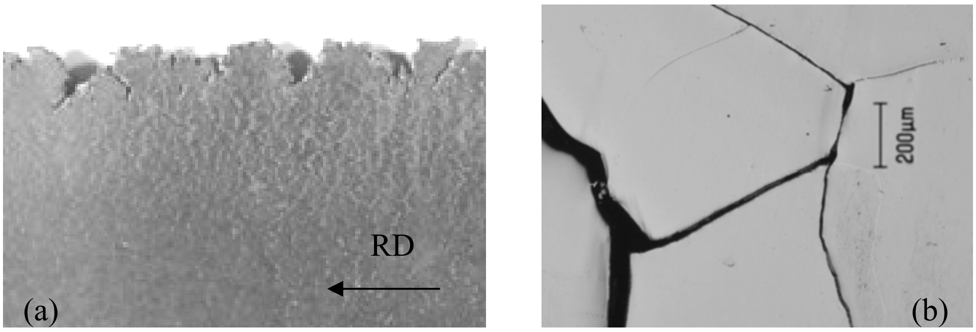


Fig. 3. (a) Edge cracking on hot rolled specimen after about 80% reduction; (b) optical micrograph of as-rolled specimen showing grain boundary fracture.

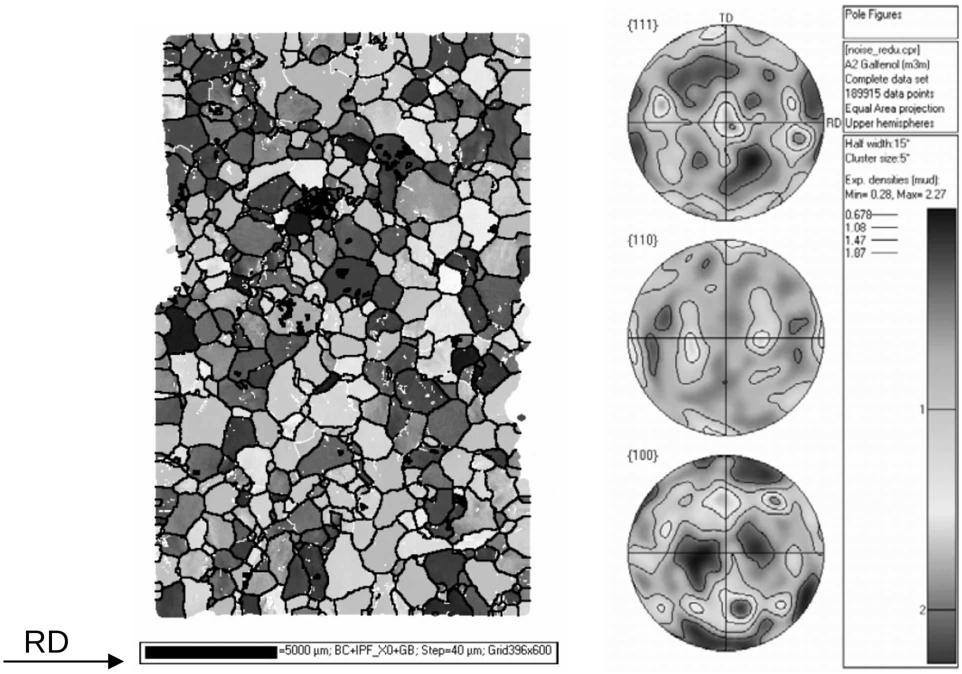


Fig. 4. Inverse pole figure (IPF) map and pole figures of a specimen hot rolled at 1000°C with about 80% reduction.

However, it appears that the hot rolling processes applied to these specimens produced sheets with a large number of orientations with very little texture. For example, Fig. 4 shows the inverse pole figure (IPF) map and the associated pole figures of a specimen hot rolled at 1000°C. It indicates a weak texture and a large number of orientations present. It is believed that dynamic recovery and recrystallization occurred during deformation and significant grain growth occurred during reheating. In addition, as shown in Fig. 5, there seems to be a significant increase in grain size as rolling temperature increases. For comparison, average grain size of as-received arc-melted buttons is less than 200 μm.

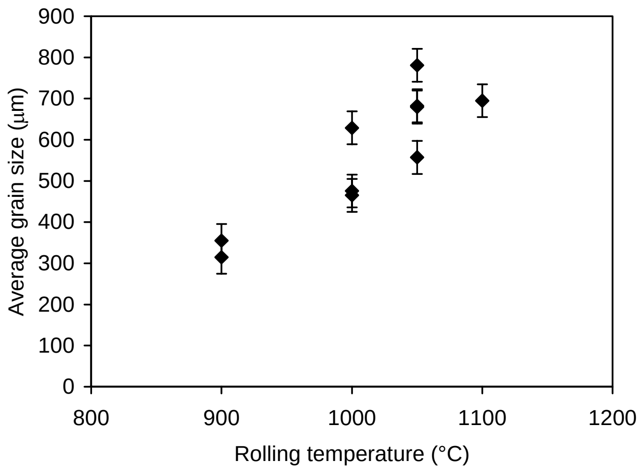


Fig. 5. Average grain size as a function of rolling temperature, at a total reduction of about 80%.

Preliminary warm rolling experiments were also carried out on some of the hot rolled specimens. As shown in Fig. 6, it was possible to successfully warm roll some of specimens to a thickness of less than 0.5 mm with only minor edge cracking, although EBSD analysis has not been carried out to determine the texture of the specimens.

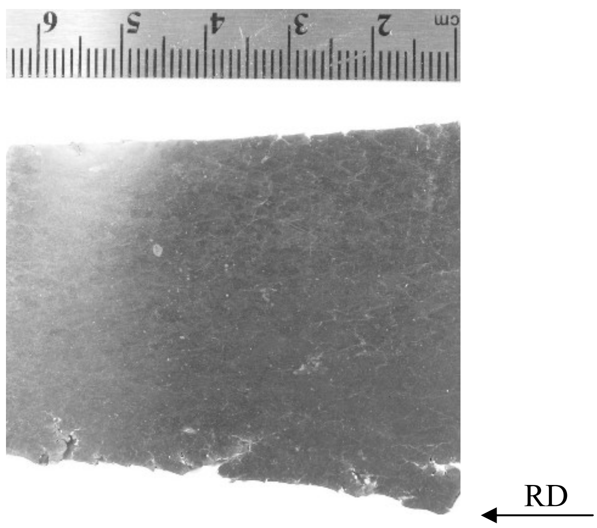


Fig. 6. A Galfenol specimen after warm rolleing to a thickness of about 0.5 mm.

## Summary

In this work, the feasibility of using conventional thermomechanical processing approaches to obtain thin, textured sheets of Galfenol is being examined. The effects of various rolling conditions on the formability and texture evolution of polycrystalline Galfenol are being investigated. Results from hot rolling experiments showed that binary Fe-Ga is prone to edge and surface cracking, even at relatively high rolling temperatures. Such cracks are shown to be associated with intergranular fracture. However, careful control of rolling conditions can minimize the formation of cracks. These results also suggested that significant dynamic recovery and recrystallization occurred during the deformation process, resulting in a large number of grain orientations with very little texture. Preliminary results also showed that the specimens can be successfully warm rolled to a thickness of less than 0.5 mm. EBSD analysis will be carried out to determine the texture after warm rolling. Further work will be performed to investigate the effects of subsequent annealing and cold rolling and to identify the optimized thermomechanical conditions that could enhance [100] texture.



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