High temperature plasticity of polycrystalline Galfenol (Fe-Ga)

Leon M. Cheng[*,a], Rosaura Ham-Su[a] and Michael A. Gharghouri[b]

[a]Defence R&D Canada – Atlantic, Emerging Materials Section, Dartmouth, NS, Canada B2Y 3Z7
[b]Canadian Neutron Beam Centre, National Research Council of Canada, Chalk River, ON K0J 1J0

ABSTRACT

Galfenol (Fe-Ga) is a promising and mechanically robust magnetostrictive actuator material. However, due to its high conductivity, it needs to be in thin sheet form to avoid excessive eddy current losses. Work is underway to develop conventional rolling processes to produce large quantities of thin Galfenol sheet, while retaining a preferred <100> crystallographic texture to optimize magnetostrictive performance. Knowledge of high temperature polycrystalline plasticity is crucial to understanding formability and crystallographic texture evolution during rolling. The deformation behavior of polycrystalline Galfenol at high temperatures was studied. Preliminary results suggest that significant dynamic recovery and/or recrystallization occur during deformation, resulting in a random texture. In-situ neutron diffraction experiments are being developed to obtain qualitative and quantitative information on the high temperature plane strain deformation of Galfenol. These experiments will be used to identify the slip systems that contribute to plastic deformation, and their dependence on temperature. Simultaneously, models of large-scale polycrystal plasticity are being developed to predict internal strains and texture evolution during deformation, which will be validated against the data obtained from the neutron diffraction experiments. Ultimately, the models will be used to develop thermo-mechanical treatments to optimize texture evolution during rolling.

Keywords: Galfenol, Fe-Ga, magnetostriction, polycrystalline, plasticity, texture, neutron diffraction, rolling

1. INTRODUCTION

Magnetostrictive materials are widely used in actuator and sensor applications[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 ($\sim 2000 \times 10^{-6}$) at room temperature and is commercially available. However, these alloys require high magnetic fields to achieve saturation and are brittle. Materials combining adequate magnetostriction at moderate applied fields and good mechanical properties are currently of interest.

It has been shown over the past few years that the magnetostriction of Fe increases significantly when non-magnetic Ga is substituted for Fe in the bcc α-Fe structure[3-10]. With ~19% substitution, single crystals of Fe-Ga (Galfenol) have been shown to exhibit magnetostrictive strains up to 400×10^{-6} along the <100> crystallographic direction[4,5] (more than 10 times that of α-Fe) with saturating fields of several hundred oersteds. 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, make 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 provide large magnetostriction along the <100> directions, their preparation is expensive. Polycrystalline Galfenol prepared by the Free-Standing Zone Melt (FSZM) technique[11] exhibits magnetostriction values comparable to those of single crystals with similar compositions. It is thus desirable to obtain <100> textured polycrystalline Galfenol using a relatively low-cost approach. Due to the high conductivity of Galfenol, device operation will require that it be laminated, or in thin sheet form, in order to avoid eddy current losses. Current lamination techniques, in which solid Galfenol (prepared by FSZM) is cut into thin sheets, are costly and time consuming. A conventional processing approach, such as rolling, may thus provide an economical means of

[*] leon.cheng@drdc-rddc.gc.ca; phone 1 902 427-2601; fax 1 902 427-3435

producing large quantities of thin Galfenol sheet, while retaining the preferred <100> crystallographic texture to optimize magnetostrictive performance[12,13].

Plastic deformation in metals during rolling results in the accumulation of dislocations, which, to a great extent, determines the mechanical properties and formability of the resulting material. Manifestations of dislocation accumulation include increased yield strength, decreased ductility, lattice rotation leading to texture evolution, development of a subgrain structure, and, possibly, damage in the form of void formation and coalescence. Knowledge of the way in which dislocations behave is crucial to understanding the formability and crystallographic texture evolution during rolling. The high-temperature deformation behavior of polycrystalline Galfenol during simulated rolling has been studied. In-situ neutron diffraction experiments are being developed to obtain qualitative and quantitative information on the plane strain deformation of Galfenol at elevated temperatures. Models are also being developed to predict internal strains and texture evolution during deformation. These efforts are discussed in the following sections.

2. MECHANICAL TESTING

Preliminary experiments were carried out to determine the flow stress – flow strain behavior of Galfenol at elevated temperatures. The materials used in this work were supplied by Etrema Products Inc. and had a nominal composition of either 18.4 at% Ga or 19.5 at% Ga. The specimens were about 6.35 mm in diameter and 10 mm in length; and were machined from directly solidified rods prepared by the FSZM technique. The specimens were compressed parallel to the growing direction. Tests above 900°C were performed in Ar using a Gleeble 1500 thermo-mechanical simulator. Tests below 900°C were conducted in air using an Instron servo-hydraulic load frame equipped with an Instron 8800 controller and a split furnace. For the latter tests, the nominal strain rate was approximately 2×10^{-2} s^{-1}, and the axial deformation was measured using the displacement of the crosshead. Specimen dimensions were measured before and after every test.

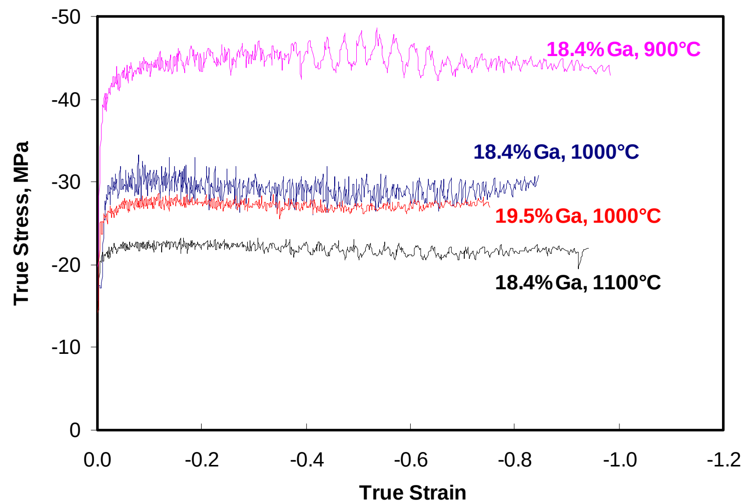

Figure 1. True stress *vs.* true strain during compression of Galfenol at different temperatures.

The true stress – true strain curves during compression are shown in Figure 1. During the tests, the specimens were heated to the test temperature at a heating rate of about 5°C/s and held at the test temperature for 1 minute before compression. The curves in Figure 1 show that the material softens as temperature increases. Moreover, there is little evidence of work hardening during compression at these temperatures. The small difference between the flow curves for 18.4 at% Ga and 19.5 at% Ga at 1000°C suggests that there may be a weak dependence of the flow stress on composition; however, further investigation is needed. In order to study the mechanical behavior of the material during rolling, an interrupted compression test was also carried out at 1000°C. During the test, the specimen was unloaded and held at the test temperature for 2 minutes after each deformation of about 0.4mm. The true stress – true strain curve is shown in Figure 2. Comparing the flow curve for the interrupted test to that of the uninterrupted test (Figure 1), there is no evidence of any significant static recrystallization or recovery during the 2-minute anneal at 1000°C.

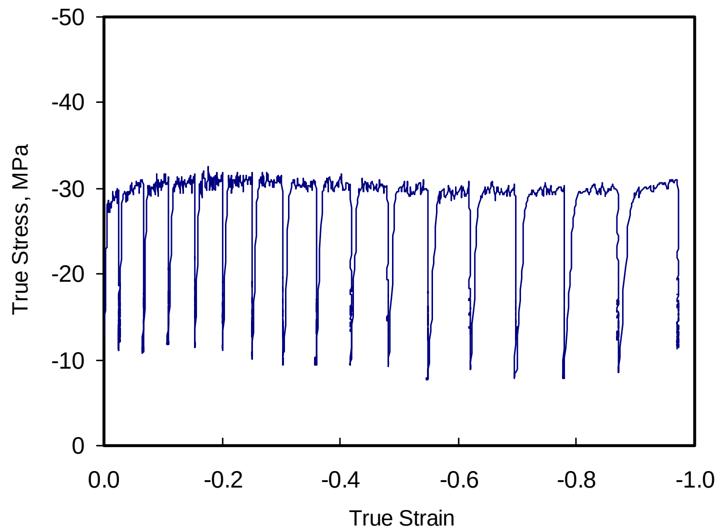

Figure 2. True stress *vs.* true strain during interrupted compression of Galfenol (Fe-18.4at% Ga) at 1000°C.

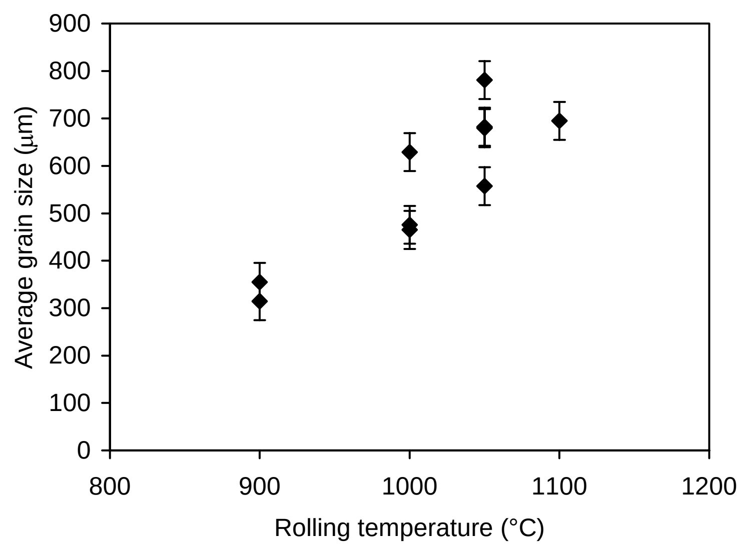

Figure 3. Average grain size as a function of rolling temperature, at a total reduction of about 80%.

However, results from rolling experiments on Galfenol specimens with the same composition (18.4 at%Ga) indicated that significant grain growth occurred during hot rolling at these temperatures. Figure 3 shows the average grain size as a function of rolling temperature, at a total reduction of about 80%. As shown in the figure, there is a significant increase in grain size as rolling temperature increases. For comparison, the average grain size of as-received arc-melted buttons is less than 200 µm. These results suggest that significant dynamic recrystallization may occur during hot rolling.

3. IN-SITU NEUTRON DIFFRACTION — PLANE STRAIN COMPRESSION

Many of the manifestations of dislocation accumulation (development of the deformed state) are amenable to observation and quantitative measurement using neutron scattering techniques. Neutrons as a probe for matter are very attractive. The ability to penetrate deeply into materials allows information to be retrieved from all regions of a bulk specimen, as opposed to other surface or near-surface techniques; it also allows the investigation of samples in a variety of specialized environments (different atmospheres, temperatures, temperature gradients, applied loads, etc.). Neutrons interact weakly with most metals, and thus do not cause damage or microstructural evolution. Neutrons respond strongly to small differences in atomic number, which makes them sensitive to heterogeneities in a material. Dynamic deformation processes can be studied by performing mechanical tests in the neutron beam.

3.1 Rolling simulated as plane-strain compression

The state of stress encountered during rolling is one of compressive plane strain, Figure 4. Therefore, to acquire an understanding of the dynamic microstructural changes occurring during rolling, it is useful to develop in-situ experiments for such a stress state[14]. These experiments can potentially provide information on the development of internal strains, on texture evolution, and on changes in the subgrain structure. A series of well-planned in-situ experiments may provide extensive quantitative information on the nature and kinetics of these dynamic processes together with the influence of temperature on these processes. This capability is now being developed to study plastic deformation of Galfenol. At the Canadian Neutron Beam Centre, a furnace for in-situ heating/cooling experiments is available. An insert is being developed for in-situ channel-die compression tests up to 800°C. Load, temperature and deformation will be monitored during testing (Figure 5).

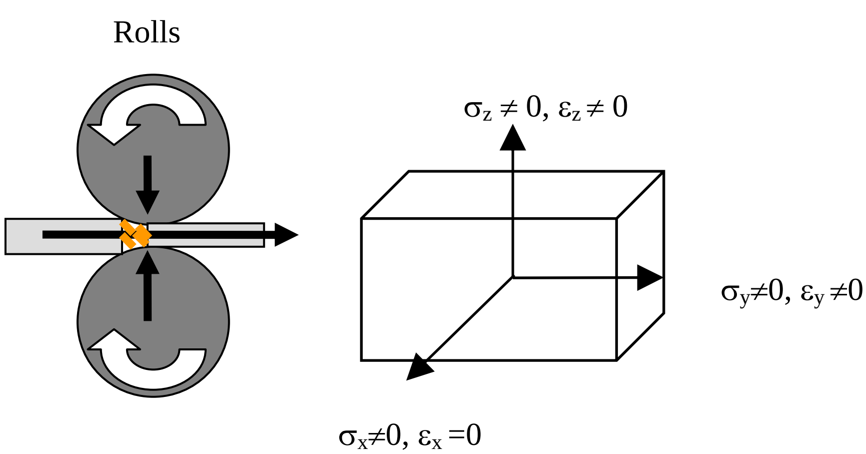

Figure 4. Plane strain compression during rolling.

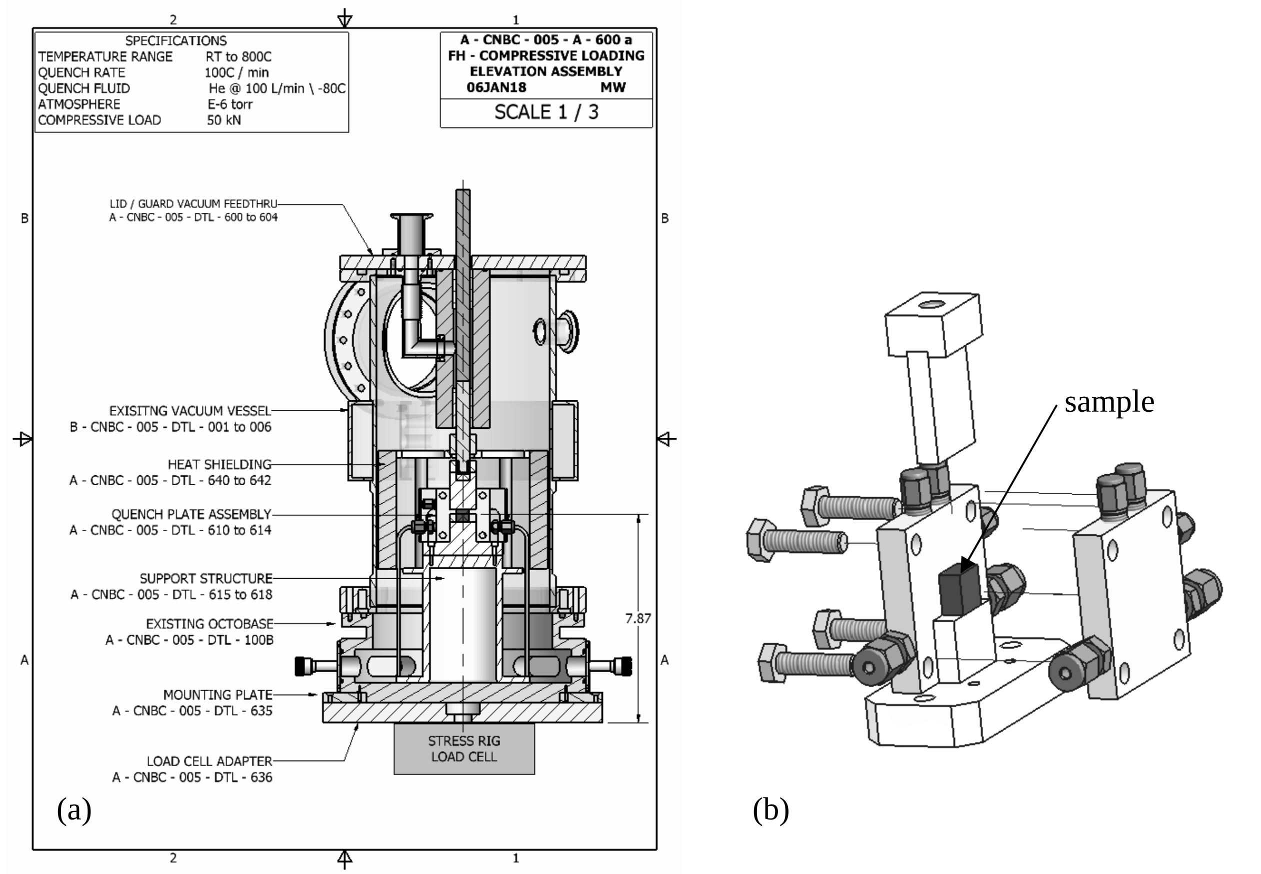

Figure 5. Schematics of (a) the compressive loading furnace assembly (not to scale) and (b) the channel-die compression assembly at the Canadian Neutron Beam Centre. The die walls will have embedded channels for cooling fluid to provide cooling rates of about 50 K/min.

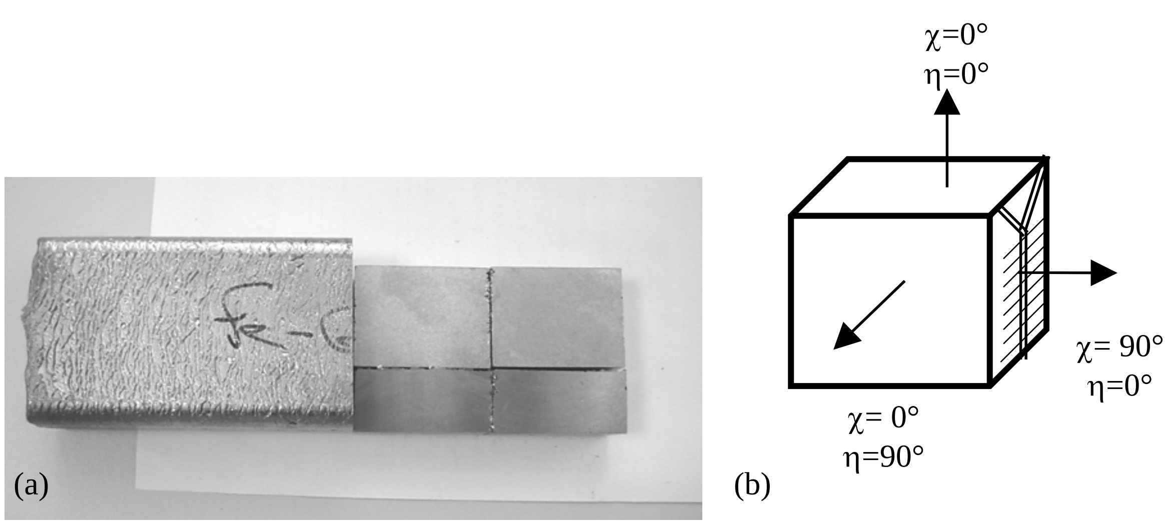

Figure 6. (a) Cast Galfenol samples for plain-strain compression tests; and (b) schematic of elongated grains.

3.2 Samples for plane-strain compression

Cast Galfenol samples (Figure 6(a)) with a nominal composition of 18.4 at% Ga provided by Etrema Products Inc. will be used for the in-situ plane strain compression investigation. The grains are elongated along the cooling direction, giving a grain structure as shown in the schematic in Figure 6(b). The texture of three as-cast samples determined by neutron diffraction showed that the samples have a strong crystallographic texture with the elongated grains growing preferentially along <100>. The pole figures for one of the samples are shown in Figure 7.

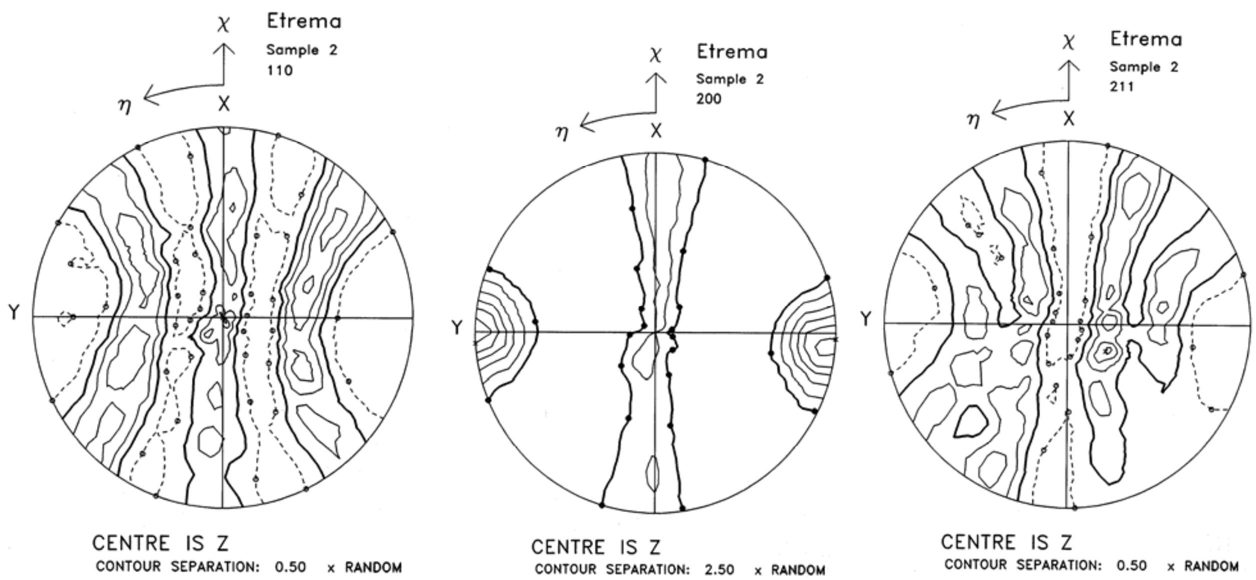

Figure 7. Pole figures for a cast Galfenol sample; the angles are according to Figure 6(b).

Neutron diffraction is a statistical tool, which gives information on populations of grains with given orientations. If the number of grains in the sampling volume is low, the signal acquired by the detector will be weak. Thus, the strong texture of the samples will limit the acquisition of data from multiple planes during the in-situ experiments. On the other hand, this strong texture is advantageous for magnetostriction and some of the plastic deformation experiments will be geared to retaining this texture. It is possible that the combination of directional cooling and forming procedures might prove to be the right combination to attain a thin, appropriately textured Galfenol sheet. It is believed that these experiments, in conjunction with texture evolution modeling, will provide an effective means to identify promising rolling schedules and thermo-mechanical treatments in a relatively short time.

4. MODELING OF TEXTURE EVOLUTION DURING FORMING OPERATIONS

The modeling is to be used in conjunction with the in-situ neutron diffraction experiments to acquire insight into the key parameters that govern the plastic deformation of polycrystalline Galfenol. In particular, the modeling is concerned with the mechanisms of texture evolution during processing and forming operations and with the interrelationship between texture and mechanical anisotropy during forming. The magnetostriction of Galfenol is crystallographically anisotropic and is highest along the <100> crystal directions. Therefore, it is of interest to identify thermo-mechanical treatments that promote a strong <100> texture.

Initially, the modeling effort is focusing on rolling operations similar to the ones used to produce thin Galfenol strips, where, to a large extent, plastic deformation in plane-strain conditions applies. There are several numerical approaches to model rolling conditions in metals e.g. upper-bound models, self-consistent approaches, or FEM. These approaches are complementary, and can be used together. However, depending on the particular situation, one approach or the other can be more convenient.

In this work, a self-consistent approach has been chosen to model the response of a polycrystalline aggregate from the known properties of the constituent grains, and from assumptions on the interaction of each grain with its environment. Interaction between the grains is treated as in the model of Eshelby and Kröner, where a grain is modeled as an elastic inclusion in a homogeneous matrix with the average properties of the aggregate. Intergranular interactions are thus described by the interaction between the inclusion and a Homogeneous Effective Medium (HEM) having uniform properties. The HEM's overall response to external loading conditions is the same as that of the polycrystalline aggregate. Thus, each grain is assumed to be embedded in a matrix with the properties of the aggregate and a grain with a given orientation is assumed to be representative of all grains with the same orientation. It is in the properties of the aggregate that texture effects are included.

In the case of the rolling operations of interest, the alloy is deformed well into the plastic regime. One of the important differences between the plastic regime as opposed to the elastic regime is that, in plasticity, the constitutive relations are usually non-linear. In the plastic regime, the inclusion is not elastic but plastic. The deformation of this inclusion embedded in the HEM has to fulfill local equilibrium and compatibility conditions. These conditions cannot be fulfilled for non-ellipsoidal inclusions or non-linear media. Therefore, in self-consistent modelling, the non-linear response of the aggregate is approximated using a linearization procedure, which is assumed to represent the material behavior within a certain range of stresses and strain rates. Linearization of the response of the medium and the description of the grains as ellipsoids guarantee that the stress and the strain are uniform within a grain. The resulting interaction equation then relates the stress and strain in the grain to the overall stress and strain in the aggregate[15,16]. In the current work, Tomé's Visco-Plastic Self-Consistent (VPSC) code[17] is being used to describe the deformation of Galfenol in plane strain compression.

Currently, uniform plane strain compression of Galfenol at room temperature is being modeled; this will be extended to higher temperatures in the future. In the case of hot-rolling, dynamic recovery or recrystallization will probably control the evolution of dislocation substructure and grain structure, which must be taken into account. The deformation rate may vary from one grain to the other as well as within the grains. Knowledge of such non-uniformities will be critical in the development of an understanding of the evolution of Galfenol's microstructure and crystallographic texture. In addition, these models must be extended to take into account industrial processing. For example, temperature transients and changes in strain rate – common in industrial processing – must be considered. Modeling may be extended to other manufacturing operations such as deep drawing and welding. Specifically, the influence of crystallographic texture on the deformation behavior of Galfenol must be addressed. Crystallographic texture can result in uneven plastic deformation and shape anisotropies such as earing during deep drawing operations.

5. SUMMARY

In order to improve our understanding of the formability and crystallographic texture evolution during rolling of Galfenol, efforts are underway to obtain quantitative information on high temperature polycrystalline plasticity of Galfenol. Preliminary experimental results suggest that significant dynamic recovery and/or recrystallization occur during the deformation process, resulting in an essentially random texture.

In-situ neutron diffraction experiments are being developed to study the dynamic evolution of deformation during high temperature, plane strain deformation of Galfenol. In conjunction with the in-situ neutron diffraction experiments, models are being developed to acquire insight into the key parameters that govern the plastic deformation of polycrystalline Galfenol and the accompanying texture development as deformation proceeds.

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