Wiedemann effect of Fe–Ga based magnetostrictive wires*

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$(Fe_{83}Ga_{17})_{98}Cr_2$ wires each with a diameter of 0.7 mm are prepared by hot swaging and warm drawing from the casting rods directly, because the ductility of $Fe_{83}Ga_{17}$alloy is improved by adding Cr element. The Wiedemann twists and dependences on magnetostrictions of $Fe_{83}Ga_{17}$ and $(Fe_{83}Ga_{17})_{98}Cr_2$ wires are investigated. The largest observed Wiedemann twists of 245 s·cm^{-1} and 182 s·cm^{-1} are detected in the annealed $Fe_{83}Ga_{17}$ and $(Fe_{83}Ga_{17})_{98}Cr_2$ wires, respectively. The magnetostrictions of the annealed $Fe_{83}Ga_{17}$ and $(Fe_{83}Ga_{17})_{98}Cr_2$ wires are 160 ppm and 107 ppm, respectively. The maximum of the Wiedemann twist increases with magnetostriction increasing. However the magnetostriction is just one important factor that affects the Wiedemann effect of alloy wire, and the relationship between magnetostriction and Wiedemann effect is a complex function rather than a simple function.

Keywords: Fe–Ga alloy, wires, Wiedemann effect, magnetostriction

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1. Introduction

The Wiedemann effect is the phenomenon of the twisting of a rod due to magnetostriction when longitudinal and circumferential magnetic fields are applied simultaneously.[1−3] As shown in Fig. 1, simultaneous operation of the axial field H_a (created by current I_a through the winding) and the circular field H_c (from I_c through the rod) forms a spiral field H_s, and a twist θ is observed in the direction of the spiral field for a rod with positive magnetostriction, while a rod with negative magnetostriction twists in the opposite direction. The Wiedemann effect is a kind of magneto-mechanical effect and could be regarded as a special case of the magnetostriction. Researchers discussed the Wiedemann effect by investigating the Wiedemann twists in different metals, such as nickel and iron, and tried to establish a definite relationship between the Wiedemann effect and magnetostriction. Although none of the theoretical analyses have been supported by a satisfactory comparison with reliable experimental data, many papers have reported on the Wiedemann twists of several metal materials.[4−6] It has been suggested that the Wiedemann twists of soft iron, nickel, and cobalt are all smaller than 100 s·cm^{-1}.

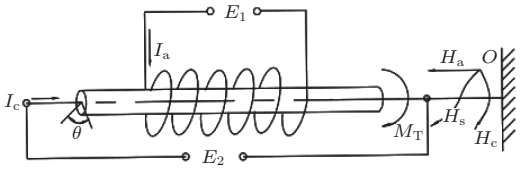


Fig. 1. Schematic diagram of the Wiedemann effect.

Investigation of the Wiedemann effect is interesting and important since there is little information concerning the effect in the magnetostrictive materials, in particular, which are now widely used in production. Borodin *et al.*[7] investigated the twisting of a ferromagnetic rod by measuring the maximum deformation of the helical springs made of the materials including Fe–Co–V, Fe–Ni, and Ni with saturation magnetostriction $\lambda_s = 70$, 25, and -26 ppm respectively. They found the greatest twisting in the specimen of material which possessed the largest saturation magnetostriction λ_s. It is necessary to investigate the Wiedemann effects of other materials with larger magnetostrictions, such as Tb–Dy–Fe alloys which have a magnetostriction of the order of 1000 ppm,[8] and those of Ni–Mn–Ga ferromagnetic shape memory

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alloys.[9,10] However the intrinsic brittleness values of Tb–Dy–Fe and Ni–Mn–Ga alloys make them impossible to be used as wires or tubes. In recent years, there has been an ever-increasing interest in the Fe–Ga (galfenol) alloy as a new magnetostrictive material because of both the magnetostriction and mechanical properties.[11,12] Magnetically, the addition of Ga increases the magnetostrictive capability of Fe over tenfold, up to 400 ppm, in a single crystal alloy.[13] Mechanically, Fe–Ga alloys are strong (> 500 MPa) and robust.[14] This combination of magnetic and mechanical properties makes Fe–Ga alloy a unique material.

Recently, our research group has investigated the preparation and the magnetostriction of Fe–Ga wire.[15] We prepared $Fe_{83}Ga_{17}$ wires with diameters in a range of 0.5 mm–0.9 mm by hot rotary swaging and warm drawing from the directional solidified rods, and a large magnetostriction of 160 ppm was obtained in the annealed wire. In this paper, we extend our previous studies of the Wiedemann effect of $Fe_{83}Ga_{17}$ wire. Additionally, we prepare $(Fe_{83}Ga_{17})_{98}Cr_2$ wires by hot rotary swaging and warm drawing from casting alloy directly and investigate their magnetostrictions and the Wiedemann effects. The Wiedemann twists of 245 s·cm^{-1} and 182 s·cm^{-1} are detected in the annealed $Fe_{83}Ga_{17}$ and $(Fe_{83}Ga_{17})_{98}Cr_2$ wires, respectively.

2. Experiment

The $Fe_{83}Ga_{17}$ wires each with a diameter 0.6 mm were prepared by hot rotation swaging and warm drawing from the directional solidified rods. The $(Fe_{83}Ga_{17})_{98}Cr_2$ wires each with a diameter of 0.7 mm were prepared by hot rotation swaging and warm drawing from the cast rods directly. Further details of the preparation method can be found in our previous work.[15] The as-drawn $Fe_{83}Ga_{17}$ and $(Fe_{83}Ga_{17})_{98}Cr_2$ wires were recrystallized at 1150 °C for 1 h and then quenched to room temperature. The final heat treatment was carried out at 800 °C for 1 h and then followed by quenched cooling.

Figure 2(a) shows a schematic diagram of the apparatus used in this work, which mainly includes the solenoid, laser source, and direct current (DC) power source. Current in the solenoid (I_a) and specimen (I_c) generating longitudinal and circular fields is provided by DC power. A small weight suspended from the specimen wire keeps it accurately vertical in the central line of the solenoid, and to prevent the weight from vibrating it was suspended in oil at the end of a long flexible cord. The tensile stress exerted on the wires is negligible because the weight is so light that it just keeps the wire vertical. A plane mirror is fixed on the free end of the specimen. The reflected parallel laser ray is focused on the screen. The twist of the wire can be calculated from the expression

$$\theta = 360S/4\pi R, \tag{1}$$

where θ is the angle of twist, S the displacement of spot, and R the distance between mirror and spot. The schematic diagram of the optical pathway is shown in Fig. 2(b).

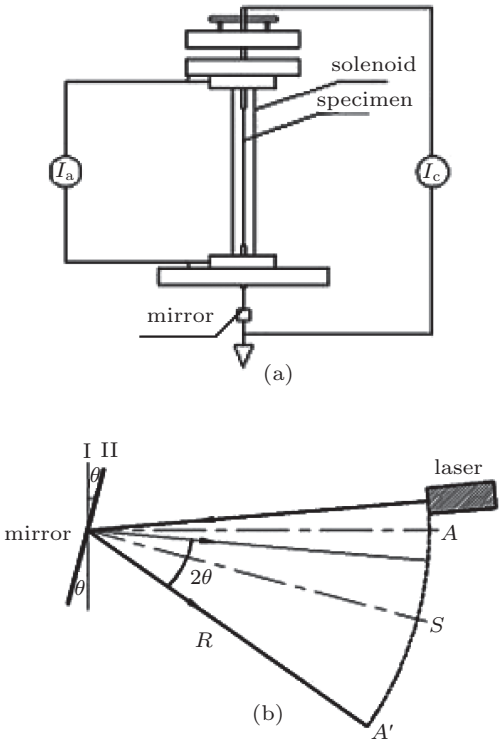


Fig. 2. (a) Schematic presentation of the Wiedemann twist measurement, and (b) diagram of optical pathway.

The magnetostriction was measured using a standard strain gauge. The size of the sensing grid element of the strain gauge is 0.5×0.5 mm. The measurement error for the magnetostriction test is of the order of a couple of ppm.

3. Results and discussion

As mentioned in Ref. [15], the improvement of deformability of $Fe_{83}Ga_{17}$ alloy is attributed to the columnar-grained structure induced by directional solidification. Our previous studies have indicated that 2 at% addition of Cr changed the fracture mode of $Fe_{83}Ga_{17}$ alloy from intergranular brittle fracture

into transgranular and resulted in an improvement of the strength and ductility.[16] So the $(Fe_{83}Ga_{17})_{98}Cr_2$ wires each with a diameter of 0.7 mm were prepared by hot rotation swaging and warm drawing from the casting rods directly.

Figure 3 displays the effects of the circumferential magnetic field (H_c) on the Wiedemann twist, for several values of invariable axial magnetic field (H_a). Values of the circumferential magnetic field are plotted as abscissa and the corresponding twist as ordinates. It is seen that the application of the circumferential magnetic field alone produces a small twist, whose value varies with the kind of specimen and the magnitude of the magnetizing field. As shown in Fig. 3, it is observed that keeping the axial magnetic field constant, the angle of twisting increases slowly for a low circumferential magnetic field, then reaches its maximum sharply, but a reversal twist at a relatively high circumferential magnetic field accrues. The characteristic accords remarkably well with results shown in earlier work on iron. The observed maximum twist angles are 66, 245, 136, and 182 s·cm^{-1} for the as-drawn and annealed $Fe_{83}Ga_{17}$ and $(Fe_{83}Ga_{17})_{98}Cr_2$ wires, respectively. The largest twist of 245 s·cm^{-1} is obtained in the annealed $Fe_{83}Ga_{17}$ wire when an axial magnetic field of 1020 A·m^{-1} and a circumferential magnetic field of 2653 A·m^{-1} are applied simultaneously. Notably, the observed maximum twist increases under the fixed axial magnetic field for the as-drawn $Fe_{83}Ga_{17}$ and $(Fe_{83}Ga_{17})_{98}Cr_2$ wires. For example, the increasing maximum twists of 35, 46, 51, and 66 s·cm^{-1} are obtained in the as-drawn $Fe_{83}Ga_{17}$ wires under the increasing axial magnetic field of 0, 770, 1540, and 2300 A·m^{-1} respectively. However, the maximum twist is detected under a specific axial magnetic field for the annealed wires. The reason can be attributed to the deformed microstructure in as-drawn wires which requires a higher axial magnetic field in order to reach the maximum twist. The explanation of the Wiedemann twist was given by Williams[17] in which a wire is magnetized circularly by passing a current through it along its length direction while simultaneously a longitudinal field is applied, and these two fields superimposed on each other give a resultant helical field of magnetization in the wire. The angle between the longitudinal field and resultant field varies with the circular field and longitudinal field. The twist reaches a maximum value when the resultant field is maximal. After its peak, the twist decreases as the circular field continues increasing.

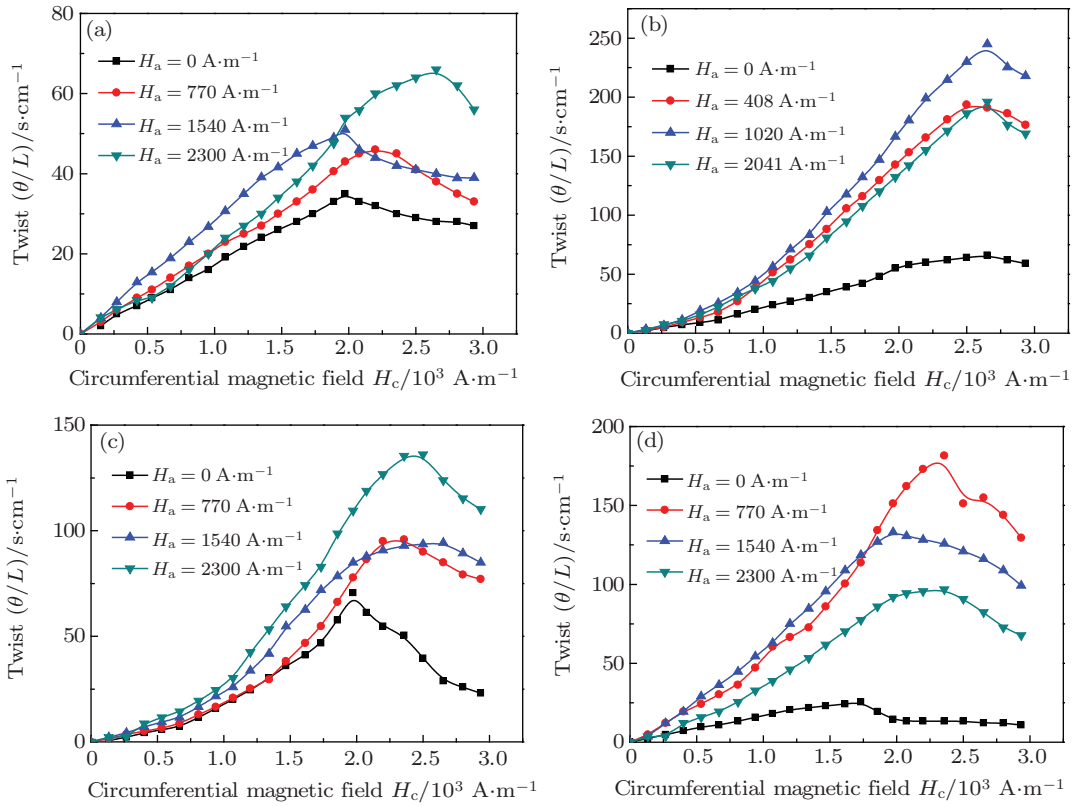


Fig. 3. (colour online) Wiedemann twists of the as-drawn (a) and the annealed (b) $Fe_{83}Ga_{17}$ wires, and the as-drawn (c), and the annealed (d) of $(Fe_{83}Ga_{17})_{98}Cr_2$ wires.

Figure 4 shows the effect of the axial magnetic field on the Wiedemann twists of the annealed $(Fe_{83}Ga_{17})_{98}Cr_2$ wires. The twist seems to increase approximately as a parabola function of the axial magnetic field. The twist is also very small when the axial magnetic field is applied alone. However, when the circumferential magnetic field is also applied and kept constant, the twist increases to a maximum value sharply under a small axial magnetic field, and then decreases sharply with the axial magnetic field increasing. So it is considered that compared with the trend of twist against the circumferential magnetic field, the Wiedemann effect is more sensitive to the axial magnetic field, with the circumferential magnetic field kept constant. As shown in Fig. 5, the larger axial magnetic field H_a is formed, the circumferential magnetic field H_c remains constant, and Φ which is the angle between H_a and the spiral field H_s will be equal to zero, and the direction of the spiral field more closely coincides with the impressed field H_a. If a change in length takes place along this spiral, it is evident that for small values of H_a the spiral will be very long, since Φ is almost 90°. For this long spiral, although it would not take a large coefficient of magnetic extension (d) multiplying H_s, a comparatively large twist would be obtained. It is very possible that for a given value of H_a where the d is a maximum, the value of H_s may drop off so that their product would be less than some previous value of H_a. This means a maximum twist in the Wiedemann effect at smaller values of H_a than at the field where the maximum elongation in the magnetostriction is reached.[18]

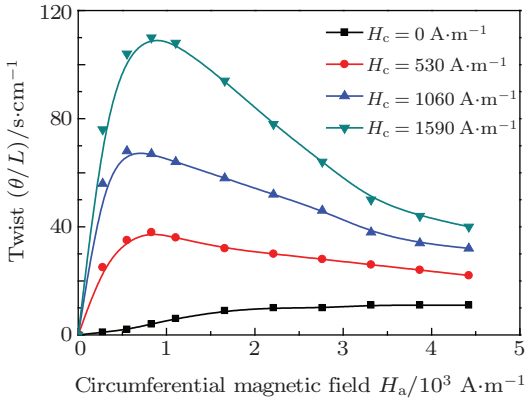


Fig. 4. (colour online) Effects of the axial magnetic field on the Wiedemann twist of the annealed $(Fe_{83}Ga_{17})_{98}Cr_2$ wire for some different values of H_c.

Figure 6 shows the magnetostriction curve of the annealed $(Fe_{83}Ga_{17})_{98}Cr_2$ wires. The saturation longitudinal magnetostrictive strain of λ_l is 107 ppm, and there is little hysteresis in the magnetostriction against magnetic field, which suggests an almost reversible magnetostriction. Although the 2 at% addition of Cr reduces magnetostriction of $Fe_{83}Ga_{17}$ wire, the magnetostrictive value of $(Fe_{83}Ga_{17})_{98}Cr_2$ wire is larger than that of the annealed $Fe_{85}Ga_{15}$ wires.[19] Our previous work reported that a large magnetostriction of 160 ppm was obtained in the annealed $Fe_{83}Ga_{17}$ wire and the structural origin was discussed also.[15]

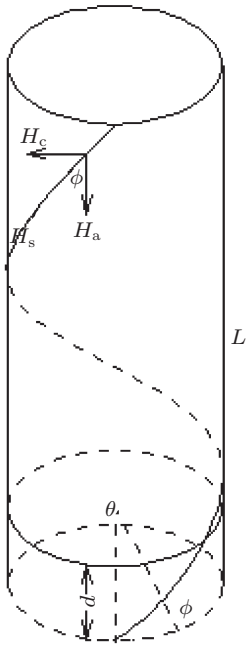


Fig. 5. Schematic diagram of the lines of magnetization when the axial and circumferential magnetic fields are applied simultaneously.

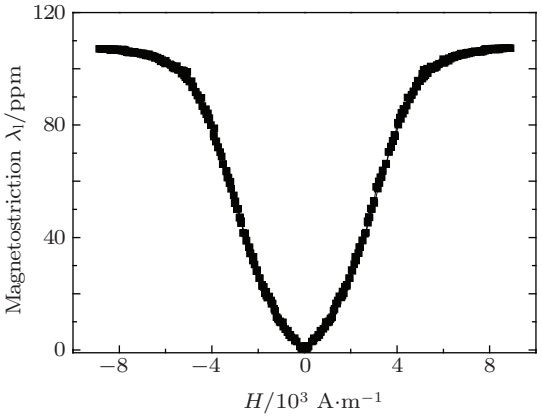


Fig. 6. Magnetostriction curve of the annealed $(Fe_{83}Ga_{17})_{98}Cr_2$ wire.

The experimental and theoretical analyses of the Wiedemann effect have been reported in previous work.[20−22] The theoretical analyses by Fromy[20] and Yamamoto[22] provided a prediction of the experimental behaviour. The twist per unit length is given by

$$\frac{\theta}{L} = \frac{2}{r}\left\{\lambda_{\mathrm{l}}(H) - \lambda_{\mathrm{t}}(H)\right\}\frac{H_{\mathrm{a}}H_{\mathrm{c}}}{H_{\mathrm{a}}^2 + H_{\mathrm{c}}^2}, \qquad (2)$$

where H_{a}, H_{c}, H are magnetizing fields on the surface of the specimen, L the length of specimen, r the radius of specimen, λ_{l} and λ_{t} are the longitudinal and transverse magnetostrictive coefficients respectively. The formula is obtained by analysing a thin cylinder and treating magnetostriction as a tensor quantity without employing tensor analysis. However, combined with some data reported by previous studies, all data shown in Table 1 do not accord with the function, and there is just a trend of the Wiedemann twist increasing with increasing magnetostriction. Magnetostriction is an important factor affecting the Wiedemann effect, but the relationship between magnetostriction and the Wiedemann effect is a complex function rather than a simple function. As a magneto-mechanical effect, the Wiedemann effect is also affected by other factors, such as permeability, elastic modulus, thermal expansion coefficient due to the heating effect of the current in it, and so on. So any attempt to provide a highly accurate prediction of the Wiedemann effect without further study is fruitless.

Table 1. Wiedemann twists and magnetostrictions of Fe–Ga wires in this work and some conventional magnetostrictive metals.

Specimens		(θ/L)/s·cm^{-1}	Magnetostriction/ppm	
			λ_{l}	λ_{t}
$Fe_{83}Ga_{17}$	as-drawn	66	28	–13
	annealed	245	160	–37
$(Fe_{83}Ga_{17})_{98}Cr_2$	as-drawn	136	33	–9
	annealed	182	107	–22
Fe–Ni wire (0.7 mm)[23]	annealed	141	26	–
Fe wire (1.0 mm)[6]	annealed	27	4	–
Ni wire (1.2 mm)[6]	annealed	90	–26	–
Co wire (0.9 mm)[6]	annealed	20	–15	–
Ni tube[24]	hot worked	3.45	–33	14

4. Conclusions

$(Fe_{83}Ga_{17})_{98}Cr_2$ wires each with a diameter of 0.7 mm are prepared by hot swaging and warm drawing from the casting rods directly. The magnetostriction of the annealed $(Fe_{83}Ga_{17})_{98}Cr_2$ wire is 107 ppm. The observed maximum Wiedemann twists of 245 s·cm^{-1} and 182 s·cm^{-1} are detected in the annealed $Fe_{83}Ga_{17}$ and $(Fe_{83}Ga_{17})_{98}Cr_2$ wires, respectively. The Wiedemann twist and its dependences on magnetostriction of $Fe_{83}Ga_{17}$ and $(Fe_{83}Ga_{17})_{98}Cr_2$ wires suggest that the maximum Wiedemann twist increases with magnetostriction increasing. Magnetostriction is an important factor that affects the Wiedemann effect of alloy wire, but the relationship between magnetostriction and the Wiedemann effect is a complex function rather than a simple function. It is difficult to forecast the degree of the Wiedemann effect only by magnetostrictive values, and other factors, such as permeability and elastic modulus.

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