

Heat treatment effects on sensitivity and hysteresis loops of magnetoelastic torque transducers

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Recent experiments have indicated that a torque transducer can be constructed based on local bands of naturally stabilized remanent circumferential magnetization within a hollow steel shaft. A strong coercive force along with the crystalline anisotropy combine to stabilize the circumferential magnetization of the sensing area of the shaft. A torqued shaft has its magnetic axis tilted into a helical orientation, which generates an axial field signal linearly proportional to the applied torque that can be sensed externally to the shaft. Our research has shown that the transducer function can be improved by appropriate sequential heat treatments in a helium atmosphere. Subsequent to all heat treatment steps, the test shafts were measured to determine the changes in axial and circumferential magnetic hysteresis properties and to track the development of the magnetic sensing area to applied torque (sensitivity). Although little change was produced in the originally narrow axial hysteresis loops, a 10%–20% decrease was observed in both axial coercive force and remanent magnetization, and correspondingly, a 50% increase was observed in sensitivity, accompanied by a higher linear saturation limit. Additionally, the heat treatment cycle significantly widened the originally broad circumferential hysteresis loops, resulting in a substantial increase in circumferential coercive force, which improves the stability of the sensory region. © 2000 American Institute of Physics. [S0021-8979(00)71008-5]

I. INTRODUCTION

In most magnetoelastic torque transducers previously described in the literature,^{1,2} a thin wall ring on a torqued shaft serves as the field generating element as the applied torque induces the tilting of an originally circumferential remanent magnetization in the ring. More recently, a new and simpler construction for a torque transducer has been discovered³ whereby local bands of naturally stabilized remanent circumferential magnetization are established within a hollow steel shaft which can itself be placed under torque. Not only does the ringless configuration reduce the complexity of the transducer itself, but it also extends the measurable range of torque to the strength limit of the shaft material rather than being limited by any slippage at the interface of the ring on the shaft.³

Central to the performance of such a torque transducer is the uniqueness and stability of the circumferential alignment of magnetic domains. Whereas this stability was provided by tensile “hoop” stress in previous ring-type sensors,^{2,4} in the present embodiment there is a primary dependence on a large circumferential coercive force, along with the crystalline anisotropy, in the material of the shaft itself. The major effect of the crystalline anisotropy is to cause the majority of domains to be uniformly distributed within a 55° cone centered around the circumferential direction in the absence of any external stress.³ This large coercive force combined with the closed circumferential configuration then preserves the integrity of the magnetically conditioned sensory region of the shaft that serves as the torque transducer. While the coercive force is a single-valued function of the chemical, metallurgi-

cal, structural, and geometric properties of a sample,⁵ a method of enhancing the circumferential coercive force through a series of heat treatments in one of the major alloys used for the ringless transducers is described. This is found to contribute not only to the stability of the transducer, but also to improved performance and sensitivity to applied torque.

II. EXPERIMENT

Results obtained with three identical 22.2 mm outside diameter and 76.2 mm long shafts with 2.5-mm-thick walls of a single composition (type 300M alloy steel—with percent by weight—Ni 1.82, Cr 0.82, Mn 0.75, C 0.43, Mo 0.40, Si 0.33, Cu 0.07, V 0.069, Al 0.06, Co 0.014, Sn 0.007, P 0.006, Ti 0.003, S 0.001, and bal Fe) are reported here. All three shafts were submitted to an identical but separate four-step heat-treatment process in order to demonstrate consistency of our results. The first step consisted of a 925 °C. anneal in an inert (helium) atmosphere. Second, for the hardening stage, the samples were heated to 875 °C. in the inert atmosphere for 1 h and then rapidly quenched in an oil bath to 80 °C. The third and fourth steps were identical and consisted of a tempering of the shafts at 300 °C in an air atmosphere for 5 h in each case followed by a slow cooling in air to room temperature.

Subsequent to each step of the heat treatment, each test shaft was measured to determine the changes in the magnetic hysteresis properties and the sensitivity of the shaft to applied torque. Hysteresis ($B-H$) measurements were taken by winding primary and secondary coils about the shafts in both the axial and circumferential directions and conducting the analysis using 60 Hz ac at currents up to 15 A. The shaft sensitivity measurement was conducted by circumferentially

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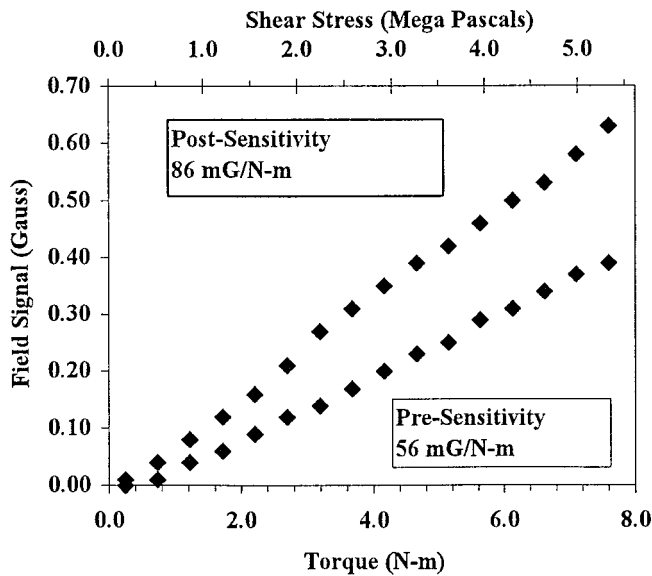


FIG. 1. Transducer field signal response is shown as a function of applied torque load and corresponding torsional shearing stress. Note the increase in sensitivity following heat treatment.

magnetizing a small segment of the shaft to serve as a sensory region and applying a torque load to one end of the shaft, thus applying a torsional shearing stress across the length of the shaft. Appropriate field sensing elements were then placed over the sensory region of the shaft to detect the axial field signal generated as the application of torque tilted the original circumferential magnetization. Each torque load test was performed to the limits of the linear field response to applied torque in either direction.

III. RESULTS AND DISCUSSION

In Fig. 1 is shown a comparison of the results of the shaft sensitivity measurements prior to and subsequent to the four-step heat-treatment procedure. The transducer field signal, which was found to be consistent in either torque direction and to reliably return to the zero torque value, was plotted against the applied torque load up to 8 N m. On the secondary *x* axis are shown the resulting values of applied torsional shear stress up to 5.6 MPa, calculated from the torque values. The field response to applied torque became nonlinear beyond 7 N m in the pretreatment case, and beyond about 9 N m in the post-treatment case, indicating a slight increase in the sensor’s linear saturation limit with heat treatment. The sensitivity, determined by an average of linear least square fits to the linear portion of the data sets, was found to dramatically increase from 56 to 86 mG/N m subsequent to the entire heat-treatment procedure, which is a definite enhancement of transducer signal and performance.

In Table I is shown a summary of the results of hysteresis measurements in the axial and circumferential directions prior to and subsequent to each step of the four-step heat-treatment procedure. In each case the values of the coercive force (H_c —the *H*-axis intercept in oersteds) and remanent magnetization (the *B*-axis intercept in Gauss) are tabulated. Figures 2 and 3 are samples of the actual hysteresis plots in the axial and circumferential directions, respectively, ob-

TABLE I. The effects of heat treatment on coercive force values and remanent magnetization in the axial and circumferential directions.

	Preheat treatment	After step 1	After step 2	After step 3	After step 4
Axial coercive force (G)	30	35	40	30	27
Axial remanent magnetization (Oe)	850	550	800	600	650
Circumferential coercive force (G)	33	40	46	38	38
Circumferential remanent (Oe)	12 300	8000	9300	11 000	11 500

tained from one of the shafts (and are typical of all three shafts) prior to the first step and subsequent to the fourth and final step of the heat treatment. All of the hysteresis loops underwent appropriate background corrections via differential comparison with data obtained in a similar manner from a paramagnetic aluminum ring. The circumferential loops shown in Fig. 3 have clearly reached full saturation. Although our available current did not allow the axial loops shown in Fig. 2 to entirely saturate, the effect on remanence and coercivity is minimal as these values were observed to undergo only negligible change in the upper regions of applied field. Little change was observed due to heat treatment from the originally narrow axial hysteresis loop for the shaft.

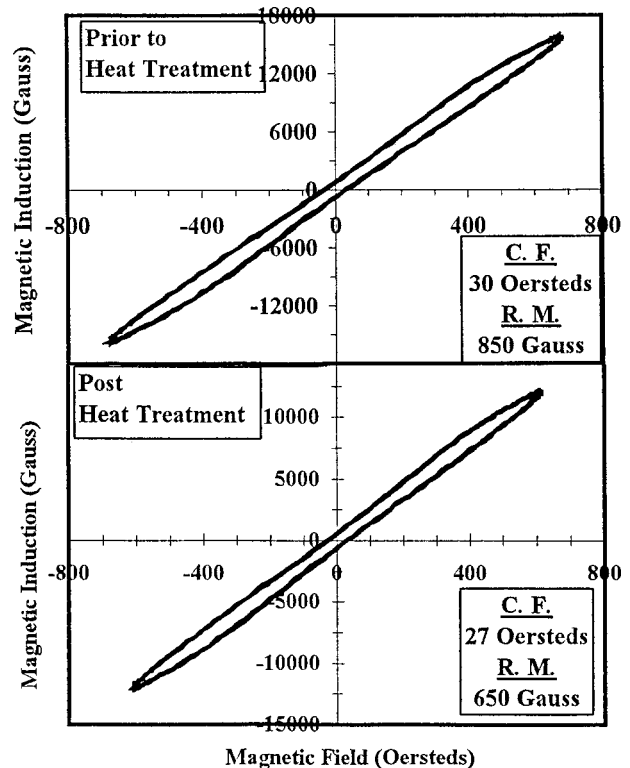


FIG. 2. A plot of the axial hysteresis (*B*–*H*) loops prior and subsequent to the heat treatment, showing a slight decrease in axial coercivity and remanence, resulting in improved transducer sensitivity.

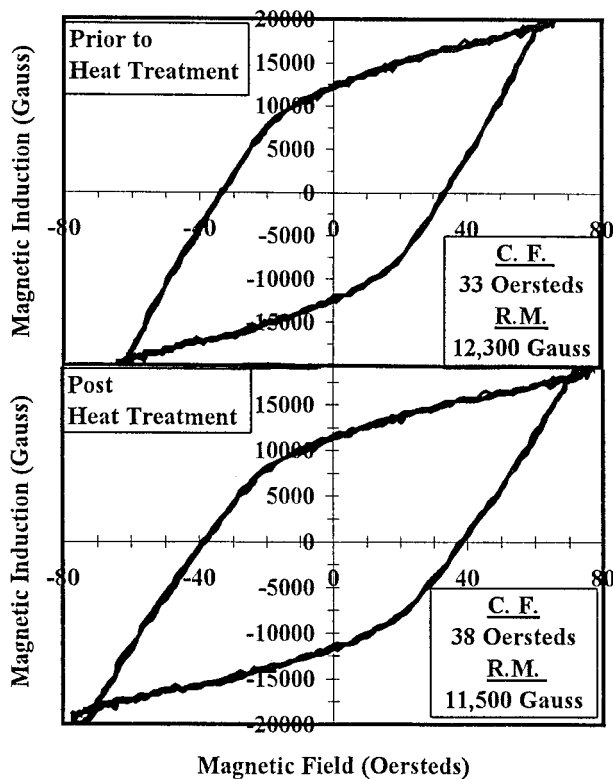


FIG. 3. A plot of the circumferential hysteresis (B - H) loops prior and subsequent to the heat treatment, showing an increase in circumferential coercive force, resulting in improved transducer stability.

However, if a comparison is made of the axial coercive force and remanent magnetization values from Table I prior to heat treatment and after the final heat treatment, a 10%–20% decrease can be noted. The enhanced transducer sensitivity previously noted appears to be dependent on the ability of applied torque to tilt the originally circumferential orientation of the magnetization in the sensory area of the shaft and produce an axial field signal, and can be directly linked with this overall decrease in the axial hysteresis parameters.

The circumferential hysteresis loop subsequent to the entire heat treatment (Fig. 3) significantly broadened from its original shape prior to any heat treatment, resulting in an overall increase from 33 to 38 Oe in the circumferential coercive force values (see Table I). As cited in the introduction, a large circumferential coercive force is necessary to effectively stabilize the magnetization of the sensory region; thus, our overall heat treatment successfully improved the transducer's stability as well as enhancing its sensitivity. It can also be noted from the circumferential values for remanent magnetization in Table I that the complete heat treatment resulted in almost no decrease in the retentivity for the circumferential magnetization of the sensory region of the shaft.

A closer examination (Table I) of the hysteresis measurements conducted intermediate to the separate heat treatment steps can provide further insight into possible structural and magnetic property changes within the samples. The first step of the heat treatment, which is the high temperature

(925 °C) anneal above the Curie temperature, is designed to eliminate the previous magnetic history of the sample and accomplish the conversion from a soft pearlitic structure to a solid austenitic structure.⁶ After slow cooling, the material should exhibit its minimum magnetic "softness" at this point, which is in agreement with the smallest values of remanent magnetization, both axially and circumferentially. The second step is designed to magnetically "harden" the sample by rapid quenching from 875 °C, accompanied by the austenite to martensite transformation⁷ and a corresponding decrease in grain size.⁷ This finer grain structure is most likely what results in the highest values of the coercive force in both the axial and circumferential directions following this step.⁸ However, the tempering process in the third and fourth steps, despite a slight decrease in coercivity, is essential to prevent the sensor from being too brittle for most applications.¹

The physical property changes which accompany the various heat treatments can be successfully modeled in two dimensions (circumferential and axial) through considerations of the total energy per unit volume due to crystalline anisotropy, externally applied stress, and externally applied magnetic field. This can be expressed as^{8,9}

$$E_{\text{total}} = K \sin^2(\Psi - \theta) + \frac{3}{2} \lambda \sigma_e \sin^2(\theta_T - \theta) - HH_k \cos \theta,$$

where K is the uniaxial anisotropy material constant, Ψ is the angle between the easy axis and circumferential direction, θ is the angle between magnetic moment and circumferential direction, θ_T is the angle of twist (when shaft is under applied torque), λ is the magnetostriction material constant, and σ_e is the magnitude of applied torsional shear stress. This free energy will be minimized at different values of θ depending on the values of K , λ , and H_k for a particular material. The larger sensitivity values observed in the heat-treated material for a given applied stress correspond to larger shifts in θ to achieve an energy minimum.¹⁰ Larger coercive forces give rise to a deeper energy minimum, thereby increasing sensor integrity.

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