The Effect of Short Range Order on the Thermal Output and Gage Factor of Ni_3FeCr Strain Gages

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Abstract. The ability of alloy 70Ni-27.5Fe-2.5Cr to form an ordered crystalline structure upon application of elevated temperature, and the resulting effects on a variety of physical properties such as magnetism, strength, electrical resistance, and specific heat are well known. This paper demonstrates that strain gages made of 70Ni-27.5Fe-2.5Cr foil with an ordered crystalline structure have both high gage factors and high thermal outputs. The thermal output for strain gages made of 70Ni-27.5Fe-2.5Cr foil is demonstrated to be about 763 ppm/ºF. The gage factor is nonlinear ranging in magnitude from about 5.2 to 3.0 for applied strains of 300 and 1300 με, respectively. The magnitude of gage factor and thermal output correspond with transformation of the crystalline structure from a state of disorder to a state of order. Practical application for 70Ni-27.5Fe-2.5Cr strain gages is demonstrated by dead-weight loading of shear-beam load cells at low applied strain levels to minimize the effect of nonlinear gage factor; and Wheatstone bridge cancellation of high thermal output.

Introduction

Crystalline order in Ni_3Fe binary and several Ni_3Fe ternary alloys has been reported extensively in the literature, primarily on two types of topics: the effect of crystalline order on material property; and the method by which crystalline order is detected. Material properties have included hardness and work hardening [1], elastic constants and strength [2], thermal conductivity, electrical resistivity and Seebeck coefficient [3], specific heat [4], and magnetic permeability [5]. The material property may actually be quite sensitive to crystalline order such as the case of specific heat appearing to be more sensitive than Mossbauer spectroscopy in detecting crystalline order [4]. Regarding the properties of thermal output and gage factor in metal foil strain gages manufactured with Ni_3Fe ternary alloys no prior research relating these to crystalline order was found. Detection of crystalline order has typically been by indirect measurement, most notably electrical resistivity. As such, the bonded electrical resistance strain gage may be ideally suited for detection of crystalline order since thermal output and gage factor involve change in electrical resistivity with the former being from change in temperature and the latter being from change in applied strain. In this paper we evaluate alloy 70Ni-27.5Fe-2.5Cr for application in metal foil strain gages with regard to temperature sensitivity (thermal output) and strain sensitivity (gage factor). These two properties are fundamental to experimental strain measurement as the former usually represents an extraneous input and must be corrected or minimized to insure accuracy.

Experimental Methods. The experimental methods used in this study are described in the following sections. Noteworthy is the attention given to the high temperature sensitivity of the conductor materials and the effort given to reduce the effect on the measurement of thermal output and gage factor.

Alloy Selection. The Ni-Fe binary phase diagram is provided in Figure 1 [7]. Alloy 70Ni-27.5Fe-2.5Cr resides in the nickel-rich portion of the binary phase diagram. At temperatures below about 932 ºF (500 ºC) there is an area designated as $L1_2$ which is characterized by single phase, face-centered-cubic crystalline structure. Upon application of elevated temperature the nickel and iron atoms reposition themselves as shown in Figure 2 with the nickel atoms preferentially occupying the face positions and the iron atoms the corner positions of the face-centered-cubic crystalline structure [8]. Also shown in the Ni-Fe binary phase diagram is alloy 36Ni-57Fe-7Cr (Isoelastic) which is commercially available in metal foil strain gages used for both stress analysis applications like design validation and failure studies; and for precision transducers sensing weight, pressure, displacement, etc. [6]. Isoelastic material possesses high gage factor and high thermal output…….

Strain Gage Construction. The strain gages used in this research were constructed using identical manufacturing processes. The conductive element was rolled 70Ni-27.5Fe-2.5Cr metal foil. The metal processing consisted of vacuum induction melting (VIM), casting into cylindrical molds, forging into rectangular cross sections, hot rolling to a thickness of about 0.125 in (3 mm), and cold rolling to a thickness of about 0.0002 in (5 µm). The cold rolling process included periods of annealing the metal generally after thickness reductions of 50 to 90 percent. The final process annealing thickness was selected to impart about 90 percent thickness reduction in the finished foil, e.g. foil with a finished thickness of 0.0002 in received a final process anneal at 0.002 in [9]…..

Measurement of Thermal Output. Thermal output was measured by bonding a strain gage to a specimen and measuring the resistance change as the specimen was allowed to freely expand or contract as the temperature was changed and without application of external mechanical loading. For each test, 20 single-element linear strain gages with 0.125 in (3 mm) gage length were bonded to aluminum specimens about 1/8 in x 1 in x 1 in (3 mm x 25 mm x 25 mm) in size with epoxy adhesive……...

Measurement of Gage Factor. The gage factor was measured by bonding a strain gage to a specimen and measuring the resistance change as the specimen was loaded to prescribed levels of surface strain. Each gage factor test used two types of test fixtures and specimens to impose different levels of applied strain……..

Dead-Weight Loading of Shear-Beam Load Cell. Shear strain gages made of 70Ni-27.5Fe-2.5Cr metal foil were bonded to four shear-beam load cells made of steel. The load cells were loaded in 50 lb (223 N) increments from 0 to 250 lb (1114 N) at room temperature, 0 ºF (-18 ºC), and 150 ºF (66 ºC)……..

Results. The differences in thermal output and gage factor between strain gages manufactured with 70Ni-27.5Fe-2.5Cr metal foil in as-rolled and annealed condition are interesting, particularly since the material develops an ordered crystalline structure when annealed at temperatures up to about 900 ºF (482 ºC). There was a clearly observable difference in thermal output and gage factor for strain gages made of 70Ni-27.5Fe-2.5Cr foil in as-rolled condition and annealed condition. Foil in the as-rolled condition corresponded to a state of disorder in the crystalline structure, whereas foil in the annealed condition corresponded to a state of ordered crystalline structure. Also, the high temperature sensitivity (thermal output) appeared to be largely overcome by using a full Wheatstone bridge circuit to cancel the thermal output component in adjacent arms. Furthermore, by limiting the magnitude of the applied strain, the nonlinear gage factor of 70Ni-27.5Fe-2.5Cr foil appeared to be manageable.

The gage factor results appear to indicate a breakdown of the ordered condition upon application of strain. It is necessary to distinguish between long range and short range order in the way resistivity changes during ordering. Long range order results in a decrease in resistivity as irregularities in the crystalline structure disappear during transition from disorder to order. Short range order produces the opposite effect with resistivity increasing due to reflection of conduction electrons encountering short range ordering domains [12, 13]. Alloying with chromium has a significant effect in the atomic structure of Ni_3Fe. The resistivity of Ni_3Fe plus 3% Cr increases after ordering which is indicative of a short range ordering process. Furthermore, and significant to this research, it has been reported there is a reduction in electrical resistance as a result of deformation in alloys in which short range ordering is linked with an initial increase in resistivity such as Ni_3Fe plus 3% Cr [14].

Conclusions

Alloy 70Ni-27.5Fe-2.5Cr exhibited a high and non-linear fractional resistance change (ΔR/R) in response to applied strain (gage factor). This was explained by varying instability of the ordered $L1_2$ crystalline structure to applied strain. The material also exhibited high thermal output reduced somewhat by post-rolling annealing process due to crystalline ordering. Finally, the nonlinear gage factor and high thermal output characteristics could be managed to some extent by limiting the magnitude of the applied strain and by using Wheatstone bridge cancellation of like strains in adjacent arms (thermal output).

References

[1] A.E. Vidoz, D.P. Lazarevic and R.W. Cahn: *Strain Ageing of Ordering Alloys with Special Reference to the Nickel-Iron System,* Act. Met., Vol. 11 (1963), p. 17-33.

[2] N.S. Stoloff and R.G. Davies: *The Mechanical Properties of Ordered Alloys*, Prog. in Mat. Sci., Vol. 13 (1968), p 1-84.

[3] J.P. Moore, T.G. Kollie, R.S. Graves and D.L. McElroy: *Thermal Transport Properties of Ordered and Disordered Ni_3Fe,* Appl. Phys., Vol. 42 (1971), p. 3114-3120.

[4] K.G. Binnatov, A.A. Katsnelson and Y.L. Rodionov: *Atomic Ordering in Ni-Fe-Cr Solid Solutions,* Sov. Phys. J., Vol. 18 (1975), p. 397-398.

[5] F. Pfeifer and H. Wegerle: *Kinetics of Ordering During Annealing of Permalloys with High Permeability*, J. Mag. and Mag. Mat., Vol. 38 (1983), p. 287-293.

[6] T.P. Kieffer and Y. Zhu: *Thermal Output Observations from Fe-Ni-Cr Metal Foil Strain Gages,* Adv. of Opt. Meth. in Exp. Mech., Vol. 3 (2013), p. 379-387.

[7] P. Franke and H.J. Seifert: *The Influence of Magnetic and Chemical Ordering on the Phase Diagram of Cr-Fe-Ni,* Comp. Coup. Ph. Diag. and Therm., Vol. 35 (2011), p. 148-154.

[8] D.E. Laughlin: *Long-Range Order in Alloys,* Ency. of Mat. Sci. and Eng., Vol. 1 (1988), p. 263-268.

[9] M. Robinson: *Strain Gage Materials Processing, Metallurgy, and Manufacture,* Exp. Tech., Vol. 30 (2006), p. 42-46.

[10] C.A. Sciammarella and F.M. Sciammarella: *Experimental Mechanics of Solids*, Wiley, Chichester West Sussex (2012).

[11] W.M. Murray and W.R. Miller: *The Bonded Electrical Resistance Strain Gage*, Oxford University Press, New York (1992).

[12] H. Lipson: *Order-Disorder Changes in Alloys,* Prog. in Met. Phys., Vol. 2 (1950), p. 1-52.

[13] P.L. Rossiter: *The Electrical Resistivity of Metals and Alloys*, Cambridge University Press, Cambridge Cambridgeshire (1987).

[14] N.A. Koneva, A.D. Korotaev and M.A. Bolshanina: *Ordering Processes and Activation Energy in Ni_3Fe-Based Ternary Alloys,* Sov. Phys. J., Vol. 9 (1966), p. 94-99.