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Thick-film weldable strain gauges

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Abstract

In this work the development of a new thick-film strain gauge specially designed for spot welding to metallic structures and components is presented. The weldable strain gauge consists of a thick-film resistor screen-printed on 0.125 mm stainless-steel and titanium carriers. Typical values have been found for the tensile strain: $GF_L = 8.7$, $GF_T = 5.2$, hysteresis 0.3% FS and linearity 0.1% FS for stainless-steel carrier.

Keywords: Strain gauges; Thick-film sensors

1. Introduction

The reversible piezoresistive effect has been widely applied to the measurement of strain. One of the most important properties of resistive thick films is their piezoresistivity. Thick-film strain gauges (TFSGs) have allowed the development of primary strain sensors or secondary sensors for weight, pressure, acceleration, etc. [1].

TFSGs screen-printed and sintered onto different substrates, mainly alumina and stainless steel, have been investigated [2]. In the usual arrangement, the thick-film resistor screen-printed onto the substrate is part of the sensor body.

Recently, weldable metal-foil strain gauges have been developed. These strain gauges are ideal for use on large structures or for applications where test or environmental conditions preclude clamping and curing an adhesively bonded gauge installation [3]. However, this kind of strain gauge presents low sensitivity, reflected in a gauge factor not better than two.

It is well known that TFSGs usually show gauge factors as high as 15 or better. This property suggests that such gauges may present an improvement in the weldable strain-gauge technology. In this work the development of new thick-film weldable strain gauges (TFWSGs) specially designed for spot welding to metallic structures and components is presented. Relevant parameters such as the gauge factor, transverse sensitivity and thermal output have been studied and the experimental results are discussed.

2. Preparation of the samples

Samples were fabricated on annealed thin foils (0.125 mm) of type 316 stainless steel (Fe/Cr18/Ni8/Mo3) or titanium (purity 99.6%).

Du Pont Pd/Ag-based conductor ink 6120 and Heraeus series HS8000 resistor ink were used. Heraeus dielectric inks (IP211 and IP9117) were applied to both kinds of substrates as an insulating medium. Before deposition of the dielectric layer, the surface of the steel and titanium carriers was roughened with appropriate abrasive paper.

In order to obtain the TFWSG, the following steps were performed with standard screen-printing, drying and firing cycles:

(i) one layer of IP 211, fired at 950 °C for 10 min;
(ii) one layer of IP 9117, fired at 930 °C for 10 min;
(iii) one layer of DP 6120, fired at 870 °C for 10 min;
(iv) one layer of HS R8140, fired at 850 °C for 10 min.

The size of the thick-film resistor was 1.6 mm × 1.6 mm and that of the carrier was 15 mm × 20 mm. Fig. 1 shows an outline of the TFWSG. Sheet-type test specimens (ASTM E8-90) for tension tests and cantilever beams (230 mm × 21 mm × 1.5 mm) were machined in SAE 1050 steel.

In order to ensure efficient welding, the surface finish of the specimens followed the next steps:

(i) degrease the specimen with a toluene solvent;
(ii) hand grind, abrade with silicon carbide paper;

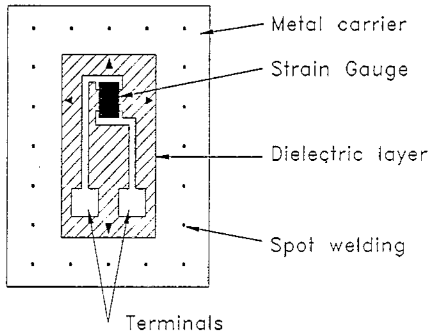

Fig. 1. Layout of a TFWSG. The size of the thick-film resistor is 1.6 mm×1.6 mm.

(iii) thoroughly wash with toluene solvent to remove all residue.

The metal carrier was pulled from the specimen surface and single spot-welds adjacent to each side of the gauge were done.

An electrical resistance direct spot welder with a Cu–Cr electrode was used. For the titanium carrier the power necessary to achieve the optimal weld was 2 kV A with a welding time of 80 ms. For stainless steel the power was 1.5 kV A and the welding time was 120 ms.

3. Experimental set-up

For gauge-factor measurements a cantilever beam was employed. A conventional metal-foil strain gauge was bonded to the test specimen to determine its modulus of elasticity, which in turn was used to calculate the strain of the TFWSG. The strain was measured with a strain indicator (P-3500 Measurements Group – Instruments Division) and the resistance of the TFWSG was determined with a Fluke 8842A 5±1/2 digital multimeter. The tensile tests were performed with an Instron 5Tn.

Temperature tests were carried out in a Heraeus HC4020 climatic chamber in the range 20–100 °C (293–373 K).

4. Results

Fig. 2 shows a plot of the relative resistance change (dR/R) as a function of tensile strains applied parallel and perpendicular to the current direction in a TFWSG. A linear response is observed, the estimated linearity being better than 0.1% of full-scale out-put. The longitudinal gauge factor GF_L was 8.7 and the transverse gauge factor GF_T was 5.2. These results were observed in both stainless-steel and titanium carriers. Lower results were obtained for the uniaxial tensile stress ($GF_L \approx 5$). The effective gauge factor of the welded strain gauge (after welding to the test member) is lower than that of the TFWSG. The reduction in the gauge factor depends on the cross-sectional properties of the specimen and on the mode of loading.

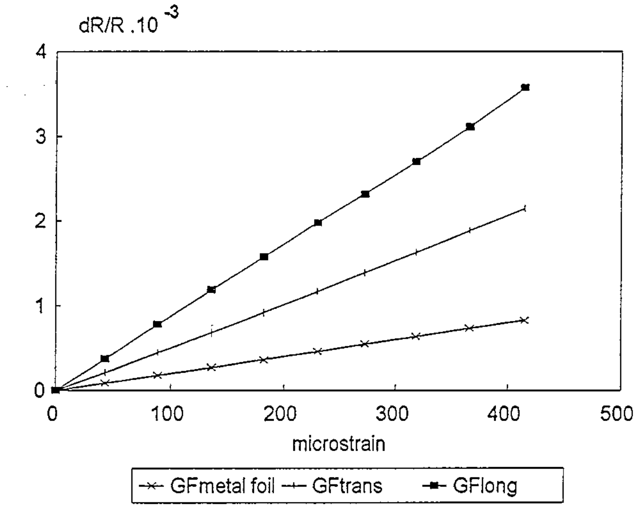

Fig. 2. Relative change of resistance as a function of longitudinal and transversal strains.

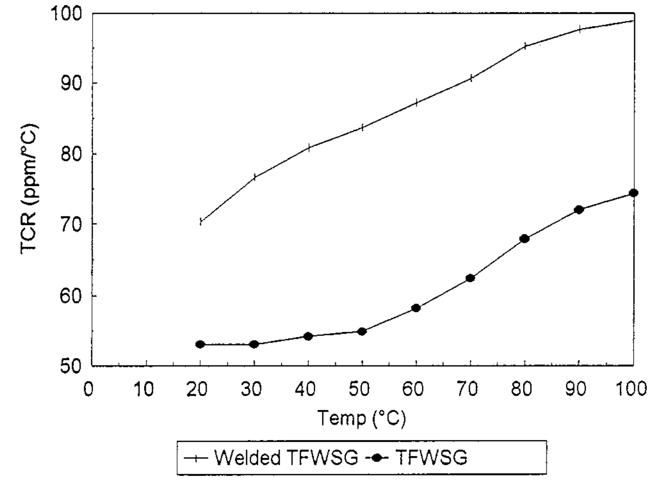

Fig. 3. *TCR* as a function of temperature for a TFWSG with stainless-steel carrier.

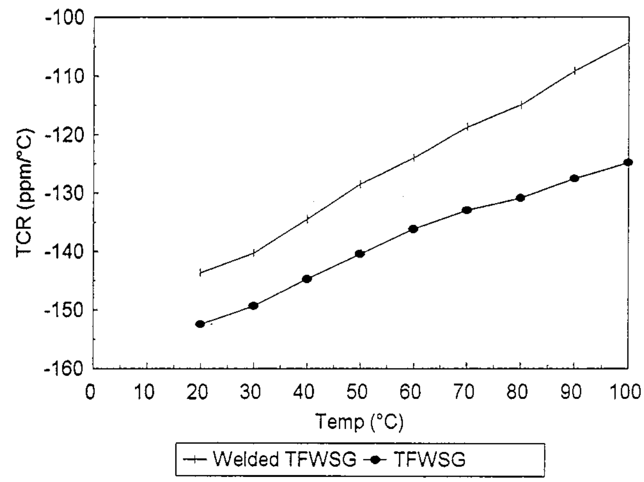

Fig. 4. *TCR* as a function of temperature for a TFWSG with titanium carrier.

The TFWSGs exhibit a slight hysteresis effect. This was calculated by analysing the maximum measured

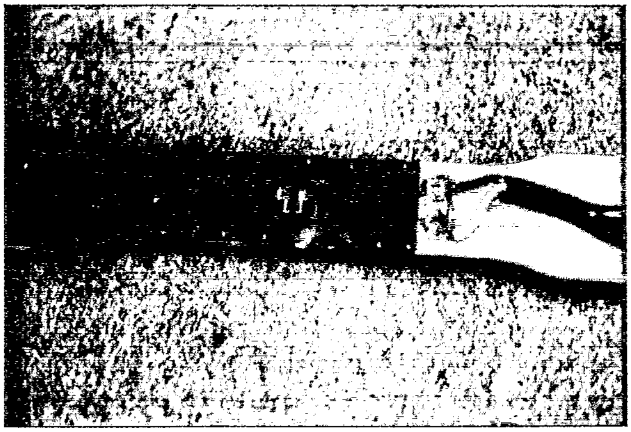

Fig. 5. TFWSG welded to sheet-type test specimen.

deviation between upscale-going and downscale-going indications of the applied strain. Typical values have been found to be of the order of 0.3% of full scale output.

The temperature dependence of the TFWSG was studied. For a stainless-steel carrier the resistance increases with temperature. This characteristic is caused by the temperature coefficient of expansion (*TCE*) mismatch between the resistive film and the substrate, producing a thermal tensile strain in the resistor. Fig. 3 presents the temperature coefficient of resistance (*TCR*) of a TFWSG on stainless steel and a TFWSG welded to a sheet-type specimen (SAE 1050 steel). This indicates that the 'specimen effect' plays an important role in the electrical characteristics of the TFWSG. Thus, it is necessary to consider the TFWSG–specimen system as a whole, without limiting the analysis to the TFWSG alone.

For the titanium carrier the resistance decreases on increasing the temperature, giving a negative *TCR* (Fig. 4). This is due to the titanium *TCE*, which is lower than that of the dielectric, causing a thermal compression strain. For this kind of sample, when a TFWSG is welded to the specimen, a thermal tension–compression compensation is observed.

Previous investigations showed how the difference in *TCR* between resistors on different substrates could be calculated [4]. The following expression was found:

$$TCR_1 - TCR_2 = \frac{2(TCE_1 - TCE_2)(GF_L - 1 - \sigma)}{1 - \sigma} \quad (1)$$

In the present case the following values hold: $TCE_{s.steel} = 17$ ppm °C^{-1}, $TCE_{Ti} = 8.9$ ppm °C^{-1}, $GF_L = 8.7$, σ (Poisson's ratio) = 0.3. Introducing these values in Eq. (1), a *TCR* difference of 171 ppm °C^{-1} between the TFWSG on stainless steel and than on titanium is obtained. The result so calculated matches very closely to those obtained from Figs. 3 and 4.

Further research is currently under way in which the strain gauge is bonded rather than welded to the specimen. Preliminary results have shown a very good *GF*, which opens new technological applications for this type of thick-film strain gauge.

A photograph of a thick-film strain gauge welded to a sheet-type test specimen is shown in Fig. 5.

5. Conclusions

Weldable strain gauges consisting of a thick-film resistor screen-printed to thin (0.125 mm) stainless-steel and titanium carriers have been developed. The good strain sensitivity found suggests they are ideal for use on large structures or for outdoor installations in inclement weather.

Typical values for tensile strain are $GF_L = 8.7$, $GF_T = 5.2$, hysteresis 0.3% FS and linearity 0.1% for a stainless-steel carrier.

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