Thick Film Heaters Made From Dielectric Tape Bonded Stainless Steel Substrates

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Abstract

Low temperature tape and thick film materials for use on stainless steel substrates in domestic appliance applications were developed. The insulating glass-ceramic coatings were applied to stainless steel bases using screen printing and tape processing. Heaters and heat regulators using PTC and other 850íC firing thick film materials were designed and built. Properties of the coated metal substrates and the heater devices are presented including initial and aged data demonstrating properties and reliability in low profile heater applications.

Key words: Heaters, Coated stainless steel, Thick film, Tape, Dielectric.

Introduction

Ever growing pressure for low cost, small size and high performance in hostile environments has led to the use of a wide variety of substrates for electronic circuitry. Insulated metals have attracted attention because of their mechanical strength, good thermal properties, large size/complex shape capability, shielding character and low cost potential. Aluminum core (IMS) and steel core (porcelain enamel), in particular, have been successfully used in a number of different applications. These include under the hood electronics where temperature and mechanical stress do not permit conventional packaging, SMT and hybrid circuit boards and as bases for low profile heaters [1-6]. They have also been used as part of the housing to reduce size and cost and in some applications to provide EMI shielding [4,7,8]. In another instance the ferromagnetic character of the core was used to advantage in making a compact direct drive motor [8].

Widespread usage of the IMS and porcelain enamel materials, however, has been limited by cost, use temperature restrictions, wet chemical processing requirements and complicated fabrication processes [1,9]. This paper discusses insulated metal substrates made from high temperature, corrosion resistant stainless steel and refractory migration resistant dielectric coatings designed to overcome these limitations.

Procedure

Metal preparation

High chromium content ferritic stainless steels were chosen for the metal base. These materials provide good corrosion resistance, adherent oxide films, high temperature firing capability and low TCE values (as compared to the austenitic forms). The data in this paper were taken from samples prepared from 430S17 stainless steel (selected because of its ready availability) but good results have also been obtained with German Standard No.1.4762 which contains a slightly higher chromium content and about one percent aluminum.

Metal preparation starts with removal of any dirt, oil or grease. The surface is then roughened and oxidized to promote dielectric wetting and adherence. Air abrasion and/or abrasive belt were used to achieve the desired roughening while the oxidation was done in belt furnaces at peak temperatures between 850º and 930ºC on 45 minute cycles. Test parts were made using 50 mm x 50 mm and 90 mm diameter 430S17 metal bases which were 1.6 mm thick.

Coating application

Dielectric coatings have been developed with a wide range of dielectric constants (K-values) and compatibility with a number of different substrates [10,11]. This paper will confine itself primarily to screen printable pastes and low firing dielectric tape materials which provide a K value of about 10 and are compatible with stainless steel substrates.

Screen printing

This application technique consisted of depositing 3 layers of dielectric paste onto metal plates using a 165 mesh screen and separately firing the layers in a standard profile 850ºC belt furnace.

Tape

Flexible sheets of low temperature tape, 125 to 175 microns thick, were laminated to the prepared metal bases using pressures of 250 to 500 psi at 75ºC. After the lamination of each tape layer the parts were fired in a standard thick film belt furnace with a peak temperature of 850ºC. The thicknesses of one and two fired dielectric tape layers were typically 90µm and 160µm respectively.

Results

Coated metal substrate properties

Thick film

Prepared 430S17 metal bases were coated with D-4913-A fired on at 850ºC. The D-4913-A, a thick film multilayer dielectric, was selected for its high initial insulation resistance and low metal ion solubility achieved through the use of lead free and alkali free dielectric materials and a high Tg vitreous phase.

Table 1 gives properties of the D-4913-A coated metal substrates. An array of 16 mm x 6 mm pads of 9695 Pd/Ag conductor was printed and fired on top of the dielectric coatings to allow measurements of insulation resistance (IR) and breakdown voltage (Vbd) to be made. The Pd/Ag conductor was fired at a peak temperature of 850ºC (45 min. cycle). The three layer dielectric coated substrates had IR of $>10^{12}\Omega$ at 25ºC whilst the Vbd was >2500 Vac. Examples were subjected to 10 refire cycles at 850ºC, and whilst the IR at 25ºC remained at $>10^{12}\Omega$, the 300ºC figure was reduced to $10^{11}\Omega$. It must be noted that the 2500 Vac in the Vbd tests was a limiting factor due to arcing between adjacent conductor pads and not breakdown of the dielectric barrier to the steel. British Standard 3456 requires a minimum breakdown voltage value of 1250 Vac for Class I appliances employing heaters on insulated steel substrates.

Table 1. Properties of 430S17 Substrate Insulated with Screen Printed D-4913-A Dielectric.

Dielectric	Layers	Thickness (µm)	No. of Refires	IR (500V)* 25°C	IR (500V)* 300°C	Vbd (ac)
D-4913-A	3	100	0	$>10^{12}$	$>10^{12}$	>2500
	3		10	$>10^{12}$	$>10^{11}$	
**D-4913-A	3	80	0	$>10^{12}$	$>10^{12}$	>2500
	3		10	$>10^{12}$	$>10^{11}$	

* Complies with British Standard 3456 for Safety of household and similar electrical appliances.

** These data are for dielectric printed and fired onto unabraded steel.

Tape

While changes in the dielectric composition can give significant improvements in the results, properties like breakdown voltage still necessitate the use of thick coatings. Tape processing provides a method of obtaining the required coating thickness without resorting to the multiple printing/firing steps associated with thick film processing.

Properties of substrates prepared by the tape coating process are listed in Table 2. Insulation resistance and breakdown voltage of samples with one or two separately fired layers of tape on

430S17 metal bases are presented. Pieces were tested using D-41030, D-41020 (both being lead- and alkali-free tapes), and a combination of the two.

Table 2. Characteristics of Tape Coated Stainless Steel Substrates

Tape	Layers	Thickness (µm)	No. of Refires	IR (500V) 25°C	IR (500V) 300°C	Vbd (ac)
D-41030	1	90	0	$>10^{12}$	$>10^{12}$	>2500
			10	$>10^{12}$	$>10^{12}$	
D-41030/ D-41020	1 + 1	160	0	$>10^{12}$	$>10^{12}$	>2500
			10	$>10^{12}$	5×10^{10}	
D-41020	1	90	0	$>10^{12}$	$>10^{12}$	1500
			10	$>10^{12}$	$<10^{8}$	

9695 conductor pads were used on all test pieces. Both single layers and the combination had excellent IR at both 25ºC and 300ºC. IR after 10 refire cycles remained at $10^{12}\Omega$ for D-41030, but was reduced for the combination and for D-41020. Samples made from two layers of D-41020 tape on stainless steel were fired in a box furnace at 850ºC and tested at 400ºC. Initial and "after ten refire" IR values were $>10^{9}\Omega$.

Adhesion of the tape coating layers was characterized by thermal shock and drop tests. The drop test consisted of allowing the substrates to fall from 2 meters onto a concrete floor ten times and examining them for cracks. Thermal shock testing was done by immersing 700ºC furnace heated samples in water. This water shock test was repeated five times and then the parts were examined for cracking. Dye testing showed no cracking of the dielectric in either test.

Compatible thick film pastes

Conductive, dielectric and resistive thick film pastes developed for firing on Al_2O_3 substrates at 850ºC were tested on the tape coated metal substrates. In this initial evaluation phase, no attempt was made to optimize the pastes for the different chemistry and TCE of the coated metals.

Table 3 provides sheet resistivity and conductor adhesion data of silver based conductors on Al_2O_3 and tape coated stainless steel. Resistance characteristics are very similar for the two substrates but the Pd/Ag materials appear to bond better to Al_2O_3 . Solderability was excellent on both substrates as noted in the table. In addition, a number of base metal conductors are available and are being studied.

Table 4 gives key dielectric characteristics of D-4913A used as a multilayer/crossover dielectric. Properties are essentially identical on the two substrates.

Resistance value comparisons of the 3900 thick film series on Al_2O_3 and tape coated metal substrates are shown in Figure 1. In general resistance values are close with the 1MΩ/sq 3916 paste showing a somewhat lower value on the coated stainless steel. TCR values were generally under 100 ppm with a few greater values noted for some of the pastes.

Table 3. Properties of Silver Based Thick Film Conductors

Conductor (type)	ρ (mΩ/sq) Al_2O_3	ρ (mΩ/sq) D-41020/ 430S17	Pull Strength (Kg) Al_2O_3	Pull Strength (Kg) D-41020/ 430S17
9912-A (Ag)	1.6	1.6	10.1	10.0
9695 (Pd/Ag)	3.5	3.5	10.9	7.4
9633-B (Pd/Ag)	28.4	27.7	9.1	6.4

Table 4. D-4913-A Multilayer/Crossover Dielectric Properties

Substrate	Dielectric Constant @ 1 KHz	Dissipation Factor @ 1 KHz	IR @ 25°C (Ω,100V)	Vbd (V/25µ)
Al_2O_3	10.2	0.3	5×10^{12}	1140
D-41020/ 430S17	9.9	0.3	6×10^{12}	1270

Positive temperature coefficient pastes were also tested because of their advantages in heater applications for which the coated metal substrates are especially well suited. They can be used to fabricate discrete temperature sensing elements or as the heating element itself providing a current limiting feature to the heater. Table 5 gives the results indicating resistance values on the tape coated stainless steel are about double those on Al_2O_3 while TCR values retain their desired highly positive values.

Applications

The tape coated stainless steel substrates were evaluated for use in low profile heater applications in which heating elements are printed directly on a "heat distribution" plate. Thick film materials have proven to be a reliable cost effective choice for heating and heat sensing control elements in these applications [6]. Layout and geometry are important design considerations in making the devices and customized configurations are sometimes needed to achieve highly uniform temperature distributions [5]. The layout shown in Figure 2 was used for initial evaluation purposes.

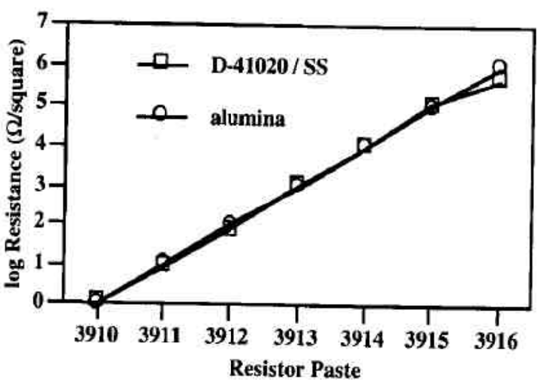


Figure 1. Comparison of Resistivity of 3900 Series Resistors on Al_2O_3 vs. D-41020 Coated Stainless Steel

Table 5. PTC Resistor Paste Properties

	Resistivity (Ω/sq)		TCR_{125} (ppm/°C)	
Resistor	Al_2O_3	D-41020/ 430S17	Al_2O_3	D-41020/ 430S17
PTC 2650-I	5.0	10.8	3006	3165
PTC 2611-I	11.0	20.6	2703	2735
PTC 2612-I	95.0	280	2320	1900

Low resistance (0.7Ω/square) 3900 series resistor paste was used for forming the meander path heating element, 9695 (Pd /Ag) for the contact pads. These materials were printed and fired on D-41030 / D-41020 composite coated stainless steel substrates at 850ºC.

Testing to date has consisted of bias humidity and heat cycling. In the bias humidity test 50 volts was applied between the stainless steel base and top surface circuitry. These voltage biased plates were put in a humidity chamber held at 85ºC and 85% relative humidity. After 500 hours of such testing no change in insulation resistance occurred.

Heat cycle testing consisted of heating the substrates to 300ºC by application of power to the part for 2 minutes, holding at 300ºC for 2 minutes and then shutting the power off for 2 minutes (which allows it to cool to about 175ºC). After more than 3500 of such cycles no short circuits, open circuits or cracks in the tape coating have been detected.

A more practical test was devised in which a heater element, as shown in Figure 2, was attached to the base of a flat bottomed stainless steel bowl using a thermally conductive silicone adhesive, Dow Corning Q1-9226. Connection was made to the Pd/Ag terminations by ultrasonically bonding 300µm aluminum wires. The two following experiments were conducted:

1. With the bowl containing 300 ml of cold water, 100 Vac was applied to the element (120W) and the temperatures of the heating element and the water were monitored (see Graph 1).

2. With a fresh charge of 300 ml of cold water, 230 Vac was applied (620W) and temperatures again monitored (Graph 1).

Graph 1 shows that with power level at 120W the heat loss from the test rig would not permit the water temperature to rise further than 75ºC, the element temperature stabilizing at 140ºC. At 620W dissipation the water reached boiling point in a relatively short time (225 seconds), with the element reaching 330ºC. These results indicate poor thermal conduction between the steel plate and the metal bowl, due to the dished shape of the bottom of the bowl. Uncertainty of the performance of the adhesive at higher temperatures prevented taking the tests further to the required power level of 2 kW typically used in self-heating water kettles.

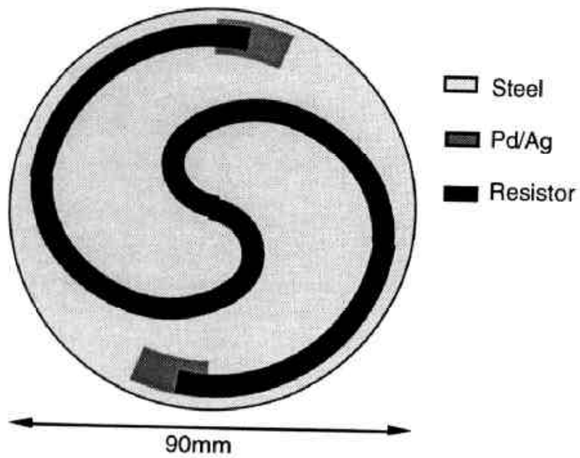
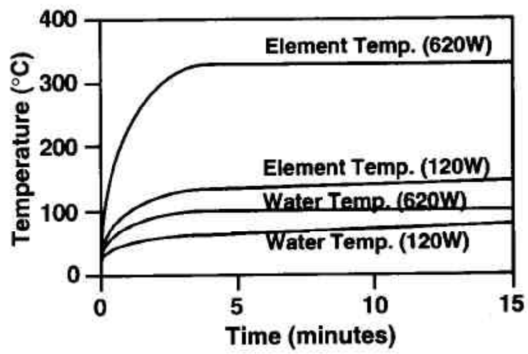


Figure 2. Heater Test Pattern



Graph 1. Performance of Water Heater

Figures 3a and 3b show thermal images of a heater element powered to 120W, at intervals of 5 seconds after switch-on. Figure 3a shows the printed side of the substrate with the shape of the resistive element clearly seen. Figure 3b shows the reverse side of the substrate, and the thermal lag and subsequent greater distribution of temperatures are apparent.

Summary & Conclusions

Insulated metal substrates consisting of glass-ceramic coating layers on high temperature corrosion resistant 430S17 stainless steel were prepared. The insulating coatings were applied using screen printing and transfer tape processing and subsequently bonded to the metal base by firing at 850ºC. Both techniques allow straight forward processing, selective coating and provide for metal base access. The transfer tape process had the advantage of lower labor cost.

Breakdown voltage values greater than 2500 volts ac were achieved with both tape and thick film coated substrates having sufficient dielectric thickness. Insulation resistance also depended on coating thickness but composition was found to be more critical for maintaining high IR's at elevated temperatures. Refractory coating compositions gave IR's over $10^{12}\Omega$ at 300ºC, retaining values generally greater than $10^{10}\Omega$ after ten refires at 850ºC as a result of their diffusion resistant chemistry.

The coatings bonded well to the 430S17 stainless steel resisting mechanical and thermal shock. No cracks were observed after five direct immersions in water from a 700ºC furnace. Likewise none were produced as a result of 10 drops from a height of 2 meters to a concrete floor.

Compatible 850ºC firing dielectric, resistive and conductive thick film pastes were found. Selected pastes were then fired on rectangular tape coated stainless steel substrates to form "heat distribution" plates. Testing of these plates showed insulation resistance remained unchanged after 500 hours of 85ºC, 85% relative humidity and 50 volt bias humidity testing. They performed well in 3500 cycles of powered element heat cycle testing showing no cracks, shorts or opens. In additional testing circular heater plates were attached to stainless steel bowls and evaluated as "water heaters". Element and water temperature were monitored versus time and thermal images taken. The results were

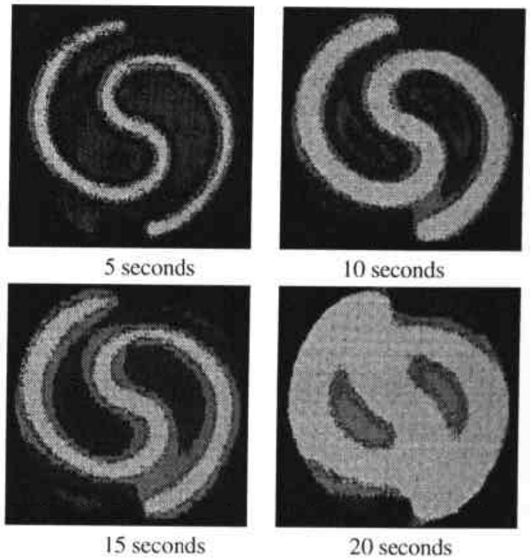


Figure 3a. Thermal Images of Printed Side of Substrate

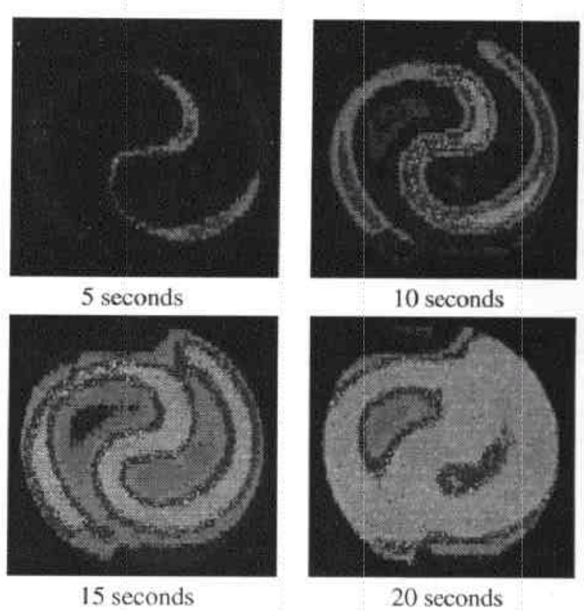


Figure 3b. Thermal Images of Reverse Side of Substrate

encouraging but indicated the importance of optimizing heat transfer between the heater plate and water container in such a design.

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