Reliability Testing on a Multilayer Chip Inductor Fabricated From a Ferrite With a 350 ºC Curie Point

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Abstract

As more electronics are used in down-hole energy exploration, under the hood automotive applications, and in other environments where temperatures exceed 200 ºC; there is a need for compact passive magnetic components that operate reliably at elevated temperatures. Most ferrites used to make multi layer ceramic inductors have Curie temperatures in the 100-200 ºC range. As temperatures rise above the Curie point ferrites lose their magnetic properties and become paramagnetic. This means that traditional multi-layer ceramic inductors suffer severe performance degradation when operated at elevated temperatures. Therefore, ferrite materials with higher Curie temperatures need to be developed to increase device performance and reliability at these high temperatures. In this work inductors were made from a low-temperature, co-fire compatible, ferrite with a Curie temperature of 350 ºC. The inductors were first subjected to a 1000 hour life test at 300 ºC during which the electrical parameters were found to change no more than 4 %. The inductance, resistance, core loss, and saturation flux density of the inductors were measured at various temperatures. Additional testing focused on the effect of temperature on the device's frequency profile and performance changes under thermal cycling and thermal shock.

Keywords: Multilayer Ceramic Inductor, Ferrite, High Temperature Inductor

Introduction

As more electronics are used in down-hole energy exploration, under the hood automotive applications, and in other environments where temperatures exceed 200 ºC; there is a need for compact passive magnetic components that operate reliably at elevated temperatures. Most ferrites used to manufacture multi-layer ceramic inductors have Curie temperatures in the range of 100-200 ºC. As temperatures rise above the Curie point ferrites lose their magnetic properties and become paramagnetic [1]. This means that traditional multi-layer ceramic inductors suffer severe performance degradation when operated at elevated temperatures. Therefore, ferrite materials with higher Curie temperatures need to be developed to increase device performance and reliability at these high temperatures. An LTCC ferrite material with a Currie temperature of 350 °C and compatible silver conductor system developed by Electro Science Labs was used in this work. While the most obvious parameters to examine when checking an inductor for performance are inductance and resistance, the properties of ferrite materials means that other parameters should be characterized as well. These properties include saturation flux, core loss, and self-resonance frequency [2]. Reliability testing at elevated temperatures should include a variety of conditions to mimic what the parts may experience in actual applications. Therefore it should include an endurance test where the part is exposed to peak operational temperatures for an extended period of time, and cycling tests where the part's temperature is cycled at a constant rate between the expected operational extremes.

Experimental Procedures

Inductance & Resistance:

All measurements were conducted on one part. A CMF 1100 furnace was programmed to ramp the temperature from 25 to 320 °C by one degree per minute and then soak at 320 °C for 30 minutes. A custom data acquisition program was set to record the inductance, quality, and resistance of the part every 30 s.

Core Loss & Saturation Flux Density:

Two parts were tested at 25, 50, 100, 150, 200, 250, and 300 °C. A Wayne Kerr magnetic analyzer was used to measure the DC resistance of the inductor and the DC bias current at which inductance decreased by 30 % from the no bias condition at that temperature. As current is related to flux density, this measurement is a proxy for direct measurements of the saturation flux. For core loss measurements the parts were excited to 100 mT using a 50 kHz sinusoidal signal generated by an Agilent 33120A Arbitrary Wave Form Generator. Real power losses in the inductor and the root-mean-square of the current (I_{RMS}) were then measured using a KinetiQ PPA2510. Core loss was then calculated by subtracting Ohmic losses in the inductor from the total power lost.

$$P_{core} = P_{total} - P_{Ohmic} = P_{total} - I_{RMS}^{2}R.$$

Frequency Profile:

One part was tested at 25, 50, 100, 150, 200, 250, and 300 °C. A HP 4194A Impedance/Gain Phase Analyzer was used to identify the self resonant frequency at each temperature. Using the self resonant frequency and inductance at different temperatures, the parasitic capacitance of the inductor at different temperature was calculated using:

$$C = ((2\pi f)^{2}L)^{-1}.$$

Endurance Test:

Five parts were soldered to York Wire & Cable 20 gauge MG mica insulated wire using 95 % Cd, 5 % Ag solder. The parts were placed in the furnace such that they were suspended near the thermocouple attached to the data acquisition unit. The other end of the high-temperature wire was run through a bulkhead to the outside of the furnace. Resistance and inductance data for each part were measured at the end of the wires outside of the furnace using a Wayne Kerr magnetic analyzer. Temperature and electrical data were saved to a PC every 30 minutes except for a brief period during which the data logging software failed.

Thermal Shock:

Seven parts were tested. A Tenney Environmental two-chamber thermal system was used. Parts were warmed to 200 °C over five minutes, soaked at 200 °C for 15 minutes, moved to the cold chamber and cooled to -65 °C over five minutes, soaked at -65 °C for 15 minutes, and finally shuttled back to the hot side to start heating up again. This test was done according to the specifications in MIL-STD-202G for a C-3 rating. Parts were tested approximately every 10 cycles. Two sample cycles are shown in Figure 1.

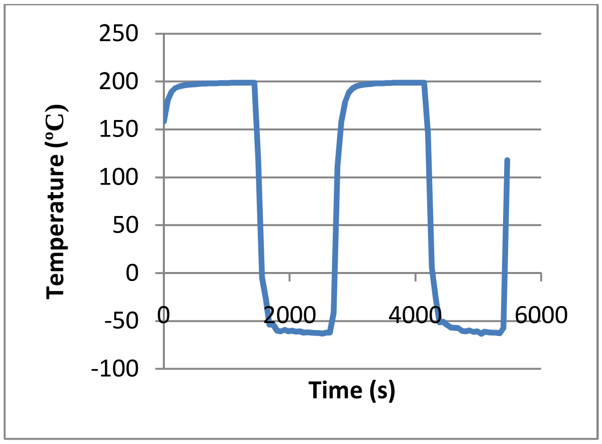

Figure 1. Two thermal shock cycles

Thermal Cycling:

Due to the upper temperature limit of the two-chamber thermal system, six parts were thermally cycled in a separate, single-chamber furnace. Parts were warmed from 25 °C to 300 °C over 30 minutes. The parts were then soaked for 30 minutes and, finally, cooled back to 25 °C over 5.5 h. Parts were tested after approximately every 20 cycles.

Results/Analysis

Inductance and resistance data has been converted to show the percentage change from the starting point or average since parts with different catalog numbers were used for the reliability and parameter testing.

Inductance and Resistance:

A linear increase with temperature was noted in the part's resistance. Figure 2 indicates that the part's resistance increases by 0.3 %/°C. This is different from the thermal coefficient of resistance of pure silver which is 0.38 %/°C[3]; however, some difference is expected as a frit material is added to the silver conductor to help it bond to the ferrite.

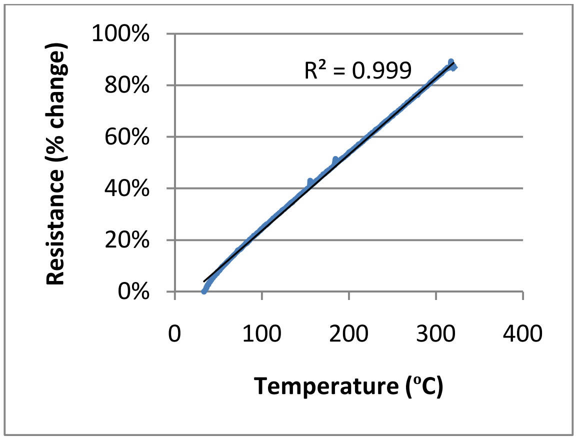

Figure 2. Percent change in resistance as a function of temperature.

Figure 3 shows how the part's inductance changes with temperature. The inductance increases with increasing temperature which is a common trait for ferrite materials [2]. Figure 4 shows a close up of the inductance vs. temperature curve for 280 – 320 °C and indicates that peak inductance is reached at just over 310 °C.

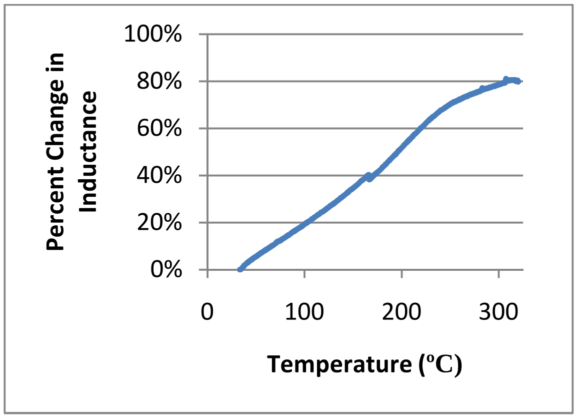

Figure 3. Percent change in the inductance as a function of temperature.

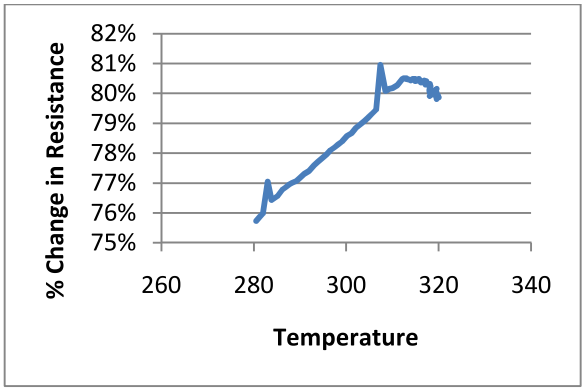

Figure 4. Close up of the peak of the inductance vs. temperature curve.

Frequency Response:

Self-resonance frequency decreases with increasing temperature at a rate of about 0.01 MHz / °C. A linear regression of the data (Figure 5) showed a high correlation value ($R^2 = 0.998$). The error in the frequency measurements is on the order of 0.02 MHz.

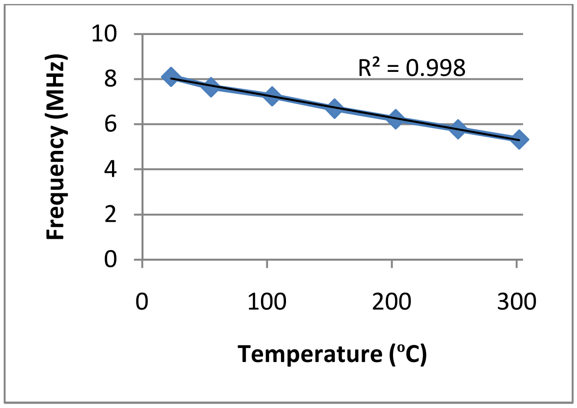

Figure 5. Self-resonance frequency of an inductor as a function of temperature.

The calculated parasitic capacitance of the inductor is shown in Figure 6.

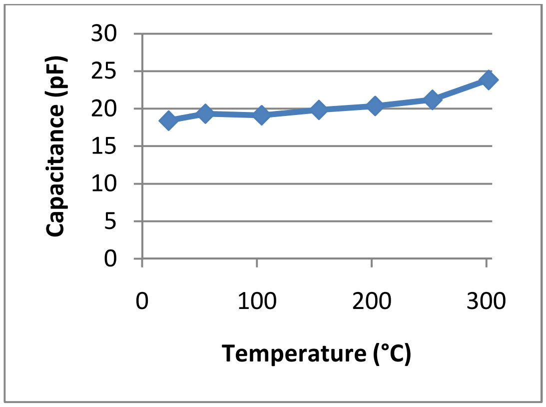

Figure 6. Parasitic capacitance of an inductor as a function of temperature.

As self-resonance frequency changes linearly with temperature and the equation relating frequency to parasitic capacitance is non-linear, the parasitic capacitance of the inductor increases nonlinearly with increasing temperature. Error in the capacitance calculations is on the order of 0.2 pF.

Core Loss & Saturation Flux Density:

Figure 7 shows the change in the bias current for which a 30 % decrease in inductance is measured as a function of temperature. The change is relatively linear ($R^2 = 0.97$) and the bias current was found to decrease by 1.6 mA/°C. Measurement error is shown in the figure.

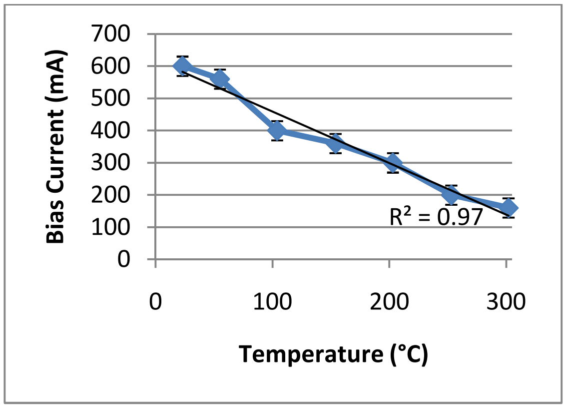

Figure 7. Bias current (at which a 30 % decrease in inductance is measured) as a function of temperature.

Figure 8 shows core losses as a function of temperature. The losses appear to have little correlation with temperature. This was not entirely expected as the core losses of a torroid made from the same material decrease at higher temperatures.

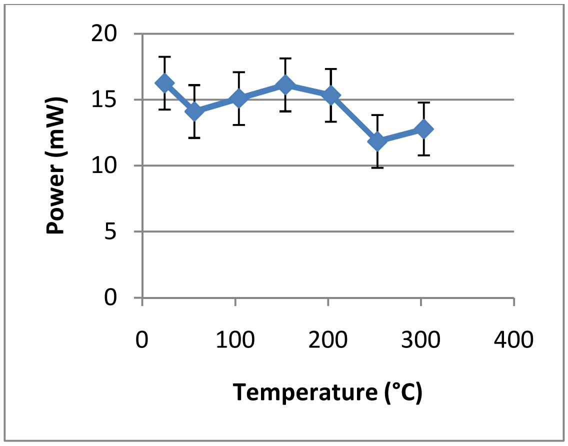

Figure 8. Core losses as a function of temperature.

Endurance Test:

Figure 9 shows the percent change in resistance as a function of time during the endurance test at 300 °C. Maximum change in resistance over the 1000 hour endurance test was less than 4 % with the average being about 1 %. The general trend is that resistance increases slightly with time.

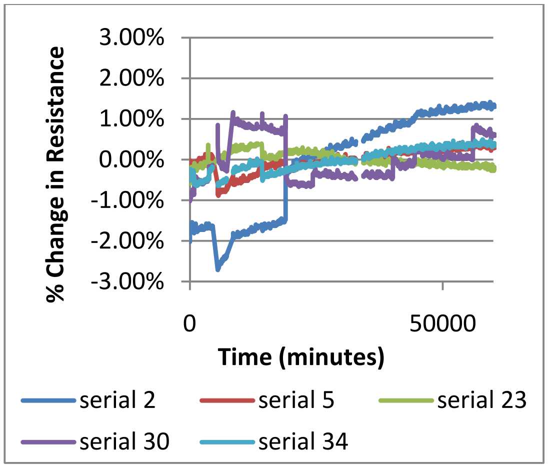

Figure 9. Percent change in resistance as a function of time during the endurance test.

Figure 10 shows how inductance changed with time during the endurance test. After an initial increase of about 1 % during the first few hours of the endurance test the inductance remained relatively stable, changing less than 0.5 % during the rest of the test. Experiments on parameter drift in resistors indicate that it is not uncommon for parameters to change in excess of 5% for similar endurance tests with similar times and temperatures [4].

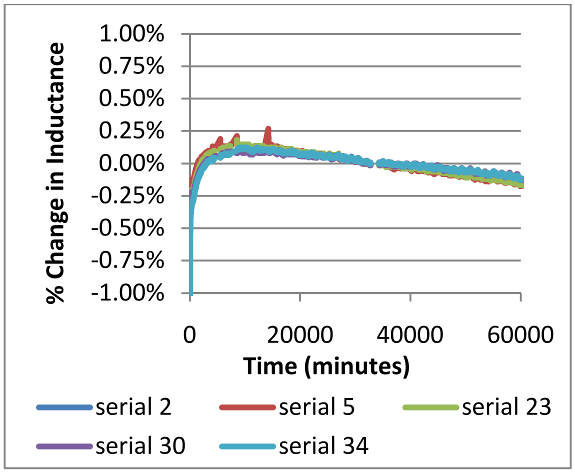

Figure 10. Percent change in inductance as a function of time during the endurance test.

Thermal Shock:

Figure 11 shows the change in inductance as a function of thermal shock cycles. The inductance of the parts increased on average by 20 - 25 % during the test with number 27 being an outlier at 32 %. Most of the change happened during the first 10 cycles. The deviation from the average after initial stressing was 4 %.

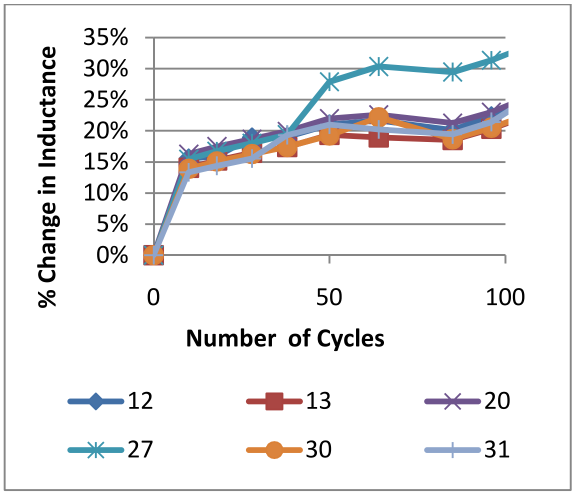

Figure 11. Change in inductance as a function of the number of thermal shock cycles.

Figure 12 shows the change in resistance as a function of the number of thermal shock cycles. The resistances of the parts increased on average about 22 % during the test. Once again, almost all of the change occurred during the first 10 cycles. After the initial shock cycles, resistance changed by less than 1 %. This indicates that for applications with rapid temperature swings the parts should be pre-stressed for maximum stability.

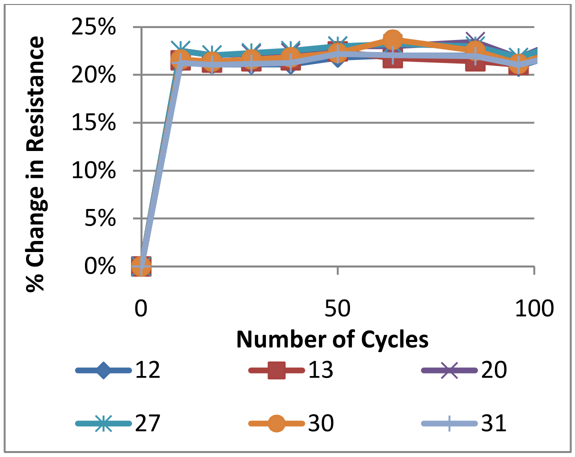

Figure 12. Percent change in resistance as a function of thermal shock cycles

Thermal cycling:

Figure 13 shows the percent change in resistance as a function of thermal cycles. Resistance changes from 2 to -6 % with an average ending value of - 6 % change from the starting value. While the temperature was not held constant for these measurements, the temperature should not have varied by more than a 3 °C which would explain up to 1 % change in the resistance values.

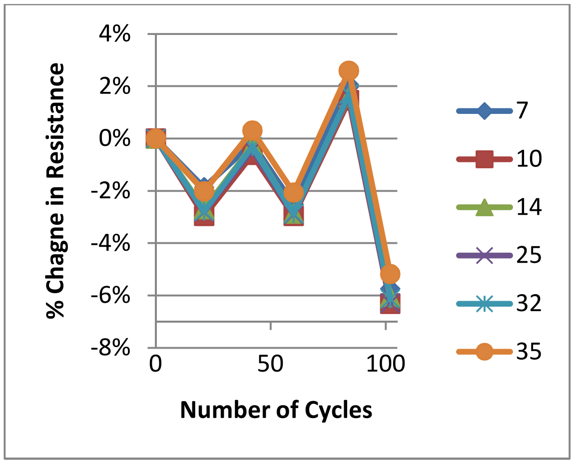

Figure 13. The percent change in resistance as a function of thermal cycles.

Figure 14 shows the percent change in inductance as a function of thermal cycles. Inductance increases range from 8 to 25 %. The data here shows a bimodal change with averages of 11% and 25 % for the two modes. Again, most of the increase happened during the first few cycles.

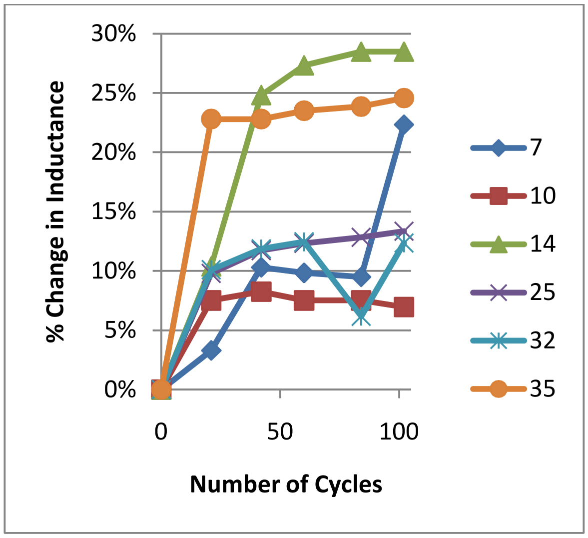

Figure 14. The percent change in inductance as a function of thermal cycles.

Conclusions

All electrical parameters change with temperature. The changes exhibited by the parts are mostly linear, meaning that their performance at any desired operating temperature can be easily determined. The reliability testing shows that, after initial stressing, the electrical parameters are stable within reasonable tolerances, the difference between two parts of the same catalog number generally exceeds the intra-part differences after stabilization during the reliability tests. This indicates that the parts undergo a thermally induced stress relief and that for maximum reliability the parts should be pre-stressed before being used in applications. The best method of pre-stressing the parts appears to be rapid thermal shocking.

References

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