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Reliability and life study of hydraulic solenoid valve. Part 2: Experimental study

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ABSTRACT

This work studies the reliability of a solenoid valve (SV) used in automobile transmissions through a joint theoretical and experimental approach. The goal of this work is to use accelerated tests to characterize SV failure and correlate the results to new comprehensive finite element models (Part 1).

A custom test apparatus has been designed and built to simultaneously monitor and actuate up to four SVs. The test apparatus is capable of applying a controlled duty cycle, current and actuation frequency. The SVs are also placed in a thermal chamber so that the ambient temperature can be controlled precisely. The apparatus measures in real-time the temperature, current, and voltage of each SV. A series of tests have been conducted to produce repeated failures of the SV. The failure of the SV appears to be caused by overheating and failure of the insulation used in the solenoid coil. The current tests are run at a 100 °C ambient temperature, 16.8 V of average peak voltage, 50% duty cycle, and 60 Hz actuation frequency. Upon failure, the solenoid electrical resistance drops to a significantly lower value due to shorting of the solenoid coil. This drop in resistance causes a measurable and noticeable increase in the average current. The insulation also melts and exits the SV. Hence, increasing ambient temperature and current is believed to cause a decrease in SV reliability.

1. Introduction

A solenoid valve (SV), an electromechanical device, controls the gas or liquid flow by changing position of valve when an electric current is passed through a solenoid coil. It is well known that solenoid valves find use in wide range of industries such as automobile industry, aerospace industry, nuclear power plant industry, and agricultural industry. In nuclear engineering applications, the valves are often situated in extreme conditions [1].

Based on an extensive literature search, the most common failures seen in solenoid valves are due to either overpowering and eventual overheating of the valves, or wearing out of the valve components.

In the automotive field, the solenoid valves are used as actuators and to control fluid pressure. The types of solenoid valves that are used are 'idle speed control valves, shift control valves of automatic transmissions and torque converter locked-up control valves' [2]. Hydraulic circuits are controlled by solenoid valves through drain opening and closing for high pressure hydraulic fluid. A few examples of automotive applications include the automatic power transmission, the

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automobile brake system, the boom control in an agricultural vehicle, and the hydraulic pump swash plate position control [3]. Solenoid valves are found in the hydraulic compact unit (HCU) of hydraulic power brake (HPB) systems and anti-lock brakes (ABS) [4–8]. An automatic transmission is often controlled by the transmission control module (TCM) which employs solenoid valves to control the transmission fluid flow to clutches [9–14].

Solenoid valves are also used in a wide variety of other commercial, domestic and military applications which require controlled motion. Some of these additional applications are: Commercial laundry equipment and facilities, commercial dishwashers, car and truck wash facilities, irrigation systems, humidification, water treatment, poultry incubators/watering equipment, and industrial maintenance, repair, and operation [15].

SV operation can generate large amounts of heat as a result of high duty cycles and electrical resistance (that is, high applied currents) thereby causing it to fail due to thermal effects and the accompanying wear of its parts. In the Part 2 paper, the multi-physics finite element solenoid valve model predictions obtained in the Part 1 paper are used to obtain a testing method and the model predictions are verified experimentally through testing a series of hydraulic solenoid valves, used in automobile transmissions.

Based on an extensive literature search, it appears that the published literature on solenoid valves' modeling and experiments is surprisingly scarce. However, the existing literature does provide guidance as to common problems seen in solenoid valves and the environmental and operating parameters which influence them. This information can then be used to design an experiment which can be used to map the failure and reliability of the solenoid valve researched in this study.

Probably, the most extensive work on solenoid valve reliability is provided by Mercer [16]. Mercer [16] provides a very thorough table which lists and maps the different parameters which influence solenoid valve performance and failure. Several critical factors that affect the reliability or failure of a 'two-way, direct acting, normally closed, packless solenoid valve' [16] are structural collapse related to material strength, fluid flow rate, component misalignment, broken spring related to fatigue strength, stroke, component misalignment, coil burnout related to mains voltage and frequency, stroke, spring force, frequency of operation, fluid temperature, aging of insulation, etc. [16]. Failure of solenoid valves can also occur gradually due to wear, leakage, noise, loss of speed as well as pressure rating.

Solenoid valves are known to exist commercially now for about 70 years and only with a higher expenditure and investment in characterizing solenoid performance can enhanced reliability be achieved. One of the major problems associated with the reliability of SVs is over-design whose effect can be just as strong as under-design of a solenoid valve. The function of a core spring in a solenoid valve is to shut the SV with respect to the pressure of the fluid. However, when a solenoid is over-designed, a highly powerful solenoid is required to overpower a spring that is designed to be too stiff. This requires the use of a larger coil which will generate larger amounts of heat via Joule heating, thereby decreasing the insulation's expected working life [16].

Baker [17] also provides some practical advice on installing and using solenoids effectively. He points out that a very common problem is solenoid burnout and it is usually the result of a valve being used for conditions it was not designed for. Providing too little or too much voltage to a solenoid valve can both result in overheating of the solenoid valve. In addition, heat can be generated due to higher cycling rates and duty cycles. Sometimes a blocked or stuck armature can overheat since power is continuously applied in attempt to free it.

Slightly more recently, Rustagi and Heilman [1] also gave suggestions on how to achieve longer and more reliable solenoid valve operation, especially for application in nuclear energy facilities. In this critical application, reliability becomes much more important. In addition, it can be very difficult to replace or repair solenoid valves due to their location in contaminated areas. Similar to the other works, Rustagi and Heliman state that overheating of the coil can be a cause of failure. Therefore, in long-term continuous cycles the voltage is often reduced to prevent excess heat generation. In addition, seal failure and rupture were also seen as a potential problem.

As previously discussed, solenoid valves may fail for a number of different reasons such as manufacturing defects, improper design, and improper selection for application. The specific mode of failure depends greatly on the original cause and the operating conditions. The following is a collected list of the various failures seen in solenoid valves:

1. 'Sticking' problem as a result of residual magnetism [16].
2. Structural collapse, coil burnout and broken spring [16,17].
3. Solenoid's coil efficiency and thus the flux density and torque output are lowered owing to heat buildup due to application of constant voltage to the solenoid [15].
4. The valve fails to open when the solenoid is energized due to low voltage at solenoid [17], solenoid failure, worn rings, and pressure drop [15].
5. The valve fails to close when the solenoid is de-energized due to bending of piston ring, foreign matter lodged on body seat and preventing plunger from seating, plunger tip is severely worn [15].
6. High duty cycles will cause the solenoid to use more power which will lead to temperature rise [15,17].
7. Due to the SV being run for longer periods at high temperature, there is thermal expansion and accompanying thermal deformations [17].
8. Wear and friction of SV components cause degradation of performance and finally failure [18]. Friction can also cause more power to be used (high temperature) [15].
9. Elevated temperatures and wear can also cause the seals to leak [15].
10. Effect of varying (that is, increasing) duty cycle and frequency on SV operation.

11. If the SV is operated at a higher than rated current, the Joule heating can cause the operating temperature to increase, which then can cause other problems in the SV.
12. Thermal cycling effects can age the materials of the SV [16].

This work focuses mostly on the thermo-mechanical failure mechanisms of the solenoid valve. It should also be noticed that in many cases these various failure mechanisms do not occur independently. Several mechanisms may be initiated or progressed due to the occurrence of another mechanism. For instance, the Joule heating could cause the solenoid temperature to rise significantly. The seals in the solenoid could then degrade due to the elevated temperatures, then causing the solenoid to leak and perhaps fail.

2. Experimental methodology

In order to monitor and evaluate solenoid valve failure, a solenoid valve experimental test rig or apparatus was designed and fabricated. The apparatus is capable of testing four SVs simultaneously. The solenoid valves are also placed in a thermal chamber to control the ambient temperature. The solenoids are powered and actuated in a controlled manner while the current, voltage and temperature are being measured. Both before and after the test on each solenoid valve the electrical resistance is measured directly using a multimeter. The goal of the apparatus is to be able to apply sufficient loadings on the SV to cause failure similar to that seen in application. When the SVs do fail, a significant change in the measured temperature and electrical resistance is expected. An accelerated testing procedure will be used to create tests which cause SV failure in a reasonable amount of time. The chosen tests are also based on the results of the multi-physics finite element model of the solenoid valve that is discussed in Part 1 of this work.

The tested solenoid valve is a normally open, three-way valve. The operating conditions are given in Table 1. To accelerate the tests and reduce the time to failure, these operating conditions may be slightly exceeded to induce solenoid failure. In application, the solenoid valve may also fail due to the designed operating parameters being exceeded.

A schematic diagram of the experimental test rig fabricated for the current project is shown in Fig. 1. It depicts the basic wiring connections among the various instruments used in this work for testing of the solenoid valves and to record the resulting test data. The instruments used are two power supply systems, an SC5 solenoid controller board, current transformers (CT), thermocouples, a National Instruments SC2345 signal conditioning block with modules and a National Instruments data acquisition (DAQ) board. Three types of modules, namely, an analog voltage input module (0–42 V range, 10 kHz data acquisition rate), an analog voltage input module (0–5 V range, 10 kHz data acquisition rate) and a thermocouple input module are used in the SC2345 signal conditioning block to condition the raw signals. The LabView™ (LV) graphical programming software is used extensively to gather voltage, current, and temperature data of the solenoid valves that are being tested.

The solenoid valves are placed in a Delta Design 9039 thermal chamber. After preliminary testing, it was found that the thermal chamber was actually too effective at controlling the temperature of the solenoid valve. When the solenoid valves were inside the chamber, the measured increases in temperature from the ambient temperature were actually less than when the solenoid valves were outside the chamber. This is because the thermal chamber has a fan which circulates the air so that the temperature is uniform throughout the chamber. This unfortunately also causes forced convection which tends to hold the solenoid valve at the same temperature as the chamber. In contrast, when the solenoid valve is outside the chamber, the air is mostly still and the much less effective mechanism of free convection is dominant. In addition, free convection was used during modeling of the solenoid valve to consider the heat dissipation from the solenoid valve (see Part 1 paper). To reduce the effect of the forced convection, metal boxes were placed over the valves in the chamber (see Fig. 2). This practice was very successful at increasing the rise in temperature in the solenoid valves due to Joule heating. This in turn allowed for more control over failure of the solenoid valve.

An SC5 solenoid controller board is used to control the solenoids simultaneously at a specified peak current, sustained current, voltage, actuation rate and duty cycle. A duty cycle is defined as the ratio of 'on' time (that is, the time for which the solenoid valve is under actuation) to the total period of actuation. The higher this ratio, the more load the solenoid valve is under. By increasing the duty cycle, the solenoid valve can be stressed and caused to fail.

Two power supply systems are used to supply a voltage of 20 V to an SC5 solenoid controller board to actuate the five SVs and 5 V for current transformers (CTs). The CT for each SV measures the current that is passing though each SV.

E type thermocouples are used to measure the operating temperature of the SVs during their cycling process. As shown in Figs. 3 and 4, the thermocouples are placed to come into contact with the side of the SV's metal casing. Although the

Table 1
Tested solenoid valve rated operating parameters

Parameter	Value
Operating current	1.8 A
(Cycling) Frequency	61.2 Hz
Coil resistance	3.4 Ω
Operating voltage	12 V
Operating temperature	−30 to 130°C

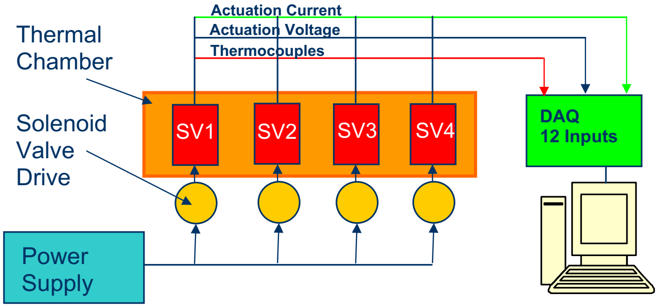

Fig. 1. Schematic diagram of solenoid valve experimental test rig.

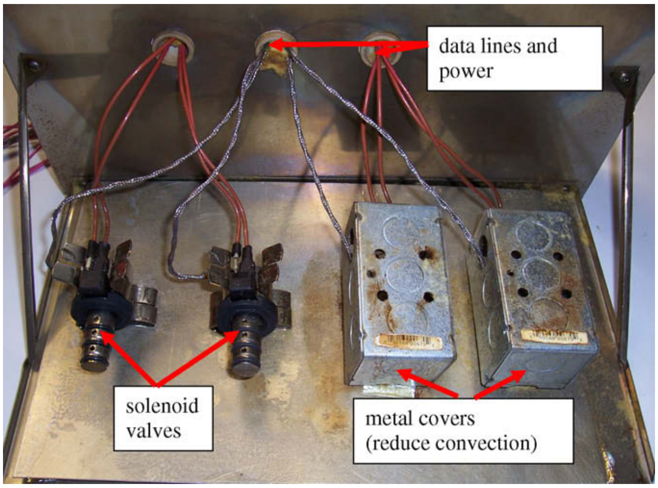

Fig. 2. Photograph of the solenoid test fixture that is inserted into the thermal chamber.

thermocouple is not measuring the temperature of the SV coil directly, the measured temperature should be proportional to the coil temperature. It is also shown later by experiment and theory (Part 1) that there is only a few degrees difference between the coil temperature and the measured external temperature. It is expected that when the solenoid valves fail, their measured temperature will rise and their measured electrical resistance will change. The voltage across each solenoid is measured directly in volts and is conditioned through the analog input voltage modules.

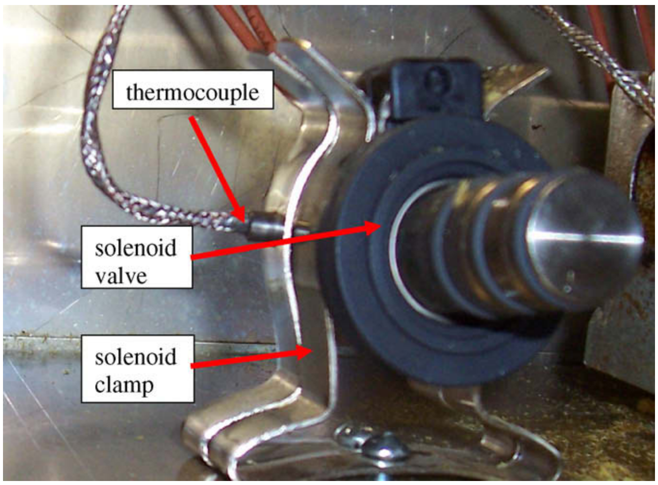

Fig. 3. Photograph showing solenoid valve test fixture and thermocouple.

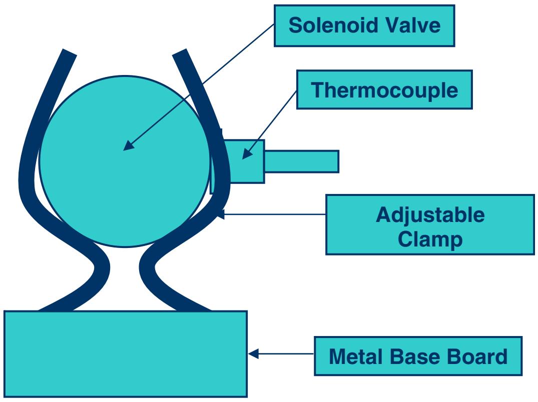

Fig. 4. A schematic of the solenoid valve test fixture and thermocouple mount.

The output of the current transformers (CT) is a voltage which is proportional to the current powering the SV. The input voltage signal from current transformer (CT) is also first conditioned through another analog voltage input module (5 V, 10 kHz). It is then converted to current (for each SV). This type of module is chosen specifically based on CT specifications. For each of the SV in operation, an independent CT is used. To measure the electrical resistance of each solenoid valve, a multimeter is used. For a completely or a partially solenoid failed valve, the resistance is measured when its temperature reduces to room temperature. Similarly, for a solenoid valve that is run for a specified test duration of 24 h but has not undergone failure, its resistance is measured when it cools down to room temperature.

It was also found that when the solenoid valves do fail, the wires in the coils short and cause the resistance to drop. This causes the current to increase significantly since the power source is held at constant voltage. This actually caused failures of the control board channels. To alleviate this problem Type BAF-3 fuses (Fast acting 3 Amp rating) were inserted in the power lines to the solenoid valves. Therefore, if the current applied to solenoid valve increased past 3 A, the fuse would blow and cut-off the power. This practice also reduced the risk of fire due to a failed solenoid valve. It was observed that the fuses blew multiple times when a solenoid valve failed.

Thus, through experimental testing of the SVs, we obtain the resistance of the SV, the applied current flowing through the SV, the applied voltage across the SV and the temperature of SV. These data are then used to characterize and analyze solenoid valve failure. The results of the theoretical model from the Part 1 paper will also be correlated to the results of experimental measurements.

3. Experimental results

A total of 22 solenoid valves are tested for a maximum period of 24 h at a temperature of 100 °C in a thermal chamber, 16.8 V of average peak voltage, 50% duty cycle (DC) and 60 Hz of cycling frequency. Originally the tests were run at a 80 °C ambient temperature but failure was not occurring at a sufficient rate so the ambient temperature was increased to 100 °C. This implies that the solenoid valves are scheduled to run for 5,184,000 (approximately five million) cycles in 24 h with no failure.

A sample of the voltage and current waveforms (providing the applied voltage and current for all the solenoid valves) generated during testing of the solenoid valves are displayed in Figs. 5 and 6. From Fig. 5, it can be noticed that the applied average peak voltage during the tests is 16.8 V. In addition, the waveforms are not perfect square waves, but that is similar to what the solenoid valves would bear in an actual application.

The recorded actuation current is also shown in Fig. 6. The actuation current lags the actuation voltage. Once the voltage is actuated, the current increases at a reduced rate to the expected current which is equal to the voltage divided by the resistance. This is due to electrical inductance in the solenoid valve and power lines.

Although a total of 22 solenoid valves are tested, Figs. 7–10 show the current, the calculated running average of the current, and the measured temperature as a function of time for 4 of the solenoid valves. Figs. 7 and 9 show peak current and maximum temperature values at which complete failure has occurred for 2 valves, whereas Figs. 8 and 10 show the current, running average and temperature data for a completely failed valve and for a valve where no failure has occurred. It is clearly evident that solenoid failure is marked by a sudden increase in temperature and current. Once failure occurs the solenoid valve ceases to actuate and the protective fuse blows causing the applied current and voltage to reduce to zero. These clear failure points are used to extract the time to failure for each solenoid valve. A detailed set of the extracted results and observations on all solenoid valves tested in this work is included in the following sections (see Table 2).

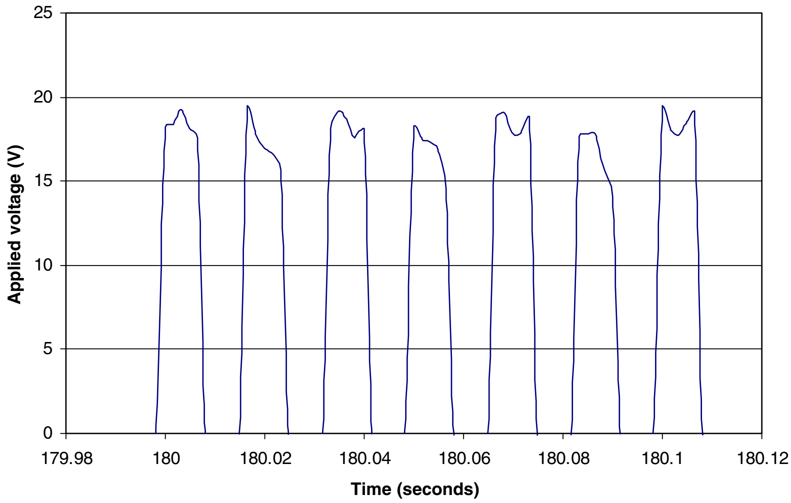

Fig. 5. Variation of actuation voltage with time for a solenoid valve in operation.

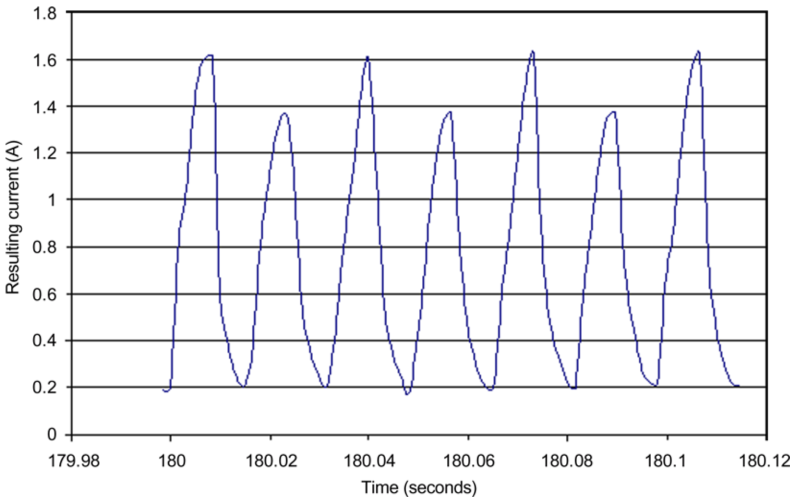

Fig. 6. Variation of actuation current with time for a solenoid valve in operation.

3.1. Direct solenoid coil temperature measurement

As discussed in Section 2, the temperature is measured during a test using thermocouples that are pressed against the outside of the metal casing of the solenoid valve near the coil. Based on the finite element results discussed in Part 1 paper, it is believed that these external temperatures are very close to the coil temperature. To confirm this the solenoid coil can be used as a thermistor to measure temperature. As the temperature increases, the coil wire will expand and lengthen, thus causing a measurable increase in the electrical resistance. However, this measurement cannot be made easily while the solenoid valve is in operation. In this work the resistance of the solenoid valve was measured before and immediately following a test. These resistances were then used to confirm the coil temperature. The dependence of resistance on temperature is given by the following equation [19]:

$$R = R_{ref}(1 + \alpha(\Delta T)) \quad (1)$$

where R is resistance (Ω) at a given temperature (T) (°C); R_{ref}, resistance (Ω) at reference temperature, T_{ref} (°C) (generally 20 °C), that is, 3.4 Ω; α, temperature coefficient of resistance for a given material (for copper, the material used as conductor in solenoid coil, the value of α is 0.004041/°C); and ΔT is the difference between T and T_{ref}.

A plot of resistance versus the temperature is thus shown in Fig. 11. The trend confirms that the method is very effective at measuring the coil temperature and that the coil temperature is nearly the same as the external temperature of the thermocouple. It is seen that in this work for a particular value of temperature (for example, 80 °C) the measured value of resis-

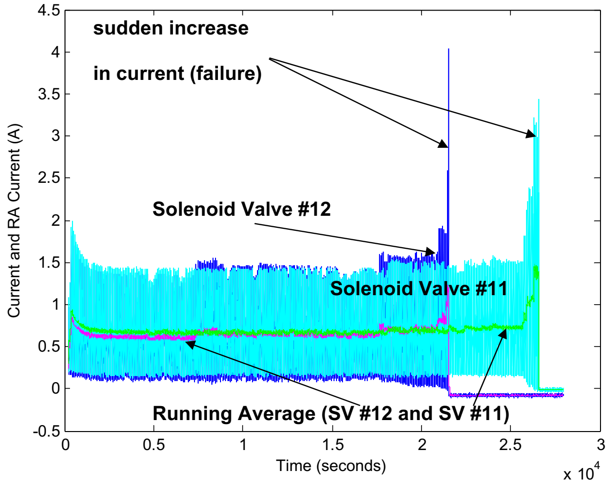

Fig. 7. Variation of applied current and running average for current as a function of time for two completely failed solenoid valves.

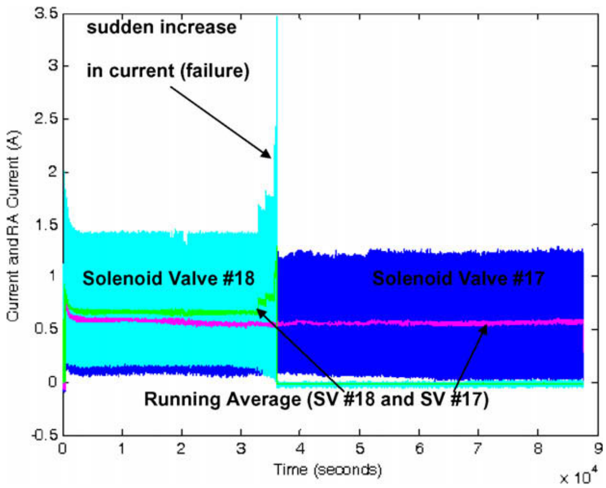

Fig. 8. Variation of applied current and running average for current as a function of time and also showing one completely failed solenoid and one solenoid that did not fail.

tance by using a multimeter is 4.2 Ω. When the above equation is used to find resistance at 80 °C and for $\alpha = 0.004041/°C$, the same value of 4.2 Ω is obtained. Similarly, for various temperatures, the resistance measured from a multimeter (experimental) and that calculated from the above equation (theoretical) match very closely.

3.2. Categorization of results

As shown in the previous sections, the tests in this work have succeeded at producing a controlled failure of the solenoid valve. However, due to manufacturing tolerances and experimental inconsistencies, the solenoid valves do not fail at precisely the same moment and for the same conditions. It has been observed that the tested solenoid valves can be categorized into three types or cases:

(a) solenoid valve run for 24 h (no failure);
(b) partial failed solenoid valve but still actuating for 24 h;
(c) completely failed solenoid valve.

These three categories are also represented in many of the following plots of the data. In addition, differences in the solenoid wire cross-section after a solenoid has failed can be observed. This is shown in Sections 3.3 and 3.4.

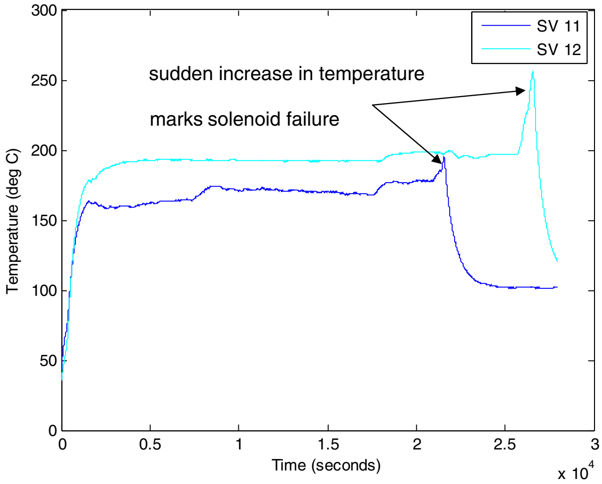

Fig. 9. Variation of temperature with time for two completely failed solenoid valves.

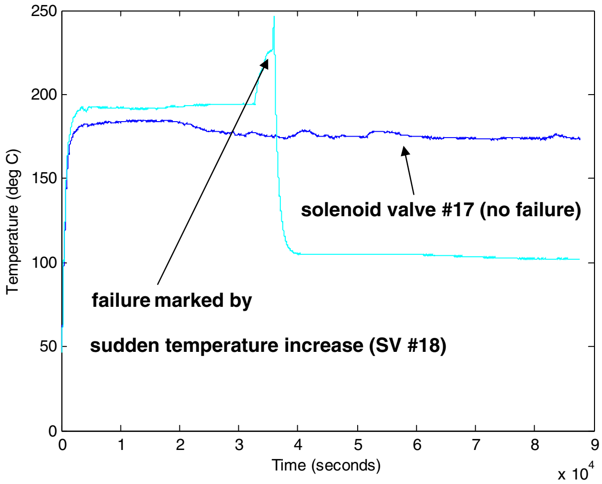

Fig. 10. Variation of temperature with time for one completely failed solenoid and one solenoid that did not fail.

3.3. Analysis of results

The cumulative density function (CDF) is used extensively to test or study the reliability of components and thereby predict life of components. Fig. 12 shows the calculated experimental CDF and the cycles to failure for the solenoid valves. In this plot only the data for the solenoid valves that have either partially or completely failed have been considered. Fig. 12 signifies that the chances of failure of SVs increases as the cycles to failure increase.

The calculated CDF appears to show that the failure rate does not follow a Weibull distribution. Rather, the failure rate appears to level off as the number of cycles is increased. A logarithmic function is fit to the CDF data that might be used to make rough approximations for solenoid reliability. The current analysis actually finds that the failure of the tested solenoid valve is correlated better with the maximum temperature. This confirms the theory that the failure mechanism is a thermo-mechanical one that occurs when the temperature and stress are large enough to cause the insulation to fail and the coil wires to short.

The tests on all the tested SVs (a total of 22 SVs) are conducted for 24 h. However, SV 15, 23, 29 were prematurely stopped before the full 24 h. This might be because other solenoid valves in the same test (SV 16, 24, 30) failed quickly (in the range of 6–10 h) and so unexpectedly the power supply became switched off. Nineteen solenoid valves are either run for full 24 h with no failure or run until they exhibit either partial or complete failure.

From the solenoid tests, four key outputs are extracted for all valves (see Table 2). These key outputs are the maximum temperature reached during tests, the number of cycles run, the Δ Resistance (the change in resistance) and the peak current observed at failure or at the end of a 24 h test. The key parameters are taken into account in analyzing the performance of

Table 2
Solenoid valve recorded and calculated/measured data for 100 °C ambient temperature, 50% duty cycle, 60 Hz actuation frequency, 16.8 V actuation voltage

Solenoid valve	Maximum temperature (°C)	Number of cycles (N)	Δ Resistance (Ω)	Peak current (A)	Status
9	178	4487400	0.6	1.58	Partial failure
10	181	5248800	0	1.46	No failure
11	197	1292820	1.7	4.04	Failure
12	256	1594080	1.7	3.43	Failure
13	172	5184000	0	1.26	No failure
14	269	2582400	2.1	2.97	Failure
15	176	1744320	0	1.36	Incomplete
16	223	1744320	0.5	1.7	Partial failure
17	176	5257500	0.1	1.23	No failure
18	246	2157660	1.8	3.47	Failure
19	173	5342280	0.1	1.27	No failure
20	197	5342280	0.1	1.39	No failure
21	171	5235600	0.1	1.21	No failure
22	301	1678440	1.7	2.94	Failure
23	161	1283100	0.1	1.21	Incomplete
24	265	1283100	0.8	5.44	Failure
25	171	5197740	0	1.29	No failure
26	274	1286520	1.5	3.43	Failure
27	153	5244540	0	1.27	No failure
28	255	972960	1.9	3.48	Failure
29	174	842460	0	1.27	Incomplete
30	227	842460	2.1	2.88	Failure

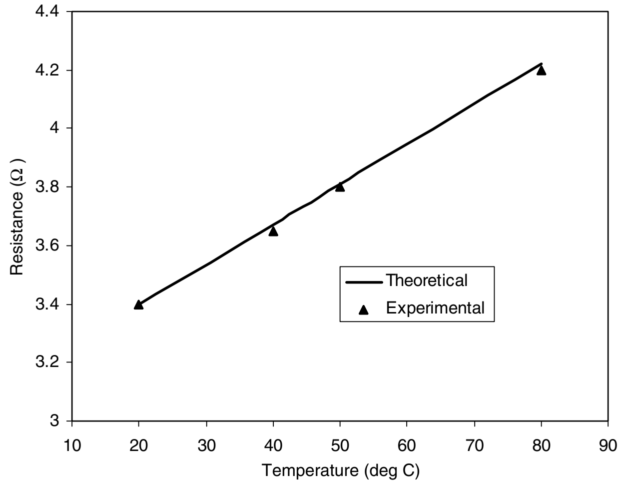

Fig. 11. Variation of resistance with temperature.

solenoid valves and to study their reliability, and thus to predict and find ways to improve the reliability and the life of SVs tested in this project.

In each of the following four plots (see Figs. 13–16), the tested SVs are categorized into (a), (b) and (c) types. All the plots clearly exhibit a common trend that illuminates our fundamental understanding about the solenoid valve reliability, performance, and behavior when they are subjected to accelerated operating conditions and temperatures. As will be discussed further, this common trend also indicates and defines the failure mechanism of the solenoid valves. This will then help in prediction of life of solenoid valves and methods to further improve reliability and performance of solenoid valves. To understand the failure mechanism even further, a visual inspection of the tested solenoid valves is also presented later in this work (see Section 3.4).

Fig. 13 shows a clear change in the electrical resistance of the solenoid valves with respect to the maximum temperature reached during each test. The resistance of each new SV measured before testing is 3.4 Ω and indicates that each wire is insulated from all nearby wires by a thin polyamide-imide insulation. The melting point of the insulation material (polyamide-imide) used in the solenoid coil is approximately 200 °C [20]. Therefore it is believed that if the temperature and stresses in the coil are high enough, then the solenoid insulation will fail. The drop in resistance means that the solenoid valve coil wire has shorted so that the current can bypass significant portions of the coiled wire. For most of the valves that belong to the (c) case (complete failure), the change in resistance is high (there is a drop in resistance from the original 3.4 or 3.5 Ω for a new solenoid valve to a very low value varying in the range 1.2–2.5 Ω).

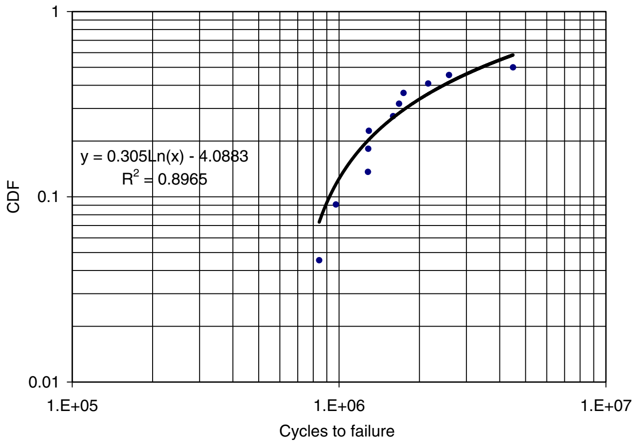

Fig. 12. The calculated experimental cumulative density function for failure of the solenoid valves.

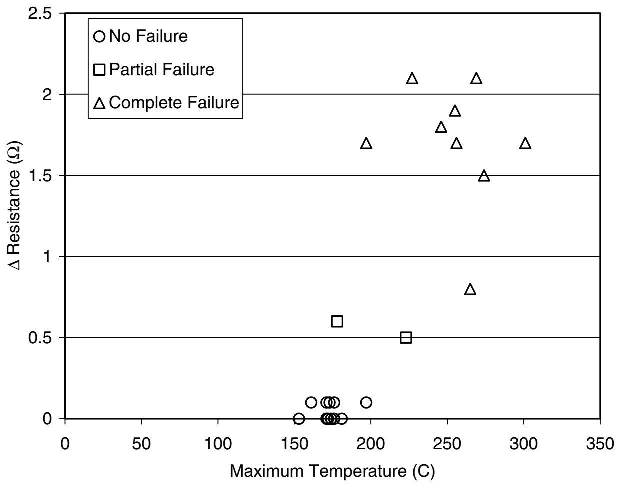

Fig. 13. Variation of change in resistance in relation to the maximum temperature for the tested solenoid valves.

The change in resistance is also shown as a function of the number of cycles in Fig. 14. The results show that for the failed solenoid valves almost a million cycles or more were still required for failure to occur. This suggests that the failure may also be a cyclic process as the wire insulation is slowly degraded over many cycles of operation. However, it also appears that many solenoid valves survive for many millions of cycles without reaching failure. Surprisingly, in this work for all the valves tested for more than 5 million cycles ((a) case valves), there were no signs of failure which is validated by extremely small changes in resistance of the order of 0–0.2 Ω, even after the valves were cycled for 24 h. It could be that there are differences in the manufacturing tolerances of the solenoid valves that allow some valves to operate for longer before failure. The performance of (a) type of valves clearly proves the well established fact that many SVs run for very long durations to the order of many years without failure when operated at the rated operating conditions. In contrast, the current tested SVs are subjected to more severe operating conditions (16.8 V average peak voltage, 100 °C, 50% DC, etc.) and are made to run in these conditions for at least a period of 24 h (that is, approximately 5 million cycles). Despite this, many of them run well even after 5 million cycles while being exposed to these operating conditions (the accelerated test conditions). The problem is some of them do fail, and it appears to be significant portion.

An interesting observation is that the sound level or tone of actuation emitted by the solenoid valves was lowered to a good extent over the duration of many tests, even for those that did not fail. All the 22 SVs tested in this work (note these valves are tested at 60 Hz cycling frequency) produced a very distinct well heard clear actuation sound at the start of each test. Perhaps there is a run-in period where the sound level is higher, but with additional wearing in, the parts start operating more efficiently. It is often observed in the testing of mechanical components that during this wear-in period many components will fail, but those that survive then have very long lives. This could explain what is being observed in the current tests of solenoid valves.

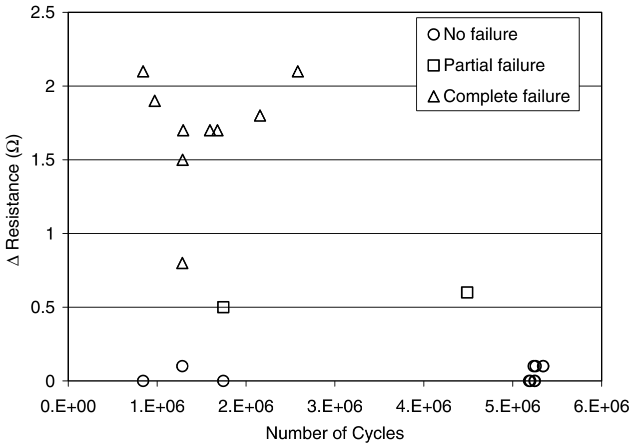

Fig. 14. Variation of change in resistance Vs number of cycles for the tested SVs.

It is observed from Figs. 13 and 15 that for the reasonable ambient temperatures of 100 °C and applied electrical loads that these valves are subjected to high temperatures (in the range 200–300 °C) which is well above the melting point of the coil insulation. Fig. 15 also presents perhaps the best correlation of data and the clearest indicator of failure. The peak current of the completely failed solenoid valves are all above a value of approximately 2.8 A and there also appears to be a separation of the data at approximately 200 °C. Initially for each of the valves when it begins to operate, the applied peak current is approximately 1.3–1.4 A, but this applied peak current increases in gradual steps until a point of complete failure occurs due to a corresponding gradual drop in the resistance of the SV to a very low value (Table 2). The valves have then been exposed to extreme temperatures that eventually cause complete failure as the coil insulation starts to melt (see Fig. 26) which causes shorting of the solenoid coil copper wires due to a lack of insulation between them. At complete failure, there is also considerable thermal expansion and deflection in the coil region or wire cross-section (see Figs. 23, 25 and 26). In fact, the coil wire can be bulged out, melting out of the insulation, and show the presence of pores or vacant spots in and around the core region (see Section 3.4). The wire cross-section of the (a) case solenoid valves (non-failure) shows none of the observations noted for the (c) case. Instead, these samples exhibit in an expected manner, a neatly arranged close packed helical wound coil structure [21] of a SV with a thin layer of polymer insulation clearly seen between all the copper wires. This is typical of any solenoid valve that has not shown any signs of failure.

Only two partial failures (type (b)) of the solenoid valves have been achieved in this work out of 22 valves tested. In all the 4 plots, these partial failures appear in between the data points of the (a) and (c) cases. The drop in resistance (see Fig. 14) is quite low compared to the (c) cases, likewise the peak current (Fig. 15) and the maximum temperature attained during each test (see Figs. 13, 15 and 16), and the number of cycles to failure (see Figs. 14 and 16) are lower than those achieved or shown by the (c) cases. However, similar to the (c) case samples, when the cross-section of the wire region is examined under a microscope for the (b) cases, moderate thermal expansion or localized bulging out of the cross-section of wire is observed. There are also some vacant regions and locations where with a lack of insulation between the two copper wires exists, thus causing shorting. However, these regions are usually localized and less severe for the (b) case than the (c) case. Due

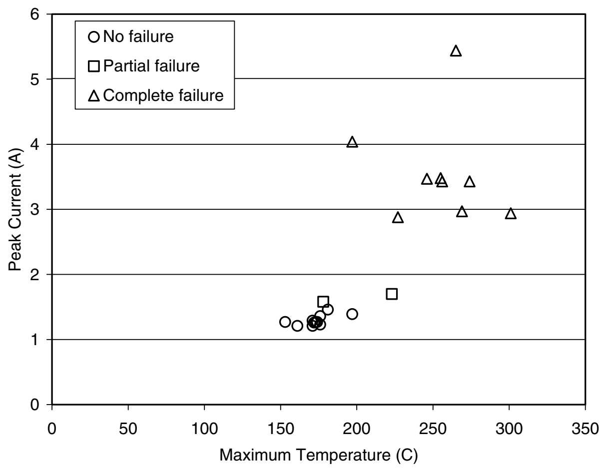

Fig. 15. Variation of peak current as a function of maximum temperature for the tested SVs.

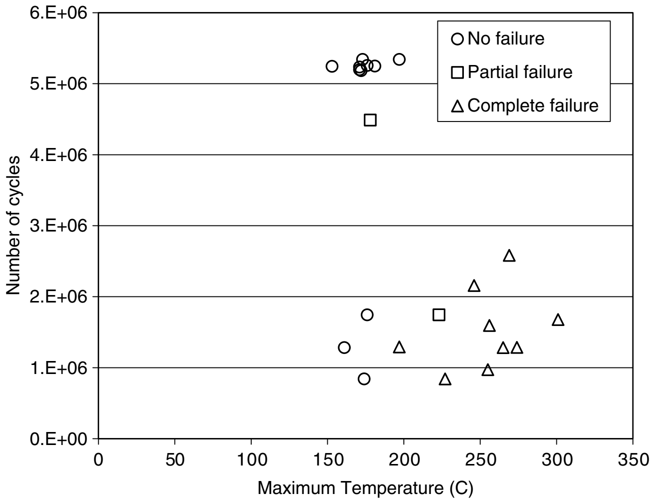

Fig. 16. Variation of number of cycles as a function of the maximum temperature for the tested solenoid valves.

Fig. 17. A macroscale photograph of a SV belonging to (a) case (the solenoid valve was run for 24 h without failure).

Fig. 18. A macroscale photograph of a solenoid valve belonging to (b) case (partially failed but still run for 24 h).

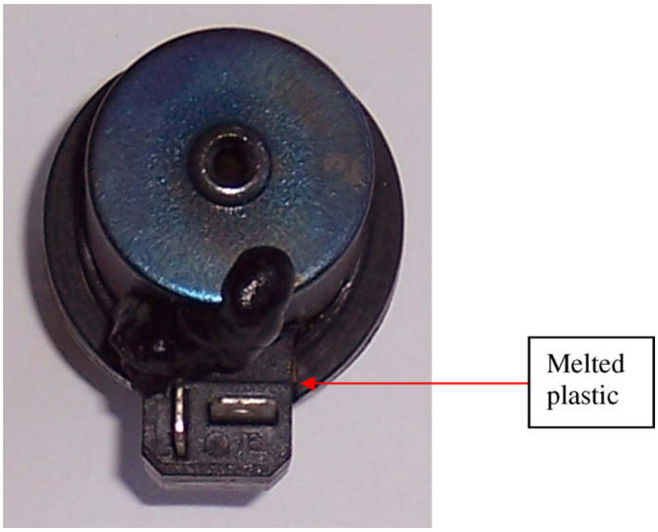

Fig. 19. Macroscale photograph of a solenoid valve belonging to the (c) case (completely failed).

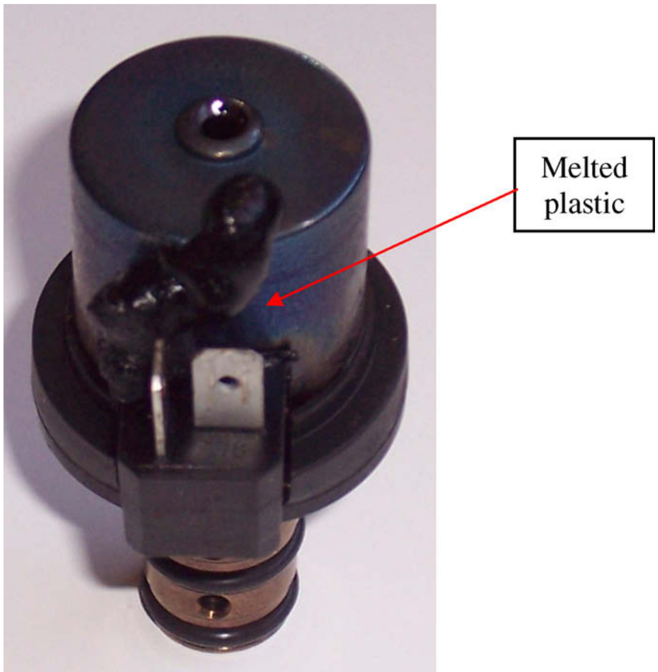

Fig. 20. Macroscale photograph of a solenoid valve belonging to the (c) case (completely failed).

to shorting only, the resistance has dropped from the original values of 3.4–3.5–2.9 Ω in both the two partially failed solenoid valves. There is also disorder of the wire arrangement in both the partially (intermediate disorder) and the completely (excessive disorder) failed solenoid valves which is not present in the (a) case. Therefore, these valves are classified as partial failures due to a low change in resistance, still successful solenoid actuation, and limited melting of insulation.

Fig. 16 shows the variation of the number of test cycles as a function of the maximum temperature reached during each test for all SVs. From this it shows that the higher maximum temperatures reached by the solenoid valve might be due to high peak currents. Then these high peak currents are in turn probably a result of the large drop in resistance of the solenoid valve from 3.4 to 3.5 Ω to the range of 1.2–2.5 Ω. Since these lower resistances are caused by high temperatures, there does seem to be a viscous cycle that the solenoid valve may enter once the threshold of failure is reached. Alternatively, the solenoid valves subjected to moderately high temperatures in the range 150–185 °C run extremely well for at least 5 million cycles (that is, approx. 24 h) with no signs of failure, therefore these tests belong to the (a) category.

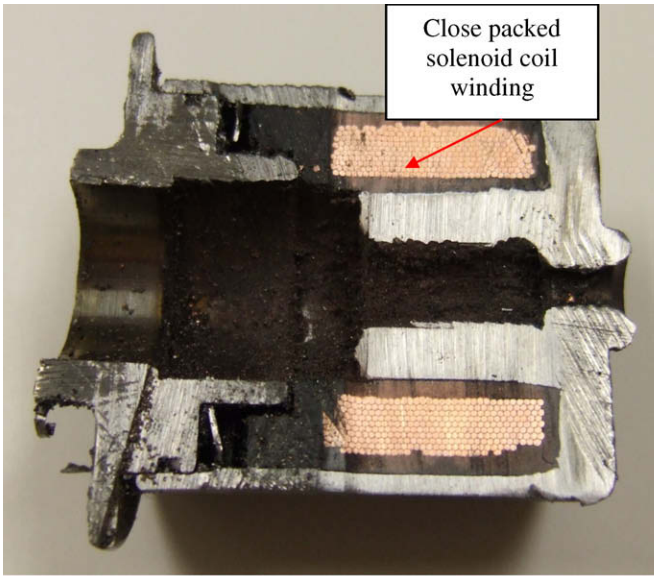

Fig. 21. Cross-section of a (a) type tested solenoid valve.

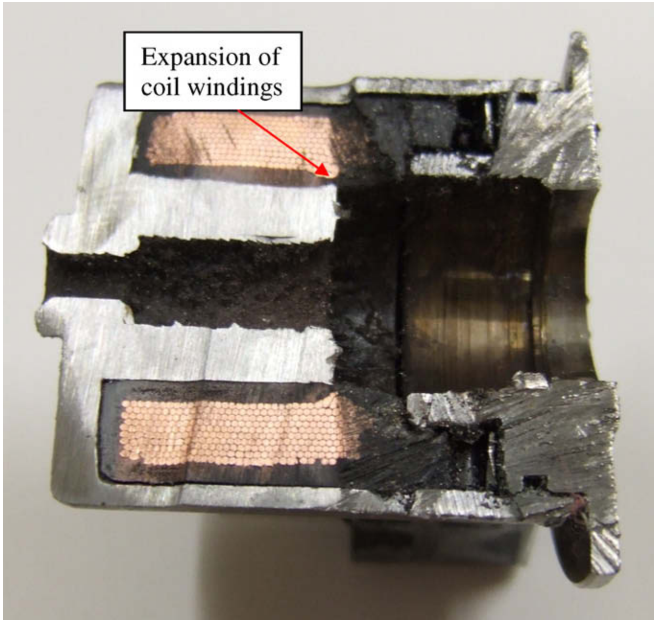

Fig. 22. Cross-section of a (b) type tested solenoid valve.

From Figs. 13–16, for the (c) case, there are clear signs of failure and severe operating conditions. Namely, these are the very high peak currents and the corresponding rises in temperatures in the solenoid coil to a value greater than the melting point of the insulation. Together these will lead to large changes in resistance values and thus complete failure of solenoid valves. This analysis thus provides a clear indication of the failure mode and failure mechanism. This result will then assist in the prediction of life, performance and the ability to improve reliability of solenoid valves.

3.4. Visual analysis of failure mechanism

As mentioned earlier, based on the occurrence of failure or no failure, the solenoid valves tested in this work are classified into three types. For each of the (a), (b) and (c) cases, photographs are taken at three perspectives, namely, the macroscale external view (for outer structure of the solenoid valves), the macroscale cross-section and the microscale cross-section.

The macroscale level view of the external solenoid valve and cross-section was photographed simply using a digital camera. The microscale level photographs of the cross-section were taken using a digital camera mounted on a microscope. The cross-sections of the solenoid valves were obtained by cutting open several of the tested solenoid valves. The solenoid valves were cut using a band saw and hand saw. The surfaces of the cross-section were then ground smooth.

The following photographs (Figs. 17–27) of the (a), (b) and (c) cases, show very clearly the variation of damage to the coil, insulation material between the copper wires and the plastic material that surrounds the coil structure (see Fig. 19) due to the high applied currents and thus high temperatures. It can be observed that the maximum or most intense damage is present for the (c) case and relatively no damage imparted to the coil of the (a) case solenoid valves.

For the (a) and (b) cases (see Figs. 17 and 18), where both are run for 24 h and about 5 million cycles, the outer structural appearances of the valves are similar. The presence of a brownish color is observed over most of the outer region of the valves since the outer casing of the valves is made of iron (due to iron oxidation and exposure to extreme temperatures in the range 150–200 °C) unlike the silver color of the valves seen prior to testing.. In addition, some bluish discoloration of the surfaces can also be seen due to the high temperatures that are encountered. In contrast, for the (c) case valves (see Figs. 19 and 20), along with the discoloration in the outer structure, plastic material is seen oozing or coming out of valve due to exposure to very high temperatures in the range of 200–250 °C. The color of the type (c) failed solenoid valve is also a deeper blue than the other samples, indicating the occurrence of higher temperatures. Again, the existence of extreme temperatures in the valves is due to the applied current and the build up of Joule heat in addition to the heat in the ambient air of the thermal chamber.

Figs. 21–23 show the macroscale photographs of the cross-sections of tested solenoid valves (including (a) non-failure (b) partial failure and (c) complete failure). One can observe that the organization of the coil wire array continues to degrade from the type (a) non-failure solenoid valves to the type (c) complete failure valves. For the intermediate type (b) samples it appears that any obstructions in the coil hexagonal packing structure is located and limited to the corners of the coil. However, the type (c) solenoid valve samples show a very unorganized coil with wires that have even completely separated from the bulk coil into the black plastic casing material. This same black casing material was seen in the earlier photographs exiting the solenoid valve in a melted form. For complete failure the melted plastic may have also helped cause failure by mechanically obstructing the actuation of the valve plunger in the center axis of the solenoid valve. Some of the coil wires appear to not only have left the coil structure but are approaching the steel casing or core of the solenoid valve. This could cause further shorting of the solenoid, and perhaps even leak electrical current into any components surrounding the solenoid valve in application.

Figs. 24–27 display the microscale photographs of the tested solenoid valve cross-sections for various levels of severity. Although all samples showed some signs of stress in the coil, the partially failed (type (b)) and completely failed (type (c)) solenoid valve cross-sections showed many more shorts between the coil wires and disorganization of the coil structure than the tested but not failed samples (type (a)).

At first, considering type (c), there are a few number of vacant spots or separation between many of the copper coil wires (Figs. 26 and 27) (probably due to the melting of insulation material due to very high temperatures in the range of

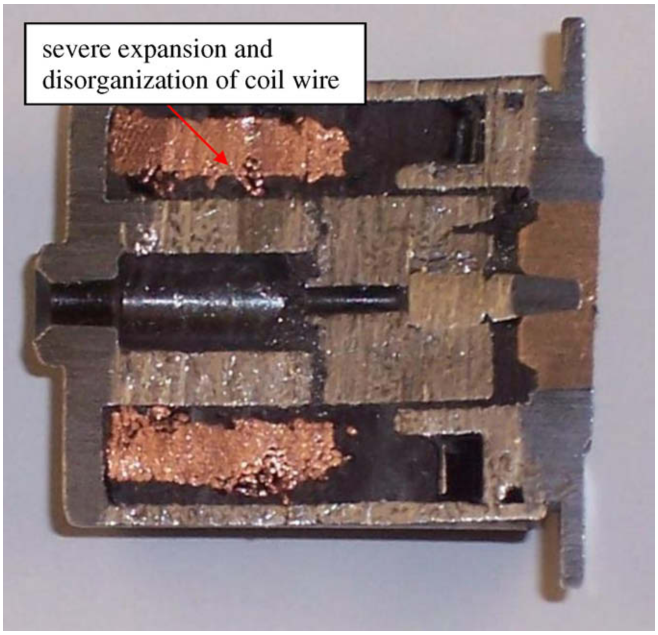

Fig. 23. Cross-section of (c) type solenoid valve.

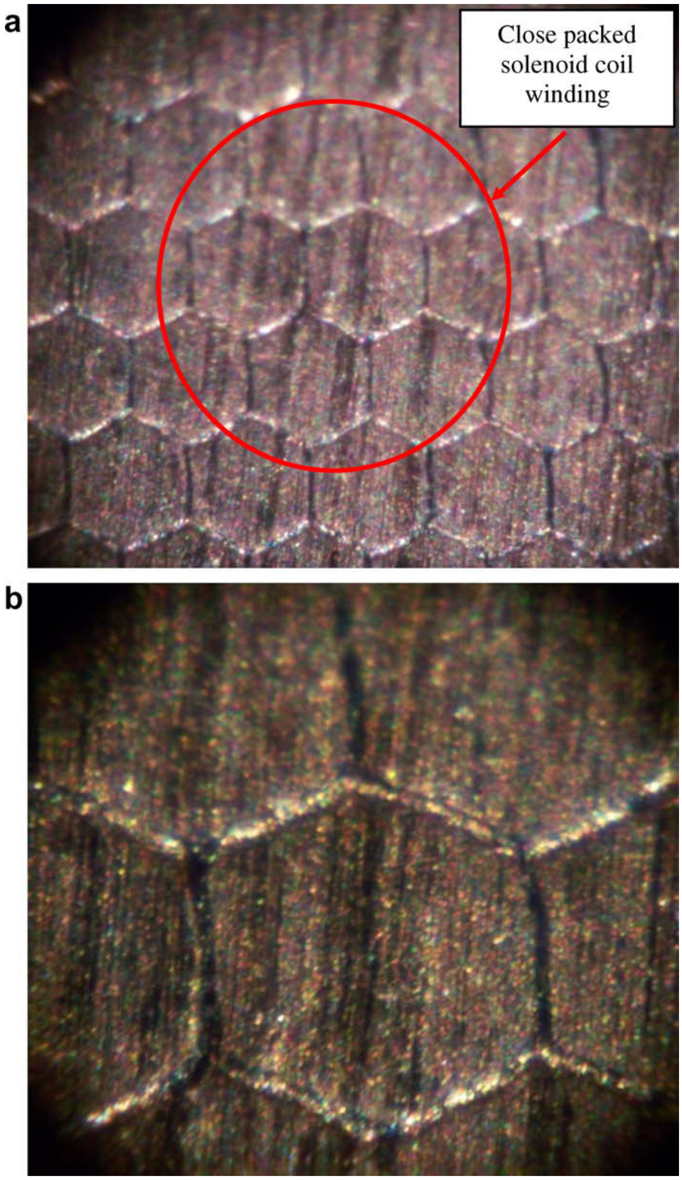

Fig. 24. Microscale photographs of the case (a) solenoid valve cross-section.

200–250 °C). Also, at complete failure, there is good amount of expansion or spreading out of the wires observed in the coil region (Figs. 26 and 27) whereas for the (a) case, the copper wires remain neatly arranged in a hexagonal manner (Fig. 24).

Now, coming to case (a), none of the features seen in (c) case can be observed and the copper windings at the end of a 24 h test are seen to possess the same helical coil structure along with the insulation material between them, which is typical of an operational solenoid valve (see Fig. 24). In fact, this verifies the very definition of a solenoid coil or solenoid which is defined as 'a long wire wound in a close packed helical structure'[21]. However, even for the tested type (a) solenoid coils, the wires appear to have been compressed together to become hexagonal in shape (originally they were circular). As found in the finite element model, the increase in coil temperature can cause very high compressive stresses which will press the coil wires together. This phenomena is also seen in the other failed solenoid valves, along with more severe signs of stress in the coils.

In case (b) (see Fig 27), a partial failure of the SV can be recognized in that the windings at one end have undergone expansion towards the central part of solenoid valve (see Fig. 22). This is observed to a smaller extent than that seen in the (c) case where a large amount of expansion of the windings toward the central part of the SV can be seen in several regions of the coil (see Figs. 26 and 27). Therefore, it is observed that there is disorder of the wire winding arrangement in both the partially (intermediate disorder) and completely (excessive disorder) failed SVs which does not occur in case (a) solenoid valves. Also, there are no vacant regions in the coil region as there is no melting of the plastic material since

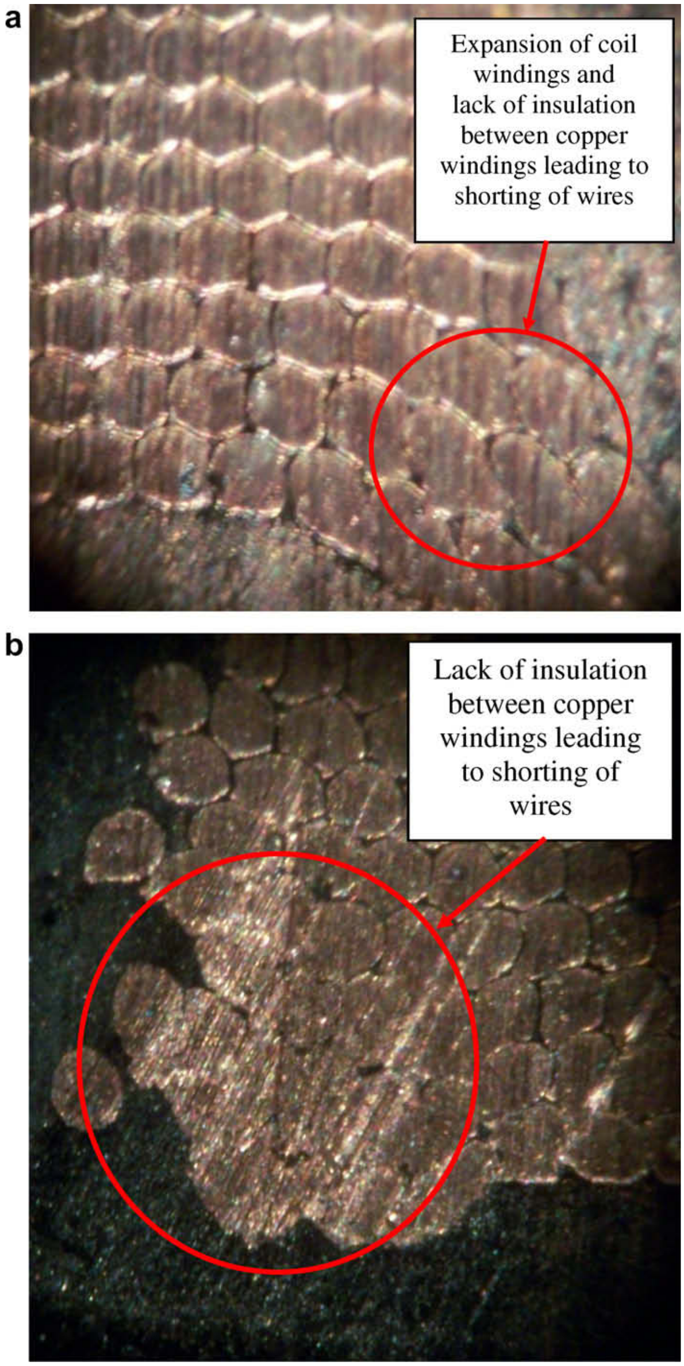

Fig. 25. Microscale photographs of a type (b) solenoid valve.

the maximum temperature values recorded in the (b) cases is less than those in (c) cases. However, a lack of insulation between the copper windings that causes shorting between them is noticed. It appears that, due to shorting only, the resistance has dropped from the original value of about 3.4 Ω to about 2.9 Ω in both of the two partially failed solenoid valves. Thus, due to a low change in resistance and no melting of plastic material, these valves are classified as partial failures.

4. Conclusions

An experimental rig to test the solenoid valves has been fabricated and solenoid valves are tested at a constant current, duty cycle and actuation frequency for a fixed duration to characterize their reliability. The solenoid valves are also placed

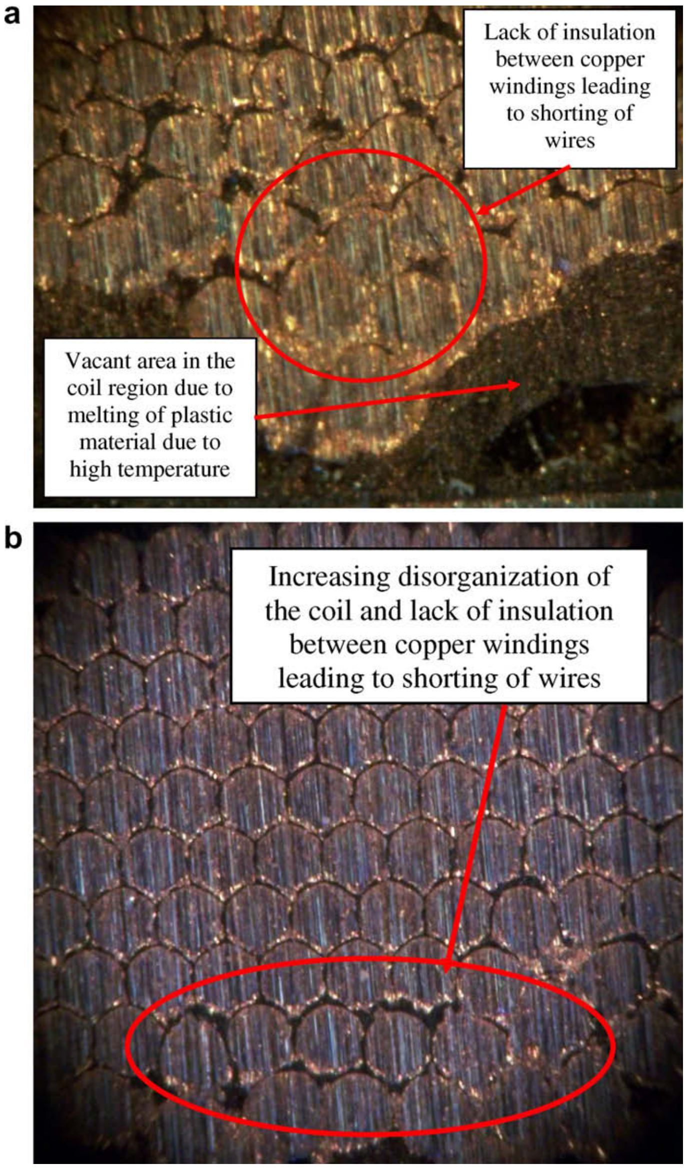

Fig. 26. Microscale photographs of type (c) solenoid valve cross-sections (part 1).

inside a thermal chamber that is held at a constant elevated temperature that is similar to what is seen in the automotive transmission application. The influence of temperature on solenoid valve reliability and life is then observed to be very important. Additionally, during testing of a solenoid valve, valuable information such as real-time applied voltage, current flow and resistance and frequency of solenoid valve cycling has been obtained.

For 100 °C ambient temperature, 50% duty cycle, 16.8 V of applied voltage, and 60 Hz actuation frequency, failure of the solenoid valve was repeatedly caused for many test samples. It appeared that samples that reached a temperature of 200 °C failed completely due to melting and degradation of the insulation between the coil wires (as predicted by the finite element model, see Part 1 of this work). Once the wires begin to short, the overall electrical resistance of the solenoid valve decreases. Since a constant voltage was applied to the tested solenoid valves, the applied current will then increase. They may increase the temperature further and result in very high temperatures in the solenoid valve (up to 300 °C). The temperatures are so high that the metal casing and core discolors to blue and plastic within the solenoid valve melts and exits the casing. The melting plastic can also inhibit motion of the plunger. This is the observed dominant failure mechanism in this work. Microscale photographs of the coil cross-section also revealed that the wire structure of a failed solenoid valve was much less organized than the tight hexagonal structure of a functioning solenoid valve. In addition, at the microscale, the shorts between the coil wires can be seen where the insulation has been squeezed out from between the wires.

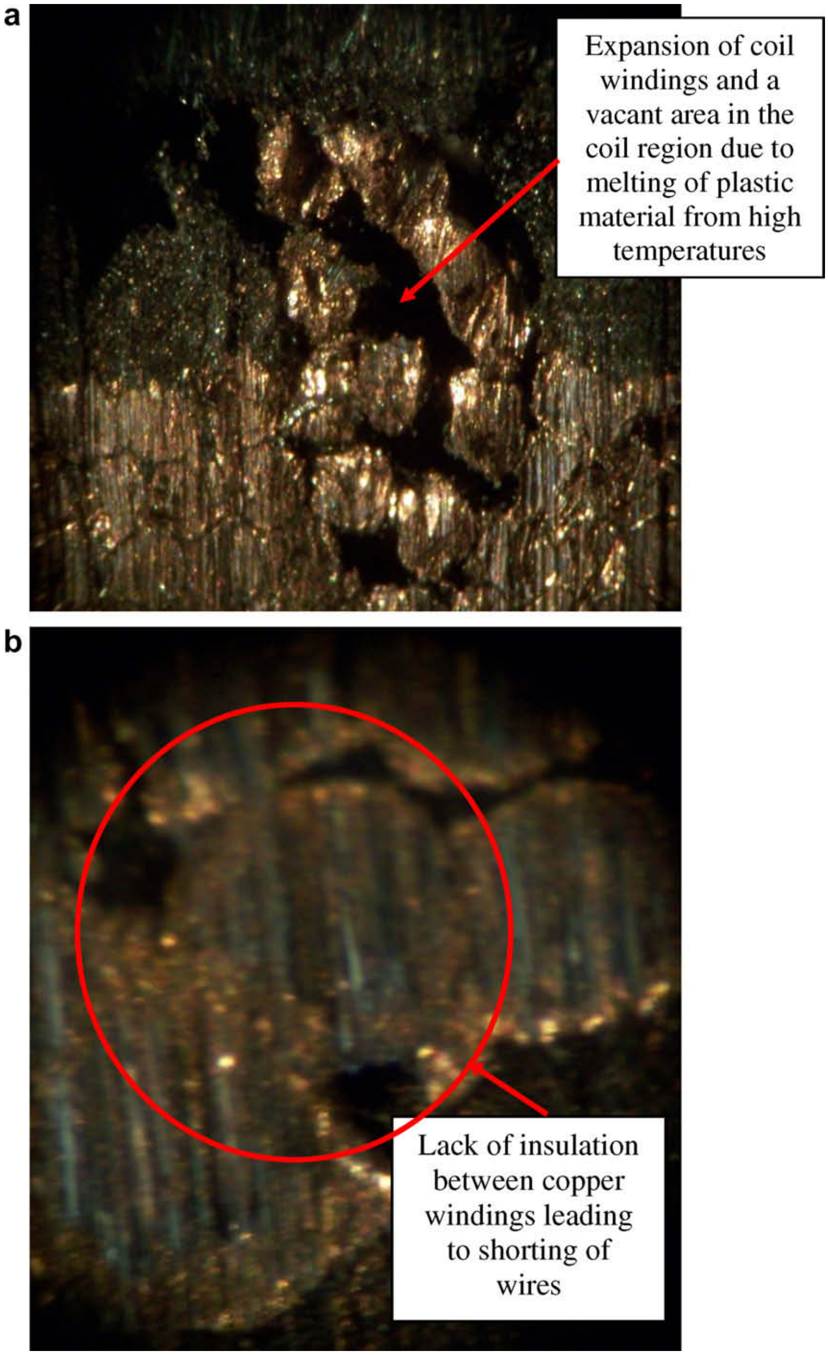

Fig. 27. Microscale photographs of type (c) solenoid valve cross-sections (part 2).

Acknowledgements

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