Thermal Buckling Behaviour of Fuse Wires

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Abstract

Previous observations in the fuse reliability investigation indicated that cyclic currents gave rise to resistance changes and buckling of fuse elements. In this report, the authors present thermal buckling observations of wires due to d.c. currents and pulsed currents. Wires in two types of commercial miniature fuses were used as test objects. The average temperature rise across a fuse wire is determined according to resistance measurements. Observations of displacements have been performed by using high speed photography for pulsed currents and a microscope for d.c. currents. A simple analytic approach is given to calculate the displacements due to thermal effects. The interaction between the motion of the fuse wire and the thermal expansion is discussed. Quantitative agreement has been achieved between theoretical predictions of displacements and experimental observations from both microscope and high speed photography. As regards the critical temperature rise for thermal buckling, discrepancy between experimental results and theoretical values can exist. Finally it is concluded that only a part of thermal strain is contributed to mechanical strain from both theory and experiments. During buckling, this fraction is almost constant.

Keywords: electric fuse, thermal buckling

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Notation

\( A \)  
cross sectional area
\( E \)  
modulus of elasticity
\( F \)  
force
\( I_n \)  
area moment of inertia about neutral axis
\( k \)  
spring constant
\( d_f, L_f \)  
diameter and length of a fuse wire (17.5 [mm])
\( I, i, i(t) \)  
current through the tested fuse
\( l_c \)  
undeformed length
\( M \)  
moment
\( P \)  
compressive force
\( P_\sigma \)  
critical load
\( q \)  
gravity for a unit length
\( R_0 \)  
initial resistance before the pulsed current
\( R(t) \)  
time dependent resistance during the current flowing
\( R(L_1, T), R(L_2, T) \)  
measured resistances for the length \( L_1 \) and \( L_2 \) at temperature rise \( T \)
\( t \)  
time
\( T \)  
temperature difference referred to initial temperature
\( T_\sigma \)  
critical temperature rise
\( X, Y, D \)  
displacements in \( x, y \) and radial directions
\( x, y, z \)  
coordinates
\( x_c, y_c, z_c \)  
local coordinates
\( U, u, u(t) \)  
voltage across the tested fuse
\( U_T \)  
total potential energy
\( V \)  
shearing force
\( W_b \)  
energy due to the length increase
\( W_d \)  
deformation energy due to the compression
\( W_m \)  
strain energy due to bending
\( \alpha \)  
temperature coefficient of the electrical resistivity
\( \beta \)  
coefficient of free thermal expansion
\( \delta \)  
deflection factor
\( \rho \)  
electrical resistivity
\( \rho_m \)  
radius
\( \Delta I \)  
change in \( I \)
\( \Delta \epsilon_{th} \)  
thermal strain
\( \Delta \epsilon_a, \Delta \epsilon_m \)  
apparent strain and mechanical strain
Chapter 1 Introduction

Fuses are protective devices for electrical circuits and equipment. They are designed to carry the nominal current and to safely interrupt faulty currents. Fuses are classified into three categories: miniature fuses, low voltage fuses and high voltage fuses. A conductive strip or wire in the fuse, which carries the current, is academically defined as a fuse element.

One of the principal characteristics of a fuse is its $I - t$ characteristic. It is defined as a curve where the value of melting time is expressed as a function of the prospective symmetric current, under stated conditions of operation. In the short time range, the Joule integral $\int I^2 t$ is defined as the integral of the square of the current over a given time interval.

In a wide variety of applications, deterioration of $I - t$ characteristics can lead to unreliable functioning of electrical systems. In order to improve the reliability of electrical system, reliable application and lifetime estimation of fuses are required by users and manufacturers.

1.1 Lifetime study of fuses

During normal load situations, the current through fuses may be grouped conveniently under two headings: continuous current and pulsed (cyclic) current.

- Continuous load current is defined as the current under the stationary condition carried by fuses at the normal load.
- A cyclic current is specified as a repeated pulsed current with a certain on time and off time. The waveform of pulsed current is the same in each period. Cyclic currents take place in the circuits of power electronics, for example, rectifier circuits. Motor starting current, inrush magnetizing current of no load transformers, inrush current on charging capacitor or capacitor banks can also be considered as pulsed currents.

Limitation of fuse lifetime, caused by oxidation of silver coated copper wires, was investigated [Nutsch, 1991] for continuous currents.

For cyclic duties, compressive stresses are induced due to temperature rise during current flow. During the period without current, the compression is released due to cooling. This thermal effect becomes cyclic in nature. More than continuous heating, this cyclic heating results in ageing of the fuse element. In the former investigations, resistance changes, movement and cracks of fuse elements have been noticed. Some specific properties are stated below.

For fuse selection for the protection of semiconductors, it was recommended [Stevenson, 1976] that the r.m.s. value of an occasional overload current should not exceed 85% of the current value from $I - t$ characteristics for the same duration. For frequent overload currents, the limit was reduced to 70%. For cyclic duties, the current for the on time was suggested not to exceed 50% of the value of current corresponding
to $I - t$ characteristics. For this duty and in case of overload duration above 1 hour, the r.m.s. current was limited to the rated current. It was suggested that the lifetime of fuses be consumed by electric currents.

After 15 kV high voltage expulsion fuses were exposed to cyclic currents, deterioration of $I - t$ characteristics has been observed [Mocarzel, 1989]. Fuse wires made of copper, tin silver copper alloy, and tin lead alloy were used in the experiments. The amplitude of pulsed current was 120% of the fuse rated current. The on time was 1 hour. A long off time was adopted to cool down the tested fuse.

For high voltage fuses, experimental motion studies of elements have been undertaken for model fuselinks [Arai, 1983] in cyclic lifetime tests. The notched fuse element was made of silver. For a straight fuse element, movement of the element was observed during pulsed current by X-ray photography. When fuses experienced cyclic currents, originally bent fuse elements were changed into ripples.

As regards the resistance changes, measurements have been performed on different element materials. The on time of pulsed current was 1 hour during the cyclic tests. Fuse elements of silver, copper, silver coated copper, nickel coated copper [Nutsch, 1991] copper, tin silver copper alloy, and tin lead alloy [Mocarzel, 1989] were studied.

The microstructural changes of subminiature fuses have been examined by using scanning electron microscope (SEM) and energy dispersive X-ray microscope (EDX) [Williams, 1981]. The fuse elements were made of silver copper alloy wires. After the wire experienced the pulsed current of an on time up to 225 microseconds, partial melting and recrystallization were found in localized areas within the grain structure. Segregation was found at the surface of a wire. After fuses were applied to cyclic currents [Arai, 1983; Mocarzel, 1989] and continuous current [Nutsch, 1991], cracks induced in the fuse element have been reported.

Several methods for lifetime estimation for specified currents were presented in the past.

For fuses, exposed to a cyclic current, the number of pulses which fuses can withstand, was considered as a linear function of the percentage of the rated current [Stevenson, 1976]. The on time and off time from five seconds to 10 minutes were used during tests.

Taking the energy dissipation during the pulse current as criteria [Williams, 1982], lifetime limits were determined for fuses of copper silver alloy wires. The thresholds of lifetimes at different temperature rises were expected to be: maximum lifetime condition at 100 °C; greater than 20000 cycles at 300 °C; greater than 1000 cycles at 500 °C; potential single pulse at 800 °C.

For cyclic duties, based on the Manson - Coffin law, ageing in fuse elements was explained by thermal fatigue and crack growth. Cracks were found in the element notches and also along fuse wires. Lifetime data were presented [Arai, 1983; Costa, 1990] as a function of current. As the thermal effect was taken into account directly [Wilkins, 1990], the lifetime observations were fitted and presented as a function of a combined
variable of temperature rise and mean temperature. A coefficient has been introduced [Arai, 1983; Wilkins 1990] to relate the mechanical strain when deflections occur with lifetime estimation. In principle, its value can be determined from the lifetime regression analysis.

For both cyclic currents and constant currents, fuse lifetimes have experimentally been found to decrease as the amplitude of current increases. In the above methods, the estimation relies on the curve fitting of experimental data in lifetime tests and thus reliable applications of fuses highly depend on experience.

Since 1990, the experimental evaluations of fuse lifetimes have been undertaken [Meng, 1993] on miniature fuses provided by Littelfuse BV, Utrecht, the Netherlands.

Experiments started with miniature fuses made of a silver clad tin-zinc alloy wire. The fuse wire about 17.5 mm long was positioned inside a tubular glass body. In cyclic tests, the pulsed currents of rectangular and half sinuous waveforms were applied. The on time of the rectangular pulsed current was varied from 5 ms to 12 ms and off time two seconds to eight seconds. The on time of the pulsed current with the half sinuous waveform was 7.5 ms and the off time was seven seconds.

Significant resistance changes and motion of fuse elements have been detected during the lifetime of fuses. Resistances were measured until operation of fuses. From 18 series of tests, it was found that the average resistance just before fuse operation was about 110% of initial resistances.

It was observed that the lifetimes decreased as the \( I^2t \) value of pulsed current increased. Based on the stress-strain relationship, a model has been established to estimate the fuse lifetime. In the model, the stress release due to the motion effects has been allowed for. The coefficient related with the mechanical strain is defined as a deflection factor. The deflection factor required can be determined by high speed photography and the value is independent of lifetime data. Unfortunately, difficulties of the model arise for general applications.

Obviously, fuse lifetimes are influenced by deformation or deflection of the element. However, the physical mechanism behind it or how the deflection factor depends on the fuse element construction is still badly understood. It is therefore very important to investigate the buckling behaviour or motion of current carrying fuse elements.

1.2 Thermal buckling

Mechanical components are designed to endure static and dynamic loadings. When they are subjected to temperature variations, they tend to buckle and produce large deflections and sometimes become unstable. This instability has drawn considerable attention and has been widely investigated for various constructural components in mechanical engineering in the past. It continues to this day to be a topic of interest [Reissner, 1989; Simões, 1990]. Thermal buckling is a term used to describe this instability due to thermal origin. Thermal buckling solutions are dependent of boundary conditions, component geometry and temperature distribution.
Miniature fuses are defined as being for the protection of electric appliances, electronic equipment and component parts thereof normally intended to be used indoors. A miniature fuse is composed of a fuse wire or element, end caps and glass tube. For the reason of simplicity, the fuse wire is considered straightly positioned inside a tubular glass body as shown in figure 1.1 and thus it is visible. The wire ends are fixed onto two end caps. Therefore, the fuse wire can be assumed to be a column with two fixed ends. The column is one of the components in mechanical engineering.

To explain the basic concept of buckling, first the wire is assumed to be initially stress free and uniformly made. As regards the boundary conditions, the wire is assumed to be a symmetrically fixed end column. The assumption implies that

- The fixed ends are statically responding to any load;
- The offset differences at end positions in manufacture are omitted.

Column dimensions are simplified to be wire diameter and length. The basic geometry and notation for the fuse wire are shown in figure 1.2, where the wire length $L_f$ is taken to be 17.5 millimetres. The coordinates are assigned according to figure 1.2 (a).

When a force $P$ is exerted on the end of the column in figure 1.2 (b), first this only results in compression. As the force $P$ is increased further, movement of the column occurs in the direction perpendicular to the force $P$. In another words, buckling happens. This force is noted as a critical load $P_{cr}$. From the literature [Timoshenko, 1961; Thangaratnam, 1989], this load can be determined. The buckling of column under various boundary conditions has been widely studied [Timoshenko, 1961]. For a fixed end column, as is shown in figure 1.2 (c), the displacement can be described by

$$D = 0.5 \, D_{\text{max}} \left( 1 - \cos \frac{2\pi z}{L_f} \right) \quad (1.1)$$

where $D_{\text{max}}$ is the amplitude of the displacement. The formula is valid for constant load and uniform column with fixed ends.

When an electric current flows, the wire attempts to expand as the temperature of the wire rises due to joule heating. As temperature rise passes a critical limit, the wire starts to move and buckling takes place. Accordingly, this limit is defined as a critical temperature rise.

As regards the effects of temperature rises, the following assumptions are made:

- As current flows through the fuse wire, the temperature distribution is uniform along z axis;
- The deflection is small and the deformation is elastic.

The first assumption implies that the heat transfer from the wire to end caps is neglected. The second assumption resumes that law of elasticity can be used directly. Under the above assumptions, the displacement equation (1.1) is considered valid for thermally induced displacement.
It is well known that free thermal expansion of a wire can be calculated as $\beta T L_f$ in a small strain range. From equation (1.1), the increase of length is derived to be $(\pi d_{max})^2/(4*L_f)$. At first glance, it seems that the increase of length is equal to the free thermal expansion of the fuse element.

However, because of boundary constraints, compression of the fuse wire takes place during the pulsed current. The free thermal expansion will be larger than the calculated length increase by using equation (1.1). Unfortunately, in literature a direct analytic approach has not been found to calculate this difference. To understand the mechanism, this work is initiated.

1.3 Scope of this work

As discussed in the first section, the motion, resistance changes and crack growths are three basic phenomena in fuse ageing. They are related with the fuse lifetime reduction. To study the physical origin of fuse ageing, for simplicity, miniature fuses are chosen as test objects in this report. Attempts will be made to predict the buckling of fuse wires. Efforts are also to be made to measure the displacements during buckling by microscope and high speed photography. The contents of this report are outlined as follows:

Chapter 2 presents experimental results of temperature dependence of resistivity of fuse elements. According to these characteristics, the temperature rise is determined from the measured voltage and current in the following chapters.

Chapter 3 covers effects of d.c. currents on displacements for fuse elements.

Chapter 4 presents observations of displacements during the pulsed current for Ag/Sn-Zn fuse elements.

In chapter 5 a theoretical model is established to predict maximum displacements due to thermal effects caused by d.c. current and pulsed current. Comparison of observations with calculations is presented.

Chapter 6 summarizes main conclusions from the previous chapters. A few suggestions are also made in the chapter for future work.

The objectives of this work are to understand the interaction between the motion and the thermal expansion of fuse wire and to predict the displacements for any specified current. Other basic problems such as the dependence of lifetime on resistance, oxidation and crack growth will not be covered in the work.
Chapter 2  Dependence of resistivity on temperature

2.1 Introduction

To study thermal buckling of fuse wires, the temperature rise of fuse wire has to be determined for pulsed currents and d.c. currents. Because of obvious difficulty to directly measure the temperature rise of thin fuse wire, an alternative approach is to be adopted. As the temperature rises, the resistance of the wire increases. When an electric current is passed through a fuse wire, the resistance can be obtained from the measured voltage and current. Afterwards the average temperature rises can be evaluated from resistance changes. Therefore the key point is to find the relationship between temperature rise and resistivity or temperature coefficient of resistivity.

In this chapter, attempts are to be made to realize different procedures to measure the resistance of fuse wires by using a micro-ohmmeter and the four terminal method.

2.2 Descriptions of resistivity measurements

Two types of wires were used as test objects. Type A was a pure nickel wire and type B was a silver clad alloy wire (Ag/Sn-Zn). Type B was made from 50% silver and 50% alloy (85%Sn &15%Zn) by weight. The values of diameter are 50 μm for type A and 103 μm for type B. For type B wires, the cross sectional dimension is shown in figure 2.1.

For type A wires, the resistivity data can be found in the references [Goldsmith, 1961; Tslaf, 1981]. For type B wires, the resistivity data at different temperatures are not known. Because of the relatively small diameter of wires, the resistivity might be influenced by the manufacture process. For this reason, resistivity measurements are needed.

A temperature stabilized oven was used to heat sample wires. The heating temperature of the oven was up to 600 °C. Indicated temperature values on the control panel TCN4 of the oven were inspected by a thermometer. The maximum difference was found to be 7 °C among temperature values of 100, 200, 300, 600 °C.

In the experiments, resistance of sample wires was required to be measured corresponding to different temperatures. Contact resistance and connection resistance may cause errors in the measurement of low resistance. In order to accurately define a resistance it is necessary to cancel or limit these influences.

At room temperature, resistance of sample wires for given lengths was accurately measured by a Keithley model 580 micro-ohmmeter. The measuring scheme is shown in figure 2.2. The measuring probe a and b were positioned at the point aa and bb of the fuse wire. The resistances of probe a and b were eliminated due to the design of the micro-ohmmeter. Thermoelectric voltages due to junctions of dissimilar metals in the circuit were eliminated by the micro-ohmmeter in the so called 'pulse drive mode'. Therefore, the measured resistance $R$ was simply the wire resistance at given length. On the lowest range 200 mΩ, 10 μΩ resolution can be achieved according to the
manufacturer data of the micro-ohmmeter. The wire length was measured by using a rule, the absolute error is 0.5 millimetre. The relative error can be easily limited to be smaller than 1% for a length of about 3 cm.

Figure 2.3 presents the setup for measuring the connection resistance $R$ at different temperatures without fuse wires. The measured resistance $R$ consisted of the connection resistance $R_1$ from point $aa$ to point $c$, the contact resistance $R_2$ between point $c$ and point $d$ and the connection resistance $R_3$ from point $d$ to point $bb$. The connection resistance $R$ was 20 mΩ at the room temperature.

Figure 2.4 shows the setup for measuring the resistance of nickel fuse wires. The measured resistance $R$ consisted of the sample resistance $R_{ni}$, the connection resistance $R_1$ from point $aa$ to point $c$, the contact resistance $R_2$ between point $c$ and point $cc$, the contact resistance $R_4$ between point $d$ and point $dd$ and the connection resistance $R_3$ from point $d$ to point $bb$. This resistance was measured in the temperature range from 20 to 620 °C. A long sample wire was used to obtain the electrical resistivity. The resistance of the sample wire was chosen to be about 3 ohm at the room temperature and therefore relatively accurate measurements can be achieved.

Because of low resistance of an $Ag/Sn-Zn$ wire, different measuring methods were employed. Moreover, the melting temperature of this material was between 198 and 250 °C according to the manufacture information. This suggested that above 198 °C, diffusion between silver and alloy (Sn-Zn) brought about some influence on resistance. It might lead to an increase in resistivity. To reduce the material diffusion influence on resistivity, the measuring time at high temperature above 200 °C should be kept as short as possible.

First the two wire method was used, the measuring scheme is the same as shown in figure 2.4. The measurements were performed with two wires, these wires have different length $L_1$ and $L_2$. The resistance difference between these two measurements is only dependent on sample wire resistance, as the contributions of the connections and contacts are cancelled. Therefore, the resistivity is independent of the wire length and connections.

On the other hand, the connection resistance has been measured according to the measuring scheme in figure 2.3. The resistance of $Ag/Sn-Zn$ can be obtained by subtracting the connection resistance from the measured resistance in principle.

The four terminal method was also applied to measure the resistance of $Ag/Sn-Zn$ wires. The scheme is shown in figure 2.5, the resistance of the sample wire can be figured out by the ratio of voltage to current. A Keithley 179 TRMS digital multimeter was used to measure the current. The measuring current was supplied by a d.c. source. The supply voltage was in the range from -15 to 15 volts. The d.c. source was in series with a 200 ohm resistor. The measuring current was regulated to have a constant value of 40 mA. The rated current of the wire was 800 mA and therefore the temperature rise caused by the measuring current can be neglected as compared with the oven temperature. A Fluke 8000A digital multimeter was used to measure the voltage across the sample wire. The measured resistance $R_m$ was the result of sample resistance $R_s$ and volt meter resistance.
Resistivity \( R_v \) ( \( R_v > 10 \, \text{M}\Omega \) ) in parallel.

### 2.3 Results and discussion

Resistance increase is contributed by the resistivity change, length increase and the cross sectional change. Thermal expansion coefficient is about \( x \times 10^{-5} \) and temperature coefficient of resistivity for metals and alloys is about \( x \times 10^{-3} \), where \( x \) is a digit from 1 to 9. In this study, the contribution from dimensional changes is about 3% of the contribution due to resistivity change. Therefore, the resistance change due to length increase and cross sectional increase is neglected. Consequently, the wire diameter and length are assumed to be kept constant for the determination of resistivity.

The connection resistance is shown in figure 2.6 as a function of oven temperature. It consists the contributions from the measuring wires both inside and outside the oven. Because two parts have fixed lengths for measuring the connection resistance and the sample resistance, the influence on the sample resistivity is cancelled. The data can be fitted into a line and hence the resistance of connection is described by

\[
R_{con} = R_{co}(1 + \alpha \, T)
\]

where \( R_{co} \) is the resistance at reference temperature (the temperature rise \( T=0 \, ^\circ\text{C} \)) and \( \alpha \) is the temperature coefficient of resistivity. \( R_{co} \) and \( \alpha \) were found to be 18.9 milliohm and \( 3 \times 10^{-3} \) by using a linear curve fitting method.

For type \( A \) materials, the measuring results of resistivity according to the scheme in figure 2.4 are presented in figure 2.7 and compared with a relationship from the reference \[Goldsmith, 1961\]. At a temperature of 20 \( ^\circ\text{C} \), the resistivity of nickel wire was measured to be \( 8.9 \times 10^{-8} \, \text{ohm.m} \). It was the same as given by the wire manufacturer. From two references, the values were found to be \( 6.92 \times 10^{-8} \, \text{ohm.m} \) \[Tslaf, 1981\] and \( 7.2 \times 10^{-4} \, \text{ohm.m} \) \[Goldsmith, 1961\]. As the temperature increases up to 320 \( ^\circ\text{C} \), the phase change point is reached. The temperature observed in this experiment was lower than 365 \( ^\circ\text{C} \) which was given in the reference \[Goldsmith, 1961\]. Above this point, the resistivity increases at a slope more or less comparable to the slope in the reference \[Goldsmith, 1961\]. As the observations were compared with properties from other sources which were presented with different types of marks in the reference \[Goldsmith, 1961\], a reasonable agreement was recognized. Because of phase change, the resistivity is a nonlinear function of temperature rise.

For type \( B \) material, a sample wire 37 cm long was used in measuring the resistivity at room temperature (20 \( ^\circ\text{C} \)). The resistance was obtained to be 1.645 ohm and thus the resistivity was \( 3.7 \times 10^{-8} \, \text{ohm.m} \) at this temperature. The measuring data of resistances of two different lengths are displayed in figure 2.8. From these data, resistivity can be calculated.

The measuring data of resistance by subtracting the connection resistances are presented in figure 2.9. Results from the four terminal method are presented in figure 2.10.
Comparison among results obtained by using different measuring methods is made in figure 2.11 for type B material. Below 200 °C, the resistivity obtained from the different methods falls in the same range and can be fitted with a linear function of temperature. The coefficient is found to be $4.5 \times 10^{-3}$. For higher temperatures, the spread in resistivity for each measuring method drastically increases. This is probably due to the oxidation and the diffusion between different atoms in the fuse element. Both processes depend on temperature and time. Because diffusion of Ag/Sn-Zn wires is not known, this coefficient is still assumed in the temperature range from 200 to 300 °C in the following chapters. This assumption is probably only valid for the short current conducting time.

Finally, it is concluded that the resistivity of nickel wires is a nonlinear function of temperature. For Ag/Sn-Zn wires, the temperature coefficient has been found to be $4.5 \times 10^{-3}$ in the temperature range from 20 to 200 °C.
Chapter 3  A study of effects of d.c. currents on buckling

3.1  Introduction

When fuse wires are heated by electric currents, thermal expansion of the wire is caused. As discussed in the first chapter, a fuse can be imposed with continuous current or pulsed current. This chapter describes attempts to observe the buckling effects of fuse wires due to d.c. currents. The objective of this experiment is to find a correlation between the displacement and the temperature or d.c. current.

3.2  Experiment

Two types of fuses were taken as test objects, fuse wires were made of the materials mentioned in chapter 2. Two ends of the wire were soldered on to the fuse end caps. The overall length of fuses was 20 millimetres and the length of fuse wires was taken as 17.5 millimetres. The fuse wire was assumed to be made and constructed uniformly.

The experimental setup is shown in figure 3.1 (a). The d.c. current in test can be supplied up to 10 amperes by changing the supplying voltage of a d.c. source from 0 to 50 volts. The test current was measured by a Fluke 8000A digital multimeter. As the test current was above the measuring limit, the voltage across a standard resistance $R$ of 50 ohms was measured. The test current was then defined according to the resistor voltage. The voltage across the fuse was measured by a Keithley 179 TRMS digital multimeter. The current was turned off by switch $S$. To reduce the influence of creep, oxidation and diffusion, the measuring time was kept as short as possible.

When the d.c. current was exerted to fuses, under the stationary situation displacements were measured by using a NIKON microscope. The amplification consisted of the contributions from a large format adaptor (four times), a CF PL projective lens (2.5 times) and an objective lens (five times). An amplification of 50 was used and thus a length of 1 mm in the eye piece corresponded to a length of 20 $\mu$m of the real object. Consequently, the minimum amplitude of detected displacement was 10 $\mu$m.

Before measurements of the displacement are carried out, it is necessary to know whether the glass tube of a fuse will influence the measuring results or not. For this reason, the diameters of bare wires were measured by the microscope first without current. Later the diameters of fuse wires covered with the glass tube were measured with and without current flowing.

In principle, the buckling could be expected to take place in a random direction, because the displacement due to the wire weight is negligible. Five different ratings of fuses (with similar wire shape) were tested to examine the buckling behaviour. The measuring scheme of displacements is shown in figure 3.1 (b), where $X$ and $Y$ show the measuring direction for the displacements along the $x$ axis and the $y$ axis. By moving the object station of the microscope along the $z$ axis, the displacement of the tested wire can be obtained at different locations of the $z$ axis. The displacement values of $X$ and $Y$ were derived from measurements with observation angles differing 90 degrees for different
3.3 Results and discussion

From the diameter measurements, diameter values of wires given by manufacturer were confirmed by the measured bare wire diameter with a deviation of about 3 μm. The average diameter of wires in the glass tube with and without current flowing is the same as the mean of bare wires. The deviation is about 10 μm and is consistent with the accuracy determined by the setup. From these results, it is assumed that the influence of the glass tube on the displacement can be neglected.

For nickel fuse wires, an example of measured displacements X and Y is given in figure 3.2. In the figure X is the displacement in the direction of the x axis; Y is the displacement in the direction of the y axis and D is the total displacement. The cold resistance of the fuse was 769 mΩ. The d.c. current in the test was 505 mA; the voltage was 1.80 V and the resistance was 3.56 ohm.

In measuring displacements, four nickel fuse samples were used. Figure 3.3 (a) presents voltage - current characteristics of nickel wires in the current range from 0 to 700 mA. In order to view the details in the small current range, voltage - current characteristics in the current range from 0 to 400 mA are presented in figure 3.3 (b). Corresponding displacements at the middle point of fuse wires are shown in figure 3.4 for different d.c. currents.

Buckling mode examination is made in figure 3.5 for a silver-alloy (Ag/Sn-Zn) wire. In the figure X is the displacement in the direction of x axis; Y is the displacement in the direction of y axis and D is the total displacement. The test current was 960 mA and the voltage across the fuse was 82 mV. The cold resistance was measured to be 79 mΩ at a current of 80 mA.

Five fuse samples of Ag/Sn-Zn wires were used to measure the displacements at the middle point of fuse wires. Figure 3.6 presents voltage - current characteristics of Ag/Sn-Zn wires. Corresponding displacements at the middle point of fuse wires are shown in figure 3.7 for different d.c. currents.

For nickel fuse wires, the value of d.c. current for visible displacements is found about 183 mA in figure 3.3 and figure 3.4. The buckling starts nearly at the same current, the deviation is smaller than 5 mA. The current is 58% of the rated current of the fuses.

For Ag/Sn-Zn fuse wires, the average value of d.c. currents for the buckling was 308 mA with a standard deviation of 209 mA in figure 3.6 and figure 3.7. The minimum d.c. current for buckling is 80 mA which is 10% of the rated current of fuses; the maximum value is about 600 mA for visible displacements. Four fuses start to move at relative small currents, the buckling of the other sample takes place at the highest current of 600 mA. The different response may be brought about by the spread of fuse wire dimensions and the connection difference.

During buckling, the wire motion was observed to have a predetermined direction. A
possible reason is that in practice fuse wires were not uniformly made or connected to the end caps. After buckling, the wire moved slowly backwards. Very small differences existed between the new position of wire and its original position before the current was applied. The maximum value was found to be 20 μm in the experiments. It is about 2% for nickel fuse wires and 4% of the total displacement for Ag/Sn-Zn wires. Fortunately, this difference did not grow up after several measurements. Perhaps a prestress has been built up during the fuse manufacturing. During the experiments, some kind of conditioning is created and consequently the prestress is compensated.

Voltage - current characteristics are shown in figure 3.3 and figure 3.6 for two types of fuses. It can be seen that the voltages across fuses increase with d.c. currents.

In figure 3.8, the measured displacements due to the d.c. current of 505 mA are presented as cross markers for a nickel fuse wire. In figure 3.9, the measured displacements due to the d.c. current of 960 mA are presented for a Ag/Sn-Zn fuse wire. Measurements in figure 3.8 and figure 3.9 were performed at the different locations along the z axis for a fuse wire.

Figure 3.8 shows that the displacements are likely symmetric against the position z = 10 mm. However, figure 3.9 shows a shift in the buckling. The maximum displacement occurred at z > 10 mm. A possible reason for these phenomena is asymmetry of the fuse connection.

From voltage and current measurements, the resistance of fuse wires can be found out. Results of resistance are given in figure 3.10 for nickel fuse wires and in figure 3.12 for Ag/Sn-Zn fuse wires.

In chapter 2, the resistivity relationship between the fuse wire material and the temperature has been defined, thus for a specific resistance value, the temperature of the wire may be obtained. The displacement as a function of temperature rise is given in figure 3.11 for nickel fuse wires and in figure 3.13 for Ag/Sn-Zn fuse wires.

3.4 Conclusions

For both types of fuses, buckling can be observed for the d.c. current. After the current was switched off, the wire went back to its original shape. During buckling, the wire motion has a predetermined direction. The measurements show that the displacement of wires increases as the d.c. current or temperature rises.
Chapter 4 Effects of pulsed currents on buckling

4.1 Introduction

As a fuse is exposed to a pulsed current, thermal expansion of the fuse wire occurs. Thermal strain is defined as a strain originated by temperature rise. The magnitude is equal to the product of the thermal expansion coefficient and the temperature rise of the fuse wire. The strain range is noted as $\Delta \varepsilon_{th}$.

As it is discussed in Chapter 1, the deflection may have significantly influence on the lifetime of fuses due to pulsed currents. Because of buckling, the apparent strain is produced from a part of the thermal strain. Its strain range is noted as $\Delta \varepsilon_a$. The difference $\Delta \varepsilon_m = \Delta \varepsilon_{th} - \Delta \varepsilon_a$ is the mechanical strain that will cause mechanical stress. The mechanical strain range is noted as $\Delta \varepsilon_m$.

To describe buckling phenomena, a deflection factor is introduced. This factor is defined as the fraction of the mechanical strain to the thermal strain. The deflection factor is noted as $\delta$ and it follows

$$\delta = \frac{\Delta \varepsilon_m}{\Delta \varepsilon_{th}} = 1 - \frac{\Delta \varepsilon_a}{\Delta \varepsilon_{th}} \quad \text{(4.1)}$$

Similar definitions are also given in other references [Arai, 1983; Wilkins, 1990].

In this chapter, in attempting to describe the buckling effects, experiments will be performed to detect the buckling mode and the displacement due to pulsed currents.

4.2 Experiments

Ag/Sn-Zn fuse wires were selected as test objects. The experimental setup was constructed as shown in figure 4.1. It consisted of an electric circuit to produce a single pulsed current (not cyclic), an optical system to measure the displacement during the pulsed current and computer based control units. The control units transferred control commands from a computer to triggering devices and exchanged trigger signals between the optical system and the electric circuit.

The principle scheme of the electric circuit is shown in figure 4.2. Capacitor C was loaded, when switch S closed. A resistor $R_c$ (220 ohms) was used to limit the charging current. As the switch was turned off, a pulse current was generated during the discharge of capacitor C (1.3 mF) through inductance L (2.2 mH) and loop resistance $R$ (about one ohm). Because the fuse resistance greatly influenced the current, it was therefore suggested to calibrate the circuit before experiments started.

Because of the triac Tic263M, only a positive current was allowed to flow through the tested fuse. The current during the discharge was measured by a shunt of 19.4 m$\Omega$ and a current transformer. The transformer was connected to an oscilloscope through a coax cable which was terminated with a 50 $\Omega$ resistance to match the cable impedance. In case
of the use of the shunt, the current was determined with a differential amplifier and a four-channel Bakker digital oscilloscope (12 bits, maximum 64 K memory and 1 M samples per second for each channel). Fuse voltage was determined with a differential amplifier and the Bakker digital oscilloscope.

The optical system was composed of a high speed camera (Dynafax model 350 framing camera), several lenses and light sources. Each exposure may contain 224 frames. The time resolution was chosen to be from 100 $\mu$s to 500 $\mu$s (10000 pictures to 5000 pictures per second) dependent on the rotating speed of the camera.

Before the photographic measurement, the system was aligned by means of a laser beam, a slit and a beam expander to guarantee the highest spatial accuracy in the measuring. The alignment scheme is shown in figure 4.3.

An IEEE interface PM 2101, a digital multimeter PM 2535 and a switch PM 2121 were used to measure the resistance of fuses in the time interval of two pulsed currents. To synchronize the measurement, the following procedures were made. A control signal was produced by a computer and put into delay unit PR20 via IEEE488 bus and digital I/O PM 2130. A 10-volt triggering signal with a duration of 1 ms was sent to the high speed camera. After about 40 ms, the camera shutter was released. The releasing signal was then given to the delay unit PR10. Two triggering signals of 10 volts with a duration of 1 ms were generated. One was directed to the flash tube after 2 ms. With 1 ms extra delay, the other triggering signal was organized to triac Tic 263 in the supply of pulsed currents. Shutter releasing signal from the camera and light signal from the flash tube were also written down in the oscilloscope. The light signal was taken as a time base for the dynamic displacement measuring. Meanwhile, the time reference was also obtained for the pulse current.

First an overview of the buckling mode was evaluated corresponding to a length about 5.8 mm. The visible fuse element length (10 mm) was taken as a reference for the framing pictures. Images were produced with the help of an achromat ($f=40$ mm) and a macro zoom lens. Because every exposure only took one projected component from the radial displacement, four exposure positions ($F1$, $F2$, $F3$ and $F4$) were taken to evaluate the buckling mode of the fuse element along the whole axis. The measuring scheme is illustrated in figure 4.4.

To measure displacements accurately, a larger magnification was used. The exposure positions are shown in figure 4.5 as $X$ and $Y$. An image was formed corresponding to a real object length 0.5 mm at the wire middle. The wire diameter was examined by the NIKON microscope before and after the pulsed current through the tested fuse. In the experiments, the $Pt$ values of pulsed current were chosen to be 0.22, 0.37, 0.60, 0.78 and 0.98 $A^s$ for a period of about 7 ms. For each $Pt$ value, two measurements were undertaken for the displacements in the $x$ and $y$ directions respectively. A spatial resolution of 10 $\mu$m per mm was achieved by using an achromat ($f=25$ mm) and a macro zoom lens.
4.3 Results and discussion

A typical oscilloscope diagram is shown in figure 4.6 corresponding to $I^2t = 0.98$ A²s. The measured current ($I_{fuse}$) and voltage ($U_{fuse}$) were displayed in the channel one and channel two respectively. The shutter releasing signal and the light signal from the flash tube were displayed in the channel three and channel four respectively.

The buckling mode of a fuse wire is shown in figure 4.7. This graph was made by using four exposures. Each exposure put a part of the motion along the longitudinal axis onto films with a framing time of 0.25 ms and total exposure time of 23 ms. The increase of length corresponding to the photographic measurement can be calculated.

The radial displacement $D(X, Y)$ was determined as the resultant of displacements in $x$ and $y$ directions. The measured dynamical displacement is shown in figure 4.8. It represented the displacement at the middle region (about 0.5 mm lengths) of the fuse wire corresponding to $I^2t = 0.22$ A²s. The pulsed current lasts about 6.5 ms. The figure shows that after the pulsed current flows (at the instant 2.2 ms), the buckling start immediately. The maximum displacement is reached at about 7 ms in the figure, after the pulsed current flows for about 5 ms. Afterwards, the wire starts to move slowly backwards. Therefore, the motion of the fuse wire can follow the heating process during buckling.

Maximum displacements at the middle point of fuse wires from the experiments are shown in figure 4.9 for different pulsed currents. The $I^2t$ value of pulsed currents were chosen as a variable along the horizontal axis. The maximum displacement increases with the $I^2t$ value of pulsed currents. One has to bear in mind that the experiment has been carried out for one sample at each $I^2t$ value. When more samples are used, a spread of displacements might be expected as shown in figure 3.7 for d.c. currents.

Resistance changes of fuses are mainly contributed by resistivity changes due to temperature rise. Contribution from wire length increase is negligible as stated in Chapter 2, because thermal expansion coefficient is at least 100 times smaller than the temperature coefficient of resistivity. This statement is valid for fuse wires with and without thermal buckling.

From voltage and current traces, the fuse resistance is obtained as a ratio of the voltage to the current. Because the temperature coefficient has been determined in chapter 2, the temperature rise can be obtained from the relationship between resistance and temperature. In such a way, thermal strain is obtained.

Figure 4.10 and figure 4.11 present the derived patterns for the resistance and temperature rise together with the observed maximum displacement. The results of thermal strain and apparent strain are shown in table 4.1, where $T$ is the maximum temperature rise. The strain ranges increase with the $I^2t$ value of pulsed currents.
Table 4.1 Strain ranges for different $I^2t$ values of pulsed currents

<table>
<thead>
<tr>
<th>$I^2t$ A$^2$s</th>
<th>T °C</th>
<th>$\Delta \epsilon_{th}$</th>
<th>$\Delta \epsilon_\alpha$</th>
<th>$\Delta \epsilon_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.22</td>
<td>51.8</td>
<td>0.11</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>0.37</td>
<td>101.3</td>
<td>0.22</td>
<td>0.10</td>
<td>0.12</td>
</tr>
<tr>
<td>0.60</td>
<td>163.8</td>
<td>0.36</td>
<td>0.17</td>
<td>0.19</td>
</tr>
<tr>
<td>0.78</td>
<td>204.8</td>
<td>0.45</td>
<td>0.21</td>
<td>0.24</td>
</tr>
<tr>
<td>0.98</td>
<td>283.8</td>
<td>0.62</td>
<td>0.28</td>
<td>0.34</td>
</tr>
</tbody>
</table>

By using the definition of deflection factor, figure 4.12 is generated from table 4.1. The deflection factor is presented as a function of $I^2t$ value of the pulsed current. It can be seen that the deflection factor is nearly constant.

Photographic measurements were intended to be performed after a number of pulsed currents (above 100 pulses). The off time between current pulses was about seven seconds. For small $I^2t$ values, it was assumed that this off time was long enough to cool down the fuse wire to its initial temperature and the subsequent displacements are equal. However, for large $I^2t$ values near the melting $I^2t$ value of the fuses, cyclic strain cannot be assumed to be a constant as the number of pulsed current increased. This may cause an inaccuracy in the lifetime predictions based on the cyclic strain - stress relationship. However, the influence on the deflection factor may still be small.

4.4 Conclusions

From the experimental study for fuses experienced with pulsed currents, the following points can be stated:

1. During buckling, the motion of fuse wires can follow the heating up due to pulsed current. The displacement along the fuse wire gives the impression of a sinuous function.

2. The displacement at the middle of fuse wires has been found to increase with the $I^2t$ value of the current. In other words, the displacement changes with temperature rise.

3. Thermal strain and apparent strain increase with the $I^2t$ value of the current. The deflection factor (0.54±0.02) obtained from experiments, however, is constant for different $I^2t$ values of pulsed current.
Chapter 5 Theory of static buckling

5.1 Introduction

As it has been stated in the first chapter that a decisive solution has not been reached for the buckling of fuse wires. Attempts are to be made in this section to describe the process and view the problem in terms of energy considerations.

5.2 Buckling model

5.2.1 Deformation origin

Because the fuse wire is fixed on to end caps, thus the thermal expansion due to the electric heating is suppressed. As a consequence, thermal stresses are built up. The thermal strain induced in the fuse element is proportional to the thermal expansion coefficient and the temperature rise of fuse wire. It is expressed as

\[ \Delta \varepsilon_{th} = \beta \ T \] (5.1)

During the buckling, a part of thermal strain is contributed to the motion of wire, a part of thermal strain is converted into the compressed deformation. In addition, because of bending, a bending stress is produced corresponding to the moment \( M \) and imposed to the compressive stress.

5.2.2 Buckling concept

To simplify the problem, a fuse wire is represented by a column which is loaded statically. The assumptions in chapter 1 are taken over here. Deformation causes are limited to thermal origins; oxidation and creep of the column are neglected. Considering the deformed coordinates, the motion of the column is simplified to be one dimensional in the \( y \cdot z \) plane and the magnitude is only dependent on the spatial variable \( z \). A schematic view of the problem is given in figure 5.1, where \( q \) is gravity of a unit length. A subvolume is used to describe the equilibrium.

Under above conditions, from differential geometry, the curvature of the column is obtained as

\[ \frac{1}{\rho_m} = - \frac{\frac{d^2 y}{dz^2}}{\left( 1 + \left( \frac{dy}{dz} \right)^2 \right)^{3/2}} \] (5.2)

where \( \rho_m \) is the radius for the point \((z, y)\).

Figure 5.2 shows a local coordinate \((x_c, y_c, z_c)\) referred to the middle-plane of the column. The relation between bending stress and curvature is obtained from the balance condition.
The cross section of column is described by

\[ x_e^2 + y_e^2 = \frac{d_f^2}{4} \]  

(5.3)

For a subvolume shown in figure 5.2, a variation \( \Delta l_e \) of the undeformed length \( l_e \) is related with a force \( \Delta F \)

\[ dF = E \frac{\Delta l_e}{l_e} dA \]

(5.4)

\[ dF = E \left( \frac{\rho_m - y_e}{\rho_m} - \frac{\rho_m}{\rho_m} \right) \alpha (2x_e) dy_e \]

where \( dA = 2x_e dy_e \), \( x_e \) is determined according to equation (5.3). In case of the pure bending, \( dM = y_e dF \) is valid

\[ dM = -y_e \frac{E y_e}{\rho_m} 2x_e dy_e = -\frac{E y_e^2}{\rho_m} dA \]

(5.5)

Integrating equation (5.5) leads to

\[ M = \frac{-E}{\rho_m} \int \frac{\alpha y_e^2}{2} 2x_e dy_e = -\frac{E}{\rho_m} \frac{\pi}{64} d_f^4 \]

(5.6)

Using the notation

\[ I_m = \int y_e^2 dA = \frac{\pi}{64} d_f^4 \]

(5.7)

the relationship between the moment \( M \) and the curvature of column is rewritten as

\[ M = -\frac{EI_m}{\rho_m} \]

(5.8)

According to equation (5.2), for small deformation one may rewrite this equation as

\[ M = E I_m \frac{d^2 y}{dz^2} \]

(5.9)

The relations among load, shearing force \( V \), and bending moment \( M \) are obtained from the equilibrium of the subvolume in figure 5.1. Summing forces in the \( y \) direction gives
\[ V - q \, dz - (V + dV) = 0 \]  
\[ q = - \frac{dV}{dz} \]  

Taking the moment about point \( n \) leads to

\[ M' - q \, dz \frac{dz}{2} + (V + dV) \, dz = (M' + dM) + P \, dy \]  

If second order terms are neglected, this equation becomes

\[ V = \frac{dM}{dz} + P \frac{dy}{dz} \]  

Combination of equation (5.9), (5.10) and equation (5.12) leads to

\[ EI_m \frac{d^4 y}{dz^4} + P \frac{d^2 y}{dz^2} = V \]  

If the gravity of fuse wires is neglected \((q = 0)\), then a general equation for the displacement \( y \) is given by

\[ EI_m \frac{d^4 y}{dz^4} + P \frac{d^2 y}{dz^2} = 0 \]  

For a column with two fixed ends, the boundary conditions are

\[ y(z) = 0 \quad \text{for} \quad z = 0; \quad z = L_f \]  
\[ \frac{dy}{dz} = 0 \quad \text{for} \quad z = 0; \quad z = L_f \]  

Investigating the possibility of curved forms of equilibrium [Timoshenko, 1961], the displacement is found to be

\[ y(z) = 0.5 \ D_{\text{max}} \ (1 - \cos \frac{2\pi z}{L_f}) \]  

In a more general form, \( y(z) \) and \( D_{\text{max}} \) are replaced by \( D(z,t) \) and \( D_{\text{max}}(t) \). Substitution of equation (5.16) into (5.14) leads to the critical load \( P_{\sigma} \)

\[ P_{\sigma} = P = EI_m \left( \frac{2 \pi}{L_f} \right)^2 \]  

However, to specify the maximum displacement, other conditions have to be
considered. Here the postbuckling is assumed to be described also by equation (5.16).

For a spring, the stored energy is expressed to be \( W = 0.5 k x_0^2 \). In this expression, \( k \) is spring constant and \( x_0 \) is the displacement. Following this concept, the total energy in the analysed system is divided into the deformation energy, the strain energy due to bending and the energy due to the length increase in the bending shape. Using equation (5.16), the real length increase of a fuse wire is found to be

\[
\Delta L = \int_0^{L_f} \left\{ \sqrt{1 + \left( \frac{dy}{dz} \right)^2} - 1 \right\} dz = \frac{\pi^2}{4 L_f^2} D_{\text{max}}^2 L_f \tag{5.18}
\]

The energy due to the length increase is

\[
W_b = \frac{1}{2} E A \left( \frac{\pi^2}{4 L_f^2} D_{\text{max}}^2 \right)^2 L_f \tag{5.19}
\]

The deformation energy due to the compression is

\[
W_d = \frac{1}{2} E A \left( \beta T - \frac{\pi^2}{4 L_f^2} D_{\text{max}}^2 \right)^2 L_f \tag{5.20}
\]

The strain energy due to bending follows from substitution of equation (5.16) into (5.9)

\[
W_m = \int M d(\frac{1}{2} \alpha) = \frac{L_f}{2} \int \frac{M^2}{E I_m} \, dz \tag{5.21}
\]

\[
W_m = \frac{1}{16} E I_m L_f D_{\text{max}}^2 \left( \frac{2\pi}{L_f} \right)^4
\]

The total potential energy consists of \( W_d, W_b \) and \( W_m \). Denoting by \( U_T \) the total potential energy, one may write

\[
U_T = W_d + W_b + W_m \tag{5.22}
\]

During the buckling, at any given time instant, the total energy of the system will be a constant. In another word, the total potential has to be minimum for realizing a possible buckling mode. Let \( \eta = D_{\text{max}}^2 \), use the derivative of \( U_T \) to a position variable \( \eta \). It follows

\[
\frac{dU_T}{dD_{\text{max}}} = \frac{dU_T}{d\eta} \cdot \frac{d\eta}{dD_{\text{max}}} = 0 \tag{5.23}
\]

for \( D_{\text{max}} > 0 \), the derivative of \( U_T \) to a position variable \( \eta \) is zero.

The maximum displacement can be obtained from equation (5.23) to be
Substitution of equation (5.24) into (5.16) leads to an expression of buckling shape for the static condition.

According to equation (5.24), let $D_{\text{max}}$ go to zero, the critical temperature rise can be found to be

$$T_{\alpha} = \frac{4 \pi^2 I_m}{L_i^2 \beta A}$$

(5.25)

Because in the prebuckling, the thermal contribution is converted into the compression completely, according to equation (5.17)

$$T_{\alpha} = \frac{P_{\alpha}}{A E \beta} = \frac{4 \pi^2 I_m}{L_i^2 \beta A}$$

(5.26)

Obviously, the same result as in equation (5.25) is found from the critical load expression.

5.2.3 Influence of wire connections

In previous sections, the fuse wire was assumed to be symmetrically fixed to both ends. This assumption leads to a simple understanding of buckling phenomena. In practice, the connections are not always symmetric, it is therefore of practical interest to see what can happen during the buckling due to different connections. As the connection is concerned, two problems are involved. One case is that the fixing point is not located at the centre of caps. The other case is that one side of connection has more soldering material than the other side. In this section only first case will be discussed. Objective of this section is to consider the influence of buckling in assembly of fuses.

Schematic connection views of a miniature fuse are shown in figure 5.3. The origin of the coordinates is located in the centre of the caps. The two fixing points are considered to be randomly positioned within a circle with a radius $r$. Inside the left cap, the wire end is fixed at point $P_1(0, r_1)$. The fixing point of the wire for the right cap is at point $P_2(r_2 \cos \Theta, r_2 \sin \Theta)$. Assume $r_1 = r_2 = r$, the projection of the fuse wire at the $x$-$y$ plane is shown in figure 5.3.

To find the maximum eccentric distance $r$, it is assumed that the buckling of the fuse wire can still be described by the cosine function. The reference position of the wire is taken as a position variable instead of using variable $z$.

The problem becomes to find the minimum distance between a line and a circle. The line is defined by two point $P_1$ and $P_2$. The circle represents the internal surface of glass tube with its radius $R_g = 1.5$ mm. The circle can be described by equation
\[ x^2 + y^2 = R^2 \]  

The fuse wire is described by

\[ y = y_r + \frac{y_i - y_r}{x_i - x_r} (x - x_r) \]  

The middle point of the line is \( P_w(0.5*(x_l - x_r) + x_r, 0.5*(y_l - y_r) + y_r) \), where \( x_r = r \cos \Theta, y_r = r \sin \Theta; x_l = 0, y_l = r \). If \( P(x, y) \) is an arbitrary point at the circle. If the maximum displacement of the fuse wire exceeds the minimum distance between \( P_w \) and \( P \), the fuse wire may touch the internal surface of glass tube. The coordinates of point \( P_w \) are

\[ x_w = \frac{x_l + x_r}{2}, \quad y_w = \frac{y_l + y_r}{2} \]  

The coordinates of point \( P(x, y) = P_g(x_g, y_g) \) are found to be

\[ x_g = \frac{(x_l + x_r) R_g}{\sqrt{(x_l + x_r)^2 + (y_l + y_r)^2}} \]
\[ y_g = \frac{(y_l + y_r) R_g}{\sqrt{(x_l + x_r)^2 + (y_l + y_r)^2}} \]

where the minimum distance between \( P_w \) and \( P_g \) is reached.

Moreover, if a line is connected between the origin and the point \( P_g \), then the point \( P_w \) is found to be a point in the line. It is therefore that the minimum distance \( D_{gw} \) can be calculated by

\[ D_{gw} = R_g - \frac{1}{2} \sqrt{(x_l + x_r)^2 + (y_l + y_r)^2} \]  

Using the given coordinates, the minimum distance can also be written as

\[ D_{gw} = R_g - r \sqrt{\frac{1 + \sin \theta}{2}} \]  

As it is known, the maximum displacement \( D_{max} \) can be calculated according to (5.24). Let \( D_{max} = D_{gw} \), then in principle, the maximum allowed eccentric distance \( r \) can be found for a given fuse wire, as all material properties are known. Examples of calculations are given in the next section.
5.3 Theoretical results

To explain the basic concept of thermal buckling, the total potential energy is calculated for two types of fuse wires. Length, diameter and thermal expansion coefficient values are from the fuse manufacturer. Elasticity of nickel is from the literature [9] and examined by experiments. Elasticity of Ag/Sn-Zn fuse wires is found out from the experiment. Besides cross sectional area A and area moment of inertia $I_m$ are calculated.

Example 5.1 Total potential for nickel fuse wires

Calculated potential curves for different temperature rises from $T=0$ to 1200 °C are shown in figure 5.4. Following material properties were used in the calculation.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of fuse element</td>
<td>$L_t=17.5$</td>
</tr>
<tr>
<td>Diameter of fuse element</td>
<td>$d_t=50$</td>
</tr>
<tr>
<td>Thermal expansion coefficient</td>
<td>$\beta=13.3\times10^{-6}$</td>
</tr>
<tr>
<td>Elasticity</td>
<td>$E=199.5\times10^9$ Pa</td>
</tr>
<tr>
<td>Cross sectional area</td>
<td>$A=1.96\times10^{-9}$ m$^2$</td>
</tr>
<tr>
<td>Area moment of inertia</td>
<td>$I_m=3.07\times10^{-19}$ m$^4$</td>
</tr>
</tbody>
</table>

Example 5.2 Total potential for Ag/Sn-Zn fuse wires

Calculated potential curves for different temperature rises from $T=0$ to 300 °C are shown in figure 5.5. Material properties were used in the calculation for Ag/Sn-Zn fuse wires as follows.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of fuse element</td>
<td>$L_t=17.5$</td>
</tr>
<tr>
<td>Diameter of fuse element</td>
<td>$d_t=103$</td>
</tr>
<tr>
<td>Thermal expansion coefficient</td>
<td>$\beta=22.1\times10^{-6}$</td>
</tr>
<tr>
<td>Elasticity</td>
<td>$E=61\times10^9$ Pa</td>
</tr>
<tr>
<td>Cross sectional area</td>
<td>$A=8.33\times10^{-9}$ m$^2$</td>
</tr>
<tr>
<td>Area moment of inertia</td>
<td>$I_m=5.52\times10^{-18}$ m$^4$</td>
</tr>
</tbody>
</table>

To see the influence of connections, calculations were performed for nickel fuse wires and Ag/Sn-Zn wires.

Example 5.3 Possible motion of nickel fuse wires considering asymmetric connections

Figure 5.6 shows the calculated results for a nickel fuse wire. The conditions for the calculations are

- melting temperature: 1455 °C
- temperature rise: 1435 °C
- coordinates $P_1$: $x_1=0$, $y_1=0$;
- coordinates $P_2$: $x_2=0$, $y_2=r$;
- motion direction: y axis;
In this situation, as \( r \) reaches 0.78 mm, the wire will possibly touch the glass tube. If \( y_i = r \) is used, then the maximum value for \( r \) will be 0.4 mm.

**Example 5.4 Possible motion of Ag/Sn-Zn fuse wires considering asymmetric connections**

For a Ag/Sn-Zn fuse wire, similar calculations can be performed. The conditions for the calculations are

- **melting temperature**: 350 °C
- **temperature rise**: 330 °C
- **coordinates** \( P_l \): \( x_l = 0, \ y_l = r; \)
- **coordinates** \( P_r \): \( x_r = r, \ y_r = 0; \)
- **motion direction**: \( \phi = 45^\circ \)

If \( r = 1.2 \) mm is reached, the wire will possibly touch the glass tube.

When the calculation conditions are changed to

- **melting temperature**: 350 °C
- **temperature rise**: 330 °C
- **coordinates** \( P_l \): \( x_l = 0, \ y_l = r; \)
- **coordinates** \( P_r \): \( x_r = 0, \ y_r = r; \)
- **motion direction**: \( \phi = 90^\circ \)

The wire will possibly touch the glass tube for \( r > 0.84 \) mm.
5.4 Comparison of theoretical calculations with experiments

In this section, comparison of theoretical results with the measurements for d.c. currents and pulse currents will be made. Some experimental results presented are from chapter 3 and chapter 4.

5.4.1 Displacement

The temperature rise of the fuse wire is directly related with the resistance changes of the fuse wire. By measuring the fuse current and voltage, the resistance of fuse wires $R$ can be obtained from

$$ R = \frac{U}{I} \quad (5.33) $$

If the resistance changes due to the length and cross sectional area increases are neglected. The temperature rise is determined from

$$ \rho (T) = \rho_0 \frac{R}{R_0} \quad (5.34) $$

when the measured resistivity as a function of temperature rise is known.

Displacements calculated from equation (5.24) are shown in figure 5.7 for nickel fuse wires and figure 5.8 for Ag/Sn-Zn fuse wires together with the experimental results for d.c. currents.

Figure 5.9 shows the buckling shape of a nickel fuse wire calculated from equation (5.16) and (5.24) together with experimental results for a d.c. current $I=505$ mA and voltage $U=1.804$ V. The initial resistance $R_0$ was 769 mohm. The temperature rise is found to be 700 °C. The maximum displacement is then obtained from equation (5.24). Substitution of the maximum displacement into equation (5.16) leads to the theoretical curve.

Figure 5.10 shows the buckling shape of a Ag/Sn-Zn fuse wire. Observations were made for a d.c. current $I=960$ mA, voltage $U=82$ mV. The initial resistance $R_0$ was 79 mohm. The temperature rise was found to be 18 °C. Similar to figure 5.9, the theoretical curve is also presented.

For low frequency pulsed currents, the dynamical response of wire can be approximated by the stationary solution. Because the natural frequency (860 KHz) of the fuse element [Steinberg, 1988] is much higher than the frequency of the pulsed current 90 [Hz], the effect of self excitation (resonance) is neglected. From the pulse test stated in chapter 4, the acceleration of the wire during the pulsed current can be estimated from the measured displacement. The influence of radial acceleration is very small compared with the action of the bending moment in the buckling, therefore this reaction is also omitted at the time being.
The measured maximum displacements are given in figure 5.11 for Ag/Sn-Zn fuse wires. Experimental results are from chapter 4. Good agreement is found between measured data and predictions based on equation (5.24).

Figure 5.12 shows the buckling shape of a Ag/Sn-Zn fuse wire. Observations were made for the pulsed current, where \(I_t=0.98 \, A\). The temperature rise was found to be 283 °C. Calculations are obtained based on equation (5.16) and equation (5.24).

### 5.4.2 Critical temperature rises

Experimental results of critical temperature rise for buckling are summarized in table 5.1 for nickel fuse wires.

**Table 5.1** Buckling data related with critical temperature rises from experiments for nickel fuse wires

<table>
<thead>
<tr>
<th>No.</th>
<th>(R_0) [mΩ]</th>
<th>(I) [mA]</th>
<th>(U) [mV]</th>
<th>(T) [°C]</th>
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<tr>
<td>1</td>
<td>769</td>
<td>183</td>
<td>166</td>
<td>21.7</td>
</tr>
<tr>
<td>2</td>
<td>827</td>
<td>183</td>
<td>171</td>
<td>15.7</td>
</tr>
<tr>
<td>3</td>
<td>789</td>
<td>183</td>
<td>172</td>
<td>23.1</td>
</tr>
<tr>
<td>4</td>
<td>788</td>
<td>183</td>
<td>168</td>
<td>19.9</td>
</tr>
</tbody>
</table>

Experimental results of critical temperature rises are summarized in table 5.2 for Ag/Sn-Zn fuse wires.

**Table 5.2** Buckling data from experiments related with critical temperature rises from experiments for Ag/Sn-Zn fuse wires

<table>
<thead>
<tr>
<th>No.</th>
<th>(R_0) [mΩ]</th>
<th>(I) [mA]</th>
<th>(U) [mV]</th>
<th>(T) [°C]</th>
</tr>
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<tr>
<td>1</td>
<td>75.3</td>
<td>400</td>
<td>30.7</td>
<td>4.0</td>
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<tr>
<td>2</td>
<td>79.8</td>
<td>699</td>
<td>59.4</td>
<td>14.2</td>
</tr>
<tr>
<td>3</td>
<td>75.5</td>
<td>481</td>
<td>37.2</td>
<td>5.8</td>
</tr>
<tr>
<td>4</td>
<td>78.9</td>
<td>195</td>
<td>15.4</td>
<td>0.4</td>
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<tr>
<td>5</td>
<td>73.9</td>
<td>421</td>
<td>32.0</td>
<td>6.3</td>
</tr>
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</table>

Theoretical critical temperature rise can be calculated from equation (5.25) for fuse wires. For Ag/Sn-Zn wires, it is about 4 °C and to agree with experiments. For nickel fuse wires, the experimental results are likely higher than the calculated value 1 °C. However, as the method for the temperature rise determination is concerned, this difference is neglected for the whole temperature range (up to 700 °C) in the experiment.
5.4.3 Deflection factor

Before the buckling, because the wire is motionless, thermal strain is equal to mechanical strain ($\delta = 1$). Refer to chapter 4, the apparent strain is found by combination of equation (5.18) and (5.24). After some symbolic manipulations, the deflection factor $\delta$ during the buckling is given as

$$
\delta = \frac{1}{2} + \frac{2 \pi^2}{L_i^2} \frac{I_m}{A} \frac{1}{\beta \gamma}
$$

Comparison is made in figure 5.13 for nickel fuse wires, where d.c. currents flow through the fuse wires. Comparison is made in figure 5.14 for Ag/Sn-Zn fuse wires, where both d.c. currents and pulsed currents have been used in experiments. Temperature rises are found out by using the relationship between resistivity and temperature rise. The relationship has been presented in chapter 2.

Comparisons show that theoretical values of deflection factor are slightly lower than results from the experiments. However, a general agreement between calculations and experimental results is obviously seen from figure 5.13 and figure 5.14.

5.5 Conclusions

Fuse wires attempt to move because of heating generated by electric currents. A physical model has been established in this chapter based on several assumptions. Two important assumptions will be discussed here, because other assumptions can be easily fulfilled.

In the model, deformation is assumed to be elastic. This assumption can be violated, because the mechanical strain increases with temperature.

It is not necessary to require a uniform distribution of temperature, because the average temperature is considered to contribute to thermal strain. Since the compressive force can be considered as a constant along the z axis, local effects might be different, but the total influence on the displacement will be the same.

The described model has presented predictions of critical temperature rise for buckling, displacements and deflection factor. Some specific characteristics from the present study are as follows:

(1) Displacement predictions have been verified by experiments for both types of fuse wires.

(2) Theoretical values of deflection factor are decreased from 1 to about 0.51 as the temperature or d.c. current increases.

Experimental values of deflection of fuse wires are slightly higher than predictions. For nickel fuse wires the experimental value is obtained to be about 0.6 for d.c. currents above 300 mA.
For Ag/Sn-Zn fuse wires, the experimental value obtained is about 0.54 for pulsed currents if $P^2 t > 0.17 A^2 s$.

(3) From a theoretical point of view, if the eccentric distance of connections exceeds a specific value, fuse wires can touch the internal surface of the glass tube. This value is purely dependent on assembly of the fuse connections and properties of wire materials.

(4) Discrepancy is observed between predicted and experimentally determined critical temperature rises for nickel fuse wires.
Chapter 6 Conclusions and suggestions for future work

6.1 Conclusions

Mechanical strain is a fraction of thermal strain due to buckling. It plays an important role in the lifetime estimation of fuses. This report deals with an investigation on the behaviour of thermal buckling of miniature fuse wires due to the heating of electric currents. The problem of maximum displacement depending on temperature rise of fuse wires has been addressed. Both the displacement and the buckling shape of the fuse wire have been studied for pure nickel fuse wires and Ag/Sn-Zn clad wires. In particular, attention has been paid to the deflection factor during the buckling based on terms of energy considerations. The main results obtained in the report are as follows:

1. Resistivity of pure nickel fuse wires obtained from the experiment is a nonlinear function of temperature. Its temperature dependence is found in a good agreement with literature results.

2. For Ag/Sn-Zn fuse wires, temperature coefficient of resistivity is obtained to be $4.53 \times 10^{-3}$ from the experiment as the wire temperature is lower than 200 °C.

3. Buckling shape of fuse wires can be described by a cosine function. The magnitude of displacement changes with d.c. currents to which fuse wires are exposed. Three situations can be distinguished:

   Buckling due to the heating of d.c. currents will not occur until the critical temperature rise is reached.

   The magnitude of maximum displacement of fuse wires increases with d.c. current, which can be calculated by using material properties and temperature rise.

   After d.c. current is switched off, the wire will move backwards. The difference between new position and its original position is not significant (less than 20 μm) in our experiments.

4. As the pulsed current for about 7 ms is applied to fuses, the static buckling model can also be used to calculate the displacement of fuse wires. Agreement has been found between the predictions and the observations from high speed photography.

5. The deflection factor from theory is obtained to be about 0.5 after buckling happens. The value is comparable with the experimental results.

6. From a theoretical point of view, if the eccentric distance of fuse wire connections exceeds a specific value, the wire may touch the internal surface of glass tube of fuse because of thermal buckling.
6.2 Suggestions for future work

(1) In the work, it is assumed that deformation is elastic and the contribution of creep is neglected. For low temperature which is below 0.5 melting temperature of the wire material, these assumptions may be valid. For the temperature above, deformation can be plastic. Then, the problem is how the deflection factor can be determined, although the predictions are found to be in good agreement with observations.

(2) It seems that the static buckling model is suitable for predictions of fuse wires during the pulsed current in the work. The question is what the limit for the static buckling model is, as high frequency pulsed currents are concerned.

(3) As stressed in chapter 1, the origin of this work is to estimate the fuse lifetimes. Now, it is possible to calculate the shape of heated fuse wires. The fraction of the free thermal expansion is known and so the stress. As from material properties the relation between cyclic strain and lifetime is known, it should be possible to predict fuse lifetime related with $\dot{\dot{t}}$. 
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## Figures

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**Figure 1.2 (a)**

Lf = 17.5 mm
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