Durability Enhancements in Cadmium Element High Voltage Current Limiting Fuses

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Abstract

The elements of all fuses but especially those of high voltage current limiting fuses are subject to deterioration by thermal and mechanical cycling due to the variable nature of the loading and overloading in most circuits.

The difference in the nature of this cycling according to the type of distribution system circuit is examined, e.g., short time transients such as transformer inrush currents to long term virtually fixed levels of load such as on shunt capacitors.

The paper describes how the nature of the cyclic loading affects the fusible elements in different ways due to the different mechanical and metallurgical phenomena involved.

Alternate compressive and tensile stresses develop at the widely different temperature occurring during the load cycle which draw special emphasis to the combination of deformation mechanisms which act during each half cycle of a thermal-mechanical fatigue sequence. Grain size is found to be a significant factor for controlling the durability of fuse elements in both load cycling and steady state modes.

Attempts to improve those properties relating to performance as a fuse element are described and the metallurgical reasoning stated together with an examination of the effectiveness of those improvements.

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1. Introduction

Very few high voltage current limiting fuses (CLF) are applied such that they carry a steady value of load current. In addition to widely varying values of load current there are transient currents varying in duration from a cycle or two to many seconds which arise from:

1. Energization transients such as magnetizing current inrush of transformers and charging current inrush of capacitors.
2. Hot and cold load pickup.
3. Through faults cleared by a downstream device.

These variations in current cause temperature excursions in the elements from as low as ambient, which may be -40°C, when the fuse has been off load for some hours to high values of perhaps up to 150°C where overload conditions occur.

In CLF's containing elements which have local reductions of cross section these 'bridges' will, under short time transient current conditions, rise in temperature much more rapidly than the bulk parts of the element.

These temperature excursions, either slow changing and uniform throughout the element or quickly changing and local to the reduced areas will cause stresses in the metal of many types including tension and compression, creep forces and fatigue processes.

In addition the various thermo mechanical processes can cause changes in the micro structure of the metal from such phenomena as grain growth, cavitation, grain boundary sliding, twinning, and dislocation networks.

These degradation processes and the effects of additives or dopants have been investigated for some CLF element metals (1) (2) and also for expulsion fuse element metals (3).

As far as is known to your authors no such work has been done on cadmium in connection with fuse elements. The paper describes the experimental work done primarily at Georgia Tech Research Institute in Atlanta, GA and also at the Kearney Research Laboratory in McCook, IL.

2. The Nature of Fuse Loads and Transients

In most devices a steady state load or duty is less demanding than a cyclic load or duty simply because the term steady state implies that nothing is changing.

For h.v. C.L.F.'s this non steady state or cyclic condition is almost without exception the case. Circuits and devices are subject to or the generator of transient currents while changes in connected load and system faults further complicate the picture.

The effect of load changes and transient currents is to produce temperature changes in the elements and since all metals expand with temperature then stresses of one kind and another are generated within the materials and it is necessary to design and apply the fuses such that these stresses remain within the long term capability of the material in the same way that structural materials must be used within well defined limits of stress.

Different effects are produced depending on rates of change of temperature especially in non uniform elements.

In many applications h.v. C.L.F. ratings must be chosen not on the basis of load considerations but such that they are able to repeatedly withstand the transient currents which may be anticipated. These transients have numerous origins and while the pre-arcing time/current or I^2t data for the fuse may be readily available it is more difficult to predict the actual conditions that will occur in the field.

In many cases 'rules of thumb' have developed from a combination of actual measurement and analysis both of which have been tempered by experience. Some of the commonly considered causes of transient current generation together with some commonly accepted quantification are as follows.

2.1 Magnetizing Current Inrush

A commonly used definition of long standing is that the worst case magnetizing current inrush integrates to a value equivalent to $12 \times I_n$ for 0.1 sec, where I_n is the transformer rated current. Another commonly used rule is that the inrush equates to $25 \times I_n$ for 0.01 sec.

2.2 Capacitor Charging Inrush

An uncharged capacitor appears as a short circuit at the instant of switching in and the first few loops of current can be very high and at high frequency. Further a capacitor connected to an overhead line protected by a recloser will at the instant the recloser clears the circuit be charged to peak voltage. A fast reclose operation, say .25 seconds, could result in closing at the opposite polarity so that the capacitor would have almost double voltage impressed across it with consequent effect on the current inrush.

The inrush current will also be increased if a capacitor bank is energized in close proximity to an already energized bank.

An oscillogram for a typical charging inrush is shown in Fig. 1, this is for a 7.2kV, 100 kvar capacitor having a rated current of 13.9 amps energized in a circuit having a fault level of 10.2kA. The peak current was 350 amp and the inrush was limited in duration to a few milliseconds.

2.3 Cold Load Pickup

If a loss of supply is of long enough duration all of the load controlled automatically, such as by thermostats, will be switched to the on condition thus causing a loss of diversity. When the supply is restored this situation is very demanding on the distribution system and its components. The effect of cold load pick up has been characterised as equating to $6 \times I_n$ for 1 sec, $3 \times I_n$ for 10 sec and $2 \times I_n$ for 5 min. or 15 min. for winter in a cold climate.

2.4 Overload

In the North American continent it is not uncommon for a transformer to be overloaded to 2 to 2.5 times its normal rating.

2.5. Lightning

There is no consensus, at this time, as to exactly what causes fuses to operate under thunderstorm conditions. However, operate they do and some users choose to have a minimum fuse rating or I^2t withstand to mitigate the problem of fuse operations due to lightning.

2.6. Through Faults

Operation of downstream devices subjects upstream fuses to the effects of the fault current as limited by the downstream device. If the fault levels are known then data should be available to predict the let through I^2t of the downstream device.

3. Effects of Current Changes and Transients

The effect of any of these conditions is to cause the fuse element temperature to change along its complete length or in a non uniform manner.

For load and overload conditions the rate of change of temperature is slow, there is a great proportion of the generated heat lost from the elements and the filler and other fuse components are also subject to a rise in temperature.

Generally the elements will expand to a greater degree than the other components and the accomodation of this expansion may cause localized stress both during the heating period and the subsequent cooling period.

For short time currents such as capacitor charging inrush there will be very little heat transfer from the element and in elements with local sections of reduced cross section there will be little heat transfer from the reduced area into the bulk of the element. Using numerical methods (4) it has been shown that even for a melting period as long as .11 seconds the temperature at the center of a reduced section immediately before melting was 880°C compared with 205°C at a point some distance away from the area of reduced section. Clearly for a shorter melting period the temperature differential would be even more marked.

The effect of the temperature differential is to rapidly expand the area of reduced cross section and consequently set up compressive stresses later to be replaced by tensile stresses as the elements cool.

The effects of expansion and contraction first became evident in silver element fuses used in circuits supplying direct-on-line induction motors where the starting currents of about 6 times the motor rated current exist from about 6 to 60 seconds depending on the nature of the drive. It was found that the expansion produced in the elements tended to be taken up at 1 or 2 locations causing the formation of 'kinks' (5) which could not readily straighten out on cooling causing residual tensile stresses which increased after every subsequent start up of the motor until failure occurred. A solution to this particular aging problem is to manufacture the fuse elements with pre-formed expansion bends distributed along the whole element length, this accommodates the expansion on a per unit length basis and prevents the formation of kinks. Such arrangements have been tested to give the equivalent of 21,000 starts. (5)

4. The Effects of Temperature Excursions

a. Atomic diffusion. The metals employed for fuse elements experience long times at elevated temperatures during normal usage. Metal atoms are well known to diffuse under such condition and thereby alter microstructural characteristics of the elements. Diffusion mechanisms thus affect mechanical behavior and corrosion characteristics. For many fuse metals, recrystallization normally occurs even at room temperature. Thermal diffusion is also a factor in metallic oxidation processes. Elevated temperatures involved here greatly accelerate these processes.

b. Mechanical stresses. First, mechanical stresses may be introduced during thermal excursions by two primary mechanisms. Differences in the temperature coefficients of expansion between the fuse housing and the fuse elements lead to tension, compression and flexure stresses on the relatively soft metallic elements. Second, thermal gradients are induced in the element metals during rapid thermal excursions. This is particularly true for the notch configurations in fuse elements where both higher resistances and lower mass exist in the notch. The power transients of several cycles at high frequencies associated with either capacitive switching or lightning strokes produce high temperature gradients. The high gradients in the notched regions result in high compressive stresses in the fuse element. Mechanical stress concentration factors also cause notched regions to be more susceptible to mechanical damage mechanisms.

c. At temperatures of approximately 0.4 of the melting temperature (on the absolute scale) most metals recrystallize and grain growth can occur. (1) These processes are accelerated with temperature, roughly, according to the Arrhenius expression for reaction kinetics.

5. Metallurgical Mechanisms

A principal consequence of excessive grain growth is a greatly reduced mechanical strength. Grain boundaries are interfaces which retard dislocation motion and thereby provide mechanical strengthening. Pure Cd experiences growth in grain size at temperatures above 100°C so that the grain boundary hardening mechanisms are not effective. Plastic deformation takes place by both slip and stress twinning in Cd. In addition, grain boundary sliding appears in pure Cd filaments under the various thermal and mechanical stress loads applied to fuse materials.

Experiments were conducted to add selected metallic dopants to pure Cd in order to retard grain growth in Cd fuse elements. Such techniques are regularly employed to enhance the mechanical strength of the alloys used in aircraft and other high performance structural systems. Several dopants were considered for Cd to enhance structural performance. Of these, alloys involving Zn and Ag were prepared and evaluated under various laboratory conditions. Intermetallic compounds form from these dopants with Cd. The goal was to inhibit grain growth at temperatures up to 150°C without adversely affecting the fatigue strength of the element metal. Many intermetallics result in internal interfaces which are brittle or otherwise greatly reduce fatigue strength.

The thermal stability of the microstructure in Cd based fuse element materials were evaluated for several compositions of Zn and Ag doped alloys. The forming processes of flat element configurations (rolling, etc) generate small grains. It was the objective to maintain the small grain size.

6. <u>Laboratory Testing of Fuse Materials</u>

The laboratory testing of fuse material included

a. Tensile behavior.

b. Cyclical mechanical testing.

c. Mechanical creep.

d. Microstructural studies.

e. Current cycling experiments.

The stress-strain curves in monotonic tension tests demonstrated increased tensile strength and greatly enhanced thermal stability of the tensile strengths of both Ag and Zn doped alloys of Cd compared to that of pure Cd. These are illustrated in the curves of Figure 2 and Table 1. As expected the tensile strength of pure cadmium decreased to a lower value than that of the alloys after simple oven aging. Stress-strain curves for both Cd2%Ag and pure Cd are shown in Figure 2. Deformation takes place primarily by slip mechanisms in cadmium but deformation twinning also occurs. The small horizontal displacements on the stress-strain curves corresponded to the creation of twins during the test.

Strain controlled fatigue tests to failure were conducted on fuse elements of pure Cd and of the doped alloys. A special microfatigue apparatus was modified to impose mechanical strain cycles on individual fuse elements while they were conducting representative current. Details of the cylical hysteresis curves were monitored for the progress of mechanical degradation mechanisms. Several curves of the force amplitude plotted as a function of the cycle number are provided in Figures 3 & 4. The force amplitude of pure cadmium elements is comparatively small and decreases significantly with both aging time and numbers of cycles. Metallographic examinations demonstrated that the Ag & Zn doped Cd specimens retained the initial small grain structure while pure Cd experienced significant grain size growth with thermal aging. The degradation mechanisms observed in pure Cd links included slip patterns and extensive grain boundary (GB) sliding along with the initiation of microcracks. The small grain size retained in the doped alloys inhibited both extensive slip and GB sliding resulting in the higher force amplitudes. Degradation in the doped Cd specimens was primarily associated with the growth of microcracks. A key factor for the durability of fuse elements shown by Figures 3 & 4 is that, subsequent to thermal aging, the doped alloys retain relatively large force amplitudes while no significant reduction occurs in the numbers of cycles to failure.

The mechanical creep rates of Cd, Cd2%Ag and Cd2.5%Zn are shown in Table II. The creep rates were found to decrease with thermal aging in each case. However, while the differences for pure Cd were not large, those for the alloys were quite significant. The large reduction in creep rates for the alloys is attributed to the segregation of the doping metal in grain boundaries. While grain size greatly increases with thermal aging of pure Cd specimens, that of the doped metals remains stable. Cd demonstrates greater creep at elevated temperatures.

Durability comparisons were also made by subjecting complete fuses to current cycling tests. The test samples were connected in series to ensure exactly similar conditions and the current cycled 'ON' for 4 hours and 'OFF" for 4 hours on a continuous basis. To reach an earlier conclusion the current density was chosen to be approximately double that of a highly loaded in service condition. Resistance values were checked every working day and if sufficient change was noted that could result from an open element the fuse was removed from the circuit. The results of the tests are given in Table III.

On dismantling the test samples it was observed that the elements giving the best performance had self generated expansion bends distributed along their lengths, see Fig. 5. This was similar to observation made in previous research (5) but in that case the elements contained pre-formed expansion bends which changed their size and distribution. The increased strength and creep resistance of the doped material made it more favorable for the elements to form the wave shaped patterns rather than deform by microstructural mechanisms such as slip or grain boundary sliding.

Samples of elements taken from the fuses after the tests were polished and etched to allow examination of the grain structure. While grain growth was evident in the Cd the Cd2%Ag alloy was essentially unchanged from the as rolled condition.

7. <u>Conclusions</u>

The doping of cadmium with both silver and zinc brought significant improvements to the durability of current limiting fuses. Thermal expansion and contraction with current cycling and surges introduces mechanical stress cycling to the fuse metals. The small additions to the cadmium altered melting points by insignificant amounts but greatly affected the mechanical performance of the elements. Alloying provided an effective control to maintain small grain size through long periods of thermal aging. The long aging times are analogous to long term service operating conditions. The principal parameters affected by grain control were the mechanical strength and creep rates. Strain controlled fatigue lifetimes were decreased somewhat with doping but not by a significant amount. The critical objective was to provide sufficient doping to stabilize the microstructure of the metal without significantly degrading the strength during mechanical cycling. The relatively high strength and very low creep rates resulting from doping provided durability for the thermal cycling environment of an operating current limiting fuse.

References

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Table I

Mean Tensile Fracture Strengths (grams)

Material	As Received	Aged 96 hrs. at 150°C
Pure Cd	582	441
Cd 2%Ag	988	639
Cd 1%Ag	916	566
Cd 2.5%Zn	790	835
Cd 1.5%Zn	732	790

Samples were 0.050" x 0.0075"

As received: samples taken directly from the manufactured roll

Table II

Comparison of Creep Rates of Cadmium and Alloys

Metal	Creep Rates (mm/hr) As Received	Aged 150°C, 23 hrs
Pure Cd	0.10	0.05
Cd 2%Ag	0.11	0.0025
Cd 2.5%Zn	0.019	0.0034

Table III

Current Cycling Tests

Element Type	No. Cycles to Fracture	Tensile Strength of Samples (gm)
Cd 2%Ag	270, 323	785
Cd 1.5%Zn	95	
Cd 2.5%Zn	131, 139	685
Cd	70, 79	342

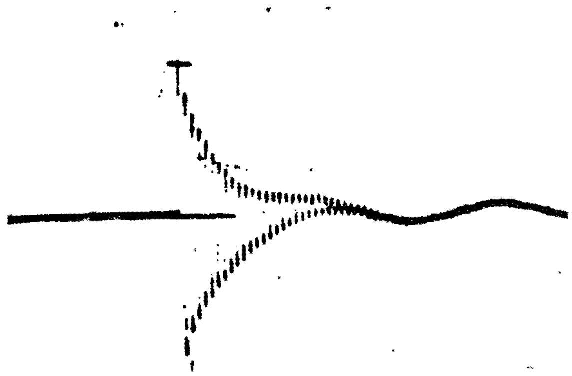

Figure 1. Capacitor charging current inrush

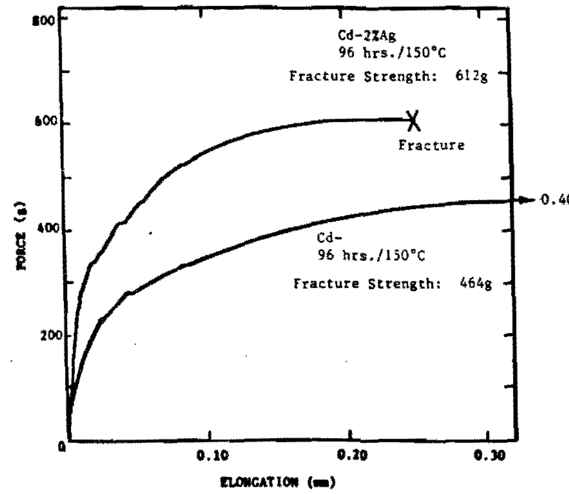

Figure 2. Tensile 'stress-strain' curves for Cd and Cd2%Ag that were annealed at 150°C for 96 hours. The effects of twinning can be noted from the discontinuities in the curves.

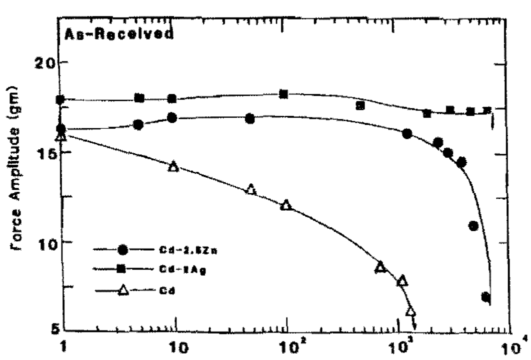

Figure 3. N(cycles)

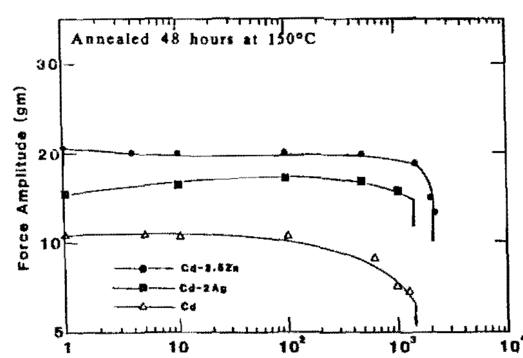

Figure 4. N(cycles)

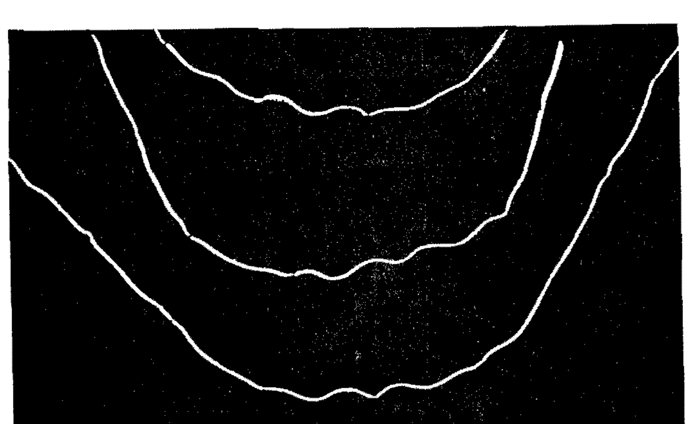

Figure 5 Self generated expansion bends in Cd/Ag elements (edge view) Note sinusoidal type random bands as opposed to sharp kinks at element notches known to occur in pure metal elements.