DETERIORATIONS AND CYCLES TO FAILURE OF H.V. CURRENT-LIMITING FUSES SUBJECTED TO CYCLIC LOADING

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INTRODUCTION Reports stated that there was a possibility that h.v. current-limiting fuses which were made according to old national power fuses standard failed in normal survice after running for many years on a high voltage motor circuit. On that opportunity, the investigation about the applications of the fuses to cyclic loading in the field were carried out, and particularly a lot of vital interests concentrated on the deteriorations of the fuses subjected to cyclic loading[1].

It has been known that cyclic pulses or overcurrents of short duration such as motor starting current, inrush magnetizing current of no load transformer, inrush current on energization of a capacitor or capacitor banks and other occasional overcurrents may cause fuse elements to deteriorate. Especially in high voltage circuit, serious trouble may occur when the current-limiting fuse operates under deterioration of elements in normal current conditions.

The method to estimate deteriorated degree or to anticipate the life of failure of elements were required by both the user and the manufacturer in order to avoid accidental and unexpecting premature operation of current-limiting fuses subjected to cyclic current. Thus it was intended to investigate the deteriorations and the life of cycles of fuse elements in detail.

A series of tests were undertaken to investigate the deteriorations and cycles to failure about model current-limiting fuses and some consideration was given about the expression of the life of cycles relating to elements subjected to repeating simple pulse current.

TEST SAMPLES AND THEIR TIME/CURRENT CHARACTERISTICS A kind of model current-limiting fuse was employed as test samples for the purpose of investigating cycles to failure and deterioration phenomena of elements subjected to cyclic loading and assessing the effect on the deterioration by the fuse element construction and pulse current waveform, further because of avoiding complex effects on the results of cyclic tests under the influence of different constructions of verious kind of type of fuses.

Fig.1 shows a model fuse link. The main components and materials of the model fuse link are a silver ribbon element, granular quartz sand, a normal ceramic barrel and end caps. A single element was stretched in a cylinder

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barrel filled with quartz sand. The construction of the model fuses was made as simple as possible.

Fig.2 shows the silver ribbon element of model fuses. The dimension of the element of model fuses is 1.5 mm in width and 0.2 mm in thick, it has notches every 8 mm regularly along its length, the minimum width of the notch is 0.8 mm. Some of the elements were bent and others were straight. Fig.2(b) shows the form of the bends. Fuse links with the bent elements have larger electric resistances than those with the straight ones, since the bent elements are longer than the straight ones.

Fig.3 shows the pre-arcing time/current characteristics of the sample model fuses. The fuses with the straight elements are longer pre-arcing time than those with the bent ones at the same prospective current below about 85 A. Pre-arcing Joule integral of the fuses falls under constant region below about 2 msec of pre-arcing time.

LIFE CYCLE TESTS The simple pattern of current was selected as test pulse current. For this test, s-factor is defined by the ratio of the value of pulse current to the current on the pre-arcing characteristics at the same time duration. Thus the s-factor is expressed by following equation

$$S = \frac{I}{I_m} \quad \ldots\ldots \quad (1)$$

where I is the magnitude of pulse current, I_m is the melting current corresponding to the same pre-arcing time as the pulse duration. The magnitude of pulse current is obtained by multiplying the current on the time/current characteristics of the same time as the pulse duration by the value of s-factor.

Fig.4 shows an example of pulse cycles in the test. The s-factor, pulse duration and current off period when making the tests were selected from the values listed in Table 1. It was taken into account in the selection of pulse duration that the duration of the pulse of 10 sec simulated the motor starting currents and 0.1 sec simulated the transformer magnetizing inrush current. The current off period was determined so that cumulative temperature rise at the center of the barrel surface owing to the repeated pulse kept saturated temperature as low as possible.

Three samples were connected in series in the test circuit and wiring of the test circuit was arrenged in reference to JEC-201 temperature rise test[2].

CHARACTERISTICS OF CYCLES TO FAILURE VERSUS VALUE OF S-FACTOR Fig.5 shows the experimental results of cycles to failure versus the value of s-factor for the sample fuses. Experimental results of life cycle tests shows significant difference of number of cycles to failure between fuses with the sraight elements and those with the bent ones. Fuses with the straight elements are quite lower cycles to failure than those with the bent ones at the same value of s-factor. For example, for S = 0.8 number of cycles to failure of fuses with the bent elements is beyond 10,000, on the other hand that with the straight ones is below 1,000.

Increasing the value of s-factor close to one, cycles to failure of fuses with the straight elements and those with the bent ones approach different values from one, the former is several tens and the latter is several hundreds.

Number of cycles to failure of fuses with the straight elements is observed relatively much scattering, however that with the bent ones is relatively closely found as observed in Fig.5.

DEFORMATIONS Three samples were mounted in the vertical orientation. A upper end cap was higher temperature rise than a lower one by convection cooling. It is observed that the distribution of fracture positions inclines to the upper portion of a barrel and this inclination is much distinguished for the fuses with the straight elements. It is assumed from these results that the deviations of the distribution of fracture positions concentrated in the upper side of the barrel are effected on the higher temperature deviations from its symmetrical distribution along the length of the fuse link and lower density of filler sand in the portion.

To gain some informations on cyclic fracture, some studies were undertaken about the samples on the cyclic test and after test finished and a fracture element taken out from the barrel.

X-ray photographs of the geometric patterns of the straight elements were taken before, during and after pulse current for one pulse cycle. From these photographs as shown in Fig.6, it is observed that the straight element is straight before a pulse current, bends clearly at two positions during the pulse current and again restores during pulse off period. On the other hand, it is seen that the shape of the bent elements is much the same before, during and after the pulse current. It is confirmed from the above observations that thermal expansion of the element arises owing to heating during pulse duration, compressive stress acts on the element and then as cooling occurs for current off period, the element contracts and may be subjected to tensile stress in the case of occurrence of the plastic deformation.

For the fuses with the straight elements, it is considered that excess strain over the longitudinal compressive strain limit below which the element is held straight acts on the some sections of the element and results in occurrence of local deformation looking like folded or arc shapes at some positions on the element. The same deformed shapes repeat at the same positions every pulse currents. The shapes of deformation resembling folded triangulars were often observed near a upper portion of the barrel on x-ray photographs taken after cyclic test completed. On the other hand, x-ray photographs taken about the fuses with the bent elements show no visible change of shapes of the element during a pulse cycle. It is supposed that thermal expantion of the bent elements by heating distributes evenly along the element and so the strain distribution is uniformly along the element.

In case of the larger value of s-factor than about 0.8 and longer pulse duration than about 10 sec, the pattern of bends of the bent elements deformed gradually in accordance with progressive increasing number of repetitive pulse current, ultimately original bends disappeared and changed into ripples as shown in Fig.7. The cause may be expressed as follows. As the value of s-factor closes to unit and the pulse duration is longer, the temperature of an element is kept higher for a long time, plastic deformations occurs due to the developement of thermal copressive stress depending on high temperature and its long holding time.Cumulative plastic deformation of the element subjected to cyclic loading in high temperature gives rise to the permanent deformation of the elements and the gradual and progressive disappearance of the original bends of the element every repeating pulses.

CRACKS AND FRACTURES The elements taken out from a fuse link after cyclic test completed were inspected by means of x-ray photographic and electron-microscopic examinations. Fig.8 shows cracks formed on a element. Fig.8(a) shows cracks occurred along the polycrystallic grain boundaries and Fig.(b) shows the grown up cracks. The cracks occurred not only at reduced section width of notches but also at the full section width.

Fig.9 shows cracks and their growths on a section of the fractured element. Extended cracks are observed at the full section width under the influence of the prior cold bending work. Two bends and two notches deformed and cracks extended along the borders of bent portions can be seen in a front view of the element corresponding to the side view.

It is observed that some fractures occur at notched portions apart from the minimum cross section and others occur at the full section width. The phenomena of fractures occurred at the positions except the minimum reduced cross section of the element are remarkably different from the melting of elements owing to over current. It is distinctive features for failure of elements subjected to cyclic loading.

It was observed that many fractures occurred during current off period and some fractures occurred during pulse duration. The information of the instant of the fracture happened is given by the precise inspection of the torn surface of elements. The arc burning mark of the torn surface suggests that the fracture of elements happened during pulse current in low test voltage and in the case of no arc mark, fractures happened during current off period.

It has been known that the cause of the phenomena such as occurrence of cracks, growth of cracks and fracture eventually happened on the metal subjected to cyclic loading is the fatigue.

CONSIDERATION OF CYCLES TO FAILURE From the investigations of the elements subjecting to cyclic loading under testing and the elements after the test completed, it is observed that cracks are formed on the element, then gradually extend and ultimately lead to failure. It may be concluded that the cause of the failures of elements subjected to cyclic loading are mainly due to the fatigue.

It is stated in the studies of fatigue that the stress-strain loops set up in the constrained elements subjecting to repeated expansion and contraction under cyclic pulse current. The steady-state stress-strain loop which settles down in a first few cycles of pulse currents has inelastic strain each cycle.

Manson-Coffin's experimental law gives the following relationship between cycles to fatigue failure and the inelastic strain on the stress-strain loop within the range of low number of cycles to fatigue failure

$$N^{\alpha}E_p = C \text{ ...... (2)}$$

where N is cycles to failure, E_p is the magnitude of the inelastic strain and C is a constant. The constant C depends mainly on material property and temperature. Experimentally α is often taken 0.5, C is derived from the contraction of the area of the wire test specimen obtained from static tensil test.

INELASTIC STRAIN The temperature rise of elements according to the pulse current depends on dissipated energy and the thermal conductivity of fuse link. Providing that an element is constrained completely and no free expansion of the element occurs, thermal strain which is composed of the elastic strain and inelastic strain equals thermal expansion and is expressed as follows

$$E_t = \beta\Delta\Theta \text{ ...... (3)}$$

where E_t is the thermal strain, β is the thermal expansion coefficient, $\Delta\Theta$ is temperature rise difference.

Providing that sand fills uniformly a barrel, the straight elements of which temperature rises quite high deform theoretically like sine waves and practically deformations being alike sine waves are often observed in the vicinity of a lower cap. It is considered that sand is rarely filled uniformly in the barrel mounted in vertical orientation. Many experimental results of the fuses with the straight elements reveal that the local deformations of folded shape as a triangular arise in a few positions along an element and the local deformations of arc shapes arise at the reduced section width of an element. On the other hand, supposing from the test results, the strain of the bent elements distributes uniformly together with temperature rise, the deformation of elements occurs evenly along the longitudinal direction of an element.

It is concluded that the local concentrated strain occurred in the straight element amounts to one time or more the thermal strain expressed in Eq.(3). It is assumed that the strains of the bent elements are smaller than the thermal strain expressed Eq.(3) owing to the effect of reducing thermal strain under the influence of uniform distribution of strain and uniform movement of elements.

RELATIONSHIP OF CYCLES TO FAILURE VERSUS S-FACTOR Providing that the straight element is completely constrained by sand filler and end caps, no displacement of the element in sidelong direction occurs, the thermal expansion of the element equals the total strain. It is simply assumed that the temperature rise of the element is proportional to the square value of s-factor throughout the most part of length of the element. The melting point is given when the value of s-factor is equal to unit. Then the temperature rise of the element is given by the function of the value of s-factor as follws

$$\Theta = \Theta_m S^2 \text{ ...... (4)}$$

where Θ is the temperature rise of the element, Θ_m is the temperature rise of the melting point.

It is assumed that the inelastic strain expressed in Eq.(2) nearly equals the total strain expressed in Eq.(3) in the case of no deformation of the straight elements. As mentioned above, the local deformations were mainly observed in experimental results for the straight elements. It is calculated that the strain in this case increases some multiples of that of the straight element rigidly constrained. On the other hand, in the case of the bent element, its strain is reduced below that of the thermal expansion, since the deformation is evenly distributed along almost all length of the bent element.

Thus the inelastic strain expressed in Eq.(2) is given as follows,

$$E_p = k\ \beta\ \Theta_m S^2 \ \ldots\ldots\ (5)$$

where k is the factor indicating the proportion of the strain depending on the deformed shape to that of the thermal expansion and may be related to temperature rise and pulse current waveform. Corresponding to the patterns of deformation, k may be classified as follows, $k = 1$ for the straight elements rigidly constrained and not deformed, $k > 1$ for local deformations on the stsaight elements and $k < 1$ for the bent elements.

Substituting (5) in (2) gives

$$N = (\ 1/\beta\ \Theta_m\ )^2 (\ C/k\ )^2 S^{-4} \ \ldots\ldots\ (6)$$

As temperature of the elements varies between the maximum and the minimum value for a pulse cycle, it is difficalt to obtain the appropriately analytical expression about the constant C as some function of the temperature. So the following experimental results are directly used. Fig.10 shows the curve of constant C versus temperature about silver wires obtained experimentally from static tensil test. The constant C depending on temperature rise as shown in Fig.10 is expressed by following equation within the range of temperature between about 400°C and 900°C,

$$C = \mu\ \Theta^{-\gamma} \ \ldots\ldots\ (7)$$

where μ, γ are constant. In the cyclic life test, temperature of the element goes down near ambient temperature every pulse off periods, so introducing (4) and (7) into (6), Eq.(6) reduces to

$$N = (\ \mu/\beta\ )^2\ \Theta_m^{-2(\gamma+1)}\ k^{-2}\ S^{-4(\gamma+1)} \ \ldots\ldots\ (8)$$

Substituting (1) in (8), and plotting the results calculated from Eq.(8) on the magnitude of pulse currents on a log-log scale, the linear relation is obtained between cycles to failure and the magnitude of pulse currents. This expression shows the same relationship as obtained previous experimental work [3].

Four curves calculated from Eq.(8) for k=0.2, k=0.6, k=1 and k=10 are shown in Fig.5. Data of cycles to failure of the bent elements on log-log scale mostly distribute between two curves of k=0.2 and k=0.6 and data of the straight elements distribute under the curve of k=1. It is observed that the tendency of data distribution for the bent elements coincides nearly with these calculated curves, however the tendency of data distribution for the straight elements differs from the curve of k=10. One reason is considered as follows. The above discussion is based on the assumption that the constant k is constant throughout the range of the test. In practice, it is suggested that the k of the bent elements is almost constant, but the k of the straight elements is appreciably variable according to the test conditions, that is, the strain ranges very wide due to local deformations. As another reason, comparatively low cycles to failure around s=0.6 to 0.7 are considered under the influence of quite low value of constant C at the temperature of about 300°C, since the straight elements may still receive strong stress actions until the low value of s-factor.

For the bent elements, strain is reduced below the strain corresponding to the thermal expansion, because of the uniformed distribution of deformation and displacement. This effect is expressed by means of the relation of $k<1$ and the bends of the elements improve the life of cyclic loading.

On the other hand, for the straight elements, thermal expansion consentrates some fixed positions of the element. Strains of these positions increase over the strain equating to thermal expansion, it is expressed by means of the relation $k>1$. It is stated from the relation that local deformations shorten and scatter the life of cyclic loading.

It is expected that in the region of low cycles under about 10^4 cycles Eq.(6) or (8) serves the presumption of number of cycles to failure of current-limiting fuses subjected to cyclic loading.

CONCLUSION Cyclic life tests were carried out for the model current-limiting fuses.

In most cases, the local deformations occur in the straight elements due to thermal expansion.

The bends of the elements disappear and change into ripples as the value of s-factor approaches one and pulse duration is longer.

The process of the occurrence of craks, their growth and ultimately fracture happening on the elements due to cyclic loading is caused by fatigues.

The expression deduced from Manson-Coffin's law relating to fatigue fracture and the k-constant introduced with respect to deformed shapes is expected to give the estimation of the life of cyclic loading about the same type fuses as model current-limiting fuses with the bent elements in the region of low cyclic failures.

REFERENCES
[1] Technical report, (II) No.155, IEEJ, Sept. 1983
[2] Standard of JEC "Power Fuses" JEC-201-1977
[3] G. Stevenson:"Cyclic loading of fuses for the protection of semi-conductors." International Conference on Electric Fuses and their Applications. April 1976

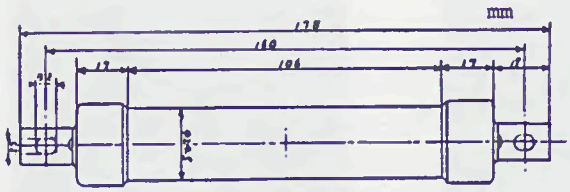
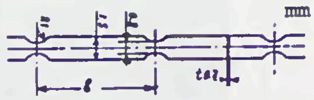


Fig.1 A model fuse link used for life cycles tests



(a) Front view

(b) Side view

Fig.2 A silver ribbon element of the model fuses

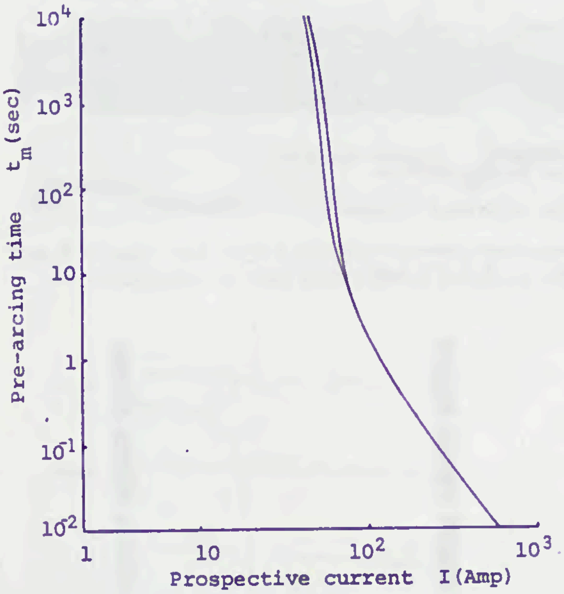


Fig.3 Pre-arcing time/current characteristics of the model fuses

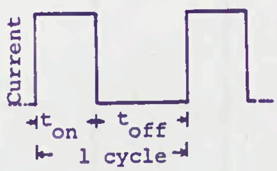


Fig.4 An example of pulse current cycle

		pulse duration t_{on} (sec)			
		0.1	1.0	10	100
S	0.9	60	120	1200	1800
	0.8	60	120	1200	1800
	0.7	60	120	600	1200
	0.6	60	120	600	1200

Table 1 The values of s-factor, pulse durations: t_{on} current off period: t_{off}

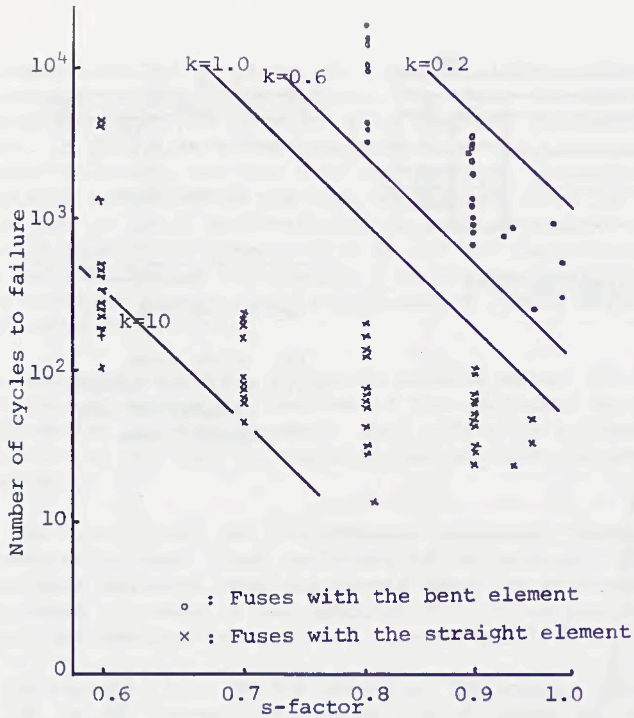


Fig.5 The experimental results of cycles to failure versus the value of s-factor and the curves obtained using Eq.(8)

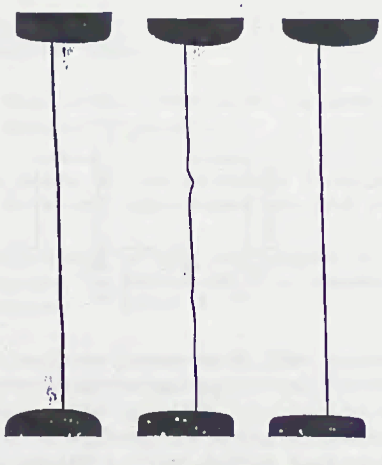


Fig.6 Deformations of the straight element before, during and after pulse current

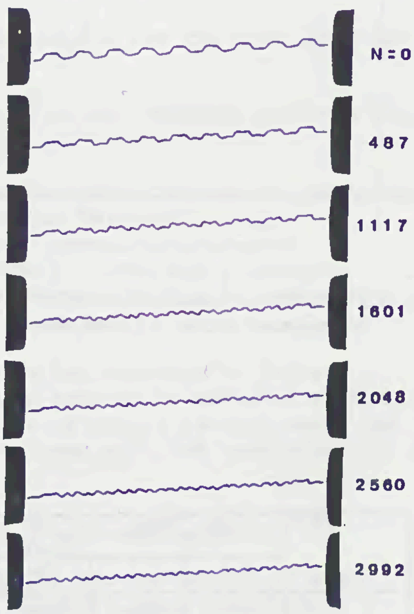
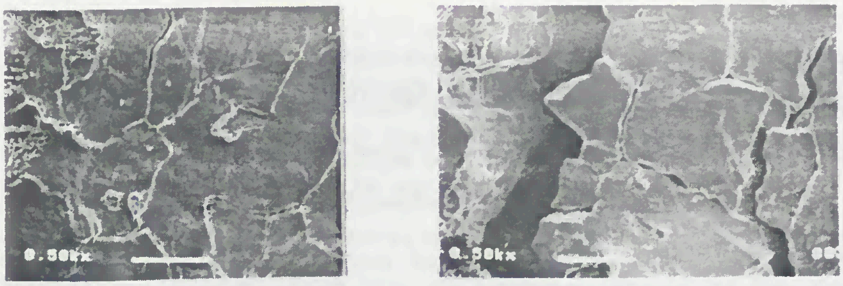
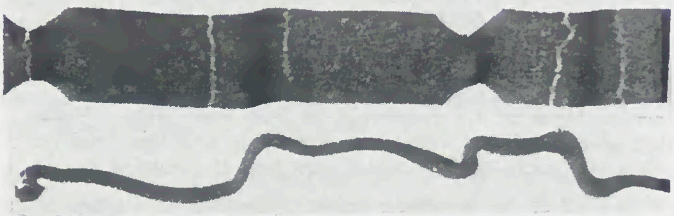


Fig.7 Original bends disappeared and changed into ripples, N is cycles of pulse current



(a) cracks (b) grown up cracks

Fig.8 Cracks



a front view

a side view

Fig.9 Cracks and their growth at the full section of width under the influence of the prior cold bending work

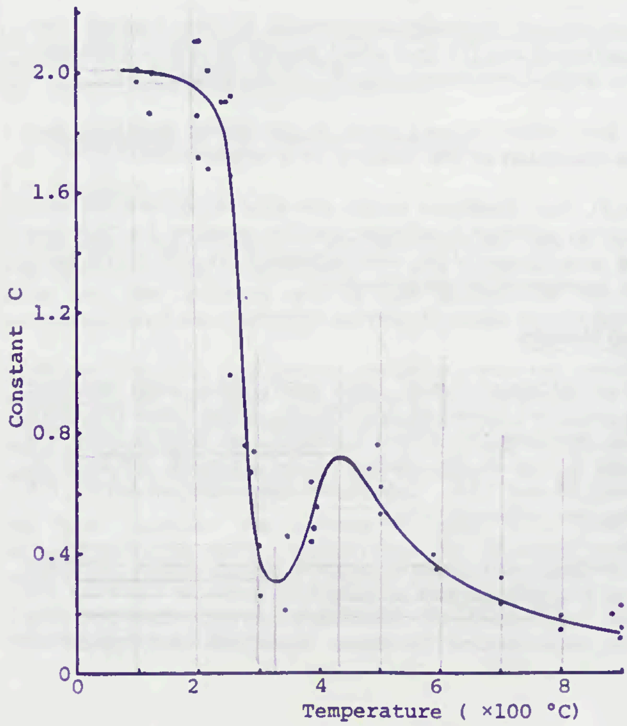


Fig.10 The constant C for silver wire having diameter of 0.7 mm as a function of temperature