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MECHANICAL PROPERTIES AND EVALUATION OF COIL INSULATION FOR HIGH VOLTAGE

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I. INTRODUCTION

It is important for the security of reliability of high voltage rotary machines to study the properties of the insulation of the winding and evaluation of reliability. The increase in capacity, decrease in size, increase of the numbers of startings seen in pumping up power plants and other usage conditions for the machine have recently become stringent. For these reasons, evaluation and securing of reliability are becoming increasingly demanded.

We have performed voltage-endurance test, thermal cycle test, and various other functional evaluations of coils with the objective of securing reliability and improving insulation for same time. Currently, we are proceeding further with claricication and quatitive study of phenomena about them and reliability evaluations.

In this report mechanical breakdown of coil insulation by electro-magnetic force, thermal strain considered to be the main causes of deterioration by thermal cycle, and other so-called mechanical properties are described.

II. VARIOUS PROBLEMS FOR MECHANICAL RELIABILITY OF COIL INSULATION

The stresses exerted in coil insulation are caused by deformation of bending and torsion when the machine is constructed and carried. The deformation of bending and torsion are caused by the electro-magnetic force generated at short circuiting, at the time the machine is started and stopped or the load is changed suddenly. The thermal strain are caused by temperature changes during operation. The rubbing and wear are caused by electro-magnetic force. The state of these stresses are different inside the slots or at the edge of the slot. For the functional test of coils, the load of these must be considered. The state of load is outlined in *Table 1.*

The mechanical load of the coil of rotary machine was described above. The technical problems to guarantee reliability are as follows:

1) Analysis and quantitive treatment of study of load with machines

This is a problem of examination and analyzing the load with machines. The establishment of measurement techniques for stain and deflection under high voltage, magnetic field and high temperature and methods of

Table 1 Mechanical load on rotatry machine insulation

Position \ Cause	Thermal stress	Electro-magnetic force	Stress at construction and carrying
	Coefficient of thermal expansion Temperature distribution Elastic modulus Shape Restraint of thermal expansion	Flux density B Electro-magnetic force $F = I \times B$ Vibration, deformation of coil Rubbing, wear	Deformation at construction Vibration when carrying
Inside slots	◦Elongation stress of insulation layer ◦Thermal expansion restraint and deformation by end support	◦Vibration, wear when operating	◦Deformation when constructed
Outside slots	◦Elongation stress of insulation layer ◦Thermal expansion restraint and deformation by end winding support ◦Concentration of stress at the edge of slots	◦Vibration, wear when operating ◦Impact deformation at short circuiting ◦Impact deformation repetition when starting and stopping	◦Deformation when constructed ◦Vibration when carrying
End windings	◦Elongation distortion of insulation layer ◦Thermal expansion restraint and deformation by end winding support ◦Specificity of edge bent part	◦Vibration when operating ◦Impact deformation at short circuiting ◦Repetition of impact at starting and stopping	◦Deformation when constructed ◦Vibration when carrying

numerical analysis of electromagnetic force and thermal stress are important.

2) Study of the relationship between mechanical load with machine and mechanical stress in insulation layer.

Analysis of deformation and stress of coil shaped composite materials by bending moment and other mechanical loads.

3) Study of the relationship between stress and mechanical properties of sulation

Study of $\Delta\tan\delta$, voltage endurance and other characteristics changes, or mechanical strength. Study the relationship between fatigue phenomena and life.

4) Establishment of suitable evaluation methods

Establishment of tests and evaluation methods considering a suitable load and method of acceleration at estimate of life time. Moreover, estimation of reliability considering Weibull analysis, multivariate statistical method, and other statistical approaches.

5) Analysis of basic phenomena

Analysis of fatigue phenomena of composite structure, fracture phenomena, change of micro-structure, and other basic phenomena and study of the relationship with the basic characteristics of various materials.

III. MECHANICAL PROPERTIES OF COIL INSULATION LAYER

The drop of the characteristics of the coil insulation layer by the mechanical load, when machines are constracted and operated, influences the life of the machine and is an important problem in securing reliability.

tant problem in securing reliability.

We are proceeding with analysis of electromagnetic force test of the mechanical load with a machine, and studies of mechanical properties of coil insulation. The mechanical characteristics of a coil are described here.

1. Bending deformation and fracture of coils

The deformation due to bending was considered as a primitive cause of deformation of a coil. The deformation of the coil is generated by the bending moment M. If this deformation reach fracture conditions, a drop of electrical properties, B.D.V. and $\Delta\tan\delta$ of the coil are caused by the fracture of the micro-structure. We tested various model

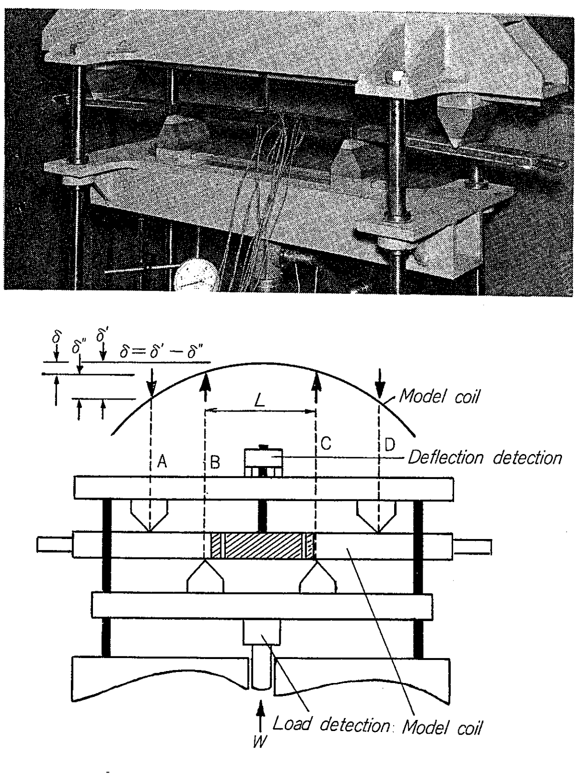


Fig. 1 Bending test of coil

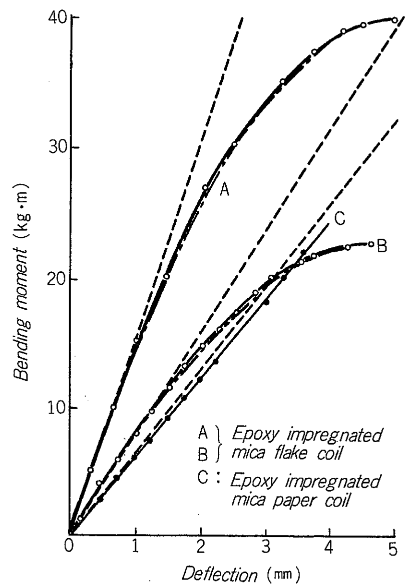


Fig. 2 Relationship between bending moment and deflection

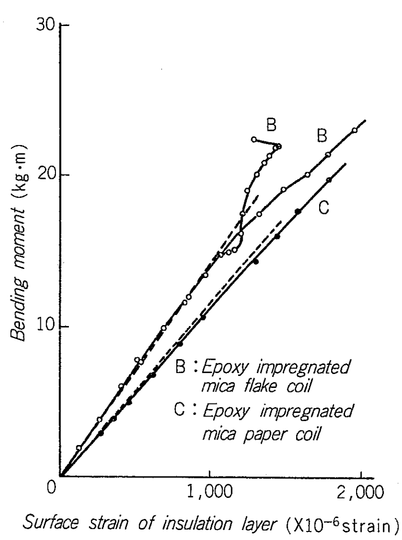


Fig. 3 Relationship between bending moment and strain

coils and studies the relationship between their deformation and fracture to grasp the behaviour of these. The equipment used is outlined in *Fig. 1.*

Fig. 2 shows the relationship between the bending moment M and deffections. *Fig. 3* shows the relationship between bending moment M and surface strain of the insulation layers. Since the deformation behavior of some coils almost linear up to fracturing, others are non-linearity.

In linar region, if the deformation of coil is treated by material mechanical method, the formula (1) is applied to bending moment M, elastic modulus Ei, Ec, radius of gyration r, and distance form newtral line h.

$$\int_{Ai+Ac} \frac{E}{r} h^2 \, dA = M \quad \cdots\cdots (1)$$

Ai, Ac: Cross sectional area of insulation layer and conductor

If the apparanent rigidity of the coil is made EI,

$$EI = EiIi + EcIc \quad \cdots\cdots (2)$$

Ii, Ic: Moment of inertia of insulation layer and conductor

The differential equation of the bending curve is,

$$EI \cdot \frac{d^2y}{dx^2} = M \quad \cdots\cdots (3)$$

If the relationship between the deflection δ between CD and bending moment M and the relationship between the surface strain of insulation layer and M are calculated by using these relationships,

$$\delta = \frac{L^2 M}{8EI} \quad \cdots\cdots (4)$$

$$e = \frac{HM}{EI} \quad \cdots\cdots (5)$$

H: Thickness of coil

The value calculated by using these equations are shown by the dotted line in *Fig. 2* and *Fig. 3.* Application of these to deformation at the linear region of the coil is comparatively good. The non-linear part is generally treated experimentally. These can be displayed in various ways, but one example is given below.

$$\delta = \frac{L^2}{8} \mu_0 (1 - \sqrt{1 - \beta M}) \quad \cdots\cdots (6)$$

μ_0, β: Parameter according to shape and volume modulus

L: Distance bewteen support points

Display by means of this equation is shown by the single chain line in *Fig. 2.*

When studying the behavior of the coil end part, it is basically analyized by material mechanics, including recent structural analysis techniques. However, for application, consideration of the elastic behavior of the spacers and binding, and of the non-linear characteristics by experimental result are necessary. Changes of the electrical characteristics of coil insulation of rotary machines which given

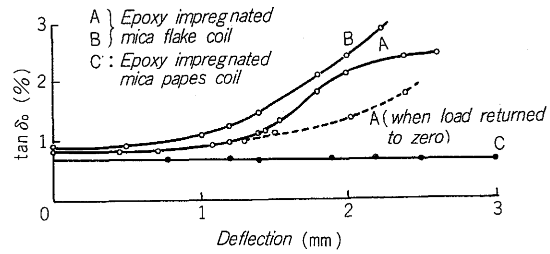


Fig. 4 Relationship between tan δ_0 and deflection

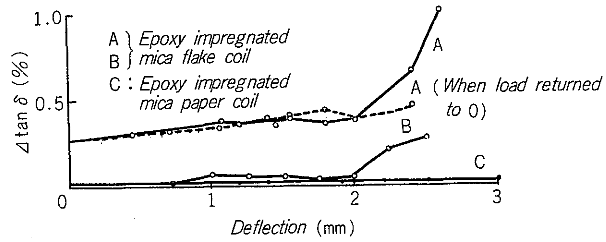


Fig. 5. Relation between $\Delta\tan\delta$ and deflection

such deformation are produced by partial structural fracture inside the insulation layer and is finally mechanically fractured and the breakdown voltage of the insulation layer drops considerably. Example are shown in *Fig. 4* and *Fig. 5*, $\tan\delta_0$, $\Delta\tan\delta$ begin to increase from a certain point. Removal of the load recovers the change in their amount to a certain extent, but they do not recover completely. Moreover, they also may be no change of the electrical characteristics up the final fracture, depending on the material. Such examples are frequent with epoxy impregnated mica paper coil. The one of the reasons of this is considered to be due to the small number of defects in mica paper coils.

The condition of fracture of insulation have been given as the general conditions, maximum stress or maximum strain, etc., of fracture mechanics. They also differ according to the fracture mode and material. In the case of coil insulation layer, the layer tends to fracture when the surface stress or distortion has reached a fixed value. However, this may also differ somewhat according to the shape and it must be clarified as a composite structure fracture condition.

2. Repated fatigue characteristics of coil

Various alternating stresses exerting in a coil insulation layer and their behavior of fracture is evaluated with the stress amplitude and number of cycles until mechanically or electrically fractured as the life.

Generally, fatigue life is set by the stress amplitude and mean stress. The concepts of the behaviour of these are shown in *Fig. 6.* Life N when a certain stress (distortion) amplitude and mean stress (distortion) have been loaded on the coil is set, and these form one curve.

The outline of this curve is treated for epoxy impreg-

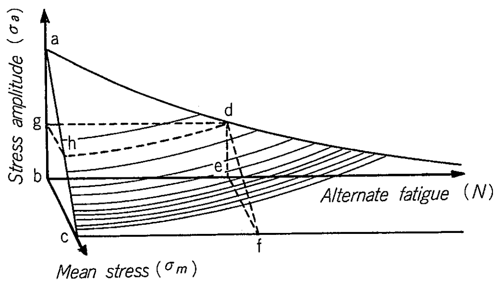


Fig. 6 Relationship between stress amplitude, mean stress and fatigue life time

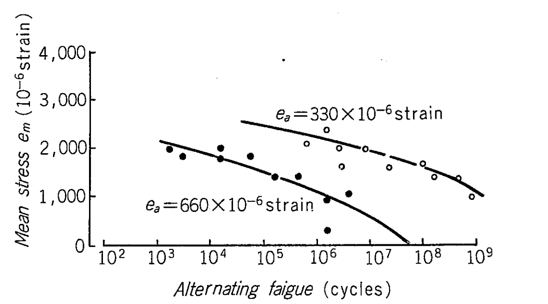


Fig. 8. Relationship between mean strain and fatigue life time

nated mica flake insulation layer. The relationship between the stress amplitude e_w and life N of both swings in shown in *Fig. 7.* This is generally known as the *S-N* curve and various function forms have been conceived. However, it is made linear by log-log-plot in the case of a coil, and

$$N = Ke_w^{-n} \quad \text{.......................} \quad (7)$$

is established. The effect of mean stress (distortion) e_m is shown in *Fig. 8.* With the stress amplitude e_a and e_w, e_m and e_T as parameters, if displayed by

$$e_m = e_T\,(1 - \frac{e_a}{e_w}) \quad \text{..................} \quad (8)$$

and Eq. (1) is substituted,

$$e_m = e_T\,(1 - n\frac{e_a}{\sqrt{K}} \cdot {}^{n}\!\sqrt{N}) \quad \text{.............} \quad (9)$$

Fig. 9 shows the relationship between e_m and ${}^{n}\!\sqrt{N}$. This is almost linear, and e_T is found by extrapolating N at 0, a value of about 3200μ strain is shown. Therefore, the curve shown in *Fig. 6* is indicated by Eq. (9) with e_T almost constant. These are the alternating fatigure behaviour generally seen.

As coil evaluation methods there is the *S-N* curve method and e_m-*N* curve method.

It must be understood that the former is expressed by the difference point of view of this curve. Because the mean stress applied to the coil is small, the *S-N* curve is more important as reliability evaluation with an actual machine. We also perform evaluation by *S-N*, except in special cases.

Information beneficial in improving reliability is

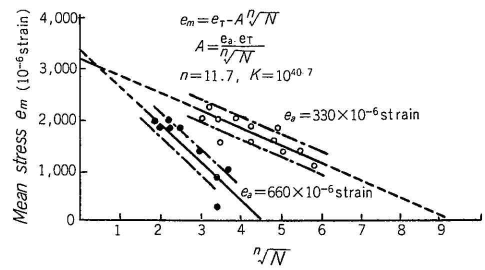
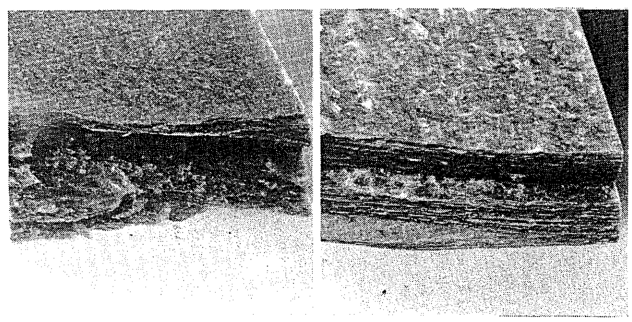


Fig. 9 Relationship between mean strain and n root of N



(a) Impact fracture (b) Alternative fatigue fracture

Fig. 10 Fracture surface of impact and fatigue fracture

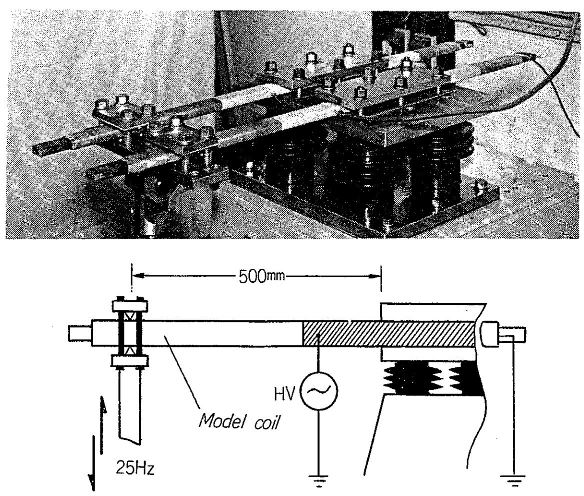


Fig. 11 Fatigue test of coil

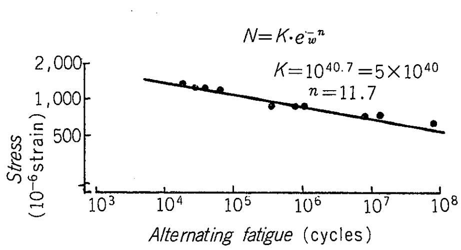


Fig. 7 S-N curve of coil

comprehending the phenomena by a quantitive study of these and observation of the fracture face and a study of the insulation layer composite structure and material basic characteristics, etc. The fracture surfaces by impact and alternating fatigue fracture is shown in *Fig. 10*. The former shows a minute difference which is considered to be caused by the fracture mode.

In this way efforts are proceeding on studying general phenomena and improvement of reliability considering the load conditions of the actual machine even for alternating fatigue characteristics. The equipment used in fatigue testing is outlined in *Fig. 11*.

3. Characteristics of impact

A coil receives impact by abrupt short circuits and may be deformed and fractured. To study the behaviour of these is also important in reliability evaluation.

If the apparent bending rigidity of the coil at impact is made EI, the energy received by the coil at a short circuit is changed to distortion energy U [Eq. 10] stored in the coil body, distortion is produced and the coil is fractured under certain conditions.

$$U=\int\frac{EI}{2}\left(\frac{d^2y}{dx^2}\right)^2 dx \quad \cdots\cdots\cdots\cdots\cdots\cdots \quad (10)$$

y: Deflection

x: Position on coil

To study the deformation behaviour and fracture conditions of a coil at such impact we manufactured the impact tester shown in *Fig. 12* and also conducted studies on these.

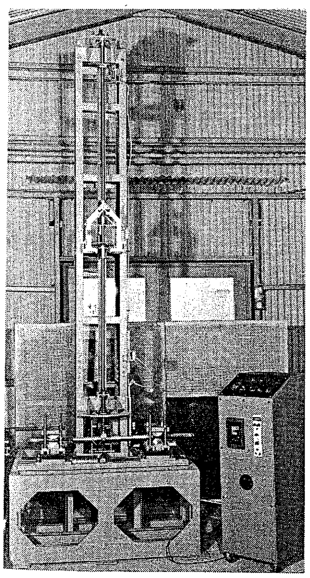


Fig. 12 Impact test of coil

4. Mechanical characteristics and reliability of coil

Part of the studies conducted by us on the mechanical characteristics of a coil and its basic problems were described above. Actual reliability evaluation requires clarification of these basic problems and grasping of the state of the load of the actual machine, and a study on the involution behaviour with thermal deterioration and electrical deterioration.

For these problems, we analyze the electromagnetic force of the coil end part, and measure the electric field, end coil deformation and the state of stress with an actual machine and obtain clear reliability evaluation, higher reliability insulation development policy, and rational design conditions.

IV THERMAL DISTORTION PRODUCED AT THE COIL INSULATION LAYER

The coil of high voltage rotary machines has a composite structure of copper, mica, resin, and some kinds of materials. Therefore, thermal stress is exerted in the insulation layer by the difference of thermal expansion coefficient between the insulation layer and conductors and temperature distribution. Moreover, when the coil is housed in a core and is fastened by coil end supports, thermal expansion of coil is restrained by the external restraint of these supports, and then thermal distortion may be produced by them too. These distortions become the main causes of deterioration by thermal cycle. By these reasons, quantitively studying and comprehending them are important in securing reliability of machines.

We have performed thermal cycle tests using a model core simulating to the machine and have studied reliability of large coils. The generation mechanism of thermal distortion and its features have been grasped and optimization of the conditions of thermal cycle test planned and various analysis and studies conducted by changing the temperature rise and fall conditions or the condition of restraint for call and conducting various experiments.

1. Measurement of thermal stress

We have manufactured equipment capable of freely setting the temperature rise and fall conditions, which are the main cause of thermal distortion, and have measured the thermal strain under various conditions, including core restraint. A block diagram of this equipment is shown in *Fig. 13*. Thermal distortion was measured by using a strain

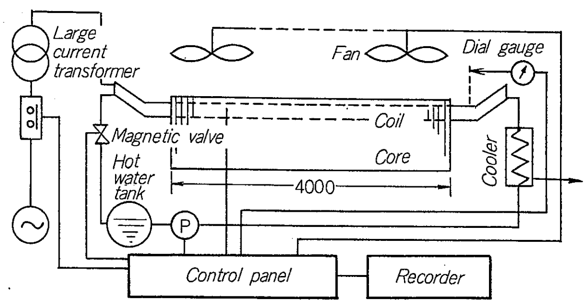


Fig. 13 Schematic diagram of thermal cycle test

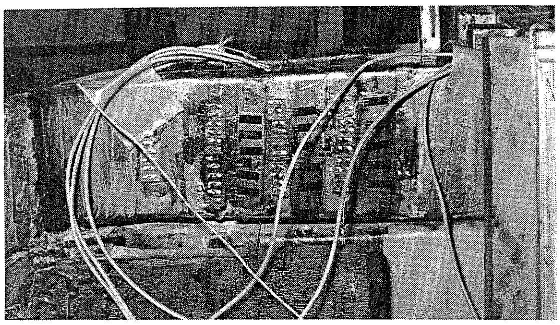


Fig. 14 Measurement of thermal strain by strain gauge

gauge such as that shown in *Fig. 14* and an adhesive that is stable at high temperatures.

2. Thermal distortion and thermal stress produced in the insulation layer

Temperature T_0 (usually room temperature) is the standard temperature and the residual stress of the insulation layer when the coil was made is $\sigma_r\ (T_0)$, the thermal stress insulation layer at the problem temperature T produced by the coefficient of thermal expansion difference and coil temperature distribution is $\sigma_T\ (\Delta T)$, the thermal stress due to external restraint of the core and end supports is $\sigma_0\ (\Delta T)$. And then the thermal stress $\sigma_i\ (\Delta T)$ actually generated at the insulation at temperature T is expressed by,

$$\sigma_i (\Delta T) = \sigma_T (\Delta T) + \sigma_0 (\Delta T) + \sigma_r (T_0) \quad \ldots\ldots (11)$$

$$\Delta T = T - T_0$$

Therefore, when discussing the generation mechanism these thermal stresses are considered independent and can finally be added.

3. Thermal stress σ_r caused by difference of coefficient of thermal expansion

Since the conductor and insulation layer expand almost uniformly under the condition that thermal expansion of the coil is free (from restraint of core) if the effect of the end is disregarded and they are considered to be mechanically equilibriumed, thermal expansion ΔL is,

$$\Delta L = \frac{\int_{Ai} \alpha i Ei (Ti - T_0)\, dA + \int_{Ac} \alpha c Ec (Tc - T_0)\, dA}{\int_{Ai} Ei dA + \int_{Ac} Ec dA} \quad \ldots (12)$$

αi, αc: Thermal expansion of insulation layer, conductor

Ti, Tc: Temperature of insulation layer, conductor

Ai, Ac: Cross section area of insulation layer, conductor

Simulating the thermal expansion under the condition of considering the insulation layer thin and the heat conduction of the conductor good,

$$\Delta L = \frac{\alpha i Ei Ai \Delta Ti + \alpha c Ec Ac \Delta Tc}{EiAi + EcAc} \quad \ldots\ldots\ldots\ldots (13)$$

Considering the thermal stress σ_i is exerted in the insulation layer at this time,

$$\sigma i = -\bar{K} \alpha i Ei\, (Ti - T_0) \quad \ldots\ldots\ldots\ldots\ldots (14)$$

$$K = \frac{1 - \{\alpha c\, (Tc - T_0)/\alpha i\, (Ti - T_0)\}}{1 - (AiEi/AcEc)} \quad \ldots\ldots (15)$$

Where $\bar{K}$ is the restaint coefficient of the insulation layer by the conductor and σ_i indicates the elongation stress at $K < 0$ and the compression stress at $K > 0$.

At the linear part of the test coil, the thermal stress distribution of the long direction of the measured results had been considered to be uniform and the effect of the end is considered to be ignorable. *Fig. 15* shows the change of temperature and thermal stress at the thermal cycle test. The measured values and calculated values correspond. When machine is operated $\bar{K}$ is considered to be minus, but if the conductor is cooled abruptly by accelerating the test time, Tc becomes smaller than Ti, and since K becomes positive, compression stress such as that illustrated in *Fig. 15* is produced. Our thermal cycle test is set so that the elongation stress, that is, $\bar{K}$ becomes minus, the same as an actual machine, except in special cases.

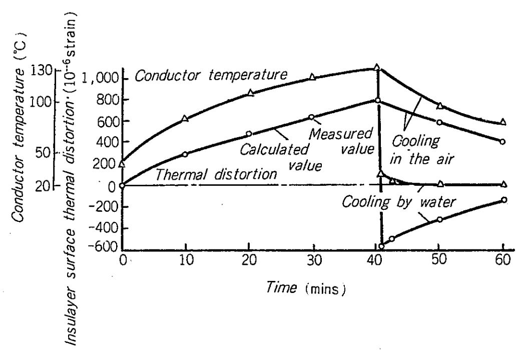


Fig. 15 Change of thermal strain on insulation surface by temperature variation

4. Thermal distortion, thermal stress due to mechanical restraint of the core

The following two problems of thermal distortion generated when a coil is mounted in a iron core are considered:

(1) Effect of the core on the temperature distribution of the coil.

(2) In the case that the iron core prevents thermal expansion of the coil, mechanical restraint causes thermal stress.

(1) is estimated with the equation previously given, but (2) is more important. To comprehend the effect and features of this, we mounted the coil in a core much stronger than

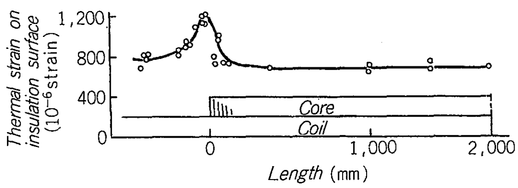


Fig. 16 Distribution of thermal strain on insulation surface

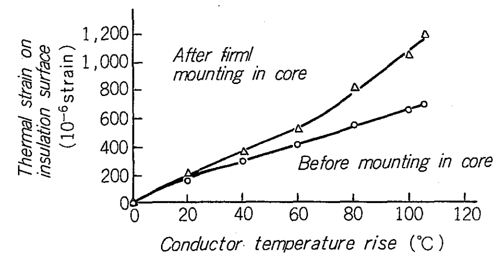


Fig. 17 Change of thermal strain on insulation surface near core end by temperature variation

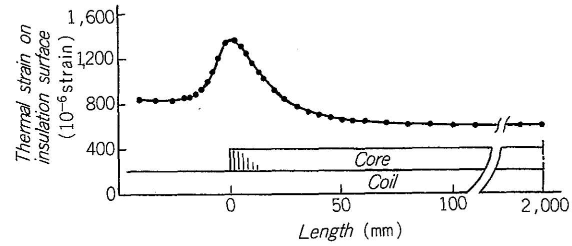


Fig. 18 Distribution of thermal strain on insulation surface (calculation)

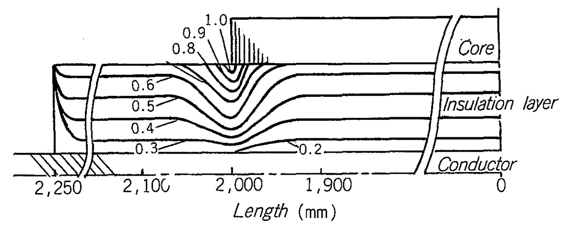


Fig. 19 Distribution of thermal stress in insulation layer

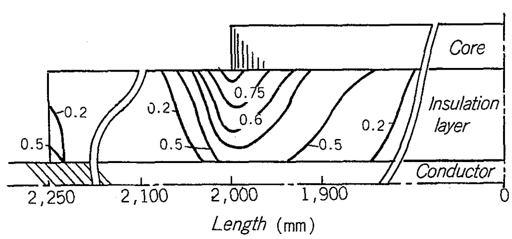


Fig. 20 Distribution of shearing stress in insulation layer

usual. And to make the coefficient of thermal expansion difference of the coil and core large, we made the temperature of the core lower than that forecast for the actual machine. Under these conditions we stress of the insulation layer of the core. The results are shown in *Fig. 16*. The thermal stress value inside the core is smaller than that forecast from the thermal expansion and temperature difference and shows a tendency to increase at the edge of core as shown in *Fig. 17*. The amount of thermal expansion showed somewhat smaller values. These indicates that shearing stress $\tau(x)$ is produced at the wall of the slot and coil and that thermal expansion is obstructed.

To understand the generation mechanism of $\tau(x)$, if the shearing deformation inside the insulation layer is ignored, the elongation [change of thermal expansion $U(x)$ by the core] at coil point x due to $\tau(x)$ is expressed by,

$$U(x) = (l/AE)\left[\int_0^x x\tau(x)\,dx + x\int_x^L \tau(x)\,dx\right] \quad \cdots (16)$$

$$AE = AiEi + AcEc$$

l: Girt of coil, L: length of coil, x: Point on coil

If the above equation is rearranged and $\partial U(x)/\partial x = e(x)$ is used,

$$\tau(x) = -(AE/l)\,\partial e/\partial x \quad \cdots\cdots (17)$$

From the measured value of e, at the inside of the core, e is constant and $\frac{\partial e}{\partial x}$, and e tends to increase near the edge because of the effect of the edge of core. If $\tau(x)$ is analogized from these, almost the same trend as when the boundary surface between the coil and core is bonded is shown. Therefore, while the generation of the shearing force shows the same tendency as bonding, the coil should be viewed as rubbing the core wall. The amount of surface stress found by the finite element method when the amount of deflection caused by rubbing has been compensated and the wall is considered to be bonded is shown in *Fig. 18*. The trends are well matched. The thermal strain distribution at this time is shown in *Fig. 19*. The mechanics of the insulation layer edge are also shown in the distribution diagram. The effect of the edge is not considered in these and the validity of the assumption of **IV** para. **3** is shown. Stress concentration is shown at the edge of the core and the results of measurement are well matched. The effect on the area near the conductor is comparatively small. The shearing force distribution is shown in *Fig. 20*.

5. Residual distortion, stress

Residual distortion is produced by the coefficient of thermal expansion difference when returning to room temperature from the forming temperature of the coil, and can be calculated with the equation given in **IV** para. **3**. In the results of our measurements a value somewhat lower than the calculated value was obtained. An example is shown in *Fig. 21*.

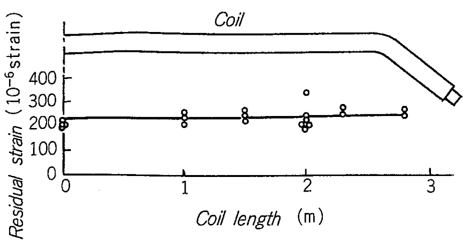


Fig. 21 Distribution of residual strain

6. Thermal strain produced in the insulation layer and evaluation

Considering thermal stress the main cause of deterioration at the thermal cycle and clarifying the generation mechanism and generated amount of these is important in evaluation and forming counter-measures. Generally, the generation of thermal strain is based on the coefficient of thermal expansion difference and temperature difference and from restraint of the thermal expansion by the coil end support. We added restraint conditions far stronger than forecast for the actual machine to this and conducted experiments to determine the generation mechanism and the features of the thermal strain generation state. The results are outlined in *Fig. 22*.

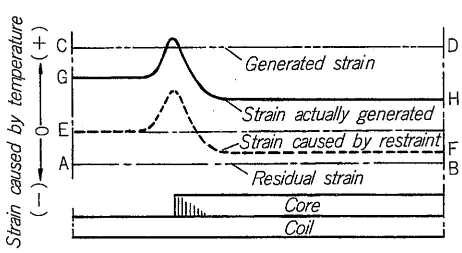


Fig. 22 Mechanism of thermal strain generation of coil insulation layer

At room temperature a coil insulation layer has a residual strain (A-B) produced at forming and a thermal strain (C-D) exerted by the coefficient of thermal expansion difference and temperature difference caused by changes in temperature. When the restraint of the core is large, the thermal expansion of the coil is restrained and the thermal strain shows a decrease in the slot and a concentration (E-F) of thermal strain is produced at the edge of core. The total strain (G-H) of these is the actual thermal strain. Suitable conditions setting considering these features and the state of the actual machine is necessary in evaluating the thermal strain of a coil insulation layer.

To study the effect of these thermal strains of coil impregnated epoxy resin, a thermal cycle test of several thousand cycles was performed under the firmly restrained condition. The test state is shown in *Fig. 23*. As a result, the breakdown voltage of the coil insulation layer at even this thermal cycle test of several thousand cycles was 10% less than initial breakdown voltage. Coil impregnated epoxy resin has performances capable of amply withstanding even thermal strain.

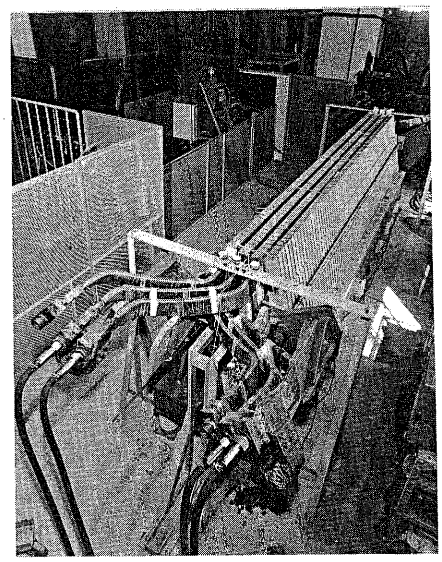


Fig. 23 Thermal cycle test of coil for large machine

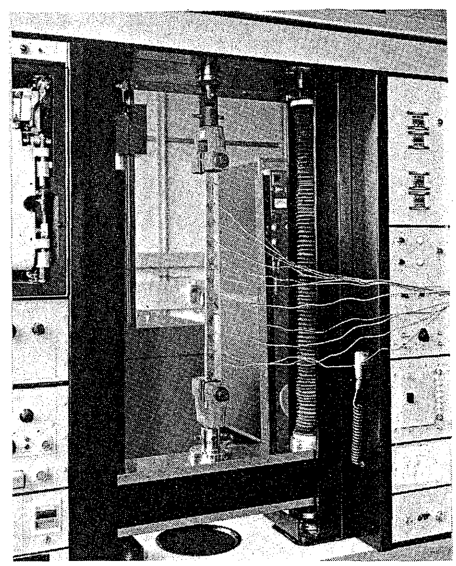


Fig. 24 Tensile fatigue test of coil

We are performing repeated tensile fatigue tests such as shown in *Fig. 24* and are also studying acceleration tests accompanying the recent increase in pumping up power plants.

V. CONCLUSION

A basic outline of the various problems of mechanical characteristics, including the effect of thermal strain, was given here. We will make efforts to improve the performances and reliability of coil insulation for high voltage rotary machines by adding evaluation, investigation, and analysis for these in the future.