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The Residual Stress of Magnet Wire and Crazing

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Synopsis

It is well known that crazing occurs sometimes when a magnet wire is immersed in an impregnating varnish after coiling. A quantitative study between residual stress of a magnet wire film and crazing is presented in this paper by using a magnet wire having poor adhesive strength between the film and the conductor. The residual stress of a magnet wire was found to be maximum in the range of 3–5% elongation. A morphological study of crazing which occurred in cross-linked and linear polymers is also described in this paper.

INTRODUCTION

A magnet wire is manufactured by coating enamel on the conductor and baking it in an oven. It is well known that crazing occurs sometimes when a magnet wire is immersed in an impregnating varnish after coiling, and also that crazing is most severe at 3–5% elongation. When magnet wire is used for electric appliances, crazing is one of the most important defects, because it decreases the dielectric strength of the magnet wire, and the reliability of the electric appliances also decreases.

Some papers concerning the crazing of magnet wire have been published. One of them discusses the spherulite hypothesis,[1] and another is a qualitative explanation[2] which combines viscoelastic and thermodynamic theories. Recently, an orientation hypothesis[3] was proposed. But the basic problem of crazing of magnet wire is not clearly understood in theory or in practice.

The following are outstanding characteristics of crazing of magnet wire: (1) crazing is most severe at 3–5% elongation; (2) crazing can be eliminated by appropriate heat annealing; (3) crazing can be avoided by appropriate heat annealing.

The quantitative relation between the residual stress of the magnet wire film and the degree of crazing after elongation which is determined by using a new method is discussed in this paper. A morphological study of crazing which occurred in cross-linked polyesterimide wire and in linear polyamide wire is also described.

THEORETICAL CONSIDERATIONS

Crazing occurs when elongated magnet wire is exposed to solvent and/or the gas of solvent. It is evident that the residual stress of the film is a main

TABLE I
Samples (Bare Wire, 1.0 mm Diam.)

Enamel	Film thickness, (mm)	Glass temperature (°C)	Melting point, (°C)
EI, polyesterimide	0.051	188	—
AI, polyamidimide	0.050	282	—
N, polyamide	0.051	60	259

factor affecting crazing.[4,5] It is necessary to obtain the stress of the magnet wire film after coiling or elongation. But a magnet wire which is used practically is a composite material having a good adhesion between the conductor and the film, making it very difficult to obtain the residual stress of the film after elongation.

The authors developed a new method to obtain the residual stress of a magnet wire film after elongation by using a magnet wire which has poor adhesive strength between the conductor and the film. The quantitative relation between the residual stress of the film and the crazing could be studied by this method.

EXPERIMENTAL

Sample

In this experiment, it is most important to use a magnet wire having poor adhesion between the conductor and the film. Such a magnet wire was manufactured in the following ways: (1) A bare wire is baked in an oven, so as to have an oxidative surface, and then enamel is coated onto the oxidized surface under the usual conditions. (2) A bare wire is annealed in a preannealer without steam in the enameling process.

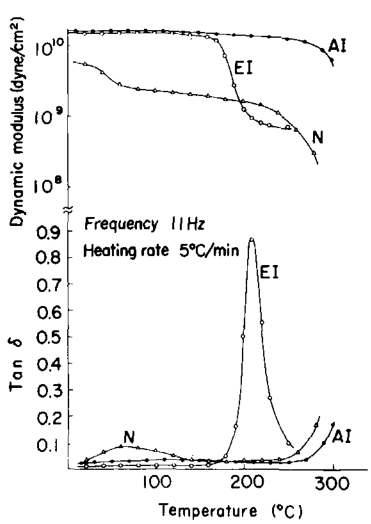

Fig. 1. Viscoelastic behavior of films of EI, AI, and N.

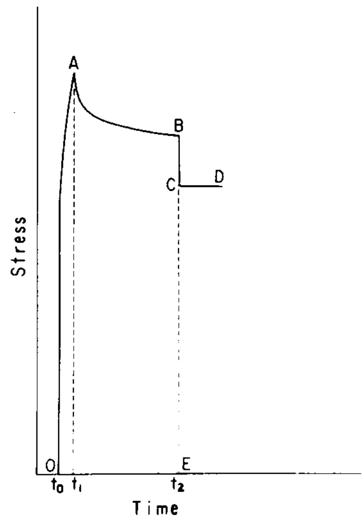

Fig. 2. Residual stress of magnet wire film after elongation.

The above method was applied in this experiment. Samples are indicated in Table I. The viscoelastic behavior of these films[6] are shown in Figure 1.

Measuring of Residual Stress

An Autograph S-100 manufactured by Shimazu Seisakusho, Ltd., was used for measuring the stress relaxation. When a magnet wire was elongated, the stress increased (OA in Fig. 2), then the elongation was stopped at t_1 and the stress of the wire relaxed (AB in Fig. 2). The film of the elongated wire was cut with a razor at t_2, so that the film shrinks due to the residual stress of the film and the stress decreases suddenly (BC in Fig. 2). BC is the residual stress of the film at t_2 after elongation and CE is the residual stress of the conductor. The residual stresses of the film were obtained under various elongations.

Stress Relaxation Due to Crazing

When a solvent was applied on the surface of the film at t_2 instead of cutting the film, the stress of the film decreased from B to C due to crazing, as shown in Figure 3. BC′ is the stress relaxation due to crazing. After crazing occurred, the film was cut, and then the stress decreased again (DE in Fig. 3). DE is the residual stress of the film after crazing occurred. Where MEK was used for occurring craze, $(t_1 - t_0)$ was 10 sec, $(t_2 - t_1)$ was 1 min, and $(t_3 - t_2)$ was 1 min.

RESULTS

The residual stresses of EI, AI, and N after elongation from 1% to 20% are shown in Figure 4, and the stress relaxations due to crazing are shown in Figure 5.

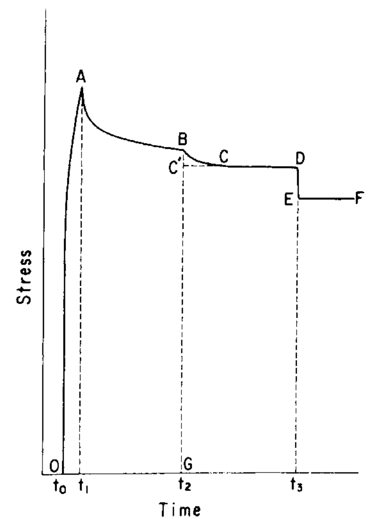

Fig. 3. Stress relaxation by crazing and residual stress of film.

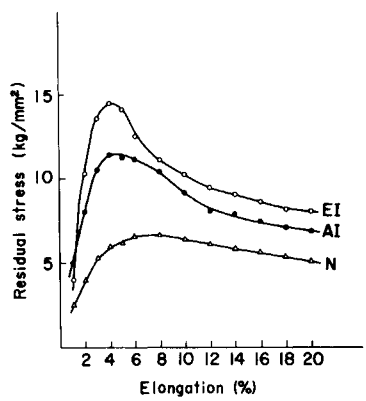

Fig. 4. Residual stress of EI, AI, and N.

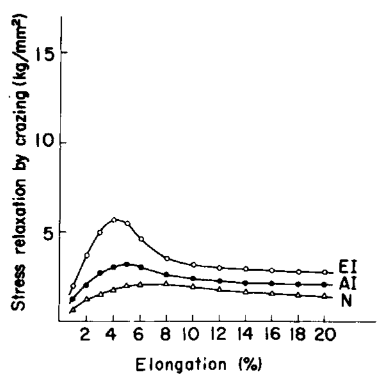

Fig. 5. Stress relaxation by crazing of EI, AI, and N.

TABLE II
Number of Crazing vs. Elongation[a]

Elongation, %	Number of crazing, no./5 mm
0	0
1	5—20
3	many
5	many
7	90—140
9	60—70
11	50—60
13	40—50
15	30—40
17	20—30

[a] Sample: EI. Samples were immersed in MEK at 1 min after elongation for 5 sec for crazing to occur. Crazing was counted by using an optical microscope (× 40).

DISCUSSION

Relation Between Residual Stress and Mechanical Model

The crazing of the magnet wire is most severe at 3–5% elongation as indicated in Table II.

Figure 4 shows that the residual stress does not increase linearly in proportion to the elongation. Crazing of a magnet wire after elongation occurs to relax suddenly the residual stress of the magnet wire film. It is understandable why crazing is most severe at 3–5% elongation.

A mechanical model was used for quantitatively explaining the residual stress of the film-versus-elongation curves. Figure 6 shows the mechanical

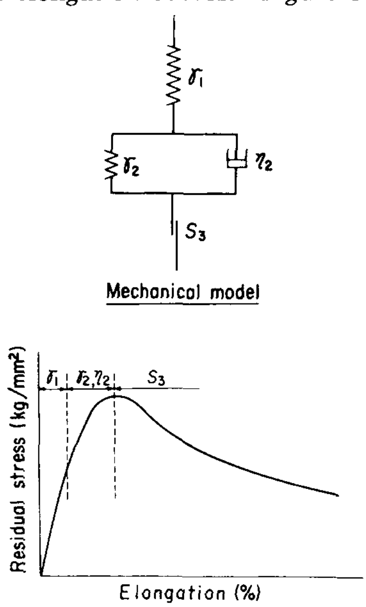

Fig. 6. Mechanical model; instantaneous elasticity (γ_1), retarded elasticity (γ_2,η_2), and plastic flow (S_3). Residual stress vs. elongation indicating the role of each element in the mechanical model.

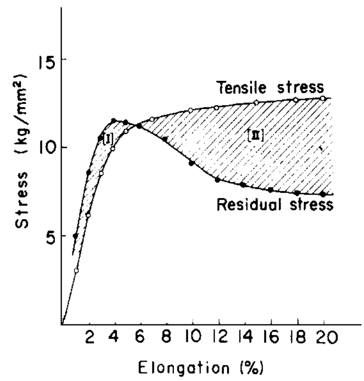

Fig. 7. Tensile stress and residual stress vs. elongation of polyamidimide.

model, and it shows each element's role in the residual stress-versus-elongation curve.

When the elongation starts, the spring γ_1 operates at once. In this region, the residual stress increases in proportion to the elongation. As the elongation increases, the retarded elasticity, that is, the combination of spring γ_2 and dashpot η_2 starts to work. In this region, the residual stress does not increase linearly in proportion to the elongation. Furthermore, the plastic flow element s_3 starts to work in the plastic region which begins at 5–6% elongation.

The residual stress which is stored in the instantaneous elasticity and the retarded elasticity decreases in the plastic flow region. The residual stress relaxes by about 25% when crazing occurs, as indicated in Figure 5.

Tensile Stress and Residual Stress

The stress–strain curve of a tubed film obtained from a magnet wire was compared to the residual stress–strain curve of a magnet wire film obtained by this method. Figure 7 shows the tensile stress curve and the residual stress curve of polyamidimide.

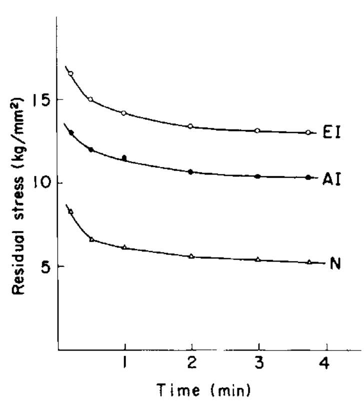

Fig. 8. Residual stress relaxation of EI, AI, and N after 5% elongation.

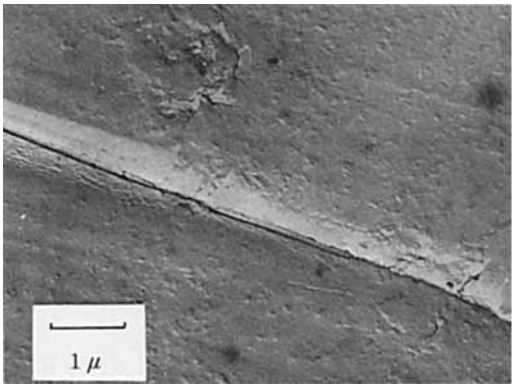

Fig. 9. Crazing of polyesterimide (×10,000).

In region [I] shown in Figure 7, the tensile stress was less than the residual stress. In the tensile stress–strain curve, the weak part of the tubed film elongated first. On the other hand, in the residual stress–strain curve, the magnet wire film elongated homogeneously with the conductor, so that the tensile stress seems to be less than the residual stress. When the tubed film was elongated more, the tensile stress continued to increase, but the residual stress began to decrease. Region [II] in Figure 7 represents the consumption of the stored energy due to the plastic flow.

Relaxation of Residual Stress

It was found that crazing has a strong relation to the residual stress of the films as indicated in Figure 4 and Table II. The residual stress of three samples are shown in Figure 8, and the difference of their residual stress is rather large.

As the residual stress is high, crazing is more likely to happen. Polyamidimide is very superior compared to polyesterimide in both physical and chemical properties. Polyamidimide is estimated to be a good material for crazing

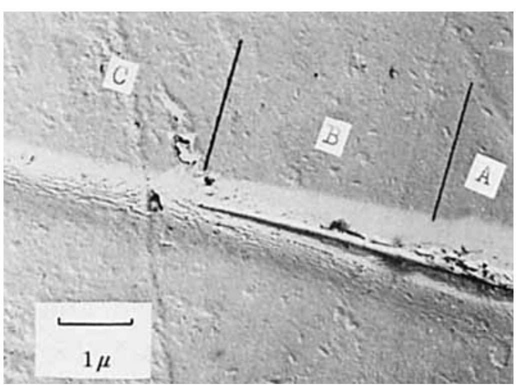

Fig. 10. Point of crazing of polyesterimide (×10,000): (A) crack region; (B) crack transition region; (C) Crack and crack transition region of under layer.

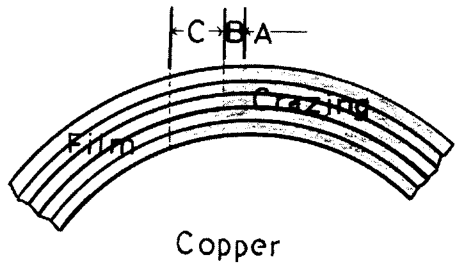

Fig. 11. Schematic diagram of crazing.

compared to polyesterimide, because the residual stress is about ⅔ that of polyesterimide, as shown in Figure 8.

Polyesterimide is a crosslinked polymer, and molecular chains are unlikely to slip; on the other hand, polyamidimide is very stable linear polymer having a rigid chemical structure, so that slips between the molecular chains are apt to occur.

Morphological Study of Crazing

A morphological study of crazing seems to be useful. Figures 9 and 10 show the crazing of polyesterimide, and Figures 12–14 show the crazing of polyamide. These crazings occurred under the following conditions: (1) 3% elongation; (2) samples were immersed in MEK for 5 sec at 25°C, 1 min after elongation.

Figure 9 shows that the crazing proceeds at right angles to the stress direction; this narrow crack seems to be produced by the sudden solvent shock. The width of this crazing is about 0.1–0.2 μ.

Fig. 10 shows the point of crazing of polyesterimide. We can separate the crazing in three parts from the electronmicroscope: [A] is the crack region, [B] is the crack transition region, and [C] is the crack and crack transition region of the under layer. In regions [B] and [C], we could not see the crack in Figure 10, but a crack was observed in the under layer which was brought into focus by using an optical microscope (×1500).

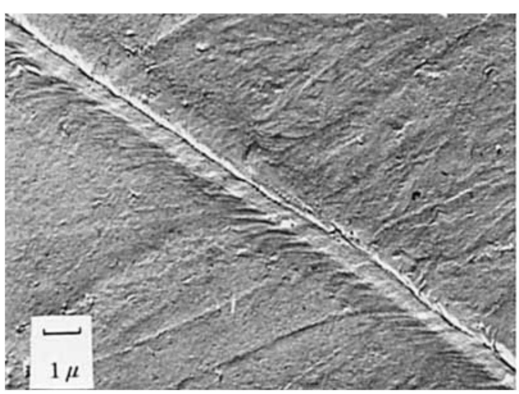

Fig. 12. Crazing of polyamide (×5000).

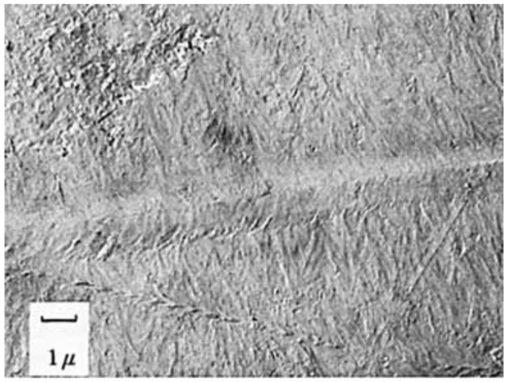

Fig. 13. Crazing of polyamide (×5000).

From this information, we can estimate that crazing seems to have a tendency to proceed in the underlayer of the film.

Figure 11 shows the schematic diagram of crazing indicating the crosssectional cut by the crazing line of Figure 10.

Figures 12 and 13 show crazing of polyamide (nylon 66) wire, and Figure 14 shows the point of crazing of polyamide wire. There is quite a difference between crazing of polyesterimide and that of polyamide.

These crazing occurred in only the surface layer at a depth of 0.1–0.2 μ. We can see the orientation[7] of the polymer chain at crazing in the polyamide film, as shown in Figures 12–14, especially Figure 13.

CONCLUSIONS

1. Crazing of a magnet wire film relaxes suddenly the residual stress after elongation. It was found that crazing is most severe at 3–5% elongation, because the residual stress is a maximum at 3–5% elongation, by using a magnet wire having poor adhesion between the conductor and the film.

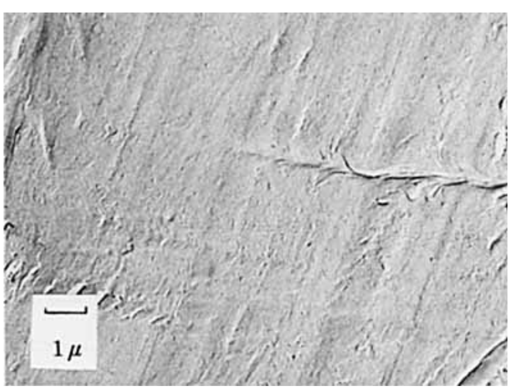

Fig. 14. Point of crazing of polyamide (×5000).

2. Crazing of magnet wire film which is manufactured by coating enamel and baking it several times is in the form of a microcrack. It proceeds from the surface to an underlayer as shown in Figures 10 and 11.

3. Crazing of polyamide (nylon 66) wire was negligible. From observations with an electron microscope, the orientation of the polymer chain was found as shown in Figures 13 and 14.

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