Stress-Strain Relation of Polyvinyl Chloride Sheath Used for Electrical Cords

By

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Abstract

In general, polyvinyl chloride compounds are widely used as a sheath material of electrical cords for indoor use. In this paper, a stress-strain relation of the polyvinyl chloride sheath is analyzed by the experimental data derived from a number of tensile tests. As a result, the stress-strain relation can be numerically expressed by a hyperbola which is based on tne two parallel element Vigot model.

1. Introduction

This paper discusses a stress-strain relation of the sheath of polyvinyl chloride insulated electrical cords based on the experimental data derived from tensile tests. The cords are intended mainly for indoor use with electrical appliances of rated voltages not exceeding 300 V a.c., under the requirements specified by the Japanese Industrial Standard: JIS-C-3306 "Polyvinyl Chloride Insulated Cords for Electrical Appliances". Especially, the sheath of solid, round and flexible cords are required to achieve high reliability and enough safety. The sheathes are made from a polyvinyl chloride compound of which materials are suitably selected, proportioned and treated.

At present, a large amount of electrical cords has been manufactured day by day to satisfy the great demands for various electrical appliances. JIS-C-3306 specifies the tests which are to be made before supplying the manufactured cords in order to demonstrate satisfactory performance characteristics to meet the intended application. One of the important characteristics is the tensile strength and the elongation at the break of the sheathes. Heat resistance also strongly affects the sheath quality. Thus, a large number of tensile tests have been made to see whether the polyvinyl chloride sheath will comply with the requirements

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specified by JIS-C-3306. Later, it will be shown that the stress-strain relation of the polyvinyl chloride sheath can be expressed as a hyperbola based on the test data.

2. Experimental Method

Many tensile tests were carried out to assure the quality of the sheathes which were made from polyvinyl chloride compounds according to the specification of the JIS-K-6723 "Plasticized Polyvinyl Chloride Compounds". The ingredients of the compounds were PVC (42.7%), DOP (25.6%), CCR (21.4%), F-500 (8.5%) and a stabilizer (1.7%). They were heated in a mixture fireplace at 125±1.5°C for 30 minutes and kneaded to form a compound by a rolling machine for 13 minutes.

Many test specimens were made from the sheathes. The testing machine and method were in full accordance with the JIS-C-3005 "Testing Methods for Plastic Insulated Wires and Cables". First, the sheath was kept at room temperature (16~32°C) for more than 12 hours. After that, the sheath was cut into specimens with a punching die of dumb-bell shape No. 3, specified by the JIS-K-6301 "Physical Testing Methods for Vulcanized Rubber". The thickness and length of the specimens were 1.00±0.15 mm and 100 mm, respectively. Two gauging lines were marked on the surface of each specimen. Each line was at a distance of 10 mm apart from the center of the specimen. (See Fig. 1.) The distance between the two lines was measured during each tensile test. The initial distance was 20±0.5 mm.

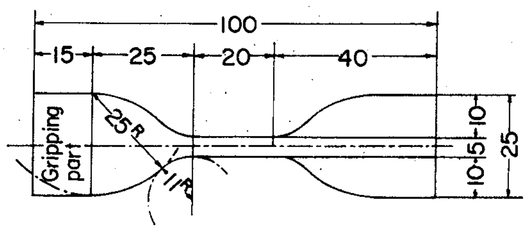

Fig. 1 Specimen of dumb-bell shape No. 3
Unit : mm

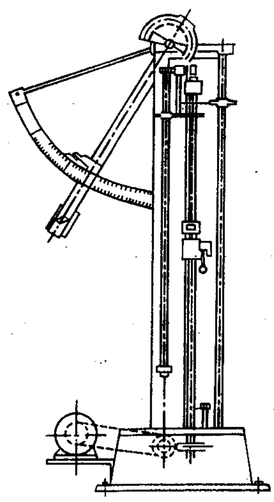

Fig. 2 Tensile testing machine

Before the tensile test, the specimens were kept at room temperature (16$\sim$32°C) at least for one hour. Then, they were set one by one on the tensile testing machine of a pendulum type. (See Fig. 2.) Its standard pulling speed is 50 mm per minute, and the pulling load can be changed within a range from 0 to 20 Kg.

The stress increased according as the specimen was lengthened. The distances between the two gauging lines and the pulling load were measured during the test and at the moment of breaking of the specimen. If the specimen was cut off outside the part specified by the premarked two gauging lines, then another specimen was retested. Test temperature was kept at 20 ± 1.5°C.

Furthermore, JIS-C-3306 requires the heating tensile tests for the sheath. The specimens were heated at 100 ± 2°C for 100 hours. The temperature differences at various parts of the test specimens were kept within ± 2°C against the heating temperature. Then, they were kept at room temperature at least for 12 hours. Thereafter, the tensile strength and elongation of each specimen were measured within 48 hours.

3. Tensile Stress and Strain of the Sheath

Let W and L be the width (mm) and the thickness (mm) of each tensile test specimen, respectively. The cross section area S (mm^2) of the specimen is given by

$$S = W \times L. \tag{1}$$

Stress σ (Kg/m^2) is defined as

$$\sigma = p/S, \tag{2}$$

where

p is the pulling load (Kg) at any pulling instant,

and

S is the corresponding minimum cross section area (mm^2) of the specimen. The value of the width W was determined by the mean of the values measured at ten points of each test specimen by a digital micrometer. The value of thickness L was determined by the minimum of the measured values.

It is noted that the stress applied just before the breaking of the specimen gives the ultimate tensile strength of the sheath. The values of the stress and the strength were determined by the mean of values measured from many test specimens.

For the purpose of investigating the effect of heating on the strength, the residual strength R(%) is introduced as follows:

$$R = \frac{\sigma(\mathrm{A.H})}{\sigma(\mathrm{B.H})} \times 100\ (\%)\ , \tag{3}$$

where

σ(A.H) and σ(B.H) are the strengths of the sheath after heating and before heating, respectively.

On the other hand, the strain or elongation $\varepsilon(\%)$ of the specimen is defined as follows;

$$\varepsilon = \frac{l(p)-l}{l} \times 100\ (\%)\ , \tag{4}$$

where

$l(p)$ is the distance between the two gauging lines at the beaking of the specimen, (mm), and p means the corresponding pulling load (kg). l is the initial distance between the two gauging lines (mm).

The values of the strain were determined by the mean of values obtained from many test specimens.

4. Results

Table 1 shows the experimental data derived from the tensile tests of the sheathes before heating and those after heating. Using the data, the values of stress versus the values of strain are plotted in Fig. 3. The lower and upper curves show the results from the tests before heating and those after heating, respectively.

It is noted that the stress applied just before the breaking of the specimen gives the ultimate tensile strength of the sheath. The test data derived by the

Table 1 The experimental data

tensile test before heating			tensile tests after heating		
time t(sec.)	strain $\varepsilon(\%)$	stress $\sigma(\mathrm{Kg/mm})^2$	time t(sec.)	strain $\varepsilon(\%)$	stress $\sigma(\mathrm{Kg/mm^2})$
5.	22.80	0.250	5.	20.00	0.276
10.	48.30	0.485	10.	43.00	0.550
15.	77.30	0.701	15.	69.50	0.798
20.	108.80	0.898	20.	103.00	1.035
25.	142.50	1.078	25.	140.50	1.212
30.	176.90	1.240	30.	178.00	1.351
35.	213.10	1.375	35.	217.50	1.510
40.	244.90	1.449	40.	250.00	1.630
45.	282.60	1.607			
at break	315.00	1.641	at break	263.00	1.632

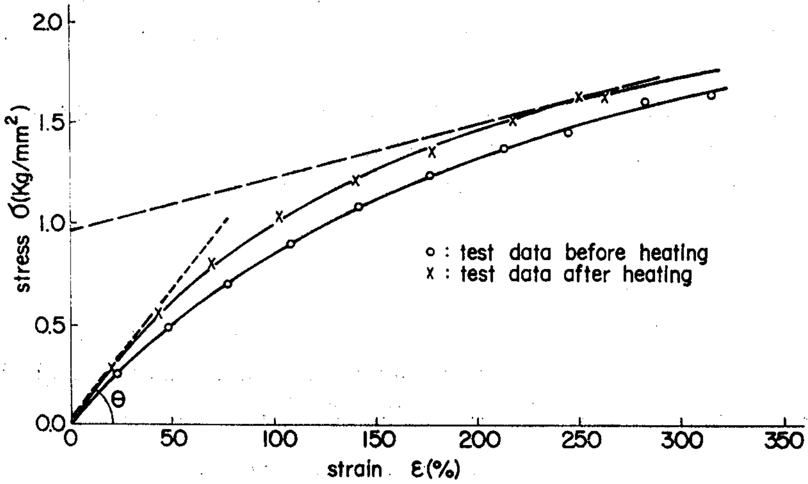

Fig. 3 Stress-strain relation

experiments assures that the ultimate tensile strength before heating is 1.641 Kg/mm^2, while JIS-C-3306 specifies that the standard strength value of the sheath of electrical cords should be not less than 1.0 Kg/mm^2. Furthermore JIS-C-3306 specifies that the residual tensile strength of the sheath should be not less than 85% of the one before heating. In the present experiments, the residual strength of 99.5% was ensured from Eq. (3), since σ(A.H) is 1.632 and σ(B.H) is 1.642.

On the other hand, JIS-C-3306 specifies that the strain at the breaking of the sheath before heating should be not less than 120%, and the strain at the breaking after heating should be not less than 80% of the value before heating. In the present experiments, the strains at the breaking of the sheath before heating and after heating were 315% and 263%, respectively. The residual strain at breaking after heating was 84.5% of the one before heating. According to the above observations, the compounds tested at the experiments have been proved to be suitable for the intended electrical appliances.

As shown in Fig. 3, the stress versus strain curves are not linear but concave downwards. That is, the stress is not strictly in proportion to the strain. However, in a small range of the strains, the relationship between the strain and the stress can be considered to be linear. Thus, the tangential line of the stress versus strain curve at the origin gives the spring constant κ in the linear spring model. The spring constant κ is defined as follows;

$$\kappa = \tan\theta = \frac{d\sigma}{d\varepsilon}, \tag{5}$$

where $d\sigma/d\varepsilon$ is a differential coefficient of the stress function σ of the strain ε at the origin, and θ is an angle between the tangential line of the function and the horizontal line.

In practice, the tangential line of the stress function at the origin should be estimated by the experimental data measured at some points near the origin. The estimated expressions of the tangential lines for the each test are given as the following form:

$$\sigma = L + \kappa\,\varepsilon\,, \tag{6}$$

where κ corresponds to the spring constant in the linear model, and L denotes the vertical axis intercept, while the tangential lines should pass through the origin. The experimental data determined the following expressions:

$$\sigma = 0.11 + 0.00784\,\varepsilon \qquad \text{for the test before heating,} \tag{7}$$

and

$$\sigma = 0.06 + 0.01010\,\varepsilon \qquad \text{for the test after heating.} \tag{8}$$

In Fjg. 3, the detted line shows the tangential line at the origin for the test after heating.

One of the important characteristics is the tensile behaviour of the sheath just before its breaking. It can be also expressed by the differential coefficient of the stress function σ of the strain ε at the breaking point. In Fig. 3, the dashed line shows the tangential line of the stress versus strain curve at the breaking point. The corresponding differential coefficient, i.e. the linear spring constant κ, can be derived from the experimental data. It is noted that the tangential line at the breaking point does not pass through the origin, and it intersects the vertical axis at a point. The tangential lines at the breaking point were determined by the experimental data as follows;

$$\sigma = 0.48 + 0.00422\,\varepsilon \qquad \text{for the test before heating,} \tag{9}$$

and

$$\sigma = 0.46 + 0.00520\,\varepsilon \qquad \text{for the test after heating.} \tag{10}$$

From the data obtained by the tensile tests, the strain of the sheath rapidly becomes large around 20 seconds, in the case of the maximum pulling weight of 20 Kg and a pulling speed of 50 mm per minute.

5. Analysis of the stress-strain relation

As mentioned above, the experimental data show that the stress versus strain curve of the sheath is not linear but concave downwards. This is reflected by the fact that the polyvinyl chloride compound is plastic and not elastic in every way. The sheath can not perfectly spring back to the original size after being pulled out. However, in the case of tensile tests, it is convenient to analyze the stress-strain relation under the assumption that in a range of small strain values, the polyvinyl chloride compound behaves as if it were entirely elastic. Thus, Hooke's law can be applied to plastic materials in their elastic region. That is, the stress σ is expressed by the strain ε as follows:

$$\sigma = k\,\varepsilon\,. \tag{11}$$

The constant k is called elastic modulus or spring constant.

It is noted that as the strain value increases, the increasing rate of the stress becomes small, because of the viscosity of the polyvinyl chloride compound. In the case of viscous material, the stress depends on the velocity of the strain. Then the stress-strain relation is given by

$$\sigma = h\,\frac{d\varepsilon}{dt}\,, \tag{12}$$

where h is called the viscousity coefficient and generally is a function of elongation speed $d\varepsilon/dt$. A mechanical model of viscous material can be expressed by a dash-pot.

If the polyvinyl chloride compound is assumed to be Newtonian, or a linear viscous material in the range of large values of strain, then the viscousity coefficient h is constant. Also, in the tensile tests with a constant pulling speed, the elongation speed $d\varepsilon/dt$ can be considered as constant. Therefore, it can be assumed that the stress-strain relation is expressed as

$$\sigma = \frac{h}{\varepsilon}\,\varepsilon\,. \tag{13}$$

It is noted, however, that the polyvinyl chloride compound has both properties of elasticity and viscosity, i.e. viscoelasticity. In this case, the stress-strain relation can be analyzed by a two parallel element Vigot model, consisting of a spring with the elastic modulus k and a dashpot with the viscosity coefficient h, as shown in Fig. 4. From the viewpoint of electrical circuit analogy and the calculating method of parallel circuit impedance, the following stress-strain relation is derived:

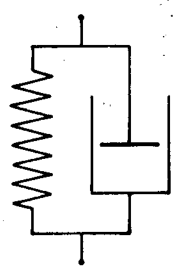

Fig. 4 Vigot model.

$$\sigma = \frac{1}{\frac{1}{k}+\frac{1}{h/\varepsilon}}\,\varepsilon\,. \tag{14}$$

This expression can be rewritten as

$$\sigma = \frac{\varepsilon}{\alpha+\beta\,\varepsilon}\,, \tag{15}$$

or

$$\varepsilon/\sigma = \alpha+\beta\,\varepsilon\,, \tag{16}$$

where α and β are equal to $1/k$ and $1/h$, respectively.

Using the experimental data given in Table 1, the values of ε/σ versus the values of ε are plotted in Fig. 5, where the points are considered to be arranged in a straight line in both cases of the tensile tests before heating and after heating. The estimated straight lines are given by

$$\varepsilon/\sigma = 83.85+0.3357\,\varepsilon \qquad \text{for the test before heating,} \tag{17}$$

and

$$\varepsilon/\sigma = 63.37+0.3668\,\varepsilon \qquad \text{for the test after heating.} \tag{18}$$

This fact means that the stress-strain relation of the sheath can be explained by the two parallel element Vigot model from a global viewpoint of the simple tensile tests.

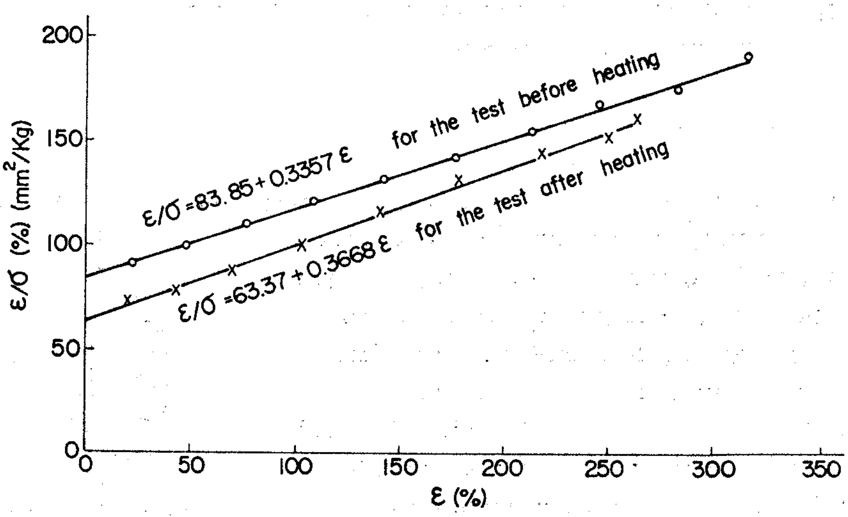

Fig. 5 Relation between strain/stress and strain

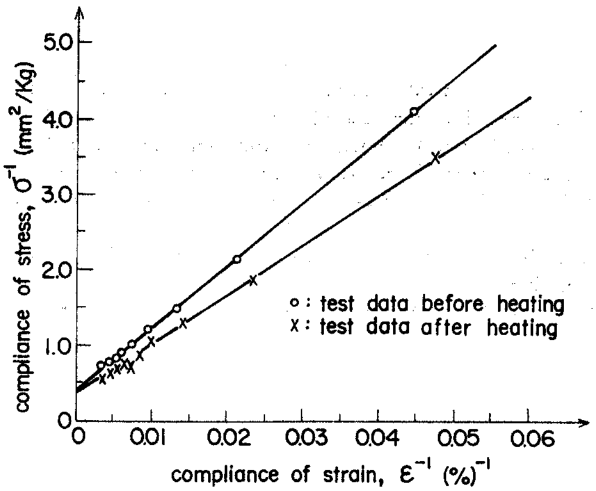

Fig. 6 Relation between compliance of stress (σ^{-1}) and compliance of strain (ε^{-1})

It is noted that Eq. (16) can be also rewritten as

$$(1/\sigma) = \beta + \alpha(1/\varepsilon)\,. \tag{19}$$

That is, the reciprocal of the stress is strictly in proportion to the reciprocal of the strain, as shown in Fig. 6. Thus the experimental data determine the functional form of the stress-strain relation given by Eq. (15) as follows:

$$\sigma = \frac{\varepsilon}{83.85+0.3357\,\varepsilon} \quad \text{for the test before heating,} \tag{20}$$

and

$$\sigma = \frac{\varepsilon}{63.37+0.3668\,\varepsilon} \quad \text{for the test after heating.} \tag{21}$$

In Fig. 3, the two curves are drawn by Eqs. (20) and (21). These curves show that the stress-strain relation of the polyvinyl chloride compound sheath can be numerically expressed by a hyperbola of Eq. (15), based on the two parallel element Vigot model.

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