MANUFACTURE AND TESTING OF ENAMELLED WIRE

by R. J. H. ALINK *, H. J. PEL *) and B. W. SPEEKMAN **).

Enamelled wire, which is used for winding coils, is at present one of the basic materials of the electrical industry. The present article gives a short survey of its manufacture, methods of testing and of the problems connected with the chemical and physical structure of the insulating lacquer.

One of the basic materials of the electrical industry is insulated copper wire, used for winding coils, transformers, rotors, stators etc. Originally copper wire surrounded by e.g. rubber or cotton was used for this purpose, but nowadays enamelled copper wire (more accurately “enamel lacquered wire”) is used almost exclusively. The great advantage of insulating with enamel is that a very thin layer of the insulator is sufficient, so that coils with a relatively high “space factor” (i.e. coils in which a relatively large part of the volume is taken up by copper) can be obtained.

The variety of demands made on enamelled wire in the electrical industry has led to the development of a number of types differing in the chemical composition of the enamel layer. Pope’s factory in Venlo (Netherlands) makes mainly the following four types:

a) Oil-lacquer enamelled wire, the oldest type of enamelled wire 1);

b) “Povin” wire, which is very strong;

c) “Posyn” wire, which can be easily soldered: the layer of enamel is readily removed when the wire is dipped into molten solder;

d) “Potermo” wire, which is resistant to quite high temperatures (up to about 155 °C).

All the above-mentioned types of wire are manufactured in more or less the same way, starting from chemically different lacquers. This article starts with a brief description of the manufacturing process. We shall then consider the demands which are made on enamelled wire, and the methods of testing whether these demands are met with. After this section, which deals with the practical side of the matter, follows a theoretical discussion of the relationship between the most important properties of the various types of wire and the structure of their insulating layer. Finally we shall pay special attention to a recent investigation which illustrates the presence and the danger of microscopic “flaws” in the enamel layer.

Manufacture

The manufacture of good enamelled wire entails applying the lacquer as thinly as possible to the wire, as otherwise it collects in drops and is thus unevenly distributed over the wire. It is therefore necessary to apply a number of coats of lacquer one after the other to get the required insulating thickness, which may be e.g. 16 μ for a copper wire 0.1 mm in diameter. The usual procedure is to pass the wire a number of times alternately through a lacquer reservoir and a muffle furnace: when it passes through the lacquer reservoir, the wire is covered with a thin coat of liquid lacquer; it is then dried (“muffled”) in the furnace, returned to the reservoir for a new coat of lacquer, and so on, until the enamel layer has the desired thickness.

The machines which are used for this process may mainly be divided into two types: those in which the wire is led vertically through the furnace, and those in which it is led horizontally. Machines of these two types are shown in figs 1 and 2 respectively.

Certain characteristic differences between the two types may be seen from these figures. The following will help to clarify these differences. The force of gravity makes a horizontal wire lie in a slight curve (a “catenary”), which has undesirable consequences for the manufacture. The furnace of the horizontal machine must therefore be relatively short. Vertical machines, where this difficulty does not arise, can use furnaces 10 metres or more in length. The short horizontal machines have the advantage that the wire can be threaded through by one man, while the attractive point of the vertical machines is that, for

*) Philips Research Laboratory, Eindhoven. — Our late colleague Dr. Alink, who died in 1959, had as part of his work carried out a series of investigations on enamelled wire. The results of these investigations form part of the material of this article.

**) Pope’s Wire and Lamp Factory, Venlo, Netherlands.

1) See e.g. J. Hoekstra, Philips tech. Rev. 3, 40, 1938.
Fig. 1. Two *vertical* machines for the manufacture of enamelled wire. The one on the left is 14 m high. Each of these machines processes a number of wires at a time, each wire passing a number of times alternately through a lacquer reservoir and a muffle furnace. See also figs. 3 and 4.
a given drawing rate, the wire remains longer in
the furnace. This is especially important with
thick types of wire, where the lacquer is applied in
relatively thick coats, and which therefore need
rather a long drying time.

In general it is desirable for economic reasons to
let one machine process a number of wires at a time.
The advantage of this will however be lost if the
wire breaks often, and if the whole machine has to
be stopped each time a break occurs. Thick wire
does not break very often, but with thin wire this
possibility must indeed be kept in mind. As a
logical conclusion, the manufacture of enamelled
lacquer will flow out through these slits; this ends up
in a gutter, whence it is pumped back into the
reservoir.

Fig. 4 shows the part of the machine where the
16 finished wires are "coiled".

**Demands made on the wire and methods of testing**

The finished wire is tested as regards a consid-
erable number of properties. The uniformity of
the enamel layer is of prime importance for wire to
be used for winding purposes: the enamel must not
show any inhomogeneities or pits, and must be
applied equally thickly all round the copper. The

wire has tended towards the use of horizontal
machines for thin wires, with one wire per
machine (fig. 2), and multiple vertical machines
for thick wire, taking 8 or more wires at a time
(fig. 1).

**Figures 3 and 4** show some details of a vertical
machine which enamels 16 wires at a time, applying
6 coats of lacquer to each wire. Fig. 3 shows the
lacquer reservoir at the bottom of the machine.
We see here $6 \times 16 = 96$ slits in the slanting wall
through which the wires are drawn up via a roller
to the furnace. It is inevitable that a small stream of
mechanical, electrical and chemical properties of
the enamel layer are also of great importance. We
shall mention a few of the methods described in
standard specifications for the testing of enamelled
wire in these respects.

Holes and other large flaws in the insulation are
detected by passing the wire through a conducting
liquid (mercury or a solution of common salt), while
a voltage is applied between the core of the wire and
the liquid. The circuit also contains a resistor, a neon
lamp and a counter. If the resistance of the enamel
layer in contact with the liquid is less than e.g.
Fig. 3. The lacquer reservoir for a vertical machine. This machine supplies 16 wires at a time with a six-coat insulating layer. We see here how the wire is drawn up through 96 slits in the wall to the muffle furnace above. The thin stream of lacquer which flows out of these slits is caught in a gutter and pumped back to the lacquer reservoir. The degree of “muffling” is judged with the aid of a colour sample (the reel on the left); the colour of the enamelled wire is darker if the wire is muffled at a higher temperature or for a longer time. If the colour is lighter or darker than that of the sample, the rate at which the wire is drawn through the machine is decreased or increased, respectively.

Fig. 4. Rotating containers in which the 16 finished wires coming from the machine in the background are “coiled”.
10,000 Ω anywhere, a current flows through the circuit which lights up the neon lamp and sets the counter in operation (see fig. 5).

A uniform thickness of the enamel layer is of importance not only in connection with the insulation resistance, but also because a very constant wire diameter (standard deviation of less than 2%) is demanded for certain winding methods. We shall not discuss here the fairly simple methods used for testing the thickness of the wire.

In order to check the layer structure of the enamel insulation simply and rapidly, the wire in question is placed for about 1 minute at an angle of 45° in a reagent which is capable of dissolving the enamel. A slanting cross-section of the enamel is then to be seen on the wire, and the various layers can be clearly seen with the aid of a magnifying glass (fig. 6).

The mechanical tests cover such diverse properties as resistance to wear, flexibility, etc. There are, for example, wear tests in which the number of strokes of a loaded reciprocating needle which the insulation can stand is determined. The flexibility and "windability" are tested by winding the wire round pins of roughly the same diameter as the wire itself. It is also stipulated that the wire after being wound in this way remains undamaged if the temperature is suddenly increased. This demand, which is one of the most stringent with which the wire must comply, is mainly of importance in connection with treatment which a coil may undergo after it is wound ("compounding" or impregnating).

As far as the electrical properties of the enamel are concerned, the breakdown voltage in particular is of importance. This can be determined e.g. by winding a piece of wire round a polished steel cylinder, and applying a gradually increasing voltage between the core of the wire and the cylinder. Other electrical properties which it is desirable to know are the insulation resistance and the dielectric losses. Measurements of the insulation resistance carried out as an aid in the investigation of the physical structure of the enamel layer are discussed on p. 349.

The chemical properties of the enamel which are of special interest to the electrical engineer are the thermal aging and the resistance to solvents and impregnating agents. We shall mention thermal aging again briefly towards the end of the article, but for the rest we will leave this subject here: any further details would carry us too far into the practical aspect of the investigations. We shall now consider enamelled wire from a theoretical point of view.

Relationship between the chemical structure and the properties of the enamel layer

It is a difficult but rewarding task to try to find some relationship between the observable properties of enamelled wire and the chemical composition of the enamels used. We are far from having a complete insight into this matter, but what has already been reached is worthy of mention.

General principles of the structure of lacquer enamels

Lacquers may be divided into two groups: physically drying and chemically drying.

A physically drying lacquer consists of a volatile solvent with a macromolecular substance, e.g. nitrocellulose, dissolved in it. When such a lacquer is applied to an object, the solvent evaporates and the residue forms a layer on the object in question. This process takes place without any chemical change, i.e. the molecules do not react with one another. The enamel layer thus formed can be redissolved in the original solvent, and also has a tendency to soften.
when heated. These lacquers are therefore also sometimes called thermoplastic lacquers.

An enamel layer with entirely different properties is obtained if the molecules of the lacquer in question do react with each other, forming a three-dimensional network, as is the case with the chemically drying lacquers. The layer thus formed will not have the tendency to soften on heating, and is resistant to the usual solvents (though it may swell to a certain extent in some cases).

It will be clear that only the second type of lacquers, which are also known as thermosetting lacquers, come into consideration for use as insulation for wire. Thermoplastic lacquers are sometimes used as an extra layer on a wire which is already insulated with a thermosetting lacquer ("Thermoplaç" wire). When a coil wound with this wire is heated, the outer layer will soften and thus cause the work to adhere rigidly to the copper everywhere, the enamel layer can easily be stretched with the copper without breaking.

We shall discuss a third general "structural principle" of lacquer enamels with reference to the oldest type of lacquer, oil lacquer.

Oil lacquers are made according to a principle going back to the last century for the preparation of e.g. carriage lacquer. The main ingredients of such lacquers were naturally occurring resins (rosin, copals) and drying oils (linseed oil, tung oil). Modern wire enamels with an oil base still use natural drying oils. The natural resins have however been replaced by synthetic resins, which gives the advantages of a more constant composition and a wider possible range of properties.

In the new oil lacquers as well as in the old ones we find an important structural principle, which is manifest to some degree in all types: there is a certain balance between the ingredients of a flexible nature and those of a more rigid nature. The first are here represented by the drying oils with their long linear carbon chain, the second by the resins, whose molecules contain a large number of rings (see fig. 7).

If the molecular network in question is formed only of the flexible components, as in e.g. rubber, we obtain a very elastic product, which however has the disadvantage of being soft and liable to swell in many solvents: molecules of the latter can easily penetrate the "open" network and cause it to expand. On the other hand, if the network is formed only of rigid components (as e.g. in certain synthetic resins) the result is a hard but brittle substance.

The combination of resins and drying oils actually used is just what is needed to give enamelled wire its excellent properties for use in winding coils: the enamel combines good flexibility with a considerable resistance to mechanical and chemical effects.
Now that we have learnt some general structural principles, we may show how the individual properties of certain types of enamelled wire can be understood against their structural background.

"Povin" wire

As our first example we shall consider the entirely synthetic lacquer for "Povin" wire. This lacquer also has two main ingredients, which show the above-mentioned balance of properties. The first ingredient is polyvinyl formal, whose molecule is characterized by a) a mainly linear structure, b) the occurrence of ring systems of the 1,3-dioxane type, and c) a large number of hydroxyl and acetate groups (see fig. 8). The second ingredient is a synthetic resin marketed under the name "Novolak". Of this substance we need only mention that its molecule is mainly made up of rigid components and also contains a number of hydroxyl groups.

It is not yet quite clear what chemical reaction takes place between these two ingredients during the manufacturing process. It is assumed that the hydroxyl groups of the "Novolak" as well as those of the polyvinyl formal play a part in the formation of the three-dimensional network. This will not, however, contain a large number of chemical bonds, as in the case of oil lacquers: the chemical structure of the ingredients simply does not allow this.

![Fig. 8. The chemical structure of polyvinyl formal, an important ingredient of the insulation of "Povin" wire.](image)

There is however plenty of opportunity for the formation of physical bonds, i.e. hydrogen bonds. These will be formed between the hydroxyl groups of the "Novolak" resin and the oxygen atoms in the dioxane rings of the polyvinyl formal.

Apart from the wide-meshed "loose" network of chemical bonds, a close-meshed network of hydrogen bonds will thus be formed. Each individual hydrogen bond is weaker than a chemical bond, but because of their great number a very strong structure results. Such a structure is just what is needed in a wire enamel: it may be expected that when the wire is bent, during which process the enamel layer is subjected to considerable strain, many of the quite weak hydrogen bonds will be broken. They will thus offer very little resistance to bending, while the breaking of the hydrogen bonds will lead to very little permanent damage: if the strain is relieved e.g. by heating for a short time, a new network of hydrogen bonds will immediately be formed, so that the old strength is regained. This is the reason for the excellent mechanical properties of "Povin" wire to which we alluded at the beginning of this article.

"Posyn" wire

As mentioned, the particular property of "Posyn" wire is that its enamel layer can be removed by dipping in molten solder. Here too, the connection between this property and the chemical structure of the enamel layer may be clearly seen.

The chemical bonds which hold much of the network together are formed by the reaction:

\[ -N=C=O + HO- \rightarrow \text{H} \]  
\[ \text{O} \]  
\[ N-C-O- \]  

i.e. the reaction between an isocyanate group and a hydroxyl group. Now this reaction is a reversible reaction, which proceeds in the opposite direction at high temperatures. When the wire is dipped in the molten solder, the three-dimensional network breaks up into fragments of low molecular weight as a result of the reversal of this reaction. These fragments evaporate, and the copper which is thus exposed comes out of the solder bath covered with solder.

"Potermo" wire

The enamel of the recently developed "Potermo" wire has one of the least complicated network structures: the network is formed by the esterification of terephthalic acid with simple polyalcohols such as ethylene glycol and glycerol. The way in which the network is built up of these components is shown in fig. 9.

The excellent resistance to high temperatures of "Potermo" wire has been found by experiment to be due to the fact that oxygen from the air has very little effect on it. It is not entirely clear why a network like this should be so insensitive to oxygen, but on the other hand it is not altogether surprising: the network does after all consist practically entirely of benzene rings and ester groups, which are known not to react easily with oxygen. The
other groups are probably sufficiently well shielded by the oxygen-resistant groups.

It is clear from the above what a complicated interplay of factors determines the quality of enamelled wire. In fact, the situation is even more complicated, because not only the structure itself, but has certainly not yet reached its final stage, the preliminary results fully justify great attention to this subject.

The first method used is based on measurement of the discharge time of a capacitor formed by clamping a metre of enamelled wire between tin foil. The tin foil is earthed, and the core of

![Network Structure of Insulation](https://example.com/network_diagram.png)

**Fig. 9.** The network structure of the insulation of “Potermo” wire. I: glycerol; II: terephthalic acid; III: ethylene glycol. These three components occur in various sequence in the network.

also “flaws” in the structure have an influence on the quality. We shall devote the last section of this article to this important subject, in particular to an investigation in this field carried out in the Research Laboratories in Eindhoven.

**Investigation of “flaws” caused by mechanical stresses**

It has been indicated in the foregoing how rather large flaws in the insulation are detected during the routine inspection of the wire. Work has been going on in the Research Laboratories over the past few years with a view to developing more refined methods for studying enamelled wire under mechanical stress. It has been found that measurement of the insulation resistance of the enamel layer, if carried out by sensitive methods, shows up the presence even of microscopically small cracks produced by such stress. Although this investigation

the wire connected to an electrometer. The capacitor so formed is charged to a known voltage, and the time needed for it to discharge to a certain lower voltage is measured. This time depends in a simple way on the unknown insulation resistance and on the capacitance, which is also unknown. In order to eliminate the latter unknown, a second measurement is carried out with a calibrated resistor included in the circuit in parallel with the capacitor.

Measurements on dry (and unstressed) enamelled wire gives a high value of the insulation resistance (e.g. $10^{13} - 10^{14} \, \Omega$) for all types of wire, as long as there are no real holes in the enamel layer. Measurements on damp enamelled wire normally indicate a relatively small reduction in this resistance, the precise value of the reduction showing characteristic variations with the type of wire. The reduction increases in the order: oil-lacquer enamelled wire — “Posyn” wire — “Povin” wire.
This picture alters considerably as soon as the wire is subjected to bending tests, so that stresses are produced in the enamel layer. Even a slight bend (radius of curvature e.g. 1 m) in the wire produces a considerable reduction in the insulation resistance (e.g. by a factor 10-100) when the measurements are made on damp wire. If the wire is bent rapidly, or bent around a pin or a sharp corner, the effect is increased so much that the method is no longer applicable, because the capacitor discharges too fast.

The following method is used for further study of the problem. The core of the strongly bent wire is connected to the negative terminal of a battery, and the wire is dipped into a solution of common salt containing a little phenolphthalein. The other terminal of the battery is connected to a nickel rod which is placed in the same solution. Electrolytic effects are immediately produced: bubbles of hydrogen gas, together with OH\(^{-}\) ions, are produced at the bends in the immersed wire. The latter can be observed from the red colour assumed by the phenolphthalein at the outer side of each bend. This is what would be expected if one assumed that small cracks can be produced by tensile stress.

This method gives a negative result if the wire is only slightly bent, even after long periods of time, which surprised us at first. Careful microscopic investigation finally produced a fairly complete picture of the nature of these flaws. When the wire is quickly bent round a pin, one observes cracks suddenly forming in the enamel layer after some time. Even if the wire is bent slowly and slightly, very fine cracks are observed after enough time has elapsed. These hair cracks, however, do not extend right through to the core, but are restricted to a few outer layers of the insulation. It may be assumed that such cracks do produce a considerable decrease in the resistance, but do not allow electrolytic effects to occur. If the enamelled wire is warmed, the hair cracks often close up again; they can then no longer be observed under the microscope, and the insulation resistance is observed to have increased again. The hair cracks can be regarded as fairly “harmless” precursors of the cracks produced by e.g. bending round a sharp angle.

Cracks of the latter type are most undesirable in a coil wound with enamel wire: if the coil is internally damp, they allow undesirable small currents to flow — i.e. they can cause a certain measure of short-circuiting. If such currents contain a DC component, they can also cause severe corrosion of the copper wire as a result of electrolysis. If the corrosion is allowed to proceed far enough, the copper wire may even break.

So much for this investigation. Its results throw an interesting light on various practical developments of recent times. For instance, for the winding of coils the rectangular cores and formers which were formerly common are being replaced more and more by ones with rounded corners. Moreover, attempts are being made to improve the quality of the coils by using waterproof materials for separating the windings.

As far as understanding of the above-mentioned phenomena is concerned, it will be clear that science still has a lot of ground to win from empirical knowledge in this field; and this is just what makes this subject so fascinating. There is thus no better way of closing this short survey of the work on enamelled wire than with the mention of a couple of examples which are still not easy to understand. Fig. 10 illustrates the curious complications which are found in the thermal aging of enamelled wire. Quite un-

---

Fig. 10. Thermal aging of “Posyn” wire in a sealed tube for 48 hours at 180 °C. Surprisingly enough, the insulation is damaged more by thermal aging under these conditions than when it is exposed to the same temperature for the same time in air.
expectedly, “Posyn” wire in a sealed-off tube shows a more rapid deterioration of the insulation than the same wire which is simply exposed to the air. This phenomenon is found to a greater or lesser extent with all “solderable” wires. It is not so pronounced with “Posyn” wire, but it is still not entirely suppressed. *Fig. 11* shows a series of ring-shaped cracks which are produced when a bent piece of “Povin” or “Posyn” wire is dipped in a solvent. This phenomenon, which is called “solvent cracking”, is very closely connected with the mechanical stresses present in the enamel layer; if the wire is heated to 100-120 °C after bending, so that the mechanical stresses in the enamel are relieved, solvent cracking does not occur. It is also very strange that such cracks are quite absent when oil-lacquer enamelled wire is used.

**Summary.** Among the properties required of enamelled wire used for the winding of coils are flexibility and resistance to mechanical and chemical effects. The “enamel” insulation consists of “chemically drying” lacquers, which are applied in several coats by passing the wire a number of times alternately through a lacquer reservoir and a muffle furnace. This process is carried out horizontally for thin wire but vertically for thick wire. To obtain satisfactory enamel layers the following conditions must be satisfied: a) the formation of a three-dimensional network of atoms which b) is firmly attached to the copper and which c) contains both flexible and rigid elements. The last requirement is illustrated for the case of oil-lacquer enamelled wire. Further, a theoretical explanation is given for the great mechanical strength of “Povin” wire, for the remarkable fact that “Posyn” wire can be soldered through the enamel layer, and for the thermal resistance of “Potermo” wire. Finally, a recent investigation of microscopic “flaws” produced by mechanical stress is described, and a number of phenomena which are as yet rather difficult to understand are mentioned.