Stress Systems in the Solderless Wrapped Connection and Their Permanence

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The solderless wrapped connection is initially held together by the hoop stress in the wire which enters the connection as a result of the tension put on the wire by the wrapping tool. Measurements made out to a time of 1.5 years at room temperature show that the tension has decreased to 70 per cent of the one day value (8000 lbs per square inch) in this period. Two methods of extrapolation are discussed, both of which indicate that at least half of the initial one day value will remain at the end of forty years at room temperature.

Another set of stresses enters the connection as a function of time, namely the diffusion forces produced by diffusion of the tin plating into the brass terminal and copper wire. A number of experiments are discussed which show that the activation energy of diffusion is materially reduced by the shearing stresses in the connection. Measurements at two temperatures, which allow extrapolation to room temperature, indicate that at the end of two years the force required to strip the wire from the terminal has increased by 5 per cent over the initial value and that at the end of forty years the increase will be 20 per cent. Support for these conclusions is furnished by tests on actual connections that have been in the field for one year and ten months, which show an increase of 5 per cent in the stripping force even though the relaxed hoop stress is only 68 per cent of the initial value. The increase, which is due to diffusion forces, can be made higher by using zinc, cadmium or aluminum plating, and the fusion occurs in a shorter time.

INTRODUCTION

As discussed in a series of papers,[1] the solderless wrapped connection is an efficient and inexpensive method of connecting a wire to a terminal. All the tests made so far indicate that it is mechanically sound and sufficiently free from the effects of corrosion to have a trouble free life of at least forty years. Photoelastic and stress studies show that the

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[1] The Solderless Wrapped Connection, B. S. T. J., **32,** May 1953.

connection is initially held together by the hoop stress in the wire which enters the joint as a result of the tension put on the wire by the wrapping tool. As time goes on, another system of stresses are generated, namely, the diffusion stresses caused by the diffusion of one part of the connection into the other which eventually eliminate the surface between the wire and the terminal and in effect join the two together.

It is the principal purpose of this paper to describe a number of experiments which show how these stresses develop, how large they are and how they can be increased by substitution of a different type of plating between the terminal and the wire. A comparison of the strength of a joint formed by a tin plated copper wire and a bare copper wire both wound on nickel silver or brass terminals shows that the diffusion forces develop more quickly when the wire is tin plated than when it is bare. Measurements made at different temperatures show that the activation energy of diffusion is decreased in proportion to the hoop stress in the wire indicating that the shearing stress at the contact surfaces aids diffusion. This activation energy is considerably less for tin than for copper. The diffusion joint has a strength per unit area equal to the limiting shearing stress of the tin plating. This is in the order of 3,000 pounds per square inch for tin but is considerably higher for other types of plating such as zinc, aluminum or cadmium. Measurements of the stripping force of connections made with bare and tinned copper wire on zinc, aluminum or cadmium plated terminals show that the stripping force increases by a factor of two as a function of time, and the time required for the diffusion forces to operate is considerably less with these types of plating.

The combination of relaxation and diffusion stresses that are discussed later show that as the mechanical strength due to the hoop stress decreases, the strength due to diffusion increases and at the end of forty years the standard tin plated wire on nickel silver or brass terminals will be at least 20 per cent stronger than it is initially. The extensive corrosion tests described in Footnote 1, taken together with the mechanical strength tests described here, show that the standard connection should not fail in the forty year period under consideration.

RELAXATION OF HOOP STRESS AS A FUNCTION OF TIME

The rate of relaxation of the hoop stress in the wrapping wire is an important quantity for the stability of the connections. This has been studied by wrapping 24 gauge wire with a constant tension of three pounds around a spring steel terminal 0.0124 inches thick and 0.062 inches wide. As shown by Figure 11 of Mallina's paper,[2] this causes the terminal to twist through an angle of about 25° when 100 turns are wrapped around the terminal. This twist is the result of a torque which is caused by the fact that the wire has a hoop stress and the wire does not come back on itself but advances by the thickness of the wire for each turn. As shown previously,[2] the total torque is equal to

$$\text{Torque} = (\text{W.F.})\left(\frac{2ab}{a+b}\right)L \tag{1}$$

where (W.F.) is the wrapping force, $2a$ and $2b$ the thickness and width of the terminal and L the total length of the wrapped section. Hence, by calibrating the spring constant, the average hoop stress can be evaluated. In this manner, Mallina[2] has found that after transient creep (defined in this paper as the loss in stress during one day) has occurred, the stress level for the standard 24 gauge connection is about 8,000 pounds per square inch.

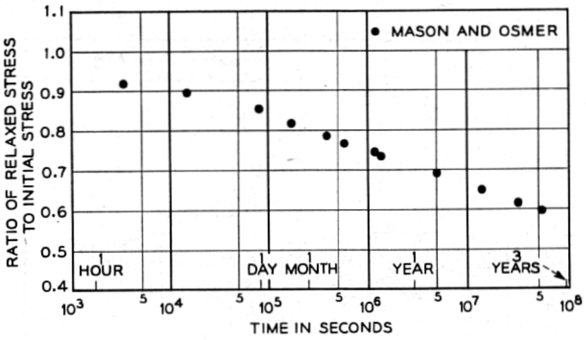

Fig. 1 — Relaxation of stress in copper solderless wrapped connection at room temperature.

This same technique can be used to measure the loss in hoop stress as a function of time for all one has to do is to put a pointer on the spring and observe the rate the angle decreases. It will be noted that this system reproduces all of the stress systems and strain hardening that occur in the wrapped solderless connection, and hence a measurement of the relaxed angle is the most representative measurement of the relaxation of the solderless wrapped connection. Fig. 1 shows an average of the results of four such springs from the time of their intial formation out to a period of one year and one month. The rate of relaxation is quite rapid during the first day (transient creep) but at the end of one

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[2] R. F. Mallina, Solderless Wrapped Connections, Part I — Structure and Tools, B. S. T. J., pp. 525–555, **32,** May 1953.

year and one month the average hoop stress is 5,900 pounds per square inch and it is decreasing at the rate of 240 pounds per square inch between the first and second year. In the previous paper,[3] since the transient creep occurring during the first day is somewhat variable, the angle of twist reached 24 hours after the connection had been made, was taken as the initial 100 per cent value and the relaxation has been plotted with respect to this. Fig. 2 shows this plot with data from Mason and Osmer and a set of eight relaxing springs measured by Mallina and McKettrick all plotted on the curve. At the end of 1.5 years, the observed stress is 70 per cent of 8,000 pounds per square inch or 5,600 pounds per square inch on the average.

The measurements out to 1.5 years by this method appear to be the longest measurements of stress relaxation in annealed copper wire in the literature. Since the wrapped solderless connection is expected to last at least forty years, it is desirable to be able to extrapolate the stress value out to forty years time. Several methods are possible. According to theoretical treatment,[4] stress relaxation proceeds as follows:

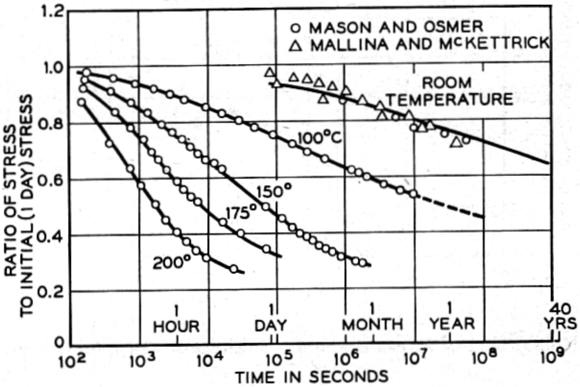

Fig. 2 — Relaxation of stress in tinned copper wire as a function of time and temperature.

$$\sigma_0 - \sigma = \frac{kT}{\beta} \log_e (1 + t/t_0) \qquad (2)$$

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[3] W. P. Mason and T. F. Osmer, Solderless Wrapped Connection, Part II — Necessary Conditions for Obtaining a Permanent Connection, B. S. T. J., **32,** pp. 557–590, May 1953.

[4] See *Progress in Metal Physics*, Volume IV, Pergamon Press, Limited, 1953, Chapter V, Theory of Dislocations by A. H. Cottrell, pp. 233 and 251 to 260; Kuhlmann, D. and Z. Physik, **24,** p. 43, 1952; and Proc. Phys. Soc., **64,** p. 64, 1951; and A. H. Cottrell and V. J. Ayetekin, Inst. Metals, **77,** p. 389, 1952. The last reference gives data for stress relaxation in zinc which shows that it obeys equations (2), (3) and (4).

where σ_0 is the initial stress, σ the final stress, k Boltzmann's constant, T the absolute temperature, t_0 a time determined from the equation

$$\sigma_0 = -\frac{kT}{\beta} \log \left(\frac{\beta A t_0}{kT} \right) \tag{3}$$

and A and β are constants in the fundamental equation

$$\frac{d\sigma}{dt} = -A e^{-(H-\beta\sigma)/kT} \tag{4}$$

where H is the activation energy in the absence of any stress.

The result of (2) is that for times large compared to t_0, the stress difference $\sigma_0 - \sigma$, plotted on logarithmic paper will be a straight line relation. Hence, in Fig. 2, for times in the order of forty years, the indicated stress level is 60 per cent of 8,000 pounds per square inch or 4,800 pounds per square inch.

Another method of extrapolation which essentially makes use of (4) is to measure the rates of relaxation at different temperatures and determine an activation energy for each stress level by comparing the logarithms of the times for the same stress levels as a function of temperature. The constant A in (4) is usually considered to have a temperature factor T in it and is usually written as $A'T$. With this relation, (4) can be written

$$-\frac{d\sigma}{A'Te^{-(H-\beta\sigma)/kT}} = \frac{-e^{-(H-\beta\sigma)/kT}}{A'T} \, d\sigma = dt \tag{5}$$

Integrating this equation between the limits σ_0 and σ, we have

$$t = \frac{k}{\beta A'} e^{H/kT}[e^{-(\beta\sigma/kT)} - e^{-(\beta\sigma_0/kT}] = \frac{k}{\beta A'} e^{(H-\beta\sigma)/kT}[1 - e^{-\beta(\sigma_0-\sigma)/kT}] \tag{6}$$

Hence, if the quantity

$$e^{-\beta(\sigma_0-\sigma)/kT}$$

is small compared to unity, we have

$$(H - \beta\sigma) = k \log_e (t_1/t_2) \Big/ \left[\frac{1}{T_1} - \frac{1}{T_2}\right] \tag{7}$$

As shown by Fig. 3, the value of β is about 6 calories per pound per square inch and hence if $\sigma_0 - \sigma$ is at least 800 pounds/square inch (i.e., for all values of relaxation of 0.9 or less) this factor will be less than 1 per cent for all temperatures used and hence we can use (7) to evaluate values of the activation energy H-$\beta\sigma$.

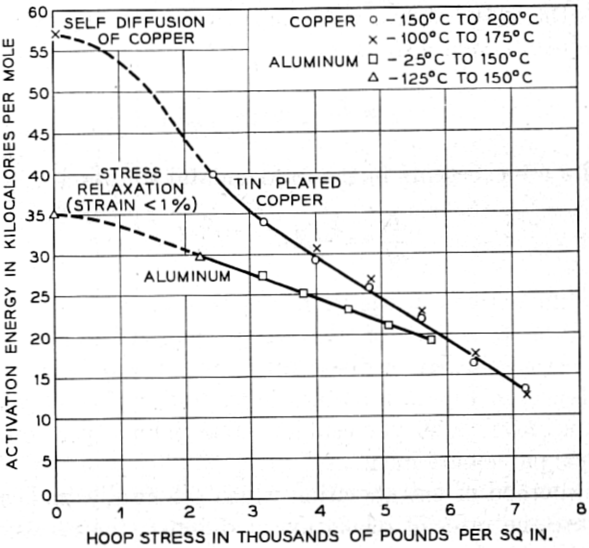

Fig. 3 — Activation energy for stress relaxation as a function of hoop stress.

Measurements of the rate of stress relaxation for tinned copper wire at 200°C, 175°C, 150°C, and 100°C are shown by Fig. 2, and the activation energies plotted against average hoop stress are shown by Fig. 3. Values are given using 150°C to 200°C as the temperature range and 100° to 175° also. Both ranges give the same activation energies within the experimental errors and show that down to about 0.4 relaxation the activation energies satisfy an equation of the type

$$H' = H - \beta\sigma \tag{8}$$

The curvature exhibited by the relaxation versus log t shown for all temperatures indicates that the activation energy must increase faster than (8) for low values of relaxation and the dotted line shows a hypothetical curve ending up at the self diffusion activation energy for copper, 57 kilocalories per mole.

To apply this method in general, one has to take account of any transformation such as recrystallization in the temperature range of measurement. For example, Fig. 4, shows similar curves for aluminum wire. Recrystallization in aluminum is known to occur at temperatures above 150°C and this change is shown in the relaxation measurements by the lower values of relaxation that occur for long times. If one takes values of time above and below the recrystallization temperature, the activation energy will appear higher for this range than for a temperature range below the recrystallization temperature. The agreement of the activation energy for copper for the two temperature ranges shown by Fig. 3, shows that no transformation occurs from 25°C to 200°C and hence we can extrapolate the relaxation to room temperature taken as 25°C, with the result shown by the solid line labelled 25°C. This agrees well with the measured values and indicates a stress at the end of forty years equal to 5,200 pounds per square in.

DIFFUSION STRESSES IN SOLDERLESS WRAPPED CONNECTIONS

In addition to the hoop stresses, another set of stresses develops as a function of time, namely, the diffusion stresses caused by the diffusion of one part of the connection into the other. The first experiment that showed the presence of these stresses was the stripping force tests of Fig. 23 of the previous paper referred to in Footnote 3. These measurements were carried out on connections which had been held at 175°C for lengths of time up to ten days and it was found that the stripping forces did not decrease with time. A more careful set with twenty connections for each point have recently been run with the results shown by Fig. 5, solid line labelled 175°C. From this curve, it is seen that the stripping force decreases to 88 per cent of its initial value of 15.5 pounds average for six turns of 24 gauge tinned wire and then increases to 120 per cent of the initial value at the end of ten days. Similar increases are shown at 100°C over a longer period of time and recent tests of solderless wrapped connections that have been in the field for one year and ten months show that the stripping force is about 5 per cent higher on the average than it was when the connection was formed.

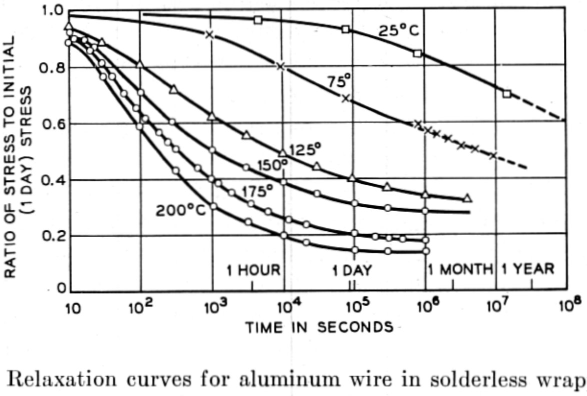

Fig. 4 — Relaxation curves for aluminum wire in solderless wrapped connections.

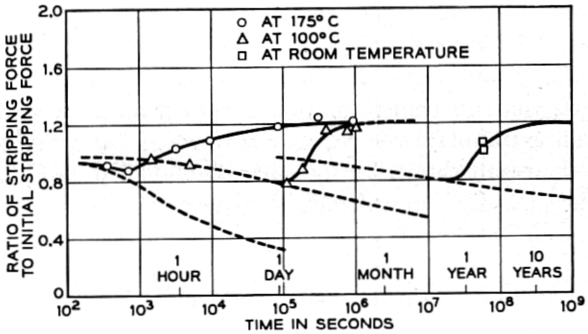

Fig. 5 — Ratio of measured stripping force to initial stripping force as a function of time and temperature for tinned copper wire on nickel silver terminals.

The dashed lines show the corresponding hoop stresses as a fraction of the initial hoop stress and hence it is evident that as the hoop stresses go down the stripping forces first decrease and then increase to higher values than were effective originally. We shall presently show that the difference between the measured stripping force and the proportionally relaxed hoop stress is due to a stress caused by diffusion of the tin in the plating into the wire and terminal of the solderless wrapped connection.

One experiment which shows that the initial stripping force is caused by the hoop stress in the wire is the experiment shown by Fig. 6. Here a terminal is made which has a slightly tapered tin plated pin in the middle and is cut back for some distance beyond the pin. The terminal is wound with five turns of No. 14 gauge (0.065 inch diameter) tinned copper wire. The initial stripping force to pull off the winding was determined and it was found to take 72 pounds force on the average to strip the wire off the terminal. A similar set of measurements was made on the force required to pull the pin out of the terminal and this averaged about 50 pounds or 70 per cent of the stripping force for the wire. Since the pin and terminal had the same coefficient of friction as the wire and terminal, and since the pin is required to support all the compressional stress in the terminal due to the hoop stress in the wire, it is evident that at least 70 per cent of the force required to strip the wire off the terminal is plain frictional force between the wire and the terminal. It is thought that the remainder of the force is due to the gouges cut in the terminal by the winding process. When the wire is stripped off the terminal, these cuts gouge out parts of the wire and hence require a higher force. This effect is equivalent to friction for a rough surface, which is higher than that for a smooth surface.

Next the terminal was held at 175°C for various times as shown by Fig. 6, where the stripping forces and the forces to pull the pins are plotted. It is seen that the force required to pull the pin decreases with time while the force required to strip the terminal increases with time. The pin force duplicates the stress relaxation curve initially but departs from this curve more and more as time progresses. This gradual departure appears to be due to some diffusion in the tin which makes partial contact with the terminal. The amount of diffusion between pin and terminal is less than that between wire and terminal for two reasons: (a) the contact area between pin and terminal is not as intimate as the contact area between wire and terminal due to excessive plastic flow in the latter but not the former case, and (b) the contact area between pin and terminal is much greater than between wire and terminal. Nevertheless, the force required to pull the pin is substantially the same as the frictional force holding the wire on the terminal due to the hoop stress in the wire. Hence, we can conclude from this experiment that the initial stripping force is due to the frictional force resulting from the hoop stress plus shearing forces required to gouge the wire.

Several experiments have been undertaken to measure the effect of diffusion separate from friction. The most successful of these was the arrangement shown by Fig. 7. Here a wire was pressed against a double-toothed sharp edged block, and a constant pressure was maintained for various times at various temperatures. An attempt was made to produce an indentation of the same magnitude as that developed in the wrapped solderless connection, although, of course, the area of contact increased slightly with time.

It was found that for aluminum or copper on nickel silver at room

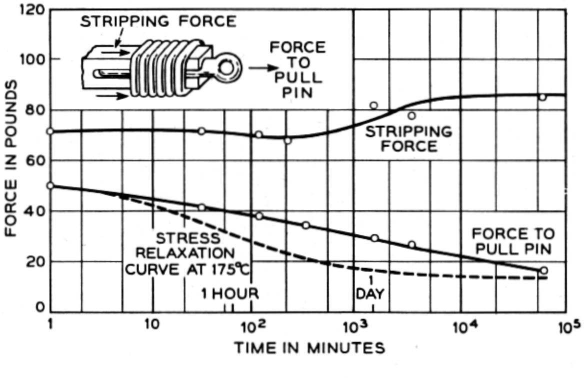

Fig. 6 — Experiment showing difference between stripping force and frictional force due to hoop stress — temperature 175°C.

temperature, no adhesion occurred even when the time of loading was very long. It was also found that if the load was removed, even momentarily, before the sample was placed in the oven, no adhesion occurred. For a given temperature there is an induction period before the wire adheres to the block, and this induction period increased, in general, as the temperature decreased. This induction period was found to be a time of nucleation. This is shown by the fact that the period increases as the square of the contact dimensions. Since diffusion is a function of $x/\sqrt{Dt}$ where x is the distance, D the diffusion constant and t the time, this observation shows that nucleation starts at a given point and proceeds for a certain fraction of the contacting surface before fusion strengths are observed. After the induction period, the fusion force — the force required to pull wire and block apart — increased at a rapid rate for the cases of copper, tinned copper, and zinc wire on a nickel silver block.

In order to account for the effect of fusion due to the increase of contact area, the ratio of the fusion force to the contact area was determined, yielding a shearing stress. The area of contact could be easily measured with a microscope since a bright surface was produced by the shearing process. The shearing stress, Fig. 8, for the case of tinned copper wire on nickel silver is shown to approach a limit of about 3,000 psi which is approximately the limiting shearing stress for tin. Hence, it appears that tin diffuses into the copper wire and the nickel silver base. Further-

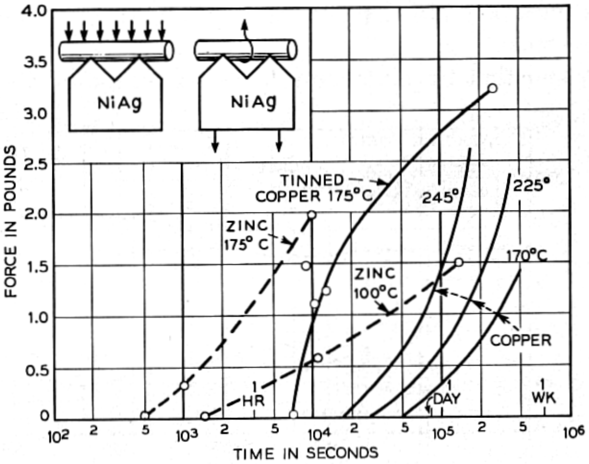

Fig. 7 — Diffusion forces for tinned and bare copper and zinc wire on nickel silver base.

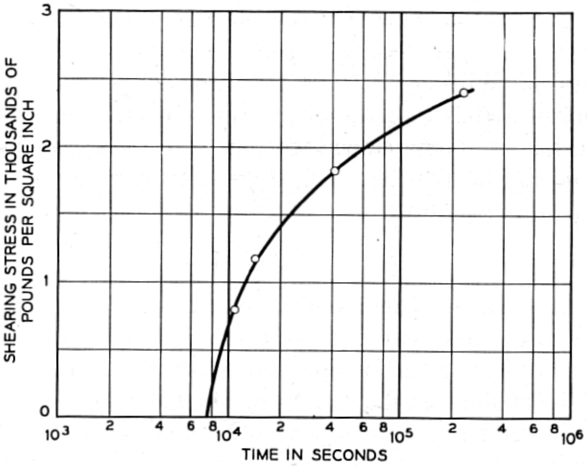

Fig. 8 — Diffusion shearing strength for tinned copper wire on nickel silver at 175°C as a function of time.

more, it appears that the fused bond will just withstand a shearing stress equal to the limiting shearing stress of tin. Metallurgical evidence for this diffusion was presented in Fig. 19 of the paper referred to in Footnote 4. In this figure, a tin plate layer between the copper and nickel silver was diffused in the two metals in a time of about 400 hours at 180°C. The new evidence indicates that this layer of tin has the shear strength of bulk tin.

The previously described data constitutes measurements of fusion forces separate from the complications of friction in the solderless wrapped connection. However, the same measurements of the effect of fusion are obtained if one subtracts from the stripping force the product of the relaxed force times the initial stripping force (about 15.5 pounds) of the actual wrapped connections. As shown by Fig. 6, the fusion force so computed divided by the area of contact of a six turn connection (about 0.0045 sq in) yields the shearing stress, previously defined. In Fig. 9, the shearing stress is given for a tinned copper wire on a nickel silver terminal as a function of time for 175°C and 100°C. By way of comparison, the constant stress diffusion process of Fig. 8, is shown plotted by the dashed line on this plot. It is evident that there is a larger induction period in the case of the 14 gauge (0.065 inch wire) than in the case of the smaller 24 gauge (0.020 inch) wire and the ratio of the times is proportional to the square of the wire diameter ratio. This is an indication that we are dealing with a nucleation process.

The previous results show that the effect of temperature above room temperature on the solderless wrapped connection is to promote fusion which brings an additional set of forces into the picture with regard to the mechanical stability of the connection. In order to determine the effect of fusion at room temperature, it is necessary to evaluate the activation energy of diffusion. This is done by calculating the value H in the simple rate equation

$$\tau = \tau_0 \exp (H/kT)$$

so that a given change of temperature corresponds to a given change of time on the fusion force curve. If we compare the 175°C curve with the 100°C curve of Fig. 9, an activation energy curve as a function of residual hoop stress is obtained as shown by Fig. 10. The value of stress is determined by the average time values used in the calculation of the activation energy. It is shown that the activation energy for diffusion of tinned copper on nickel silver in the presence of stress is in the order of 20 to 24 kilocalories per mole while that with no stress is in the order of 41 kilocalories per mole. It appears that higher stresses lower the activation energy of diffusion just as they lower the activation energy for creep and stress relaxation. Very high stresses can reduce the activation energy to a value approaching zero which is the case of cold welding. The fusion occurring in the case of the solderless wrapped connection is different from cold welding in that it takes a finite time to develop any fusion forces.

From the activation energy values of Fig. 10, it is possible to predict the rate at which the wrapped wire connection increases its strength at room temperature. Such a calculation applied to the case of tinned copper wire on a nickel silver terminal is given in Fig. 5 where it is shown

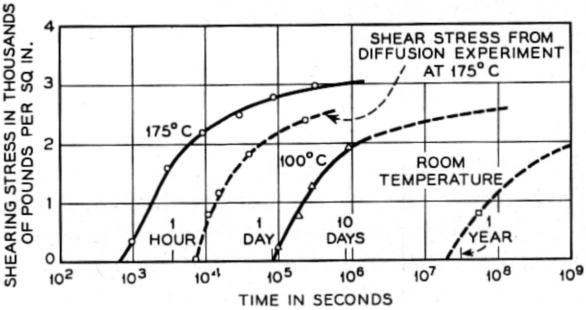

Fig. 9 — Shearing strength of copper-tin-nickel silver connections as a function of time and temperature.

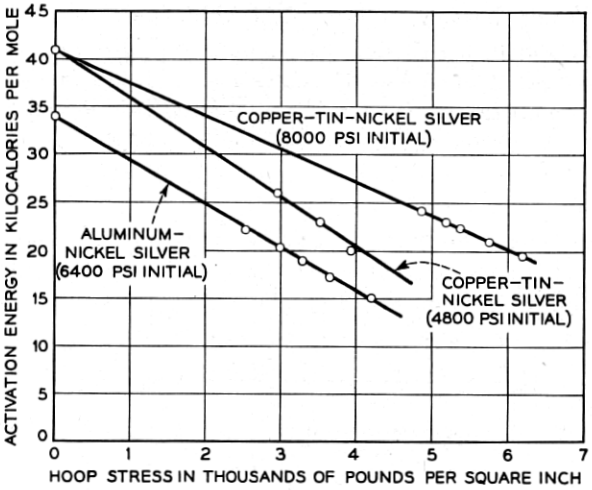

Fig. 10 — Activation energy for diffusion as a function of hoop stress.

that the strength stops decreasing at the end of six months and eventually increases to 20 per cent over the initial value at the end of forty years. Measurements on connections made one year and ten months ago, taken by V. F. Bohman, confirm this calculation.

In all probability, the stress causing the diffusion is the shearing stress applied to the tin layer by the hoop stress of the wire acting on the fixed terminal. For a given initial winding stress, this shear stress will decrease in proportion to the relaxed hoop stress as confirmed by the data of Fig. 10. If we start with a lower winding stress, a smaller indentation is made in the wire and the area of contact is smaller about in proportion to the ratio of the hoop stresses. Hence, although the compressional force on the corners is smaller in proportion to the hoop stress, it is supported by a smaller area and hence the stress on the supporting area is approximately independent of the initial value of the hoop stress. This compressional stress produces shear stresses on the layer of tin since the material of the terminal and the wire have to slide with respect to each other in producing the indentation. Hence, we should expect that the diffusion forces would start at a time independent of the value of the initial hoop stress.

This supposition is confirmed by the data of Fig. 11, obtained by winding tin plated copper wire on a nickel silver terminal with a hoop force half of the usual winding force of 1,300 grams for a 24 gauge wire. The initial strip off force was 60 per cent of that for a 1,300-gram winding force confirming the data of Fig. 16 of Mallina's paper, referred to in Footnote 2, which shows that the hoop stress decreases less rapidly than the applied tension. Fig. 11 shows the strip off force as a function of time and temperature. If we subtract the relaxed frictional force from the stripping force and divide by the area of 0.0027 square inches (60 per cent of the area of the usual connection) the shear strength curves in pounds per square inch are shown by the lower solid curves. These start sooner than the values on Fig. 9 but require a somewhat longer time to reach their final value. The activation energy obtained from these curves is plotted on Fig. 10 (4800 psi) and shows that the activation energy for the lowest stress is about the same as that for the higher stress curve, showing that the shear stress is independent of the wrapping tension. It takes longer to complete the process and as a result, the stripping force at the end of forty years is equal to the initial value rather than 20 per cent higher as in the case for Fig. 5. Corrosion tests for these lower stripping force values[5] show, however, that there is no indication of a loss of electrical contact.

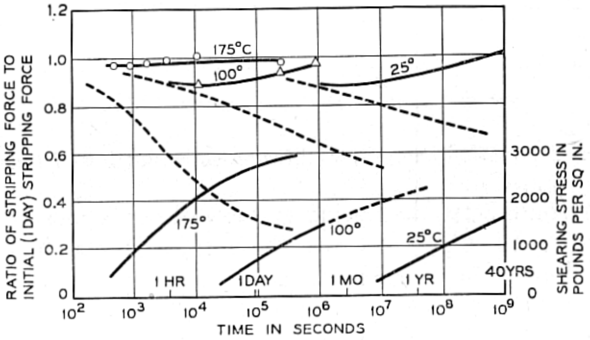

Fig. 11 — Stripping force and shear strength of copper-tin-nickel silver connections as a function of time and temperature. Initial stress is 4,800 pounds per square inch.

The method for analyzing fusion forces by subtracting relaxation data from stripping force data is verified by measurements on other metal connections. Fig. 12 shows the ratio of stripping force to intial stripping force for aluminum on nickel silver terminals as a function of time and temperature. Subtracting the relaxed force (the original stripping force multiplied by the relaxed stress ratio of Fig. 4) from the stripping force and dividing this difference by the contact area, the shearing

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[5] R. H. Van Horn, Solderless Wrapped Connections, Part III — Evaluation and Performance Tests, B. S. T. J., **32,** May 1953. See Table II.

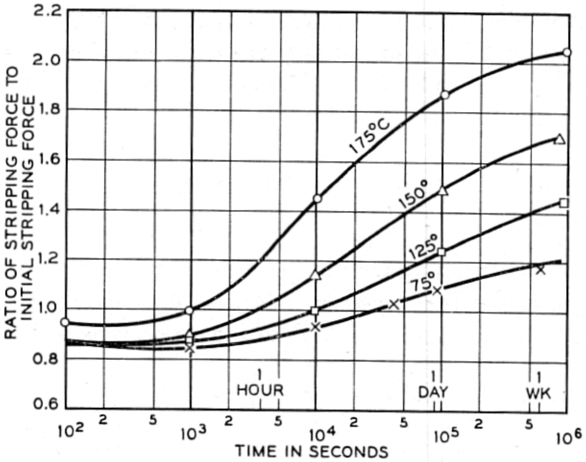

Fig. 12 — Stripping force curves for aluminum on nickel silver as a function of time for four temperatures.

strength is obtained and is shown in Fig. 13. The shearing strength thus obtained approaches 6000 psi for long times at high temperatures. This value agrees approximately with the accepted value for bulk aluminum. Calculating the activation energy of diffusion as previously outlined, one obtains the curve for aluminum in Fig. 10.

The advantage of a diffusion layer such as tin or aluminum as an element in the solderless wrapped connection is shown by the data of Fig. 14 which shows the rate of increase of the stripping force of bare

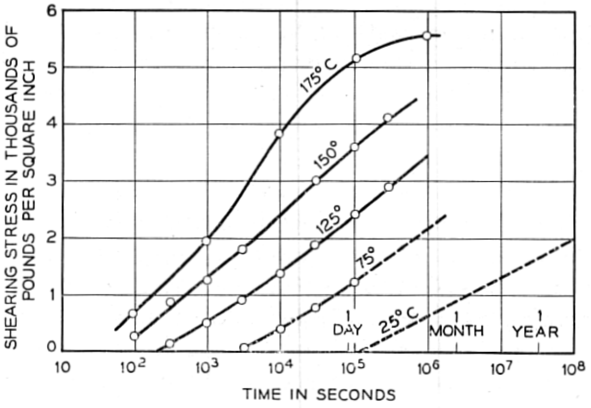

Fig. 13 — Shearing strength of aluminum on nickel silver connections as a function of time.

copper wire on nickel silver terminals at 150°C and 100°C. The increase in strength does not occur as fast as that for tin plated copper, and hence the standard connection with a tin plated copper wire is better than one formed from bare copper wire.

PROPERTIES OF SOLDERLESS WRAPPED CONNECTIONS FOR OTHER TYPES OF PLATING

A study of the factors governing the diffusion strength of the solderless wrapped connection suggests methods for increasing the rate of diffusion and the strength of the diffusing layer. These methods result in greater mechanical strength and a faster fusion of the wire and terminal. Experiments show that there are at least four metals which diffuse faster than tin, but due to the economic problems and the brittleness of some of the alloys formed, none of them are being considered for solderless wrapped connection.

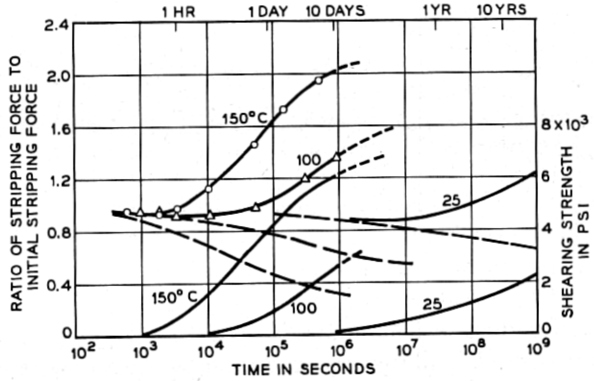

Fig. 14 — Stripping force and shear strength of bare copper on nickel silver connections as a function of time and temperature.

The reason the diffusion forces in the tin plated solderless wrapped connection do not cause an increase in strength of more than twenty per cent during the life of the connection is that the limiting shearing stress in tin is only 3,000 pounds per square inch. If now we substitute for tin plating a plating with a larger limiting shear stress, the strength of the connection should increase by a larger factor. To be of use, however, it is necessary that the diffusion forces shall develop rapidly.

The data of Fig. 10 show that if we can produce a higher shearing stress on a layer of aluminum, the activation energy can be lowered and

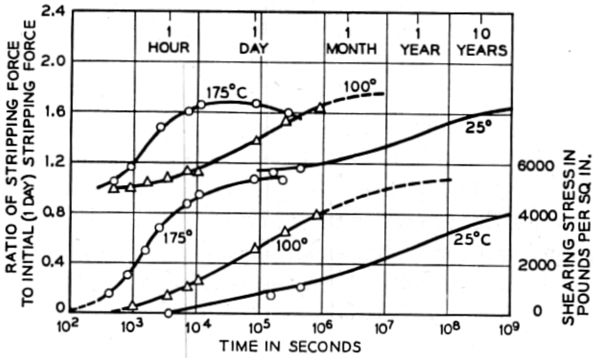

Fig. 15 — Stripping force and shear strength of copper-zinc-brass connections as a function of time and temperature.

be made to approach the cold welding condition. This requires that aluminum be placed on a stronger material such as brass, nickel silver or copper in order that the area of indentation for a given hoop stress will decrease and the shear stress will increase. Hence, the connection should form in a very short time. Furthermore, since the limiting shear stress for aluminum is near 6,000 pounds per square inch, one should except that the strength of the connection will nearly double. Since aluminum is not easily electroplated this suggestion probably is not practical.

Of all the other metals examined, the next most promising are silver, cadmium and zinc. The activation energy for diffusion of zinc into copper

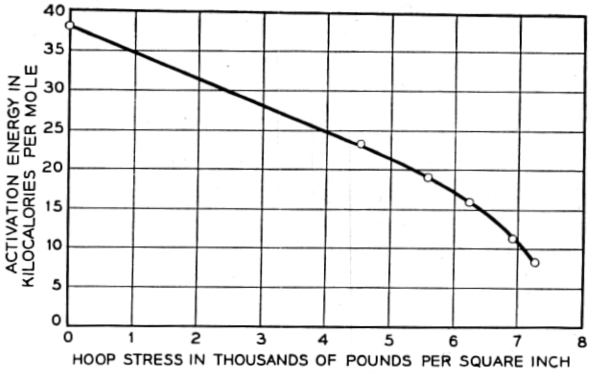

Fig. 16 — Activation energy for a copper-zinc-brass connection as a function of hoop stress.

at no stress is given[6] as 38 kilocalories per mole which is 4 kilocalories higher than that for aluminum and 3 kilocalories under that for tin. The activation energy of silver and cadmium into copper also have low values. Hence, if the effect of stress parallels that for tinned copper, zinc and cadmium should diffuse into copper and nickel silver faster than tin. Furthermore, the limiting shearing 5000 pounds per square inch. Zinc, silver and cadmium are readily plated on the terminals or the wire.

Zinc plating has been tested experimentally by constructing a solderless wrapped connection of bare copper wire on zinc plated nickel silver or brass terminals. The stripping force for a bare copper wire wrapped on a terminal plated with 0.001 inch thickness of zinc has been measured at 175°C and at 100°C as a function of time with the results shown by Fig. 15. The strength increases to 60 per cent over that found initially in a time of less than two hours at 175°C. At 100°C, the time required is a little over a day. If we subtract the relaxed force from the stripping force and divide by the area of the connection, the shear strength of the connection is as shown by Fig. 15, lower curves, for the two temperatures. From these two curves, an activation energy versus hoop stress can be obtained with the results shown by Fig. 16. These values allow one to extend the time variation of the shear stress down to room temperature with the result shown by Fig. 15. Adding these values multiplied by the area of the connection to the relaxed hoop stress, the indicated stripping force at room temperature is shown by Fig. 15, room temperature curve. This force increases at such a fast rate that the strength can be observed to increase at room temperature and corresponding measurements are shown by the circles. Since corrosion cannot occur in a region of fusion, a criterion for the corrodability of a connection is the time required to complete half of the total fusion at room temperature. On this basis, the zinc plated connection has the lowest half fusion time of any of the materials tested.

Although zinc diffuses more readily than other materials examined, it tends to form more brittle alloys and hence its use has not been seriously considered for solderless wrapped connections.

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[6] R. M. Barrer, *Diffusion In and Through Solids*, Cambridge University Press, 1941, Table 67, p. 275.