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WIRE WRAPPED JOINTS — A REVIEW

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The basic technique of wire wrapping is now well established as a simple and reliable method for joining conductor wires in a permanent, though easily replaceable, manner to more massive terminals. This paper describes the mechanical and the metallurgical basis of the joining technique and outlines the advantages. The scope of the technique as it has developed up to the present day is discussed in terms of the ranges of wrapping terminals and wrapping wires used and the types of wrapped joint that have been evolved. Finally the tools available for wire wrapping are briefly reviewed with particular emphasis on the wrapping bit.

1 THE MECHANICAL BASIS OF THE WRAPPED JOINT

The mechanical basis of the wire wrapped joint was investigated very extensively by workers at Bell Telephone Laboratories 20 years ago.[1] Their very full analysis of the joining system is still considered to be essentially correct. The work included photoelastic observations on a wrapped joint model to investigate strain patterns produced by wrapping, and the study of stress relaxation as a function of time and temperature.

The wire wrapped joint consists of a wire which is tightly wrapped around a sharp cornered terminal. Sufficient deformation is engendered in the many notches created by the terminal in the wrapping wire to create metal to metal interfaces with a high level of integrity. The wrapping wire, which is bent several times during wrapping before final positioning in the wrap, is under a high level of tensile stress during wrapping. The tensile strain which is caused remains in the wire after wrapping because the stretched wire is locked by the notches formed in it. The bulk of the wrapped wire will remain under a tensile stress with the wrapped terminal under a compressive stress: the zones, in the wrapped wire, immediately adjacent to the notches will also be under compressive stress. Since the wrapped wire is a helix, rather than a series of hoops the stresses in the wire have components in certain directions and produce a bending moment about the long terminal axis. The terminal will twist slightly until the relevant stress components in the wire are balanced by those in the terminal. The twist induced in the terminal is a useful indication of the level of elastic stress in the joint and it provides a monitor for following the process of stress relaxation at various temperatures. Extrapolation techniques can be used to predict the long term stress relaxation behaviour at room temperature using results obtained by accelerating the process at elevated temperature. The elastic stress level in the joint is of importance since it indicates the pressure with which the wrapping wire and terminal are being pressed together to maintain electrical contact.

2 THE METALLURGICAL BASIS OF THE WRAPPED JOINT

Work at this laboratory[2] has suggested that the concept of the wrapped joint as essentially a mechanical joint, with residual elastic stress keeping the relevant metal components in close contact, is not sufficiently comprehensive. The stresses involved in the notch zones are apparently sufficiently large to penetrate oxide and tarnish films and promote cold welding. Evidence of such cold welding has been obtained by unwrapping joints and examining them using scanning electron microscope and electron microprobe analysis techniques. The latter technique was used to show the transfer of metal from one component to the surface of the other, indicative of welding phenomena. Thus tin from a tinned copper wire wrap has been found to be present on the surface of a brass terminal after unwrapping. Other metal systems have provided similar evidence and the scanning electron microscope has shown examples of cold welded metal debris. The original notch produced during wrapping is modified when the adjacent notch is formed; the wire is effectively pulled towards the second notch so that while one side experiences an increased compressive stress the other experiences a shear stress. The increased compression will tend to extrude any soft terminal coating and increase the integrity of the metal to metal contact locally; such an area will frequently be one in which pronounced metal transfer can be observed.

The occurrence of pressure welding in the notches of wrapped joints provides connections which are more resistant to corrosive attack; even when the whole joint is visibly corroded electrical quality can still be high. The maintenance of satisfactory electrical quality at low levels of residual elastic stress (for example after accelerated stress relaxation) indicates the benefits of this high level of joint integrity. Because of the increased importance of the metallurgical micromechanisms in the notch the coating chosen on the terminal attains greater importance. It is suggested that it is particularly important in the case of micro-wrapped joints, where the contact areas are very small and therefore required to be of high integrity if general electrical quality is to be good.

3 THE ADVANTAGES OF WIRE WRAPPED CONNECTIONS

Whenever component leads or wire connections are to be jointed to a panel or base in an electrical assembly, soldering is usually considered as the technique to be used. However against this prevalent acceptance of soldering can be laid several disadvantages. Primarily the hand soldered joint is not of reproducible quality; the joint quality will depend very largely on operator experience and expertise. The wrapped joint quality is much more consistent, the operator can be trained very quickly to produce consistent, good quality joints and with some experience these joints can be made at a very fast rate. Most soldered joints can be made to a suitable quality in many cases, with hand soldering. If the joint does not wet immediately prolonged attention will usually achieve the goal. Because the quality of the soldered joint is dependent on operator technique, however, a certain percentage of joints will be of poor and unacceptable quality. This percentage of faulty joints may be quite low, but for assemblies which must give very high reliability, especially where large numbers of joints are used, it can be unacceptable. The percentage of unacceptable joints produced by correct wrapping techniques is extremely low, in fact it is very difficult to find any failures even when relatively severe accelerated test procedures are employed. This high level of consistency is essentially due to the inherent 'over-design' of the wrapped joint. The typical joint might involve six wrapped turns and, except for the outer wraps, there will be notches on four terminal corners for each turn. Therefore about twenty successful terminal/wire notches are normally produced, each with intimate metallic contact.

The wrapped joint need not be regarded as a permanent connection. It can be removed relatively easily when required, by unwinding the wire in the opposite direction to that used during wrapping. Fresh wrapped joints can be produced on a terminal from which previous wrapped joints have been removed. This can be performed many times before the terminal corners are sufficiently rounded to affect joint integrity. The number of rewraps will depend on the terminal material but typically the number allowed is thirty, or in the case of brass, ten[3].

Another advantage which wire wrapping holds over soldering is the absence of extraneous elements, such as solder and flux, that are required to produce the joint. The active flux which is frequently necessary to ensure good joint integrity during soldering must be carefully removed when the joint procedure is finished in order to minimise the possiblity of corrosion. Wire wrapping also avoids damage to adjacent insulation and heat sensitive components by the soldering bit, and damage caused by excess solder splashes falling into the circuitry. An additional advantage claimed for wrapped joints is that they often show less tendency to fail under vibration than soldered joints; this is though to be due to the 'graded stiffness' of the joint. The change from the terminal to the wire dimensions is less sudden, especially as the wrap does not maintain close contact on the first two terminal corners, and there is thus a lower stress concentration effect.

4 THE RANGE OF TERMINALS USED IN WIRE WRAPPED JOINTS

An appreciation of the range of terminals which are used to produce wire wrapped joints can be gained by a study of Figure 1. Many of the terminals on the right hand side of the photograph are relatively massive, .072″ x .048″ cross section being typical, and they are used extensively in panels in telephone exchange racks. An example of an array of wrapped joints made on such terminals is shown in Figure 2. This panel contains 210 double-sided terminals and some of these can be seen to have two wrapped joints on the one side. Many of the terminals on the left hand side of Fig. 1 are relay springs stamped out of suitable hard grades of spring alloys; one end of the stamping

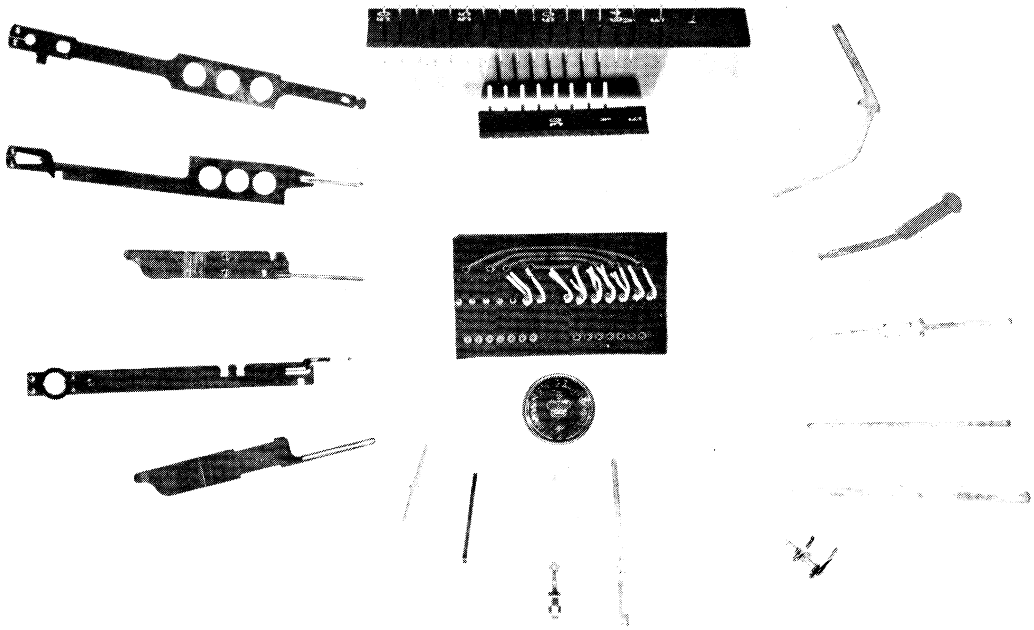

FIGURE 1 A representative selection of terminals on to which wire wrapped connections are made.

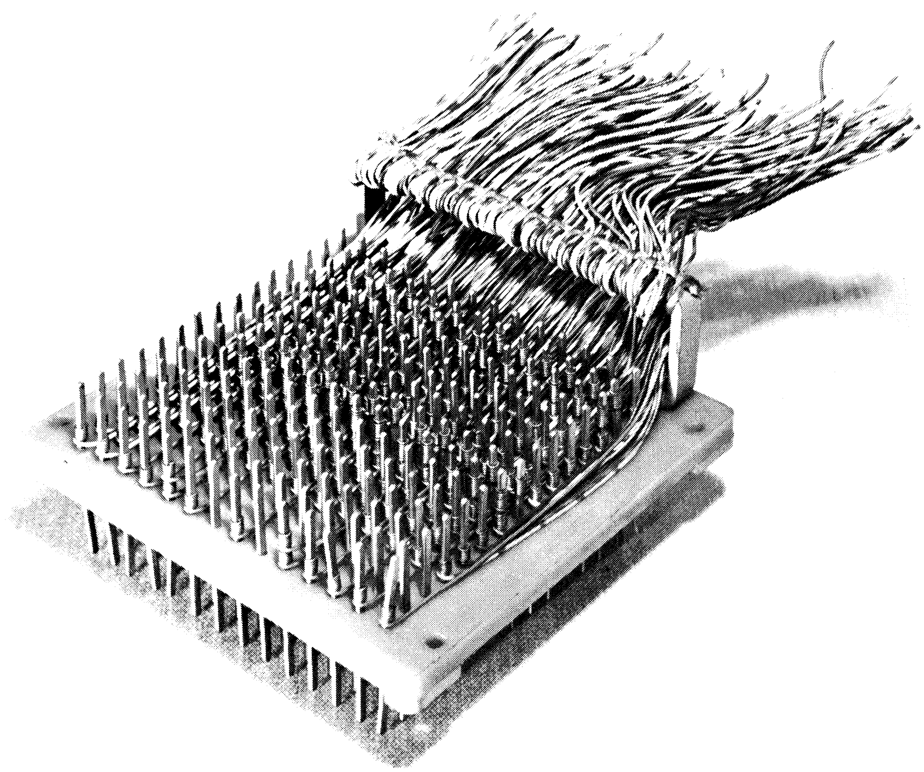

FIGURE 2 A typical example of an array of wire wrapped connections taken from a telephone exchange rack.

acts as a wrapping terminal and the central portion is located in a suitable plastic moulding. Normally the mechanical requirements of the spring end are the most critical, and to obtain suitable rigidity in the wrapping terminal, such that it will not simply distort when it is wrapped, it is generally embossed. The embossing procedure adds to the compliance of the cross section, and helps to maintain the level of elastic stress existing between the terminal and wrapped wire. This level will already tend to be low because the thinner terminal has a low torsional rigidity and cannot maintain a high level of stored elastic stress. The use of wire wrapping on the ends of close packed relay springs was the original use for which Bell Telephone Laboratories developed the technique. An example of the close packing of wire wrapped connections on a stack of relay springs is shown in Figure 3. Some terminals used for wrapping will be joined, for example by spot welding, to spring devices so that the optimum dimensions of each part can be chosen separately; two such terminals are shown at the bottom of Figure 1. Other types of wrapping terminal can be found; for example V-section and double V-section (where two V-sections are folded together apex to apex) exist. These two types do not find universal favour because it is considered that the pressure exerted by the wrapping wire can cause plastic distortion and reduction of the wrapped terminal dimensions.

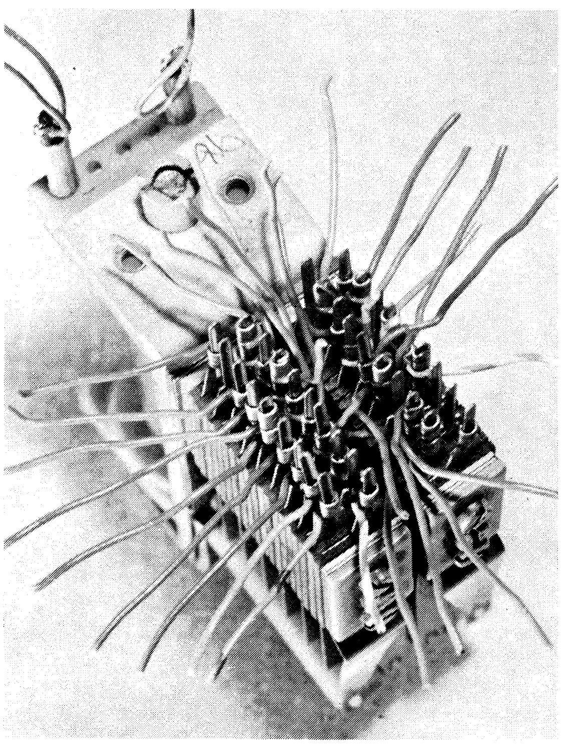

FIGURE 3 Wire wrapped connections made to the ends of each of a stack of relay springs.

Efforts have been made to standardise terminal cross section sizes .045″ square is a particularly widely used size, but each manufacturer tends to have his own particular sizes. A terminal length is chosen such that more than one wrapped joint can be made on it. A maximum of three joints is normal and in this way the density of connections can be greatly increased. The terminal length is frequently increased to provide a double sided wrapping facility, i.e. portions that can be used for wrapping exist on either side of a central mounting portion. The terminal is invariably radiused or chamfered at the tip to aid lead in of the terminal into the aperture of the wrapping tool.

All the terminals discussed above are relatively massive, but a whole range of smaller terminals are now used for wrapping. Typical cross sections of these 'micro-wrap' terminals are .025″ square and .030″ x .015″. It has also been shown[4] that wrapped joints can be made with 36 s.w.g. wire on .010″ x .015″ terminals, which enables very close density to be achieved (.050″ centres). The smaller terminals will frequently be staked into printed circuit board laminates; relatively hard beryllium-copper terminals find use here. These can be punched directly into the laminate and retained by heading the end of the terminal with a die. In another system, the small terminals are retained in metal eyelets let into holes drilled into the laminate, with interconnection finally achieved by soldering to printed circuit board lands (this system is illustrated in the centre of Figure 1).

4.1 *The Materials Used to Produce Wrapping Terminals*

Wrapping terminals are generally manufactured from relatively high strength copper-based alloys; phosphor bronze, beryllium copper and hard brass are most frequently used. Nickel silver is also encountered but generally when the terminal is one end of a one-part spring component. Monel has also been recommended where high strength and ability to withstand plastic distortion are required. It is common to find many of these materials electrotinned or solder coated. The original reason for such coatings was that if any soldering was found to be necessary subsequently it was facilitated by the terminal being already tinned.

It has been shown (as discussed above) that these relatively soft coatings in fact play a very significant role in increasing joint integrity and electrical quality[2]. Gold plating of terminals is frequently encountered where high reliability and therefore general tarnish resistance, is required. Whatever terminal material is chosen, a temper designation is selected such that the terminal is significantly harder than the wrapping wire. Thus the notch formed on the terminal edge is much less severe than that in the wrapping wire, and the terminal is capable of reuse.

5 THE WIRE USED TO PRODUCE WRAPPED JOINTS

The most common wrapping material is insulated tinned copper wire which is prestripped before being fed into the wrapping tool. This is the same type of wire used to make other types of connections, such as soldered or screwed joints, and it is normally perfectly suitable for producing wrapped joints. 23 and 25 s.w.g. sizes are most commonly used on the larger wrapping terminals. Larger and smaller gauges are also encountered, the smaller gauges being increasingly important with the trend towards component miniaturisation. Specifications generally allow fewer wrapped turns in joints using larger gauge wires. If a wrapping wire is required that will not relax appreciably at the elevated temperature which the joint must withstand, other materials are suggested. Beryllium-copper, copper-cadmium, copper-zirconium[5] or steel-cored copper have all been used. Where microwrap joints are concerned the wire used is very thin, or the order .008″ to .012″, and thus susceptible to breakage. In this instance the use of a higher strength copper alloy, 135, is common. Though aluminium wire has been thought to relax too quickly to achieve durable high quality wrapped joints, work has been carried out[6] which shows that joints can be made successfully with aluminium alloy wire. Aluminium alloys containing small additions of silicon and magnesium have sufficiently high strength to be used to wrap terminals, and provide joints which pass the normal qualification approval tests up to relatively high temperatures. For the best general corrosion resistance wrapped joints using aluminium alloy wire should be made on aluminium alloy terminals.

The wire used for wrapping is most likely to be prestripped for the required distance, and the stripped end fed into the normal wrapping bit. The most common joint produced is of the 'modified' type with the stripped length deliberately reduced to achieve a wrapped turn of insulated wire. This joint is favoured since the first notch in the wrapped wire, which is the critical zone from a vibration viewpoint, is protected and the joint can survive more severe tests.

5.1 The Use of Insulated Wire in the Production of Wrapped Joints

A development of the basic wire wrapping technique, which enables wire not prestripped of insulation to be utilised, is termed the 'Cut Strip and Wrap' process. To produce wrapped joints from such wire a special wrapping tool bit has been developed, a general picture of this bit is given in Figure 4. The basis of the technique can be followed by examination of Figure 4A.

The wire is fed along the tool as illustrated and as the tool tip revolves, one end of the wire is cut by flange Cl, which contains a slot with a knife edge, rotating in relation to the slot in flange C2. The length of wire between A and C1, which is guided by the slot in flange B, is the wire which is eventually wrapped around terminal T. Insulated wire will be

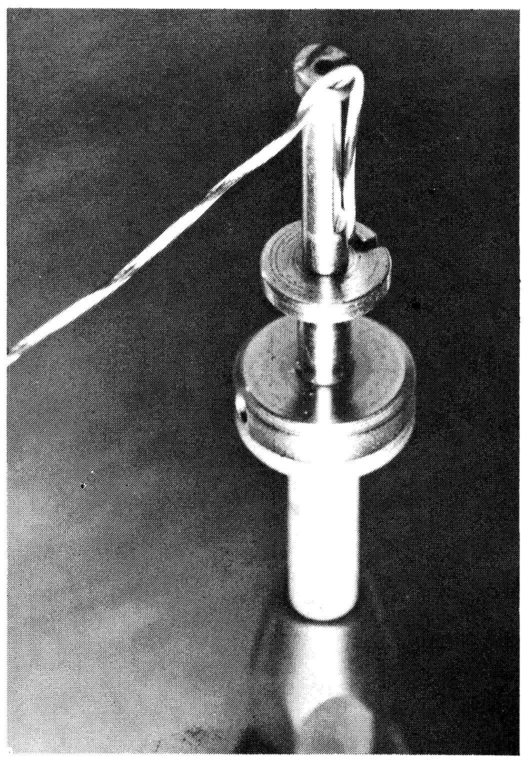

FIGURE 4 A Cut-Strip and Wrap tool tip used to produce wrapped joints from insulated wire.

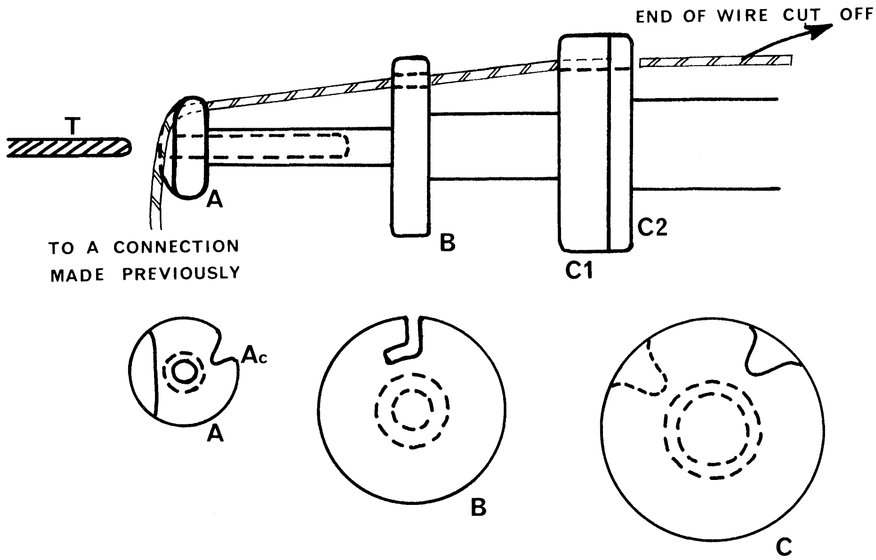

FIGURE 4a. Diagram of a Cut-Strip and Wrap tool tip.

wrapped around the terminal and moulded tightly over tip A until the pressure exerted by the cutting edge of the tip A (i.e. A_c in Figure 4A) on the wire insulation is sufficient to sever the insulation. The remaining wire between A and C1 is then drawn out of its insulation, the latter being retained behind part A, and wrapped around the terminal as bare wire. As the wraps are formed on terminal T the tool tip is pushed towards the right (in Figure 4A) and overlapping of the wraps is avoided. The process of cutting, stripping and wrapping is thus carried out using a single light hand tool and obviously offers significant economies in assembly. The process has not, however, gained the same level of general acceptance as the pre-strip and wrap procedure. This is probably because the properties which define the ease of cutting and stripping the insulation are very difficult to specify, and are found to be inconsistent. The temperature of the workshop, the lubrication that exists between insulation and wire, and the geometry of the cutting edge all profoundly affect the ease of stripping the insulation. Therefore, a wide variation in the force required to strip the insulation exists and different reels of wire, nominally similar, can exhibit different behaviour. Because of this force variation, different severities of 'snatch' are imparted to the wire when the insulation is initially severed. This snatch results from a momentary retardation of the wrapping bit when the severing occurs, followed by a momentary acceleration. Any notch which is imparted to the wrapping wire at the same moment as the snatch tends to be relatively severe and can contain incipient cracking. This severe notch will tend to be the weakest portion of the joint, but the effect can be reduced by having it formed under the insulation of the single insulated first turn. It is possible for the snatch to be strong enought to break the wrapping wire, especially when it is thin.

The angle at which the insulated wire is led towards the cut, strip and wrap tool tip is particularly important. Ideally the wire should be led in at right angles to the bit axis; at other angles the wire can be moulded across the relatively large face of the bit, creating additional frictional forces. This can cause an increase in the incidence of wire breakage, the breaks occurring a short distance along the wire beyond the wrapping.

6 SECONDARY WRAPPED JOINTS

A modification to the basic procedure of wrapping a conductor around a terminal to produce a primary wrapped joint is the procedure of binding a conductor, laid along the terminal, with a separate wrapping wire. This produces a secondary wrapped or bound joint, a type of joint which is very much less common than the primary joint. It is possible to produce such a joint with the bound wire and wrapping wire both being conductors, thus effectively providing two connections at one operation, but the system is precluded in some specifications.

The basic well-proven geometry of the primary wrapped joint is departed from in the secondary wrap, and the variation in size of the bound wire, which must be laid along the widest face of the terminal, has an obvious effect on geometric integrity. If the bound wire is too small, it will encounter a very low level of stress exerted by the wrapping wire because the wrap inevitably contains a 'natural gap' between the wrapping wire and the terminal (the gap when no bound wire is present). With very large bound wire sizes, the wrapping wire is pushed away from the terminal and the number or severity of notches in the wrapping wire is reduced.[7] The severity of the two notches which may be produced in the wrapping wire in the position closest to the bound wire will be modified by differences in the lay of the bound wire on the terminal face. The bound wire will not necessarily be positioned centrally, parallel to the axis, and this factor also affects the length of wire used to complete a wrapped turn. If the wire is offset from the central position, then redundancy occurs in the length of wire used to make a wrapped turn (that is wire additional to the minimum requirements). This redundancy, which could affect stress relaxation effects in secondary wrapped joints, can also accrue if the wrapped coil is distorted in the direction along which pressure is exerted by the wrapping tool. The number of deep notches in the secondary wrapped joint is frequently half that of a primary joint but a joint of satisfactory quality can usually be made because of the inherent overdesign of wrapped joints (as discussed above).

The bound wire used in making secondary wrapped joints will frequently be a normal circular section copper wire, particularly when the secondary wrap is used as a repair procedure. Thus if the normal primary wrap is attempted and the wrapping wire is broken in the process, the remaining wire, especially in the instance of a complex cable lay, may have insufficient slack to produce a second wrap. The end of the wire is therefore smoothed out, laid along the terminal, and bound with a suitable wrapping wire. In other instances the bound wire could be a component lead, circular or even rectangular, in various materials (Kovar or nickel are typical possibilities) which are not amenable to wrapping. The design parameters of secondary wrapped joints are at present empirical and rather broad. To rectify this situation a government-sponsored programme of work is in progress evaluating secondary wrapped joints made to the outlines given in DEF STAN 59–49/1 and investigating the effect of various joint parameters on stress relaxation behaviour.

A variation of the secondary wrapped joint is the twin bound joint. In this joint two similar terminals are bound together. Typically the dimensions of the terminals chosen for this work are such that the two together produce a square cross section. Some mention has been made in the literature of the use of stranded wire in making secondary wrapped joints

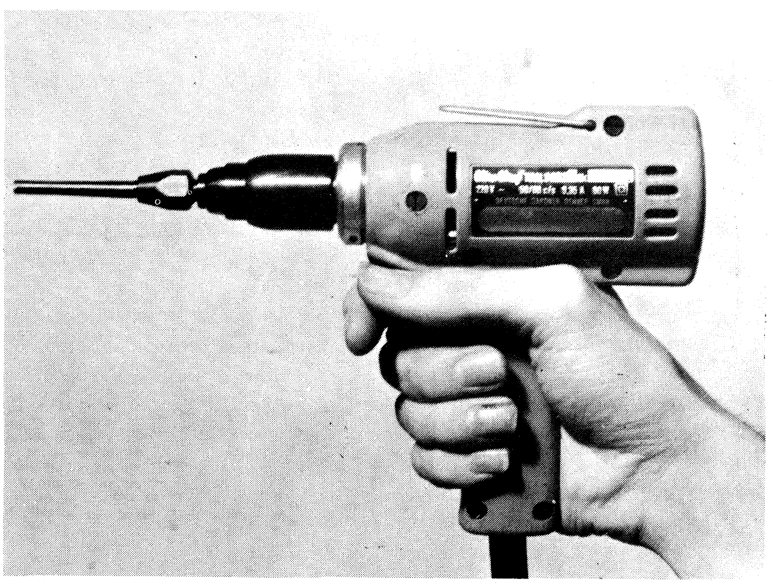

FIGURE 5 A typical electric-motor driven wire wrapping tool.

this type of joint does not, however, find universal approval.

7. THE TOOLS USED TO PRODUCE WRAPPED JOINTS

There is at present a large range of tools available for producing wire wrapped joints. The simplest tools are operated entirely manually. These are relatively inexpensive and provided the wrapping is completed in one operation, without stopping, they are capable of producing good quality joints. The most common tools are pistol type hand tools operated electrically (mains or battery) or by compressed air. The latter tool offers the advantage of a steadier application of torque to the wrapping bit and is the lighter tool to handle. It can be more expensive initially however, if compressed air lines have to be installed. A typical electric motor driven wrapping tool is shown in Figure 5; the compactness of the complete system can be appreciated. In some wrapping tools, the one important parameter which is still dependent on the operator, the lateral pressure exerted by the tool along the wrap, is controlled by a spring system supporting the wrapping bit. The reaction to the lateral force applied by the tool is ideally strong enough to provide a series of wrapped turns which are compressed tightly together, without overlapping, with very few gaps in between.

Wire wrapping procedures are now available with various levels of automatic operation. The semi-automatic machine has been used for many years; this machine indicates the terminals to be wrapped using a 'sight' driven by a numerically controlled X–Y system. The operator simply wraps the terminal indicated; the search for the correct terminal no longer depends on the operator and the percentage of wrongly positioned and missing joints is significantly reduced. Because the operator carries out the wrapping operation, a much larger error in correct terminal positioning can be tolerated; even with errors up to 30% of the connector pitch, the operator is still able to select the correct terminal. The semi-automatic system enables the number of connections made in unit time to be increased compared to the manual system. The capital outlay involved, being significantly lower than the fully automatic machine, means that this transitional system can often be shown to be the most economic.

The fully automatic machine is a recent addition to the wire wrapping machine range.[8] The connection wire is stripped at both ends and held by two separate carriages; the pattern required in the wire is then prepared by routing around a series of dressing fingers. The pattern is brought down on to the terminals and the two wire ends are wrapped by two wrapping heads. The carriages are capable of movement in the XY plane, under numerical control commands, and movement in the Z plan can be programmed into the operation to enable up to three wraps to be made on any terminal. The tolerance required on the correct positioning of the wrapping terminal tip is very tight; typically the terminal must be located within a radius of .005″ of the true position. The fully automatic wrapping system enables connections to be made at very high rates and these connections are of very high and consistent quality. The system is however expensive and only justified if large numbers of the same complex assembly are being wired up.

7.1 Wrapping Tool Bits

The normal wrapping tool tip consists simply of a cylinder with a central bore which accommodates the terminal and a slit of smaller dimensions on the circumference which holds the length of the pre-stripped wrapping wire. The bit revolves inside an appropriate sleeve feeding the wire around the terminal in a number of close wraps. The tension imparted to the wire during wrapping is important and is determined by certain bit dimensions. These are the wall thickness between the central aperture and the slit, and the radius around which the wire is fed out of the slit. The wire is wrapped under a tension which is not so large that it produces excessive notch severity, 'embrittling' the wire and making it prone to fracture. The tip over which the wire is led should be smoothly contoured since this will avoid scouring the surface of the wrapping wire. The aperture for the terminal in the tool tip should ideally be situated concentrically. If the aperture is eccentric the wrapping process will tend to create lateral oscillations of the terminal and strain the terminal mounting. The cross sectional area of the tip of the wrapping bit is kept to a minimum to reduce the space that must be provided between terminals; in this way the closest pitch of connection is obtained.

8. CONCLUSIONS

The technique of wire wrapping is well established and there is generally a good understanding of the basic mechanical and metallurgical factors involved.

The continued success of various wrapped joint systems in use and under accelerated test conditions confirms the quality of this connection procedure. The most common use of the wire wrapping procedure has been in the telecommunications industry but now a whole range of wrapped joints, of various sizes and types, are being used throughout the electronics industry. This connection system is used wherever high volume production of inexpensive, reliable connections is required. Thus the procedure is used in the production of computers, business machines, airbourne navigational equipment and machine tool control systems.

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