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THE MECHANICS OF PRESSURE CONNECTIONS

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Biographical Data

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Mr. *James H. Whitley has been associated* with *the Research Division of AMP Incorporated since 1954. At present he holds the position of Research Associate. He received his BS in Physics at Antioch College in 19.51 and his MS in Physics-EE from the Massachusetts Institute of Technology in 1954. Since joining AMP he has contributed in the fields of basic contact theory, terminal and contact design of both sliding and static contacts, and solid state diffusion behavior. In addition he has done considerable work in the area* of *ferrite magnetics and transistor circuit design. Mr. Whitley is a member of the I.E. E. E., Electrochemical Society, Faraday* Society *and American Institute of Physics. He is President of the Engineers Society of Pennsylvania.*

INTRODUCTION

Basic contact theory describes how electrical contact can be established between conductors by the application of mechanical force. It shows that even when the forces are quite low, a few pounds, the contact resistance is low - in the microhm region - a value that ought to be quite acceptable for almost any application.

The job of the mechanical design engineer is to devise configurations that will bring contacting members together and hold them together. And at first glance, that job ought to be pretty simple, seeing as the forces and pressures required are so small.

But, like so many simple-sounding design problems, the situation gets more and more complicated the farther one gets into the problem. And alas - so it is with pressure connections.

For instance, force-resistance curves for contacts usually refer to laboratory experiments using freshly-cleaned contact surfaces. The situation isn't nearly so favorable in the practical case, where the contact surfaces can never be assumed clean. And, practical connections must withstand varying degrees of mechanical abuse - shock, vibration, pushing and pulling, and environments - dust, dirt, corrosion, and temperatures. The making and maintaining of reliable contact under these conditions becomes a much more difficult design problem.

TWO MAJOR CATEGORIES OF PRESSURE CONNECTIONS

Pressure connections can be broadly classified into two types:

(1). High Pressure, "permanent" connections, such as crimps, taper pins, wrapped wire connections, and wedging connections.

(2). Lower Pressure, "separable" connections, such as pinand-socket, PC contacts, faston connections, knife disconnects, and relay contacts.

Design objectives and approach can be quite different for the two types. I want to discuss each of them briefly.

With permanent connections, the aim is to establish large-area metal-to-metal contact, and hold it there under any desired environmental condition for a long lifetime. The starting materials, say copper or brass, are assumed to be covered with natural oxide films as well as possibly some other contaminates such as oil or dirt. In making the connections, the contact surfaces must be cleaned, and at the same time they must be locked together by action of residual elastic stresses in the members. Cleaning is virtually always accomplished by the combination of high pressure, sliding, metal flow, and plastic deformation. The latter may be confined to surface layers, as in wedges, or may involve gross deformation of the parts, as in crimping. I will discuss in more detail the cleaning action and the residual contact forces in permanent connections a little later.

With separable connections the aim is to establish a solid connection having low, stable and reliable resistance when it is together, but which can be easily disconnected and remade with consistent performance as often as the need arises. This poses a different design problem. In the first place there's a limit to the amount of cleaning that can be done mechanically. Contact pressure and wiping, since this involves plastic deformations and hence, wear, cannot be too high. But it cannot be too low either, or electrical security and ability to withstand mechanical abuse will suffer. The design is always a compromise, or balance, between:

(a) high contact load, giving low resistance, good cleaning action, stable performance, and

(b) low contact load, giving low wear, long life, less effort to connect/disconnect.

The separable connection problem is helped a great deal by the use of special surface platings, which can virtually assure a "clean" contact surface. Gold plating, for instance, is used when a clean surface is needed and contact force and wipe are limited.

Probably the most important design consideration in the separable-type connection is the provision for obtaining and maintaining the proper contact force. Elastic spring force is used. The choice of spring material and spring geometry is of utmost importance. Low force-rate springs are desirable - that is, the force-deflection curve should be relatively flat, such that small changes in deflection won't change the applied force very much. And the spring should be operated conservatively - well below its yield point - such that creep and stress relaxation will be low. These desirable characteristics become more difficult to obtain as connections become smaller and smaller. Space for large deflections (as required in low-force-rate springs) just isn't available. The creativity and ingenuity of the design engineer is challenged, and he has come up with a number of working solutions to the problems. Some examples are shown in Figure 1.

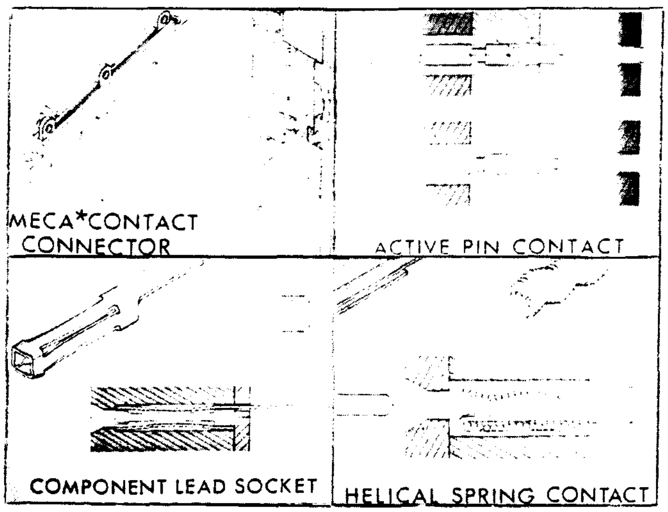


Figure 1

CRIMP CONNECTIONS

Let us turn our attention back to permanent-type connections, and consider in more detail the pressure crimp - which is by far the most widely used pressure connection today.

Perhaps it goes without saying that thecontinued acceptance and growing use of the crimp-termination technique by the electrical industry are direct results of the fact that perfectly satisfactory joints, both electrically and mechanically, can be made in this way. The outstanding performance of a crimped electrical connection is not an obvious deduction that can be made from a casual examination of one. In fact, we have ample proof that it is not obvious from our difficulty in selling the idea to electrical equipment manufacturers in the late 1940's. But, a closer look at the technique, applying some of the basic theories of electric contact, mechanics, friction, plastic flow and cold welding can reveal some interesting facts which not only make the good performance understandable, but which could guide us to even greater improvement in the method and the product.

Perhaps most of you are familiar with crimp-type connectors. Nevertheless, Figure 2 shows what I'm talking about.

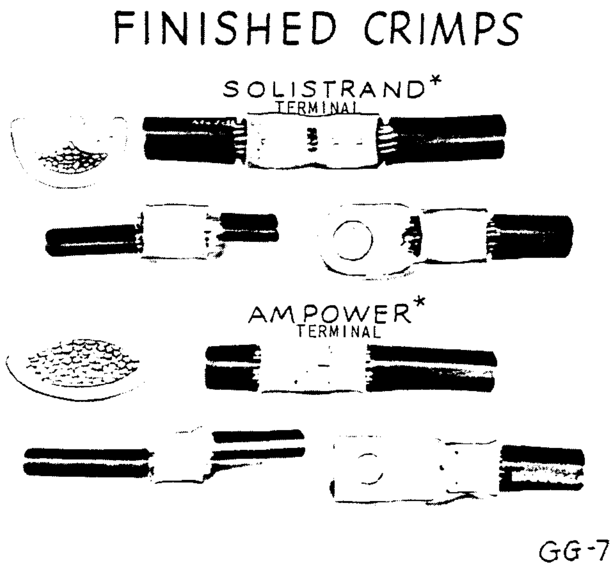


Figure 2

Here are examples of crimp-type wire splices and terminations. At the top is a "butt splice". Before crimping, the connector is essentially a hollow copper cylinder. Wires are inserted, and the connector is crimped by deforming the cross-section to a shape as shown on the left. The lower photographs show a different type of crimp deformation.

Connectors of this type are made in a wide variety of sizes, from about 1/8" overall diameter to approximately 1 inch diameter. In the case of terminals, a very wide variety of "tongue" shapes are available, but our interest at the moment is in the "barrel" portion of the device - the part which is crimped.

DIAMOND GRIP* TERMINAL

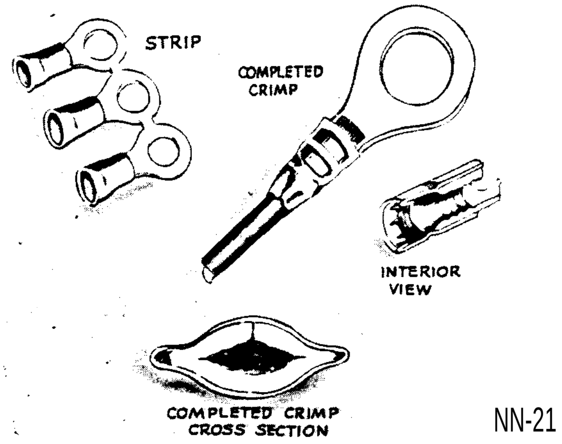


Figure 3

Figure 3 shows another style of connector which provides support and grip for the insulation of the wire as well as the wire itself. Although the insulation grip does improve the overall tensile strength of the joint, its primary purpose is to provide stress relief for the wire connection and make the connection more immune to vibration and mechanical shock damage.

PIDG* TERMINAL

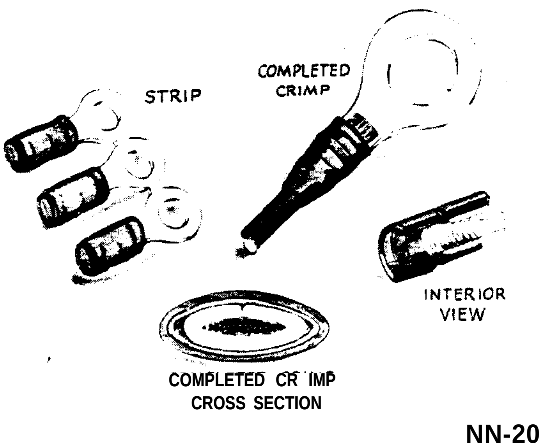


Figure 4

A particularly advantageous characteristic of crimp-type connections is that the connection can be preinsulated. In Figure 4 the outer material is an insulating plastic sleeve which is permanently bonded **to** the connector. Crimping pressure is applied through the insulating sleeve.

AMP PIDG HAND TOOLS

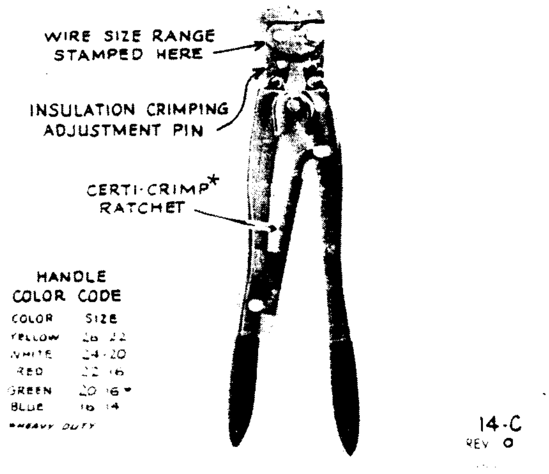


Figure 5

Figure 5 is a typical example of hand tooling for applying terminals and splices. Tooling is matched to specific connector sizes, and both terminal and tool are color coded to avoid mistakes. (Incidentally, in addition to color coding, a dot code is impressed by the crimping die, which allows later inspection to determine if the right tool was used.)

STRIP TERMINALS

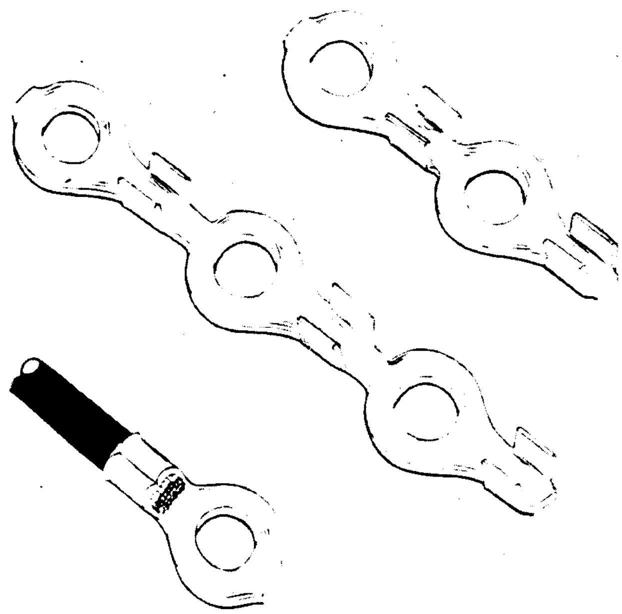


Figure 6

The crimp technique is particularly suitable for automation. Terminals can be formed in long strips, as shown in Figure 6, and applied with machinery such as shown in Figure 7. Wires are terminated at high speeds, and with operator error virtually eliminated.

AUTOMACHINE APPLICATOR

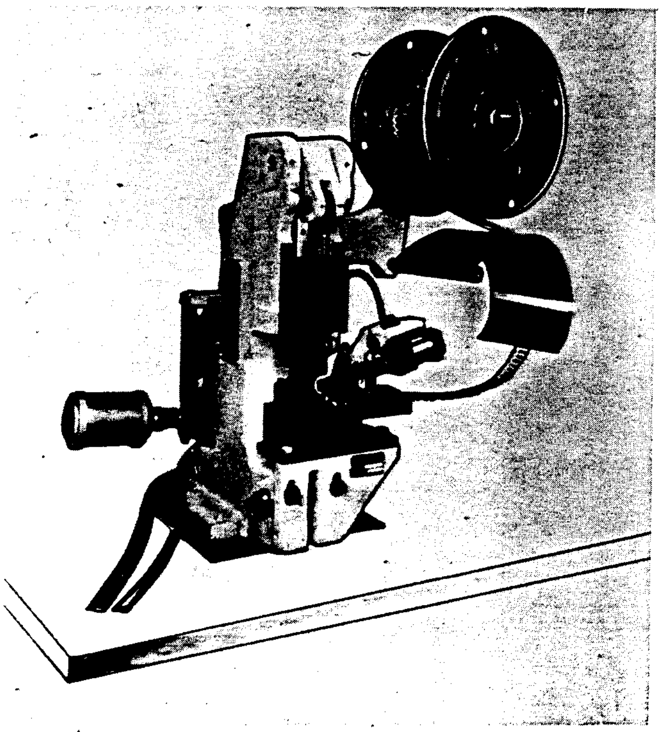


Figure 7

The obvious requirements of an electrical connection are that it must conduct electricity without too much loss, and it must hold itself together sufficiently to do so. A convenient and reasonable yardstick for comparison is the wire conductors which are being connected. It has become customary to expect that a spliced conductor should have an electrical resistance no greater than an equivalent unspliced length of conductor, and that the mechanical strength of the joint be not significantly less than the conductor. Specific requirements are called out by user specifications - military or commercial authorities. As an example, Figure 8 shows the tensile strength requirements for various wire-size connections.

Notice that in the small wire sizes, approximately 90 percent wire strength is obtained. For the larger cables, a certain reduction from cable strength is allowed by these specs. Other applications, as in the power utilities, require higher tensile strengths in the larger cable sizes used in overhead power lines.

TENSILE STRENGTH OF WIRE AND WIRE CONNECTIONS

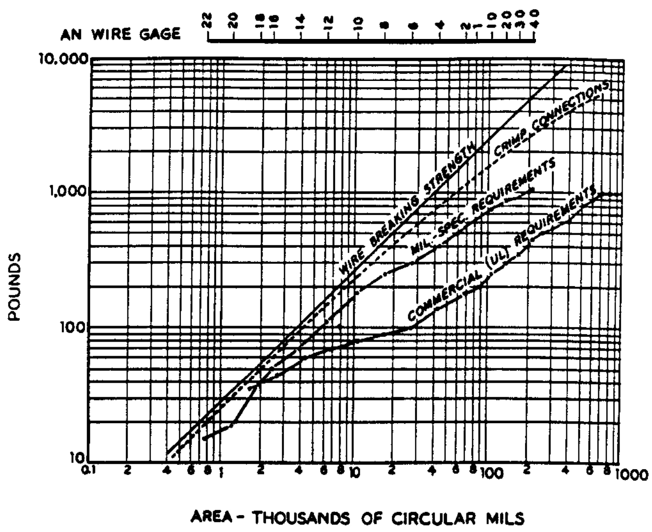


Figure 8

The electrical properties of these joints are very important. After all, their first function is to conduct current. Now, one quickly discovers that it is no trick at all to achieve low <u>initial</u> electrical resistance in a pressure joint. Just clean the surfaces, apply pressure, and you have it. The “trick” is to achieve a low resistance connection without special preparation of conductor surfaces, and to arrange to <u>maintain that low resistance</u> over the life of the joint, in adverse environments, and while it is being subjected to mechanical abuse. This, in essence, is the design problem in electrical connectors.

Although the end use is electrical, the design of connector devices and tooling is in a large part a mechanical engineering problem. It is a problem involving elastic and plastic deformation of metals, and of forging into shapes that introduce and sustain permanent stresses, and cold welding, so as to permit residual contact forces to be electrically effective.

Early design procedure was based almost entirely on mechanical strength. It was tacitly assumed that a strong joint would be a good electrical joint. We know now that this is not in general true, but it was close enough that early designs did work.

When one desires to crimp a terminal onto a wire, and once the general shape of the crimp is decided upon, the next question is how far to crimp. Figure 9 shows the type of characteristic one obtains.

As the crimp depth is increased, the tensile strength and electrical conductivity increase. When the deformation is too great both the tensile strength and the conductivity go down, because of the reduced cross-section of the members. There is optimum crimp depth for tensile strength, and an optimum for electrical conductivity, and in general these peaks do not occur at the same point. Thus it is usually necessary to compromise, in order to achieve the best combination of properties.

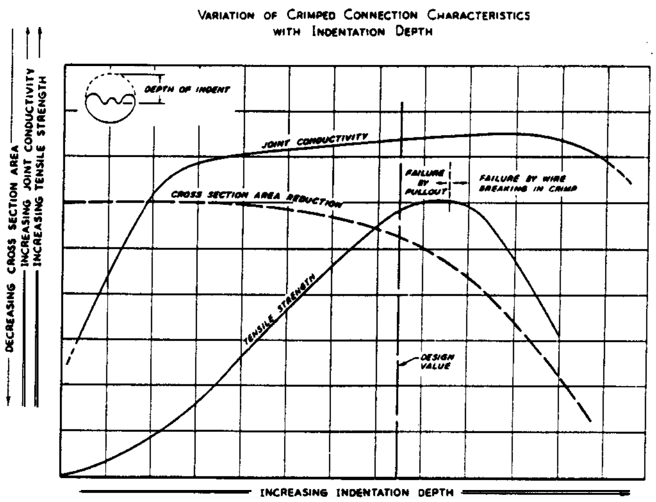


Figure 9

Although this curve represents the general shape of the crimping characteristic, the details of the curves are sensitive to several other parameters, such as:

(1) Geometry of indentation
(2) Size of termination, and wire
(3) Tubing diameter and wall thickness
(4) Material, type and temper
(5) Preinsulated or not
(6) Velocity of indentation

So, many curves of the type shown here are produced before the final design of termination and tooling is established. In the process, another variable not shown on the graph, which we could call "stability under environmental exposure", is included . . . . and the final design is related not only to initial properties of the connection but also to its ultimate application as a permanent electrical connection.

Crimp geometries differ considerably. One indent, two indents, three indents, hexagonal crimps, and folded U's are all used. The choice of crimp geometry is not a capricious one, however. It is made (by us, at any rate) after a long series of development tests, and is related to the job that must be done by the termination system. For instance, some geometries are found to be more tolerant of variations in wire - with respect to size or cleanliness - and these are used when a wide range of wire sizes must be accommodated. Our open-barrel "F" crimp is particularly suited to automatic machine application. Our "W" crimp is suitable for both solid and stranded wire. The "Diamond Grip" works with or without preinsulation, and so on.

In most cases the final design is placed such that the indentation depth is nominally just to the left of the optimum tensile strength point, as indicated in Figure 9 by the vertical line. At this point the buildup of production tolerances on terminal, wire, and tooling is just insufficient to carry over the hump into the right-hand region. It is undesirable to get into this region for several reasons. First, the tensile strength decreases rapidly. The wire has been severely weakened by extrusion, and at the same time is made harder by working. The termination is more susceptible to mechanical abuse, such as vibration and shock. The termination fails by wire breakage in the crimp area, which would help convince the reluctant user that crimping is no good because it squeezes the wire in two.

On the other hand, there are cases where operation in the "overcrimped" region is preferred. In this region both wire and terminal are extruded more, and the mechanical cleaning action is better. In some instances this better cleaning and improvement in electrical conductivity is preferred even at the expense of lowered mechanical strength.

Notice that the tensile strength peak in much sharper than the electrical conductivity peak.

The characteristics in Figure 9 apply to all size joints, large and small. A characteristic not shown is the force required to do the indenting. For small gauge joints (wire range 10 -22) the forces range up to 2,000 pounds. Die surface unit pressures range up to 100,000 psi. With larger gauge joints the forces are much higher, and eventually become impractical to obtain in "portable" tooling. This is one reason for the lower relative tensile strengths obtained on large cable terminations.

Certain applications, however, require full-tension cable splices. As for instance, in the power utilities, on overhead lines. For these cases, it has been found that multiple crimping is more satisfactory. That is, several indents are formed on a longer connection. Each "partial crimp" contributes to the total tensile strength, and to the electrical conductivity.

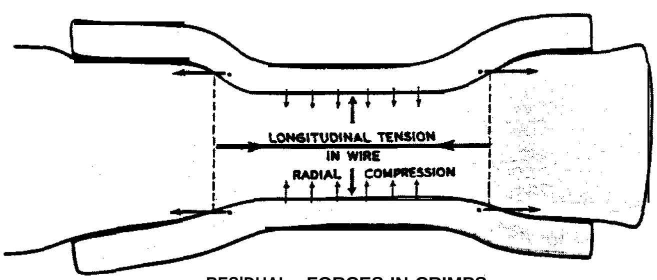
As I mentioned before, the good performance of a crimped connection is not an obvious thing, even to those of us who live with them every day. If we take a closer look at a crimp perhaps you will see what I mean.:.

In many types of connections the residual contact force which holds the connection together and maintains conductivity can be clearly identified. The taper pin wedge, the screw stud joint (with or without Belleville washers), and even the wrapped-wire joint have contact forces which can be calculated and measured fairly easily. Not so with the crimp joint. We've made many attempts to measure the residual forces in a crimp, with inconclusive results. Our results show anything from zero to several hundred pounds. I think we understand why the variation appears so large - and it will illustrate well that "there's more to a crimp than meets the eye".

Incidentally, it seems odd to me that we are not challenged more often when we summarily dismiss the subject of crimping by saying "residual contact forces are developed during crimping". Perhaps the reason is that with a record of over 30 billion successful crimped connections, the user could care less whether or not there's a "residual contact force" - the joints work, and that's all he cares about.

Nevertheless, let's examine the proposition regarding residual forces in a crimp.

First, visualize what is meant by residual contact forces. Refer to Figure 10.



RESIDUAL FORCES IN CRIMPS
Figure 10

After crimping, it is presumed that elastic forces exist in the members that act to keep the two pieces tightly together. These forces may be radial, or longitudinal, or some combination of the two. Since its not immediately clear how such forces could be set up in a crimping operation, let's consider a set of experiments that may clarify it. These experiments are hypothetical, for reasons which will emerge later - but they can serve to show some conditions that have to be present for residual force generation.

Figure 11 shows the cross section of a hollow cylinder, and of a solid wire, and of both together, - and the Force-Deformation Curves that might be obtained from each case. The last curve, lower right, illustrates the -situation when residual contact force has been achieved in the radial direction. In this case the wire tends to expand back toward its initial shape more than the barrel does, so the wire pushes out against the barrel. The magnitude of force and final dimension of the crimped region can be estimated graphically from the experiment.

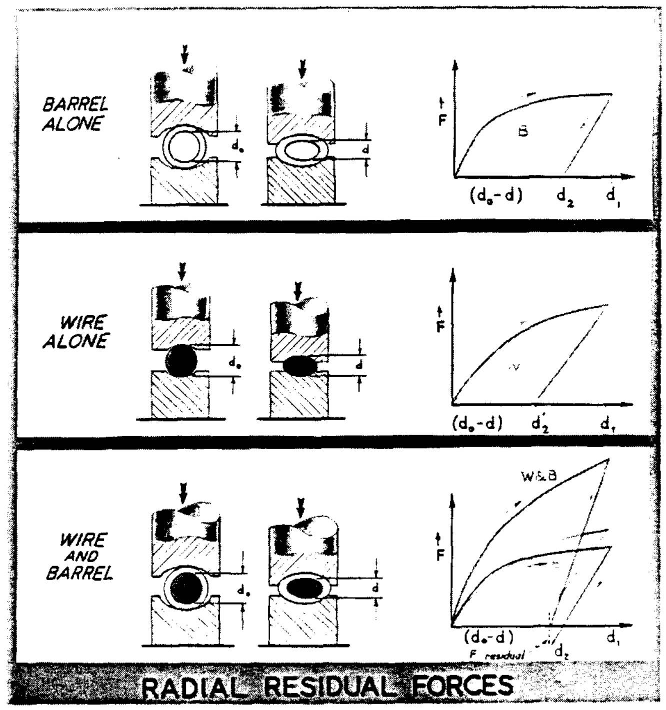


Figure 11

The conditions for radial residual force can be deduced from the figures. Some of them are:

(1) If W and B are the same material and have same elastic modulus, W must be harder (higher yield point)

(2) W must work-harden more during crimping

(3) W must require more force to deform to d, dimension

(4) If different modulus materials (or geometry influence) are appropriate, B should have highest effective modulus (meaning, it returns least toward the undeformed dimension).

Even when these conditions are present, one might get the impression that residual contact forces are likely to be pretty small - since the tendency to spring-back is nearly equal in both barrel and wire.

How about longitudinal residual forces? Here the situation looks a little more promising. A barrel, being squeezed onto a wire, tends to extrude the wire and place it in longitudinal tension in the crimp area. At the same time a sort of wedge is formed by the barrel.

Now, a wedge with an included angle less than (twice) the friction angle cannot be "squeezed" out by radial pressure on the wedge. In the case at hand, what we're saying is that the "wedge" formed by the barrel indent cannot be opened by longitudinal compression by the wire. This looks better. Whatever tension we are able to put in the wire during crimping is likely to remain there - at least a very large part of it. The conditions for this to occur are:

(1) The wedge formed by the barrel must not tend to retract too much due to its own elasticity.

(2) The angle of the wedge indent must be less than the friction angle of the materials. (This means that a shallow indent won't do.)

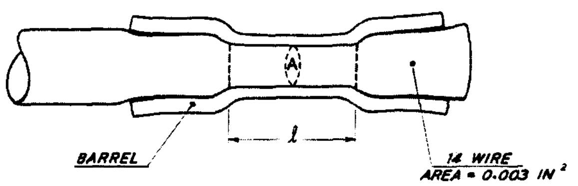
Suffice it to say, at this point, that these last two conditions are a lot easier to meet than the previous ones for radial residual force.

To pursue the point a little further - let us estimate the order of magnitude of residual force.

Figure 12 is a longitudinal section of a crimped connection. Suppose the wire under the crimp has been placed in tension equal to its yield strength. Suppose further that there was zero retraction of the wedge upon removal of the crimping tool. The dimensions on the slide are typical of a particular crimp, and the maximum residual contact force is estimated at 78 pounds.

Now this isn't bad. Seventy-eight pounds is enough force to give very low contact resistance. Can it be maintained?

ESTIMATE OF LONGITUDINAL RESIDUAL FORCES



$l_0 \cong$ 0.1 INCH = EFFECTIVE LENGTH OF CRIMPED WIRE

A = 0.0026 IN^2 = REDUCED AREA OF WIRE (20% REDUCTION)

Y.P. COPPER = 30,000 PSI AFTER WORK HARDENING

MAX. TENSION IN WIRE = 30,000 (2.6×10^{-3}) = 78 LBS.

ELASTIC ELONGATION

$$\Delta l = \frac{F/A}{E/l_0} = \frac{30 \times 10^3 (0.1)}{16 \times 10^6} = 2 \times 10^{-4} \text{ INCHES}$$

Figure 12

Using the elastic modulus for copper, one can estimate that the elastic deflection responsible for this 78 pounds force, along a (liberal) length of 0.1 inches, is only 0.2 mil. A relaxation of the crimp wedge, or differential thermal expansion, amounting to two-tenths mil could completely remove the residual force. Even when multiplied by a factor due to the wedge angle, one might be suspicious that movements on this scale could occur, and that after some time the contact force would be reduced toward zero.

So, it appears then that longitudinal and radial residual forces in crimps are likely to be small and involve small elastic deflections. If this is the case, what else is responsible for the good performance of crimps? The answer is that the connection is welded. There is undoubtedly a large degree of contact-asperity welding in a good crimp.

Basically, cold pressure welding involves the bringing together of two clean metal surfaces under high pressure. When clean metal contacts clean metal, the two weld together. If the surfaces are sufficiently clean, the only function of the pressure is to iron out irregularities of the surfaces so that large areas can contact.

This is what we do in crimping. Except that we seldom if ever start with freshly cleaned surfaces. The crimping operation must serve to clean the contacting surfaces and/or to create virgin surfaces by bulk deformation. This is what happens in crimping - and indeed, the difference between good and bad crimps may be largely a matter of how effective is this cleaning action, and consequently to what degree the connection is cold welded.

The suggestion that there is a significant amount of cold welding in a crimp is not always readily accepted. Although the cross section of a good crimp shows metal molded into a solid mass, it is possible to distinguish interface lines between contact members. Many people think a weld exists only when these interfaces completely disappear. And furthermore, the crimp does not show the mechanical strengths normally associated with full-area cold welds.

The disappearance of an interface is not a meaningful criterion of welding, however. Grain boundaries can be seen in the microscope - and surely the grains in a piece of metal are "welded" to each other. Plated coatings show an interface line, even when they adhere with strengths equal to that of the metals involved.

Interface lines disappear when recrystallation occurs. Yet,-:-cold welding (almost by definition) occurs at temperatures far below the lowest recrystallation temperature.

A better definition of welding, I believe, would include any situation where cohesion of the same order of magnitude as in the bulk material exists, and in the case of metals, where electrons can flow uninhibited across the interface between members. Thus, even tiny contact asperities are thought of as truly welded spots - and in fact, this is the starting point from which accepted theories of electric contact, friction, and wear are built.

If crimped joints are thought of as having a large number of "contact asperity welds", many of the properties of the joints can be explained. Their high electrical conductivity - their high strength, and their mechanical stability against rough treatment becomes more understandable, especially under conditions where residual contact forces would be expected to be removed by thermal annealing or by abnormal stresses on the joint.

Contact asperity welds, because of their small size, would have low mechanical strength when acting individually. But large numbers of them, constrained to act together by residual forces and plastic deformations introduced by crimping, provide a significant and perhaps dominating influence on the properties of crimped connections.

The difference between crimp joints and the structural, full-area cold weld is simply a matter of degree. Full area cold welds are achieved with large plastic deformations, starting with freshly-cleaned surfaces. The plastic deformation in crimps is relatively small, and no special preparation of the wire and terminal surfaces is done - aside from the

EXPERIMENTAL ARRANGEMENT FOR CRIMP MOVIES

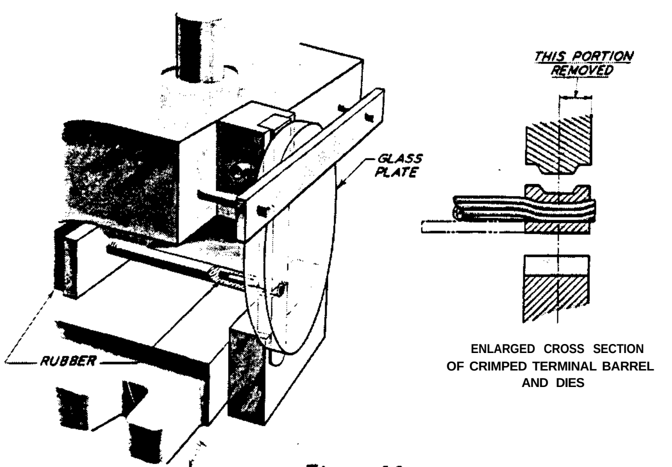


Figure 13

preferred use of plated parts. In my view, the crimp joint will be improved even further when we learn how to increase the amount of cold welding that occurs. Much of our R and D effort is directed to that end.

When trying to think about crimps and crimping, it helps to see one in action. We have made a short film strip which shows what happens inside the crimp when it is being made. Figure 13 illustrates the experimental arrangement that was used. These movies have confirmed many of our ideas about the crimping action, and have introduced us to a new and useful technique which will aid further crimp development.

CONCLUSION

Gentlemen - a main purpose of this seminar is to help answer your questions on the practical aspects of the utilization of pressure connections. I have dwelt at some length on the theoretical aspects of crimping - the purpose being to lay a foundation against which such questions may be answered. Let me conclude my remarks by answering some of the most frequently asked questions.

(1) Why so many tools? Why can't any tool and terminal be used together? Why not design a universal tool to crimp anything?

The overriding theme of these sessions is intended to answer these questions. The pressure connection, and especially the crimp, is a system - involving components, tooling, and techniques - designed as a unit - to do a certain job - with predictable results.

A crimp termination system can be optimized in several different ways. Lowest cost - highest reliability - greatest mechanical strength - widest wire size range - highest temperature limits - best corrosion resistance - highest speed of application - and so on. From what I've said, I think you can appreciate that optimization for one condition or set of conditions won't necessarily be correct for others. Our experience with crimp connections has shown, better than any theories could, that the system must be selected to suit the application - and that deviations from the tested and proven combination are likely to come back to haunt you - for the most "unexpected" reasons,

An analogous question is "why have so many different tools to attach a screw?" Why not use a Phillips screwdriver to install a slotted screw? The answer is - it won't work. Each combination of screw and screwdriver is selected to do a certain job better, or faster, or cheaper than some other combination - and that's the way the job ought to be done.

(2) For safety's sake, why not solder the crimped joints?

Would it be better to solder dip the wires before crimping?

Crimped connections don't need to be soldered for safety's sake. It's much better not to. You may damage the crimp, burn the wire, and have a bad solder joint to boot. You could also wick solder down the wire and cause it to break off from vibration later. Crimps are designed to work without solder - and they do. Why bother?

Crimps are also designed to work with undipped wires. A glob of solder in the crimp changes the deformation, metal flow, cleaning, welding and residual force characteristics designed into the crimp. Don't bother to do it - it may easily cause trouble.

(3) What is meant by a voidless crimp? Is it desirable?

The cross section of a voidless crimp shows the metal of wire and terminal compacted into a tight, void-free mass. There is no room for corrosive environments to get in to attack the contact surfaces. Full advantage is taken of the available contact area, and the contact surfaces have not separated due to crimp relaxation upon removal of the crimping tool. These are desirable things, which can be obtained by proper design without the sacrifice of other things such as tensile strength.

(4) Isn't the precision of crimp configuration and dimension overdone?

One thing that our experience has taught us, and our laboratory work continually reconfirms for us, is that the only way to get consistent, reliable, trouble-free results with crimping is to maintain tight tolerances - both on the terminal, during manufacture, and on the tooling in application. Good crimps don't just happen - they're designed that way.