WHITE PAPER

MEASURING AND UNDERSTANDING CMK ON WIRE CRIMPING MACHINES

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INTRODUCTION

Manufacturers who crimp terminals onto wires usually face rigorous quality requirements on their finished products. A statistical tool these manufacturers use to indicate finished quality level of a sample lot is the Process Capability Index or Cpk.[1] Cpk will be affected by variations in terminals, wires, processes, equipment, and environment. Manufacturers naturally have an interest in knowing that equipment that they have purchased is capable of repeatably producing quality terminations because the equipment is a contributor to Cpk. The Machine Capability Index or Cmk is a measure used to quantify the processing machine component of total capability. In many industrial settings, the Cmk is calculated from consecutive measurements of a very short run with no machine stoppages or adjustments.[2] The calculations are the same as Cpk, only sampling differs. Cmk calculations assume that the environment and incoming material does not vary in the extreme short term. In the case of terminal crimping, it may be a reasonable assumption that consecutive stamped terminals on a strip produced by an automatic stamping line are essentially the same. However, in the wire harness crimping industry, some manufacturers are now using substitute terminator analysis devices without material inputs (wire and terminals) to evaluate Cmk. The terminator analysis devices typically provide a substitute load for the crimp by using elastic machine elements that are deflected by the terminator stroke. The thinking is that this method takes out any wire and terminal variation, however, it must be understood that effects or variations from the device itself contribute to the measurements instead. The goal of this discussion is to build a foundation for thorough understanding of the use of terminator analysis devices and what parameters should be used to evaluate Cmk with them. Along this path, there are many mechanical concepts to be reviewed to get the complete understanding.

BACKGROUND MECHANICAL THEORY

When a load is applied to an object it will be deformed or be urged to move or perhaps both. If a resistance or support is supplied to create opposing and balancing reaction forces, only deformation will be possible. In a mechanical crimping machine, the terminal is essentially fixed and supported, thus, for this discussion on crimping machines and processes, the focus will be on deformation and not motion. Deformation exists in two forms: elastic and plastic. Elastic deformation is deformation that instantly disappears when the load is removed. The unloaded part geometry returns to its original shape. Think about the various types of springs you have encountered. Within certain parameters, they can be deflected repeatedly with no change in unloaded shape and no change in force required to deflect them. See Figure 1. Deformation on virtually all materials is elastic if stresses are kept low enough. However, after exhausting elastic deformation capability, ductile materials will begin to experience plastic deformation at stresses higher than the elastic limit. Plastic deformation results in a permanent change of shape (often called yielding) when the load is released. The created stress at which deformation changes from elastic to plastic for a material is called the elastic limit. Since some elastic deformation accompanies plastic deformation for common engineering materials, there will be a partial spring-back (release of the elastic portion of deformation) as the plastically deforming load is released. See Figure 2. Eventually, if stresses continue to rise the yielding materials will eventually crack, fracture, or neck down to nothing. Both the elastic limit and the fracture point are affected by what the material is and the various mechanical and thermal treatments that may have been done to it.

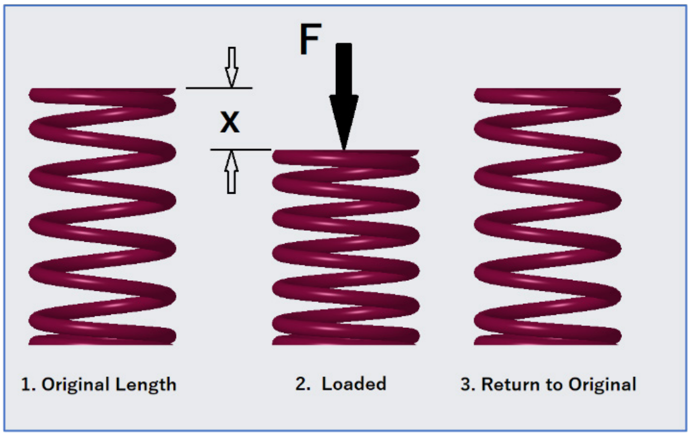


Figure 1 - Compression spring loaded within elastic limits and then load released

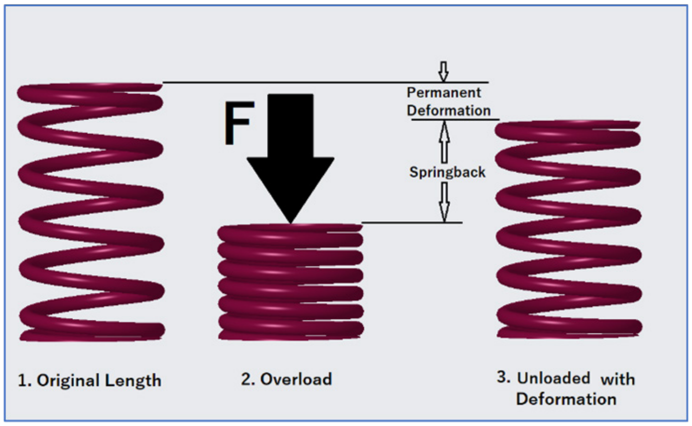


Figure 2 - Compression spring overloaded past elastic limits with resulting permanent deformation when load released.

Crimping is necessarily a plastic deformation process. It is intended to change the shape of the terminal and the wire to force them into a combined geometry that is useful for electrical and mechanical connection. Meanwhile, the components of the mechanical crimping machine, or terminator, are necessarily only going to undergo elastic deformation. If any plastic deformation occurs in the terminator frame or force-transmitting mechanism, the crimping process will change repeatedly creating process instability. Likewise, the mechanical components of a terminator analysis device will need to remain in the elastic realm for repeatability.

Another term that applies to the discussion of elastic deformation is stiffness. Stiffness is the ability to resist elastic deformation. For a simple spring, Hook's law defines the spring stiffness:

Equation 1: $F/x=k$

Within Equation 1, k is the spring stiffness constant, F is the deforming force, and x is the change in length during elastic deformation. Equation 1 assumes that the spring is initially undeformed. If the spring had some initial deformation and only the change in force and length were known, the equation would look like this:

Equation 2: $\Delta F/\Delta x=k$

The linear relationship between force and displacement in Hooke's Law has its roots in a material property known as the Modulus of Elasticity. Alternate names for the Modulus of Elasticity are Young's Modulus or the Stiffness Modulus. For general metallic materials, the Modulus of Elasticity, E, is defined as

Equation 3: $E= \sigma/\varepsilon$

Within Equation 3, σ is material stress, and ε is material strain. The Modulus of Elasticity derives from the energy required to stretch or compress the atomic bonds in the metallic lattice from their equilibrium spacing. For an axially loaded simple machine element such as a metal bar of initial length, l, and cross-sectional area, A, stress and strain are as follows: $\sigma = F/A$ and $\varepsilon = x / \ell$. In the strain relation, x is again the change in length just as it was in the spring equation above. Substituting into Equation 3 with the definitions of σ and ε we get:

Equation 4: $E=(F/A)/(x/\ell)$

Rearranging mathematically:

Equation 5: $EA/\ell =F/x=k$

Equation 1 and Equation 5 are of the same form which proves that an axially loaded metal part is in fact also a spring with a linear relationship between force and deflection under elastic loading. Note that the stiffness modulus, E, is intrinsic and describes a material in general; whereas the stiffness, k, is an extrinsic property that applies to an entire part because it includes specific geometry terms. Because a solid metal part likely has a very high stiffness, the elastic deflection is orders of magnitude less than for a common spring of similar envelop size. See Figure 3.

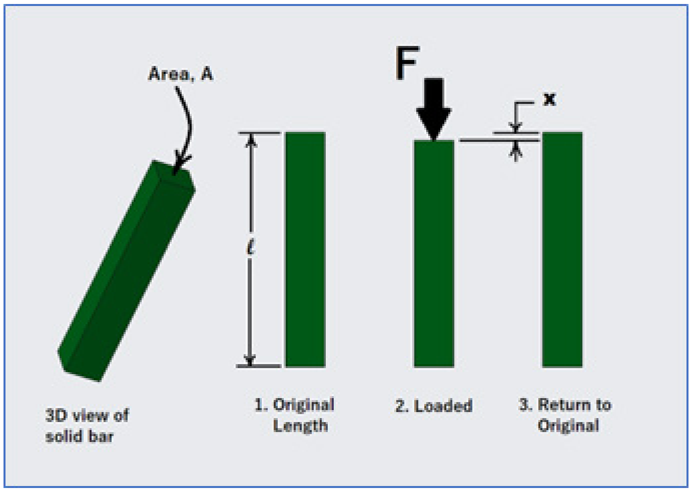


Figure 3 - Solid machine element loaded within elastic limits and then load released.

What if a machine component experiences elastic bending under load? Although bending deflection is not in the axial direction, if the loading is kept in the elastic realm, the deflection is again linear. See Figure 4.

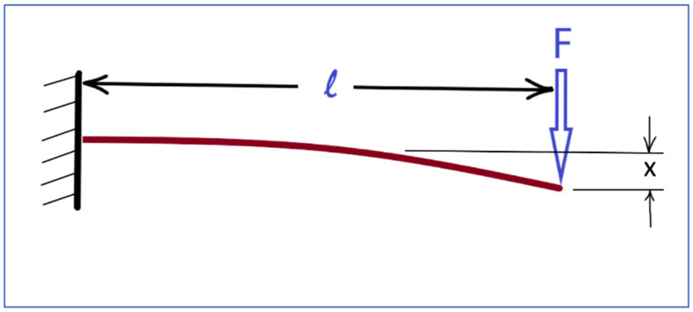


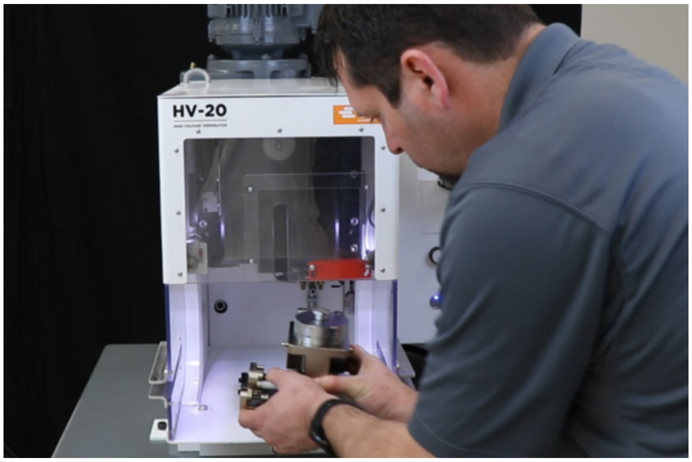
Figure 4 - Schematic depiction of beam deflection

The governing equation for deflection of a simple cantilevered beam is

Equation 6: $x=(F\ell^3)/3EI$

Within Equation 6, x is perpendicular deflection, F is the deflecting force, l is the beam length, I is the area moment of inertia of the beam cross-section, and E is again the Modulus of Elasticity. Rearranging mathematically again yields an equation of the form of linear spring rate:

Equation 7: $3EI/\ell^3 = F/x = k$



In practice, it is found that a combination of machine components forming a terminating machine with no components loaded beyond their elastic limit will function rather similarly to a linear spring with a spring constant or stiffness. For example, Figure 5 shows measured test data of TE's HV20 terminator (frame plus linkage) with applied loads in the elastic range. During crimping, the shut height of the terminator will be stretched by the load of the crimp according to the overall spring rate. Alternately, during Cmk testing where variations in crimp materials are being eliminated, the terminator shut height will be stretched by the load of the testing apparatus.

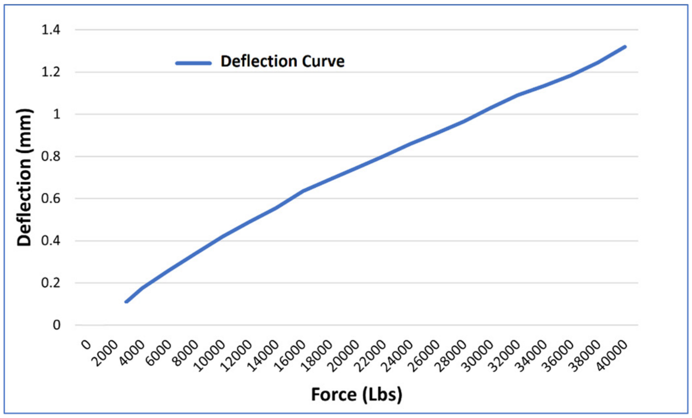


Figure 5 - Stiffness data for TE's HV20 Terminator showing roughly linear stiffness.

Though such test devices are generally stable and produce little variation there are still some sources of variation in the system. One cause could be minute variation in developed grease film thickness in bearings and slideways during each cycle. Another source could be miniscule dimensional variation among the various balls or rollers of a rolling type bearing. In many terminator designs, it is probable that a different combination of bearing balls and/or rollers is in the load path with each cycle. Some types of terminator designs rely on stopping at a programmed motion point usually with a servo valve or servo motor control. The variation in the stopping point of these terminators adds variation to repeatability that "over-center" designs do not have. An "over-center" design uses a linkage or crank mechanism that toggles through the same, most-tightly-closed geometry (center) every time with no need for a precise stopping point. Finally, we cannot forget that any variation in the testing apparatus itself, will show up as variation in the machine's Cmk.

All of these review topics are essential to give you confidence that an over-center terminator is elastic and acts like a linear spring for the following discussion on machine reliability and testing.

CRIMP HEIGHT AND CPK

The crimping of electrical terminals is universally governed by a value known as crimp height for a given terminal and wire combination. See Figure 6. The required nominal crimp height and tolerance zone is specified by the manufacturer and typically spelled out in an application specification. The nominal crimp height and tolerance are based on significant testing by the terminal manufacturer to assure that any voltage, current, resistance, pull-out force and other properties outlined in the application specification are achieved by a terminal crimped in the specified height tolerance range. Crimp height is the fundamental criteria determining quality and acceptance of the crimping process.

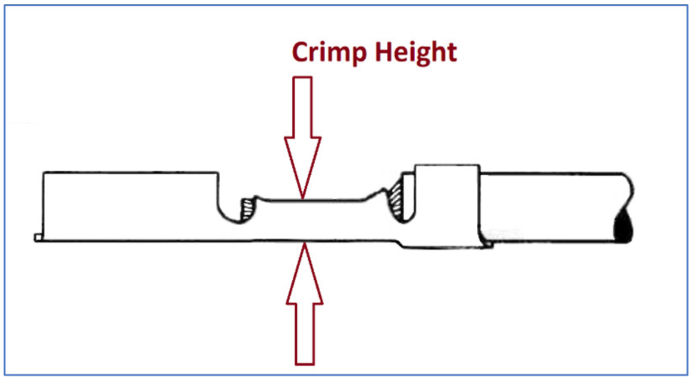


Figure 6 - Crimp Height Depiction

For the reason stated previously, a Cpk study on a terminator's output should invariably focus on the crimp height measurements of the sample population. Cpk is a measure of how well the measured variation fits within the crimp height tolerance zone specified in the manufacturer's Application Specification. The Cpk calculation utilizes the standard deviation, σ, and the mean, μ, of the sample data and compares to Upper and Lower Control Limits(UCL, LCL) which are the maximum and minimum of the crimp height tolerance zone. The Cpk must be calculated with respect to both limits, and the lower of the two calculated values is the overall Cpk. A "Min" function is used to show the selection of the lower of the two values. Equation 8 through Equation 10 show the relevant equations. Again, refer to authoritative references on quality process control for more details and explanations.[1]

Equation 8: $Cpk_{LCL}= ((\mu-LCL))/3\sigma$

Equation 9: $Cpk_{LCL}= ((UCL- \mu))/3\sigma$

Equation 10: $Cpk= Min(Cpk_{LCL},Cpk_{LCL})$

It is generally understood that a Cpk must be at least 1.33 to indicate reasonable capability, but many situations warrant the requirement of a higher Cpk in the range of 1.5 to 2.0 to indicate high capability.

CMK

As was described earlier, Cmk is a measurement to focus on the crimping machine's portion of overall capability. It is generally understood that Cmk must be at least slightly better than the desired terminal crimping output Cpk since there will be additional variation from the terminals and the wire. To be more accurate, we have to say that the Cmk will be better than Cpk if the variation and effects of the Cmk testing apparatus is less than the variation due to the terminal and wire variation. While this may generally be true, it is not given enough attention in many discussions of Cmk testing. Several companies have developed devices for the measurement of Cmk. In general, the testing device is placed in the terminating machine in place of an applicator, terminals, and wire. Cmk may be especially useful to evaluate a machine when an applicator, wire, and/or terminals are not yet available. However, a Cmk test is not necessary to know good crimps have been produced. If a required Cpk for a crimp population can be achieved, you can rest assured that your Cmk was adequate.

If a Cmk test is desired and a testing apparatus is available, shut height repeatability should be the primary focus of the Cmk testing. This is because the fundamental crimp quality measurement, crimp height repeatability, is directly related to the machine's shut height repeatability. The appropriate tolerance zone to use in LCL and UCL determination is the tolerance zone on the crimp height as specified by the manufacturer in the application specification of the eventual terminal to be processed. The equations for Cmk and Cpk look essentially the same:

Equation 11: $Cmk_{LCL}= ((\mu\text{-}LCL))/3\sigma$

Equation 12: $Cmk_{LCL}= ((UCL\text{-}\ \mu))/3\sigma$

Equation 13: $Cmk= Min(Cmk_{LCL},Cmk_{LCL})$

Unfortunately, some less-capable Cmk testing apparatuses are only capable of measuring force and not height. Force Cmk should be viewed as a secondary check rather than a requirement since terminal application specifications are not known to require a specific crimp force, only a crimp geometry. The obvious next question is: what tolerance is to be used for machine force Cmk calculation since application specifications make no mention of required force tolerance? Some of the documentation currently included with terminator testing devices does not seem to treat this question rigorously and completely. The answer to this question requires us to think back to the discussion about elastic deformation. The terminator frame and mechanism act under elastic deformation at a specific spring rate during a crimp and return to the original dimensions when the crimp load is removed. So, the unknown tolerance on the machine force, Tol_F, is related to the known tolerance on the machine shut height (and crimp height), Tol_x, by the machine's unique spring rate as shown in Equation 14:

Equation 14: $Tol_F / Tol_x = k$

Notice Equation 14 has the same form as Equation 1. Solving for the appropriate force tolerance to use for the Cmk calculation is then an easy step:

Equation 15: $Tol_F=Tol_x{}^*k$

Stated another way, Equation 15 shows what force tolerance will yield the specified shut height and crimp height tolerance. Here is where things get difficult if you want to do a rigorous analysis of force Cmk.

CMK FORCE APPLICATION:

Instructional documentation from the test device manufacturer may not cover force tolerance well or at all. For instance, in one instruction manual, the user is instructed to adjust the device to get 8 kN during a typical terminator cycle and then take force readings with a height-adjust dial turned plus and minus 0.01 mm. A similar device is available with 30 kN capacity which still instructs to use the +/- 0.01 mm. The force readings at +/- 0.01 mm are arbitrarily suggested to be used as the UCL and LCL. There is a significant problem with this approach.

The universal selection of +/-0.01 mm adjustment for force UCL and LCL determination is essentially testing what is needed for a terminal with a +/- 0.01 crimp height tolerance, which is unnecessarily restrictive. For instance, on a large terminal for 75 mm2 wire, crimp height tolerance may more likely be ten times the +/-0.01 mm range, which should lead to a force tolerance ten times larger based on Equation 15. Also, a high-force terminator for crimping such a large terminal is likely to be extremely stiff to prevent substantial deflection. The high stiffness means that a miniscule height variation will cause much higher force variation on a large terminator compared to a smaller terminator. Let’s look at some real data. Table 1 shows data from a test using a 30 kN force-only Cmk device available on the market. From the data and the user manual instruction, a user would be inclined to selected UCL = 30.76kN and the LCL = 29.28. Is this appropriate? A review of the data and subsequent calculations will shed some light on this question.

Trial	Force in kN at -0.01mm from nominal	Force in kN at +0.01mm from nominal
1	29.15	30.63
2	29.30	31.05
3	29.21	30.55
4	29.21	30.86
5	29.56	30.71
AVG	29.28	30.76

Table 1 - Sample force test on a TE HV20 terminator with a Cmk test device

The overall system stiffness, k, can be calculated from this data by filling in Equation 2:

Equation 16 : $k= ((30.76\text{kN}-29.28\text{kN}))/((0.01\text{mm}-(-0.01\text{mm})))=74\ \text{kN/mm}$

Now, a large terminal requiring a 20-ton terminator, may often have crimp height tolerance range of +/-0.08 or +/- 0.1 mm. We will use +/-0.08 for our example, but you should use the tolerance for your terminal application(s). Plugging our data into Equation 15 ,we can find the most appropriate force tolerance for a +/-.08mm crimp height tolerance and the terminator stiffness data:

Equation 17 : $$\text{Tol}_F = +/-0.08\ \text{mm} * 74\ \text{kN/mm} = +/-5.92\ \text{kN}$$

In summary, for the example data set in Table 1, a UCL= 35.92 kN and LCL=34.08 kN would be entirely appropriate for this tester and terminator combination to correspond to the +/-0.08 mm crimp height tolerance in an application specification. Notice how different these are to the artificial and arbitrary values gotten by following the test manual. Remember, as was mentioned several times, force ranges are not known to be mentioned in crimp application specifications and artificial and arbitrary test boundaries cause confusion and delay. The thorough understanding of the stiffness physics related to force Cmk device usage will lead to appropriate force Cmk values.

A FURTHER CMK TEST DEVICE CONUNDRUM

To make this review as complete as possible, there is a conundrum associated with Cmk tester devices of which you should at least be aware. The conundrum involves the total stiffness of the system. When crimping, the system stiffness is the combination of the terminator stiffness and the crimp/wire stiffness. When testing with a crimp simulation device, the system stiffness combines the terminator stiffness and the tester stiffness. Stiffnesses in series add according to the following equations:

Equation 18: $$k_{test} = (k_{term} * k_{tester})/((k_{term} + k_{tester}))$$

Equation 19: $$k_{crimp} = (k_{term} * k_{comp})/ ((k_{term} + k_{comp}))$$

It is hoped that this thorough discussion has helped build a solid understanding of stiffness physics and aid you in making logical and realistic inputs into Cmk force reliability analyses. Here is a summary of the conclusions reached:

- Crimp Height repeatability is the fundamental quality measure specified in terminal application specifications.
- A Cmk measurement device gives a picture of capability without actually processing terminals and wire.
- The logical focus of Cmk terminator measurements is shut height repeatability because it relates directly to terminal application specification crimp height repeatability.
- Terminator force Cmk measurements do not relate directly to terminal application specifications and are best considered a secondary test.
- Every terminator has a unique stiffness, and it is generally linear in nature.
- Terminator stiffness plays a large part in the resulting force Cmk results from a Cmk testing device.
- The selection of force tolerances for force Cmk should be tied to the desired crimp height tolerance and the frame stiffness and should not be picked arbitrarily.

References

[1] An excellent resource for a more thorough understanding of Cpk is A Guide to Process Capability (Cp, Cpk) and Process Performance (Pp, Ppk) | 1factory

[2] Cmk - machine capability index (six-sigma-material.com)

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