Effect of Trace Contaminants on the Process of Crimped Electrical Contacts

Mark Ondo, first author
Engineering Manager, MEng
TE Connectivity Corporation
2801 Fulling Mill Road, Middletown-PA 17057
mark.ondo@te.com

Ma'moun Abu-Ayyad, second author[1]
Associate Professor, PhD
Mechanical Engineering Department
School of Science, Engineering and Technology
Penn State Harrisburg, Middletown-PA 17057
maa21@psu.edu

KEYWORDS: Crimping Process, Electrical Contacts, Contaminants, Scanning Electron Microscopy

ABSTRACT
This paper examines the effects of contaminants on the process of crimped electrical contacts focusing on four common contaminants, grease, light oil, terminal lubrication, and natural oil (human sebum). In addition, this study investigates how the presence of certain trace contaminants affects the crimping process, including the ability to detect errors with a forced-based crimp monitoring system. Large and small variants of two contact types (Splice and F-Crimp) were used for the crimp testing, in which the effects on peak crimp force, headroom and relative dispersion were studied. To document the amount of contaminant present, Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy were used to analyze the samples. The results of this study showed that the contaminants influence the crimping process and the coefficient of friction. A strong linear correlation was observed between crimp force and coefficient of friction. Also, the experimental results showed that all the contaminants cause a statistically significant decrease in peak crimp force for each of the terminals. However, the magnitude of the decrease was much more severe for the Splice terminals.

[1] Corresponding author information: Phone: 717.948.6786, Fax: 717.948.6619

INTRODUCTION

Crimped electrical contacts are used in applications that cover a wide variety of industries, including medical, aerospace, and automotive [1][2],[3]. Because crimped contacts are used in many critical applications, the quality of these connections is of high concern [4],[5]. The terminals of the electrical contacts are formed metal devices that are mechanically crimped on the end of a wire to provide a gas tight connection between the wire and the contact [6].

Crimping is one of the most critical steps during the assembly of connectors or electrical wires [7],[8],[9]. It involves many steps such as stripping, cutting, crimping terminals on either side of the wires, and joining wires within the harness. Many of these steps can be automated, especially the crimping [10]. Whether manual or automated, proper wire crimping requires the appropriate tools and materials and must follow certain steps [11].

Previous researchers observed that natural oil had a dramatic effect on the crimping process [12][13][14]. When determining how to approach the investigation into this topic, there are several key questions:

1. Does the contact type or size have any influence on the effect?
2. What are the effects of other potential contaminants like grease and oil?
3. How do these effects influence crimp quality monitoring error detection?
4. Is there a correlation between coefficient of friction and peak crimp force?
5. Can a trace amount of contaminant present on a sample be quantified?

The purpose of this study is to examine how the presence of certain trace contaminants affect the crimping process, including the ability to detect errors with a force-based crimp monitoring system. Additionally, the focus of this study was to build on that discovery and develop a better understanding of the phenomena. The focus was on determining what influence several factors (contaminate, terminal type, and terminal size) had on the output variables and if there was a correlation of peak force to coefficient of friction.

This paper is organized into three sections. Section 1 contains an introduction to the topic of crimping and crimps process monitoring. Additionally, it covers the discovery that led to the investigation of this topic. Section 2 details each phase of the experimental testing, including the quantification of the contaminants, the crimp testing and the coefficient of friction testing respectively. Finally, in Section 3 the conclusions and recommendations are presented.

Figure 1 shows a typical good crimp connection and identifies some of the basic features in addition to illustrating an ideal cross section. Along with these characteristics, there are other attributes to a good crimp such as, when a contact is crimped on a wire and the total cross-sectional area (contact + wire) is reduced by a certain amount [15]. The crimp height is the dimension that is specified to achieve the appropriate compression of the terminal and wire. Poor mechanical and/or electrical performance may occur if the proper crimp height is not achieved [16]. A crimp that is too loose (crimp height above upper limit) will result in poor mechanical performance, and potentially poor or noisy electrical conduction [15]. A crimp that is too tight (crimp height below lower limit) may exhibit improved electrical performance but at the cost of mechanical properties.

Fig. 1 Typical Characteristics of Crimped Contacts

Figure 2 illustrates the relationship of electrical and mechanical properties with crimp height. Typically, an application specification provides several criterions that a crimp must meet to be considered acceptable [17]. Many of these criteria such as crimp height and width can be measured easily, inexpensively, and non-destructively [18]. However, some of these parameters require the crimp to be cross-sectioned (destructive) or the use of computerized tomography to be evaluated. Therefore, it is not practical, or in some cases possible, to evaluate the entire acceptance criterion for every crimp. As a result, crimp force monitoring systems were developed to monitor the quality of the crimp indirectly by closely monitoring the process.

The TE Connectivity (TE) CQMII, shown in Figure 3, is an example of an advanced crimp force monitoring system. It records the force versus position profile for each crimp. The data is then evaluated by statistically comparing an individual force profile against a set of known good crimp force profiles using several different analysis methods. Consequently, the ability to detect nonconformities is directly related to the stability of the factors that influence crimp force. Examples of these factors include wire clearance, variations in the geometry, and physical properties of the inputs such as insulation, contacts, and crimp tooling wear. Variation in the process leads to less detectability for actual crimp non-conformances [19].

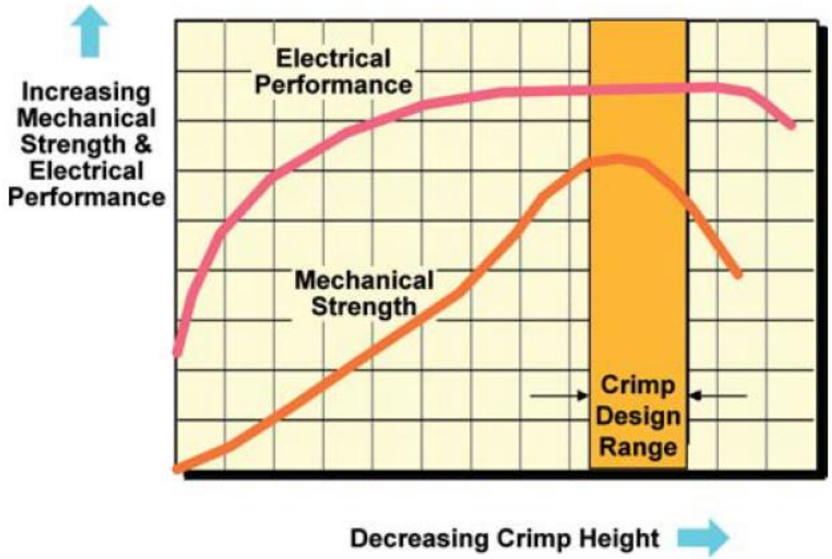

Fig. 2 Typical Relationship of Electrical and Mechanical Properties vs. Crimp Height

Fig. 3 TE CQMII Connectivity Crimp Quality Monitor

Discovery

During the development of a new crimping machine for AMPLIVAR magnet wire splices, large non-random variations in crimp height and crimp force were observed. The crimp height and crimp force would appear to be stable, then quickly change over the course of several crimps as seen in Figure 4. There was early speculation that machine variation was the cause. The assumption was that the machine is not moving to the same shut position every time, thereby causing the variation in crimp force and crimp height. However, when examining the machine data, it was revealed that the crimp height and peak force were showing a positive correlation as shown in Figure 5. This was surprising, as one would expect there to be a negative correlation. If the machine moves to a tighter shut position the wire and terminal would be compressed more (crimp height reduced), causing a subsequent increase in peak crimp force.

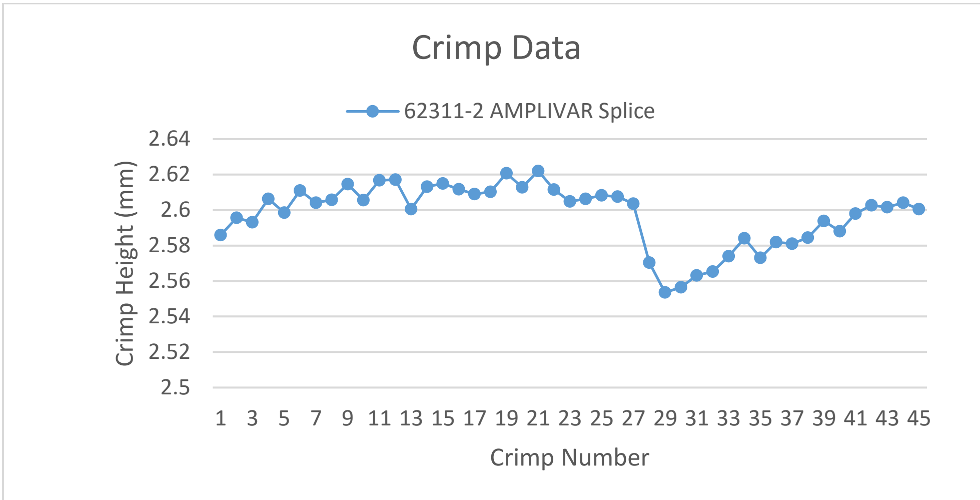

Fig. 4 Typical non-random variation in crimp height.

Since the machine frame and all other load bearing components collectively act like a linear elastic spring element, the variation in crimp height was simply the difference in machine deflection caused by the variation in crimp force. Therefore, the focus shifted to the crimp tooling itself. It should be noted that maintaining as much control of the terminal and wire throughout the application process reduces process variation. Several iterations of the tooling were made to improve control. Despite these efforts, the large variation continued.

At this point a crucial discovery was made; terminal lubricant was applied to the contact strip to see if it would improve repeatability. It improved but more importantly, it caused the crimp height and crimp force to shift significantly. It was noticed that the change in crimp height during one of the periods of large variation was approximately the same magnitude as what was witnessed when terminal lubricant was applied. This led to the hypothesis that the variation in the process was caused by variable amounts of lubricants present on the terminal strip. There are numerous potential sources for lubricants that encounter the terminal strip, as well as many components that guide and feed the terminals into the crimp area. Any of these elements could have oil or grease on the surface and could easily transfer the lubricant to the outside of the terminals. It was also noted that in many of the crimp tests, the large decrease in both crimp height and peak force would occur approximately 20 crimps into the test run which happened to correspond with how many terminals were in the strip guide.

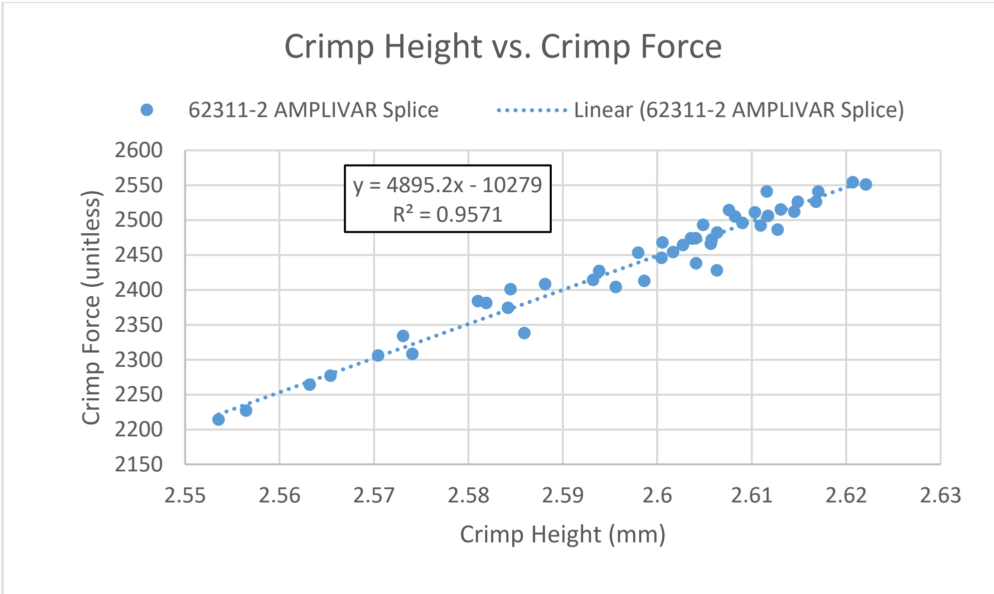

Fig. 5 Correlation of crimp height to crimp force.

There was some initial speculation that simply touching the terminals could have an effect. To test this hypothesis, all the tooling that comes in direct contact with the terminal strip was thoroughly cleaned. The terminal strip was loaded into the machine wearing nitrile gloves to prevent any contamination. Approximately 100 crimps were completed to ensure everything was stable. After this, six terminals were intentionally contaminated by touching them with a clean bare hand. The results were astonishing, as shown in Figure 6. The crimp height decreased 0.15mm [.006"] while the crimp force decreased by over 25%. The same test was run several more times with similar results. These tests show that touching the terminals can have a much greater effect than previously believed possible. Based on these results, it was apparent that additional investigation into the effects of trace contamination is necessary.

EXPERIMENTAL PROCEDURE

The first task of this research is to determine the different treatments that would be examined. The idea was to select several common substances that have a high likelihood of encountering the terminal strip during regular operation. Therefore, grease and machine oil were obvious choices because they are widely used to lubricate moving components and for corrosion protection on this type of equipment [20]. Additionally, terminal lubricant is commonly used in industry to increase tooling life and to alleviate issues with terminals sticking in the crimp tooling. Since the effects of natural oil were already clearly demonstrated, it was considered that there could be some contaminant on the terminals when they come from the manufacturer, so an additional treatment was added to the test matrix in which the terminals are cleaned. Table 1 provides the trade names for the products used for the various treatments.

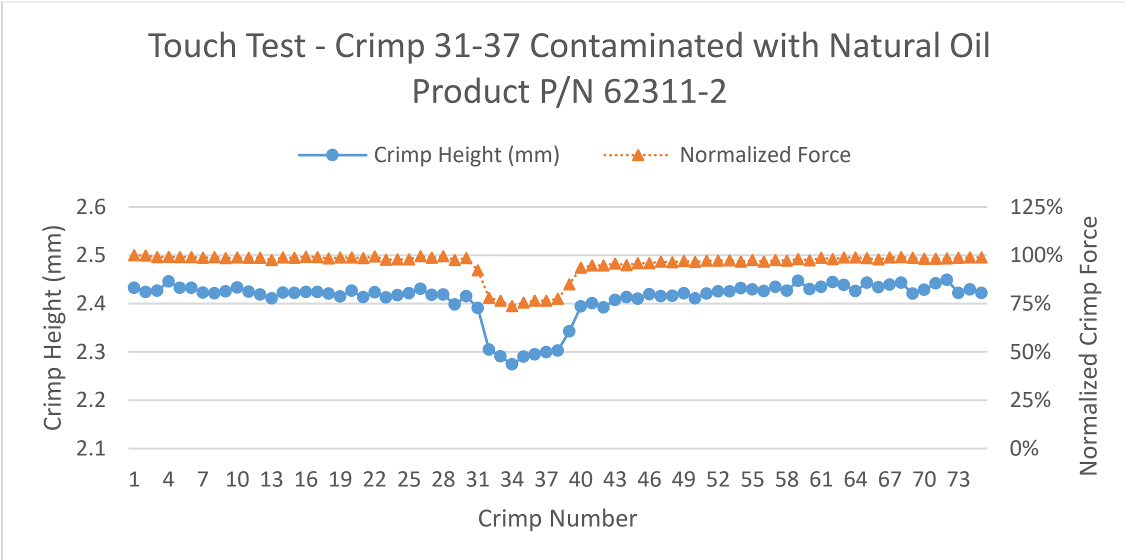

Fig. 6 Touch test results (crimp height and normalized crimp force)

Treatments	
Name	**Contaminant**
As Reeled	N/A
Cleaned	Cleaned with Denatured Alcohol
Grease	Chevron Multifak NLGI grade 2 EP Grease
Light Oil	3-in-One Light Motor Oil
Natural Oil	Human Sebum
Terminal Lube	Stoner E807 Terminal Lubricant

Table 1 Contaminant specifications

Because of the crimp force monitoring systems, there are two metrics that the wire processing industries have adopted to determine if an application can be effectively monitored. One is called Headroom, the percentage difference between a good crimp and one with all the wire strands missing. In other words, only the insulation barrel is populated.

$$\text{Headroom} = \left(1 - \frac{\bar{X}_{IO}}{\bar{X}}\right) \times 100\% \quad (1)$$

$\bar{X}_{IO}$= Mean Peak Crimp Force with Insulation Only

$\bar{X}$ = Mean Peak Crimp Force

As headroom decreases, the ability to detect wire related errors decreases as well. A headroom value of 35% is considered the industry standard for acceptable sensitivity to wire-related errors, such as missing strands. Applications that have headroom values lower than 35% are unsuitable to be effectively monitored with a force-based system [21]. The second measure is the relative dispersion of the peak force. It is the standard deviation divided by the mean peak crimp force. Industry standards suggest that relative dispersions greater than 1% become difficult to accurately monitor [21].

$$\text{Relative Dispersion} = \frac{\sigma}{\bar{X}} \times 100\% \quad (2)$$

σ = Standard Deviation of Peak Crimp Force
$\bar{X}$ = Mean Peak Crimp Force

Phase I: Contamination Application

Once the treatments were defined, the next challenge was establishing a methodology for applying the contaminants. As part of that, it is important to develop a method for measuring the amount of contaminant present on a sample to verify the amounts were approximately equal. The grease, machine oil, and terminal lubricant were applied directly to the outside surface of each side of the wire barrel of every contact in the test strip using a cotton swab. Then the excess was removed by wiping over the crimp barrels with a towel leaving only a very thin trace layer of contaminant. The natural oil or sebum (secretion of the sebaceous glands) application was handled differently. To avoid cross contamination, the participant would first wash their hands with soap and rinse thoroughly prior to application. They would then touch their forehead with all fingers, as the sebaceous glands are concentrated on the scalp and face [22]. Then each side of the wire barrel of each contact was touched briefly.

Phase II: Quantifications of Contaminants

The next step was to define a means for documenting the amount of contaminant present. Initially, attempts were made to use a microbalance scale to measure the difference in mass between a contaminated and cleaned sample. This method proved to be ineffective. The second method used involved using a Scanning Electron Microscope (SEM) and Energy-Dispersive X-ray (EDX) spectroscopy. This method is not entirely quantitative but by holding the parameters of the SEM constant throughout the testing, baseline relative levels were established. This testing was conducted at the TE Connectivity Failure Analysis Laboratory at 2900 Paxton Street, Harrisburg Pennsylvania. A Hitachi model SU3500 SEM equipped with an Oxford EDX detector was used to analyze the 6 samples which are made from 62311-2 terminals. One leg of the terminal was removed as shown in Figure 7, creating a flat rectangular test specimen approximately 8.6mm X 6.5mm. Each of the 6 specimens received one of the test treatments.

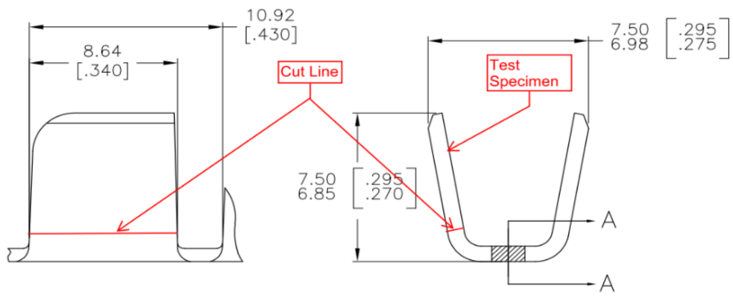

Fig. 7 Diagram of test specimen

All samples were loaded onto one sample stage and connected via conductive tape. Each sample was examined in two ways. First a backscatter electron image was captured to visually show the level of contamination with high compositional contrast. The second analysis was to capture the EDX spectra. This was helpful in determining how uniform the contaminant was dispersed over the surface and to verify consistency in the amount across the contaminants. Finally, each sample was examined under conventional and standard microscope lights for comparison purposes at the same magnification.

Phase III: Crimp Testing

The terminals selected for this phase of the testing represent a large and small variant of two general types of contacts. The one contact type is the AMPLIVAR magnet wire Splice and the other is a conventional F-Crimp type with insulation barrel as shown in Figure 8. The TE Connectivity part numbers for the selected terminals as well as the application information are listed in Table 2. It is also very important that the tooling used to crimp the terminals is appropriate. The power unit and tooling part numbers can be found in Table 3. Both power units were equipped with a TE Crimp Quality Monitoring (CQMII) system. The CQMII is an advanced commercial in-process crimp monitoring system. It utilizes a piezoelectric strain sensor mounted to the machine frame and a micron-scale linear encoder on the ram to collect force vs. position curves during the crimp cycle. This system has the capability to do sophisticated analysis on the resulting data, but for this study it was only used for collecting the crimp force data.

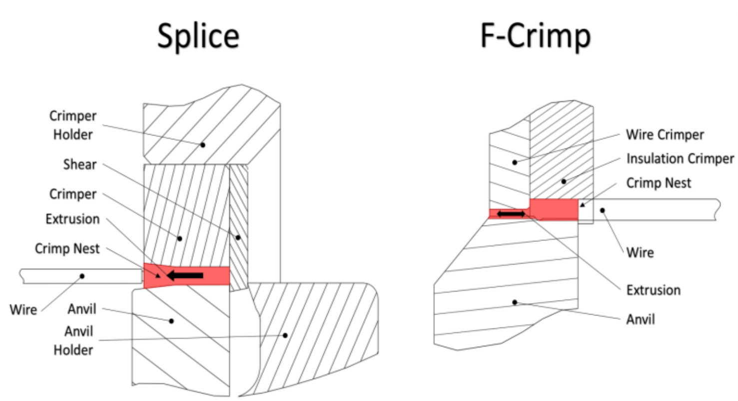

Fig. 8 Crimp Tooling Cross Sections for Splice and F-Crimp Terminals

Group	Sub-Group	Terminal		Crimp Application Data		
		P/N	Description	Wire	Strip Length	Crimp Height
Splice	Small	62303-2 REV E	SPLICE (AMPLIVAR) 9-SERRATION	2 x 24 Ga Insulated Cu Mag Wire	N/A	1.16+/-.05mm
	Large	62311-2 REV E	SPLICE (AMPLIVAR) 9-SERRATION	2 x 12 Ga Insulated Cu Mag Wire	N/A	2.62+/-.08mm
F-Crimp	Small	1-1703930-1 REV D	NanoMQS SOCKET CONTACT	.13mm^2 7-Strand Copper Wire with PVC Insulation	3.25 - 3.55mm	0.59 +/-0.02mm
	Large	62612-2 REV C	RING, ANTIROTATIONAL 8 STUD SIZE	10 AWG 103-Strand Copper Wire with PVC Insulation	5.94 - 6.76mm	2.84+/-0.05mm

Table 2 Application information

Terminal	Tooling P/N			
	Power Unit	Applicator	Tool Set	Feed Package
62303-2 REV E	APT-5A HF	N/A	1-2161790-3 REV A	2161490-7 REV C
62311-2 REV E	APT-5A HF	N/A	2217419-3 REV B	1-2161490-1 REV C
1-1703930-1 REV D	G Terminator	2151332-2 Rev N	N/A	N/A
62612-2 REV C	G-Terminator	2151343-2 Rev A	N/A	N/A

Table 3 Application tooling

The crimp testing consisted of completing 50 evaluation crimps followed by five headroom crimps (without wire). Each of the sample crimps were measured for crimp height. The peak crimp force data was exported from the CQMII Host module for analysis. The full matrix of crimp tests is shown in Table 4. These results will be discussed in the next section.

Terminal	Treatments					
	As Reeled	Cleaned	Grease	Light Oil	Natural Oil	Terminal Lube
62303-2	A + B	A + B	A + B	A + B	A + B	A + B
62311-2	A + B	A + B	A + B	A + B	A + B	A + B
1-1703930-1	A + B	A + B	A + B	A + B	A + B	A + B
62612-2	A* + B	A* + B	A* + B	A* + B	A* + B	A* + B

A: Calibrate and Learn (5 crimps) for CQMII followed by 50 Evaluation Crimps

B: Complete 5 headroom crimps (no wire in wire barrel)

*: Due to limited supply of terminals, only 35 evaluation crimps were completed

Table 4 Crimp Test Matrix

RESULTS AND DISCUSSION

Looking at the results of the crimp testing, several observations can be made. The crimp force data in Figure 9 shows a clear separation between the two un-contaminated treatments, As Reeled and Cleaned, and the contaminated treatments, Grease, Light Oil, Natural Oil, and Terminal Lubrication. To determine if the difference was of statistical significance, the data was loaded into Minitab and a One-way ANOVA was performed for each terminal. The One-way ANOVA analysis subjects the data to a hypothesis test. The null hypothesis is that the means of all the populations are equal.

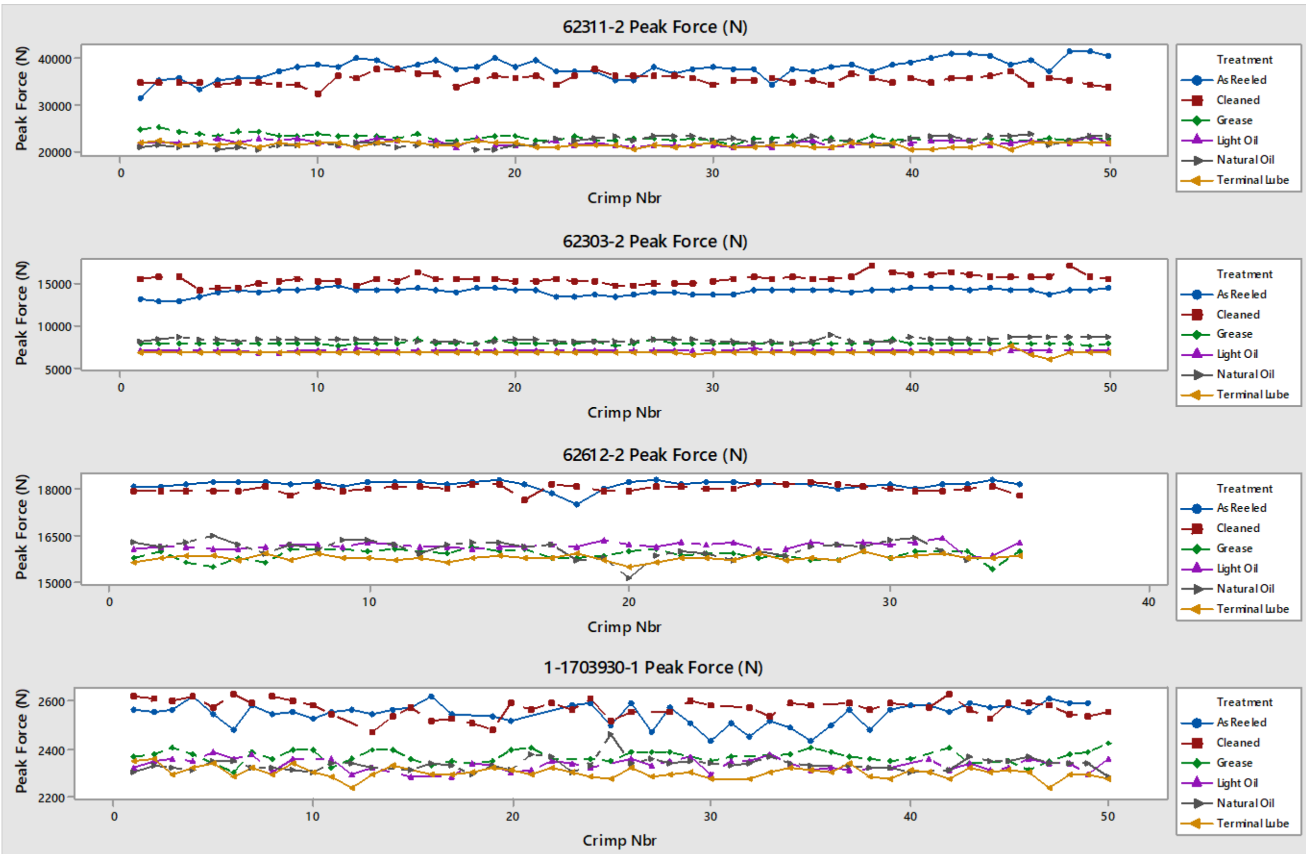

Fig. 9 Absolute Force Data for All Test Groups by Terminal

The alternative hypothesis is that the means are not equal. In this case, the analysis supports rejecting the null hypothesis. This was not surprising as the difference in means is quite extreme. Figure 10 is the Interval Plots by terminal for the mean peak crimp force. A Dunnett simultaneous comparison test was also performed on the data. The results of the One-way ANOVA simply suggested that the means were not all equal. Dunnett's comparison takes one step further and determines if the means of the levels differ from the control. In this case, the As Reeled treatment is the control, and the other treatments are the levels. Dunnett's test indicates that there is a statistically significant difference between the means of all the other treatments when compared to the control. It was noted that the Cleaned treatment was greater than As Reeled for the small terminals of each type but less than As Reeled for the large terminals.

By reviewing the plot of the Dunnett comparison in Figure 10, the means of the treatments (or levels) that have a contaminant applied are similar. Therefore, a Tukey comparison was completed to do a systematic pairwise comparison of each treatment with all the other treatments showing which levels have equal means. The results of the Tukey comparison showed that there were several levels that had statistically equivalent means in several of the test groups. A summary of the results is shown in Table 5.

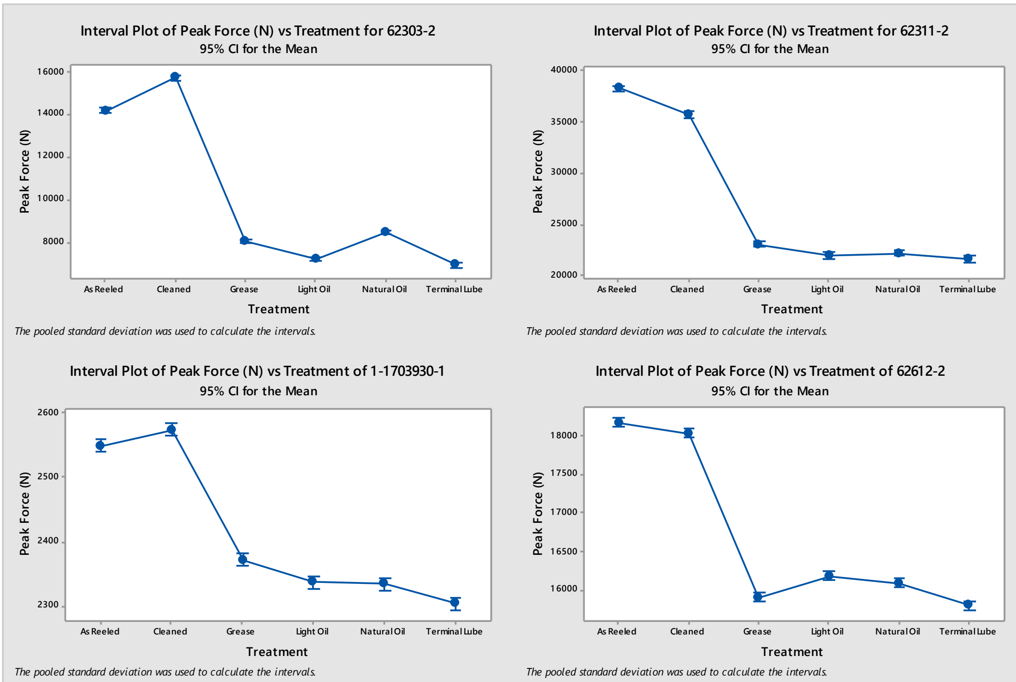

Figure 10 Interval Plots of Peak Force from One-Way ANOVA

Comparison Of Means	Splice		F-Crimp	
	62303-2	62311-2	1-1703930-1	62612-2
Cleaned - As Reeled	○	○	○	○
Grease - As Reeled	○	○	○	○
Light Oil - As Reeled	○	○	○	○
Natural Oil - As Reeled	○	○	○	○
Terminal Lube - As Reeled	○	○	○	○
Grease - Cleaned	○	○	○	○
Light Oil - Cleaned	○	○	○	○
Natural Oil - Cleaned	○	○	○	○
Terminal Lube - Cleaned	○	○	○	○
Light Oil - Grease	○	○	○	○
Natural Oil - Grease	○	○	○	○
Terminal Lube - Grease	○	○	○	●
Natural Oil - Light Oil	○	●	●	●
Terminal Lube - Light Oil	○	●	○	○
Terminal Lube - Natural Oil	○	●	○	○

● Means are equal
○ Means are not equal

Table 5 Tukey simultaneous pairwise summary of mean peak crimp force

There were no treatments that had equal meaning in all the test groups. Yet, three of the four groups showed equivalent means for Natural Oil and Light Oil. Although the Tukey test showed that many of the means of the contaminated samples are not statistically equal, but for practical purposes, they are close enough to be considered about the same. This can also be said about the comparison of As Reeled to Cleaned.

To this point, each terminal data set had been analyzed by itself. To summarize and compare the force data between terminals, the data had to be normalized. Each data set was normalized by dividing each individual value by the average peak force value for the As Reeled treatment of that terminal, effectively representing the data as a percentage of the As Reeled treatment. That made it easier to apply some additional tools in Minitab to determine what factors have the greatest effect on peak crimp force. The results are summarized in a main effects plot in Figure 11. By plotting the normalized force data using terminal size, terminal type, and treatment as the factors of interest, several indicators became apparent. The type of the terminal and treatment (particularly whether a contaminant was applied) have the greatest effects on the peak crimp force. The size of the terminal has very little effect at all. Additionally, it shows that the peak crimp force is slightly higher than the As Reeled treatment on average.

Figure 11 Dunnett Simultaneous Comparison Plots by Terminal

The preceding analysis of the peak force data is interesting and illustrative, but it is necessary to also understand it from a practical perspective. What impact would the contaminants have on a production process if encountered intermittently? To answer this question the relationship between crimp height and crimp force must be understood, as crimp height is the primary quality metric used to determine the acceptability of a crimp.

While conducting this testing, shims of know thickness were introduced between the ram and the load cell to vary the force. A known deflection was induced also through the addition of the shims and the corresponding force was recorded to measure the effective spring rate of the machines. This was done by simply calculating the slope of the linear least squares regression which was used to determine the maximum predicted change in crimp height based on the maximum difference in crimp force between the As Reeled and contaminated treatments. These results represent the practical effect on the process if a contaminant were to be encountered discontinuously as shown in Table 6. In the Splice terminals case, the crimp height would fall well out of tolerance. The F-Crimp terminals would be affected but it would not be as significant.

Terminal	Type	Machine Stiffness (N/mm)	Δ Crimp Force (N)	Predicted Δ Crimp Height (mm)	Crimp Height Tolerance
62303-2	Splice	51330	7301	0.142	± 0.05mm
62311-2			16639	0.324	± 0.08mm
1-1703930-1	F-Crimp	95239	242	0.003	± 0.02mm
62612-2			2363	0.025	± 0.05mm

Table 6 Predicted effect on crimp height based on machine stiffness.

CONCLUSIONS

During the development of a new crimping machine, an important discovery was made. It was found that simply touching the terminals with clean bare hands caused the crimp height and crimp force to drop out of tolerance. This unexpected result highlighted the need for further research into effects of trace contaminants on the crimping process. Further analysis to predict the corresponding change in crimp height showed a decrease of as much as 200% of the total tolerance for the Splice terminals while it was at most a 25% of the tolerance for the F-Crimp terminals. From a practical perspective, 25% may not be a cause for concern, but 200% alarming. When headroom and relative dispersion were examined, the F-Crimps were at or above industry standards and unaffected by the contaminants. The Splice crimps however, varied much more. Headroom decreased for all the contaminated test groups. In some cases, it went from well above the industry standard to below, having a negative influence on error detectability. Relative dispersion, on the other hand, improved with the contaminants though still did not meet the standard. The Splice terminals are clearly more sensitive, indicating that coefficient of friction is a factor, but there are other variables at play that are more influential on crimp force. A physical examination of the samples led to the belief that either the crimp tooling configuration or the unilateral extrusion of the Splice terminals could be the reason for the high sensitivity to contaminants. There is reason to believe that there are several other terminal types that may be sensitive to contaminants due to shared features. Additional testing is underway to determine what factors influence the high sensitivity of the splice terminals and relatively low sensitivity of the F-Crimp terminals. There are two separate factorial DOE’s being done with each terminal type and several different factors. The results of this testing could lead to an even better understanding of this phenomenon.

ACKNOWLEDGMENT

The authors would like to thank Vincent Pascucci – Test Engineer– SEM/EDX Spectroscopy and microscopy testing, Rodney Martens - Principal Materials Engineer – Tribometer testing, Marissa Feinman – Product Development Engineer - Crimp and tribometer testing, and Todd Troutman - Product Development Engineer – Crimp Force Calibration Testing from TE Connectivity Failure Analysis Laboratory at 2900 Paxton Street, Harrisburg Pennsylvania.

REFERENCES

[1] Shirgaokar, M., Choa, H., Ngaile, G., Atlan, T., Yu, J., Balconi, J., Rentfrowb, R., and Worrelll, W. J., 2004, "Optimization of Mechanical Crimping to Assemble Tubular Components," Journal of Materials Processing Technology, **146**, pp. 35-43. DOI: 10.1016/S092-0136(03)00842-2

[2] Galliana, F., Bellavia, L., Garia, S., G., Perta, A., and Roccato, P., 2023, "The Effect of Thermal Stresses on the Electrical Resistance of Crimped Connections," Journal of Metrology Society of India, **38**(1), pp. 71-82. DOI: 10.1007/s12647-022-0005741-1

[3] Li, P., Liu, G., Fan, J., Sun, J., Xiu, H., and Tian, C., 2021, " Mathematical model for the tensile strength of the crimping assembly of aviation wiring harness end," Scientific Reports, **11**, 17868. DOI: 10.1038/s41598-97498-8

[4] Rajak, A., and Kore, S., 2018, "Application of Electromagnetic Forming in Terminal Crimping Using Different Types of Field Shapers," Journal of Mechanical Science and Technology, **32**(9), pp. 4291-4297. DOI: 10.1007/s12206-018-0827-z

[5] Li, F., Jiang, J., Cheng, H., Xu, J., Ge, X., Li, H., Zhao, J., and Ran, Y., 2021, "Optimization of the Field Shaper Parameters in Electromagnetic Pulse Crimping of Cable," International Journal of Precision Engineering and Manufacturing, **22**(5), pp. 4291-4297. DOI: 10.1007/s12541-00577-z

[6] Yao, Y., Qamhiyah, A.Z., and Fang, X.D., 1999, "Finite Element Analysis of the Crimping Process of the Piston-slipper Component in Hydraulic Pumps," Journal of Mechanical Design, **122**(3), pp. 337-342. DOI: 10.1115/1.1286188

[7] Jongwuttanaruk, K., and Thavornwat, C., 2022, "Optimization of Mechanical Crimping in the Terminal Crimping Process Using a Response Surface Methodology," Advances in Materials Science and Engineering, DOI: 10.1155/2022/6508289.

[8] Aganbegovic, M., Schell, R., Reinhold, C., and Markgraf, V., 2023, "Influence of the Assembly Method of Medium Voltage Mechanical Connectors on the Quality of Electrical Connection," International Journal of Engineering and Technology, **15**(1), pp. 12-16, DOI:10.7763/IJET.2023.V15.1211

[9] Zhang, W., Liu, Y., Li, S., and Tang, J., 2022, "Analysis on the Crimping Quality of Overhead Transmission Line Conductors Considering Equivalent Cross-Sectional Stiffness," AIP Advances, **12**(1), DOI:10.1063/5.0098746

[10] Loete, F., Noël, S., Carrion, M., and Auzanneau, F., 2008, "Feasibility of the Detection of Vibration Induced Faults in Connectors by Reflectometry," 24th International Conference on Electrical Contacts, Saint Malo, France, DOI:10.13140/2.1.4765.7602

[11] Rhein, L., Zatz, J., and Motwani, M., 2007. *Sebum: Physical Chemical Properties, Macromolecular Structure, and Effects of Ingredients*, Informa Healthcare – Taylor and Francis Group. ISBN: 9780824729714

[12] Lee, Y., Korpela, S. A., and Horne, R. N., 1982, "Structure of Multi-Cellular Natural Convection in a Tall Vertical Annulus," *Proc. 7th International Heat Transfer Conference*, Hemisphere, Washington, DC, **2**, pp. 221-226.

[13] Ogihara, S., Takata, K., Hattori, Y., and Yoshida, K., 2006, "Mechanical Analysis of the Crimping Connection," IEEE Xplore Conference: Electrical Contacts, Busan, South Korea, DOI:10.1109/HOLM.2006.284070

[14] Wilzbacher, J., Lazuradi, L., and Marklin, W., 2004, "Measurement of Handle Forces for Crimping Connectors and Cutting Cable in the Electric Power Industry," International Journal of Industrial Ergonomics, **6**(34), pp. 497-506, DOI:10.1016/j.ergon.2004.06.007

[15] Luo, J., Wang, F., Xu, G., and Chuah, H., 2011, "Effects of Fiber Crimp Configurations on the Face of Knitted Fabrics Made with PTT/PET Bicomponent Fibers," Journal of Engineering Fibers and Fabrics, **6**(1), pp. 19-24.

[16] Yin, Z., Park, J., Choi, H., and Kim, Y., 2009, "Quality Improvement for Crimping Process of Electrical Connector Using FEM Analysis," Transactions of Materials Processing, **18**(3), pp. 229-235. DOI: 10.5228/KSPP.2009.18.3.229

[17] Rajak, A., and Kore, S., 2018, "Numerical Simulation and Experimental Study on Electromagnetic Crimping of Aluminum Terminal to Copper Wire Strands," Electric Power Systems Research, **163**(B), pp. 744-753, DOI:10.1016/j.epsr.2017.08.014

[18] Finc, M., Kek, T., and Grum, J., 2012, "Use of Thermography and Ultrasonic Inspection for Evaluation of Crimped Wire Connection Quality," 18th World Conference on Nondestructive Testing, Durban, South Africa.

[19] Ocoleanu, C., Dolan, A., Cividjian, S., and Teodorescu, S., 2014, "Temperature Investigations in Two Type of Crimped Connection Using Experimental Determinations," International Journal of Mechanical, Aerospace, Industrial, and Mechatronics Engineering, **8**(10), pp. 1633-1636, DOI:10.13140/2.1.4765.7602

[20] Rajak, A., Kumar, R., and Kore, S., 2019, "Designing of Field Shaper for the Electromagnetic Crimping Process," Journal of Material Science and Technology, **33**(11), pp. 5407-5413. DOI: 10.1007/s12206-019-1035-1

[21] Yin, Z.H., Park, J.G., Choi, H.S., and Kim, Y.S., 2009, "Quality Improvement for Crimping Process of Electrical Connector Using FEM Analysis," Transactions of Materials Processing, **18**(3), pp. 229-235. DOI: 10.5228/KSPP.2009.18.3.229

[22] Castro, T., Silva, F., and Campilho, R., 2017, "Optimizing a Specific Tool for Electrical Terminals Crimping Process," Procedia Manufacturing, **11**, pp. 1438-1447, DOI:10.1016/j.promfg.2017.07.274