Use of Thermography and Ultrasonic Inspection for Evaluation of Crimped Wire Connection Quality

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Abstract
Quality of crimped wire connections is usually evaluated from metallographic investigation of joint cross-sections and from wire pull-out forces. Quality depends upon shape of joint after deformation and upon distribution of strands in connection where strands have to be tightly compressed with no gaps between them. Previous trials of quality connection supervision were based on mentioned methods and various criteria using statistical procedures. Today’s technologies enable some other possibilities, methods and procedures for assessing crimped wire connection quality. Various non-destructive methods are used for measurement of coupling tightness which defines the quality of connection. This article gives experiences with the use of thermographic and ultrasonic method for evaluation of crimped wire connections quality. Investigations were made on the wire with 1.5 mm² cross section and the standard contact of a nominal rate 6.3 mm. Wire connection was crimped at crimp barrel and insulation grip at different crimp heights. Due to the low emissivity of contacts the measurement site was painted in black for thermographic analysis. Each crimped wire connection was heated by the electric current. On site observation of crimp barrel revealed temperature differences, which were compared with measurements from ultrasonic inspection, wire pull-out forces and measurements of contact voltage drop between conductor and contact at different crimp heights.

Keywords: Thermography, ultrasonic inspection, crimped wire connections, contact voltage drop

1. Introduction

This contribution presents the methods of crimping contacts to conductors and the processes of crimped contact connection examinations by evaluating the connection quality. Along with the classic quality measuring method, the measuring and quality evaluation of crimped contacts connection by means of a non-destructive method using an IR camera and ultrasonic instrument. Thermographic imaging analysis results and ultrasonic responses were verified using the crimp force analysis on an automated crimping machine, or by means of a macroscopic analysis of the crimp, measuring the conductor and contact pull-out forces, measuring the voltage drops with different crimp heights, and the determination of the optimum crimp heights.

2. Crimp conductor contact research

Crimping or joining connections is the technology of mechanically joining conductors by transforming the connection contact into an inseparable and electrically conductive connection. The electrically conductive connection is formed by crimping the contact crimp at the stripped part of the conductor. In this way, an electrical as well as a mechanical connection is made.

A conductor and contacts were selected for crimping. A conductor with a cross section of 1.5 mm² contains 28 conductive strands. The contacts are made of brass and are tin plated (CuZn/Sn). The size of the attachment part of the contact measures 6.3 mm.
Crimping was performed using a Komax automated crimping machine with an integrated gauge and crimping force analyzer. For the research, 500 crimp connections were prepared for the defined crimp heights of 1.6 mm, 1.7 mm, 1.8 mm, 1.9 mm, and 2.0 mm; 50 conductors were crimped at each crimp height.

Figure 1. Conductor connection crimp

Figure 1 shows a conductor connection crimp, crimped at the location of the crimp and the insulation grip. The conductor connection provides acceptable conductivity and simultaneously strengthens the mating tab and the conductor, preventing it from retracting during use.

2.1 Crimp contact quality research using an IR camera

For the purpose of the thermographic analysis, 35 crimp connections were prepared – 7 crimps for each crimp height; 1.6 mm, 1.7 mm, 1.8 mm, 1.9 mm, and 2.0 mm. The current calibrator enables controlled loading of the crimp. For this test, a current of 10 A, which is less than the prescribed maximum load current for the used conductor connection, was selected.

In Figure 2, a measuring system diagram for IR measurements is shown. To generate the current, an Iskra M 1155/3 current calibrator was utilized. This calibrator is a precise and stable source of direct currents for up to 100 A. The thermal images were produced using a FLIR B335 thermographic camera. The thermographic camera used has FOV 25° × 19° / 0.4 m and an IR resolution of 320 × 240 pixels.

The crimp, insulation grip, and the insulation of the samples were coated with a dull black paint. The dull black coating enhanced the emissivity. By doing so, the emissiveness of the connecting contact and the crimp and insulation grip approached 1. The emissivity of black coating was not determined experimentally. For this reason after review of literature we took the emissivity of black coating in value of ε =0,97 [10]. Emissivity is a function of viewing angle, of the temperature and of the wavelength. In the case of metals for instance, emissivity increases with temperature and is inversely proportional to the electrical conductivity [9].
In Figure 3, the locations are shown of the temperature difference measurements for the determination of temperature differences at the crimp and conductor insulation by the detection of thermal radiation.

The contact connections were loaded with a current of 10 A. A thermographic camera was used to measure the thermal radiation in a period of two minutes. The time of thermal radiation was determined based on preliminary testing. The thermal images produced indicate a distribution of temperature at the detection location of the crimp conductor contact sample.

\[
T_{cb} = 28.2^\circ C
\]

Figure 4 shows a thermal image of a conductor contact with a crimp height of 2.0 mm without a current load with an average crimp temperature \(T_{cb} = 28.2^\circ C\). \(T_{cb}\) was designated using temperature measurements which define the thermal field included in the matrix. We decided to perform the thermographic analysis based on the average temperature inside the selected temperature field.

\[
T_{cb} = 34.6^\circ C
\]

Figure 5. Thermal image of a contact conductor connection with a crimp height of 2.0 mm at the load current of 10 A after 2 minutes
Figure 5 illustrates a thermal image of a conductor contact with a crimp height of 2.0 mm after a two minute current load of 10 A. The calculated average crimp temperature $T_{cb} = 34.6 ^\circ C$.

We observed that both areas ought to be measured in order to define the thermal field. For our research and measurements, the selected locations of the temperature difference measurements for the determination of temperature differences at the crimp and conductor insulation by the detection of thermal radiation are shown.

![IR camera measurements](image)

Figure 6. Temperature difference measurements of all crimped conductor connections using a thermographic camera

Figure 6 shows the distribution of temperature difference measurements of all crimped conductor connections using a thermographic camera. The minimum average temperature difference was measured in samples with a crimp height of 1.8 mm at the location of the crimp. Similarly, the standard temperature difference deviation of measurement locations was the smallest in these 1.8 mm crimps.

![IR camera measurements](image)

Figure 7. Average temperature differences and the standard thermographic camera measurement deviation
Figure 7 shows the average temperature differences measured using a thermographic camera and the standard crimp deviation. The lower and upper temperature deviation limit was attained in samples with a crimp height of 1.8 mm, namely at the location of the crimp. Similarly, the temperature deviation was the least in these 1.8 mm crimps.

2.2 Crimp contact quality research using an ultrasonic inspection

For ultrasonic inspection we used crimp connections at crimp height 1.6 mm, 1.7 mm, 1.8 mm, 1.9 mm, and 2.0 mm. For measurements specific ultrasound probes were designed.

![Figure 8. Measuring system diagram for ultrasonic inspections](image)

In Figure 8, a measuring system diagram for ultrasonic inspections of crimp connections is shown. The measuring system consists of an ultrasonic instrument with a transmission method arrangement and two damped transducers. Send transducer is a 4 MHz PZT ultrasonic longitudinal wave transducer, as a receiver a 5 MHz PZT ultrasonic longitudinal wave transducer was used. In the early phase of the research ultrasonic analysis of crimp barrels is made separated from crimp tool. Crimped crimp barrels of different crimp heights were inserted between the ultrasonic probes and a constant pressure load on ultrasonic transducers was ensured.
Figure 9 shows a concept of a bad crimp and a good crimp. Figure 9a shows single signal paths through a crimp and Figure 9b shows multiple signal paths through a crimp. Expected are higher amplitudes of received ultrasonic signal at lower crimp heights.

Figure 10 shows the amplitude versus time diagram for A scan of different quality crimps. Figure 10c represents amplitude versus time for good quality crimp (Fig. 13c), were adequate compression of the crimp tool is achieved. In the amplitude diagram zero time reference on the diagram corresponds to the initiation of send pulse. Figure 10a shows the amplitude diagram for 1,6 mm crimp and Figure 10e for 2,0 mm crimp. Both can be designated as bad quality crimps. 1,6 mm crimp (Fig. 13e) represents excessively crimped connection that results also in higher
temperature difference after current load of 10 A. 2.0 mm crimp represents loosen crimped connection that results in higher voltage drop but pull-out force is still adequate.

Figure 10 shows that amplitude of the ultrasonic response and time delay of response signal offers good information about crimp quality. Delay of the response signal is correlated to crimp height. Amplitude of the response signal is influenced by a compression force between probes. Longitudinal waves in the crimp can be transmitted through a crimp via different number of signal paths. This influences the amplitude of response signal. Different number of signal paths exert influences upon response signal duration and amplitude distribution. Preliminary results show that ultrasonic measurement technique offers prediction of crimp quality.

2.3 Existing crimp quality assurance testing methods

2.3.1 Statistical management of the automated crimping process

At CABLEX-T d.o.o., crimping machines with an in-built crimp force analyzer (CFA) with two integrated piezoelectric sensors are used for automatically joining the contacts with the conductors. Upon the asymmetric placement of the crimping tools piezoelectric sensors are used to eliminate force movements. The concept of the analysis of three curve areas ensures reliable good/bad classification and the acquisition of detailed error information. The reference curve is generated based on the successful production of individual crimps. The crimping force is analyzed with a crimp force analyzer integrated in the crimping machine. The CFA compares the current crimps created during production with a reference crimp (master crimp). This master crimp is checked manually, usually by remeasuring the crimp height and the pull-out force. To evaluate a crimp, the force generated during crimping is recorded. The reference curve is created on the basis of several good crimps. The force generated during crimping is measured and recorded as a function of the angle of rotation of the crimp terminator. Two force integrated sensors are measuring the crimp force. They are connected in parallel to eliminate the possibility of force shunts. Based on the parameter of statistic formulas a \( C_p \) process capacity index and \( C_{pk} \) process centralization exceeded 1.33 at all crimp heights. The crimps meet the criteria of CABLEX-T d.o.o., whereby \( C_p \geq 1.33 \) and \( C_{pk} = C_k \).

Table 1 shows the dependency of \( C_p \) and \( C_{pk} \) from the crimp height defined on a automated crimping machine for a series of fifty samples for each crimp height.

<table>
<thead>
<tr>
<th>Crimp height [mm]</th>
<th>Index 2.0</th>
<th>1.9</th>
<th>1.8</th>
<th>1.7</th>
<th>1.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_p )</td>
<td>1.5</td>
<td>3.5</td>
<td>3.3</td>
<td>5.0</td>
<td>6.3</td>
</tr>
<tr>
<td>( C_{pk} )</td>
<td>1.5</td>
<td>3.4</td>
<td>3.3</td>
<td>5.0</td>
<td>6.2</td>
</tr>
</tbody>
</table>

\( C_p \) process capacity index – long-term capacity index and \( C_{pk} \) process centralization exceeded 1.33 at all crimp heights. The crimps meet the criteria of CABLEX-T d.o.o., whereby \( C_p \geq 1.33 \) and \( C_{pk} = C_k \).

2.2.2 Macroscopic analysis of the crimp

The quality of the crimps is assessed according to the internal rules of CABLEX-T d.o.o., rules of the crimp customers, rules of the contact manufacturers, connections and conductors and other standards, such as DIN, ISO, VDE, VDA, IEC, BS and UL standards.
Macroscopic analysis of the crimp at the location of the crimp and the insulation grip is of great importance for the assessment of the quality of the crimp. The proper crimping of the crimp at the crimp location is also very important. The crimp was first crimped on a mechanical press with five different crimp heights. A crimping tool with crimping inserts for the selected contact was selected by Schafer.

![Diagram of crimp cross-sections](image)

**Figure 11.** Crimp cross-section at the crimp location

**Figure 12.** Crimp cross-section at the insulation grip location

Figure 11 shows the cross-section of a crimp at the location of the crimp, while Figure 12 shows the cross section of a crimp at the location of the insulation grip.

![Crimp cross-sections](image)

**Figure 13.** Crimp cross-sections of various crimp heights

Figure 13 shows crimp cross sections of different crimp heights (Ch). Crimps were produced at five different crimp heights. It is very important to cut the crimp between individual crimp blades. Figures 13a and 13b illustrate air between the strands, which decreases the crimp quality. Figure 13c shows the optimum quality of the crimp with deformed strands that fit perfectly on top of each other and to the wall of the contact. Figure 13d displays an excessively crimped connection, while the burr height has also been increased. In Figure 13e, a connection has been excessively crimped, hence the increase of the burr height at the lower contact part.

At the insulation grip, it is very important that the insulation ends clamp down on the conductor insulation and hold it tightly. The insulation ends must also not penetrate the conductor insulation or make contact with the conductive strands.

### 2.2.3 Pull-out forces and voltage drops

As a means of quality measurement, CABLEX-T, d.o.o., employs the measuring of voltage drops. On the other hand, measuring of pull-out forces is employed to test the mechanical connection of the conductor and contact.

Voltage drops are measured using an Iskra M 1155/3 current generator. The process is prescribed under DIN 46249 [3] and IEC 60352-2:2006 standards [7]. Similarly, 20 samples of five
different crimp heights were selected for the measuring of voltage drops between the contact and conductor. The maximum voltage drop according to the DIN 46249 standard between the selected conductor and contact measures 6 mV. Pull-out forces were measured using a MAV force gauge. The DIN 46249 and IEC 60352-2:2006 standards describe the process. Before measuring, the insulation grip was disengaged in order not to influence the measurements. 20 samples of five different crimp heights were selected for pull-out force measurements.

2.2.4 Determination of crimp heights

Crimp cross sections at the crimp location and pull-out force measurements represent the main criteria for the determination of the crimp heights.

Figure 14. Interconnection of pull-out force, voltage drop, and temperature difference of different crimp heights of contact conductor connections

Figure 14 illustrates the dependency of pull-out forces ($F_p$), voltage drops ($\Delta U_d$), and temperature differences ($\Delta T_{cb}$) with different crimp heights of contact conductor connections. According to the DIN 46249 standard, the maximum voltage drop can measure 6 mV, and the minimum pull-out force 200 N. Cross section macroscopic images have shown that the crimp height of 1.8 mm is the most suitable. Voltage drop measurements have shown that the voltage drops are equal or less than 6 mV at crimp heights of 1.8 mm, 1.7 mm, and 1.6 mm. Pull-out force measurements have illustrated that the optimum force is achieved at a crimp height of 1.8 mm, and that all pull-out forces are greater than 200 N. Cross-sectional macroscopic images and pull-out force measurements have shown that a crimp height of 1.8 mm is the most suitable. With a crimp height of 1.8 mm, the temperature difference at the crimp and conductor insulation was the least. The indicated results acquired by using thermal imaging indicate good possibilities for the use of a thermographic camera for the determination of optimum crimp heights. From ultrasonic amplitude response we can see that the amplitude height of the first received signal is irreversible with the value of voltage drops at different crimp heights. We could define the quality of the crimped crimp barrel from the height of the first received amplitude signal and with analysis of ultrasonic signal with transformation.
3. Conclusions

A crimp is performed most effectively when the requirements of tight crimping are met, attested by thermal images, when the pull-out force is equal or greater than the required value under DIN 46249 and IEC 60352-2:2006 standards, and when the voltage drop is equal or less than stipulated by the DIN 46249 and IEC 60352-2:2006 standards or by the conductor manufacturer. Considering the requirements of the above-mentioned standards, the optimum crimp height for the selected contact conductor connection measures 1.8 mm.

The results of thermal imaging have also proven useful. Images have shown that the crimp height of 1.8 mm produces the least temperature differences. We plan to conduct further thermographic and ultrasonic experiments using an even greater array of conductors and contacts. The results indicate good possibilities for the use of thermal radiation for producing thermal images in order to establish the optimum crimp heights, which could replace the destructive voltage drop method. Also ultrasonic inspections are promising. With further ultrasonic inspections we could define different crimp connection quality.

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References