Dependency of the electrical resistance in crimped connections on mechanical stresses

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Abstract

Cables headed with crimped lugs are often used in test laboratories for rise temperature tests to validate electrical devices. Undesired power dissipation due to the electrical resistance of the crimped connection can increase during the tests, invalidating their outocome. The aim of the work made at the High Voltage and High Power Laboratory (LATFC) of the National Institute of Metrological Research (INRIM) has been the investigation of the dependence of the crimp resistance when cables are submitted to mechanical stresses comparing it whit the behaviour of the resistance of a welded connection in analogous conditions. Lugs with different crimp profiles and of different manufacturers, submitting their connected cable to rotations and twists, have been analyzed. The crimp resistance has been measured with a volt-ampere metric method supplying with constant current the crimped connection and reading the voltage drop on it. The obtained values of the crimp resistance, although less than 15 μΩ, typical of a good crimp connection, has been sensitive in the first stresses, stabilizing after. The resistance of lugs crimped with single indent has been less sensitive than that of lugs with hexagonal profile, but more than that of lugs with double indent. The resistance of welded lugs has been the most insensitive on stresses. The choice to weld all the lugs should be the most reliable but, on the other hand, the most expensive and time consuming for a test laboratory.

Keywords: crimp technique, mechanical stress, crimp resistance, lug, temperature rise test, test laboratory, measurement uncertainty.

1. Introduction

Electrical devices used in electricity transmission and distribution systems operating with currents of several hundred amperes, have to comply with rise-temperature limits in working conditions at nominal current to be validated according to their relevant standards [1, 2]. To verify if such devices respect those limits, rise-temperature tests are executed. Electrical devices must not overheat during usual operating conditions because this leads to a premature aging of the insulating materials and to an increase of the resistivity and surface oxidation of internal conductors These effects can cause component failure and fault events. Cables headed with crimped lugs are often used for rise-temperature tests. A lug (Fig. 1) is a metal terminal consisting in an attack flap and a collar. It is used for connections in industrial, automotive and test laboratories plants. Depending on its use, a lug can vary in size, shape and material. It is obtained from an electrolytic copper tube, annealed and superficially protected by an electrolytic tinning. The electrolytic copper and the annealing give to the lug a suitable resistance to traction and to oxidation and a better malleability optimizing its successive crimping. The collar of the lug is beveled and often equipped with an inspection hole to introduce correctly the cable.

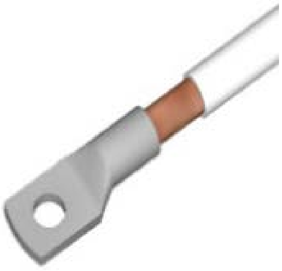

Fig. 1. Lug crimped to a cable.

Crimped lugs may therefore be an important element in a temperature rise test. If they are damaged or incorrectly crimped, can cause a temperature rise due to their power dissipation affecting or even invalidating a test result. Our focus, representing the originality of the work, is the analysis of the behaviour of the electrical resistance of crimped connections cable to lug (crimp resistance) simulating the use of the cables in test laboratories. This use is different from that in plant installations where the cables, once installed, are left in the same position for several years. Normally used cables are:

- insulated, with the external sheat in PVC, as suggested by the relevant standards [1, 2];
- not "full" cables, but corded ones, i.e. made up of strands.

In [3] an investigation of the crimp resistance was made on lugs crimped to cables of two different sections available at the INRIM High Voltage and High Power Laboratory (LATFC) of the National Institute of Metrological Research (INRIM). This paper is instead focused on the dependence of the resistance of the connection cable to lug (crimped or welded) when the cable itself undergoes mechanical stresses. The analysis has been made on lugs available at the LATFC with different profiles and made by different manufacturers.

2. The crimp technique

The crimp (connection through compression by means of a crimping tool) is an economic and common technique to make mechanical and electrical connections. It establishes a contact between two conductors applying a force to deform the metals. This force makes a contact area metal to metal locking the conductors together due to plastic deformation. The crimp allows also the cleaning from contaminants and oxides from the conductors' surfaces for the applied high pressure in the crimping act, to the metal flow, and to the deformation of the conductors. Although some papers exploited the crimp features [4–10] developing also models for early identification of connection defects [11], the state of the art and the operating principle of this technique are not yet definitely understood and therefore it is not yet totally reliable especially in automotive and avionic applications. In fact, the effectiveness of a crimped connection and the crimp resistance depend on some factors: material, cables size, crimp method, crimp profile, number of crimp indents, crimp pressure and crimp matrix. Crimping a lug to a cable is an irreversible operation, as it permanently deforms both the lug and the cable. After crimping it is impossible to remove a cable from a lug without damaging both. When the length and the depth of the crimp increase the crimp resistance decreases. Depending on the crimping matrix, different profiles can be obtained varying in length, depth, number and shape of the indents (examples in Fig. 2).

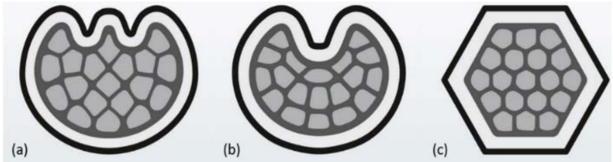

Fig.2. Section view of some crimp profiles: crimping with double indent (a) with single indent (b) with hexagonal indent (c).

Resistances of crimped connections made with the same pressure but with different profiles are therefore different. Mechanical stresses increase the crimp resistance leading to overheating points. High temperatures, atmospheric and galvanic oxidation of the lug, vibrations and lug dimensions also cause the increase of the same resistance.

3. Measurement of the crimp resistance

The resistance of a crimped connection, is made up of the equivalent resistances:

- of the conductor inside the crimped lug;
- of the lug itself in the crimped zone;
- of the contact between the cable and the attack flap of the lug.

This contact resistance is given by the sum of a constraint and film resistances. When two surfaces are coupled, the contact takes place through a large number of micro areas (spots) and the real contact surface is smaller than the apparent contact area [12]. The film resistance is due to the generation of surface films as oxides or sulphides on the materials. In this work, tin-annealed lugs have been used. Their surface film is made with tin oxide protecting the copper from corrosion. Although these films have high resistivity reducing the current flow, if thin enough (<10 nm) they conduct current by tunnel effect. Nevertheless, if the contact force in the crimp area decreases for mechanical and/or thermal stresses, the crimp resistance increases dissipating power up to values that could damage the lug so that it can no longer be used for temperature rise tests. The decrease of the contact force in the crimp area could also lead to an oxidation of the bare cable area between the lug and the beginning of the cable. In our measurements, the crimp resistance has been evaluated as the ratio of:

- the voltage ΔV between the end of the pressed collar (near the inspection hole) of the lug and the beginning of the cable (top right in Fig. 3)

and

- the current I supplied by a current generator.

3.1 Measurement setup and procedure

The voltage ΔV has been measured with a digital multimeter (DMM) through an INRIM-built Voltmetric clamp meter, while the supplied current I has been measured with a current clamp meter. The Voltmetric clamp was built to allow a stable equipotential point on the cable to carry out the measurements. The measurement setup is shown in Fig.3. The cable headed with crimped lug under test has been connected to the current generator by means of two copper bars to avoid undesired heating of the lugs, disturbing the measurements. Thermocouples, placed on the collar of the lugs have been used to verify the achievement of the thermal equilibrium by the lugs and their possible overheating. A further thermocouple has been used to measure the ambient temperature. The two cable ends marked as side + (red arrow) and side – (blue arrow), are shown in top left of Fig. 3. The measurement steps have been:

- Connection of the cable with crimped lug to the copper bars with a torque lock of (30 ± 5) Nm;
- supplying with a constant current *I* for pre-heating;
- Waiting for thermal stability by means of the thermocouples on the lugs;
- Measurement of *I*;
- Measurement of ΔV.

3.2 Measurement uncertainty

The main uncertainty components in the measurement of the resistance of a crimped connection are:

- Accuracy of the DMM and of the current clamp meter;
- Voltage noise;
- Measurement reproducibility due to the Voltmetric clamp;
- Measurement reproducibility due to the tip.

The importance of the last two components and the method to evaluate them were reported in [3] with also an uncertainty budget of a typical resistance measurement of a crimped connection in the LATFC.

Fig.3. Measurement setup with zoom of the connection between the cable lugs and the bars and of the place where voltage measurements have been made.

4. Behavior of the crimp resistance under mechanical stresses

Cables used in rise temperature tests undergo mechanical stresses during their operating life. For example, they can be twisted around their symmetry axis when they are bolted on the bars placed at the output of the current generator. They can be also rotated on the lug plane when they are connected in an electrical panel as input/output cables from the switchboard. These stresses weaken the lug crimp increasing the crimp resistance. To analyze the dependence of this resistance on stresses, lugs with different crimp profiles, obtained with different hydraulic heads have been involved. All the lugs have been replaced after each test. Table 1 reports the profiles of the lugs used for the tests. Only one cable has been used to avoid influences due to other cables. The lugs have been crimped with a pressure of about 70 MPa. As the tests have been performed with lugs made by different manufacturers, they are treated in the paper as lugs A, B and C. The test cable has been subjected to two different types of stress: - Twist locking one end of the cable twisting it around its symmetry axis of 180°, clockwise and counterclockwise, returning to its starting point (Fig. 4);

- Rotation around and on the lug plane with a sequence of four rotations around the lug plane: 45° upwards, 45° downwards, 45° to the right and 45° to the left (Fig. 5).

Table 1. Crimp profiles printed on the lugs used for the mechanical stress tests.

Profile no.	Profile type	Image
1	Single square indent	
2	Double indent	
3	Hexagonal indent	

Fig.4. 180° cable twist.

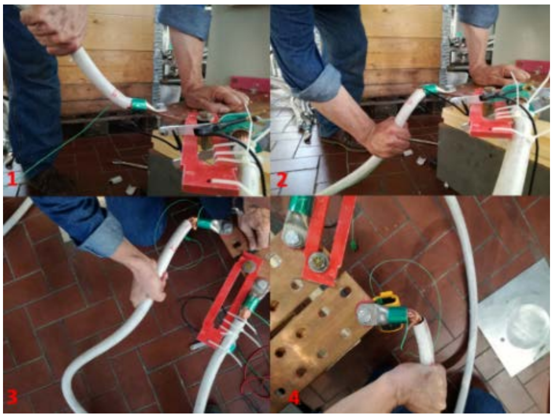

Fig.5. Sequence of the four cable rotations around the lug plane. 1) 45° up, 2) 45° down, 3) 45° to right and 4) 45° to left.

5. Measurement results and discussion

All the measurements have been made within three days. The involved measurement instrumentation has been calibrated and metrologically confirmed, with no drift evidence.

5.1 Behaviour of the crimp resistance when the cable undergoes twists

Table 2 reports the measurements made, specifying the lug type, the crimp profile and the side of the cable to which the tested lug has been connected. Five cases have been examined.

Table 2. Cases in which the crimp resistance has been measured along with the test currents.

Case	Lug	Crimp profile	Cable side with the tested lug	Current
I	A	1	+	315
II	A	2	+	400
III	B	2	+	400
IV	C	3	+	400
V	A	Tin welded, crimped and annealed	+	400

In the case I (Fig.6), the crimp resistance (R_{crimp}) has changed in particular in the first ten twists where an increase of about 40% with respect to the initial value (before the twists) can be observed. After the 10th twist, R_{crimp} has stabilized. In fact, between the 10th and the 50th twist only a residual 8% change has been detected. Also in the case II and III (Fig.7 and 8) R_{crimp} has showed a higher change in the first ten twists, than in the successive ones.

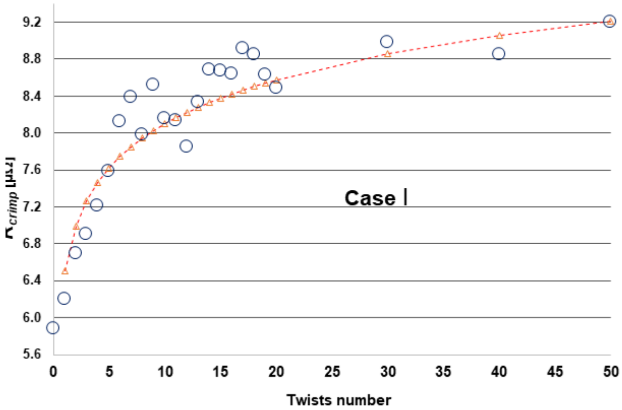

Fig.6. Behaviour of R_{crimp} in the case I.

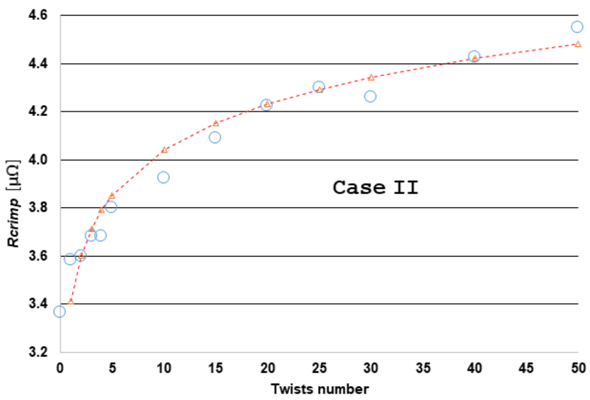

Fig.7. Behaviour of R_{crimp} in the case II.

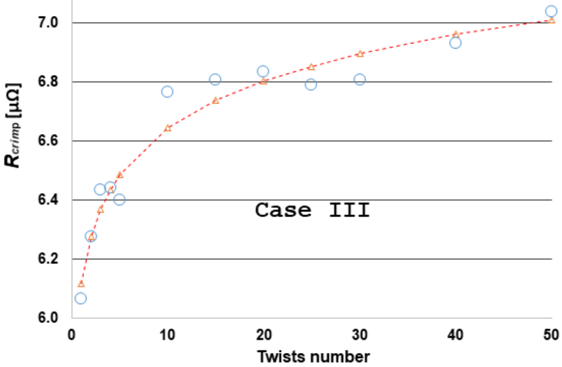

Fig.8. Behaviour of R_{crimp} in the case III.

In both tests, R_{crimp} has increased of about 20% from the first to the tenth twist. This is presumably due to the same crimp profile. Instead, the difference of the initial values of R_{crimp} (3.4 μΩ vs 5.9 μΩ respectively for the cases II and III) could be due to the different lug type and to the slightly different position of the indents on the lug. Therefore, the initial value cannot be univocally defined because it depends on many factors if the crimp is manually done. The R_{crimp} change in the cases II and III is lower than in the case I due presumably to the different crimp profile. Fig. 9 shows the behaviour of R_{crimp} in the case IV.

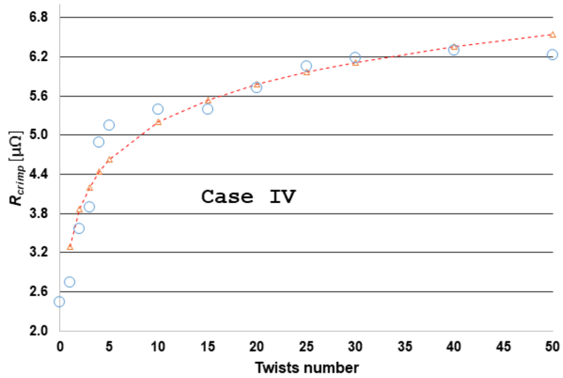

Fig.9. Behaviour of R_{crimp} in the case IV.

Case IV confirms that the greatest change occurs around the tenth twist being R_{crimp} double with respect to the initial value. This resistive behaviour is therefore different from the others showing the highest change In all cases, the R_{crimp} behaviour can be fitted with a logarithmic behaviour (dashed line in red). Fig. 10 summarizes the R_{crimp} behaviour with respect to the initial value in the four cases. As the case IV has showed the highest change, in the hexagonal profile, the contact between the lug and the cable is more sensitive to the twists. This result confirms the analogous result reported in [6]. In our measurements, R_{crimp} of the lug with profile 3 (case IV) has reached 6.2 μΩ starting from 2.44 μΩ.

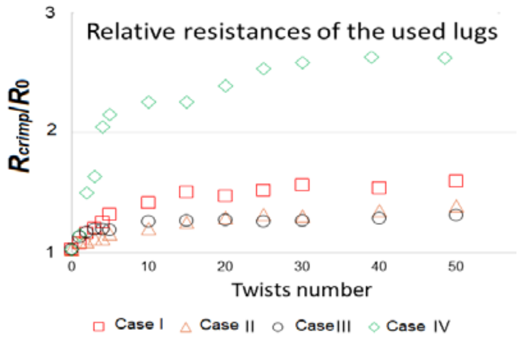

Fig.10 R_{crimp} behaviour in the four cases with respect to their initial value R_0.

If the initial value was 6 μΩ, as in case I and III, R_{crimp} with a profile 3 (hexagonal), could reach about 16 μΩ increasing three times the dissipated power at the same current. The resistive behaviour of the lugs crimped with profile 2 (double indent, cases II and III) is similar and definitely better than that in the cases IV and I. Crimped lug with profile 1 (single square indent, case I) has showed instead an overall change of about 50%, but whit $R_{crimp} \cong 9.2$ μΩ, the highest among those measured. In all tests, a significant variation of R_{crimp} at the tenth twist is observed. In a test laboratory since, during a year the test cables can undergo about five twists, after two years the measurement of R_{crimp} on each cable lug is suggested to evaluate its replacement. . The increase of R_{crimp} may be due to a relaxing of the crimped area on the lug and to the detachment of some strands from the cable when it undergoes twists. These effects increase the contact resistance between the lug and the cable, thus increasing R_{crimp}. To exploit the dependence of the cable to lug resistance with another type of connection, the resistance of a type A lug tin welded to a cable undergoing twenty twists (Fig.11), has also been measured. The resistance change has been very low (mean value ≅ 2.8 μΩ).

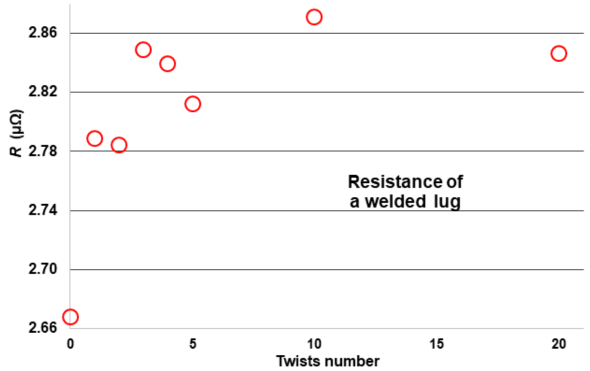

Fig.11. Resistance behaviour of a lug, tin welded to a cable undergoing twists.

Successively, the same lug has been crimped and R_{crimp} has been measured again. The results are shown Fig. 12.

Fig.12. R_{crimp} behaviour of a lug, previously welded and after crimped to a cable undergoing twists.

Comparing Figs. 11 and 12, a slight increase of the connection resistance (from 2.8 μΩ to 3.05 μΩ) can be observed. This increase may be due to a fracture of the weld in the area where the lug has been crimped. Despite this, in the successive twists there has been no increase of R_{crimp}. Afterwards, an annealing of the lug has been made to melt the fractured tin. After the annealing, R_{crimp} recovered the value when the lug was only welded (Fig. 13).

Fig.13. R_{crimp} behaviour of a lug, previously welded, crimped to a cable undergoing twists and annealed.

5.2 Behaviour of the resistance when the cable undergoes rotations

When the cable has been subjected to rotations around and on the plane of the lug, R_{crimp} has been evaluated measuring the supply current and the voltage drop between the inspection hole of the lug on the + side and the beginning of the cable on the side – as a swelling of the bare cable area on the + side has occurred (Fig. 14). When such undesired cable swelling occurs during the normal activity of a test laboratory, the replacement of the cable lug is necessary. For this reason, only one kind of rotations has been made. To the cable has been crimped a type A lug with profile 1. The measurement has been carried out at a current of 315 A. To obtain the value of R_{crimp}, the resistance of the cable has been subtracted from the obtained value (Fig. 15).

Fig.14. Swelling of the bare cable area.

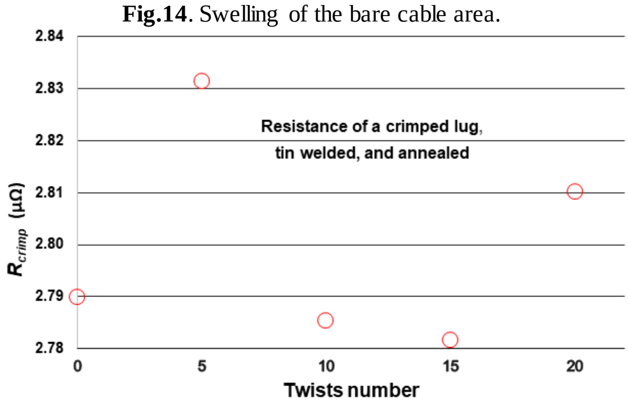

Fig.15. R_{crimp} behaviour of a lug crimped to a cable undergoing rotations on and around the lug plane.

After an anomalous change in the first five rotations, R_{crimp} stabilizes around 9 μΩ.

5.3 Examples of uncertainty evaluation

In Table 4 and the uncertainty budget of the measurement of R_{crimp} of a left crimped lug belonging to case III after the first 180° clock-wise twist, is reported. The measurement has been made with a current of 404 A in ambient temperature of 25.9 °C. The voltage read by the DMM has been 2.45 mV, while R_{crimp} has been about 6.064 μΩ.

Table 4. Uncertainty budget of the measurement of R_{crimp} of a left side crimped lug after the first twist.

Uncertainty component	Type	(%)	ν
Reproducibility due to Voltm. clamp	A	5.0	29
Reproducibility due to tip.	A	0.3	29
DMM accuracy	B	0.1	∞
Voltage noise	A	0.05	29
Current clamp accuracy	B	0.9	∞
R_{crimp} standard uncertainty		**5.1**	92
R_{crimp} expanded uncertainty (2σ)		**10.3**	

In Table 5 and the uncertainty budget of the measurement of R_{crimp} a new left crimped lug after the 2nd rotation, is reported. The measurement has been made with a current of 311.9 A in ambient temperature of 26.7 °C. The voltage read by the DMM has been 44.81 mV. The measured resistance (of the cable and of the lug) has been about 139.91 μΩ while the R_{crimp} has been about 8.876 μΩ.

Table 5. Uncertainty budget of the measurement of R_{crimp} of a left side crimped lug after the second rotation.

Uncertainty component	Type	(%)	ν
Reproducibility due to tips.[1]	A	0.03	29
DMM accuracy	B	0.01	∞
Voltage noise	A	0.1	29
Current clamp accuracy	B	1.0 [PR1]	∞
Cable resistance	B	1.5	50
R_{crimp} standard uncertainty		**1.9**	> 50
R_{crimp} expanded uncertainty (2σ)		**3.8**	

For all the measured crimped lugs, R_{crimp} has been less than 15 μΩ, although the cable has been submitted to mechanical stresses. This is a satisfactory result as 15 μΩ is a typical value of a good crimp resistance according to [13]. In this reference it is also stated that, to obtain such R_{crimp} value, a crimp pressure of 8000 psi (≅ 55 MPa) should be necessary. In our laboratory tests, a higher crimping pressure (70 MPa) than that indicated in [13], has been used. Our result confirms that higher crimp pressure allows to obtain a better conductivity even under mechanical stresses.

Conclusion

The obtained values of the crimp resistance, even when the cable to which the lugs have been crimped has been submitted to mechanical stresses, have been less than 15 μΩ, typical value of a good crimped connection. Nevertheless, for the specificity of our application, the most reliable cable to lug connection still remains the welded one, both in terms of resistive value and insensitivity to mechanical stresses. Hence, to avoid undesired power dissipation during rise-temperature tests, the best solution should be welding the lugs despite it is more expensive and time consuming than crimped connection. Future aim of this work will be the investigation of the behaviour of crimped connections under thermal stresses.

Acknowledgements

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[1] As part of the cable was swollen, this did not allow placing correctly the Voltmetric clamp. Therefore, the measurement has been carried out with two tips, one on each cable lug at the ends of the cable, thus including in the measurement the cable resistance and of the other lug.