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Compaction and welding of copper-stranded wires by resistance heating

Brykietowanie końców lin miedzianych z wykorzystaniem nagrzewania oporowego

Abstract

Resistance welding is widely recognised as a safe and economical welding method, benefits that also apply to compaction and welding of copper-stranded wires. Few published studies have documented this, but there has so far not been any scientifically established methodology in this regard.

The works presented here cover compaction and welding of copper-stranded wires. The application-oriented studies present the bonding mechanism and examination of strands towards defining a general parameter window, giving users a very simple tool for parameterisation.

We first examined the bonds using three-point bending tests first, and discovered a correlation between bending force and strand cross-section area. This led to the introduction of a factor with general validity. Compacting factor K is a simple factor for specifying strand compaction, involving the properties and therefore options for further processing such as in projection welding.

Keywords: resistance welding, wire strands, compacting, copper, conductors, metallic continuity, parameter field, sintering, projection welding

Streszczenie

Zgrzewanie oporowe jest szeroko postrzegane jako stosunkowo bezpieczna i ekonomiczna metoda spajania, która może być zastosowana do brykietowania końców przewodów, linek i taśm miedzianych. W literaturze trudno o kompleksowe opracowanie tego zagadnienia.

Prezentowana praca obejmuje brykietyzację (zagęszczanie) końców przewodów (lin) miedzianych. Badania zorientowano na ujawnienie mechanizmu wiązania i badania właściwości zgrzein oraz na określenie „okna” parametrów, dając użytkownikom bardzo proste narzędzie do parametryzacji procesu.

Właściwości zgrzein badano za pomocą testów zginania i ujawniono korelację pomiędzy siłą zginania a powierzchnią przekroju brykietu. Wprowadzono współczynnik zagęszczenia K jako prosty czynnik określający zagęszczenie włókien.

Słowa kluczowe: zgrzewanie oporowe, brykietowanie kabli miedzianych

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Introduction

Metallic continuity in electric conductors to consumer load using resistance welding has seen increasing importance as mechanical connections are not stable in the long term [1]. Compacting strands with direct resistance welding has not been given a sufficiently methodological basis to enable users to set up a welding system quickly and without using a large number of test pieces. In addition, no basis of assess-ment has been developed for compacted strands.

Flexible conductors are used to connect up electrical assemblies. Secure connection conditions require collecting individual wires in a fine-strand or ultra-fine-strand conductor – usually referred to as a strand. There are several methods available, and resistance welding compacting is one such method that does not require additional or auxiliary materials (Fig. 1).

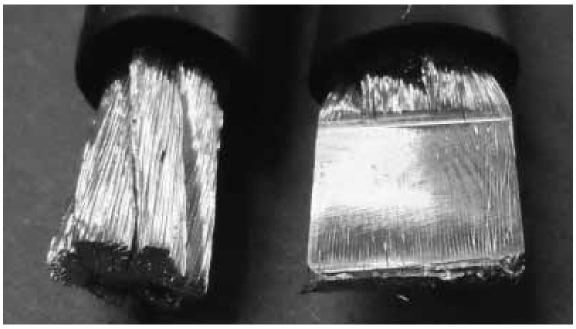

Fig. 1. 25 mm^2 strand (left) compacted by resistance welding (right)
Rys. 1. Przewód miedziany 25mm^2 (lewa strona) po zbrykietowaniu przez zgrzewanie oporowe (prawa strona)

Compacting a strand allows strands to be processed in the same way as non-stranded conductors. Resistance projection welding is enough for smaller cross sections, and is tried and trusted for cross-section areas smaller than 10 mm², which corresponds to a 3 mm diameter non-stranded conductor. Larger strand cross-section areas require resistance brazing. Figure 2 shows a projection weld on a compacted conductor with a cross-sectional area of 6 mm² onto CuSn0,15 R360 metal sheet, t = 1.2 mm. Figure 3 shows a resistance-brazed weld on a compacted conductor at 50 mm² cross-section area onto Cu-DHP R390 metal sheet, t = 2 mm.

Fig. 2. Resistance projection weld on a resistance-compacted strand, cross-section area 6 mm^2
Rys. 2. Zgrzeina oporowa zbrykietowanej oporowo końcówki liny miedzianej o przekroju 6 mm^2

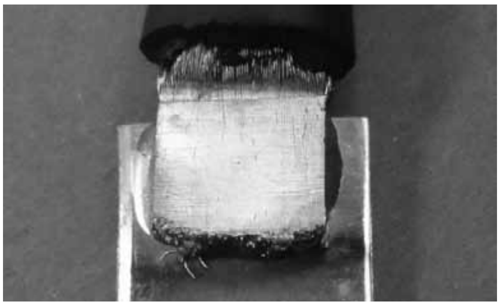

Fig. 3. Resistance brazing on a resistance-compacted strand, cross-section area 50 mm^2
Rys. 3. Luto-zgrzewana zbrykietowana oporowo końcówka liny miedzianej o przekroju 50 mm^2

Resistance heating on strands

Like all resistance welding-based methods, strand compaction is based on resistance heat for creating bonds with metallic continuity using thermal and mechanical energy.

The mechanical energy is applied as a static force using electrodes. The thermal energy is supplied from heat developing between the electrodes according to the Joule's law:

$$Q = I_W{}^2 \cdot R_{tot} \cdot t_C$$

I_W^2 – welding current
R_{tot} – total electrical resistance
t_c – current time

Joule's law describes heat development by resistance heating on the assumption that welding current and resistance during current time remain constant, which is not true in the real world as the resistance, and often welding current, depend on process-related dynamic variables as shown in Figure 4.

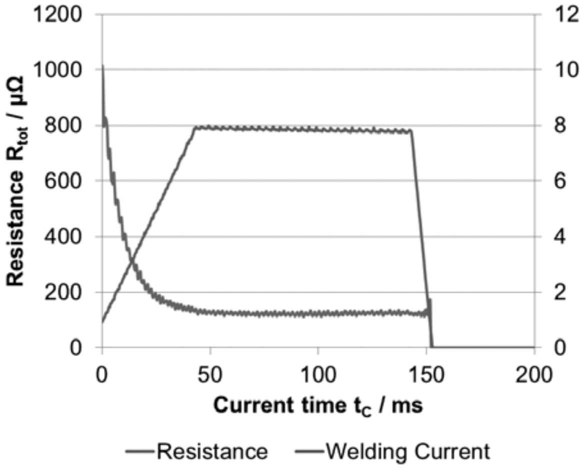

Fig. 4. Resistance projection weld on a resistance-compacted strand, cross-section area 6 mm^2
Rys. 4. Przebieg zmian rezystancji i natężenia prądu podczas zgrzewania oporowo zbrykietowanej końcówki liny miedzianej

Experimental procedure

Base materials

We performed the tests on single strands of 0.25 mm² to 50 mm² cross-section area; Table I shows all the strands. Note that the actual area Anet almost always deviates from the nominal diameter, which is derived from conductor resistance associated with a specific strand cross-section [2]. The strands were made of annealed oxygen-free copper with and without metallic coating.

Welding equipment

Preliminary remarks

All forms of current source are used except capacitor discharge. Inverter DC (1÷25 kHz), transistor-controlled DC and AC at various frequencies may be used. The current is under constant control while welding. A fixed phase angle can be used for applying AC.

Limit seating is especially beneficial in DC sources; the DC current is cut in milliseconds once the electrode reaches a preset position.

The mechanical components in welding equipment come in a variety of forms. The strands from 0.25 to 6 mm² were biaxially compacted, and strands from 16 to 50 mm² were uniaxially com-pacted (with stationary ceramic jaws) with comparative uniaxial tests using a moving ceramic jaw. The different equipment types are shown below.

Uniaxial strand compaction using stationary ceramic jaws

This technique involves inserting the upper electrode between the ceramic jaws to the strand. The ceramic jaws move to a fixed stop and remain there during compaction; the fixed stop may be the lower electrode. The gap between the upper electrode and ceramic jaws must not exceed 0.05 mm to prevent friction between the upper electrode and the ceramic jaws, and to keep the annealed copper from penetrating.

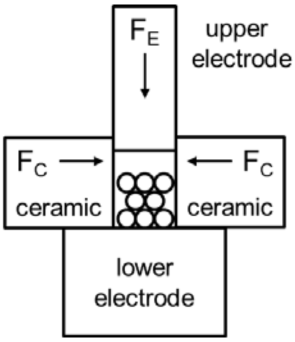

Fig. 5. Uniaxial strand compaction device with stationary ceramic jaws
Rys. 5. Jednoosiowe zagęszczanie z ruchomą formą ceramiczną

Uniaxial strand compaction using moving ceramic jaws

This form of uniaxial strand compaction involves the upper electrode forcing one of the ceramic jaws to travel with the electrode in the direction of force. The other ceramic jaw is pressed against a stop to keep a gap from the upper electrode as above as shown in the diagram in Figure 6.

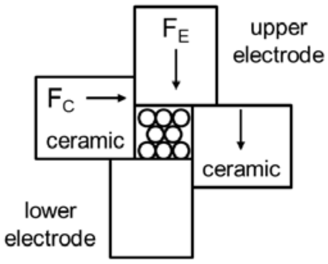

Fig. 6. Uniaxial compaction with a moving ceramic jaw
Rys. 6. Jednoosiowe zagęszczanie z ruchomą formą ceramiczną

Table I. Copper strand structure
Tablica I. Właściwości przewodów miedzianych typu linka

Nominal diameter A_N/mm²	Surface area of the copper component A_{net}/mm²	Number of wires n	Diameter of a wire d_s/mm
0.25 mm²	0.25	14	0.150
0.75 mm²	0.71	25	0.190
1.5 mm²	1.41	30	0.245
4 mm²	3.76	55	0.295
6 mm² (1)	5.42	82	0.290
6 mm² (2)	5.94	84	0.300
16 mm²	12.90	455	0.190
25 mm²	22.63	798	0.190
50 mm²	43.07	1,519	0.190
0.75 mm² + Sn	0.68	24	0.190
6 mm² + Sn	5.58	79	0.300
0.75 mm² + Ni	0.61	24	0.180

Biaxial strand compaction

Biaxial strand compaction involves all of the neighbouring elements in the compacting space moving relatively. While one electrode is fixed, the ceramic jaw moves along this electrode and moves the other electrode with it. The positive coupling effect on electrodes and ceramics means that the forces are always equal.

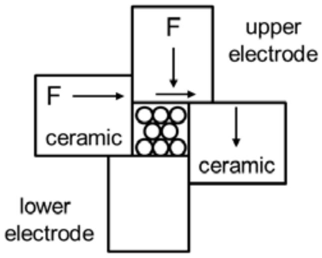

Fig. 7. Biaxial compaction with two moving ceramic jaws
Rys. 7. Dwuosiowe zagęszczanie z ruchomą formą ceramiczną

Test assessment

We first evaluated the compacted strands in a three-point bending test (Fig. 8), always calculating the welding cross-section area by measuring the edges. The relationship between bending force FB and cross-section area after welding AW (Fig. 9) eliminates the requirement for bending force measurement. Measuring the edge lengths to calculate the cross-section area is sufficient.

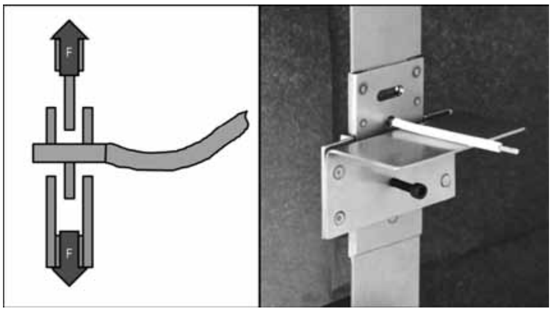

Fig. 8. Three-point test diagram (left) and in practice (right)
Rys. 8. Schemat testu trójpunktowego (lewa strona) i widok rzeczywisty przyrządu do testowania zgrzein (strona prawa)

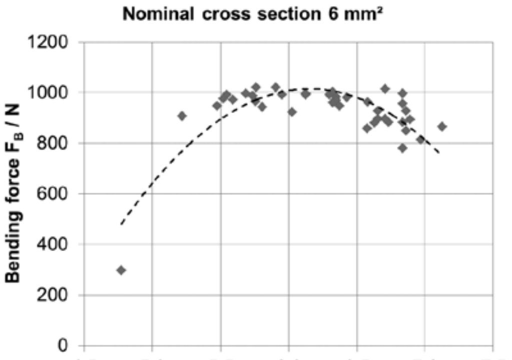

Fig. 9. Relationship between bending force and strand cross-section after welding a 6 mm^2 copper strand
Rys. 9. Zależność pomiędzy siłą zgrzewania i przekrojem czynnym brykietu na końcu linki 6 mm^2

Meaningful evaluation of strands required defining a new factor, compacting factor K, the ratio of net cross-section area (metal component in a conductor) to gross cross-section area (corresponding to the cross-section area after welding, AC).

$$K = \frac{A_{\text{net}}}{A_{\text{gros}}}$$

Note: Anet often deviates from nominal diameter AN, and this must be taken into account. Anet is calculated from wire diameter and number of wires.

This means that compaction at K<1 results in spaces. At K≥1, all of the spaces have been closed. Note that the size of K for K<0.8 is no longer valid since it can be assumed that no compaction has taken place (no bonding between wires).

A percentage of K may be used, such as K=95%.

Results

The test demonstrated that compaction at 85%≤K≤100% are best suited for subsequent processes due to good bond strength. Individual wires may fray from the bonded (and compacted) strand at levels below K = 85%. Values above K = 100% indicate strands weakened beyond tolerance levels. The metallic continuity indicates low transition resistance, slightly weakening the strand in the process. Mechanically, the compacted strand will withstand springs or screws; this is beneficial in its effect on projection welding on the compacted strand.

Welding area charts have been prepared for these limits of 85%≤K≤100%. Figure 10 shows one such chart as an example for a 0.75 mm² copper strand. Note that the welding current range is greater at shorter current times than at longer times. Current times at tW>300 ms are unnecessary from a practical point of view; this is uneconomical and may lead to excess heat dissipation in uncompacted strands and thermal damage to the insulation.

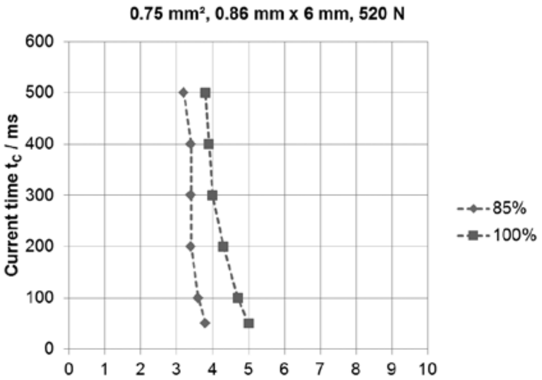

Fig. 10. Welding area chart for a 0.75 mm^2 copper strand
Rys. 10. “Okno” parametrów zgrzewania linki miedzianej 0,75 mm^2

A relationship was found in the welding area charts allowing us to use just one factor for all welding parameters, the current area AS as calculated from the required compacting length and width. This corresponds to the projected current area in a strand, or the surface on which the electrode force is applied and through which the welding current is transmitted, see Figure 11.

Electrode force FE is calculated over a specific electrode force f_E = 100 N/mm²:

The other resulting variables are shown in Figure 12.

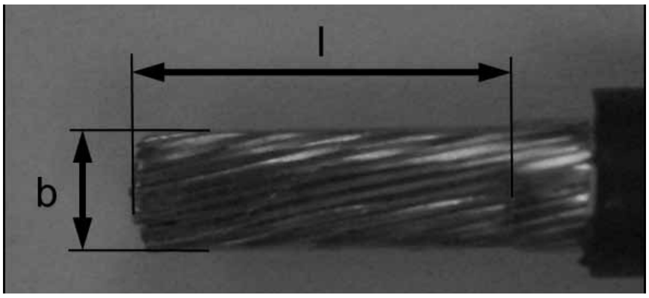

Fig. 11. Current area in a copper strand
Rys. 11. Czynna powierzchnia linki miedzianej

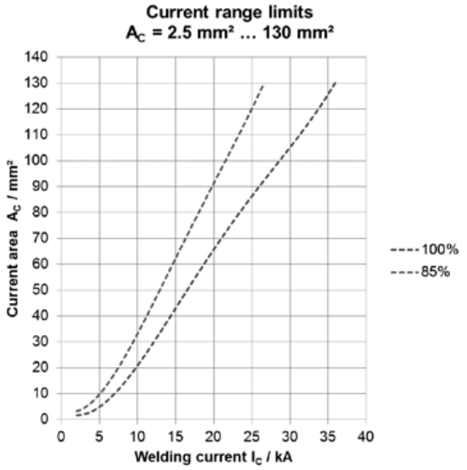

Fig. 12. Current area - current time - welding current chart
Rys. 12. Czynna powierzchnia, czas przepływu prądu, wykres przebiegu prądu zgrzewania

The following example demonstrates the formula in use and the chart in Figure 12:

A strand with a nominal diameter of 6 mm² needs to be compacted: compacting length l = 8 mm, breadth b = 3 mm. The welding parameters need to be determined. In addition, a compacting factor K = 92% is required as calculated according to compacting height h. The compacting length l and breadth b yields current area AW:

$$A_C = l \cdot b = 8\ \text{mm} \cdot 3\ \text{mm}$$

$$A_C = 24\ \text{mm}^2$$

This yields the electrode force:

$$F_E = f_E \cdot A_C = \frac{100\ N}{\text{mm}^2} \cdot 24\ \text{mm}^2$$

$$F_E = 2400\ N$$

The current range chart (Fig. 12) shows the current time and welding current. The current time may be read at a rounded value.

$$t_W \approx 100\ \text{ms}$$

It is advisable to increase the current gradually from the beginning of the compacting process to avoid voltage spikes and spatter (see Fig. 4).

$$t_{up} = 50\ \text{ms}$$

The welding current depends on the desired compacting factor of K = 92%. This is approximately midway between the blue and red curve in Figure 12.

$$I_{W,85} = 8\ \text{kA and } I_{W,100} = 11{,}5\ \text{kA}$$

Starting at IW = 8 kA, the current is increased until K = 92% is reached. The strand width b is 3 mm. The strand height l needs to be calculated. Figure 13 shows the strand in trans-verse section. The number of the copper wires is n = 82 at a diameter of d = 0.29 mm each. This is used to calculate the net copper cross-section Anet in the strand:

$$A_{net} = N \cdot \frac{\pi}{4} \cdot d^2 = 82 \cdot \frac{\pi}{4} \cdot (0{,}29\ \text{mm})^2$$

$$A_{net} = 5{,}4\ \text{mm}^2$$

From:

$$K = \frac{A_{\text{net}}}{A_{\text{gros}}}$$

$$A_{\text{gros}} = b \cdot h$$

$$h = \frac{A_{\text{net}}}{K \cdot b} = \frac{5{,}4\ \text{mm}}{0{,}92 \cdot 3\ \text{mm}}$$

$$h = 1{,}95\ \text{mm}$$

A welding machine with limit seating may be used for reproducible production of strands with a constant compacting factor.

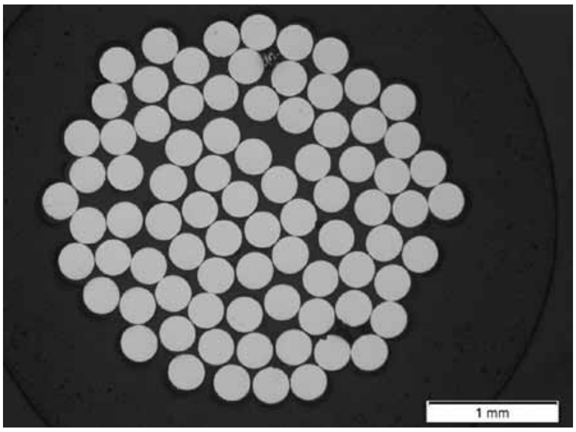

Fig. 13. Cross section of a 6 mm² copper strand
Rys. 13. Przekrój liny miedzianej 6 mm²

Figure 14 shows welds at I_W = 22 kA on 16 mm² strands based on each ten compactions at the target compacting factor of K = 100%. First, cut-off was always at t_C = 100 ms. Subsequently, the experiments were performed again using the limit seating (electrode displacement). Electrode displacement was s = 250 µm. Both cut-off options achieved approximately the same compacting factor of K ≈ 101%, but the results of the time-out were less consistent, so limit seating was taken as more suitable.

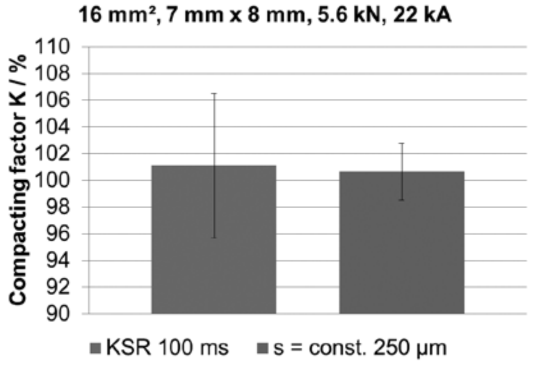

Fig. 14. Limit seating compared to time-dependent cut-off on a 16 mm² stranded wire
Rys. 14. Zakres przemieszczania elektrod (podczas brykietowania liny miedzianej 16 mm²) w relacji do czasu zgrzewania

Bonding mechanism in detail

Microsections were taken to examine the relevant processes in bonding. Resistance welding in copper-stranded wire is based on knowledge gained from research on diffusion processes. The copper does not melt; [3] and the micrographs in Figure 15 show that strand compaction involves solid-phase sintering with only one material component. Pressure and heat are both involved, so this is pressure sintering. Unlike sintering, this does not involve spherical particles as these are rod-shaped elements.

A current time or welding current limit halts the sintering process for varying compacting factors as shown in Figure 16.

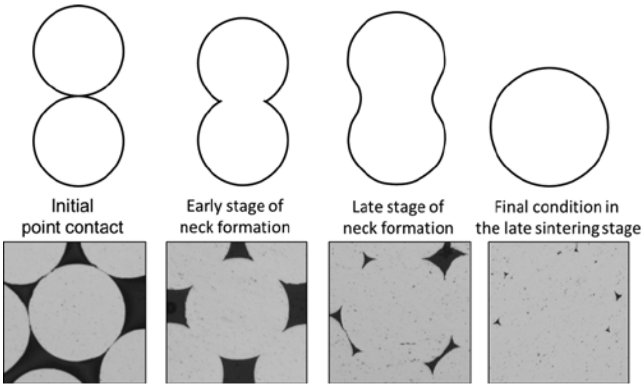

Fig. 15. Bonding in strand compaction
Rys. 15. Stopniowe zgrzewanie włókien liny

We planned to take thermographic images to estimate the temperatures during strand compaction, but were not able to achieve accurate temperature calibration. Radiation reflection and process dynamics did not yield usable results in spite of high-speed thermography. However, the results did reveal how the process works thermally. The test set-up had to be prepared to visualise the process, which involved compacting a 6 mm² strand at the full electrode length (16 mm) for the strand to reach the edge of the electrode.

The thermal images showed different stages of heating with the contact point between electrodes, ceramic jaw and strand at the beginning of the process. The heat then increased in the electrodes and ceramics until the highest temperature was reached at the end of the current time; heating was relatively low in the ceramics and electrodes. Heat dissipated in ceramics and electrodes in the holding time. The heat dissipated almost completely from the electrodes from the opened tool, with residual heat only in the stranded wire and ceramics. It can be assumed that the heating effect is a result of hindered heat dissipation from the electrodes and ceramics and constriction resistance.

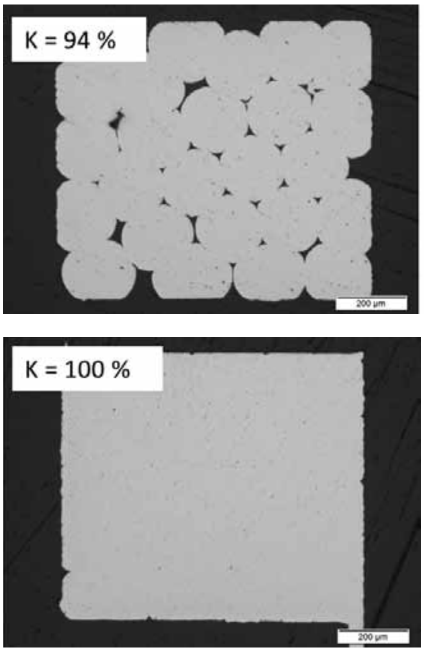

Fig. 16. Strands at varying compacting factors
Rys. 16. Włókna liny przy różnym współczynniku zagęszczenia

Summary

Resistance welding is an economical solution for compacting copper-stranded wires. The results pre-sented here from a research project are the first to assist users with a factor depending on current area. In addition, the authors recommend limit seating applied to electrode displacement.

The bonding mechanism is based on diffusion processes; the heat required for this purpose is applied by heat accumulation in the electrodes and ceramics in combination with heat resistance.

A DVS instruction is being drawn up based on these results. Future work will examine the influence of type of current and kinematics. Other topics include simulating the thermal processes involved, in particular heat dissipation and consequently strand deformation.

References

[1] Poje, R.; Fröhlich, B.; Bendisch, W.: Schweißen von Batteriepolanschlusskabeln - Widerstands-schweißen ersetzt mechanische Fügetechnik, 20. DVS-Sondertagung „Widerstandsschweißen 2007“, Duisburg, 2007.

[2] DIN EN 60228 : 09/2005: Leiter für Kabel und isolierte Leitungen.

[3] Zäh, M.: Wirtschaftliche Fertigung mit Rapid-Technologien, Hanser Verlag, München, 2006.

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