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The Effect of the Power Supply Source on the Resistance Welding Process

Abstract: The research presented in the article involved the analysis of various factors, including 1) type, length and the cross-section of the supply conduit, 2) synchronous/asynchronous operation of welding machines and 3) temperature of the conduit on supply voltage drop in resistance welding machines. The article discusses the unfavourable effect of the above-named voltage drop on the quality of welds, including a decrease in the weld nugget diameter and the reduction of weld strength.

Keywords: resistance welding, welding machine power supply, weld

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Introduction

The obtainment of a required weld diameter in the resistance welding process is one of the key parameters determining the strength of a joint. The diameter of the weld depends on three primary parameters including welding current, welding time and electrode (squeeze) force. The above-named parameters are correlated, yet during the welding process usually set independent of one another. As a result, a change in one of them without changes in the remaining ones may lead to the formation of a weld having an improper diameter or to the (complete) bonding imperfection. A parameter most susceptible to changes, particularly to changes in its value is welding current. The reason for this situation lies in the voltage-based powering of resistance welding machines. The preset parameter is welding current, yet the excitation of the current in the welding machine is the voltage on the electrodes. The value of the above-named voltage may vary depending on the type of a welding machine, its control method (stabilisation of current, percentage control) and the manner of connection to the supply network. This study is concerned with the analysis of the effect of the power source on changes in voltage of welding machine electrodes in relation to various types of welding machines and various power supply methods (methods of connection to power supply network).

Reasons for reduced welding voltage

Resistance welding machines are usually powered by one or three-phase industrial networks having a voltage of 3×400/230 V, 50 Hz (in terms of the one-phase powering of high-power welding machines it is usually a phase-to-phase root-mean-square voltage of 400 V), drawing current of up to several hundred amperes per

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a welding machine. However, the above-named consumption is of impulse nature, the welding process lasts a few hundred milliseconds followed by a few second-long pause. Presently, there are two types of commonly used welding machines, i.e. AC welding machines (AC 50 Hz) with the thyristor-based control of welding current and DC welding machines (DC 1 kHz) provided with a frequency converter (inverter or rectifier). In general, in both cases current drawn from the power supply source is similar. The cross-section and the length of the supply conduit triggers a specific voltage drop occurring only during the flow of current (when at the idle state, the voltage of the welding machine is nominal). The connection of more than one welding machine to one line may trigger increased voltage drop (i.e. when more than one welding machines work simultaneously at a given moment). If the operation of welding machines is asynchronous (i.e. when the control system prevents the switching on of one welding machine during the welding process performed by another), voltage drops will not be triggered by higher (e.g. double) welding current, yet the more frequent flow of the current resulting from a greater number of welding machines will increase the use of the conduit and, consequently leading to an increase in energy emitted as a result of power losses in the conduit. An increase in current in the supply conduit (because of the simultaneous operation of the welding machines) generates the unfavourable drop of voltage, decreasing the actual welding machine voltage in relation to supply voltage. The foregoing constitutes the first unfavourable aspect related to the reduction of welding machine voltage. The second aspect is an increase in the temperature of the conduit, which, in turn, translates into the higher resistance of the conduit and triggers the further decrease of voltage. It should be noted that power losses in the conduits are proportional to the square of current flow. As a result, a two-fold increase in root-mean-square current will result in a four-fold increase in generated power losses. The above-presented analysis demonstrates that the powering of several welding machines working asynchronously with one common conduit will generate a deeper voltage drop along the conduit than if only one welding machine is powered.

Voltage drops in supply conduits are most stochastic drops in generalised analysis as the powering of nearly every welding machine is characterised by different parameters (length, cross-section and the material of a supply conduit). As a result, it is the most difficult to identify the effect of such drops at the welding machine design stage. In addition, in cases of DC resistance welding machines it is also necessary to remember about certain voltage drops generated in the energy conversion circuit and dependent on current flow values (varying in relation to welding current). The sources of the above-named voltage drops are rectifiers, both in the frequency converter and in the output (power) rectifier. The aforesaid drops result from the occurrence of the phenomenon of commutation and, in addition to current, depend on the impedance of the circuit powering the rectifier (i.e. in particular on the reactance of the dissipation of the transformer powering the rectifier). The detailed analysis of the above-presented voltage drops is presented in the remainder of this publication.

Analytical assumptions

The analysis of voltage drops and their effect on welding current and, consequently, the weld diameter, was performed in relation to two types of welding machines, i.e. an AC welding machine equipped with a thyristor controller and a DC welding machine provided with a 1 kHz frequency converter. In both cases it was assumed that the nominal welding current amounted to 10 kA and that the transformer voltage ratio was 50:1, which translated into current drawn from the network amounting to 200 A. It was assumed that the single welding machine worked with a time of 200 ms and a filling of 10% (the time of a pause in welding amounted to 2 s). The analysis was performed for supply conduits made of aluminium (assumed output conductivity at a temperature of 20°C amounting to 30 MS/m) and copper (output conductivity of 55 MS/m) having a length restricted within the range of 30 m to 100 m and a cross-section restricted within the range of 16 mm2 to 120 mm2. In addition, it was assumed that both types of welding machines worked with the open control system (i.e. without feedback and the measurement of actual welding current, where expected welding current both in the welding machine with the thyristor controller and in the welding machine provided with the inverter was adjusted through the appropriate (constant during the process) filling of control impulses).

There are mechanisms enabling the compensation of the drop of supply voltage through the stabilisation of welding current or through the compensation of supply voltage. Welding machine control systems are capable of providing the automatic compensation of changes in voltage powering the welding machine, triggering the automatic correction of thyristor control depending on the fluctuation of voltage powering the welding machine [1]. The analysis of voltage drops addressed in this publication focuses on the selection of cross-sections (i.e. cross-sectional areas) of supply conduits and their length in relation to many factors including supply current, temperature and the simultaneous (synchronous) operation of welding machines.

Analysis of voltage drops along supply conduits

The proper selection of conduits in a power supply system comes down to the determination of their cross-section in relation to the conditions of long-term current carrying capacity, allowed voltage drop and mechanical strength [2]. Voltage drops along supply conduits depend on the type, dimensions and the temperature of conduits. The analysis of voltage drops affecting the operation of the welding machine was performed in two stages. At the first stage it was assumed that the operating temperature of the conduits was constant and mounted to 50°C. In relation to the above-presented case it was necessary to determine power losses of welding machines working individually (one welding machine) and synchronously (two or three welding machines performing the welding process simultaneously). The second stage involved the analysis of the operation of two and three welding machines connected to the power supply source by means of the same supply line and working asynchronously (each of the welding machines performed the process at a different moment). The stage included the analysis of the effect of an increase in resistivity resulting from higher conduit temperature (it was assumed that an increase in temperature was proportional to an increase in power losses emitted in the conduit).

Analysis in relation to conduit dimensions

In accordance with Ohm's law, the drop of voltage along the conduit is proportional to the flow of current and the resistance of the conduit. If temperature is constant, resistance is also constant and constitutes the function of material, length and cross-section expressed by dependence (1)

$$R_{tot} = \frac{\rho l}{s} = \frac{l}{\sigma s}$$

where ρ - specific resistivity, σ - specific conductivity, l – length and s – cross-section.

Assuming the powering of only one welding machine connected to the conduit and drawing a current of 200 A from a one-phase network, it was possible to determine voltage drops in relation to a range of lengths and cross-sections for aluminium and copper. As mentioned before, it was assumed that the operating temperature of the conduits amounted to 50°C. The calculation results are presented in Figure 1.

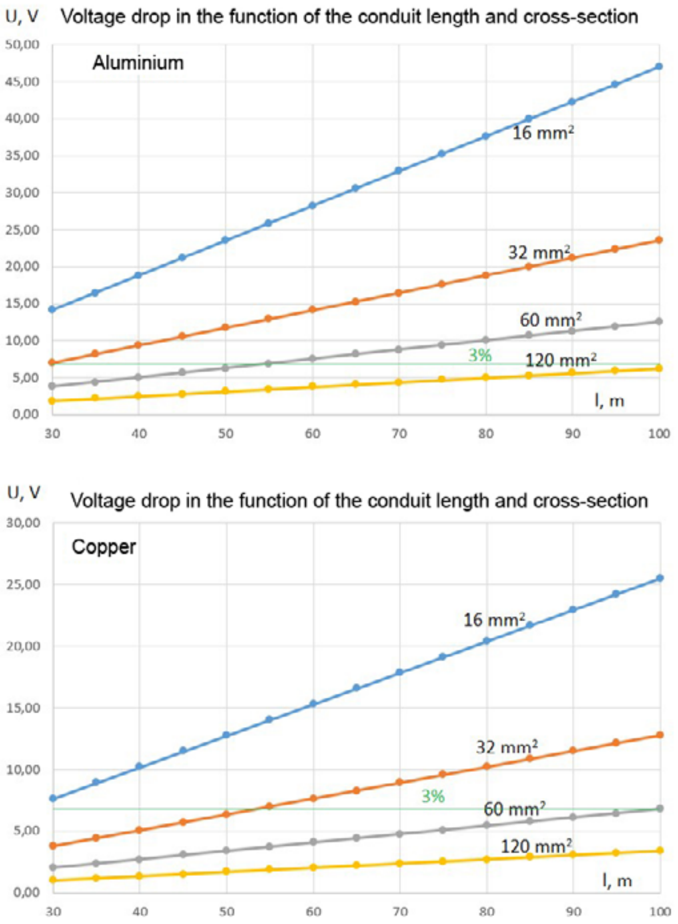

Fig. 1 Voltage drop along the aluminium conduit and copper conduits in relation to a constant load of 200 A as the function of the length and cross-section of the conduit (one wire)

In this article, the adopted (as more rigorous) limit value of voltage drop along supply conduits amounted to approximately 7 V (230 V × 0.03 = ~7.0 V) and constituted 3% of the network (phase) voltage. The above-named value results from engineering practice [3], yet there are also sources providing a higher value, i.e. 5% [4].

The analysis of the results presented in Figure 1 and 2 reveals that, in relation to the aluminium conduit, the maximum voltage drops exceed 45 V (i.e. nearly 20% of supply voltage) and 25 V in relation to the copper conduit (i.e. over 10%). The above-presented values are unacceptable for many reasons, also in view of valid regulations allowing a voltage drop (along the supply conduit) of not less than 3% [3]. The characteristics (presented in related Figures) contain a line indicating the value of 3% representing the permissible voltage drop. As can be seen, as regards aluminium conduits, the cross-section of 16 mm2 cannot be used in relation to the aforesaid loads, whereas conduits having a cross-section of 32 mm2 and 60 mm2 can be used in relation to maximum (total) lengths of 30 m and 55 m respectively. The copper conduit having a cross-section of 16 mm2 fails to satisfy the condition of a voltage drop of 3%. In relation to a diameter of 32 mm and 60 mm, the maximum lengths amount to 55 m and 100 m respectively. Taking into consideration welding machine powering (2 or 3 phase conduits), a distance between the welding machine and the supply source, in terms of acceptable voltage drop, is by twice shorter (i.e. 27.5 m and 50 m). It should be noted that the above-named lengths of the conduits are maximum and their use will significantly reduce the weld diameter (further discussed in detail in the remainder of the work).

The issue of voltage drops becomes complicated where several welding machines are powered from a common source. A related example illustrates two situations where welding machines are powered through a copper conduit. In the first case, two welding machines are powered with a common conduit having a cross-section of 60 mm2 and a length of 60 m (distance 30 m), followed by branching into sections having a length of 20 m and 40 m (respectively), where the cross-sectional area of the conduit amounts to 32 mm2 (Fig. 2a). In the second case, 3 welding machines are powered with a common conduit having a cross-section of 60 mm2 and connected to the conduit every 20 running metres (the first welding machine - 20 metres, the second - 40 metres and the third - 60 metres away from the welding power source) -o see Fig. 2b. In both cases, the operation of the welding machines is synchronous (both welding machines are powered).

In the above-presented examples the situation is as follows. In relation to the first case, the drop of voltage along the common conduit (having a cross-section of 60 mm2) amounts to

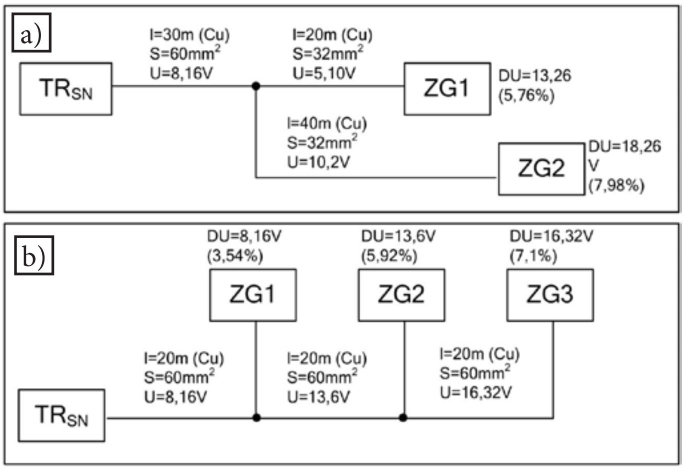

Fig. 2. Schematic diagram presenting welding machine connections in relation to the analysis of voltage drops in supply conduits (where l – distance in metres, i.e. the total length of the supply conduits in the cable is twice as long)

8.16 V. In turn, the voltage drops along conduits having a cross-section of 32 mm2 amounts to 5.1 V and 10.2 V respectively. Consequently, the total voltage drop in relation to the first welding machine amounts to 13.26 V, i.e. 5,76%, whereas the total voltage drop in relation to the second welding machine amounts to 18.26 V i.e. 7.98%. As can be seen, the voltage in all welding machines is lower than recommendable. In the second case, voltage drops depend on the value of current. In relation to the first welding machine the voltage drop amounts to 8.16 V, i.e. 3.54%, in relation to the second welding machine the voltage drop amounts to 13.6 V, i.e. 5.92%, whereas in relation to the third welding machine the voltage drop amounts to 16.32 V, i.e. 7.1%. The analysis revealed that, in relation to all of the welding machines, the drop of voltage will exceed the assumed permissible value amounting to 3%. As a result, in the above-presented examples the welding machines will not work properly because of the adopted 3% voltage drop along the supply conduits (in relation to the nominal supply voltage). In turn, only welding machine no. 1 met the 5% voltage drop criterion (Fig. 2). It should be noted that the above-presented analysis is concerned with power supply from the one-phase network (2×400 V, phase-to-phase voltage). In terms of power supply from the three-phase network (i.e. in relation to most DC welding machines provided with the inverter), values of current drawn from the mains (network) will be accordingly lower. As a result, voltage drops will be proportionally lower as well.

Analysis in relation to conduit operating temperature

As mentioned before, the utilisation factor of welding machines is relatively low. The actual welding machine operation time constitutes approximately 10% of its operation time. As a result, energy emitted in supply conduits during operation is dissipated during breaks (the thermal time constant of conduits is many times higher than the time constant of electric processes) and the resultant operating temperature of conduits is low. The analysis presented in the article assumed that the temperature of conduits accompanying the powering of one welding machine amounted to 50 °C. The analysis was concerned with the mean value of conduit temperature. Temperature increases significantly along with an increase in the

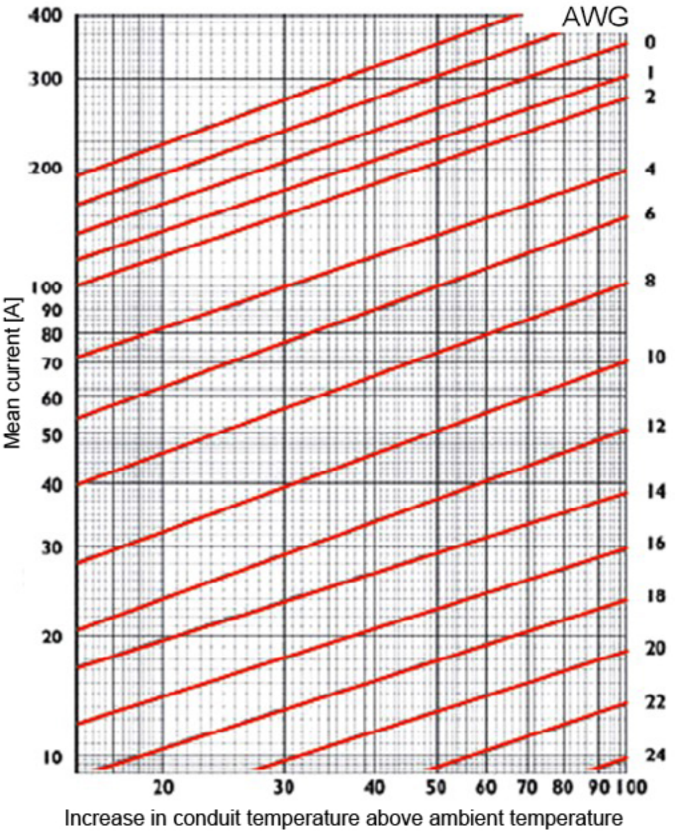

Fig. 3. Dependence of an increase in the temperature of the insulated copper conduit on current in relation to various cross-sections [5]

mean load, i.e., for instance, where the supply line powers more welding machines (even working asynchronously, i.e. with one welding machine switched on and the others switched off). Figure 3 presents an exemplary increase in the temperature of an insulated copper conduit operated in air (i.e. naturally cooled).

As can be seen in the Figure, an increase in temperature depends on the value of current and the cross-section of the conduit. A two-fold increase in current (continuous current equivalent) from 50 A to 100 A in relation to the conduit having a cross-section of 16 mm2 (6 order AWG) leads to a temperature increase of 50 °C. The foregoing means that the double loading of the conduit increases the temperature of operation from 50°C to 100°C (double increase). A change in the temperature of the conduit directly affects its resistivity and, consequently, the drop of voltage generated along the conduit. It can be expected that, even in terms of asynchronous operation, the connection of a larger number of welding machines to one common supply line will result in the drop of voltage on this line. A change in resistance depends on the value of a temperature coefficient and is expressed by dependence (2)

$$R = R_{odn}[1 + \alpha(T - T_{odn})]$$

where R_{odn} – resistance of the conduit in reference temperature (usually 20°C), α – temperature coefficient of a change in resistance, T – operating temperature and T_{odn} – reference temperature. Coefficient α in a temperature of 20°C amounts to 0.004041 in relation to copper and to 0.004308 in relation to aluminium.

Figure 4 presents characteristics of the voltage drop dependence in the function of the operating temperature of a single-wire copper and a single-wire aluminium conduit having a cross-section of 60 mm^2 and a length of 80 m, assuming the powering of a group of welding machines by a current of 200 A from a one-phase network. The operation of welding machines is asynchronous (simultaneously flowing current always amounts to 200 A, whereas a change in temperature results from a change in the number of welding machines and, consequently, an increase in averaged continuous current flowing through the conduit).

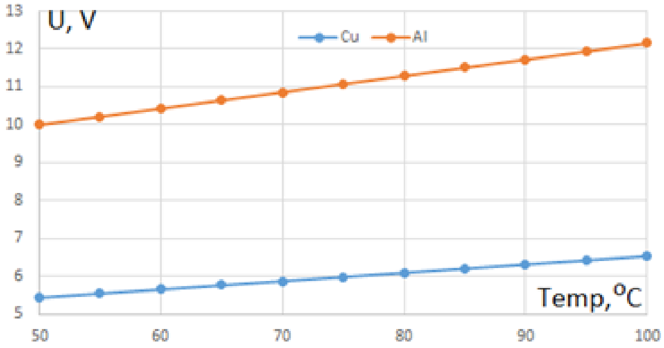

Fig. 4. Correlation between the drop of voltage and the conduit operating temperature

The analysis revealed that an increase in the temperature of the conduit triggers an increase in resistivity, which directly translates into the drop of voltage along the conduits powering one or more welding machines and that, in relation to a given conduit, a two-fold increase in temperature reduces voltage by more than 20% in relation to both of the above-named types of conduits. It should be noted that the reason for an increase in the temperature of a conduit may not only be additional welding machines connected to the same supply line but also an increase in the number of welds made using one welding machine (an increase in the duty factor) and an increase in ambient temperature (or the deterioration of the conditions of the discharge of heat from the conduit). However, the above-named phenomena require additional analysis and are not taken into consideration in this article.

Analysis of commutative voltage drops

For many reasons, today's developmental trends are focused on DC welding machines provided with an electronic power converter. The process of current conversion in the converter enables the more advanced control of current and the (faster and easier) elimination of unfavourable phenomena including voltage drops along the supply line. Because of the fact that the above-named systems usually work without feedback, proper operation requires the proper design of such systems and the proper settings of control parameters. In terms of voltage drops in the welding machine equipped with the converter, an important, yet often ignored in the design process, is the commutative drop of voltage in rectifiers. The above-named drop depends on the number of commutative processes per a voltage period (number of rectifier pulses), current flowing during the switching of valves and the substitute inductivity of the rectifier powering circuit. The inverter welding machine usually features two rectifiers, i.e. a rectifier in the frequency converter and an output (high-current) rectifier [6]. Usually, the rectifier in the frequency converter is a three-phase bridge rectifier, converting significantly lower current than that converted by the output converter, yet having a larger number of pulses. In addition, the inductivity of the network supplying the input rectifier can be significantly higher than that of the output rectifier, where inductivity is introduced only through the reactance of the output transformer. On the other hand, the output rectifier works with significantly lower nominal voltage and repeatedly higher work current. The reduction of the output voltage of the rectifier resulting from its commutation is expressed by dependence (3)

$$U_k = \frac{q}{2\pi}\omega L_s I_0 = R_k I_0$$

where q – number of rectifier pulses, ω – network pulsation, L_s – inductivity seen from the perspective of the input clamps and I_0 – current conducted by the rectifier. R_k, referred to as commutative resistance is a substitute parameter enabling the expression of commutative drop by means of Ohm's law, yet it is not resistance physically present in the system [6].

In rectifiers powered directly by the transformer (in systems, where the transformer directly precedes the rectifier), the primary source of network inductivity is the reactance of transformer dissipation. In relation to energy transformers, the above-named inductivity can be determined using dependence (4) linking the power of a transformer to the voltage of its short circuit.

$$X_T = \omega L_s = u_{z\%}\frac{U_s^2}{S_N}$$

However, it should be noted that supply systems are often provided with impedance coils (also referred to as short circuit choking coils) located between the transformer and the rectifier, increasing inductivity on the supply side.

Because of the significant scatter of values adoptable by the inductivity of the network powering the input rectifier (restricted within the range of 10^{-6} H to 10^{-1} H), the commutative drop of voltage may be restricted within the range of negligibly low (below 0.1%) to even 10% of the supply voltage value. For instance, a network having a substitute inductivity of 1 mH and supplying the bridge rectifier under a current of 200 A will generate a commutative voltage drop of 60 V. The above-named value is significant enough to be taken into consideration when determining the inverter valve controlling ratio in the frequency converter.

The transformer reactance at the output is very low (fractions of μH), whereas the rectifier has only two pulses and operates at high frequency (e.g. 1 kHz) and very high output current (e.g. 10 kA). For instance, in relation to the output transformer scattering inductivity of 100 nH, the commutative voltage drop may reach even 2 V. If the value of output voltage is restricted within the range of 8 V to 10 V, the above-named drop constitutes over 20% of output voltage.

The above-presented analysis demonstrates the significant effect of commutative drops on rectifier output voltage. The above-named drops should be taken into consideration at the design stage when developing a welding machine. However, it should be noted that commutative drops are the linear function of rectifier output current, therefore a change in load affecting the welding machine will affect a change in the value of commutative drops, thus potentially changing values of output current and directly affecting diameters of welds obtained in the welding process. The above-presented phenomenon is both unfavourable and difficult to eliminate.

Effect of reduced output voltage on the weld diameter

The presentation concerning the unfavourable effect of the reduction of welding machine supply voltage leading to a decrease in supply voltage (of electrodes) as well as the weld nugget diameter and the strength of the welded joint required the performance of technological welding tests in relation to three thicknesses of materials (sheets) subjected to welding. Sheets having a thickness of 1.0 mm, 1.5 mm and 2.0 mm were subjected to spot overlap welding. During the technological welding tests, in relation to a given sheet thickness, welding cycle parameters were adjusted to obtain the nominal weld diameters consistent with guidelines and standards [8][9][10]. Afterwards, in relation to constant electrode (squeeze) force and a constant welding current flow time, the value of current was decreased to model the unfavourable effect of welding voltage reduction presented in this article. The preset parameters of the welding cycle, obtained weld nugget diameters and the strength of the weld are presented in Table 1.

Table 1. Welding cycle preset parameters and the characteristic parameters of the welds

Sheet type and thickness	Current flow time	Welding current	Electrode force	Nominal weld diameter	Breaking force (maximum)
	ms	kA	kN	mm	kN
DX 53 (Zn) 1.0 mm	180	8.0–9.4	2.0	5.0	6.5
DX 53 (Zn) 1.5 mm	260	10.6–11.8	2.4	6.0	7.7
DX 53 (Zn) 2.0 mm	300	12.5–15.0	3.2	7.0	12.0

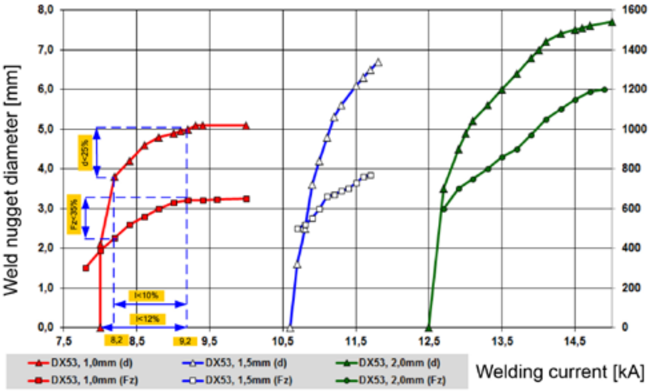

Fig. 5 Correlation between the weld nugget diameter and weld strength (in a static tensile test) and welding current

Figure 5 presents the correlation between the weld nugget diameter and the weld strength in a static tensile strength and the value of welding current. In relation to the welding of 1.0 mm thick sheets, a decrease in welding current by 10% and 12% was marked and a change in the weld nugget diameter and that in weld strength were determined. As regards a welding current decrease of 10%, the weld nugget decreased by 25% (in a peeling test), whereas the strength of the weld decreased by 35% (in a static tensile test). In turn, a welding current decrease of further 2% (12% in total) was accompanied by a decrease of the weld nugget diameter to nearly zero. The effect of welding current reduction on the weld nugget diameter and weld strength was similar in relation to the remaining sheet thicknesses, i.e. 1.5 mm and 2.0 mm.

Summary

The research-related analysis justified the formulation of the following concluding remarks:

1. All of the factors subjected to analysis (cross-section and the length of the conduit and its material, the synchronous operation of welding machines, current, percentage operation ratio) lead to welding machine supply voltage drop and, consequently, welding voltage drop (on electrodes).

2. A decrease in welding machine supply voltage reduces welding current. It should be noted that welding energy decreases along with the square of welding current. In theory, the above-named effect can be eliminated by using an operation mode featuring welding current stabilisation or can be compensated by the welding machine control system (by changing a power transistor/thyristor control angle within the so-called operation mode with percentage control). However, the entire elimination of voltage drop through compensation is not possible. Because of the higher operating frequency of DC 1 kHz welding machines in comparison with that of AC 50 Hz welding machines, the compensation of voltage drop is definitely easier in relation to DC welding machines. In turn, in relation to AC welding machines, the above-named task is very difficult.
3. The drop of (supply/welding) voltage is tantamount to a decrease in welding current. In relation to the above-presented welding of 1.0 mm thick sheets and a voltage drop of 12%, welding energy fell so dramatically that the value of the weld nugget diameter nearly amounted to zero.
4. It is definitely more favourable to use welding machine supply conduits made of copper than those made of aluminium.
5. The above-presented analysis revealed that, in relation to a given conduit, a two-fold increase in temperature results in a voltage drop of more than 20%, significantly destabilising the welding process.

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