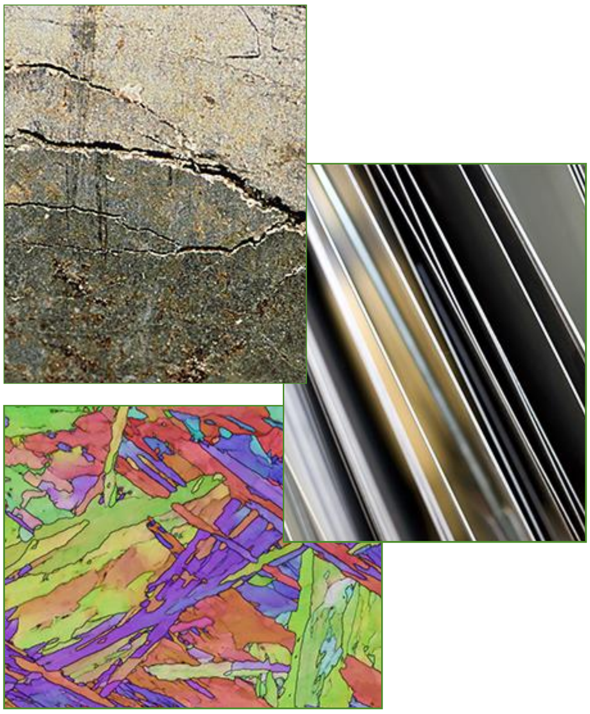

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Guideline - How to measure current, voltage and arc power in arc welding

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Report number. MEF18139

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Guideline - How to measure current, voltage and arc power in arc welding

Kjell-Arne Persson and Alexander Lundstjälk
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Scope

This guideline is produced as a part of a member project with the Centre for Joining and Structure at Swerim.

It is a compilation of information from different standards (ISO and European) and technical recommendations on:

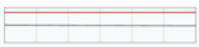
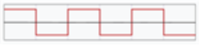
- Recommendations for measuring of current and voltage in arc welding
- What is displayed on the welding equipment or via external sensors and how it is measured.
- Demands and connection points of external measuring devices.

The guideline is mainly intended for companies that need to check displayed values of voltage and current on their welding equipment or connect external measuring devices. This is of specific interest when producing a Welding Procedure Qualification Record (WPQR), when following a Welding Procedure Specification (WPS) or when changing welding equipment.

Current, voltage, arc power and heat input are normally varying in time but often need to be represented by single values, for instance in a WPS. These single values depend on where they are measured (connection points) and how the mean values are calculated.

Definitions

Symbol	Term	Unit
I	Current	A
U	Voltage	V
i(t) and u(t)	Instantaneous values	A and V
v	Welding speed	mm/s
Q	Heat input in welding	kJ/mm
P	Real power	W or J/s
S	Apparent power ($=U_{RMS} \cdot I_{RMS}$)	VA

Waveform	Illustration	Arithmetic mean (rectified)	Root mean square
Constant		a	a
Sinus		0,637·a	0,707·a
Square edge		a	a
Triangular		0,5·a	0,577·a
Sawtooth		0,5·a	0,577·a

There are different ways to calculate the mean values for current, voltage and heat input*:

Arithmetic mean value	The arithmetic mean value of current or voltage is calculated based on averaging (rectified) instantaneous values of current. Similar for voltage. Meters can be either analogue or digital.
	$$I_m = \frac{1}{T_2 - T_1}\int_{T_1}^{T_2} \lvert i(t)\rvert \, dt \approx \frac{1}{n}\sum_{t_1}^{t_n} \lvert I_{t_i}\rvert = \frac{\lvert I_{t_1}\rvert + \lvert I_{t_2}\rvert + \lvert I_{t_3}\rvert + \cdots + \lvert I_{t_n}\rvert}{n}$$
Root mean square	The true Root Mean Square (RMS) is calculated based on the root of the averaging of the square of instantaneous values of current. RMS calculates the equivalent direct current (DC) value of an AC waveform, i.e. the equivalent DC current that would correspond to the same heating on the same load. This mean value is therefore sometimes called the effective value. Indicated RMS is based on the arithmetic mean but multiplied with a factor depending on wave shape (for sinus wave the factor is 1.11)
	$$I_{RMS} = \sqrt{\frac{1}{T_2 - T_1}\int_{T_1}^{T_2} i^2(t)\, dt} \approx \sqrt{\frac{1}{n}\sum_{t_1}^{t_n} I_{t_i}} = \sqrt{\frac{I_{t_1}^2 + I_{t_2}^2 + I_{t_3}^2 + \cdots + I_{t_n}^2}{n}}$$

Heat input

The heat input is based on the arc power divided with the travel speed (this is the same as arc energy per weld length) multiplied with an arc efficiency factor.
The most correct way to calculate the heat input is based on instantaneous values of current and voltage. Use of instantaneous values is important especially when the shape of current and voltage varies with time such as in short arc welding, pulsed arc welding or any other controlled waveforms.
In TR 18491 the heat input can also be calculated based on arithmetic mean values of current and voltage but only if the current and voltage are fairly constant (as in TIG welding or MIG/MAG welding using spray arc).

Heat input based on instantaneous values	$$Q = \eta \cdot \frac{1}{v} \cdot \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} u(t) \cdot i(t)\ dt \approx \eta \cdot \frac{1}{v} \cdot \frac{1}{n}\sum_{t_1}^{t_n} U_{t_i} I_{t_i}$$
Heat input based on arithmetic mean values	$$Q = \eta \frac{U_m \cdot I_m}{v}$$

** Since most modern measuring devices uses analogue to digital converters, calculations are expressed as sums rather than integrals. For high accuracy in measurements the sampling frequency should be at least 10 times the highest frequency in the measured arc signals.*

Guideline – How to measure current, voltage and arc power in arc welding

Why is measurement of current, voltage and heat input of interest?

- Current is used as a setting parameter in some processes (for instance in TIG and MMA and SAW in CA constant amperage mode). In other processes (for instance in MIG/MAG and SAW in CW constant wire mode) the welding current is strongly related to the wire feed speed and the current is used as a quality control parameter.
- They are used to produce or to follow a Welding Procedure Specification WPS (current, voltage and heat input that are listed in the WPS record)
- They are used for reasons of monitoring, traceability and quality assurance
- The heat input is a good measure of the cooling rate that is related to the weld's properties (to keep the heat input within recommended range specified by the material producers).

The current is typically related to weld penetration depth, the voltage to arc length and bead geometry, the heat input (arc power multiplied with an arc efficiency factor and divided by the welding speed) to cooling rate and mechanical properties. These values are therefore specified in the Welding Procedure Specification. Variation in for example stick-out length or torch angles influence the voltage and current and may result in a weld that deviates from the nominal. By monitoring current, voltage deviations from nominal values can give an early warning that adjustments are required to fulfill demands on the weld quality.
Documented values during welding are valuable for traceability and quality assurance. In this type of documentation, values that vary in time are represented by a single value, an average value. There are however different ways to calculate average values (used in different fields of application and for different purposes):

- If the current and voltage are almost constant then the mean values (complemented by a measure of deviation (max/min, standard deviation etc.)) is a good representation.
- If the current/voltage is supposed to vary, as in AC welding, pulsed welding or when the filler metal makes short circuits (short arc welding) then it is more difficult to represent it with just one single value (an average). In some application areas, such as in power supply (where the current and voltage have a regular sinusoidal shape), it is praxis to root mean square (RMS). For irregular non-sinusoidal shapes rectified mean values (absolute values) are used instead.
- Heat input is even more complicated since it includes the product of varying current with varying voltage. Heat input based on averaging the product of instantaneous values of current and voltage always gives a correct mean value. Heat input based on the product of the mean value of current times the mean value of voltage will deviate from the correct value. The deviation is small for processes with almost constant current and voltage but may deviate more than 25% for processes where the current and voltage varies strongly (such as in short circuiting welding, pulsed welding and welding with advanced pulse shaped waveforms), see table 1 and Figure 4.

What are the recommendations for measuring current, voltage and heat input in arc welding?

- In the ISO 15609-1:2004 standard (section 4) concerning WPS it is stated that values of current, voltage and heat input shall be noted. It is however not mentioned how they should be measured.
- In the standard for welding equipment (ISO 17662-1:2016 Calibration, verification & validation) it is stated that current and voltage shall be measured as a mean value based on (rectified) current and voltage according to EN 50504:2008 (Validation of arc welding equipment). In EN 50504 it is however distinguished between DC and AC power sources. For DC power sources the average is calculated based on arithmetic mean values while for AC with pure sinusoidal wave shapes root mean square (RMS) methods using either true RMS or indicated RMS can be used. For other wave shapes, arithmetic mean techniques are recommended. Measuring of the heat input refers to ISO/TR 18491:2015 (Guidelines for measurement of welding energies).
- It should be noted that calculating an average value using arithmetic mean or root mean square will deviate (more or less) depending on different waveforms.

What data is normally available from the welding equipment?

Most modern welding equipment has meters displaying current and voltage. It can be meters on the power source, on the wire feeder, on a handheld controller (pendant) or on a connected computer.

- DC power sources should use arithmetic mean values to display current and voltage
- AC power sources with sinus shaped current/voltage may show values as RMS even if they probably are measured as arithmetic mean values but multiplied with a factor to convert the value to RMS (indicated RMS). Consult the power source manufacturer.
- AC power sources with waveforms other than sinus shaped should use arithmetic mean values to display current and voltage.

Displayed on the power source (or wire feeder or control unit or external sensor)

- The values shown are typically mean values of rectified current and voltage over a short time period (fractions of a second but long enough for the welder to read a stable value). This means that the value will change slightly during welding.
- For AC power sources with pure sinus shaped current and voltage the values shown can be root mean square values even if they probably are measured as arithmetic mean values but multiplied with a factor to convert the value to RMS. Consult the power source manufacturer.

Data recorded and stored on internal memory or transferred to a connected computer

- The values can be mean values (arithmetic or RMS) from start to end of a weld. The data for ramp-up and -down are sometimes omitted. In other cases only data from a short time period, typically from just before weld end, is shown.
- Heat input (or arc power) is seldom shown directly on the power source but is often available for power sources with recording possibilities. For calculation of the heat input also information regarding the welding speed or weld length and arc time must be known. To be certain if the arc power is calculated based on instantaneous values of current and voltage or based on mean values the power source manufacturer should be consulted.

Validating and calibrating the internal measuring devices

The measuring devices available in welding equipment are validated by the manufacturer mainly to comply with the standards ISO 17662-1 and EN IEC 60974-14 / EN50504 or similar standards. The actual meters can be calibrated by comparing with certified measuring equipment. Inspection and calibration can be done by the power source manufacturer or by a certified agent. It is however important to know what the meter is expected to display, knowledge on how to perform the measurement and that suitable measuring devices are used.

Use of external measurement equipment

There can of course be reasons for using external measuring equipment or to complement internal measuring equipment and software, for instance:

- Test or calibration of internal measuring devices. This requires knowledge regarding the principles of the internal devices and how they are connected (connection points). Use of constant loads makes tests easier than to compare measurements in actual welding. NOTE! Loads or resistors must be suited for high currents.
- Monitoring. To warn if current, voltage or heat input is outside allowed range.
- Arc power measurements based on instantaneous values of power (instantaneous multiplication of current and voltage) when only mean values of current and voltage are available.
- Documentation, quality assurance and traceability. NOTE! To be able to compare measuring results with for instance a WPS it is important that measurements are based on the same principles and that connection points are similar.

Demands on external meters

External meters shall be validated according to the same standard as meters in the welding equipment, i.e. EN IEC 60974-14 / EN 50504 or similar.

Important consideration is the sampling frequency for digital meters. This should be a factor ten higher than changes in the waveform shape. A sampling frequency in the range of 2 to 10 kHz is typically adequate.

The calculation of the mean value is for current and voltage based on the arithmetic mean value of instantaneous values. The measuring time may be the arc time but will depend on the purpose of the measurement. RMS should only be used for pure sinus shaped waveforms.

Calculation of arc power is more difficult. The most accurate is to calculate the arithmetic mean of the instantaneous product of current and voltage. These meters are often identified by the terms “true energy”, “true power”, or “power factor”. Meters identified by the term “kVA”, “DC power”, or “average power” do not generally meet these requirements. Meters suitable for welding and meeting the requirements are however not easy to find.
An example of deliverer of equipment suitable for welding is HKS (part of the ESAB group).

Connection of external meters to the welding equipment

The current is typically measured using the return cable. This can be done by using different probes based on the Hall effect or as a voltage over a well-defined resistor in which the current flows, see Figure 1.

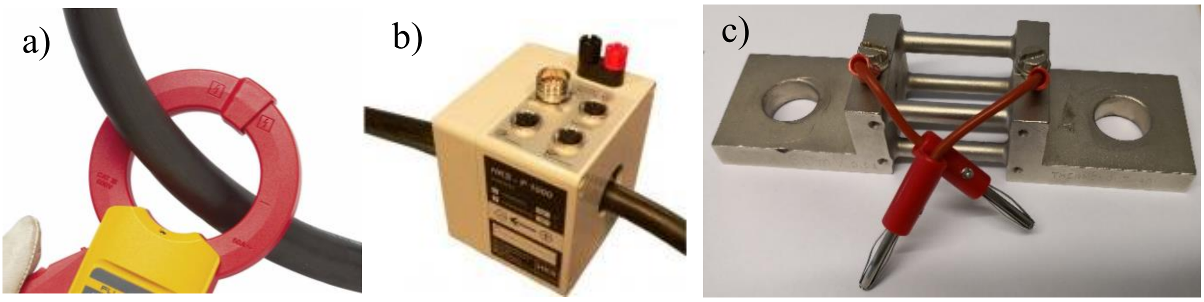


Figure 1: Sensors for current measurements: a) clamp meter b) Hall element sensor and c) current shunt resistor

Different connection points (Figure 2) for the voltage measurements will result in slightly different measuring results.

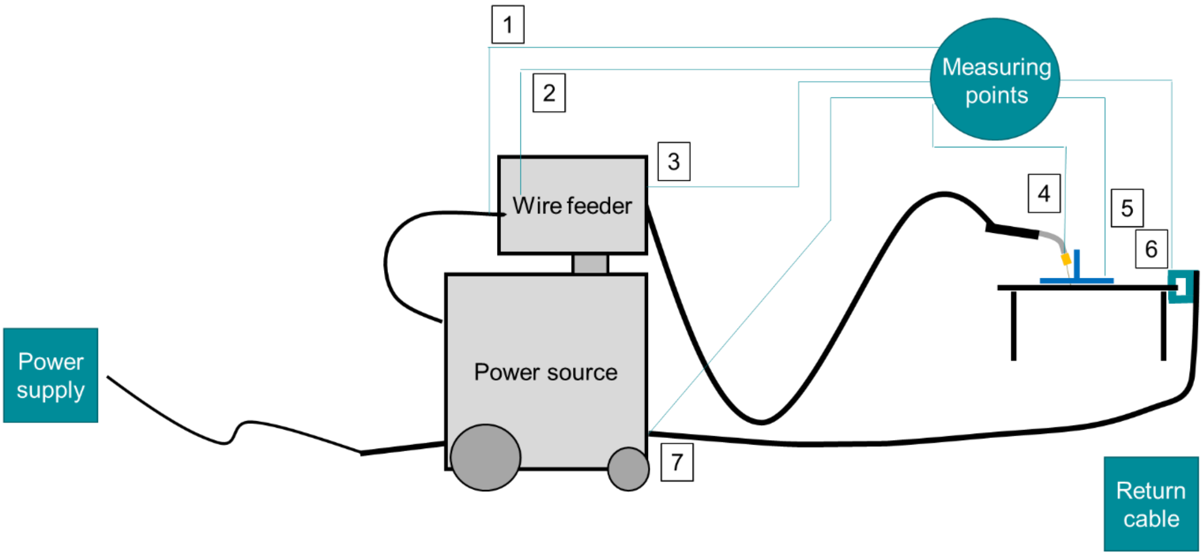


Figure 2: Illustration of different connection points for voltage measurements 1) Connection between power source and wire feeder 2) Connection point inside the wire feeder to a sliding contact to the wire) 3) At the wire feeder before the hose package 4) At the welding torch 5) At the work piece 6) at the return cable connection 7) at the return cable connection to the power source.

The most accurate connection for measuring the arc voltage is between points 4 and 5. This is often the "voltage"-value that is of highest interest for the user.

For the power source manufacturers however, the true arc voltage may not be possible to access due to varying length of cables, work object size, etc. In EN IEC 60974-14 the reference voltage is instead measured between points 1 (or 3) and 7 (or specified by the welding equipment manufacturer), i.e. the load voltage at the welding power source welding circuit connections. The displayed voltage is linked to these measuring points. This will also affect calibration and validation (and set value, when available) since they relate to the measuring of the reference voltage. However, please note that the measuring points for the reference voltage may be specified differently for different manufacturers and should be consulted in case of uncertainty).

The difference in using point 5 or 6 is typically rather small (depends on size of work object). Using point 1 or 3 instead of point 4 will add a voltage drop (that depends on cable diameters and length) and can be significant, especially at higher currents. The hose package can also act as an inductor and induce disturbance signals. Using point 2 (voltage measurements at the wire instead) or 4 should give similar results (there is no current flowing in the filler wire that results in voltage drop), however disturbance through induced signals may occur as well as disturbances from the sliding contact with the wire.

Modern power sources are often of the inverter type and the voltage may have disturbing transient signals. An electrical low pass filter close to the measuring point will be needed to remove these transient signals. Recommended cut-off frequency, according to EN 60974-14, should not be higher than 10 kHz or as recommended by the manufacturer.

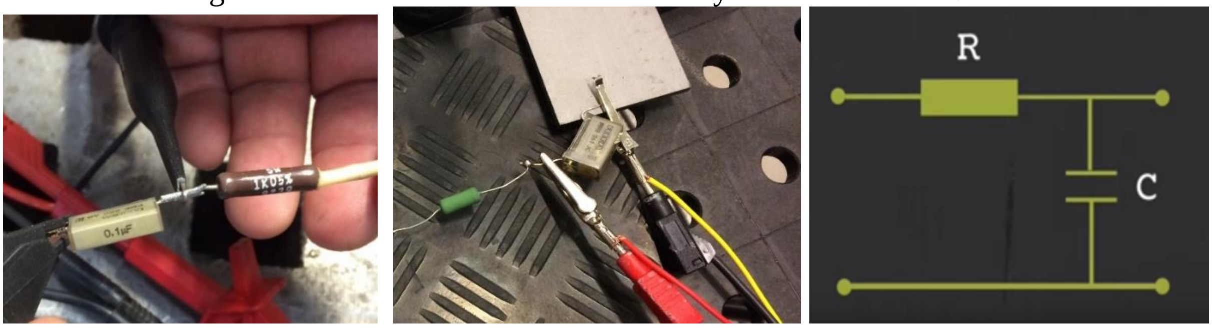


Figure 3: The photos and the schematic illustration show a low pass filter with a cut-off frequency of approximately 1.6 kHz ($f_c = \frac{1}{2\pi RC}$)*. The voltage is measured over the capacitor.*

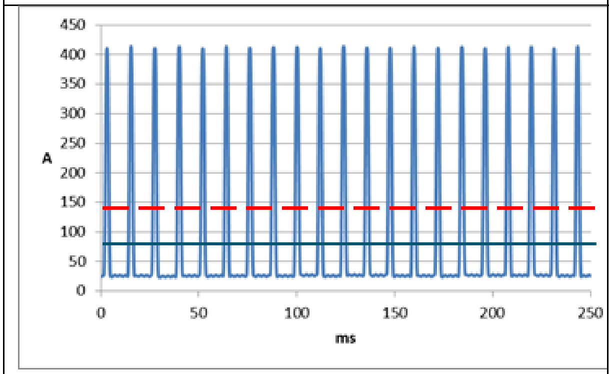
Example of deviation between arithmetic and root mean square measurements

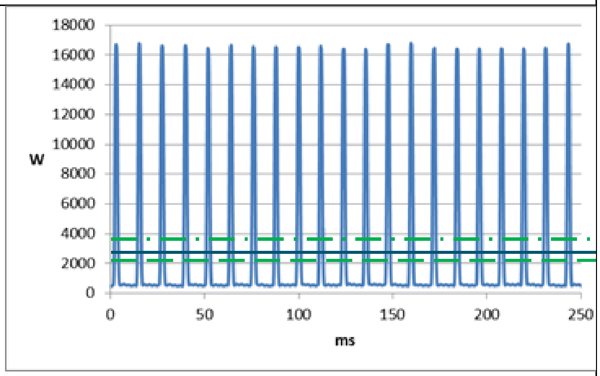
Table 1: Example of deviation between different ways to calculate the average values in MAG and SAW welding

	Current			Voltage			Arc power				
	Mean*	RMS	Diff*	Mean*	RMS	Diff*	Inst*	IxU of Mean	Diff Mean to Inst	IxU of RMS	Diff RMS to Inst
	A	A	%	V	V	%	kW	kW	%	kW	%
MIG/MAG											
Short arc	121	130	7	19.1	19.8	4	2.27	2.32	2	2.52	14
Pulsed arc	85	149	75	24.2	25.0	3	2.77	2.05	-26	3.72	34
Spray arc	185	186	1	30.2	30.3	0	5.59	5.60	0	5.64	1
SAW											
DC+	706	707	0	27.2	27.2	0	19.17	19.20	0	19.23	0
Balanced AC	464	485	5	30.5	31.0	2	14.13	14.14	0	15.01	6
Unbalanced AC 75% +2V	726	754	4	32.9	33.2	1	24.44	23.90	-2	25.03	2

** “Mean” refers to arithmetic mean, “Diff” is the difference between RMS and mean*

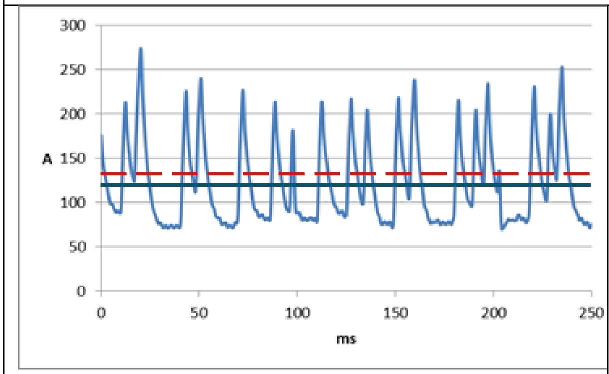
Current	*Arc power*

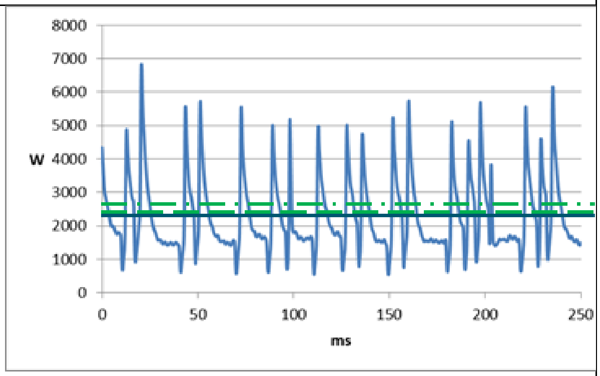




Pulsed arc

I_{mean} = 84.8 A	I_{RMS} = 148.6 A	Difference = 75%
U_{mean} = 24.2 V	U_{RMS} = 25.0 V	Difference = 3%
P_{Inst} = 2773 W	P_{IxU} = 2048 W	Difference = -26%
P_{Inst} = 2773 W	P_{RMS} = 3715 W	Difference = 34%





Short arc

I_{mean} = 121.5 A	I_{RMS} = 130.2 A	Difference = 7%
U_{mean} = 19.1 V	U_{RMS} = 19.8 V	Difference = 4%
P_{Inst} = 2270 W	P_{IxU} = 2318 W	Difference = 2%
P_{Inst} = 2270 W	P_{RMS} = 2582 W	Difference = 14%

Arithmetic mean of instantaneous values
Root Mean Square of instantaneous values
Power based on instantaneous values
Power based on mean values of current and voltage
Power based on RMS values of current and voltage

Figure 4 Example of measurement from MAG welding steel with pulsed arc and short arc

List of some standards related to measurements of current, voltage and heat input

ISO 15607:2003 Specification and qualification of welding procedures for metallic materials - General rules

ISO 15609-1, Specification and qualification of welding procedures for metallic materials - Welding procedure specification — Part 1: Arc welding

ISO 15613:2004 Specification and qualification of welding procedures for metallic materials - Qualification based on pre-production welding test

ISO 15614-1, Specification and qualification of welding procedures for metallic materials -Welding procedure test - Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloys

ISO 17671-1:2002 Welding — Recommendations for welding of metallic materials -Part 1: General guidance for arc welding

SS-EN ISO 17662:2016 Welding – Calibration, verification and validation of equipment used for welding, including ancillary activities.

ISO/TR 18491:2015 Welding and allied processes - Guidelines for measurement of welding energies

ISO 3834 Part 1-6 Quality requirements for fusion welding of metallic materials

EN 50504:2008 Validation of arc welding equipment (will be replaced by EN IEC 60974-14, First edition, 2018 - Arc welding equipment - Part 14: Calibration, validation and consistency testing)

EN 60974-1:2012 Arc welding equipment Part 1: Welding power source

EN IEC 60974-14, First edition, 2018 - Arc welding equipment - Part 14: Calibration, validation and consistency testing

This guideline was produced as a result of a project within the Centre for Joining and Structure (Swerim) with participation from: Swerim, ESAB, The Swedish Welding Commission and Dekra Industrial.

For specific questions regarding position of measuring points, calibration or validation of your welding equipment, please contact your power source manufacturer.

For questions regarding the guideline, please contact:
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