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STATISTICAL EVALUATION OF GMAW PROCESS DISTURBANCES WITH SIGNATURE ANALYSIS THROUGH ANALYSATOR HANNOVER

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ABSTRACT

For testing and optimising of arc welding processes, power sources and welding consumables different statistical methods and advanced hardware have been developed at the Leibniz Universität Hannover to investigate the metal transfer in the welding arc and the process/product quality. These advanced software and hardware systems, well known as ANALYSATOR HANNOVER, are successfully used worldwide in different welding industries (e.g. Welding Consumables, Welding Power Sources, Automotive Production, Ship building etc.). New analysator hannover software and hardware systems have been developed for arc welding process monitoring, quality assurance, process evaluation and documentation. The paper demonstrates statistical evaluations of GMAW process disturbances.

Keywords: GMAW, Process Disturbances, Computer-Aided Quality Assurance (CAQ), Statistical Evaluation, Signature Analysis, analysator hannover

INTRODUCTION

For investigation and optimisation of arc welding processes (welding parameters: voltage, current, welding speed etc.), power sources (dynamic characteristics, wave form control etc.) and filler materials (electrodes & wires) and consumables (gases & fluxes) different statistical methods have been continuously developed at Leibniz Universität Hanover for more than 45 years. The Analysator Hannover (AH) together with the AH Data Evaluation & Management System (AH-DEM) are powerful tools for quality assurance in arc welding. New software and hardware systems have been designed for arc welding process monitoring, quality assurance and documentation. The most effective method for these investigations is to record and to classify on-line electronically significant process signals and to evaluate these statistically. The random signal amplitudes and time characteristics of welding voltage u(t) and welding current i(t) allow objective statements about the welding process and its disturbances.

Statistical analyses of metal transfer in arc welding: A welding process with short-circuiting metal transfer can be divided into three different physical phases: Arc burning time with melting of electrode and base material, Short-circuiting time with metal transfer, Arc re-ignition time after the short-circuiting. These values are random variables, which can be classified statistically. From the Class Frequency Distributions (CFD) the mean values and other statistical parameters as standard deviations, variation coefficients etc. are calculated. Corresponding to this the signal amplitude values of arc welding processes with short-circuiting metal transfer can be split in three ranges: Arc burning voltage / current, Short-circuiting voltage / current, Arc re-ignition voltage / current. These ranges are also statistically evaluated by Probability Density Distributions (PDD) of the instantaneous amplitude values. The statistical analyses are carried out also for arc welding processes with free-flight metal transfer like spray transfer or pulsed transfer. For these processes short-circuiting is a process disturbance which generates spatter etc. All important data of the welding process quality can be determined from the statistical voltage-, current- and time-analyses.

Statistical evaluation with analysator hannover: The analysator hannover evaluates the following instantaneous amplitude values and time characteristics of the welding process signals u(t) and i(t) :Amplitude of welding voltage, u(t), Amplitude of welding current, i(t), Short-Circuiting Time, T_1, Burning Time T_2, Weighted Burning Time, T_3, Cycle Time, T_C

Fig.1.Defines the corresponding random time characteristics

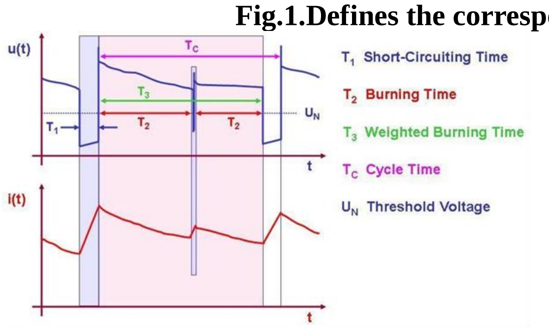


Figure 1: Random time characteristics

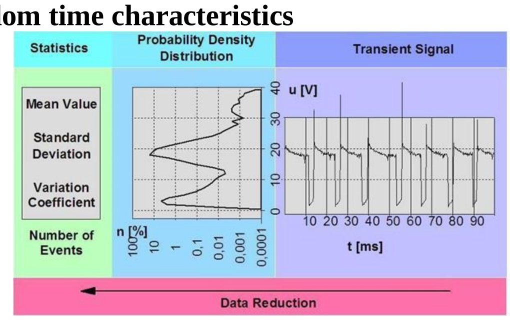


Figure 2: Data reduction during amplitude analysis

During the Burning Time T_2 [u(t) > U_N] the base metal and the filler material are molten. During the Short-Circuiting Time T_1 [u(t) < U_N], a drop transfers into the weld pool [$T_1 > T_{1MIN}$] at the work piece side or touches it only for a short time [$T_1 < T_{1MIN}$]. The Weighted Burning Time T_3 represents the time between two longer short-circuits [$T_1 > T_{1MIN}$]. Brief short-circuits are suppressed [$T_1 < T_{1MIN}$] and included in the Weighted Burning Time T_3. The Cycle Time T_C consists of T_3 and the following T_1. The time characteristics are classified in max. 1024 classes (histogram columns). From the process signals u(t) and i(t) the ANALYSATOR HANNOVER determines the following statistical distributions: PDD of the welding voltage, n(U), PDD of the welding current, n(I), CFD of the Short-Circuiting Time, N(T_1), CFD of the Burning Time N(T_2), CFD of the Weighted Burning Time, N(T_3),CFD of the Cycle Time, N(T_C). Additional to the graphical representation of these distributions, the program calculates the following statistical values:Mean value, m, Standard deviation, s, Variation coefficient, s/m, Maximum of distribution, Class of maximum (modal value), Total number of events, Minimum and maximum of the examined variables. Fig. 2 shows the amplitude signal evaluation and the statistical data reduction. Furthermore the program is equipped with the following output capabilities: Storing of test data and of protocol information, Output of a test protocol by printer, which contains all or parts of the above mentioned values, graphical representations and protocol information, Output of statistical distributions in a binary file or an ASCII-File for data processing with other software, Storing of the transient signals u(t) and i(t) in a binary file, Output of the transient signals u(t) and i(t) in a binary file.

The class ranges and the class width for the amplitude analyses and the time analyses are programmable. Furthermore the measuring time and the voltage threshold U_N are pre- selectable. The measured data, the PDD and the CFD as well as the statistical values and the process parameters can be displayed. For documentation regarding to ISO 9000 all these data can be printed out and stored on hard-disk or DVD.

Data acquisition and processing system: Different analysator hannover (AH) has been developed at the Leibniz University Hanover in the past. The analysator hannover AH-XXV is the newest generation of a computer-aided monitoring and analysing system, consisting of a 19"-rack- mounted Industrial PC and special hardware and software for data acquisition, data processing and documentation for industrial welding applications. Portable AH systems on Notebook or Laptop hardware platform are also available for welding field services. The AH-XXV is typically configured as following:

Processor:	Modern Intel or AMD CPU
ADC-Board:	16 bit, 8 Channels, >250 KS/s (max. 2MS/s)
RAM:	>4GB
Hard-disk:	>500G
DVD-Drive:	R/W

Via a standard interface the AH-XXV can be connected to a Local Area Network (LAN) for data transfer and communication with Internet. Because the Industrial PC is running under MS-WINDOWS 7 the test data files can be additionally evaluated with other typical PC- software (e.g. MS-Excel etc.). Furthermore the AH-XXV can be used as a Multi-Channel-Digital-Storage-Oscilloscope or Transient-Recorder simultaneously to the statistical analyses. All together the on-line signal recording and the statistical analyses give objective data for evaluating and optimizing welding process parameters, process quality, welding equipment, filler materials and consumables.

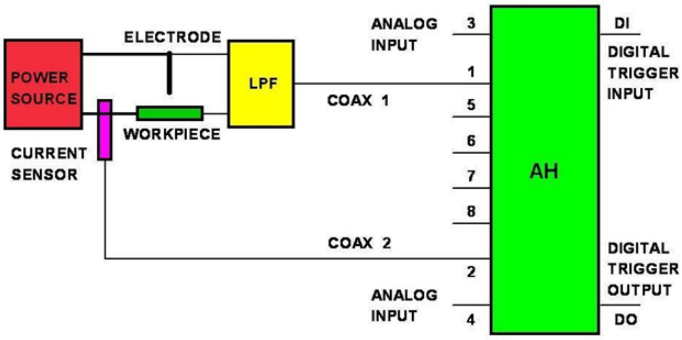


Figure.3.Block diagram of measuring set-up with analysator hannover

The block diagram of the ANALYSATOR HANNOVER measuring set-up is presented in Fig. 3. The Analog Voltage Channel 1 of the ANALYSATOR HANNOVER (AH) is connected to the welding torch (ELECTRODE) and the base metal (WORKPIECE) via the low pass filter (LPF) with voltage divider and peak clipper. A compensated HALL-Sensor (CURRENT SENSOR) feeds the Analog Current Channel 2 of the AH by a coaxial cable (COAX 2).

The ANALOG INPUT 3 and the ANALOG INPUT 4 are recording two other analog signals (e.g. wire speed, gas flow rate or synchronous marks of a high speed video camera etc.). The DIGITAL TRIGGER INPUT DI is starting the measuring period of the AH by a TTL signal. The DIGITAL TRIGGER OUTPUT DO can start a high speed video camera (TTL).

Welding procedure & statistical evaluation: With an electronically controlled GMAW set-up beads (BOP) in horizontal position have been carried out fully mechanised for evaluation and optimisation process parameters with an inverter power source (CP characteristic). Standard solid wire (ER50-6), diameter: 1.2mm, with 100% Argon (Ar 4.6 / 15l/min) and plates (mild steel / dimension: 400x50x6mm) have been used. The measuring time of the ANALYSATOR HANNOVER was set to 5 sec. for each welding test. During this time 500.000 samples of the instantaneous voltage value u(t) and 500.000 samples of the instantaneous current value i(t) have been simultaneously recorded and on-line evaluated. Three GMAW tests (e.g. TIM_254, TIM_255 and TIM_256) for each parameter set have been welded under same welding conditions for reducing statistical errors.

Fig. 4 - Fig. 7 show oscillograms of welding voltage u(t) and welding current i(t) of a typical GMAW test TIM_256 under same welding conditions. Especially the different short- circuiting phases (longer short-circuits, e.g. (G32) & (G50), T1 > 12ms, are process disturbances, Fig. 6) and the arc break-down (E), Fig. 7, (Current I = 0A), are remarkable for the chosen welding conditions. The inverter power source generates high frequency voltage spikes (J), Fig. 7, for re- igniting the arc after arc break-down. There high statistical errors occur in the sector U[35V < U < 55V], (J), due to the Aliasing Effect (under-sampling) depending on the too low sampling rate of 100KS/s, Fig. 9.

Also a strong Stick-Slip Effect (O) & (P) can be seen in Fig. 5, caused by alternating friction forces (static friction and sliding friction) inside of the connection cable between the welding torch and the wire feeder. This generates bi-modal CFD for T_3 and T_C, Fig. 13 & Fig. 14. The re-ignition after short-circuits with droplet transfer occurs with high voltage peaks (K), Fig. 4, due to the inductance in the electrical welding circuit. The maximum short- circuiting current (C), Fig. 6 & Fig. 7, and the minimum arc current (F), Fig. 6 & Fig. 7, are limited by the electronic feed-back control of the inverter power source. Significant qualitative differences can not be evaluated objectively and quantitatively from the oscillograms u(t) and i(t). Only some qualitative differences of the stochastic process signals can be subjectively recognised during the 5 sec. measuring period.

Therefore the statistical methods of the ANALYSATOR HANNOVER are needed for objective quantitative numeric evaluation of the random process signals u(t) and i(t). With the additional software module analysator hannover data evaluation & measurement AH-DEM and the integrated sub-modules the original recorded welding test data are further on statistically evaluated and printed as pictures (*.bmp, *.gif or *.jpg) in AH-Graphics and as statistic tables in 'comma separated value' format (*.csv). Different other statistical parameters like minimum current, maximum current, True Root Mean Square Values of u(t) and i(t), as well as True Electrical Power values are also calculated off-line with AH-Statistics in AH-DEM. From the random process signal u(t) and i(t) the dynamic process diagram u(i) with different working lines, the transient true electrical power signal p(t) and the process resistance signal r(t) can be calculated off-line. This software module provides also the AH-Data-Base for the recorded welding test data with different search functions (AH-Search).

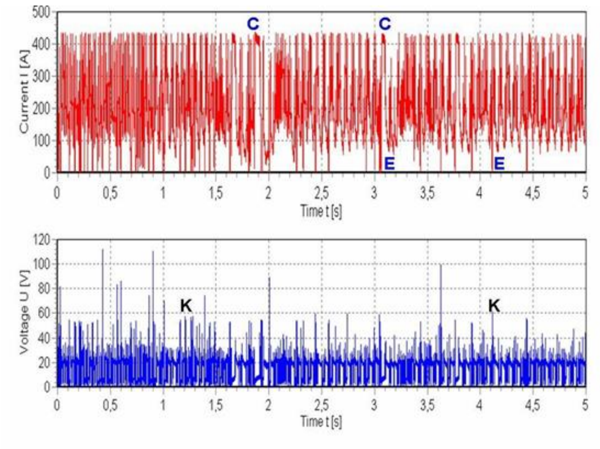


Figure 4: Oscillograms i(t) and u(t) of Test TIM_256 / Process Disturbances

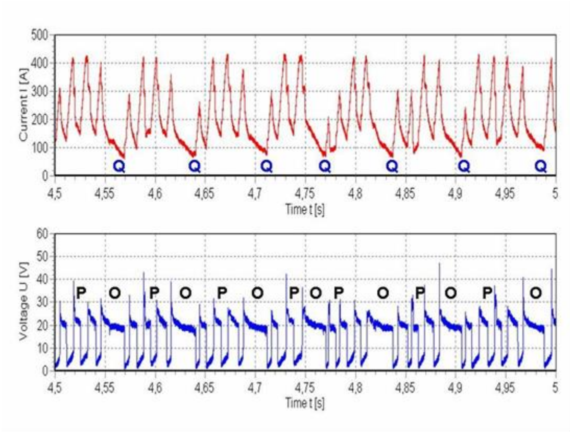
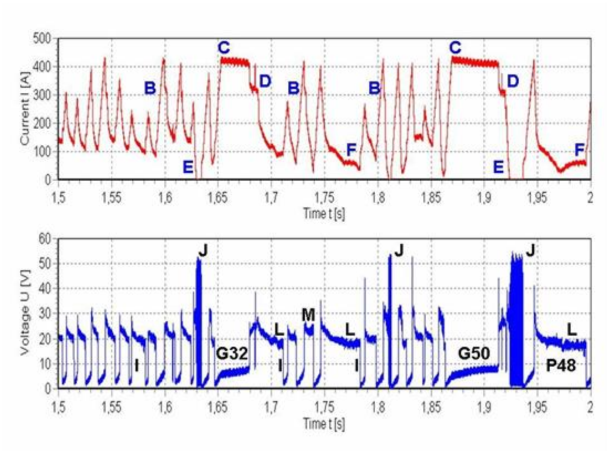


Figure 5:Oscillograms i(t) and u(t) of Test TIM_256 / Strong Stick-Slip Effect



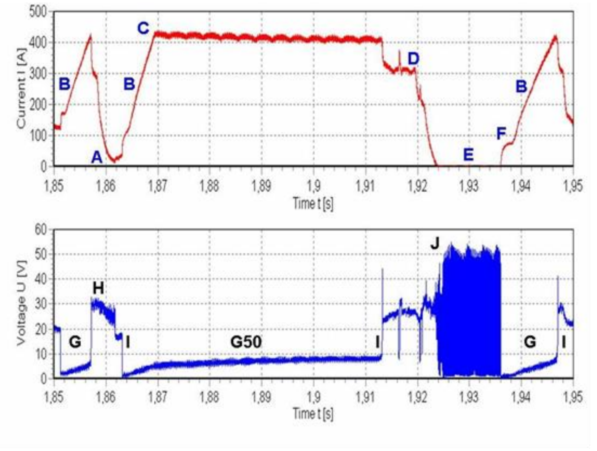
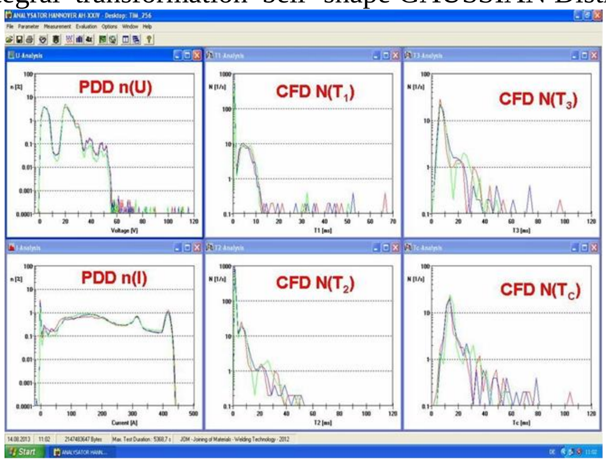


Figure 6:Oscillograms i(t) and u(t) of Test TIM_256 / Long S.C. / Arc Break-Down

Figure 7:Oscillograms i(t) and u(t) of Test TIM_256 / Long S.C. / Arc Break-Down

Fig. 8 shows a screenshot of ANALYSATOR HANNOVER AH-XXV of the three GMAW tests TIM_254, TIM_255 and TIM_256 with all registered statistical distributions. Fig. 8, left / up, is comparing the Probability Density Distributions PDD n(U) of the instantaneous voltage values of these analyses (Class width: □U = 0.5V). By the statistical AH analyses significant quantitative differences between the tests are evident and specially shown in different class frequencies in the short-circuiting and arc burning sector (0V<U<35V). The Probability Density Distributions PDD n(I) of the instantaneous values of the welding current are superposed in Fig. 8, left / down, (Class width: □I = 1.953A). By the statistical AH analyses significant quantitative differences between the tests are evident and specially shown in different class frequencies in the low-current sector (0A<I<50A). The middle and the right pictures are showing the Class Frequency Distributions CFD of the random time variables, Fig. 1: Short-Circuiting Time T_1, Arc Burning Time T_2, Weighted Burning Time T_3, Cycle Time T_C.

All statistical distributions show multi-modal characteristics (more than one relative maximum), which means different physical phenomena (e.g. arc burning (L), arc break-down (E), short-circuiting (G), arc re-ignition (K) etc., Fig. 8 & Fig. 9) are superposed during the measurement. The transformation from the time domain (oscillograms u(t) & i(t)) to the probability domain (PDD) is following definite rules, e.g.:Constant amplitudes in the time domain are generating relative maxima in the probability domain. Linear slope up (e.g. short-circuiting current) and linear slope down in the time domain are generating constant sectors in the probability domain (Equal Distribution). Steep slope up & steep slope down, e.g. regarding to short-circuits, are generating relative minima in the probability domain. 'White Noise' process signals generate by GAUSSIAN integral transformation bell- shape GAUSSIAN Distributions.



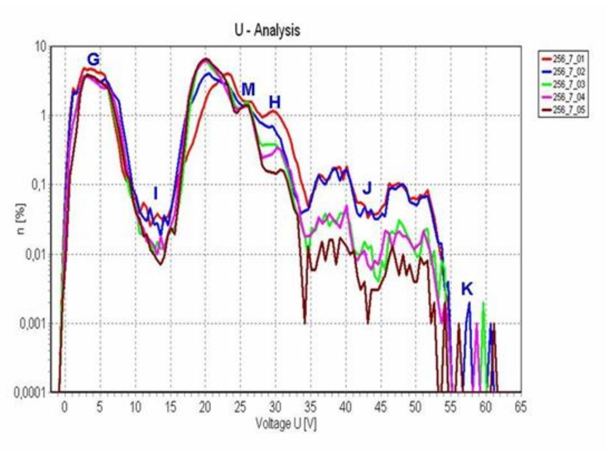


Figure.8:AH-Screenshot / Test: TIM_254, TIM_255, TIM_256

Figure.9:Multi-modal PDD n(U) / Class Width: □U = 0.5V / Test TIM_256

Class Width: □U = 0.5V / Class Width: □I = 1.953A; U_N: 13V / T_{1min}: 1ms / Class Width: □T_1 = 1ms / Class Width: □$T_{2,3,C}$ = 2.5ms; Left (up): PDD n(U) of welding voltage u(t) Left (down): PDD n(I) of welding current i(t) Middle (up): CFD N(T_1) of Short-Circuit Time T_1; Middle (down): CFD N(T_2) of Arc Burning Time T_2; Right (up): CFD N(T_3) of Weighted Burning Time T_3; Right (down):CFD N(T_C) of Cycle Time T_C

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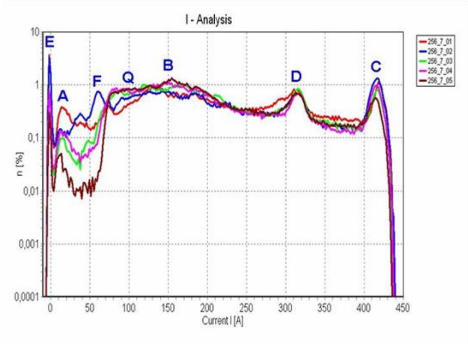

Figure 10: Multi-modal PDD n(I) / Class Width: □I = 1.953A / Test TIM_256

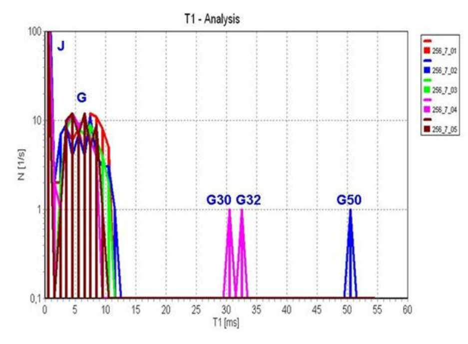

Figure 11: CFD $N(T_1)$ / U_N: 13V / Class Width: □T_1 = 1ms / Test TIM_256

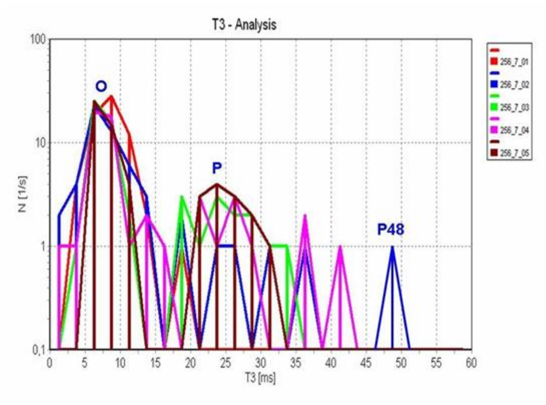

Figure 12: CFD $N(T_2)$ / U_N: 13V / Class Width: □T_2 = 2.5ms / Test TIM_256

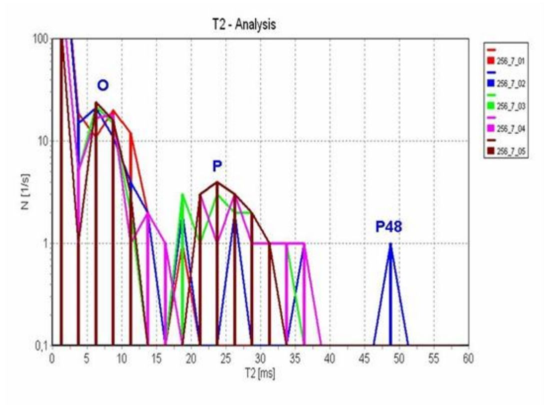

Figure 13: Bi-modal CFD $N(T_3)$ / U_N: 13V / T_{1min}: 1ms / Class Width: □T_3 = 2.5ms

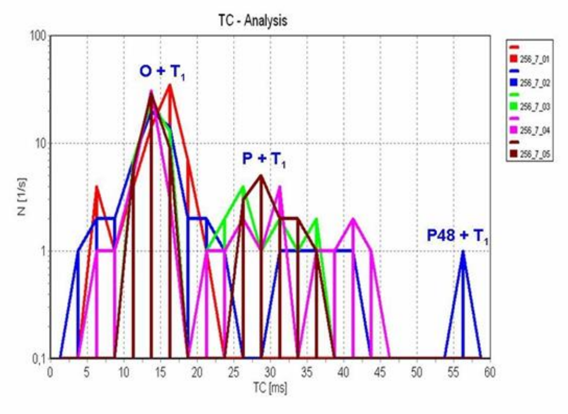

Figure 14: Bi-modal CFD $N(T_C)$ / U_N: 13V / T_{1min}: 1ms □□ Class Width: □T_C = 2.5ms

After the original on-line measurements off-line analyses have been carried out with the AH-XXV for further evaluation of the typical GMAW test TIM_256. The 5s GMAW test was split in five 1s-time-slices (256_7_01 to 256_7_05), Fig. 9 - Fig. 14, Tab. 1, for evaluating the tendency of the process quality in the measuring period. Tab. 1 gives the statistical values of the 1s-time-slices of TIM_256. The short-circuiting detection threshold voltage was set to U_N = 13V, Fig. 1, and the class width of the Short Circuiting Time T_1 to □T_1 = 0.5ms. The mean value of the Short-Circuiting Time was decreasing from T_1* = 6.70ms with a mean standard deviation ST_1 = 2.41ms to T_1* = 5.80ms with a mean standard deviation ST_1 = 1.78ms. The number of Short-Circuits N_1* in 1 sec. measuring time is decreasing from N_1*=66 to 57. The mean value of the Arc Burning Time was increasing from T_2* = 7.5ms to 11.37ms, Tab. 1. The welding voltage mean values U_W are similar (about 15V), but the standard deviation S_{UW} of the welding voltage of segment 256_7_05 shows as a minimum

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S_{UW} = 8.42V, Tab. 1, which demonstrates higher process quality for the last 1s-segment (Test: 256_7_05) of test TIM_256.

The Arc Burning Voltage U* in the sector U [14,38V < U < 127,88V] decreases from U* =25.23V (Standard Deviation S_{UW}* = 5.75V) to U* = 21.39V (Standard Deviation S_{UW}* = 2.98V) in the last second (Test: 256_7_05), which demonstrates also the higher process quality at the end of the welding test TIM_256. Corresponding herewith the Relative Arc Burning Time increases from B_U* = 54.40% to B_U* = 66.71% with increasing T_2*, Tab. 1. These statistical analyses of the selected GMAW test TIM_256 prove objectively the different process quality during the 5 sec. measuring period. All statistical distributions demonstrate the typical droplet transfer with mostly relative 'short' short-circuits, T_1 < 12ms, and 'longer' short-circuits, T_1 > 12ms. Furthermore different process disturbances like stick slip effect and arc break-down, which generates controlled voltage spikes by the inverter power source for arc re-ignition, can be found.

CONCLUSION

The analysator hannover realises by statistical analyses of arc welding processes: Objective and reproducible values for developers of filler materials (solid wires, coated electrodes, flux-cored wires etc.), consumables (gases, fluxes etc.), equipment (power sources, wire feeders etc.). Cost saving in the developing phase by time saving (staff & energy) and material saving (base metal & consumables). Quality assurance & documentation [CAQ] according to ISO 9000 ff. in the production line (filler materials, consumables & equipment etc.). Validation / calibration of welding procedure & equipment. Concluding the results of the investigations carried out: The on-line data acquisition and statistical analyses of the random welding process signals u(t) and i(t) with the analysator hannover give objective statements for optimisation of arc welding processes, welding equipment, filler materials and consumables.

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