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Resistance Welding Applications in Electronics, Electrical Engineering and Precision Mechanics.

1. Introduction

The growing use of heavy-duty electronic devices and components in motor vehicles has led to increased use of previously unused or only rarely used bonding methods [1]. While soft soldering and crimping were the most frequently used methods until just a few years ago, these methods are today reaching the limits of their possibilities due to the steady increase in power density in the devices. Soft-soldered connections are dependable up to approximately 125°C, whereas crimp connections are subject to aging with rising contact resistance as they get older.
The same applies to numerous electronic devices, whose functional density is increasing as their size and weight fall, e.g. portable electronic devices.

Owing to these constraints, bonding methods with the following pad requirements have been used increasingly in the past few years:

- low electrical resistance,
- high thermal stability,
- high mechanical strength,
- good corrosion resistance.

The properties may only change within tight tolerance ranges over the complete product lifecycle. Resistance welding fulfills these requirements to a high degree.

2. Applications

Resistance Welding in the Automotive Industry

The product lifecycle equates, depending on the vehicle class, to a total mileage of 300 000 to 500 000 km, in exceptional cases even significantly higher (e.g. taxi use), or a running time of 10 to 15 years. At the same time devices are having to become smaller with the same high level of integration, leading directly to higher temperatures due to higher power densities.

Depending on the function of the device, there are highly different constraints for construction of the pads. Whereas sensors emit only very low signal currents and accordingly only need small wire cross sections, electric motors in electronic power steering systems require peak currents of several hundred amperes (figure 1) and starters even of several kiloamperes, albeit only briefly. The heat loss must be kept to a minimum and dependability of the bond is obligatory. This necessitates correspondingly large cross sections.

Similarly stringent requirements apply to actuators, e.g. safety fuses, airbag triggers (figure 2) and charge primers. In these cases the electric resistance between the two welding spots must lie within very tight tolerances. Magnetic coils, which are usually made of enameled copper wires with diameters of 0.025 mm and more, must satisfy similar high demands on dependability (figure 3).

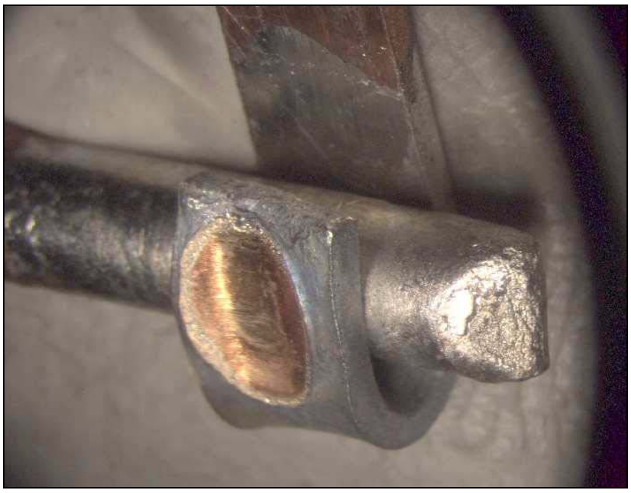


Figure 1. Heavy-Current Application - Reactor Wire. Diameter 3 mm.

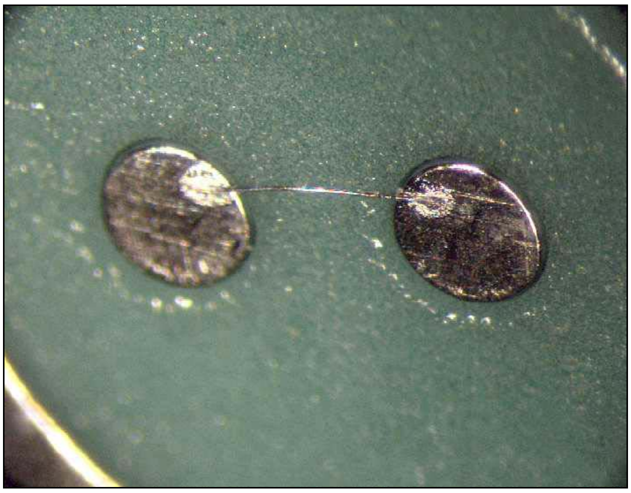


Figure 2. Micro Application - Airbag Trigger Wire. Diameter 24 µm.

Figure 3. Welding Application - Enameled Copper Wire on Square Pin. Wire diameter 70 µm.

These requirements inevitably limit the possible materials that can be used to a high degree. Copper or copper-base alloys are first choice. In many cases they represent a good compromise between high electrical conductivity and adequate mechanical strength. The electrical conductivity ($\lambda_{el.}$) of industrially pure copper (e.g. E-Cu58) is about 58 MS/m. E-Cu58 is therefore the second-best conductor of electricity, only surpassed by silver at 62 MS/m. Its relatively low tensile strength of about 300 N/mm² compared to, for example, steel can be increased with various alloying constituents. Alloying with, for example, 0.15% Sn increases the strength up to 490 N/mm² and with 6% Sn, even to 720 N/mm², albeit at the price of a reduction in electrical conductivity to about 50 MS/m and 9 MS/m respectively. The electrical conductivity of CuSn6 is therefore the same as that of S235 (old designation St37). However, CuSn0.15, with a tensile strength of up to 490 N/mm² and an electrical conductivity of about 50 MS/s, represents a good compromise for many applications.

Resistance Welding in Precision Mechanics and Electrical Engineering/Electronics

Beginning with the quality requirements for electrical bonding for safety-related connections in automotive engineering such as:

- repeatability of the bonding process,
- dependability of the connection,
- possibilities for process monitoring,

there are further appropriate applications for resistance welding. It is used, for example, to manufacture mechanically very strong carbide tools (figure 4). It is also used to join antennae of very thin enameled copper wire to terminal points on organic base materials (figure 5) so that safety-related information can be transmitted reliably in an extremely large temperature range. In the lamp industry the process is used to join refractory metals without causing cracks in the very sensitive sintered metal (figure 6). Fusion welding methods are far inferior in such applications because the solidification process of the molten mass is often very problematical and leads to embrittlement and cracking.

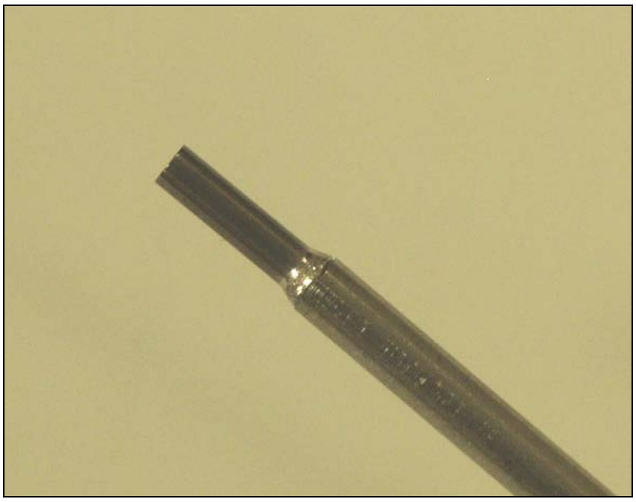


Figure 4. Precision Mechanics Application -
Tooth Drill with Carbide Tip.

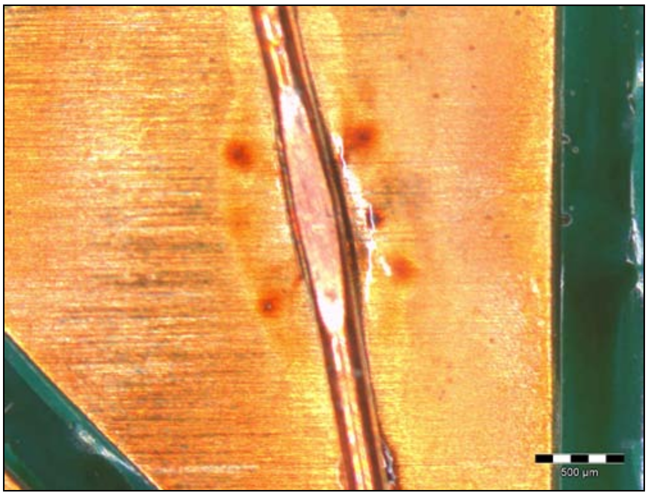


Figure 5. Electronics Application - Welded
Enameled Copper Wire Diameter 50 µm.

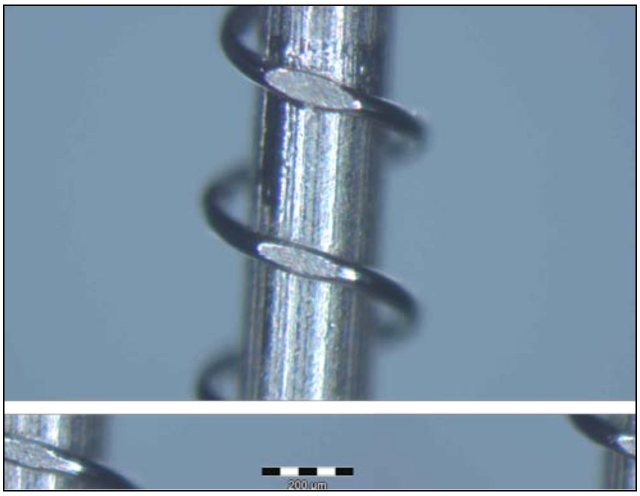


Figure 6. Lamp Production Application -
Tungsten Wire Diameter 60 µm -
Electrode for Discharge Lamp

3. Principles of the Process

While the good electrical conductivity of copper is very advantageous for operation of the products, it is more a disadvantage for fabrication by resistance welding. As the term resistance welding already says, the heat arises at the bonding point by resistance heating. In contrast to resistance welding of steel, the resistances are, however, usually much lower; likewise the mechanical strength and thermal stability of the parts, while the thermal conductivity is significantly higher. There is only a minor difference in specific heat capacity. This largely balances out. If one takes the different densities of the materials into consideration, the heat capacity can then be regarded as the same for identical part geometries. In keeping with these differences in the materials, there are several significant differences between resistance welding of copper and steel.

	$R_{p0.2}$ [MPa] (ϑ=20°C)	$R_{p0.2}$ [MPa] (ϑ=300°C)	$\lambda_{el.}$ [MS/m] (ϑ=20°C)	$\lambda_{th.}$ [W/mK] (ϑ=20°C)	C_p [J/kgK] (ϑ=20°C)
E-Cu58	≈180	≈55	≈58	≈400	≈390
S235 (St37)	≈235	≈155	≈9	≈80	≈470

Table 1: Selected Material Data of Copper and Steel

4. Thermal Equilibrium

Difference to Welding of Steel

As can be seen from table 1, there are considerable differences in electrical and thermal conductivity between copper and steel. The electrical conductivity of copper is about six times as high and the thermal conductivity about five times as high as that of unalloyed and low-alloy steel.
Due to the low contact resistance, this leads in resistance welding of copper to significantly lower heat development by the Joule effect at the bonding point than when welding steel.

The formal correlation is: $Q = I^2 \cdot R \cdot t$ [J]

The high thermal conductivity of the material also results in the heat dissipating very quickly into the surroundings and material further away from the actual welding point heating up. For this reason times are selected for resistance welding that lie about one order of magnitude under those for resistance welding of steel. A large part of the heat development in resistance welding of copper comes from the contact resistance between electrode and part being bonded. The electrode materials tungsten (W), molybdenum (M) and titanium-zirconium-molybdenum (TZM, 0.5% Ti, 0.08% Zr, 0.02% C, rest Mo) usually used for welding of copper have far higher specific resistances than the base material that is to be welded. This leads to relatively strong heating at the pad between electrode and workpiece. This heat is transmitted by heat transmission into the workpiece and supplies a considerable part of the energy needed to produce the bond. When welding steel the heat arises primarily from the high contact resistance at the bonding point and the high material resistance of the parts being bonded.

Types of Bonds

Due to the differences between the resultant maximum temperatures and the mostly small sizes of the parts, the formation of a molten mass is only possible to a limited extent in resistance welding of materials with good conductivity (figure 7). The formation of a molten mass is not absolutely essential.
The weld joint is created in the semi-plastic state of the materials (diffusion welding, surface welding). In this regard it must be noted that the surfaces are not only of importance for the contact resistances of heat development, but also for the formation of the metallurgical weld joint. If, for example, highly oxidized metals are welded together, these oxides cannot dissociate in the molten mass, but settle in diffusion welding on exactly the welding plane, with the result that the dynamic strength of the joint drops drastically, although oxidized surfaces actually cause a higher contact resistance and therefore also higher temperatures. For this reason surface and coating specifications are very important and often determine weldability.

The main advantage of diffusion welding is the usually higher dynamic strength due to the lower bonding temperature and consequently lower metallurgical stress concentration.

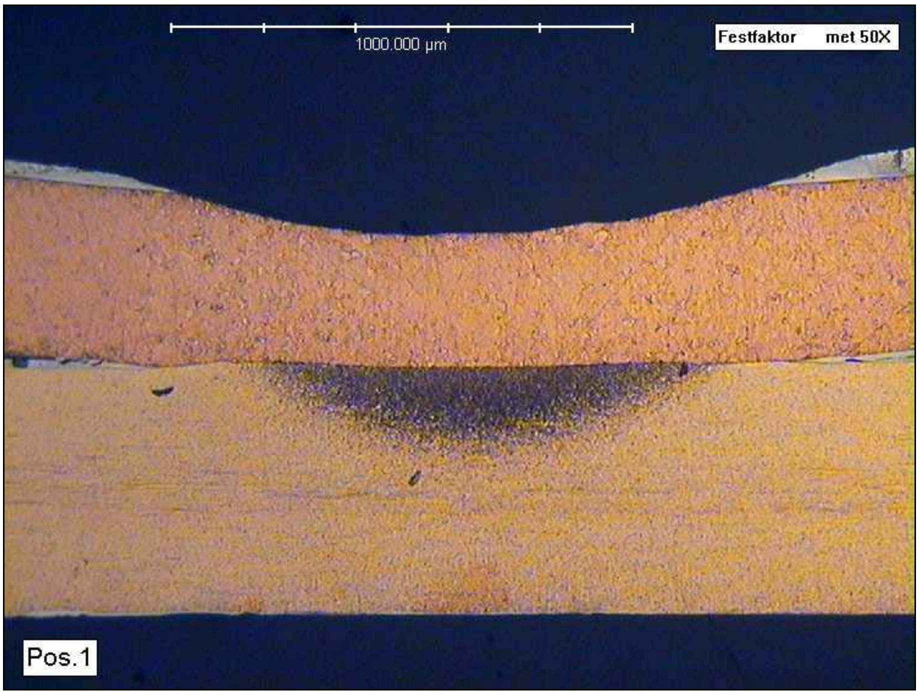


Figure 7. Micrograph. Spot-Welded Joint.
Bottom Material CuSn6 Tin-Plated 2 – 5 µm, Top Material E-Cu58 Tin-Plated 2 – 4 µm.

5. Dynamic Influences

The Three-Dimensional Process

Resistance welding is a manufacturing process described by an electrical, mechanical and time dimension. The fourth dimension is the material, which, however, the welding equipment has to date not been able to influence. For the repeatability of the process this means that the dynamic stability of the individual electrical and mechanical process parameters is very important. Uncontrolled electrical and mechanical vibrations during the process change the heat formation and thermal conduction and for this reason should be avoided by process control or at least detected by monitoring.

Active Control of the Mechanical Axis of the Welding Process

While the electrical dimension is only relevant as long as the weld current is flowing, the mechanical parameters have an influence on the quality of the joint before, during and after flowing of the weld current. They influence the contact conditions responsible for the formation and dissipation of the heat. In the first step of the process the welding electrodes must bond the parts together constantly as quickly as possible in order to produce repeatable electrical and thermal conditions. The initial deformation after application of the welding load is considerable especially in the case of the mostly soft materials. Thereafter the weld current is released, which leads to a mechanical “glitch”. If the mechanical system then vibrates due to unfavorable spring-mass ratios, repeatable starting conditions of the process can be influenced negatively. The electromechanical influence of the weld current can also cause vibrations in the electrode system. The last step of the process is the retraction of the electrodes. The hold time has an influence on the speed of cooling of the parts being joined and therefore on the metallurgical properties of the joint. It is clear in all steps of the process that quickly adjusted devices have an undeniable advantage over passive, uncontrolled welding equipment, especially when also considering the short process time due to the mostly quick indirect cooling of the parts. Inverter current sources for quick adjustment of the electrical parameters and servoelectric weld pincers (figure 8) as stiff, active mechanical axis have proven there worth in practice and are state of the art [2, 3].

A distinction is drawn between the basic principles of the construction of weld heads:

- mechanical
    - foot actuation with spring system
    - cam actuation with spring system
    - pneumatic adjustment with spring system
    - motor-driven adjustment with spring system
- pneumatic
    - direct pneumatic
    - pressure control by proportional valve
- servomotor-driven
- electromagnetic
- piezoelectric

It is important in the case of all basic principles to stabilize the dynamic electrode load. For the electrode movement this requirement means a low-inertia acceleration characteristic or follow-up characteristic. The greater this acceleration needs to be for the respective welding application, the greater the influence of the mass that is to be accelerated is. For this reason high-quality weld heads are equipped with extremely light electrode systems so that critical welds can be controlled better. The influence of the moved mass on the aforementioned vibration effects is analogous. These vibrations can only be minimized by reducing the mass and increasing the stiffness of the system.

Figure 8. Servo Weld Pincer.

6. Process Monitoring and Evaluation

100% Control

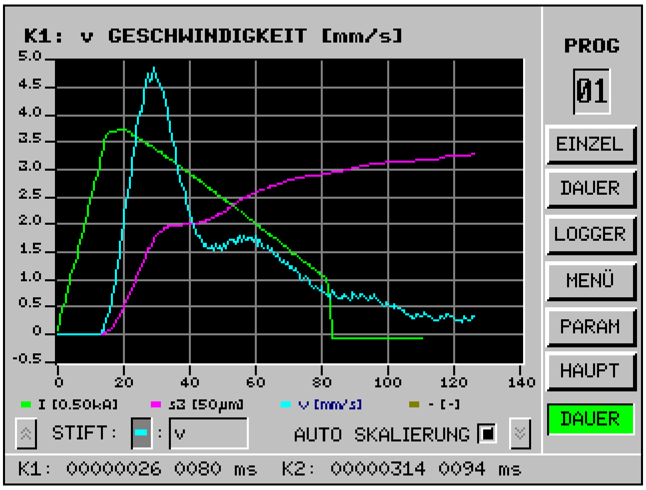
Process analysis and process monitoring are important aspects of quality assessment especially in the case of bonds in electronics, electrical engineering and precision mechanics because every poor weld can possibly lead to the total failure of a complete component. This is particularly true in the case of small parts if the complete bond consists of only a single welding spot. The aim in these applications, in particular, is to achieve zero welding error production.

For evaluation at least one parameter per process dimension is monitored. The aim is to ensure heat input by monitoring the electrical parameters such as current, voltage or derived variables. The mechanical process parameter force describes the thermal and electrical bonding. The difference between heat input and heat dissipation at the weld is derived indirectly from the penetration and represents 100% process monitoring for dynamic repeatability.

Graphic Evaluation and Analysis

Various diagrams of the process parameters provide detailed information:

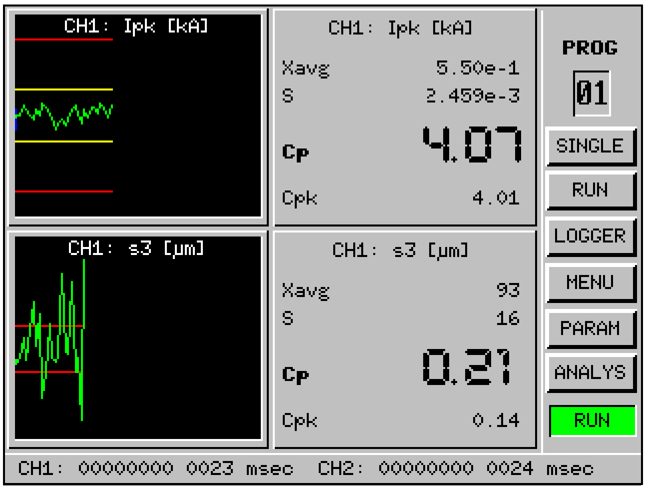
- dynamic process waveform (individual process evaluation) (figure 9)
- PLC runchart (trend) (figure 10)
- histogram (stability, analysis of systematic errors) (figure 11).



STIFT: v AUTO SKALIERUNG ☑

K1: 00000026 0080 ms K2: 00000314 0094 ms

Figure 9. Waveforms.

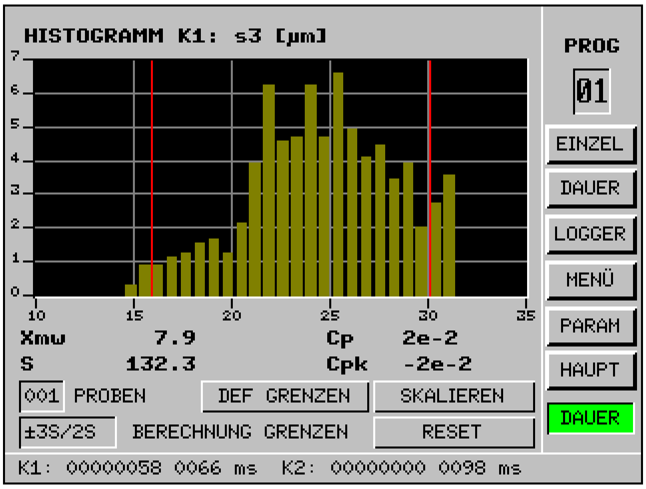


CH1: Ipk [kA]
Xavg 5.50e-1
S 2.459e-3
Cp 4.07
Cpk 4.01

CH1: s3 [µm]
Xavg 93
S 16
Cp 0.21
Cpk 0.14

CH1: 00000000 0023 msec CH2: 00000000 0024 msec

Figure 10. PLC Runchart.



Xmu 7.9 Cp 2e-2
S 132.3 Cpk -2e-2

001 PROBEN

±3S/2S BERECHNUNG GRENZEN

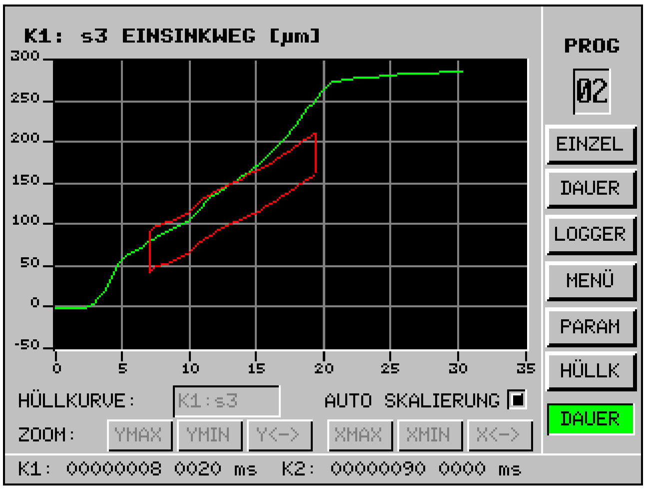
K1: 00000058 0066 ms K2: 00000000 0098 ms

Figure 11. Histogram.

For example, excessively progressive penetration waveforms can be detected as accelerated movements during the welding process and the profile of the weld current then adjusted. Secondary maxima in the Gaussian energy distribution can uncover a disruptive shunt at the weld. Also helpful is the possibility to identify visible changes in the process parameters in the PLC runchart and to initiate countermeasures in time before defective parts are produced.

Static and Dynamic Monitoring

A distinction is drawn in process monitoring between static and dynamic monitoring. Static monitoring is the comparison of measured numeric process parameters with set limits. Dynamic monitoring, by contrast, is the comparison of every single point of a waveform. This envelope waveform monitoring is therefore a combination of quantitative and qualitative monitoring. The main aim is to find and mark parts whose process parameters display unwanted vibrations or variations during the short process and therefore do not correspond to the defined process waveform (figure 12).



PROG 02

HÜLLKURVE: K1:s3

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K1: 00000008 0020 ms  K2: 00000090 0000 ms
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Figure 12. Bad Weld – Penetration Outside Envelope Waveform

Interactions on Reaching Limit Values

In addition to control of the electrical and mechanical parameters according to certain setpoint curves, controls that react interactively to infringements of set limit values are also useful. In such cases the process sequence can be changed or stopped when a limit is reached. Some time ago the “path-dependent current cutout” heralded a real jump in quality. New interactions such as, for example, APC aim at stabilizing the starting conditions of the process [4].

7. Trend

The trend in process technology is heading towards adaptively controlled processes. Future systems will definitely optimize themselves or at least detect sources of error from feedback information on the quality of the welded parts. What, however, remains important with all the complexity of the process are intuitive, easy operability and simple describability.

8. Literature

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