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Aluminum Resistance Spot Welding and its Welding Quality System

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Abstract:

Resistance spot welding (RSW) is a method of assembling a welding piece into a lap joint and pressing it between two electrodes, and using resistance heat to melt the base metal to form a solder joint.

Compared with riveting or other welding methods, spot welding has the advantages of high joint quality, fewer auxiliary processes, high production efficiency, no need to add welding materials, and easy to realize mechanization and automated production. It is widely used in automotive, aerospace, and electronic technology industries.

In early phase of testing the quality of solder joints is to evaluate through destructive testing, to test the tensile strength of the sample solder joints and to measure the nugget diameters.

Although this method can directly correlate the inspection parameters with the quality of the solder joints, it costs enormous time, labor and cost to the welding production, and cannot fully guarantee the quality of the welding. It is not possible to implement online inspection and thus has poor real-time performance. Therefore, by detecting factors that affect the quality of the welding spot, such as welding current, welding voltage, force between electrodes, dynamic resistance, etc., the welding quality can be indirectly judged and the online inspection of the welding quality is realized, which has become a common method for testing the quality of spot welding. This is also the basic idea adopted by the classifier of welding quality system (WQS), which produce on-line classification of the solder joints according to their physical conditions.

In this thesis, I performed a theoretical analysis on the aluminum RSW (described in the first chapter). The difficulties of aluminum RSW is introduced, also a comparison has been made between steel RSW. Further, the dynamic behavior of aluminum RSW is explored in detail. And I have implemented a fuzzy rule-based system (described in the third chapter) to analyze the quality of the RSW system (described in the second chapter).

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Chapter 1 **The Research on Aluminum Welding**

1.1 Background of aluminum welding

1.1.1 Application of aluminum alloy in automotive industry

In order to alleviate the harmful effects of pollution and energy consumption on human health and socio-economics, there is an important problem in the new generation of automobile manufacturing: energy conservation and emission reduction. To achieve the goal of energy saving and emission reduction, one way is to develop new energy technologies for automobiles, and the other is to develop lightweight technologies for automobiles.

The fuel consumption of a car is mainly derived from the total weight of the car. On the premise of maintaining the same performance and quality of the car, reducing the weight of the car can show good fuel-saving effects.

The car body accounts for 30% of the total weight of the car, and the weight of the car will bring 60% of the fuel consumption. For each 10% decrease in this number, the fuel consumption of each car will reduce by 6% -8% compared with the previous one. The exhaust gas of cars will drop by 5%. Therefore, it is a wise choice to use lightweight materials in the automotive industry.

Reducing the weight of the car is one of the important measures to reduce fuel consumption. The lightweight technology of the car is a major trend in the development of the modern automobile industry. To reduce the self-weight of automobiles, it is necessary to generally use low-density and high-strength lightweight materials such as aluminum alloys and magnesium alloys on the premise of ensuring the safety and comfort of automobiles.

In the 1980s, Germany, the United States, and Japan has begun to use aluminum materials in the automotive industry. In 1984, the amount of aluminum used in each car produced in the United States was 39.7 kg. After ten years of development, it has increased by 120% compared with the previous one. In 2000, the aluminum content of each car was 116 kg. However, as of 2005, The rapid increase in the amount of aluminum has reached 172kg. Across Europe, in 2002 alone, aluminum consumption in the automotive industry reached more than 1.5 million tons.

In Japan, the body of the sports car NSX and many auto parts, are made of aluminum alloy materials. The whole car is about 200kg lighter than steel. It is estimated that the fuel consumption of the car is 87% of the original.

The study found that, to achieve the same mechanical performance index, aluminum is about 60% lighter than steel. Using aluminum only on the inner and outer panels of the car can reduce the weight of the entire vehicle to about half of the original. Under the same impact conditions, aluminum is twice as resistant as steel.

Aluminum alloy cars are favored for their energy saving, safety, comfort, and environmental friendliness. Aluminum alloys are favorable for its easy recycling, fewer production processes, large load capacity, and abundant resources.

Said in the racing world: "When you don't know how to modify a car, it is a good choice to reduce its weight." As early as 1994, Volkswagen developed the all-aluminum frame structure Audi A8. Its strength and safety level are far more than the traditional steel body, at the same time with a reduction of weight by 40%.

Lightweight cars theoretically reduce the load on the engine when going uphill, reduce the wear of the front wheels when going downhill, and get better maneuverability when turning. For every 100kg of car weight, fuel consumption can be reduced by 0.7L km. Therefore, aluminum alloy materials for automobile bodies have important practical significance for energy saving, driving safety, and vehicle weight reduction.

1.1.2 Aluminum resistance spot welding in industry

Resistance spot welding are usually used for body panels, and the quality of the welding is affected by a variety of welding parameters, such as: current, welding time, electrode pressure and condensation environment, which would be discussed in detail in the following chapters.

At present internationally, automobile bodies are mainly 5xxx series and 6xxx series deformed aluminum alloys, which are mostly connected by resistance spot welding, and the welding performance is good and stable. In the general body assembly, resistance spot welding of aluminum alloy is convenient for mechanization, automation. It shortens the production cycle and guarantees required quality. Therefore, aluminum alloy spot welding technology is often used in automobile body assembly.

However, the spot welding of aluminum alloys is more difficult comparing with that of steel. The resistance of aluminum alloys is small and the heat transfer is fast, therefore large current and electrode force are required for fast welding. This is helpful to make up for the defects such as surface connection, depression, bonding, and overheating.

In addition, spot welding requires high equipment power and control accuracy. The surface must be treated well before welding, but no additional welding material is required. At present, medium-frequency spot welding robots are widely used in Europe, and the amount has reached 40% by 2015. It can be seen that intermediate-frequency spot welding machines are gradually replacing the positions of industrial frequency welding machines for welding aluminum alloys. This is also the case which this article focuses on.

1.2 The main challenges in resistance spot welding of aluminum alloy

The unstable quality of aluminum alloy spot welding joints is mainly reflected in the following aspects.

(1) Splatters and splashes are severe.

Aluminum is very active, and can easily form an oxide film on the surface of aluminum alloy material. This layer of oxide film has a dense structure, a very high melting point, and extremely poor electrical conductivity. This makes the contact resistance on the contact surface relatively large. Under hard gauge welding conditions, more heat is generated on the contact surface. On the other hand, aluminum alloy materials have a low melting point and a narrow plastic temperature range during heating and melting, so it is easy to cause splashes on the contact surfaces between workpieces, and cause splashes between electrodes and workpieces. Spatters and splashes will take away parts Heat and molten metal have seriously affected the size of the nugget diameter and are extremely detrimental to the quality of the solder joint.

(2) Poor surface quality of solder joints.

Aluminum and copper alloys are prone to form low melting point (547 ℃) eutectics, and the resistivity of this low melting eutectic is relatively large. The large heat generation on the contact surface causes local melting of the electrode and workpiece contact surface, and A more severe eutectic reaction occurs, so that the adhesion between the electrode and the workpiece occurs, which deteriorates the surface quality of the solder joint. The adhesion and spatter of the electrode to the workpiece severely damaged the continuity of the electrode surface, and then worsened the contact state between the electrode and the workpiece during subsequent solder joint welding, which caused the contact between the electrode and the workpiece to change from continuous contact in the initial macroscopic to non- continuous. Under hard-coded conditions, this macroscopic discontinuous contact exacerbates the generation of spatters, local melting, and blocking, which is even more detrimental to the surface quality of the solder joint.

(3) The size of the nugget fluctuates greatly.

The local melting and splashing of the contact surface between the electrode and the workpiece and the adhesion between the electrode and the workpiece destroy the continuity of the electrode surface. In the process of continuous spot welding, the discontinuity of the electrode surface has strong randomness, which makes the contact state between the electrode and the workpiece and the workpiece very unstable. In addition, due to the surface condition of the workpiece, electrode pressure, welding current and other factors, the nugget diameter fluctuates greatly in continuous spot welding.

(4) Defects are easily generated inside the nugget.

Compared with arc welding, aluminum alloys have less metal melting during spot welding. The 2A16 aluminum alloy resistance spot welding spot surface defect analysis and process optimization have a larger thermal conductivity, so the nugget cooling speed is very fast. In addition, aluminum alloy is a non-magnetic material, and the flow velocity in the liquid nugget region is very small. When the nugget is solidified, it is easy to form shrinkage, shrinkage and porosity. Although these defects have little effect on joint strength, they have a significant effect on joint fatigue performance.

(5) Nucleus shift.

Nucleus shift also occurs frequently in resistance spot welding of aluminum alloys. When spot welding with different thicknesses and different materials, the nugget is not symmetrical to the bonding surface, but is shifted to thick plates or weldments with poor thermal conductivity. As a result, the size on the bonding surface is smaller than the nugget. diameter. At the same time, it also makes the penetration rate smaller than the specified value in thin pieces or welding pieces with good electrical and thermal conductivity, which reduces the bearing capacity of the solder joint.

(6) Low electrode life.

Due to the large contact resistance between the electrode and the workpiece, the temperature on the contact surface is particularly high, which results in a strong tendency of alloying between aluminum and copper, therefore, the copper alloy electrode would burn very seriously during spot welding of aluminum alloy.

The main component of the alloy layer formed by the copper-aluminum alloying reaction is a CuA, an intermetallic compound, and its resistivity is about 5 times that of copper. In the subsequent welding process, the presence of the alloy layer would further increase the contact resistance between the electrode and the workpiece, and consequently increase the heat generation between the electrode and the workpiece.

The increase in the roughness of the electrode surface also exacerbates the locality between the electrode and the workpiece. The occurrence of melting and spattering also intensify the degree of copper-aluminum alloying reaction. The above factors in all contribute in the acceleration of electrode burn-out speed during the spot welding of aluminum alloy and hence shorten the service life.

1.3 Differences between steel and aluminum welding tasks

Based on the steel welding scenario, the aluminum welding equipment and weld quality system are developed, even though, the aluminum RSW (resistance spot welding) and steel RSW in many way shares similarities, there are some significant differences exist.

Therefore, it is necessary to conduct a comparison. The most fundamental differences lie in the physical characteristics of the materials, and what maters the most in the welding procedure are electric conductivity; thermal conductivity; melting temperature and surface quality. According to these four categories, the effects and reactions that shall be taken into consideration during the transaction between steel welding and aluminum welding are illustrated in Table 1.3.1.

Table 1.3.1 Differences between steel and aluminum welding tasks

Property	Pure iron (FE)	Aluminum materials EN-AW ..., AA ...	Effects on aluminum spot welding tasks	Possible / necessary reactions
Spec. electric conductivity [m / (Ω mm^2)]	10.3	17 ... 36	• Lower material resistance • Lower heat transformation • Greater influence of shunts	• Increase welding currents (up to approx. 50 kA, if necessary) • Position the spots optimally and accurately • Take into account clamping positions relative to the required spot positions
Spec. thermal conductivity [W / mK]	67	120 ... 235	• Great influence of cooling • Stronger influence of workpiece geometry and spot position	• Increase welding currents (up to approx. 50 kA, if necessary) • Create good and *constant* cooling conditions • Position the spots optimally and accurately
Melting temperature [°C]	1532	658	• High dynamics in the melting behavior	• Decrease weld times (typ. 70 ... 120 ms) • Use guns with fast repositioning behavior
Surface quality	good conductivity, targeted use of coating	low conductivity, oxidation	• High contact resistance at the beginning of the weld • Quick alloying of the workpiece to the electrodes. • Stronger tendency to electrode sticking • High electrode wear	• Use slope for better coupling • Considerably reduce dressing intervals • Wash sheets • Use special coats of the sheets

1.4 Basic scheme

As talked in the previous, due to the differences of material physical properties, the welding procedure shall be modified accordingly.

Considering the electric conductivity, aluminum is almost 3 times larger than that of steel; this ratio is roughly the same for their conductivity. Even though in melting temperatures, aluminum requires half the heat than steel, in order to create a reliable spot, aluminum welding still requires much larger welding currents, but also shorter welding time.

The basic welding practices as defined in the Aluminum Association recommended guidelines also include relatively large face diameter and shallowly radiused electrodes (compared to steels). These electrodes are used primarily to avoid excessive indentations during welding [2].

The varies resistances during the welding procedure shall be taken into consideration ahead of practice, they are especially important for the research period. The most typical resistances are the resistance of the electrodes, the resistance of the sheets, the resistance of faying surface. The positioning of the resistances during a normal welding activity is shown in the figure below.

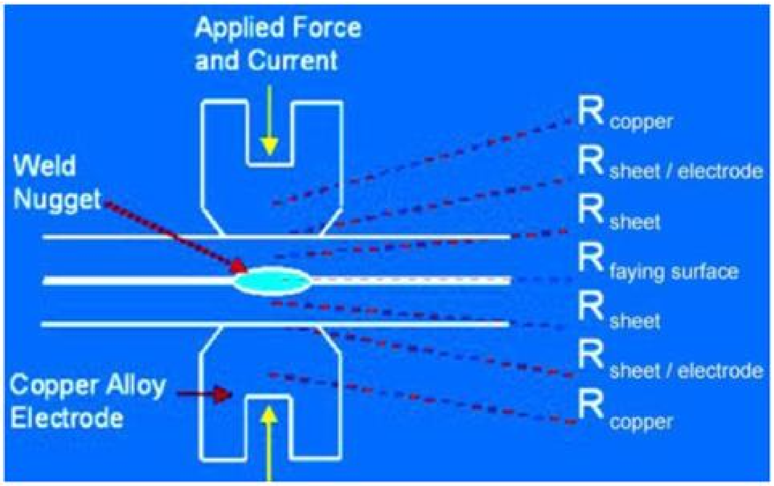


Fig. 1.4.1 Resistances in Aluminum welding

Spot welding of aluminum alloy is to form a dense nugget by applying current and pressure to the workpiece which is in contact with the electrodes. According to Joule's law, the total heat in the welding zone is:

$$Q = I^2 Rt \tag{1.4.1}$$

The resistance of the workpiece directly determines the amount of heat generated. Due to the high thermal conductivity of aluminum, the heat generated partially will be lost to a great degree, which makes it difficult to gather sufficient energy on the spot. In order to increase the contact resistance, it is necessary to choose a suitable size of the electrode face diameter, so as to achieve the adequate resistance heat and thus generate the welding nugget.

1.5 Surface pretreatment

One of the biggest characters of aluminum is its oxide film, which has a very high resistance. This feature has brought up quite some obstacles during the practice as illustrated in *1.2*.

In the procedure of resistance spot welding, currents are generated and the heat comes from the Joule Effect. Thus, a high resistance cover can greatly affect the welding activity, and therefore influence the quality of the spot.

This comes back to the total resistance, by adopting surface pretreatment, a stable resistance is the goal to be achieved. However, the surface contact resistance can be contributed by many factors, such as the surface topology, the cleanness of the sheet and the residuals, etc.

The most popular surface pretreatment techniques are illustrated in the following table.

Table 1.5.1 Surface treatments for automotive aluminum alloys

Mill-finished sheet:	Generally weldable but heavy or variable oxide can give an inconsistency.
Chemically deoxidized or abraded sheet:	The removal of oxide just prior to welding can impart a consistent but very low surface resistance, so a much higher welding current is required. Such controlled procedures are used for aerospace quality welds.
Surface modification treatments:	Some specially designed chemical surface treatments, often applied by the material supplier, give a medium to high surface resistance and can be consistent. Good weldability can be achieved.
Anodized, heavy chromate or other passivation treatments, or dry-lubricated sheet:	These treatments usually give very high resistance, and sometimes completely insulating, surface layers and are usually unweldable.

1.6 Power configuration

The technology used in power supplies and equipment has an impact on production processes and then endurance of electrodes. In industrial production, the pulses of different frequencies of the power supply are suitable for welding of different materials.

For the welding of copper and its alloys, because of their physical properties, a rapid heating process is generally required, therefore low high frequency power sources are often adopted. On the other hand, medium and low frequency sources are more commonly used in resistive materials such as iron, nickel as well as aluminum.

In an aerospace context, two types of power supplies have dominated resistance welding of aluminum. These included frequency converter (FCDC) and capacitive discharge (CD) systems. The basic power supply arrangements for FCDC and CD systems Both power supply configurations result in DC current flowing into a low-impedance secondary. See further information in Ref. [1].

However, for automotive welding, these two power sources are not used in the industry, and one of the main reasons is their high cost. Therefore, the aluminum spot welding originally used in automobiles has adopted AC power supply. The AC power supply is highly versatile, economical, and simple to maintain, but its power factor is low, that is to say, a low the heat generation efficiency, what ‘smore it has a large impact on the power grid, which may affect the normal use of other electrical equipment.

A more suitable approach is to use a medium frequency DC power supply (MFDC). MFDC spot welding machine has balanced three-phase load, low input, no grid transition, and high thermal efficiency (up to 95%), and thus energy saving.

In body-in-white (BIW) welding, a 160KVA AC welding machine is often used, but if an MFDC welding machine is in use, only 44KVA is sufficient.

The medium-frequency power system is diagramed in Fig. 1.6.1.

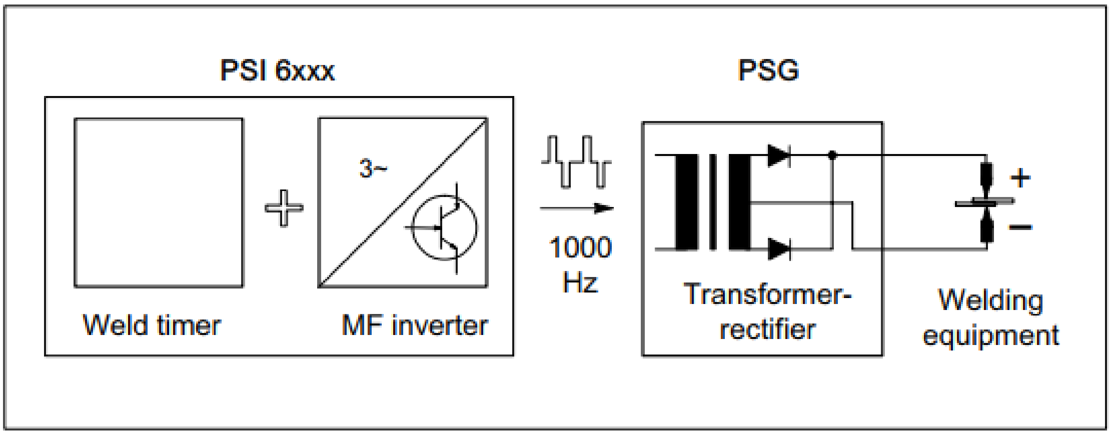


Fig. 1.6.1 Block diagram overview: PSI 6000 with transformer

Firstly, the three-phase AC power is filtered in the weld time, and then through a inverter, it is transferred into 1 kHz, and then an IGBT block is applied which modulated the power in to an medium frequency square wave. Next it is rectified by the rectifier diodes in the transformer, and become medium frequency DC, which is directly supplied on the welding electrodes.

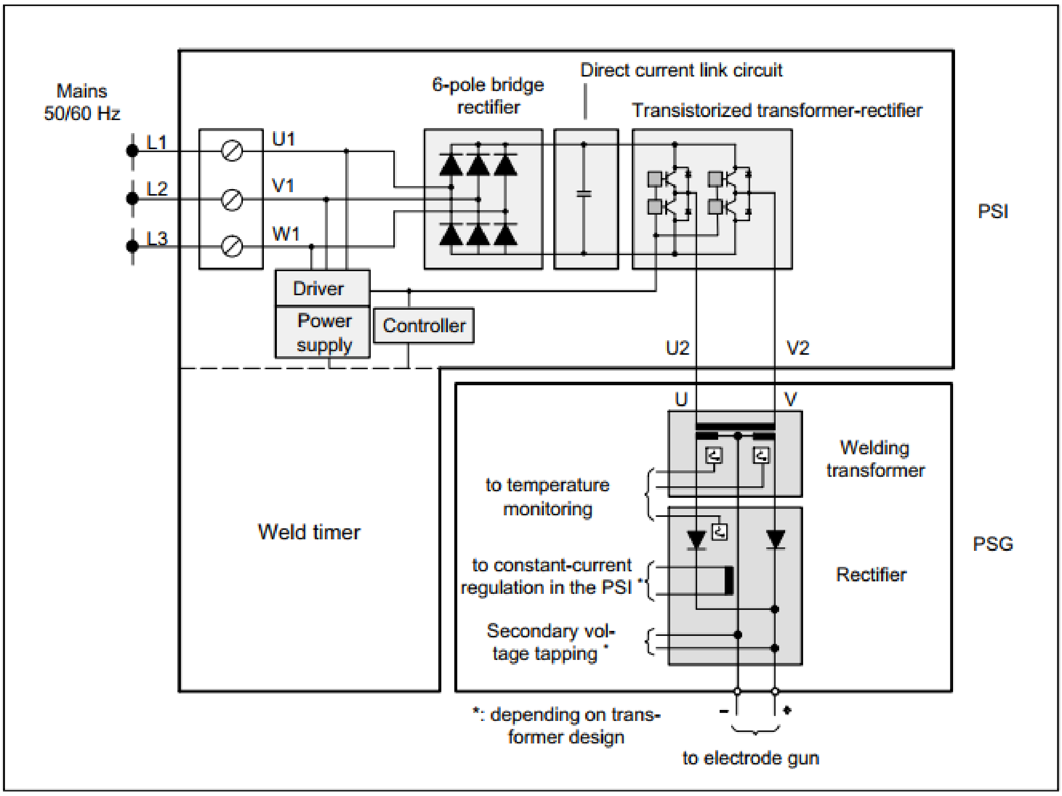


Fig. 1.6.2 Detailed block diagram of a medium-frequency inverter system

1.7 Process regulation and monitoring of Al RSW

In aluminum welding, force of the electrodes is usually attached with great importance. The variation of the force on the electrodes in a way can reflect the status of the welding activity.

The requirements of the equipment depending on the regulation methods can be categorized into 2 setups.

- current sensor for the secondary current
- voltage sensor for the electrode voltage

And/Or:

- force sensor for the welding gun

1.7.1 Parameterization of the force

Due to the thermal expansion during the weld time, the material is pressed against the electrodes. This leads to an increase in the actual force measured, the theoretical relation can be seen from Fig. 1.7.1.1.

From the characteristic of the actual force, it is possible to draw conclusions about the thermal and mechanical processes taking place during the welding process and derive an assessment of the welding quality.

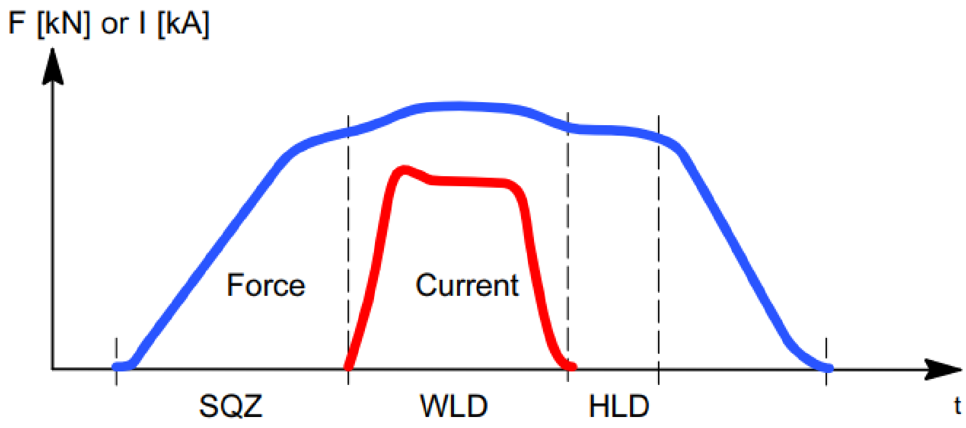


Fig.1.7.1.1 Impact of thermal expansion on the actual force

Several force characteristics of standard welds has been shown in Fig.1.7.1.2. All characteristics are based on the same workpiece combination where the current was increased in 500A steps from 4 to 11 kA and the other parameters have remained identical:

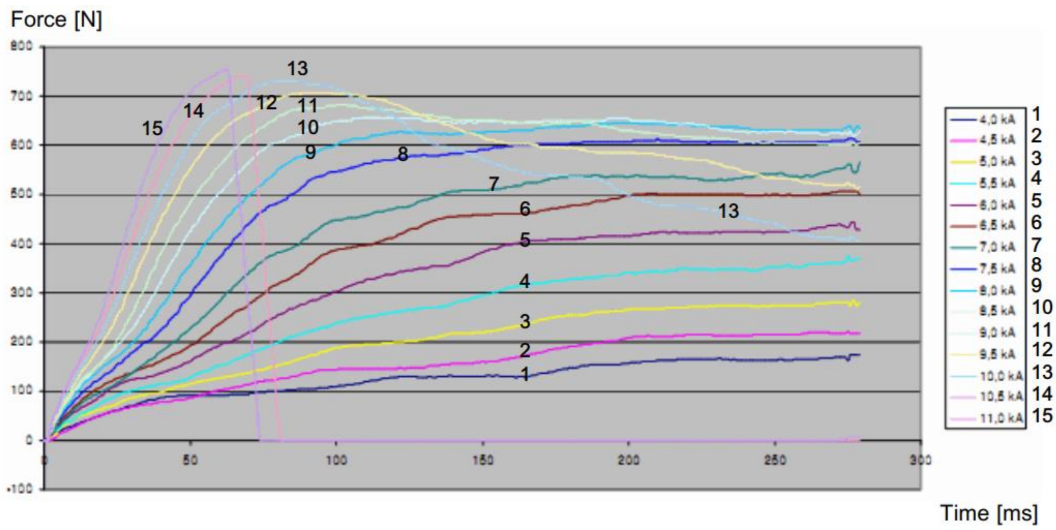


Fig.1.7.1.2 Examples of force curve characteristics

All force characteristics were recorded under ideal conditions. However, to be noted, the force characteristic can not fully represents all the theoretical variations due to different working circumstances, different disturbances and welding gun properties.

- In case of low currents (curves 1 to 5), the curves rise up slowly and gradually reach to a threshold value. In this case the currents are between 4 to 6 KA. The material between the electrodes is not heated sufficiently and therefore expands only a little.
- As the current increases, the force characteristic curve goes up in the beginning and pick up the pace along with the increase of current. This is because the workpiece is swelling quicker when being heated under higher temperature considering the former case, which generates an increasing reaction force on the electrode.
- For high currents (curves 12 and 13), it shows a continuous increasing slop in the first phase and after reaches the top, a gradual decrease is observed. This character actually presents good welding spot (at 9.5 KA) and is due to the electrode sinking in.
- For even higher currents shown in curves 14 and 15, it can be seen after the first phase of expansion, the force drops dramatically afterwards, in this case, the currents applied are 10.5 KA and 11 KA. It denotes the splatter of material has taken place.

1.7.2 Parameterization of the dynamic resistance

Standard operation of aluminum resistance spot welding is quite different from steel resistance welding in the aspect of dynamic resistance, as shown in Fig. 1.7.2.1

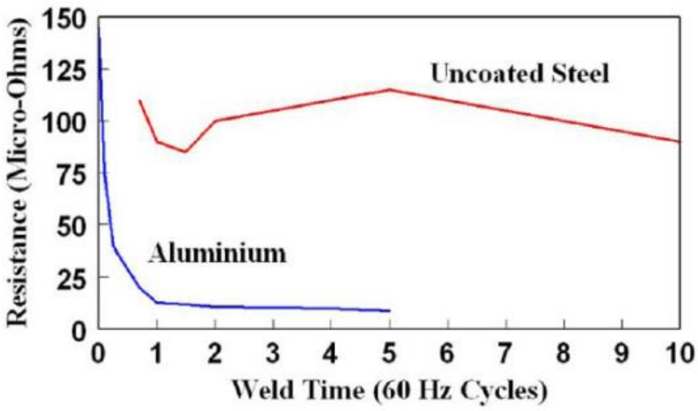


Fig.1.7.2.1 Resistance of aluminum and steel during spot welding

Characteristic for aluminum spot welding is a rapid fall of the electrical resistance in the beginning. Actually, the dynamic behavior of the resistance value - which is determined by the breakdown of the contact resistances in the system is more important than the initial (static) value.

Another distinct difference is the pre-condition phase. It is witnessed of a steep pulse of the dynamic resistance, and so as the voltage and current changes along (in constant current mode), where the current is called preconditioning current. This variation is shown in the following graph (Fig. 1.7.2.2) in the red circled region. It describes the burning or punctuation of the oxide film. The green curve represents the dynamic resistance, the blue one is the current and the red curve shows the voltage. The actual aluminum welding happens afterward.

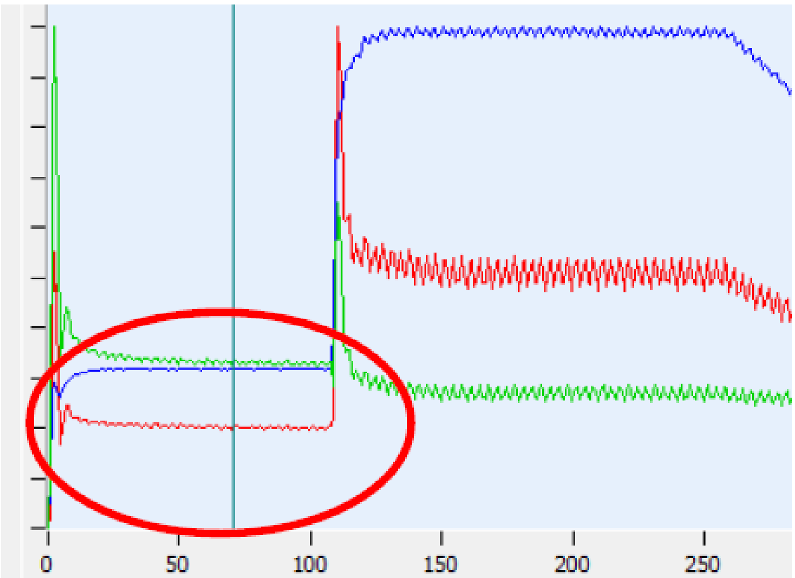


Figure 1.7.2.2: Example for a long conditioning time of an old charge (red circle)

In Fig.1.7.2.3 a reference curves for aluminum resistance welding is illustrated, where the orange one shows the variation of the force, the green one shows the dynamic resistance, the red one shows the current.

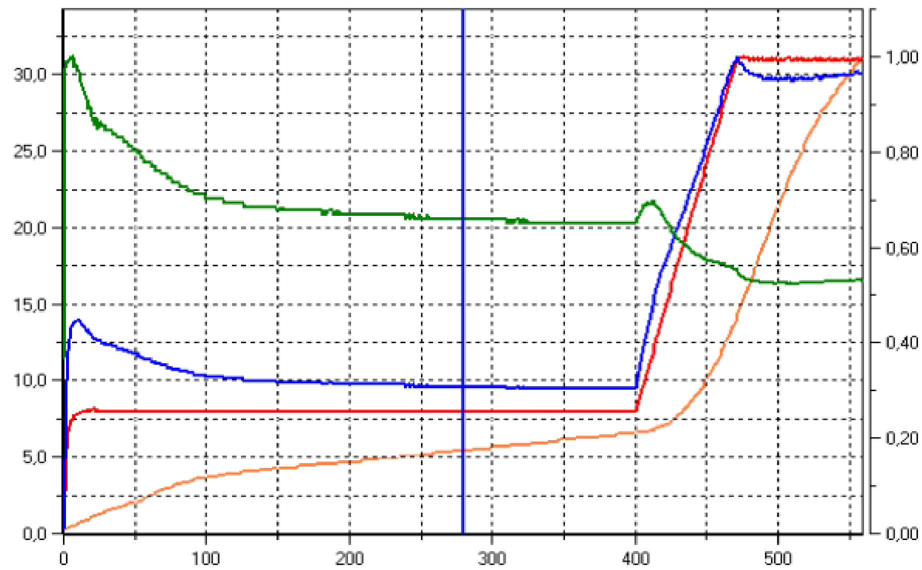


Fig.1.7.2.3 Reference curve for Al RSW

The resistance of the aluminum compound drops from relatively high values at the beginning of the weld because the sheets warm-up and the breaking of the oxide coats to a low value.

Since the resistance of aluminum is very small, it can be seen as no significant change in the resistance curves of welding. The resistance continues to decrease until the end of the welding time where the solder joint gradually expands to the expected diameter. And due to the material expansion, the force profile increases alongside till it reaches the threshold.

1.8 Conclusion

The resistivity of aluminum alloy is low, and its temperature coefficient of resistance is relatively small. Because the change in resistivity from room temperature to melting temperature is only about 3 times, it is difficult to describe the change in electrical parameters of resistance spot welding of aluminum alloys, which brings huge difficulties in the closed-loop control of aluminum alloy resistance spot welding.

The quality issue of spot welding of aluminum alloy not only includes fluctuations in the size of the nugget, but also associated with severe splashing and splattering, poor surface quality of the welding spot, and easy adhesion between the workpiece and the electrode. Therefore, the quality problems faced by spot welding of aluminum alloys are far more complicated than those of low carbon steels.

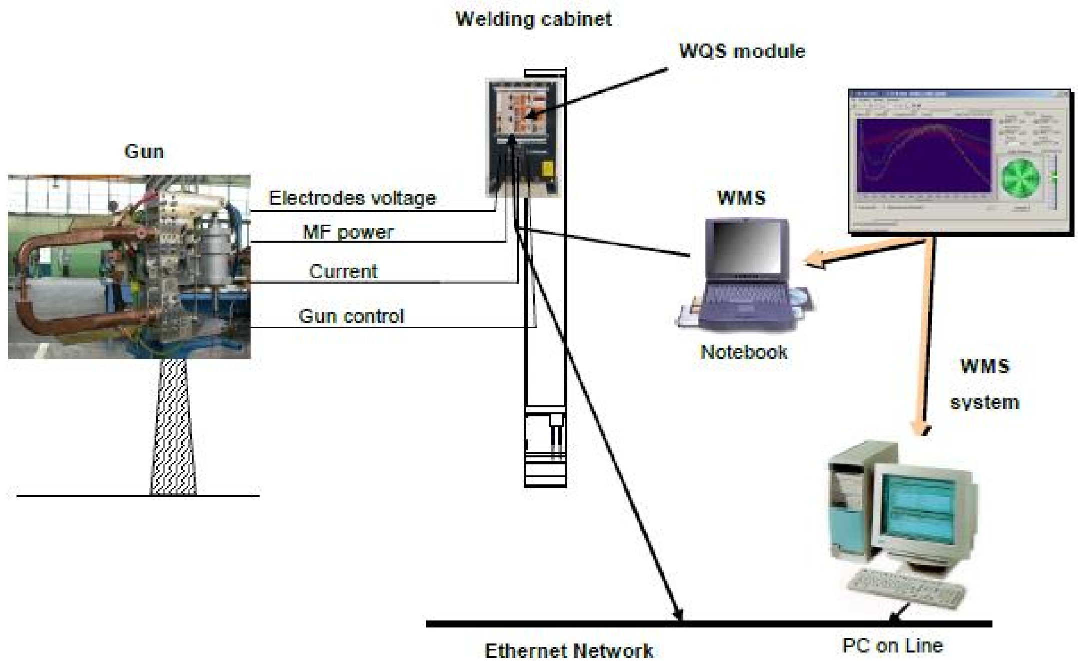
Chapter 2 Welding quality system

2.1 Introduction of WQS

ISI-Welding produces and supplies a proprietary software that has the purpose of monitoring and storing the welds carried out. It communicates with the hardware via the ethernet port.

With the WQS (Welding Quality System) it is possible to assess in real time the actual quality of the weld spot and at the same time correct the process parameters so as to obtain the required result.

The WQS function can be used on all welding stations with MFDC Weld 334m+ inverter fitted with WQS options.



Generally, during the welding phase of a car body, different types of sheet thicknesses and different materials are involved. Each thickness and each material require a different type of set of operating parameters of the welding gun. These parameters, such as the current, the force to be applied to the electrodes, the welding time, are decided by an expert, usually a technologist of the production plant according to certain available tables and by experience. Verification of the correct choice of these parameters is carried out with point tensile tests using destructive tests.

Before the welding phase, both manual and robotized machines are programmed with a series of parameters depending on the type of bodywork. These parameters are used in the WQS classifier system, to define the fuzzy logic implemented, in order to allow online quality checking features.

2.2 The functions of WQS

First and foremost, two significant signals shall be derived from the welding gun, which are the welding current and the welding voltage. These signals are sampled with sampling frequency 100 kHz, 12-bit resolution.

WQS displays the most significant waveforms associated to the weld spot, i.e.: current, voltage, resistance, the force applied to electrodes, etc. Those data provide useful information about weld nugget and the operating condition of the welding station.

The system also provides rating and classification of welding spots.

For each weld spot, waveforms and characteristic parameters are saved on PC by the WMS (welding management system) software.

The user can select among several quality welding samples and save them in a learn-in database for each welding program and for each welded joint. The system processes this database and take the required information to rate subsequent welds (i.e. by matching the characteristics of the new welds with those of the learn-in database).

In all modes the signals involved in the welding are saved: welding current, welding voltage, force applied and so on.

To conclude, the procedure of starting up the WQS consists 2 steps as shown in Fig.2.2.1 :

Step 1: Optimizing of Welding Parameters, traditional procedure

Step 2: Optimizing of Parameters and WQS activation.

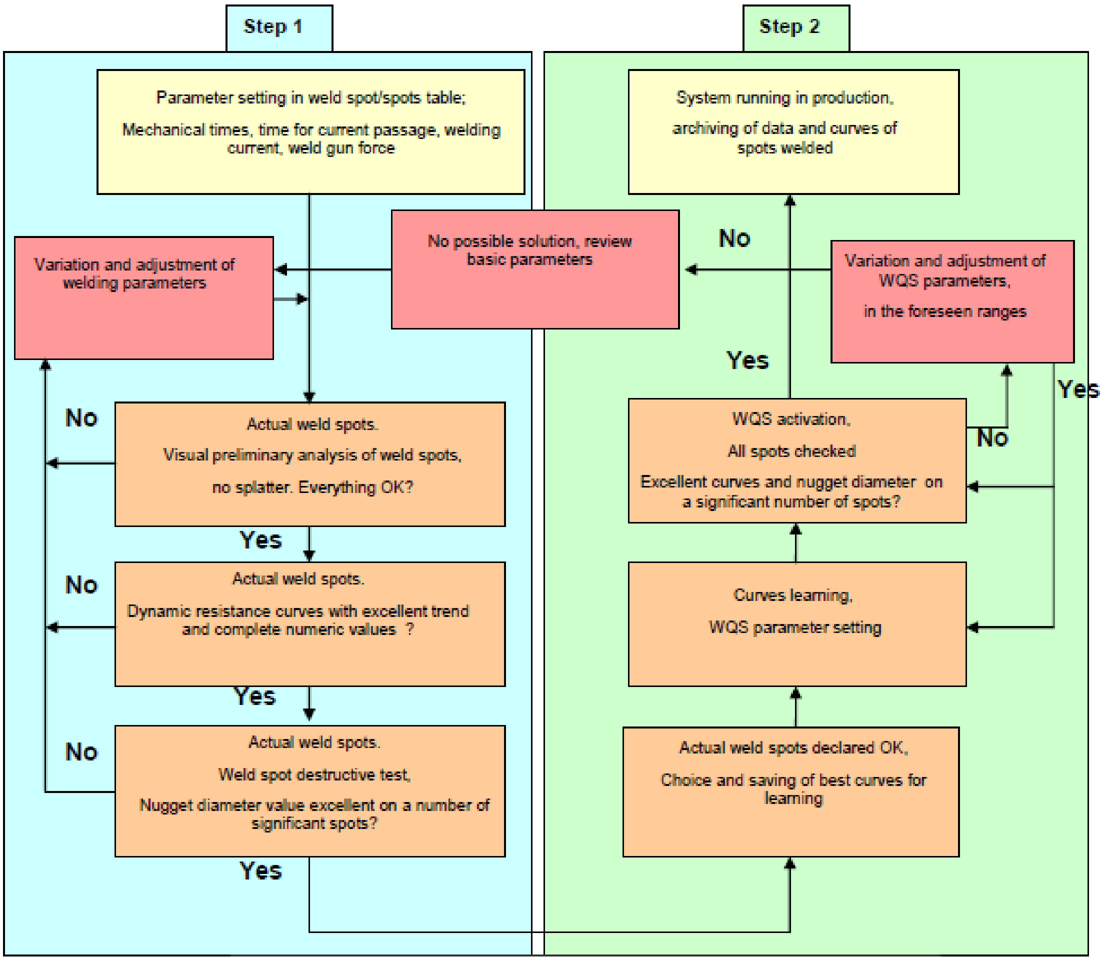


Fig. 2.2.1 WQS start up procedure

2.3 **WQS signals**

The results of a welding activity can be viewed and analyzed in the WQS window of the WMS welding supervisor system. The general interface is shown in the following figure.

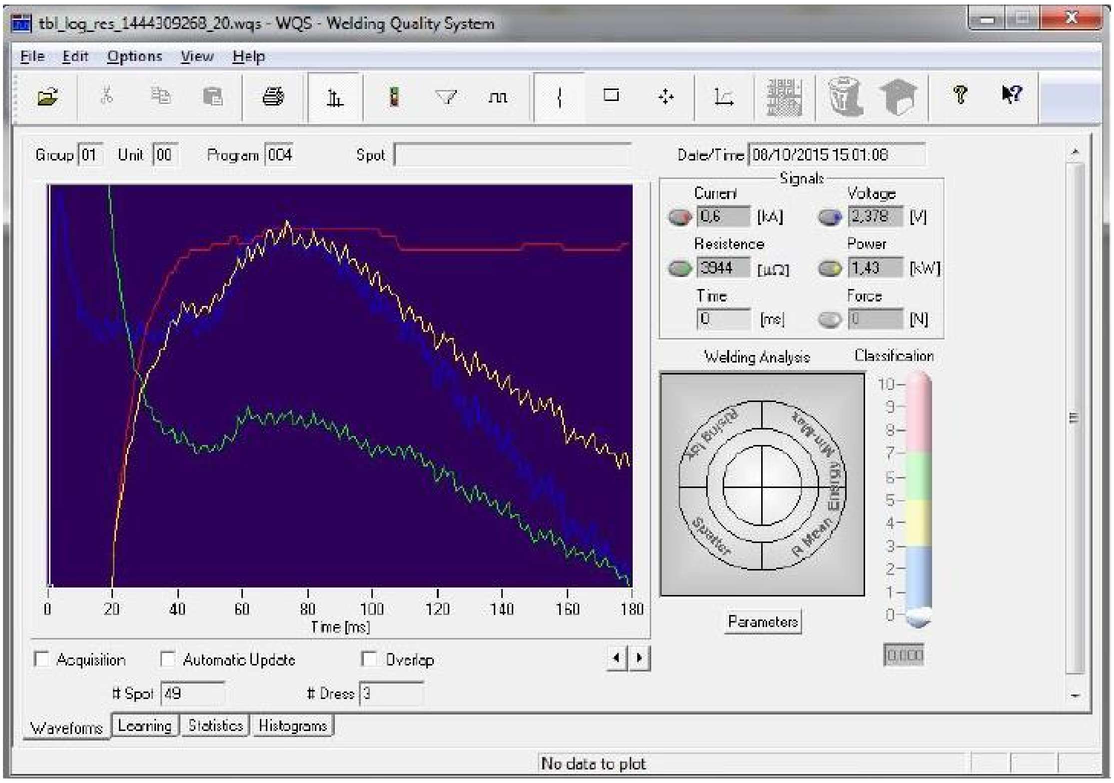


Fig.2.3.1 WQS interface

This window consists of four overlaid cards: Waveform, Learning, Statistics and Histograms.

The waveforms reveal the characteristic signals: welding current (red), secondary voltage (blue), dynamic resistance (green) and welding power (yellow).

There is other information of the welding signals that are calculated based on the four basic parameters.

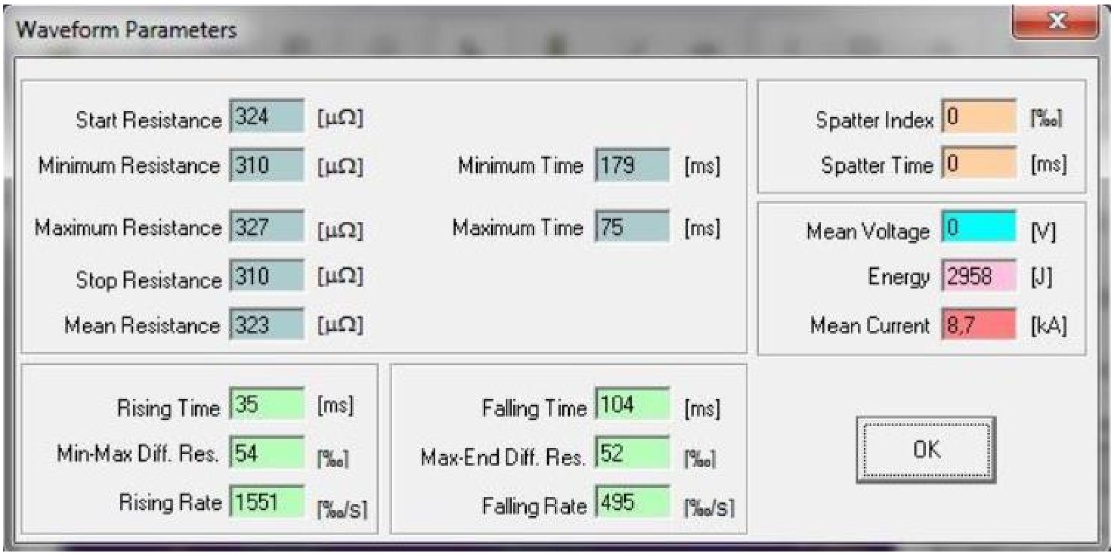


Fig. 2.3.2 WQS waveform parameters

- **Start Resistance**: resistance value averaged during the first sampling, after the inhibition time. The value is in microOhm[μΩ].
- **Minimum Resistance**: minimum resistance value detected after the inhibition time, but before recognition of maximum. The value is in microOhm [μΩ].
- **Minimum Time**: it is the time value when theminimun resistance occurs. This value, in milliseconds [ms], is a multiple of the sampling interval.
- **Maximum Resistance**: maximum resistance value detected after recognition of minimum. The value is in microOhm [μΩ].
- **Maximum Time:** instant of time in which the maximum resistance is detected. This value, in milliseconds [ms], is a multiple of the sampling interval.
- **Final Resistance**: resistance value averaged during the last sampling interval, before the end of the welding pulse. The value is in microOhm [μΩ].
- **Average Resistance:** resistance value averaged over the whole welding pulse duration, after the inhibition time. The value is in microOhm [μΩ].
- **Rising Time**: time interval that passes between the minimum and maximum resistance value. This value, in milliseconds [ms], is a multiple of the sampling interval.
- **Min-Max** Diff.Res.: it is the difference between the minimum and the maximum value of the resistence in [‰].

- **Rising Rate**: it is the ratio between the maximum – minimum resistance difference and the "Rising Time". This value is expressed in [(‰)/s].
- **Falling Time**: time interval that passes between the resistance maximum point and final point. This value, in milliseconds [ms], is a multiple of the sampling interval.
- **Resistance maximum-end difference**: resistance difference detected between maximum value and end value. Value in ‰.
- **Decreasing Index**: the ratio between the resistance difference between maximum-end point and falling time. Value in ‰/s.
- **Splatter Index**: threshold for splatter detection. This value is zero if the variation does not exceed the programmed threshold. Value in ‰, like dynamic resistance drop.
- **Splatter Instant**: instant of time in which a splatter is detected. This value in milliseconds, is a multiple of the sampling interval.
- **Energy**: thermal energy delivered in the welding circuit (transformer, weld gun., metal to be welded) Value in Joule [J].
- **Mean Voltage**: Mean voltage value on the duration of welding profile pulse after inhibition time. Value in [V]
- **Mean current**: Mean current value on the duration of welding profile pulse after inhibition time. Value in [kA].

The signals above can describe a welding procedure in a very detailed way. Therefore, they can reveal the information of the quality of a specific welding spot. The learning and classification process are mainly depending on them.

2.4 **Classification**

In the WQS windows there is a chart to display the welding quality It shows up to eight welding parameters.

In classification function the system displays the welding quality. To activate this feature, welding pulses should be produced and they are utilized for the learning phase. In this case the radar displays all the parameters and the classification bar is active.

Each section of the pie chart corresponds to a welding parameter (Fig.2.4.1) and according to the quality of the parameter it may be shown in three different colors (Fig.2.4.2), the meaning of each categories is illustrated in table 2.4.3.

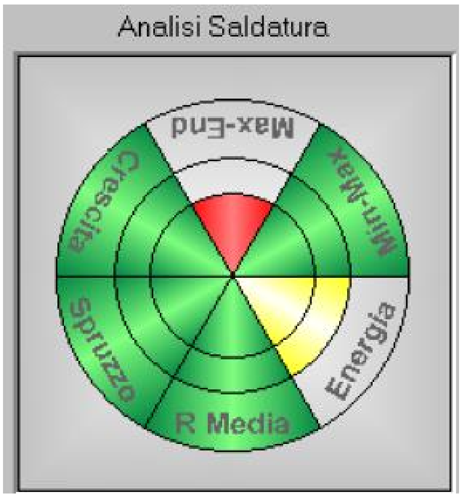


Fig.2.4.1 Welding spot pie chart

Green: the welding parameter is in good condition

Yellow: the parameter is in intermediate condition

Red: the parameter is not acceptable.

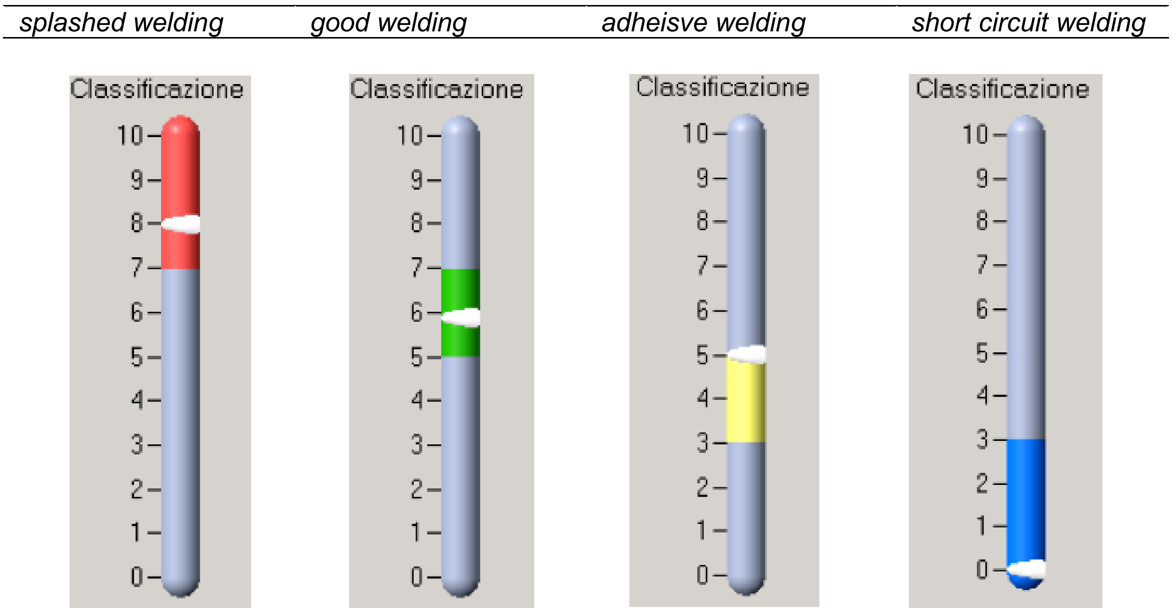


Fig.2.4.2 Welding spot quality bar

Table 2.4.3 Implication of the quality classification

Indicator position	Colour	Result
0-3	Blue	Short circuit welding. There are no workpiece are placed in the welding gun.
3-5	Yellow	Adhesive welding. The energy and other parameters in the welding are lower than the welding parameters used in learning procedure.
5-7	Green	Good welding. These parameters show great consistency with the parameters obtained in the learning procedure. The waveforms have got the same behavior.
7-10	Red	Splashed welding or too much energy. The weld spot has received thermal energy that is too high in relation to that for learning

A learning procedure is necessary for each WQS program, or for each weldable spot index with a WQS program. The procedure consists of inserting in the learning acquisition list a certain number of items obtained from the main list of weld spots considered to be of good quality. The accuracy of the classification depends on the number of acquisitions inserted (a greater quantity improves accuracy) and according to the accuracy of the selection. It is therefore recommended to make the choice using appropriate external technological methods, for example with peel tests and dimensions check, or ultrasonic measurement. It is also recommended to insert at least 5 items.

Chapter 3 Fuzzy rule-based classifier

3.1 Introduction

The fuzzy logic method is used to describe the fuzzy phenomenon with a certain mathematical function, so as to make a fuzzy problem numerically clear. In fuzzy logic, the variables are words instead of numbers.

Which means that fuzzy method essentially is defuzzification, instead of fuzzification. For example, "big current" is a fuzzy phenomenon, and once a membership function is used to describe "big current", "big current" is no longer fuzzy, and "big current" is equal to this membership function. How to determine the membership function is another problem. For example, the membership function can be determined through the study of data, and the membership function implementation can also be performed based on expert knowledge and other methods. Both methods are adopted when establishing the fuzzy rules for WQS classifier.

The aim of the classifier is to verify the quality of the welding points performed by an electric welding gun in the production of automotive bodywork. This job requires eliminating or possibly reducing the manual verification of the joints that is used to be done by doing destructive tests.

In fact, currently to verify whether the welding activity took place in an acceptable way, the joint must be opened by measuring the force adapted. The advantage of this system is not only that it can reduce the verification costs but also able to reduce the number of joints on the bodywork.

It is worth noticing that the joints on the car body are produced on different thicknesses of material and due to the vast amount makes it impossible to examine all of them. This would further reduce the costs in the production phase. As a result, the production times would decrease, and at the same time the safety of the production would be improved.

The welding joints are classified into three groups:

- Adhesive welding
- Good welding

- Splashed welding

In order to verify the possibility of classification of the different types of welds it is necessary to sample different welds.

Certain welding tables have been taken into account which provide a weldable area depending on the current and welding time and the experience of the technicians. The tables provide indicatively the parameters to be entered to obtain the desired welding according to the parameters (force applied to the electrodes, welding current, welding duration, for details, refers to Chapter 2).

To check how the welding resulted, tensile tests were carried out on the sheet used. The automotive bodywork is galvanized steel and all data are related to this material.

Signals from other welds were further sampled for the validation of the algorithms implemented in the project.

3.2 Classifications

The signals that would be distinguished be the WQS are those pertaining to four different types of welding:

- SPLASHED

It is defined as a "splashed" weld when material is expelled during the welding phase. This occurs especially if the current is forced too high, or if the pressure between the electrodes and the sheets to be welded is too low. In the latter case material ejection occurs in the first milliseconds of the welding process. This behavior occurs due to the fact that transformations of the material to be welded are involved during the passage of current. If the electrodes are not able to perfectly follow the variations of the material, areas are formed in which the electrodes of the clamp are not well in contact with the material and electric arcs are created.

- GOOD

A “good” weld is supposed to meet the requirements of BS EN ISO 18595:2007. This International Standard is applicable to the welding of 2 sheets or plates of dissimilar thickness where the thickness ratio is less than or equal to 3:1. It applies to the welding of three thicknesses where the total thickness is less than or equal to 9 mm

[6].

The welding of coated material, e.g. zinc-coated or anodized material, is not within the scope of this International Standard.

- ADHESIVE

It is defined as a "adhesive" weld when the fusion phase between the sheets has not occurred completely. The welding point (core) appears smaller and the tensile tests are not exceeded.

- SHORT CIRCUIT

"Short circuit" welding is defined when there is no sheet metal between the electrodes. In reality it is not a real welding because there is no fusion between materials, but it can be taken into consideration for the generation of alarms during production.

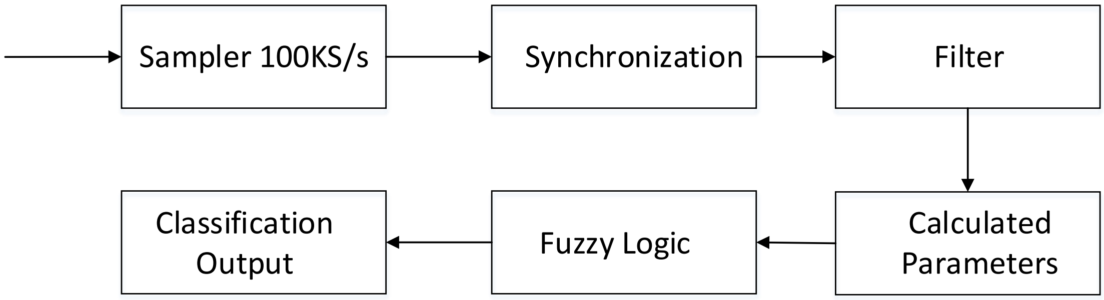
In order to verify the possibility of classification of the different types of welds it is necessary to sample different welds.

In order to obtain them, certain welding tables have been taken into account which provide a weldable area depending on the current and welding time and the experience of the technicians. The tables provide indicatively the parameters to be entered to obtain the desired welding according to the parameters (force applied to the electrodes, welding current, welding duration).

To check how the welding resulted, tensile tests were carried out on the sheet used. Signals from other welds were further sampled for the validation of the algorithms implemented in the project.

3.2.1 Algorithm of signal processing in the classifier

The basic scheme is illustrated in the following graph.



- Sampler:

It is used to sample the input signals. The sampling frequency is 100 kHz with 12-bit resolution.

- Synchronization:

This block is used to synchronize the sampled signals to calculate the average every millisecond. This is because the voltage is sampled in PWM form. In practice, every millisecond is calculated the average of the values of the two waveforms and the instant of integration is provided by the falling edge of the voltage. Since it is sampled at 100 kHz, the number of points averaged is 100.

The advantages would be:

1) less data to be processed in the subsequent phases
2) noise reduction in the two signals

The output signals of the block are the averaged voltage and the current of the welding gun.

- Filter:

To lower the noise, the signals coming out of the synchronizer are filtered by an 2nd degree IIR (Infinite Impulse Response) filter. It is necessary because there are noises caused both by the operating welding gun and by neighbor equipment. The following graph shows the signals before and after filtering.

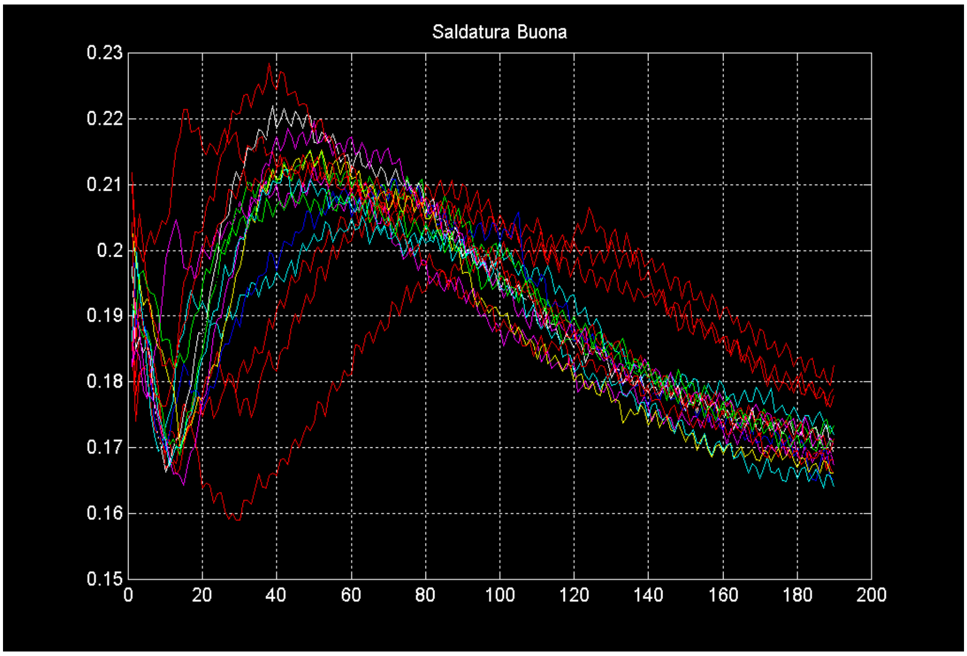


Figure: Dynamic resistance before filtering

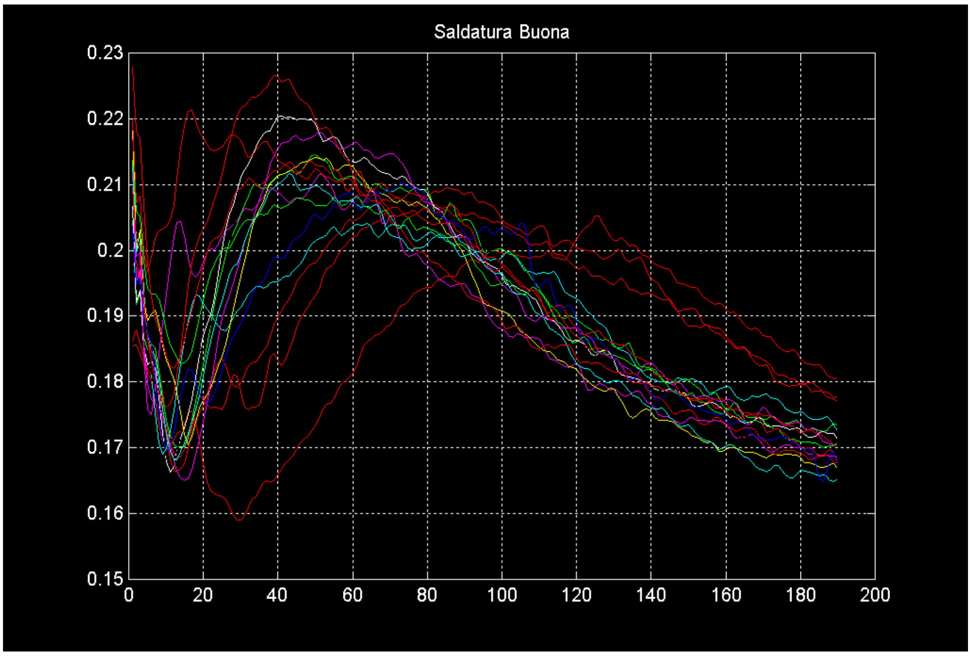


Figure: Dynamic resistance after filtering

- Calculations of the parameters:

From the voltage and the current averaged every millisecond, the dynamic resistance is calculated from the ratio between V / I (V = average voltage; I = average current).

In the first phase of analysis, the power obtained by the product between V * I, on which the same parameters of dynamic resistance were calculated, was also taken into account.

Since the trend of resistance and power in the time domain are very similar, it was preferred to calculate the parameters only for the dynamic resistance.

On these waveforms different types of parameters have been calculated. Many of these are used to describe the trend over time of the resistance or power and therefore morphological parameters must be considered; others are based on energy considerations.

3.3 The fuzzy logic of the classifier

In order to recognize the quality of the welding spots online, fuzzy logic is adopted in order to establish the fuzzy model the following procedures have been adopted:

The classifier is built on 7 inputs with 13 rules, and each of the rules depends on resolving the inputs into four different fuzzy linguistic sets: spot is short-circuited, spot is good, spot is adhesive and spot is splashed.

The action of transfer exact values of the inputs into fuzzy linguistic sets is call fuzzification. And according to the membership functions of each input, the degree of alignment is obtained, which is called the membership.

Essentially, the fuzzy logic section of the system is a fuzzy inference (fuzzy reasoning) system which is a method of uncertain reasoning. It uses fuzzy judgement as the premise and uses fuzzy language rules to introduce an approximate fuzzy conclusion.

The basis of the fuzzy inference system is fuzzy logic, which is developed from two-level logic syllogism. The conclusions obtained by this method of reasoning are consistent or close to human thinking.

Two important inference rules for fuzzy inference:

1) Generalize Modus Ponens (GMP)

    Premise 1 ： If x is A, then y is B.

    Premise 2 ： x is A’.

    Conclusion: y is B’.

2) Generalize Modus Tollens (GMT)

    Premise 1 ： If x is A, then y is B.

Premise 2 ： y is B'.

Conclusion: x is A’

Fuzzy inference is a mapping process from a given input to an output using fuzzy logic. It mainly includes the following five aspects.

1) Fuzzification of input variables,

2) Apply the fuzzy operator AND or OR

3) Implication from the antecedent to the consequent

4) Aggregation of the consequents across the rules

5) Defuzzification

3.3.1 **Fuzzification of input variables**

That is, the determined input is transformed into a fuzzy set described by membership. The variables (input signal and output signal) of the fuzzy system are bounded. In the system, this finite boundary is generally called the domain of the variable, it is the range of changing of the actual system, and the basic domain of the variables are all exact quantities. The domain of the input variable can be determined through experiments or theoretical guidance, and it often does not change during the reasoning process. Before carrying out fuzzy inference, we must first quantify the input variables and output variables within the domain respectively, that is, to establish the hierarchy. For example, the domain of the output in the fuzzy inference system shall be classified into short circuit; adhesive spot; good spot; splashed spot.

Determination of membership function

Membership function is used to represent the degree of membership of fuzzy points in fuzzy domain. Membership functions are generally given based on experience. The choice of membership functions is subjective. Generally speaking, the steeper the shape of the membership function, the higher the resolution and the higher the classification accuracy. Conversely, if the membership function changes slowly, the characteristics to be evaluated will go smoother and the stability will be better.

Common types of membership functions include triangles, bells, Gaussian, and trapezoids. The type of membership functions used in inputs are trapezoids, while in output the functions are in triangles.

In order to implement the fuzzy inference system, the input and output variables are firstly fuzzified, and the membership degree is determined by the selected membership function. The input variables are parameters extracted from the characteristic curve during spot welding, such as initial resistance, maximum dynamic resistance, and energy consumption. The output for each fuzzy rule is one or more of the classifications of welding points among short circuit; adhesive spot; good spot; splashed spot, and the values are in fuzzy set, this process will be further discussed in the next section.

Triangle membership functions are adopted for the outputs and the trapezoidal membership functions are used for inputs. The algorithms are shown in Fig3.3.1.1.

$$\mu(x,a,m,b) = \begin{cases} 0, & \text{if } x < a \\ \dfrac{x-a}{m-a}, & \text{if } x \in [a,m) \\ \dfrac{b-x}{b-m}, & \text{if } x \in [m,b) \\ 0, & \text{if } x \geq b \end{cases}$$

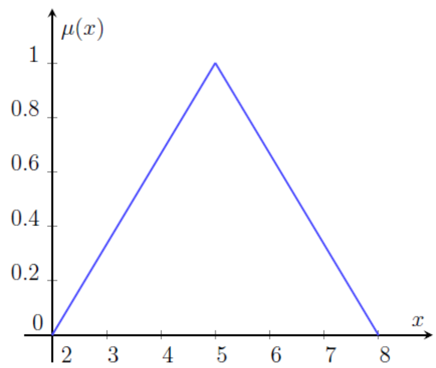


Fig.3.3.1.1: Triangle membership function： $a = 2$, $b = 8$, m=5

$$\mu(x,a,m,b) = \begin{cases} 0, & \text{if } x < a \\ \dfrac{x-a}{m-a}, & \text{if } x \in [a,m) \\ 1, & \text{if } x \in [m,n) \\ \dfrac{b-x}{b-m}, & \text{if } x \in [m,b) \\ 0, & \text{if } x \geq b \end{cases}$$

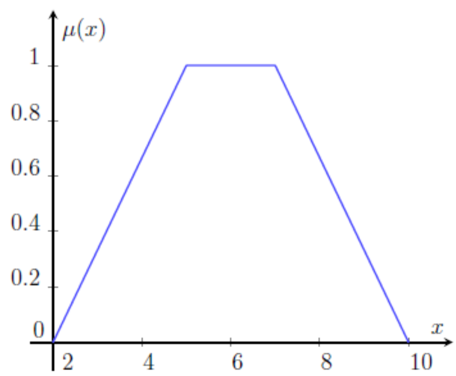


Fig3.3.1.2: Trapezoid membership function： $a = 2$, $b = 10$, m=5, n=7

Where x is an input of the system, $\mu(x)$ is the corresponding membership, a, b, m, n determine the shape of the function.

What is actually calculated in the system are the intervals of the minor bases and the major bases of the trapezoids, by altering the two bases, triangle shape membership functions can also be derived from that of trapezoids. The reason of choosing input membership functions as trapezoids is mostly due to the simplicity of construction in the codes without losing too much accuracy comparing with other types of membership functions, such as sigmoid and gaussian. The trapezoids membership functions also greatly reduce the calculation and since the system is conducted on FPGA, a large quantity of complex-shaped membership function would significantly affect the performance.

MATLAB Graphical User Interface (GUI) is used to describe the membership functions of the inputs and outputs. Fig.3.3.1.3 is an example of an input: stop resistance and its membership functions.

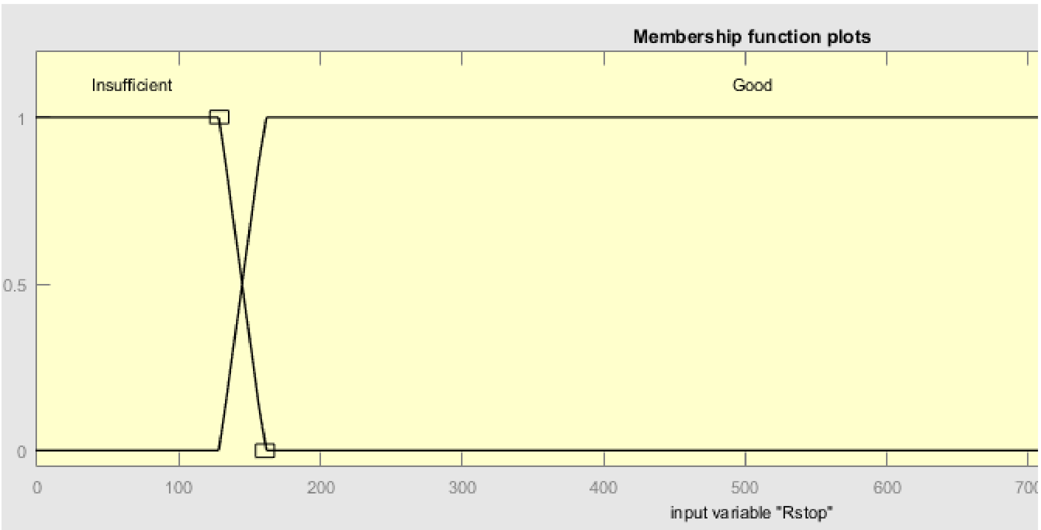


Fig.3.3.1.3 Membership function plots of stop resistance

3.3.2 **Apply the fuzzy operator AND or OR**

In the fuzzy inference system, there’s in total 7 inputs being evaluated. For each rule, each input would generate a degree of obedience according to its membership function while the output of the rule is usually a single fuzzy set. As a result, the outcome of the rule should decide how to determine the contribution from different fuzzified inputs. This is where fuzzy operator came into use.

Establishment of fuzzy rules

Fuzzy rules are the core part of the design of fuzzy system, and they are the power module for fuzzy solving. The integrity, interference and compatibility of the rules are related to the reliability and robustness of the inference system.

The main principle for determining fuzzy control rules is to follow the dynamic resistance characteristics and related electrical parameters of aluminum spot welding, including the resistance at the beginning of welding, the maximum resistance (after the oxide film punctuation), the slope of resistance increase and decrease, the total energy consumed in the welding process, etc. They are discussed in detail in Chapter 1. For instance, after pre-conditioning, when a sharp drop in resistance is detected, according to the definition of fuzzy rules, there is a high possibility of a splash of the material. This rule can be interpreted as (3.2.2.1)

- *7. If (RSplashIndex is Spr) then (output1 is spruzz)* (3.2.2.1)

By applying the WQS, it is required to determine several welding points as a standard, this can be achieved through the learning process. The standard reference curve and the measurement parameters mentioned in *Chapter 2* are adopted as the parameters of the fuzzy inference system. These parameters are used to define, such as the input and output domain of the system; parameters of membership functions and so on. In this way, with the fuzzy rules, high adaptability to aluminum alloys with different thickness, different working environments, and different welding equipment can be achieved.

3.3.3 **Implication from the antecedent to the consequent**

After completing the calculation of the membership function and the specification of the rules, the next step needs to be performed is fuzzy implication. Fuzzy implication can be regarded as a kind of fuzzy operator, whose input is the degree of satisfaction of the rules. and the output is a fuzzy set.

Mamdani fuzzy inference system

The fuzzy inference system adopted in this article is based on Mamdani model. As shown in the following graph, it is a multi-input-single-output (MISO) Mamdani system, this is also the scheme of the fuzzy logic module in the WQS classifier, where X represents the inputs, and Y the outputs.

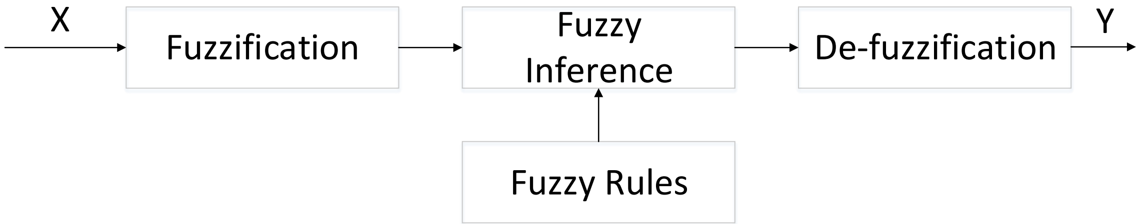


Fig. 3.3.3.1The structure of a fuzzy system based on Mamdani model

The specific process of its reasoning is: Suppose the input vector is $x = [x_1, x_2, \cdots, x_n]^T$, where x_i is fuzzy linguistic variable, and let:

$$T(x) = \{A_i^1, A_i^2, \cdots, A_i^{mi}\}, i = 1, 2, \cdots, n \tag{3.3.3.1}$$

Where $A_i^j (j = 1, 2, \cdots, m_i)$ is the j th linguistic variable of x_i, it is a fuzzy set defined in the domain U_i, and the corresponding degree of membership is:

$$\mu_{A_j}(x_i)(i = 1, 2, \cdots, n; j = 1, 2, \cdots, m_i) \tag{3.3.3.2}$$

The output is also a fuzzy variable, and $T(y) = \{B^1, B^2, \cdots, B^{m_y}\}$, where $B^j (j = 1, 2, \cdots, m_y)$ is the j th linguistic variable of y, it is a fuzzy set defined in the domain U_y. The corresponding degree of membership is $\mu_{B^j}(y)$.

Assume the fuzzy rule describes the relationship between the input and the output is:

$$R' : IF(x_1 is A_1' \text{ and } x_2 \text{ is } A_2' \text{ and } \cdots x_n \text{ is } A_n' \text{) THEN(y is } B' \text{)} \tag{3.3.3.3}$$

Then, for a given x, the applicability to each rule is:

$$a_i = \min\left\{\mu_{A_1^i}(x_1), \mu_{A_2^i}(x_2), \cdots, \mu_{A_n^i}(x_n)\right\} \tag{3.3.3.4}$$

3.3.4 **Aggregation of the consequents across the rules**

（Continued with Mamdani system）

Up to now, the results of rules are abstracted, it is called the consequents, then it is needed to reach a general fuzzy set to denote the output, i.e. to aggregate all the consequents.

And the membership of fuzzy set B^j can be conducted applying the output of each fuzzy rule:

$$\mu_{B_i}(y) = a \wedge \mu_{B^j}(y) \tag{3.3.4.1}$$

Therefore, the total fuzzy set of the output is:

$$B = \bigcup_{i=1}^{m} B_i \tag{3.3.4.2}$$

$$\mu_B(y) = \max\left(\mu_{B_i}(y)\right) \tag{3.3.4.3}$$

A example of the implication and aggregation process is illustrated in Fig.3.3.4. It is a 2-input-1-output mamdani system, with 3 rules. It fully revals the procedure introduced above in a more straight forward way.

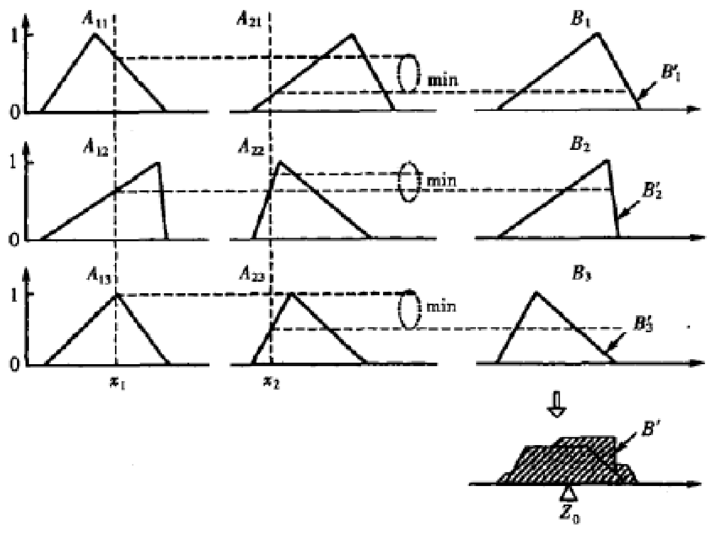


Fig. 3.3.4 Mamdani inference process

3.3.5 **Defuzzification**

The result obtained by fuzzy inference is a fuzzy set or membership function, but in practice, a certain value is required. This value is denoted in the classification bar of the WQS, and its domain is from 0 to 10. The process of taking a single value that could best represents the inferred fuzzy set is called defuzzification.

Different methods can be adopted and the results obtained are usually not exactly the same. Common defuzzification methods include the center of gravity (COG), the weighted average method, and the first of maximum (FOM) method. The calculation of the FOM method is simple, but it does not consider the influence of other values with smaller membership degrees, which means that the representative is not well enough, and it is often used in simple systems. The computational complexity of the weighted average method is higher than that of the FOM method, but the accuracy is insufficient for the classifier to specify the welding spot. Therefore, the most complicated method among the three, the center of gravity defuzzification is adopted, which fully meets the requirements of the system.

The principle of the center of gravity method is to take the center of gravity of the membership function curve and the area of the siege of the abscissa as the representative point. Theoretically, the center of gravity of a series of continuous points in the output range should be calculated as:

$$u = \frac{\int x\mu_N(x)\mathrm{d}x}{\int \mu_N(x)\mathrm{d}x} \tag{3.3.5.1}$$

However, in practice, it is sufficed to calculate the center of gravity of several discrete values in the output range with a small enough sampling interval (100KHz in WQS) to meet the precision requirements. Thus, the calculation becomes:

$$u = \frac{\sum x_i \cdot \mu_N\left(x_i\right)}{\sum_{\mu_N}\left(x_i\right)} \tag{3.3.5.2}$$

By applying MATLAB GUI, the process can be simulated as shown in Fig.3.3.5, the fuzzy set of the output (the shaded area) is obtained based on previous procedures, and then the center of the gravity is calculated, which leads to an determined value, this would be the final output of the fuzzy inference system.

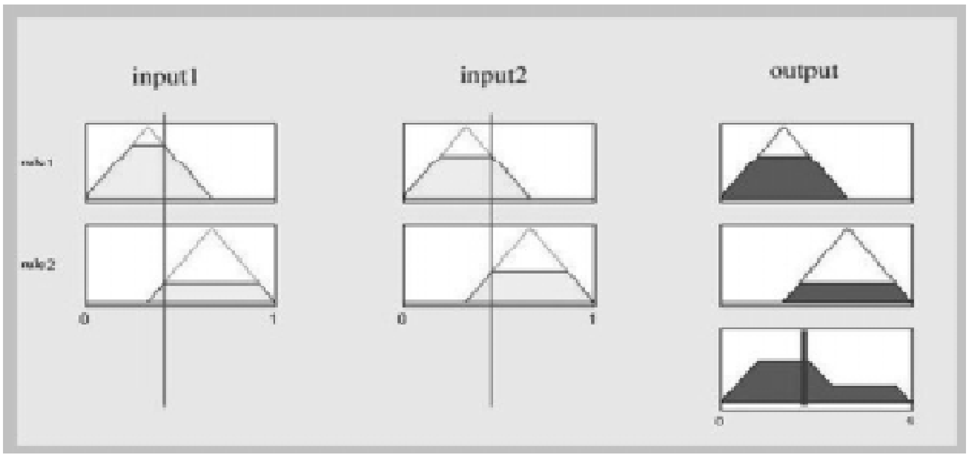


Fig. 3.3.5 Fuzzy inference system on MATLAB

3.4 Simulation of the fuzzy inference system

The inference system of the fuzzy logic is simulated by MATLAB fuzzy logic designer. The interface of the fuzzy system is shown in the following figure.

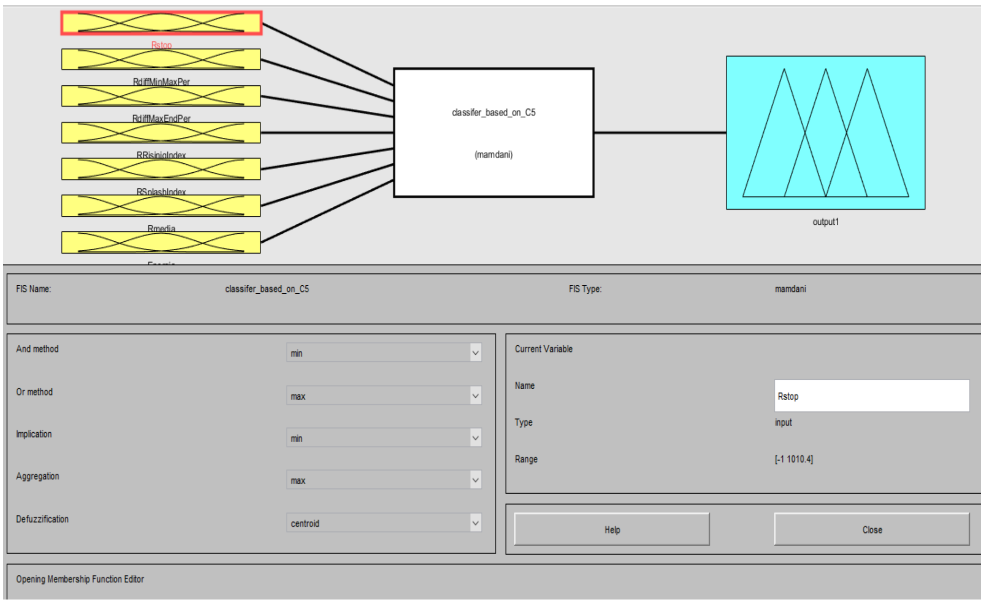


Fig.3.4.1 Simulation of the WQS fuzzy system

The following graph is an example of a simulation of the fuzzy logic in the rule viewer interface.

In order to justify the fuzzy system, spots shall be checked through sheer test to determine the actual quality. During the simulation, inputs sets obtained from the welding quality system are in hexadecimal, the parameters of interest are fed into the fuzzy logic simulated in MATLAB. An example of simulation interface is shown in Fig.3.4.2.

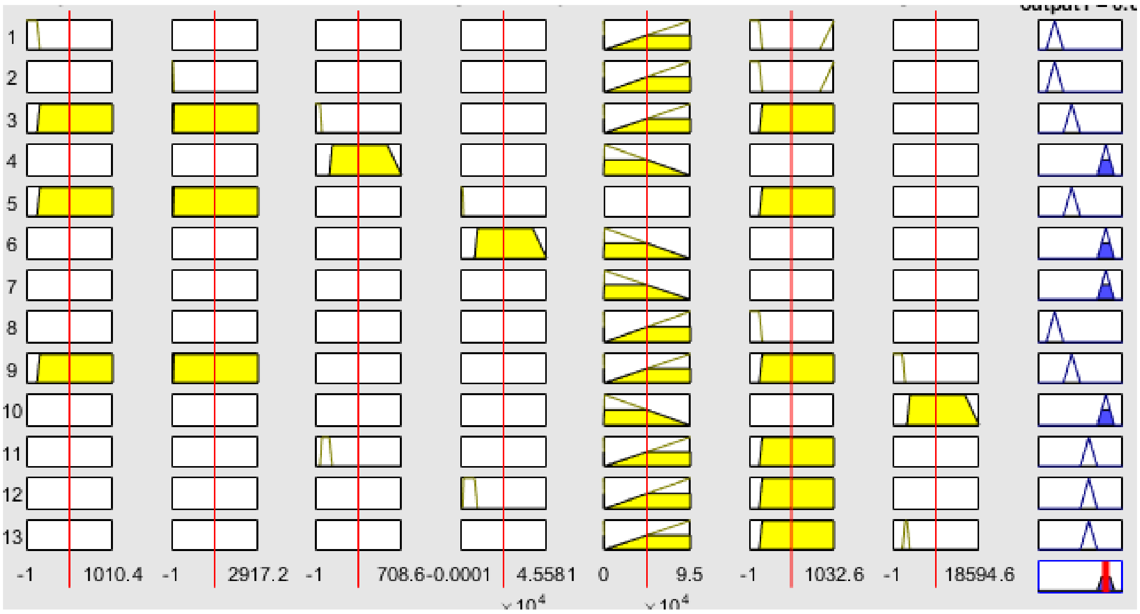


Fig.3.4.2 Rule viewer interface of the WQS fuzzy system

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