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Use Of Dynamic Resistance And Dynamic Energy To Compare Two Resistance Spot Welding Equipments For Automotive Industry In Zinc Coated And Uncoated Sheets.

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***Abstract:* -** Resistance spot welding is a fabrication process highly used in the structures assembly. This fact evidences the importance of this welding process control, due to its efficiency, productivity speediness and straightforward simple automation. This work aimed to study the weldability of zinc coated and uncoated steel sheets for automotive industry, comparing the performance of two welding equipments with two current output kinds: alternating current (AC) and medium frequency direct current (DC). The welding parameters were kept constant: 260 kgf (force), 150 ms (time) and 7.0 kA (welding current), based upon an optimization parameters methodology. The joints were characterized using optical metallography (spot diameter, indentation depth and weld penetration depth), mechanical tensile-shear tests and electrical measurements: contact electrical resistance, dynamic resistance and dynamic energy. The results showed that welding in medium frequency direct current was more efficient in generating heat in zinc coated sheets and uncoated sheets than alternating current equipment. In welding using AC and DC equipments in zinc coated sheets, the spot weld time formation was 25ms longer than uncoated steel sheets spot weld time. The burn of zinc during welding did not damage the spot weld formation with AC or DC equipments. The electrical contact resistance increased with the roughness and also presented 52% higher in uncoated sheets than in zinc coated sheets. Finally, the increase in dynamic resistance and dynamic energy augmented the spot weld diameter for both welding equipments. As a final conclusion, the medium frequency direct current equipment presented better results than wave alternating current.

***Key-words:* -** resistance spot welding; zinc coated steel sheet; uncoated steel sheet; dynamic contact resistance; automotive industry.

I. INTRODUCTION

The resistance spot welding is widely used in the modern vehicles auto-body assembling process. Each spot weld presents different conditions due to misalignment of the electrodes, gap between the plates and plates surface conditions. The optimum welding parameter condition during welding has to consider the electric current magnitude intensity and duration, the force between the electrodes; the electrodes shape geometry, the electrodes materials and properties, and presence of coating sheets material. Therefore, the resistance spot welding process behavior control is extremely important to all welded structure productivity and quality [1].

Automotive industry must match the desires of customers to deal with global competition, such as resistance to chassis corrosion, high resistance welded joints when exposed to mechanical stresses, impact absorption ability, low cost and comfort.

1.1. Resistance Spot Welding Process

The joining of two pieces using the electrical resistance spot welding is done by heat generation due to the passage of electrical current and by applying pressure. During the process, the pieces are heated and fusion occurs at the contact point located on the faying surface [2].

Through the movement of electric current between the electrodes in contact with the parts, enough heat is generated (by Joule effect) in the contact resistance between the surfaces to start the sheet metals fusion [3]. As the electrodes apply force between the parts, the merging surrounding solid metal is under pressure,

preventing liquid metal expulsion by through contact faying surface. This produces a joint with metallurgical characteristics similar to the forging process. Liquid metal loss avoidance is crucial since the process has no metal addition, and a drop in mechanical resistance may occur. The electrode pressure also controls the contact resistance between the materials. The electrodes are water cooled due to the high temperature achieved during welding at the electrode/sheet faying surface and at the contact surface area with the work piece. The cooling inefficiency causes premature electrodes wear and influences mechanical properties of the spot weld. This electrode cooling also helps the spot weld. After fusion, the electrodes remain exerting a force between pieces to allow the solidification of metal. [4].
The secondary circuit of a spot welding machine and plates to be welded are composed in a series of resistances, as shown, schematically, in Figure 1.
There are at least five resistors connected in series, producing the joint warming. The sum of the resistances is expressed in the formula below [5]:

$$R = R_{eletrode-pieceA} + R_A + R_{Weld} + R_B + R_{eletrode-pieceB} \tag{1}$$

The most important resistance formation required for the spot weld is located at the interface of the plates to be welded (R_{weld}). The magnitude of this contact resistance depends on the roughness surface of the material base metal and on the size, strength, and electrode contact face geometry and pressure applied between the electrodes. This is the most important point for the generation of heat to produce the spot weld. The electrode/sheet faying surface also has a significant contact resistance, which should be kept lower than sheet/sheet faying surface contact resistance to avoid melting at electrode/sheet contact resistance. This is one reason for using copper as an electrode material and also the electrode water cooling system, but the contact surfaces of the electrodes do not reach the melting temperature during the passage of current due to high thermal conductivity of the electrodes and the fact that they are usually cooled by water.
The resistance R in equation (1) is influenced by the welding pressure and the effect of contact resistance of the interface between the pieces. The pieces to be welded must be firmly fixed to enable the passage of current flow. If the force of the electrode increases, it will be necessary to increase the current to compensate the decrease in the contact electrical resistance drop at the sheet/sheet faying surface [5].

1.2. Heat Generation

The heat required in the process of spot welding is produced by electrical contact between the pieces to be welded, as shown in Figure 2. Due to the small value of these resistances (depicted in figure 1) relatively high currents are required to develop the heat necessary for welding [6]. The magnitude of heat generated depends on three factors:
- welding current (Amps); - electrical resistance set (ohms); - current flow time interval (seconds).

The heat generated during the welding process can be calculated by equation (2) [2]:

$$Q = k\int_0^t R(t).I^2.dt \tag{2}$$

Where:
Q = Heat generated [(cal]),
R = equivalent set of electrical resistance, [(ohms)],
t = current flow time (seconds),
I = welding current [Amps],
k = Joule equivalent constant = 1 / 4. 185

1.3. Welding Parameters

Industries often use internal standards to define the spot welding parameters and spot characteristics. The values adopted by these standards depend on the acceptance quality criteria and also the welding electrodes shape. It becomes necessary to define the process parameters to control the amount of heat generated in the transformation of electrical energy into heat in the materials that will be welded. The main process variables are: electrode pressure (force), electric current, welding cycles (time), and equipment electrical output type.

The welding pressure is produced by an external force applied by the electrodes on the joints and affects the value of total contact resistances, in particular the contact resistance at the faying surface. The parts to be welded must be well fixed in the region where the operator will do the weld to ensure the passage of current. An increase in electrode pressure results in a total electrical resistance decrease and, consequently, a

decrease of the generated welding heat, keeping all other parameters constant. Thus, electric current or the number of welding cycles (time) must be increased to compensate the reduction of the electrical resistance [7].
In the beginning of the nugget formation the welding current flows through the micro contacts between the two sheets [4] up to start to melting to build up the nugget. The welding current is the most important welding parameter since it has a greater influence in the nugget size than other parameters. An electrode diameter increase reduces the current density and the heat generated during welding, which can cause significant decrease in the nugget size, decreasing the mechanical strength of the welded spot. Excessive current density causes liquid metal expulsion at the faying surface, that can result in internal voids or cracks in the nugget, which impairs the weld mechanical properties [7].

The welding time (cycles) determines the total heat amount per spot since the other parameters remain constant. The electrical resistance during welding should cause, together with the welding time (number of cycles), an adequate heating in the welded joint to produce a suitable nugget size.

The original electrode geometry for a specific weld changes with the amount of produced welds. To increase electrode life is important to control electrode overheating to avoid geometry damage and, consequently, the nugget size. The geometrical electrode losses are caused mainly by the pressure, number of cycles, welding current, electrode water cooling system, and the presence of zinc sheet coating. . The losses increase with increasing welding time and temperature of the metal [1]. The equipment current output type is important to control the heat generated during welding. Actually, these equipments can produce alternating or medium frequency direct current.

1.4. Contact electric resistance

Contact electric resistance can be explained as the surface roughness micro contacts between conductors which cause electrical current flow [8], as illustrated in figure 2. The electrode pressure applied to establish these micro contacts between the conductors and electrode cross-sectional area defines the value of the contact resistance. There is a correlation between the contact resistance, the pressure in the electrode surface and the condition of the sheet to be welded [9]. Usually, contact resistance between the faying surfaces is the highest one.

1.5. Dynamic electrical resistance

The electrical contact is responsible for Joule effect heating at the faying surface and, consequently, by the formation of the weld nugget during the steel sheet welding. The contact electric resistance at this place changes rapidly during the welding time and, therefore, is dynamic in nature [10]. Figure 3 shows a schematic picture of a dynamic electrical resistance during welding.
Based on figure 3 there are five stages of the electrical dynamic resistance during the formation of a nugget [11]:
Stage I: Surface oxides fragmentation and roughness collapse, producing the micro contacts.
Stage II: Heating concentrated at the sheets faying surfaces. Electrical resistance decreases with increasing contact areas and the resistivity increases with temperature. The competition between these two mechanisms defines the point 'α' in figure 3.
Stage III: Resistivity increases with increasing temperature up to the formation of the first liquid that determines the transition to Stage IV, in the curvature inflection, defining point 'β' in figure 3.
Stage IV: Three mechanisms take place at this stage: (1) temperature of the material continues to rise, increasing its electrical resistivity; (2) fusion at the faying surface increases the cross-sectional area, decreasing the electrical resistance; (3) the sheet material strength decreases with increasing temperature, and mechanical collapse happens in the roughness reducing electrical resistance.
Stage V: Nugget grows and expulsion of liquid metal might happen.

1.6. Heat generation comparison between the types of welding current equipment output

Figure 4 shows a comparison of heat generation between the welding equipment with alternating current (AC) and medium frequency direct current (DC). The greater heat production is observed in the welded joint with the welding equipment in medium frequency direct current. For this reason, the behavior of contact resistance R_{weld} in function of time is different for the two equipments [8].

The difference between welding nugget size produced by these two equipment types is better observed at lower current magnitudes. For current values close to liquid metal expulsion the size of the nugget between DC and AC are quite similar [12].

The DC welding current allows a faster effective heat generated. In other words, a constant increase in the current concentrates more heat in less time in the weld zone than AC welding equipment, allowing lower welding currents, and expands the capability of welding with different steel types and sheet coatings [9].

II. MATERIALS AND METHODS

In this work, two plain steel sheet types were used: uncoated and zinc coated sheets, both of them with a thickness of 0.8 mm. The sheets were overlapped and welded with two different welding equipments, AC and DC medium frequency. Welding parameters were optimized and fixed with 260 kgf of electrodes force, welding time of 150 ms (9 cycles) and welding current of 7 kA. The dimensions of the tensile test specimens used were based on EN ISO 14273 standard, as depicted in Figure 5.

A digital oscilloscope differential probe tip was used to measure the magnitudes of voltage. To acquire the magnitude of current, a coil-type Rogowski flexible, with the integration of the signal of the coil executed in MM315 Miyachi Weld Tester, was utilized. Figure 6 shows the differential probe tip to measure the voltage during welding. These data were processed by a specially developed program to obtain the dynamic resistance and energy during welding.

As an acceptance criterion for this paper, for coated and uncoated sheets of 0.8 mm thick, the minimum nugget diameter was 3.1mm and the minimum force to the tensile test was 230kgf. The nugget size was measured by a macrograph, using optical microscopy. Tensile-shear tests were done in a testing machine under laboratory conditions. The tensile speed was remained constant during test. Analysis of electrical resistance versus contact surface roughness of Zn coated and uncoated sheets were carried out at the roughness measuring instrument (Mitutoyo, USA) under laboratory conditions.

III. RESULTS AND DISCUSSION

3.1 Dynamic resistance and dynamic energy in DC and AC welding in uncoated steel sheets

Figure 7 shows the comparison between the RMS dynamic resistance and RMS dynamic energy of the spot weld made with the same welding parameters, using DC and AC welding equipments and uncoated steel sheets, as a function of time. The red line refers to DC medium frequency equipment and the blue line represents the result of AC equipment.

It can be observed in figure 7(a) that the dynamic resistance at DC was greater than AC dynamic resistance during welding with the same parameters in uncoated sheet. This result is related to the most efficient heat produced in DC due to a higher dynamic resistance and to electrical constructive characteristics of the welding equipments, as shown in figure 4(a).

Regarding the comparison of the values of the AC and DC welding dynamic energies of uncoated sheets, the total dynamic energy during welding in DC was 9% higher compared to the total dynamic energy in AC welding. This result is also related to the difference in dynamic resistance for the two welding conditions.

3.2 Dynamic resistance and dynamic energy in DC and AC welding in zinc coated steel sheets

Figure 8 depicts the comparison between the RMS dynamic resistance and RMS dynamic energy of the spot weld made with the same welding parameters, using DC and AC welding equipments and zinc coated steel sheets, as a function of time. The red line refers to DC equipment and the blue line represents the result of AC equipment.

As a remarkable result the dynamic resistance at DC during welding was greater when compared with the dynamic resistance in CA. Comparing figures 7 and 8, the dynamic resistance of uncoated sheet is higher than zinc coated sheet dynamic resistance. This is due to the difference between electrical resistivity of steel (180 nΩ.m) and zinc (59 nΩ.m), which is approximately 1/3 of the steel resistivity, as can be noted in the result of figures 7(a) and 8(a).

Comparing figures 7(a) and 8(a), the shape of dynamic resistance is also different for uncoated and zinc coated steel sheet. Figure 8(a) for DC current and zinc coated steel presented two minimum resistance values, identified as numbers 1 and 3, and two dynamic resistance peaks, named 2 and 4. After minimum resistance 1, the solid zinc is heated up to reach dynamic resistance peak 2, where zinc started to melt and vaporize, decreasing the dynamic resistance up to point 3 in the figure. After reaching point 3, the zinc was melted and vaporized, starting the micro contact and collapse of steel roughness, up to reach point 4. Figure 9 shows a schematic drawing of the zinc burn represented by the stages 2 and 3 of the dynamic resistance of figure 8 (a). It can be observed that the zinc coating fills all the roughness of the sheets. This filling in the valleys and peaks of the sheets roughness does not allow a complete deformation of the steel roughness, giving a dynamic resistance close to zinc value. After the zinc burn (melting, vaporization and diffusion), the peaks and valleys of the sheets roughness meet and the micro contact collapse happens. This collapse increases the contact area decreasing the dynamic resistance.

Regarding the comparison of the DC and AC welding dynamic energies values in zinc coated sheets, the total dynamic energy during DC welding was 16.7% higher than the total dynamic energy in AC welding. This result is related to the most efficient heat generation in the DC welding compared to the AC welding with the same welding parameters, and presented in figure 4(a).

3. 3 Comparison between dynamic resistances and energies in AC welding for uncoated and zinc coated sheets

Figure 10 shows the comparison between the dynamic resistances (a) and energies (b) in AC welding of the weld made with zinc coated and uncoated sheets.

It can be observed that the dynamic resistance during welding in AC with zinc coated sheet presents lower values if compared with the dynamic resistance in AC with uncoated sheet. This result is related to the fact that zinc coating has lower resistance to current flow, approximately 1/3, as presented previously in this paper, when compared to carbon steel. This explains the drop in dynamic resistance at time zero in figures 7(a) and 8(a).

Observing the Fe-Zn phase diagram, zinc is a strong ferrite stabilizer. Assuming a part of zinc coating is dissolved into the nugget, producing an iron-zinc alloy, the nugget became ferritic (bcc) in a large temperature range when compared to uncoated steel, which is mainly austenitic (fcc) in high temperature. As ferrite has a lower resistivity than austenite [WW], the dynamic resistance of zinc coated sheet is lower than uncoated sheet, as presented in figure 10 (a).

One can also note the formation of the nugget on AC welding with zinc coated sheet begins with a delay of approximately one and a half cycle after the formation of the uncoated sheet nugget, as shown at stages 1 and 2. This is due to the zinc effect, similar to the previous explanation.

Regarding the comparison of the values of the dynamic energies in zinc coated and uncoated steel sheets in AC welding, uncoated sheets presents 15% higher dynamic energy than zinc coated sheets. This result is also related to the greatest efficiency in heat production in uncoated sheet AC welding. As the zinc coated sheet has a lower resistivity, the dynamic resistance is lower and the Joule heating effect is reduced, decreasing the dynamic energy for zinc coated sheets.

3.4 Comparison between dynamic resistances and energies in DC welding for uncoated and zinc coated sheets

Figure 11 shows the comparison between the dynamic resistance and dynamic energy of the spot weld made with the same DC welding parameters in zinc coated and uncoated sheets.

It can be observed in figure 11(a) that the dynamic resistance during DC welding with zinc coated sheet was lower than the dynamic resistance with uncoated sheet. This result is similar to figure 10(a), and has the same explanation.

One can also note that the formation of the DC weld spot with zinc coated sheet begins with a delay of approximately one and a half cycle after the formation of spot welds in uncoated sheets, as stages 1 and 2 in figure 11(a) have shown. The values of the dynamic energies in DC welding of uncoated sheet where 7.3% higher than those of zinc coated sheet. This result is related to the most efficient heat generation in DC welding of uncoated sheets.

3.5 Analysis of electrical resistance versus contact surface roughness of Zn coated and uncoated sheets

Figure 12 represents a schematic view of surface roughness measurement in the region where the electrode pressure is applied compared to the as-received surface roughness sheets. As a consequence, there is a surface roughness difference between these two regions. The lower surface roughness is found in the region of applied force compared to the outside region of original sheets. This is due to the collapse of the peaks of the roughness in these regions.

Table 1 depicts the comparison of mean surface roughness inside and outside the electrode pressure region for zinc coated and uncoated sheets, measured in three samples. Analyzing table 1 one can note different mean values, with zinc coated sheet presenting the highest mean value and lower dispersion in values.

Table 1 - Comparison of surface roughness inside and outside the electrode pressure region in Zn coated and uncoated sheets.

	Rz roughness on the sheet surface		Rz roughness on the electrode pressure region	
	Uncoated	Zinc coated	Uncoated	Zinc coated
Mean (µm)	3.526 ± 0,475	4.066 ± 0,363	3.156 ± 0,549	3.374 ± 0,504
Variation (%)	13.5	8.9	17.4	14.9

Figure 13 shows the graph of contact electrical resistance (R cont.) versus surface roughness (Rz) inside the Zn coated spot region and uncoated sheet, using a constant force between electrodes of 260 kgf.

It can be observed in Figure 13 a comparison between electrical contact resistance inside the spot region for Zn coated and uncoated steel sheets. It can be observed, in table 2, that the mean value of the contact electrical resistance in uncoated sheet is 52% greater than the mean of contact electrical resistance in zinc coated sheets.

Table 2 - Comparison of electrical contact resistance inside the spot in zinc coated and uncoated sheets.

	Electrical contact resistance (µ□)	
	Uncoated	**Zinc coated**
Mean (µm)	**299.37 ± 25.28**	**109.87 ± 5.16**
Variation (%)	**11.0**	**4.7**

Analyzing table 2, it is possible to observe that the variation and standard deviation of electrical contact resistance in uncoated sheet was higher than in Zn coated sheets. This result is related to the roughness variations, outside and inside the spot region, and the resistivity of zinc compared with carbon steel.

3.6 Comparison of spot weld dimensions and mechanical strength welded with AC or DC for uncoated sheets.

Table 3 shows the measured dimensions from macrographs and mechanical strength by tensile-shear tests of the uncoated sheets AC/DC spot weld.

Table 3 –Spot welding dimensions for AC/DC for uncoated sheets.

					Welding parameters		
	d (mm)	**p (mm)**	**Indentation (mm)**	**Tensile force (kgf)**	**Electrode force (kgf)**	**Welding time (ms)**	**Welding current (kA)**
AC uncoated sheet	**4.4**	**1.1**	**1.3**	**473.5**	**260**	**150**	**7.0**
DC uncoated sheet	**4.6**	**1.2**	**1.4**	**487.0**			

It can be observed in this table that the spot diameter and tensile force in the welding on DC output equipment present in welded sheets were higher when compared to welding in AC output equipment. These results are related to the most efficient heat production in DC welding, with the same welding parameters. This higher heat generation efficiency is showed in figure 7 for total dynamic energy showing a result of 9% higher in DC welding in uncoated sheet. This produces a spot with large dimensions, influencing the tensile-shear test result.

3.7 Comparison of spot weld dimensions and mechanical strength welded with AC / DC for zinc coated sheets.

Table 4 shows the measured dimensions from macrographs and mechanical strength by tensile-shear tests of the zinc coated sheets AC/DC spot weld.

Table 4 –Spot welding dimensions for AC/DC for zinc coated sheets.

					Welding parameters		
	d (mm)	**p (mm)**	**Indentation (mm)**	**Tensile force (kgf)**	**Electrode force (kgf)**	**Welding time (ms)**	**Welding current (kA)**
AC Zn coated sheet	**3.2**	**1.0**	**1.1**	**336.5**	**260**	**150**	**7.0**
DC Zn coated sheet	**4.1**	**1.1**	**1.4**	**339.5**			

In this table the spot diameter and tensile force of DC welding presented higher values in zinc coated sheets than welding in AC output. These results are related to the most efficient heat generation in DC welding with the same welding parameters. This higher heat generation efficiency is showed in the plot of total dynamic energy in figure 8, which shows a result of 16.7% higher energy generation in DC welding in zinc coated sheet. These results also influenced the nugget geometry.

3.8 Comparison of spot weld dimensions and mechanical strength welded with AC in uncoated and zinc coated sheets.

Table 5 shows the measured dimensions from macrographs and mechanical strength by tensile-shear tests of the uncoated and zinc coated sheets AC spot weld.

Table 5 –Spot welding dimensions for AC welding for uncoated and zinc coated sheets.

					Welding parameters		
	d (mm)	p (mm)	Indentation (mm)	Tensile force (kgf)	Electrode force (kgf)	Welding time (ms)	Welding current (kA)
AC uncoated sheet	4.4	1.1	1.3	473.5	260	150	7.0
AC Zn coated sheet	3.2	1.0	1.1	336.5			

It can be seen by analyzing table 5 that the spot diameter and tensile force of AC welding presented higher values in uncoated sheets than zinc coated sheets. These results are related to the most efficient heat generation in uncoated sheet AC welding with the same welding parameters. This higher heat generation efficiency is showed in the plot of total dynamic energy in figure 10, which shows a result of 15.0% higher energy generation in AC welding in uncoated sheet. This result also influenced the nugget geometry, which produce a higher nugget diameter for AC welding uncoated sheet.

3.9 Comparison of spot weld dimensions and spot mechanical strength with DC in uncoated and zinc coated sheets.

Table 6 shows the measured dimensions from macrographs and mechanical strength by tensile-shear tests of the uncoated and zinc coated sheets DC spot weld.

Table 6 – Spot welding dimensions for DC welding for uncoated and zinc coated sheets.

					Welding parameters		
	d (mm)	p (mm)	Indentation (mm)	Tensile force (kgf)	Electrode force (kgf)	Welding time (ms)	Welding current (kA)
DC uncoated sheet	4.6	1.2	1.4	487.0	260	150	7.0
DC Zn coated sheet	4.1	1.1	1.4	339.5			

Analyzing table 6, the spot diameter and tensile force of DC welding presented higher values in uncoated sheets than in zinc coated sheets. These results are related to the most efficient heat generation in uncoated sheet DC welding with the same welding parameters. This higher heat generation efficiency is showed in the plot of total dynamic energy in figure 11, which shows a result of 7.3% higher energy generation in DC welding in uncoated sheet. This result also influenced the nugget geometry, which produce a higher nugget diameter for DC welding uncoated sheet.

IV. FIGURES

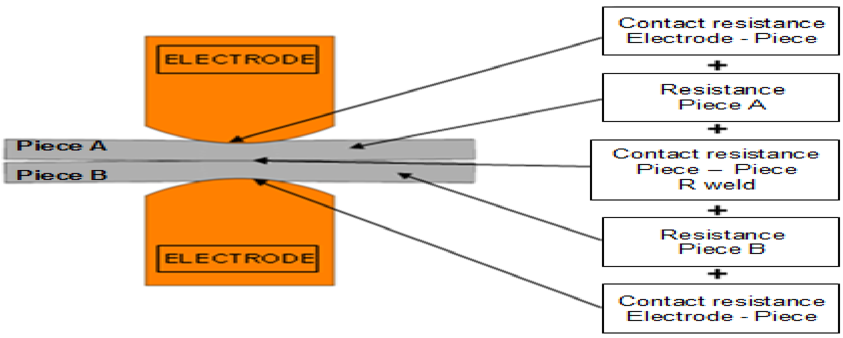


Figure 1- Scheme of electrical resistance between the electrodes in resistance spot welding.

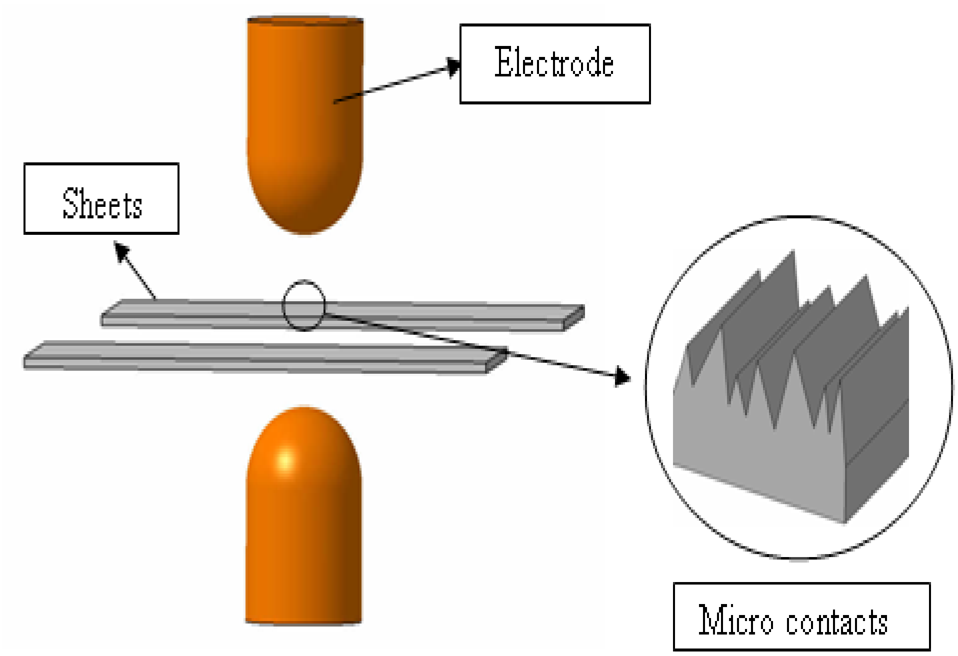


Figure 2 - Sheet surface roughness which defines the contact resistance.

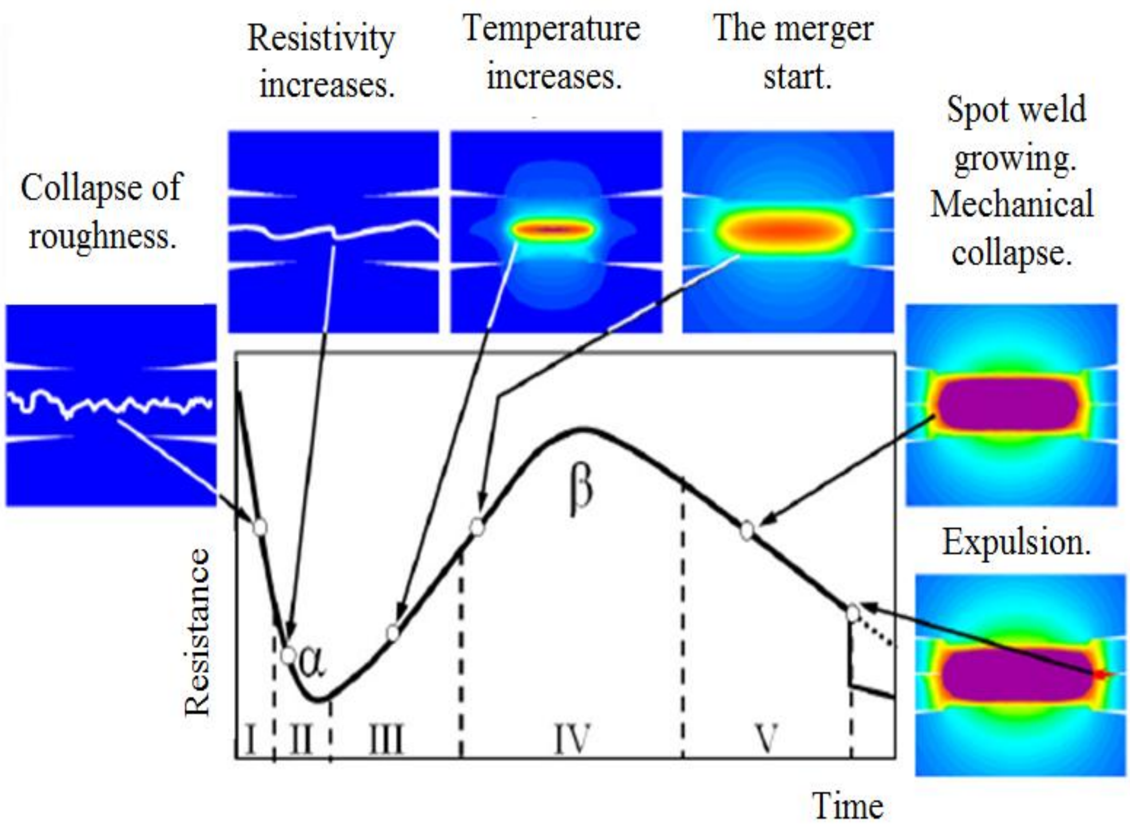


Figure 3 - Scheme of the dynamic electrical resistance during the formation of a nugget. Adapted from reference [11].

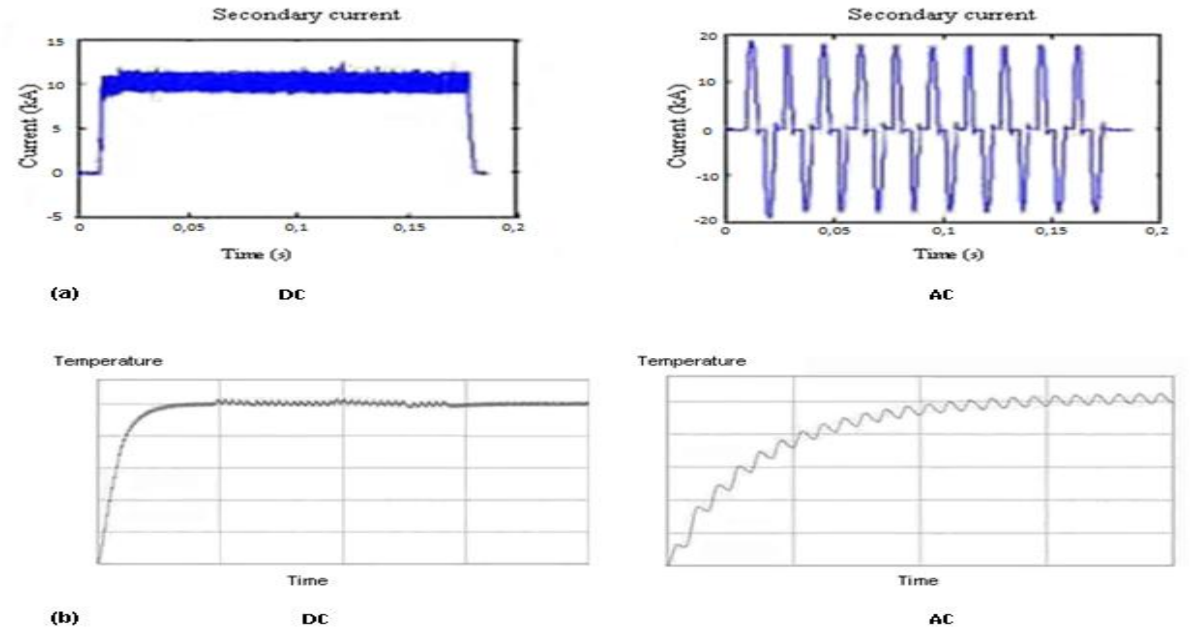


Figure 4. (a) Shape of the DC and AC current outputs [12]; (b) Heat generation in DC and AC welding equipments [8].

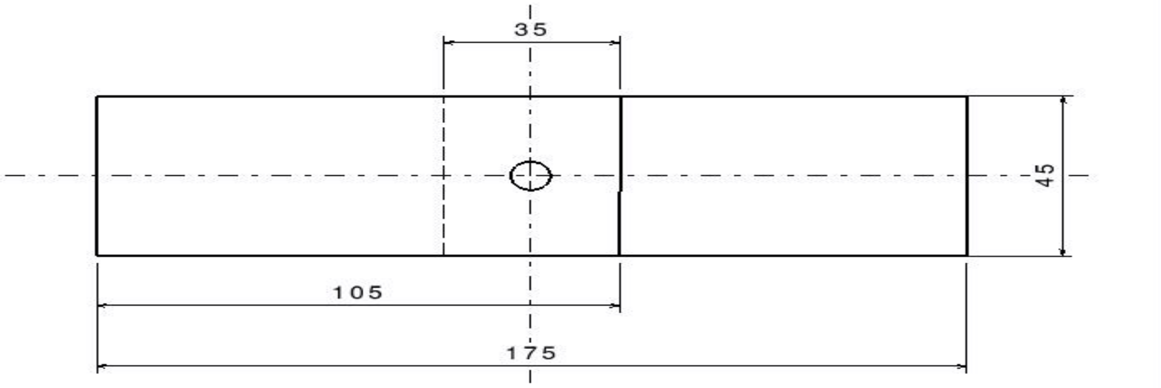


Figure 5- Dimensions of specimen in accordance to standard EN ISO 14273.

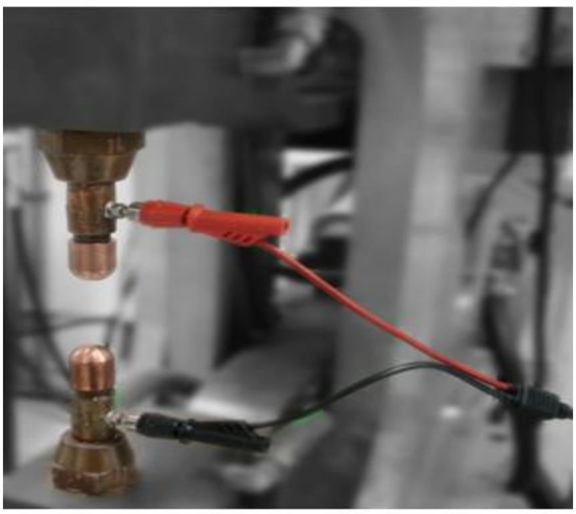


Figure 6 - Differential probe tip to measure the voltage during welding.

(a)

(b)

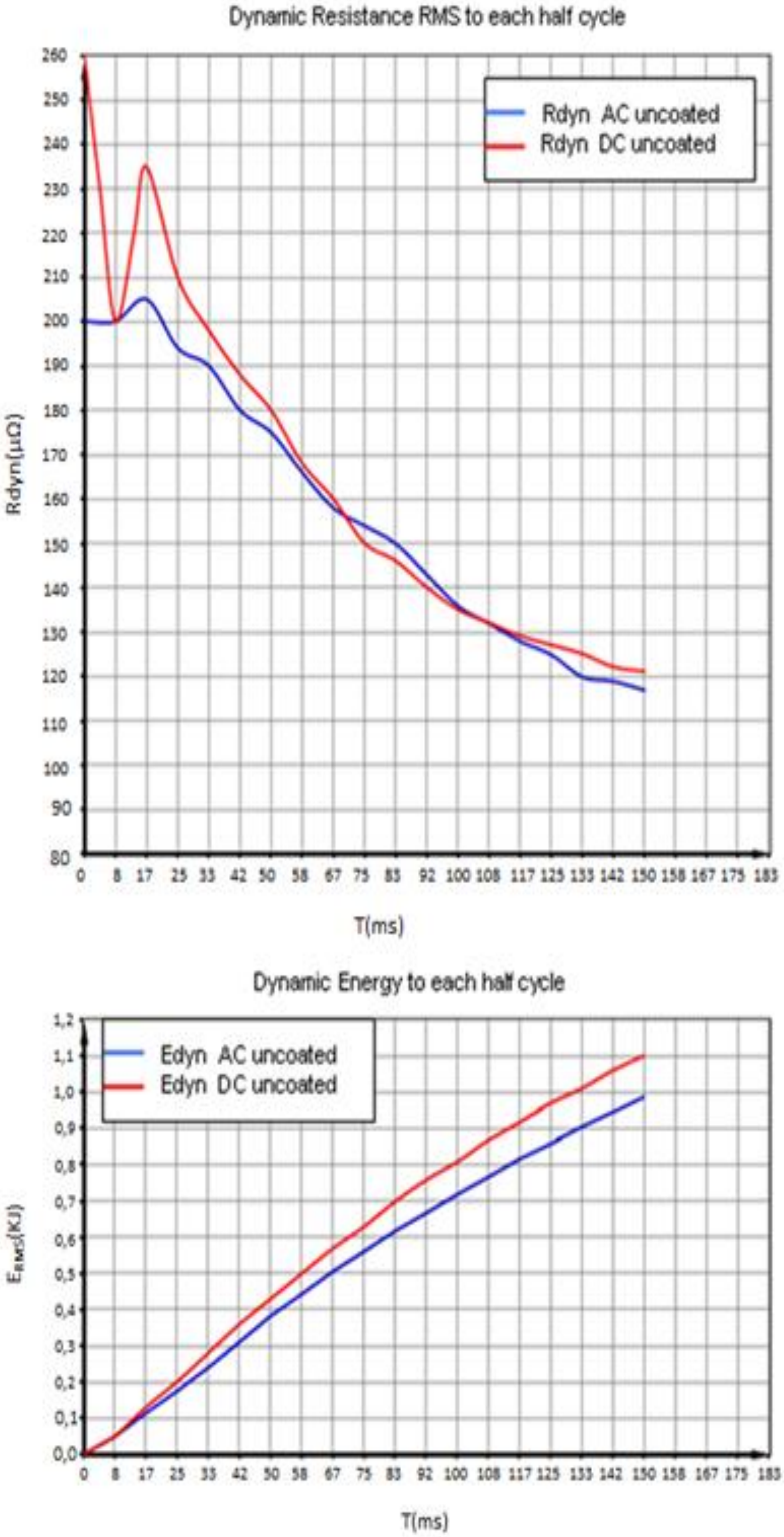
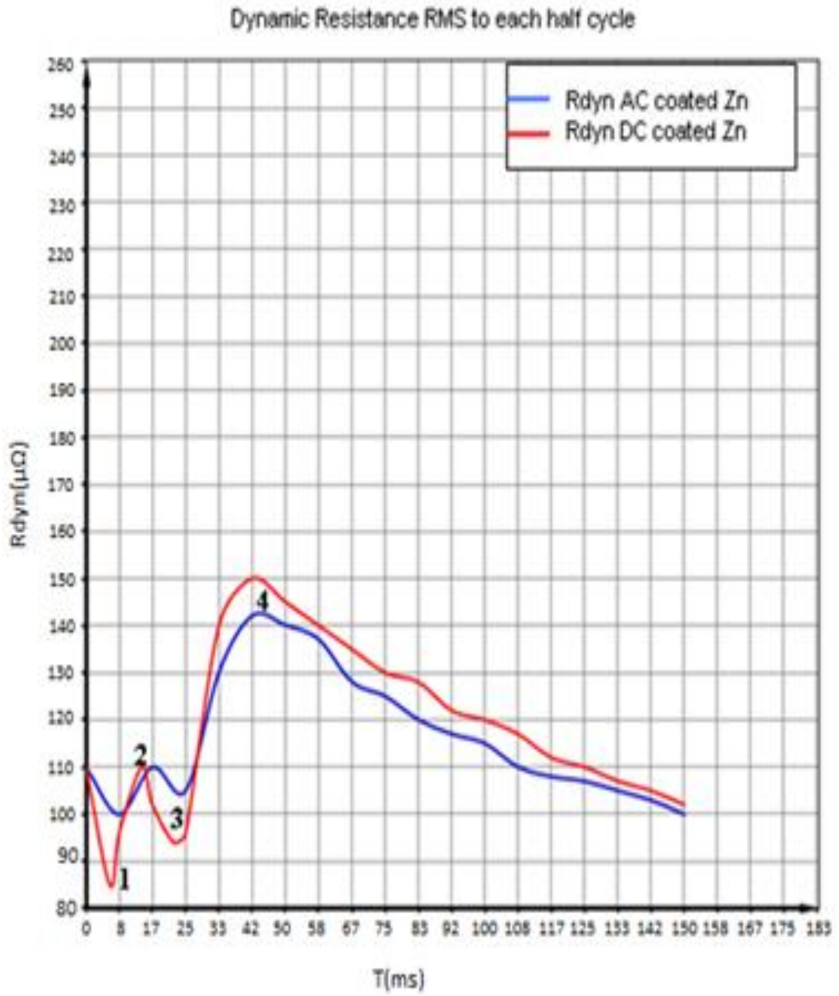


Figure 7 – (a) RMS dynamic resistances (μΩ) and (b) RMS dynamic energies (kJ) in AC and DC welding in uncoated steel sheets, as a function of time (ms).

(a)



(b)

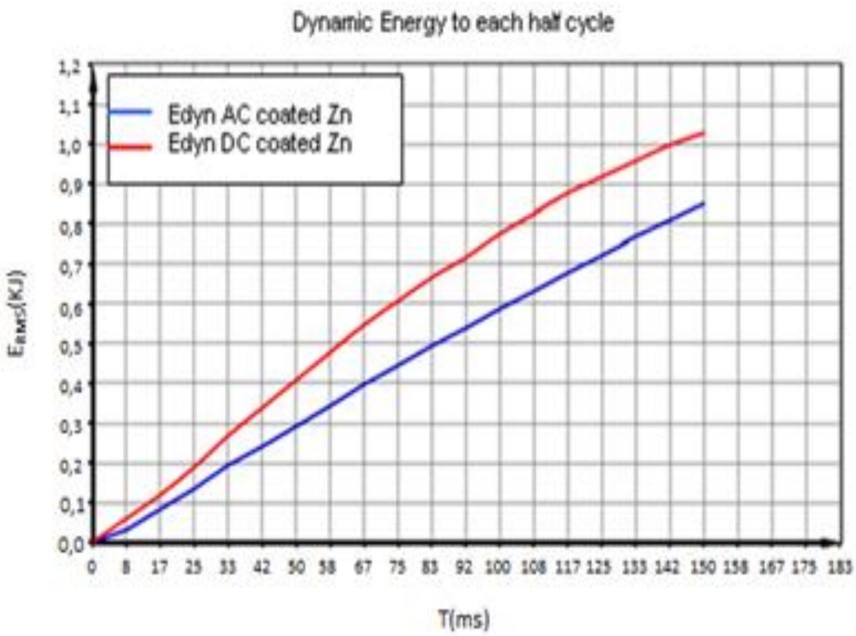


Figure 8 – (a) RMS dynamic resistances (μΩ) and (b) RMS dynamic energies (kJ) in AC and DC welding in zinc coated steel sheets, as a function of time (ms).

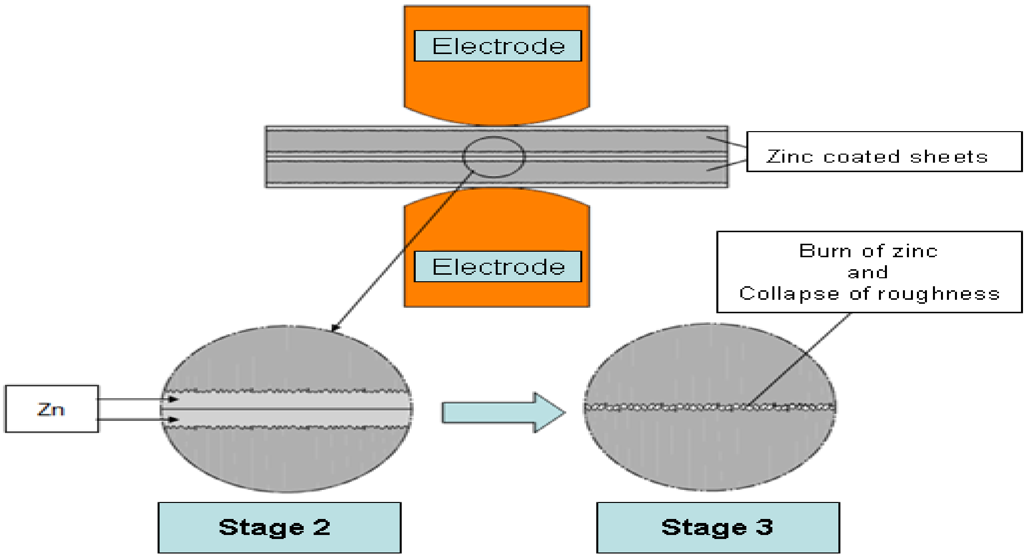


Figure 9 - Schematic drawing of the zinc burn (melting, vaporization and diffusion) represented by stages 2 and 3 of figure 8(a).

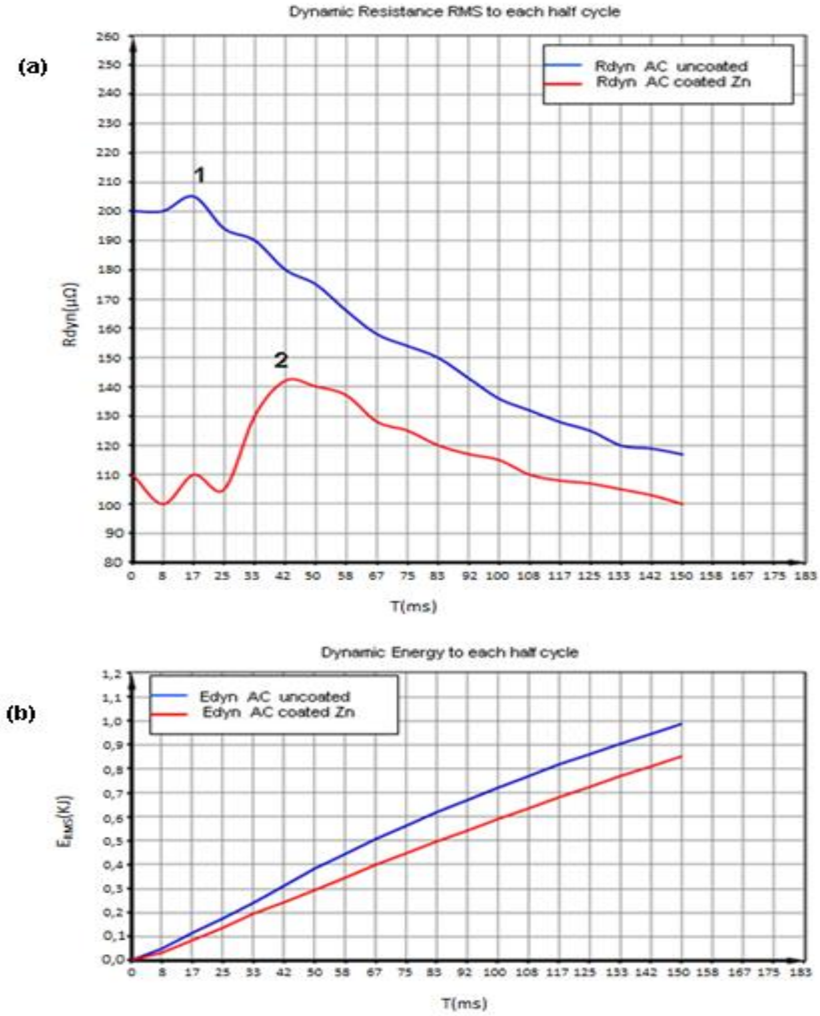


Figure 10 - (a) RMS dynamic resistances (μΩ) and (b) RMS dynamic energies (kJ) in AC welding in zinc coated and uncoated steel sheets, as a function of time (ms).

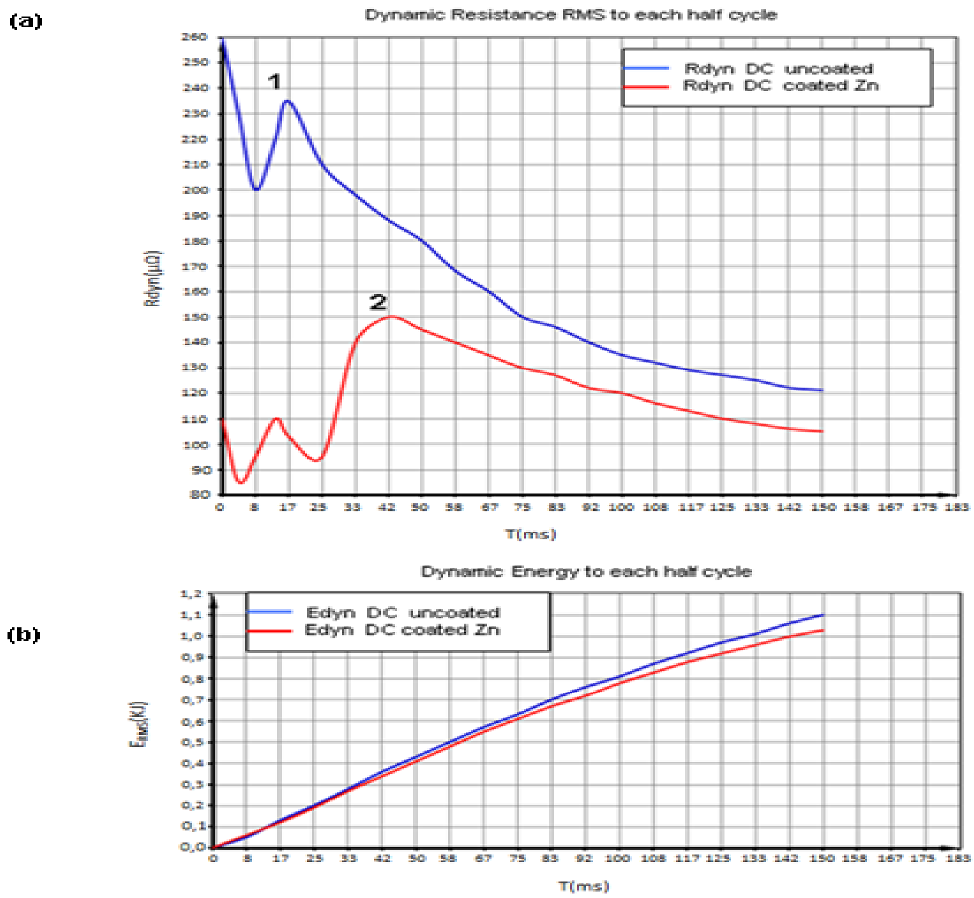


Figure 11 - (a) RMS dynamic resistances (μΩ) and (b) RMS dynamic energies (kJ) in DC welding in zinc coated and uncoated steel sheets, as a function of time (ms).

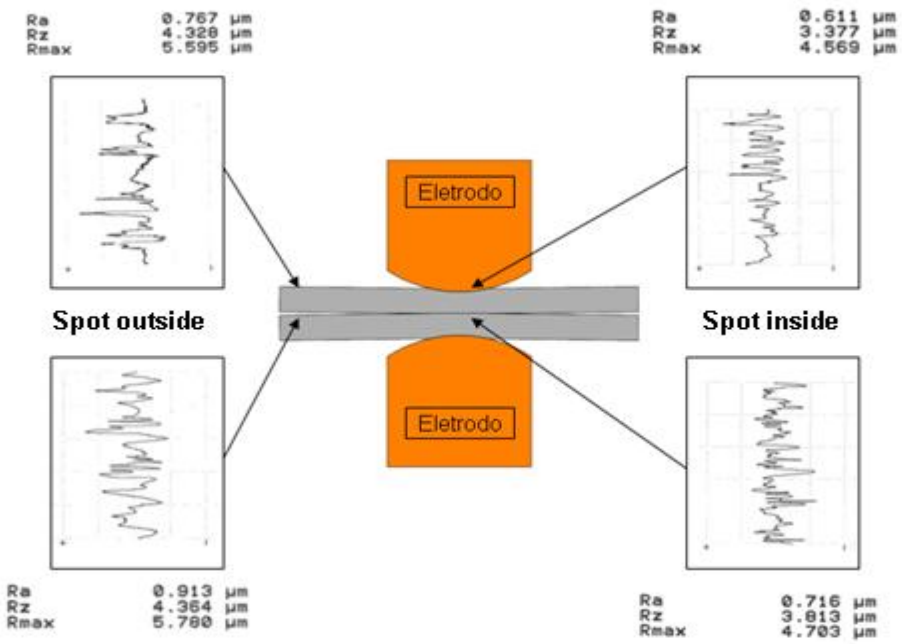


Figure 12 - Example of surface roughness of steel sheets inside and outside of the action line of the force exerted by the electrodes, with a force of 260 kgf.

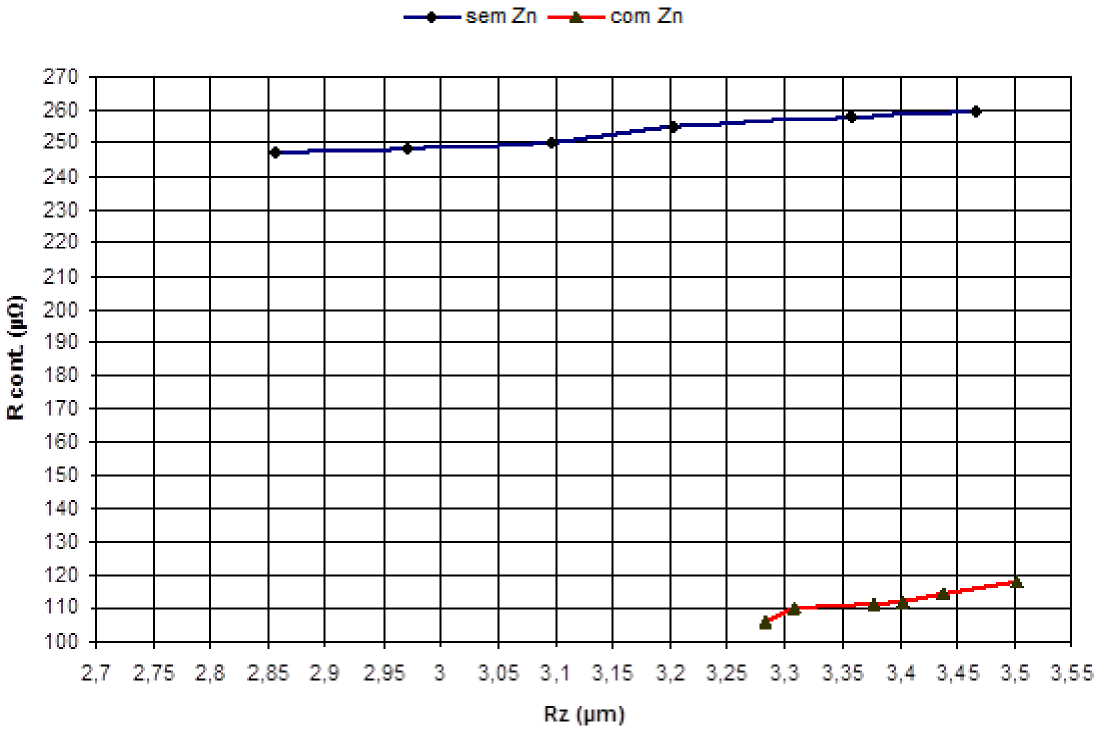


Figure 13 - Contact electrical resistance (R cont. µΩ) versus surface roughness (Rz-µm) inside the spot in Zn coated and uncoated sheets using an electrode force of 260kgf.

V. CONCLUSIONS

Based on the materials and experimental methodology used in the experiments carried out is possible to conclude:

a) The resistance and dynamic energy in DC welding with uncoated sheets were 8.6% and 9.0% higher than in AC welding, respectively. It can be concluded that DC welding with uncoated sheets, with same conditions and welding parameters, is more efficient in generating heat when compared to AC welding uncoated sheets.
b) The resistance and dynamic energy in DC welding with zinc coated sheets were 3.4% and 16.7% higher than in AC welding, respectively. It can be concluded that DC welding with zinc coated sheets, with same conditions and welding parameters, is more efficient in generating heat when compared to AC welding zinc coated sheets.
c) Dynamic resistance during welding, AC and DC with zinc coated sheets showed a small decrease in dynamic electric resistance for a short period of time, approximately half of a cycle. It can be concluded that with zinc burning, the steel surface roughness of the sheets touch and, therefore, their collapse happens. This fact increases the contact area and decreases the dynamic electrical resistance. It can be also conclude that zinc burning does not affect the formation of the nugget during the welding process.
d) The contact electrical resistance increases with surface roughness increase. It can be concluded that with increasing roughness the micro contacts decrease and, consequently, the contact resistance increases. This fact increases the electrical resistance to passage of current.
e) The resistance and dynamic energy in AC welding with uncoated sheets were 31.0% and 15.0% higher than zinc coated sheets AC welding, respectively. The AC welding nugget formation with zinc coated sheets starts about 25ms after the nugget formation with uncoated sheets. It can be concluded that the Joule effect at the interfaces in zinc coated sheet is lower due to the better electrical conductivity of zinc coating.
f) The resistance and dynamic energy in DC welding with uncoated sheets were 34.6% and 7.3% higher than in zinc coated sheets DC welding, respectively. The nugget formation in DC with zinc coated sheets starts about 25ms after the nugget formation with uncoated sheets. It can be concluded that the Joule effect at the interfaces in coated sheet is lower due to the better electrical conductivity of zinc coating.
g) The electrical contact resistance in uncoated steel sheets with constant welding parameters (electrode force of 260 kgf) was 52% higher than in zinc coated sheets. It can be concluded that the surface electrical contact resistance is lower because the zinc coating have a lower electrical conductivity.

h) The nugget diameters showed to be higher when the resistance and dynamic energies were higher. It can be concluded that the higher the resistance and dynamic energy higher will be the efficiency in heat generation to the spot weld formation.

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