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About weldability and welding of Al alloys: case study and problem solving

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ABSTRACT

Purpose: Among many disciplines within engineering, welding is probably one of the most inexact – rather more of an art than a science. As weldment is meant the *complete* joint comprising the weld metal, heat affected zones (HAZ) and the adjacent parent metal and should have the same properties as the parent metal. This paper aims provides a basic understanding of the metallurgical principles involved in how aluminium alloys achieve their strength and how welding can affect these properties. The most important and applied welding processes to Al alloys are here shortly introduced, as well as the preparation of parent metals prior to welding and good welding practice to avoid and/or keep under control defects and failures. Some case studies with possible failures will be introduced together with actions and suggestions to solve the observed problems.

Design/methodology/approach: Two sheets of the EN AW 5454 (AlMg3Mn) alloy were weld with resistance welding process and after a mechanical processing of lamination was observed the presence of the defect. The microstructure of the defect as well as the welded part were evaluated with stereomicroscope (LEICA MS5), optical microscope (LEICA MEF4M), and with SEM analysis (LEO 1540 VP equipped with an energy dispersive X-ray spectroscope Oxford Link Pentafet).

Findings: The well welded part was analysed with optical microscopy and electronic microscopy resulting with the attended mechanical properties. Micro-hardness indentations on the joint demonstrated the good mechanical properties of the joint while with the microscopic observations were identified the orientation and presence of precipitates typical of this alloy. In the defect, microscopically observations showed the presence of oxide inclusions.

Research limitations/implications: There are a number of problems associated with the welding of aluminium and its alloys that make it difficult to achieve this ideal. The features and defects that may contribute to the loss of properties comprise the following: gas porosity, oxide inclusions and oxide filming, solidification (hot) cracking or hot tearing, reduced strength in the weld and HAZ, lack of fusion, reduced corrosion resistance and reduced electrical resistance.

Originality/value: This case study illustrated clearly the importance of the cleaning on the surfaces to obtain a well welded joint ensuring the desired mechanical properties.

Keywords: Heat affected zones, Weldability, Aluminium alloys

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MANUFACTURING AND PROCESSING

1. Introduction: welding structures and procedures

Nowadays, more and more applications requiring welded structures. The increasing applications need lightweight and high performance materials are in the automotive, aeronautic and marine industries.

Generally speaking, a welded part is composed by three regions: the parent metal, the HAZ and the welded metal. The welding process of aluminium alloys involves a variety of issues and precautions necessary to obtain a well joint, as technological problems, right choice of filler metal, possible defects and inclusions into the welding pool and attention on the thermal effects in the heat affected zone (HAZ). The main parameter influencing the welding process is the thermal cycle that depend on position and distance from the welding line, kind of welding, thickness of the pieces, kind of materials (its thermal conductivity and specific heat) and the initial temperature of the pieces.

Welding of Al alloys means keep attention to many variables listed in the next section, in order to realize a welding pool coherent with the matrix and free of defects.

Later in the text, in the case study section, an example of HAZ and its fine-grain structure for a resistance welding process will be showed.

2. Aluminium welding technologies

The welding technologies use vary methods, some with a non-consumable electrode, others that employ a filler metal that acts as an electrode and other technique that use only mechanical friction without reaching the melting point. The *weld metal* is an as-cast structure composed by the parent metal and the filler ones (when filler is required) and its mechanical properties depend on its composition and grain size. In fact, many parameters affect the weld process and the structure obtained, as the amount of dilution factor parent-metal/filler-metal, that in turn depends on the process employed, the position of the components to be welded, the heat input of the process used, the require of multi-pass in thick parts and so on. Table 1 summarizes the main aluminium welding technique used at the present day [1].

3. Issues and advantages in welding aluminium alloys

Nowadays, the metallurgical effects and processing of Al alloys need to be improved because more and more welded structures are now realized with aluminium alloys. The driving force lead to prefer Al alloys for certain applications instead of the more commonly steel is its specific resistance [2]. Furthermore, parity of stiffness for aluminium alloys and steel correspond to lighter aluminium components (of about 50% of weight saved). Certainly, common problems involve the aluminium welding as the steel welding, as the presence of defects in the welded joint.

Al alloys are classified into two groups: non-hardenable alloys that cannot increase their strength with heat treatments and hardenable alloys that can reach higher mechanical properties after heat treatment. Hardenable alloys are based on AlCuMg, AlMgSi, AlZnMg and AlZnMgCu while the alloys AlSiCu, AlSi, AlMg, AlMgMn and AlMn belong to the non-hardenable group. In the hardenable group the strength is achieved after a quenching from high temperature to RT stopping the precipitation of the elements dissolved in the Al matrix. The age hardening follows the quenching, high temperature promotes the precipitation of a second phase, after a certain incubation time. Precipitate avoid or limit the dislocation movement into the matrix increasing the joint strength. The hardening temperature play an important role and lead to obtain different forms of precipitates: coherent particles (the same crystal structure of the matrix, different composition), partly-coherent particles (partially similarity with the crystal structure of the matrix) and incoherent particles (with a lattice structure different from the matrix ones). Moreover, lower aging temperature promotes long incubation time and higher tensile strength.

In non-hardenable alloys no precipitations are present, so is necessary a cold working to achieve high mechanical resistance. A high content of alloy elements lead to obtain a solid solution strengthening.

Table 1.
Principal welding techniques used to weld aluminium and its alloys

Welding process	Characteristics	Filler metals	Electrode
Tungsten Inert Gas (TIG) [3]	Arc welding process working in DC or AC current. Atmosphere: Ar, He or a mixture of Ar and He. Manual or automatic.	Not always necessary. Rods or wires. During the welding is necessary maintain the rod tip into the inert column gas for avoiding oxidation. The welding wires should be cleaned and degreased before use. After the cleaning process they must be stored in controlled conditions and after the open of a set of rods they must be used as soon as possible. Diameter of the rods depends on the thickness of the components to be welded.	Pure tungsten, tungsten and zirconia (ZrO_2), tungsten and thoria (ThO_2), cerium, lanthanum. Particular attention must be required in case of fracture of the electrodes and contamination of the weld pool.
Metal Inert Gas (MIG)	Arc welding process with a continuously fed wire. Atmosphere: Ar, He or their mixture. The presence of oxygen or nitrogen cause porosity. Higher defect at the ending of the weld lead to use a run-off table to finish the weld. Manual or automatic.	The filler metal act as electrode ad is continuously feed into the weld pool. The filler must be cleaned to avoid surface contaminations and porosity into the joint. The filler must be conserved in unopened packaging.	
Friction Stir Welding	A wear-resistant tool made with steel for Al alloys rotate into the weld line heating and plasticizing the metal. The metal flows from the joint to the back of the tool tip without any melting. Several advantage: This method lead too joint different kind of alloys together and joint difficult-welding alloys as the 2xxx or 7xxx series; no losing of low-boiling-point alloy elements; structure with fine grain size. The disadvantage is that require a run-off table at the end of the joint to remove the tool. Recently, retractile tools were studied.		
Resistance Welding	Process that require pressure and heat to melt the metal. In the spot welding pressure is provided by clamping two sheets between two electrodes (made in copper). A current flowing into the electrode and heat is generate by resistance to the flow of this current melting the metal. A weld 'nugget' is formed. No filler metal is required in this kind of process. The heat generated depends on the resistance at the interface so depends on the resistivity and surface condition of the parent material and on the pressure applied by the electrode. The high electrical conductivity of the Al and its alloys make difficult the resistance welding because required high current furthermore the electrode in Cu alloys with Al. The spot welding is a variant: sheets of aluminium alloy are overlapping and weld together in a single pass and the nugget results intern and the surfaces of the sheets remain solid.		

The welding process could cause a decreasing in mechanical resistance of the Al-alloys. Particularly, in the HAZ the mechanical properties could be different of those in the parent metal with possible loss in strength. In fact, structural transformations in HAZ depends on chemical composition of alloy, maximum temperature reached and strictness in the thermal cycles. In the precipitation hardening alloys, where the second phase (precipitates) confers mechanical resistance at the piece, as a results of the heating process the HAZ is affected by a thermal treatment [4] similar to a solubilisation that remove the reinforcement second phase. In the work-hardening alloys as results of the heating process the HAZ is affected by grain growth similar to the recrystallization treatment while if the alloy is in the as-cast or annealed state the properties of the HAZ match with those of parent metal.

In order to realize a welded joint some important steps are required. First of all the handling and storage are quite important. Aluminium is a soft material and could be easily damaged so the storage area must be a place in the warehouse equipped to contain the alloys, indoors in a cleaned and ventilated area. The second step is the thermal cutting process, generally realized by plasma-arc, laser-beam, water jet or with mechanical cutting techniques. The cutting process must ensure an accurate edge preparation that will guarantee a full penetration of the filler metal between the two parts obtaining a defect-free joint. The metal edge is cut obtaining the *chamfer* with a shape and an angle dependent on the specific welding process and on the thickness and positions of the welding parts. Moreover, the chamfer must let to a clear vision of the weld pool, especially in manual welding, to ensure a comfortable position for the operator and its equipment.

After the thermal or mechanical cutting the edges must be cleaned. Cleaning and degreasing processes must remove the lubricant employed during the cut with brushing, spraying or vapour degreasing by clean tools that must be specific for aluminium keeping attention on possible contaminations. Sometimes a chemical cleaning could be required. After the cleaning, the parental material must be welded as soon as possible to avoid contaminations, preferably within the first four hours, and during this time is sufficient cover the cleaned metal with polythene sheets. If more than four hours are passed, is necessary an additionally cleaning.

Defects detected in a joint could be grouped in dependence of their *forms* or the *causes*. Based on their forms, there are two-dimensional or three-dimensional defects while grouping on the causes there are metallurgical or operational defects. 2D defect are cracks, with high dangerousness while 3D defects are score inclusions or pores with a spherical or quasi-spherical shapes, less dangerous than 2D ones. Moreover, 2D defects are always not acceptable while 3D defects are classified in dependence of their positions and/or dimension. The *causes of defects* could be metallurgical or operative. Metallurgical defects could be detected on the welded metal as well as on HAZ or in parent material; operative defects are those caused by the welding process, as no-penetration, lack in fusion, gluing, gaseous or solid inclusions, cracks or other defects. Lack in penetration or in fusion is a very common defect caused by a wrong preparation of the fusion faces, low process-current or high velocity of the welding. Gluing are defects typical of MIG or TIG techniques, caused by high velocity in the welding process or low thermal load. Inclusions could be solid (for instance score, oxide particles or tungsten electrode inclusions) or gaseous (pores, blows) caused by dirt or oxides or wrong use of the weld torch. In this sense, cleanliness of the parent metal before the welding procedures is extremely important in achieving low porosity. Furthermore, is possible to obtain profile defects caused by higher cord of welding obtained for instance by high number of passes or an incorrect preparation of the fusion faces. The wrong positioning of the pieces, spits and sprays are others possible defects.

UNI EN ISO 6520-1 2008 regulates the defects while UNI EN ISO 5817 2008 quantifies the quality of a welded part in dependence of the defects present in the joint giving limits to their dimensions. UNI EN ISO 17635 2010 showing the non-destructive methods to evaluate a welded joint.

One of the major problems in welding Al-alloys is its melting point, quite different of that of its oxide. In fact, aluminium alloys melting points are about 660°C, while its oxide, the corundum, melt at 2054°C. Hence, before and during the welding process of Al alloys is necessary removing the surface oxide layer in order to avoid oxide inclusions into the welding pool; in fact oxide inclusion is one of the most common defects in a Al-welded part. If impurities and score are presents into the alloy, they segregate at the core of the welded part because is the part that solidifies last. In this sense, could be helpful working with inert atmosphere of Ar or He, or using special filler materials containing deoxidising agents producing a score up the melt metal. This score could be entrapped into the welded part between one pass and the other one, so it is necessary making a cleaning treatment after each pass.

In the welded metal is possible to observe the loss of alloying elements as magnesium that have a low boiling point or lithium for its higher oxidation tendency. At the state of the art, with the aim to avoid loss of elements, the choice of the filler metal follow regulations as the AWS A5.10 [5]: filler metals could contain a high percentage of some volatile elements normally present into the alloy, with the purpose of reintegrate them into the weld pool, or for example Ti and Zr than reduce the risk of hot cracking.

During the weld process not only the edge preparation and the cleanness of the surfaces are important. In truth, a variety of properties of the aluminium influence the final joint.

The heat conductivity of Al is three times higher than those of steel (2.3 $Wcm^{-1}°C^{-1}$ for Al, 0.75 $Wcm^{-1}°C^{-1}$ for steel) so aluminium requires higher heating rate than steel in order to avoid lack in adhesion reaching full penetration of the joint. Moreover, this high conductivity is related to difficulties to melt the ceramic oxide layer covering the metal surfaces causing possible defects as oxide inclusions into the welding pool. In this sense a pre-heating of the joint could be helpful.

The thermal expansion coefficient CTE of Al is very high, twice of those of steel ($24·10^{-6}°C^{-1}$ for Al, $12·10^{-6}°C^{-1}$ for steel), moreover, the modulus of elasticity of Al is three times larger of steel leading to higher energy absorption and higher flexion of the Al-pieces causing intense distortions, buckling phenomena and high tensions during the welding process. In this case, it is possible to set the pieces with a certain slope with the aim to avoid or reduce the distortion, or perform a post-heat treatment. The phenomena of the hot-cracking is strictly related to the CTE and very common in the Al-Mn alloys and increase with increasing of the pre-heating of the welded pieces.

An operative problem in welding aluminium alloys could be observed during the warm-up phase. In fact, the steel pieces change their colour reaching a red tint when close to the melting point, whereas, Al alloys not changing in colour causing difficulties to deduce when the piece is going to melt: in this case the operator experience is crucial.

The electrical conductivity and the antimagnetic state of Al alloys influence the welding processes too. In fact, the higher electrical conductivity causes difficulty when the heat for welding is realized with an electrical resistance while the antimagnetic property lead to maintain stable the arc used in some welding technique. The space lattice of Al and its alloys is FCC (face-centred cubic). The FCC structure give to Al certain properties as ductility, formability and high toughness at low temperature. Each grain in the Al-welded structure represent a crystal and crystals size and grain boundaries are the ones that affect the metal properties. During the welding process the metal structure is heated and the grain size tend to increase with the temperature with a consequent reduction in the yield and the ultimate tensile strength. Fortunately, the higher aluminium thermal conductivity let to dissipate the heat process quickly and the grain growth in the HAZ is lower and considered as a marginal effect.

During the heating no solid state transformation happen in the crystal lattice of Al, consequently is possible achieving hardening only in the precipitation hardening alloys.

4. Case study: defect in a resistance welding joint

4.1. Materials and experimental methods

In this case of study is presented a defect of lack in adhesion founded in a joint made with resistance welding technique. The Al alloy is the EN AW 5454 (AlMg3Mn), an aluminium alloy commonly used in the automotive sector with composition showed in Table 2. Two sheets were weld with resistance welding process and after a mechanical processing of lamination was observed the presence of the defect. The microstructure of the defect as well as the welded part were evaluated with stereo-microscope (LEICA MS5), optical microscope (LEICA MEF4M), and with SEM analysis (LEO 1540 VP equipped with an energy dispersive X-ray spectroscope Oxford Link Pentafet).

Table 2.
Chemical composition of Al alloy 5454

Chemical composition EN AW 5454								
	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn
Max.	0.2%	≤0.1%	≤0.4%	3%	1%	≤0.25%	≤0.2%	≤0.2%
Min.	0.05%			2.4%	0.5%			

The sheet was cut and investigated into the defected zone and in a distant zone where a well joint was obtained. With the aim to separates the two edges of the joint without any modification or alteration of the surfaces involved, a low mechanical traction stress was applied on the sample in order to observe the surfaces of fracture and the part involved in the lack in adhesion.

Overall were realized three samples: the two surfaces-fracture samples named #1 and #2 and one sample in the joint named #3.

Sample #3 was mounted in resin for the characterization, polished with SiC paper of 180-400-800-1000 grit, with diamond suspensions of 6, 3, 1 µm and finished with colloidal silica (0.3 µ). With the aim to observe the micro-structure this sample was etched with keller (30 sec) and after a re-polish treatment with the weck's reagents (5 sec).

Samples #1 and #2 were ultrasonically cleaned in acetone for 15 minutes at 45°C before the microstructural observation.

5. Results

The metallographic analysis of the sample #3 was conducted analysing the polished surface. Two different etching evidenced the plastically deformations caused by the resistance welding process and the precipitates orientation and then the grain boundaries.

With the keller reagent was empathised the orientation of the precipitate along the welded line while with the weck's reagent the grain boundaries were evidenced, Figure 1.

The plastic deformation on the microstructure are 'plastic flux lines' of the material after the mechanical deformation. The precipitates in the parent metal as in the HAZ and in the welded metal are homogeneously distributed leading to a theoretical uniformity in the mechanical strength. Actually, after micro-hardness indentation was possible to observe that the mechanical hardness is higher in the welded zone, Figure 1.

The failure analysis for the welded part with lack in adhesion was conducted with the SEM. The microstructural analysis evidenced a three-part structure division. The part named ZONE I is those of lack in adhesion. In ZONE II is evidenced the lack in adhesion with a different morphological structure and finally in ZONE III a ductile-fracture surface where the joint resulted successfully welded. With a higher magnifications were evidenced a certain amount of inclusions. The EDX analysis identify those inclusions as oxides (Fig. 2) and those scales are localized in the welded metal in ZONE I (Fig. 3).

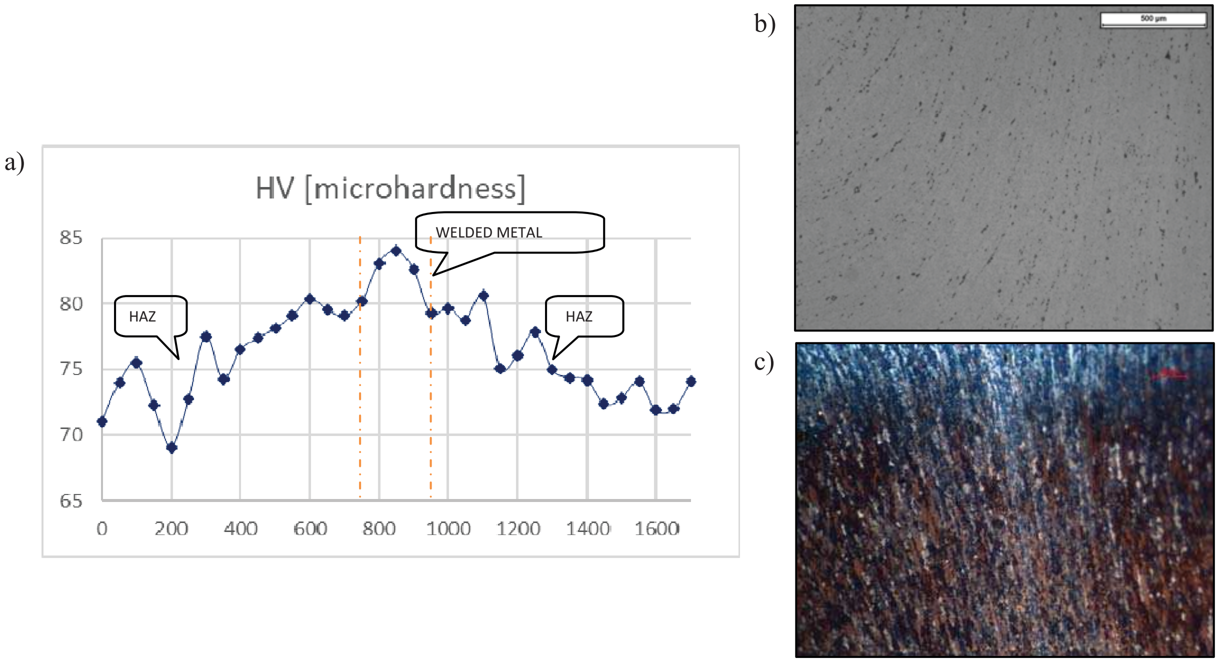
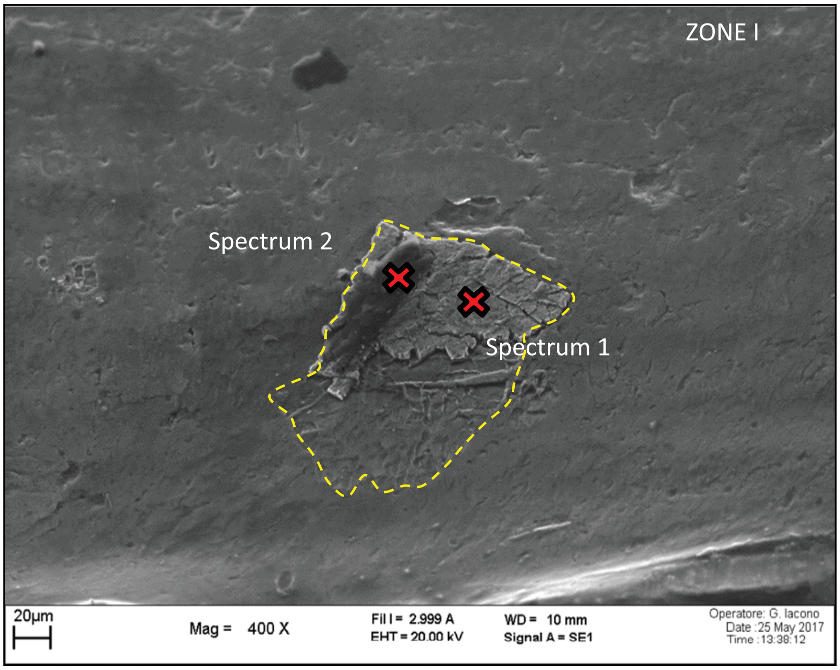


Fig. 1. a) Micro-hardness-Vickers test, b) the sample#3 after keller attack at magnification 100x at the optical microscope. The image shows the deformation in the precipitate orientation between the HAZ and the welded metal, c) the same sample analysed with a polarizer to emphasize the effect of the Weck's reagent, magnification 100x. The welded part has vertical orientation



Spectrum 1

Element	Atomic %
Al	5.60
O	59.21
Mg	0.6
Fe	34.58
Totals	100.00
Element	Atomic %

Spectrum 2

Element	Atomic %
Al	21.17
O	57.28
Mg	2.02
Fe	19.53
Totals	100.00

Fig. 2. Oxide inclusions in the lack-in-adhesion-zone

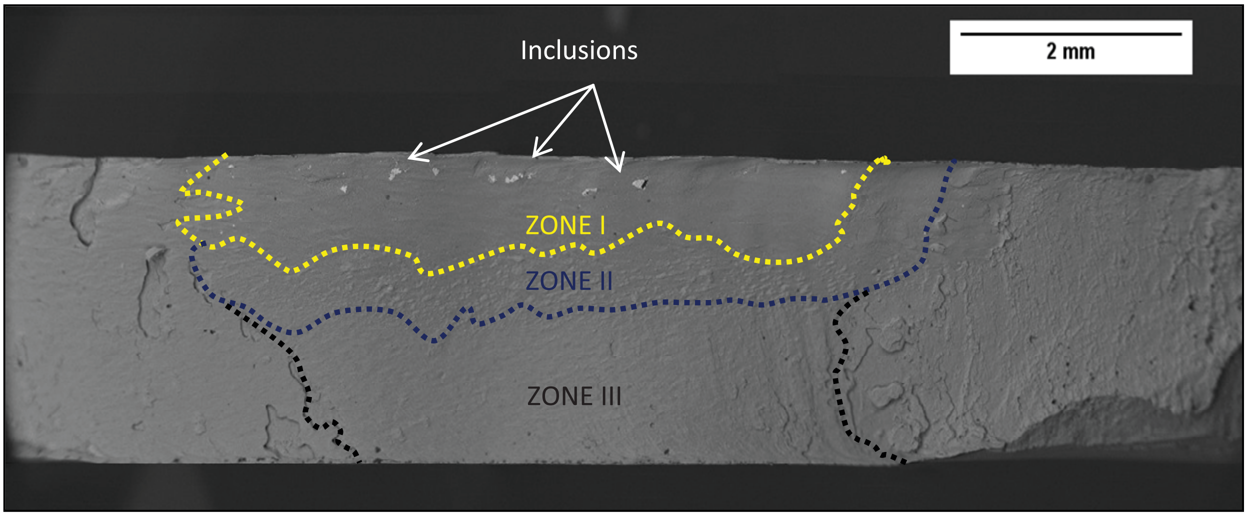


Fig. 3. SEM-QBSD micrograph. The section of the welded part is composed by three part. The dotted lines follow the different zone

6. Discussion

A resistance welded sheet was analysed with the aim to argue causes of de-adhesion in part of the joint. The well welded part was analysed with optical microscopy and electronic microscopy resulting with the attended mechanical properties. Micro-hardness indentations on the joint demonstrated the good mechanical properties of the joint while with the microscopic observations were identified the orientation and presence of precipitates typical of this alloy. In the defect, microscopically observations showed the presence of oxide inclusions.

Those oxides are iron based, present before the welding of the aluminium sheets remaining trapped at the edge of the sheets causing the lack in adhesion. In fact, during the resistance welding process those oxides did not melt causing discontinuity regions. The little presence of oxides could be explained easily: the joint was manipulated and transported without any precautions furthermore after the separation process the ultrasonic cleaning process could be removed a large part of those inclusions.

This case study illustrated clearly the importance of the cleaning on the surfaces to obtain a well welded joint ensuring the desired mechanical properties.

7. Conclusions

This paper aims provides a basic understanding of the metallurgical principles involved in how aluminium alloys achieve their strength and how welding can affect these properties. The most important and applied welding processes to Al alloys have been shortly introduced, as well as the preparation of parent metals prior to welding and good welding practice to avoid and/or keep under control defects and failures. Some case studies with possible failures have been analysed together with actions and suggestions to solve the observed problems. This case study illustrated clearly the importance of the cleaning on the surfaces to obtain a well welded joint ensuring the desired mechanical properties.

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