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CHARACTERIZATION OF ALUMINIUM ALLOY CAPACITOR DISCHARGE JOINTS USING NON DESTRUCTIVE AND MECHANICAL TESTING

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ABSTRACT

This work considers the possibility to apply the improved hybrid Capacitor Discharge Welding process (CDW), based on projection Welding principles, to aluminium alloy Al 5754.
The innovative aspects are the effective possibility to weld aluminium alloys with CD Welding process and establish the mechanical weld characteristics and defects presence as function of the technological parameters.
Intrinsic CDW process characteristics need to be investigated on the base of interaction between the technological aspects and the related mechanical properties. The geometrical and technological factors are combined to improve the welding efficiency and reduce defects size.
In order to assess the technological parameters, visual and ultrasonic inspection of the most significant welded joints were performed and room temperature tensile and fatigue tests were executed to verify the welding results.

Keywords: capacitor discharge welding, Al 5754, static test, fatigue test, ultrasonic test.

INTRODUCTION

The present paper deals with new developments of the CDW process, referred particularly to aluminium alloy 5057 butt joints, with the innovative aim to study the process characteristics on Al based alloys and analyse the mechanical behaviour to improve the weld properties.
The CDW process is an electrical resistance welding technology, realized through intense current pulses discharged by large capacitors; stress concentration effects at the weld toe are reduced, obtaining thin sound welds and achieve good material integrity (Venkataraman, 1988 and Alley, 1991).
The main CDW welding parameters (energy input, applied forces and igniter dimensions) were studied in order to optimise the welding process on Al 5057 butt joints; critical process characteristics are the contact conditions as function of pressure between the parts, number of discharges at different power inputs, as well as the electrodes gripping system (Dattoma, 2010).
A second innovative aspect is to modify the igniting points geometry (Chiozzi, 2008) on the section to be welded and optimize new weld characteristics; the goal is to better impose the local fusion processes more uniformly on the whole area and enhance the weld properties. An innovative trapezoidal contact geometry (Figure 1) with suited welding parameters were studied on the base of previous works (Palano, 2010) in which CDW simulations are performed.
This research focuses the attention on the Multipoint CDW technique (MCDW) conceived by the authors (Casalino, 2006), which represents an hybrid version of simple capacitor

discharge welding and classic projection welding (Palano, 2012). It is proposed with the aim to joint larger surfaces and free from defects typical of CD Welds, such as porosity and lack of fusion.
In this work, butt-weld rectangular section specimens are machined to adopt a trapezoidal contact profile on one of the parts to be welded.
The static and fatigue properties were finally analysed for the welded joints and the results were correlated to process parameters, in order to enhance the CDW process for repair purposes of mechanical components, despite the fact a brittle character was observed for the welded joints. Static tests produce good results with respect to base metal if the proper welding parameters are used,.
Tensile tests on joints with different applied energy are done, so identifying the optimal process configuration; in fact, the efficiency of the CDW technique in terms of repeatability and welded product quality is to be to guaranteed for future applications. Thanks to the fracture section analysis of best welded specimens, the set of optimal welding parameters to enhance mechanical strength and welding bead homogeneity was selected.
At last, the welding quality in terms of defects presence was analysed by means of ultrasonic controls and then fatigue tests were performed according to ND control validation on specimens.
The ND ultrasonic controls (Green, 1987) were realized also to verify if the parameters selected with a weld visual analysis allow to obtain a reduced presence of defects.

MATERIALS AND METHODS

Capacitor Discharge Welding

The CDW process essentially consists of high-intensity current flow discharged onto small igniters, positioned between the parts to be welded (Dattoma, 2010); they are fused into a plasma state by Joule effect, melting narrow layers of base metal at the joining surfaces, to achieve the final weld with the aid of forging forces (Alley, 1991).
The CDW process gives cooling rates greater than 10^6 K/s, to be attained with Electron Beam welding or Laser welding, among welding technologies (Venkataraman, 1988; Casalino, 2007); it is also worth pointing out the welding profile deformations induced by this process are negligible, reducing the subsequent machining and control costs (Chiozzi, 2008 and Palano, 2010).
According to authors works (Dattoma, 2010 and Chiozzi, 2008) and in relation to scientific literature data (Venkataraman, 1988 and Alley, 1991) , small diameter welded bars can be achieved up to 6 mm with cylindrical single igniter geometry. For wider surfaces, distributed igniting points such as the multipoint trapezoidal profile have to be used, to produce a round weld and a more uniform process on the whole section, experimenting the multipoint version of the CDW process (Casalino, 2006; Casalino, 2007;Chiozzi, 2008; Palano, 2010; Palano, 2012).

EXPERIMENTAL ACTIVITIES

Welding equipment

The welded joints have been realized by means of a capacitor discharge welding machine Daiko TDA. Large batteries (8320 F) are connected to discharging pulse transformers for the secondary welding circuit working at 10–15 V on welding specimens.

In order to perform CDW welding on rectangular section specimen, a special welding device was purposely designed. It serves several functions: to clamp the specimens into the machine, to apply calibrated loads and to ensure perfect electrical continuity at the electrodes (Figure 1). An adjustable contrast system is fixed to specimen axis, in order to control the welding depth and the material deformability.

Welding tests

In this work the CDW process is applied to weld aluminium alloy 5754 in butt-weld rectangular sections 9 X 19 mm; specimens are machined to adopt a trapezoidal contact profile (Figure 2).

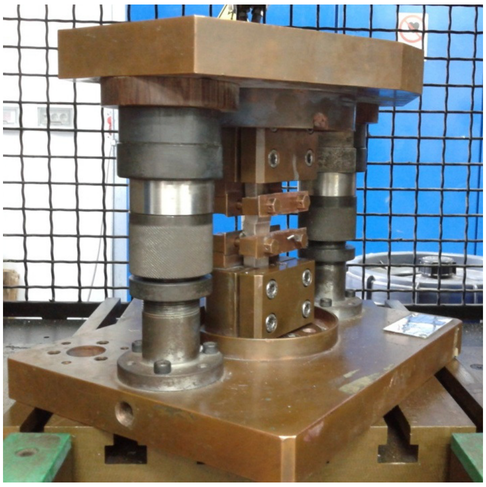


Figure 1: Welding equipment.

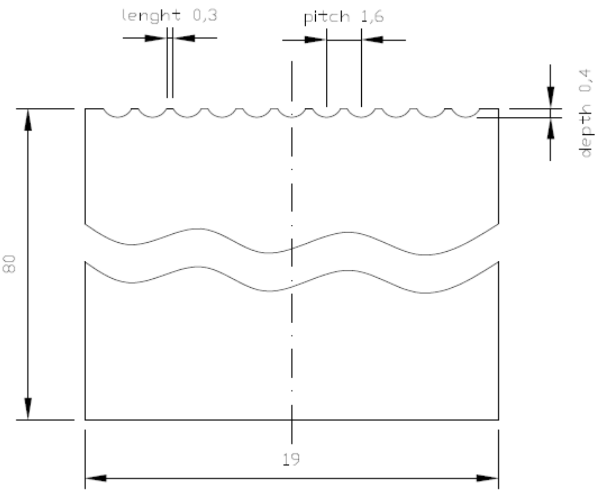


Figure 2: trapezoidal profile for the joints.

Up to now no data besides the authors (Chiozzi, 2008; Dattoma, 2010; Palano, 2010; Palano, 2012) concern the mechanical and fatigue behaviour of the CD Welded joints; defects such as porosity and lack of welding uniformity are presents and repeatability is critical, since the process can be unstable due to electro-mechanic interactions.
On the bases of these presuppositions, it was decided to experiment CDW aluminium specimens, using a large number of specimens to select the best welding parameters and enhance the weld characteristics; the aluminium alloy 5754 is an aluminium-magnesium alloy, easily formable and weldable by fusion, characterized by high corrosion resistance in marine environment. Finally, no heat treatments were done on the parts prior and after welding, whilst a gas shielding transparent chamber with Argon gas was used to prevent oxidation during welding.
The test welding session was performed in two phases: firstly several welding parameters sets were studied and secondly the parameters that produced the best welds in terms of mechanical properties were selected to weld other specimens for deeper investigations. This way, the characteristics of the joints welded with the same parameters are compared, in order to verify the results repeatability.
In the first welding session the process parameters were modified from time to time on the bases of previous work procedures and available numerical data; the energy was furnished in five discharges. According to Table 2, the fundamental discharge is only the fourth or the fifth and the third for some cases, since a single discharge of maximum power is insufficient;

others discharges are of lower intensity for pre-heating purposes. All specimens were welded by applying a force in the range 20-30 kN.
In Table 1 and 2 the input parameters employed in each discharge and the output welding outcome given by the machine are summarised for all specimens. In Table 1 the pre-heating process cycle, to be applied before welding to set the specimens into grips and heat and deform the contact profile to eliminate any discontinuities before welding, are described.

Table 1: Example of pre-heating process cycle, to be applied before welding.

F (daN)	E1(J)	E2(J)	E3(J)	E4(J)	E5(J)	Ip(kA)	Ii (C)
3000	2000	3000	4000	5000	6000	72	n.d

Table 2: Input parameters and welding outcome for the first set of welded specimens.
The significance of the symbols is: F the compressive force applied; E_i the electrical energy of the i_{th} discharge; I_p the maximum current peak; I_i is the integrated current over time.

Specimen	F (daN)	E_1(J)	E_2(J)	E_3(J)	E_4(J)	E_5(J)	I_p(kA)	I_i (C)
1	2500	2000	4000	6000	8000	10000	n.d.	n.d.
2	3000	2500	5000	5000	18000	5000	156	953
3	3000	2500	4000	4000	20000	10000	156	963
4	2500	2500	4000	6000	22000	15000	156	911
5	2000	2500	4000	6000	22000	15000	156	606
6	2000	2500	4000	8000	20000	25000	156	882
7	2000	3000	6000	10000	25000	35000	156	571
8	2500	3000	6000	8000	12000	25000	156	984
9	2500	4000	8000	12000	25000	15000	156	943
10	2500	4000	8000	15000	25000	25000	156	1010
11	2500	4000	8000	15000	30000	15000	156	917
12	3000	4000	8000	12000	25000	15000	156	920
13	3000	4000	8000	12000	30000	15000	156	920
14	2500	4000	8000	12000	30000	15000	156	930
15	2500	2500	4000	8000	20000	25000	156	930
16	2000	2500	4000	8000	15000	25000	156	887
17	2500	2500	4000	8000	15000	30000	156	909

One of the most important problems during aluminium welding is the presence of a oxide superficial layer on specimens, alumina, which interferes with the welding process (Ronnhult, 1980; Spinella, 2005; Han, 2010; Li, 2007).
Therefore it has to be manually removed before and specimens have also to be cleaned. Special spacers must also be used to correctly place the specimens into grips, in order to assure concentricity and geometrical stability for each specimen and reduce angular misalignments between the welding parts. Finally, a copper tinned made flexible spacer has to be placed on specimen sides to better accommodate it into grips and assure the optimal conductivity (Figure 3). During the welding tests it can be observed the applied force on

specimen is directly proportional to the electric discharge value, according to diminished contact resistance.
In some cases, i.e. specimen 5 welded with force 2000 daN and electrical discharge 22000 J, resulted burned because the low force value doesn't guarantee sufficient contact area able to avoid electrical arc to occur. The same phenomenon was verified for specimen 7 and 14.

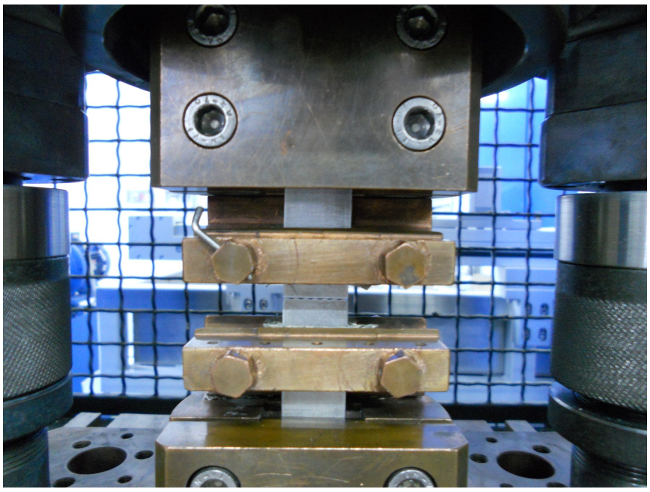


Figure 3: Specimen assembled in the welding equipment.

The explosion due to electric arc strikes must be avoided, not only to obtain good welds, but also because it can damage the electrode surface with some aluminium inclusions.
The first welding tests on aluminium alloy revealed the importance of preheating of the specimen (Table 1), that is realized with a welding prescribed cycle, characterized by low values discharges, aiming also to warm the contact spots before fusion takes place. The discharged current intensity diagrams are reported as follows for the best welded specimens. The analysis of these diagrams allows to control the I_p limit values and modify the technological parameters for successive welding tests.

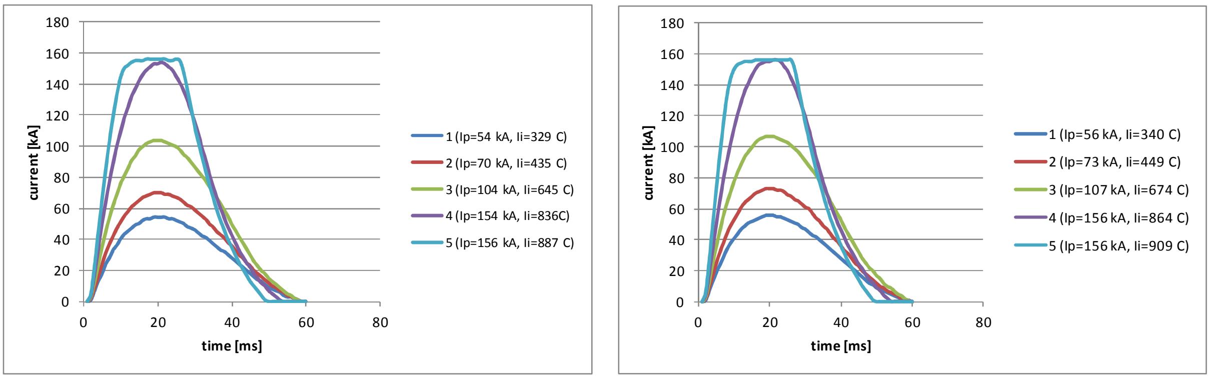


Figure 4: Discharged current intensity for the 5 measured pulses on specimens 16 and 17.

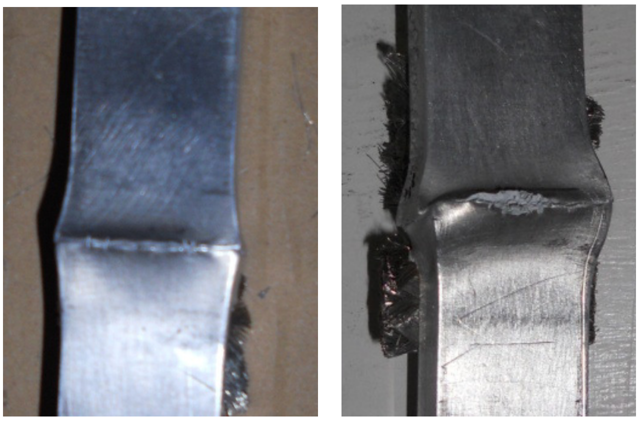


Figure 5: Welded specimens examples n. 13and 17 after welding.

Tensile test results were used to compare different welded specimens; it appears the optimal parameters are referred to welded specimens 9 and 17 (Table 4).
These welds seem to be optimal; reduced volume expulsed from the weld is observed with small distortion of the parts and the weld bead seems to be homogeneous in shape and thickness around the welded profile, as previously proved for Multipoint contact CDW studies (Palano, 2010 and Palano 2012).
According to these results, a second series of welding tests was planned and executed on the bases of technological parameters referred to specimens 9 and 17; ulterior small changes were included: from specimens 30 two preheating cycles were used and the welding discharges ramp was slightly modified in such a way to increase the energy raise before the final discharge, as visible by the parameters in Table 3. These changes seem to produce a thicker weld bead and increase of weld penetration depth, considered as reliable indicator of good welds (Palano, 2012).

Table 3: Input parameters for the best welded specimens.

Specimen	F [daN]	E1 [J]	E_2 [J]	E_3 [J]	E_4 [J]	E_5 [J]
18	2500	4000	8000	12000	25000	15000
19	2500	2500	4000	8000	15000	30000
20	2500	2500	4000	8000	15000	30000
21	2500	4000	8000	12000	25000	15000
22	2500	4000	8000	12000	25000	15000
23	2500	2500	4000	8000	15000	30000
24	2500	2500	4000	8000	15000	30000
25	2500	2500	4000	8000	15000	30000
26	2500	2500	4000	8000	15000	30000
27	2500	3000	6000	10000	15000	30000
28	2500	2500	4000	8000	15000	30000
29	2500	3000	6000	10000	15000	30000
30	2500	3000	6000	10000	15000	35000
31	2500	3000	6000	10000	15000	35000
32	2500	3000	6000	10000	15000	30000
33	2500	3000	6000	10000	15000	30000

Good welds are found to specimens 24-28, for which the weld aspect is optimal, but characterised by small penetration depth values. Specimens 27-29 produce the better alignment and depth results, indicating good fusion takes place in the welded volume, whilst specimen 30 is welded with higher energy input in similar conditions and different gripping spacers. All results are not easy to be interpreted, especially if considering a limit in energy exists, above which the specimens can explode during welding (as for specimen 31, E_{max} = 35000 J) and a good compromise seems to bring force and energy values the highest as possible before mechanical and electrical collapse occur. For this reason, the use of preheating cycles before welding seems crucial, as well good specimen mounting operations are proved to be very influent on the final result; they need to be carefully done and standardised.
Last welding tests on specimens 32 and 33 produce the so far best achievable results. In fig. 6, the discharged current is displayed for the specimen 33, showing a large integral area I_i to be optimised and the peak levels are considerably high, without reaching the input parameters limit values previously described. For these welds the weld bead seems to be visually with optimal shape, i.e. the thicker, constant and coherent around the weld line.

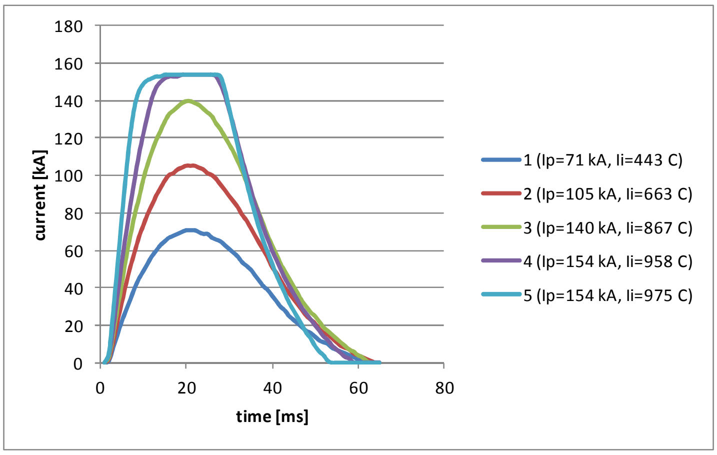


Figure 6: Discharged current intensity for the 5 measured pulses on specimen 33.

Uniaxial tests

The uniaxial tension tests were be performed to determine the mechanical properties of al welded specimens. This data show the reference values for the successive fatigue tests with welded specimens.
The tests execution procedure was be referred to ASTM E8M-0425, it is the reference for room temperature tensile tests.
Test machine was Instrom axial-torsional with load cell of 250 kN according to ASTM E 418 and ASTM E 46719. Tests were be performed in displacement control with 0.5 mm/min translation speed of axial actuator for every test. Fourteen uniform rectangular specimens were being tested.
The longitudinal strain of the specimen was estimated with an extensometer. The unit permits to verify the signal of extensometer and compute the strain of specimen during the whole test
In this experimental analysis, the mechanical parameters, like maximum load, ultimate tensile stress and elongation at break have been evaluated and those data for every test are reported in table n.4.

Table 4: Uniaxial tension test results

Specimen test number	Area$_I$ [mm^2]	Maximum Load [kN]	Elongation [%]	UTS [Mpa]
2	184.8	22.0	0.30	119
4	171.0	25.5	9.61	149
6	184.8	42.8	5.72	232
7	192.6	19.5	0.48	101
9	183.8	49.2	13.99	267
10	171.0	6.0	2.27	35
11	185.3	22.8	3.09	123
12	183.8	13.3	0.11	73
13	184.1	28.9	10.33	157
14	188.2	19.2	0.58	102
16	185.8	39.0	5.10	210
17	187.5	51.5	4.43	275
18	184.8	36.4	4.60	197
19	187.5	44.2	6.44	236

UT control procedures

The ND controls allows generally to detect internal defects, whose size is critical for the welded specimen testing. In particular, they allow to detect position and size of defects with simple instruments and proper commercial probes for thin welded parts. In this work, the selected probe is an MWB 45-4 with integrated wedge (fig.6). It represents a classical contact angle beam sensor with deflection angle 45° and emission frequency of 4 MHz.

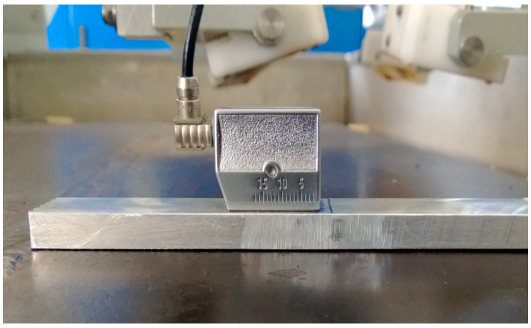


Figure 6: Selected Ultrasonic probe MWB 45-4

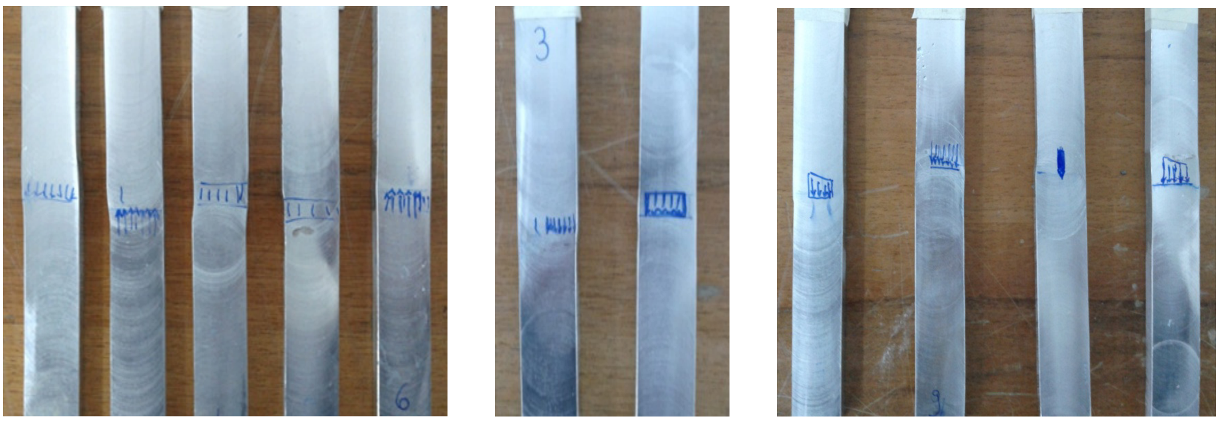
The G.E. USIP 40 system with software is used specimen scanning, using procedures similar to standards for welded butt joints. An unique transmitter/receiver probe for Pulsed-echo method, which output data displayed A-Scan diagrams.

Specimens were prepared by leveling the external prismatic surfaces, in order to cut out the typical slags due to CD welding process and locate the probe in maximum proximity of the thin weld bead.

Defect severity selection is based on the magnitude of defect signals as function of depth or distance, through opportune comparison with references curves, said DAC curve and achieved with artificial defect measurements on similar materials, in order to better define the acceptability of the weld.
DAC curves were obtained from a metallic sample where 3 mm artificial defects were produced and analyzed with specific signal gain according to the defect depth. The curves are representative of different defect conditions: 80% of the reference signal and two curves at -3 dB and at -6 dB below the previous one, typically used to determine dangerous defects; also a + 3 dB curve is reported to represent large size defects.
This way, in table 5 are reported the final measurement data referred to monitored specimens and in particular the extension of defect area; the severity of the single defects is indicated, according to obtained results and the specimens were divided into three different groups: the group (a) contain the small and scattered defects; the second group (b) with extensive lack of penetration in part of weld bead and in the third group (c) the lack of penetration or "cold weld" defect widespread (Fig.7).

Table 5: ND tests results after ultrasonic scanning on both specimen sides.

N°	Gain [%]	Signal level peak [%]	% dB damage range	Approximate Lateral extension [mm]	Severity
20	8.5	87	> -6 dB	10	High
21	8.5	85	< -6 dB	14	Medium
28	8.5	98	-6 dB	12	Medium
25	-1.5	98	> +3dB	12.5	High
22	-1.5	100	> +3dB	13	High
23	-1.5	70	0 ÷ +3 dB	10	High
32	3.0	70	-6 dB ÷ -3 dB	8	Low
26	0.5	98	0 ÷ +3 dB	9	High
27	0.5	63	-3dB ÷ 0	8	Low
33	2.5	45	< -6 dB	Small spot defects	Low
30	2.5	54	-6dB ÷ -3 dB	7	Low



a. **b** **c**

Figure 7: Classification in three different classes of specimens. (a) Large defects, (b) medium size presence, (c) small defects.

In Fig.8 three different A-scan examples of ultrasonic inspections are reported, in which the typical peaks could be clearly identified. In Fig. 8.a the encountered leak of penetration through thickness in weld bead is reported; this defects is distributed along the central area of weld bead, therefore it was classified as critical for the integrity of the component. In Fig. 8.b the specimen shows several small defects, typical of arch welding, but everyone is contained in the area below -6 dB. Despite the low amplitude of the signal, this specimen was considered in group (b) defects, because they are sparsely distributed along the welding surface.

Finally, Fig. 8.c shows an A-Scan of specimen with small sparse defects, included in the group (c) with good welding quality. The good results as for specimen n.33 could be obtained thanks to optimization processes, based on previous weld tests. Basically in Al CD welds a certain level of defectiveness is always presents; the size and distribution of which determines the joint behavior.

The defects with smaller amplitude of -6 dB, even if they are extended along the lateral surface, were classified as not relevant, because they were considered as bonding defects during the welding process.

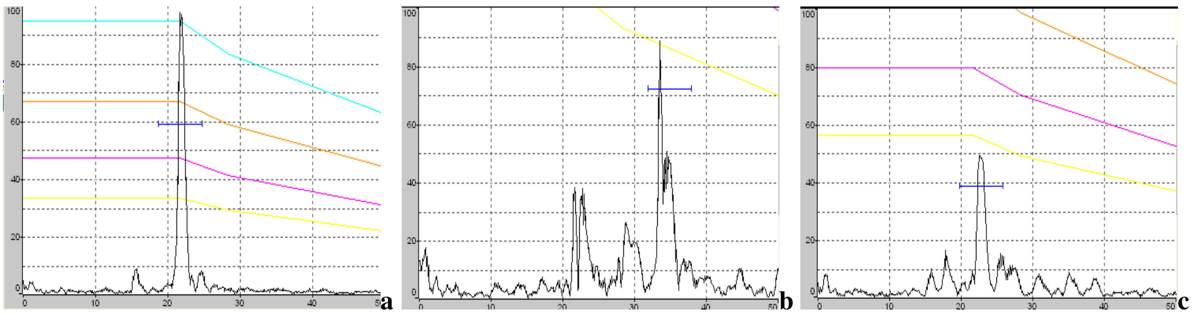


Figure 8: A-scans of CD welded specimens. (**a**) specimen n.25 with high percentage of defect area, (**b**) specimen n.20, medium size, (**c**) specimen n. 33 with typical small sparse defects.

Fatigue tests

The fatigue Wöhler curve is achieved for the welded specimens and presented in Fig 9, up to the material limit stresses at $2x10^6$ cycles; tests have been conducted with specimens of 8.00 mm thickness at room temperature. The fatigue tests were performed on welded specimens with the optimal parameters identified in the first step welding and which presents low or medium defects, detected by ND-inspection. In total, the tested specimens are six. Despite the small number of specimens, some indications can be clearly observed (table 6). The specimen n. 33 was tested with a 70% of maximum static load; although the failure was achieved at about 1800 cycles, rupture did not occur in weld bead as expected, but in base material (Fig 10a). It means probably the quality of welding permitted the two borders of specimens to be jointed in an acceptable way. At contrary, specimen n. 30 was tested at 35% of maximum static load and it reached the material stress limit at $2x10^6$ with rupture in the weld (Fig. 10b). The trend of the curve represent the typical Wöhler curve behavior with a decreasing load limit as function of number of cycles up to failure. More tests may define accurately the fatigue limit for design purpose, but it can be ascertained the behavior of CDW Al joints is structurally reliable, provided that loading conditions are restricted well below the weld ultimate limit statically calculated.

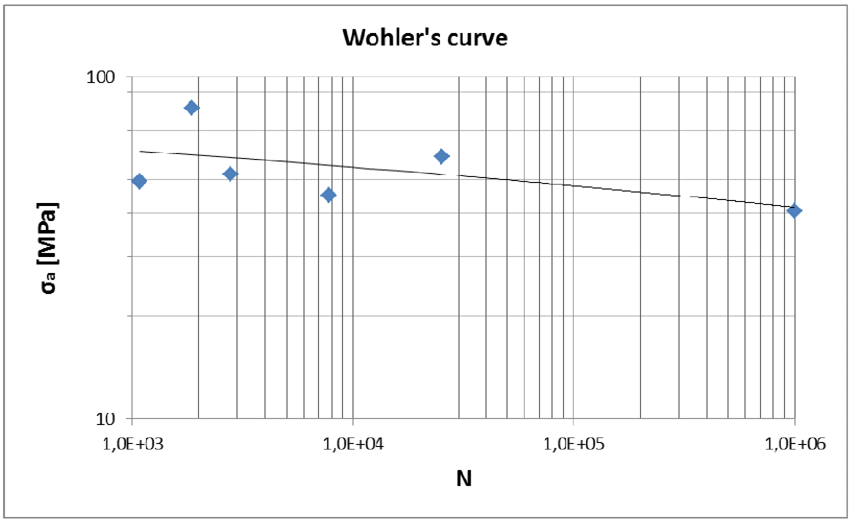
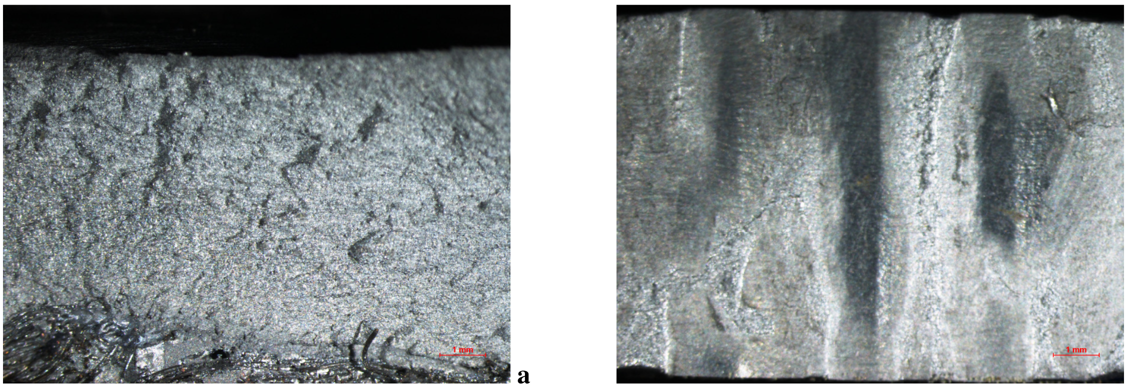


Fig. 9**:** The Wohler curve after fatigue tests on CDW specimens in Al alloy.



a b

Fig.10: Fracture surface of specimen n33 (**a**) and specimen n.30 (**b**)

Table 6: Fatigue tests results

N	σ_{max} [MPa]	σ_m [MPa]	σ_a [MPa]	F_m [N]	Fa [N]	cycles
33	180	99	81	14256	11664	1869
32	130	71,5	58,5	10296	8424	25362
28	115	63,25	51,75	9108	7452	2806
27	110	60,5	49,5	8712	7128	1087
21	100	55	45	7920	6480	7782
30	90	49,5	40,5	7128	5832	1000000

CONCLUSIONS

This work represents a further step in the study of the applicability of an innovative welding technique such as CDW, in its variant multipoint on aluminum and its alloys.
In particular, joints of rectangular section, in aluminum alloy 5754 using the Multipoint Capacitor Discharge Welding (MCDW) technique were realized.
An optimization process was performed with a procedure that consists in two pre-heats and a series of discharges which reaches the high energies more quickly.
Moreover, the subsequent ultrasonic testing, have largely confirmed the assumptions developed by a visual inspection of the specimens. The best results, in fact, were achieved by

the specimen 33, which is characterized by a good welding with limited size and acceptable extension of a defect.
Certainly, only the ultrasonic controls are not sufficient to characterize the joints, so fatigue tests were performed on the same specimens. The results validate the UT outputs and make them more reliable.

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