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Inconel 718 and TiAl6V4 welded joints with Multipoint CDW Process under high temperature testing

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Abstract

Welding methods employed to date for repair purposes, such as TIG (tungsten inert gas), EBW (electron beam welding), MPW (micro plasma welding) and PW (Projection Welding) lead to large Heat-Affected Zones and elevated distortions induced in the welded component. In alternative to the above-stated methods, linear friction welding and Capacitor Discharge Welding provide drastic reductions in the size of the HAZ, assure good mechanical properties and allow elevated dimensional accuracy.

The CDW process is performed by the means of an high-intensity current flow, produced by the discharge of a capacitor battery; several specimens of Inconel 718 and TiAl6V4 materials in the form of circular bars have been welded with several combinations of the main parameters involved. In particular, the Multipoint contact welding profile has been conceived in order to improve the geometrical continuity and the joint strength. All the specimens have been machined according to ASTM standards and Static and Fatigue tests at room and high temperatures have been done to analyse the Multipoint CDW Process and to validate the welding technology. Different energy input and applied force have been used to weld each specimen type, resulting in extremely variable performances in terms of static strength and total deformation of the welded joint. The metallurgy of significant welded specimens has been analysed and the CDW performances have been established according to micro structural studies.

The CDW welding process is an extremely complex process, since is dependent on many factors, but is a promising tool with many technological and structural advantages; Multipoint CDW can be used for repair and production purposes in several mechanical and aeronautical applications.

Key words: Capacitor Discharge Welding, Tensile Tests, Fatigue, Metallurgical analysis, Welding parameters, HAZ, Multipoint contact profile

Multipoints capacitor discharge welding of Aeronautical materials.

The conventionally defined CDW welding is generally used for the rapid welding of dice and bolts of small dimensions; generally the process differs from resistance welding methods because of the higher current values and minor application time; CDW is performed by the means of high-intensity current flow, produced by the discharge of a capacitor battery (Fig. 1). The discharged energy is applied onto a small igniter, positioned between the two parts to be welded (Fig. 2); the igniter starts to evaporate in a plasma state and melts narrow layers onto the pieces to be welded; during the whole process, the pieces are pressured each other and in the final stage forging takes place to realize the welded joint.

Some of the advantages of the CDW technology are:

- assure high quality welding, exempt from heavy deformations of the original profile; good shape contiguity with rapidly solidified microstructure is achieved.
- the heat affected zone extension is minimized and very narrow welded metal layers are produced (0.1 mm thick);
- absence of defects such as cracks and porosity and stress concentrators after notch effects due to least material to be expulsed from the welded zone.

These characteristics of CDW let us conceive the idea to enhance the repair process of mechanical components through the CDW process. For this aim, several cylindrical specimens with bore diameter of 12 mm have been machined in aeronautical materials, in order to be welded with the CDW process on the bases of preliminary welding trials performed in previous works [2] on AISI 304 bars. The CDW process with Multipoint welding profile (Figure 3) has been proposed with good results. The authors named this process “Multipoint Capacitor Discharge Welding” process (MCDW), whose characteristics are placed between those of CDW and PW. With the proposed contact profile the contact area between the pieces is progressively extended due to the applied pressure between the electrodes. Heating is produced all over the welded section due to the Joule effect at each contact peak and to resistivity increases with temperature.

The new multipoint welding profile has been conceived to solve some process limitations [2-5]; in fact, the weld surface extension is limited in the conventional CDW technology by the current discharge curve shape and inductive phenomena and some defects such as localised burns and porosity are not avoided; more over a good welding material distribution is not assured; thereafter the choice of several igniting peaks, a number of 6 in particular, alternated with calibrated gaps of only 0.4 mm depth. This way the welding process is localized in more regions of smaller width. The sinusoidal shape is needed to avoid geometrical discontinuities between the contact regions and the gaps; the molten material flows from the contact peaks to fill the remaining voids in the welded section. This way, the requisite of uniform distribution of the joined zone is simply satisfied due to the possibility to distribute the welding power among several welding spots; an adequate distribution of these contact positions can be optimized for the whole extension of the zone to be joined, so that each individual point gives birth to a limited welding pool during the forging phase. In addition, the correct vain dimensioning design shell optimize the outlet flow for the forging material and the constant presence of calibrated pressure allows the joint to be in perfect welding conditions, facilitating the expulsion of the entrapped gases developed during the electric discharge.

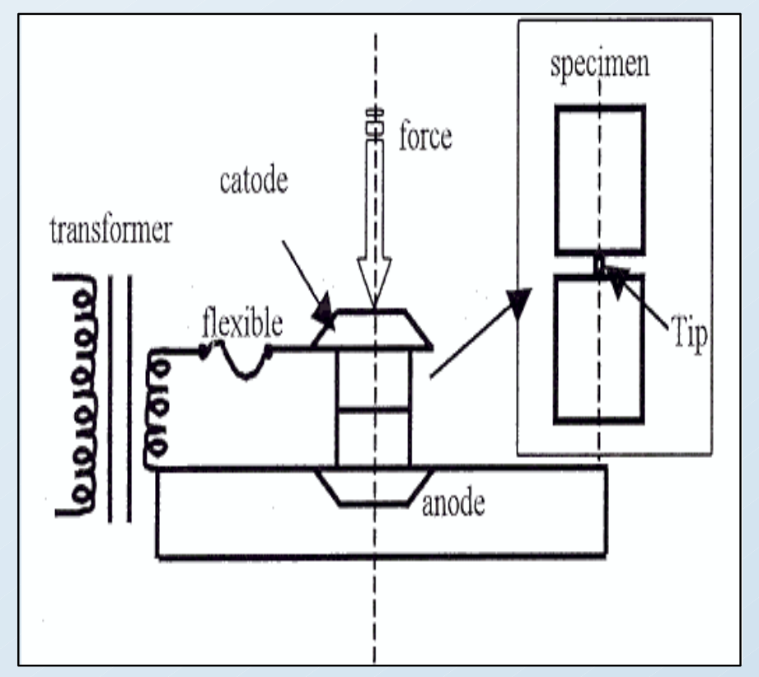

Figure 1. CDW and PW discharge circuit

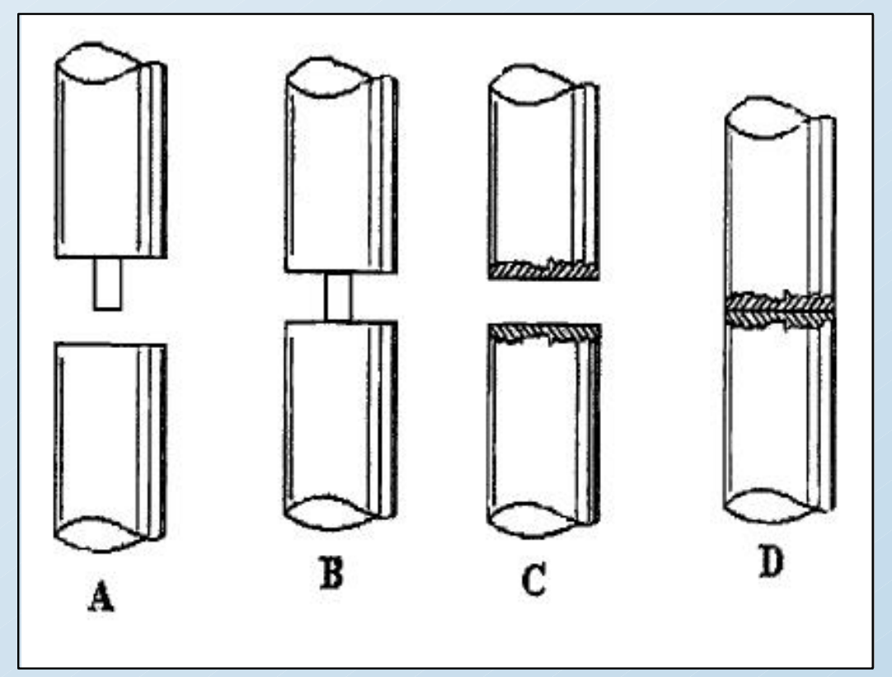

Figure. 2. Welding pinciples of the CDW process

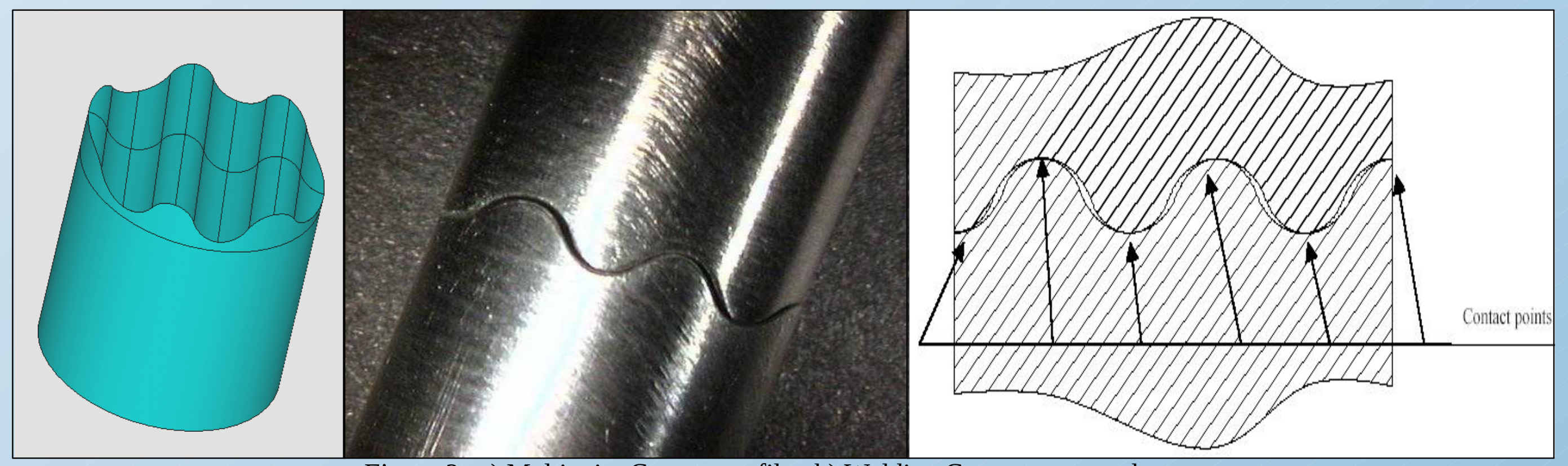

Figure 3. a) Multipoint Contact profile; b) Welding Contact spots and geometry.

A special tool has been designed in order to clamp the specimens into the capacitor welding machine and to apply controlled pressures and the needed energy input (Fig. 4). This way, the process parameters have been studied for Inconel 718 and Ti alloy materials [3] (Tab. 1).

The parameters are: energy input, pressure force, multipoint profile geometry (number of peaks and gap depth), maximum current and the axial controlled deformation.

Very poor technical literature is available regarding the CDW technology; up to now, only small surfaces have been successfully welded, but no data are provided about static resistance and high cycle fatigue behavior [4-6].

Aeronautical industries are interested into this welding technology and the University of Lecce has an active role in the process development. The physics of the capacitor discharge process is well known and some applications have been recently developed [7,8]. The innovative aspect proposed by the authors is the multipoint contact profile between the welding surfaces and an the application on advanced materials.

Capacitor Discharge Welding (CDW) and Projection Welding (PW) processes are capable to produce excellent butt welded joints at cooling rates greater than 10^6 K/s, with the achievement of good grain refinements and reduced segregation. The welding mechanism is similar, and for both processes an upsetting force is placed, in order to bridge the gap between the welding edges and assure good electrical continuity. For PW process, the capacitor discharge effect is used on similar geometries, but the welding surface area is heated up to the melting point only, using either lower energy or larger tip geometries with elevated external forces. Elevated thermal and mechanical deformations occur due to the high compression forces and Joule effect [9]; finally, the heat affected zone is larger. In this work, an hybrid version of the CDW and PW processes described above has been used and is presented as “Multipoint CDW process” (MCDW). For large diameters and not weldeable materials, defects such as porosity and lack of welding uniformity are still presents and repeatability is critical, since the process is unstable due to electro-mechanic interactions.

Material type	N° of discharges	Energy Input [kJ]	Maximum current [kA]	Applied Force [KN]
Inconel 718	3	35÷40	~80	45
TiAl6V4	2	25÷30	~50	35

Table 1. Optimized welding parameters.

Figure 4. Flexible tulip grip, applied to ensure alignment and reduce electrical losses.

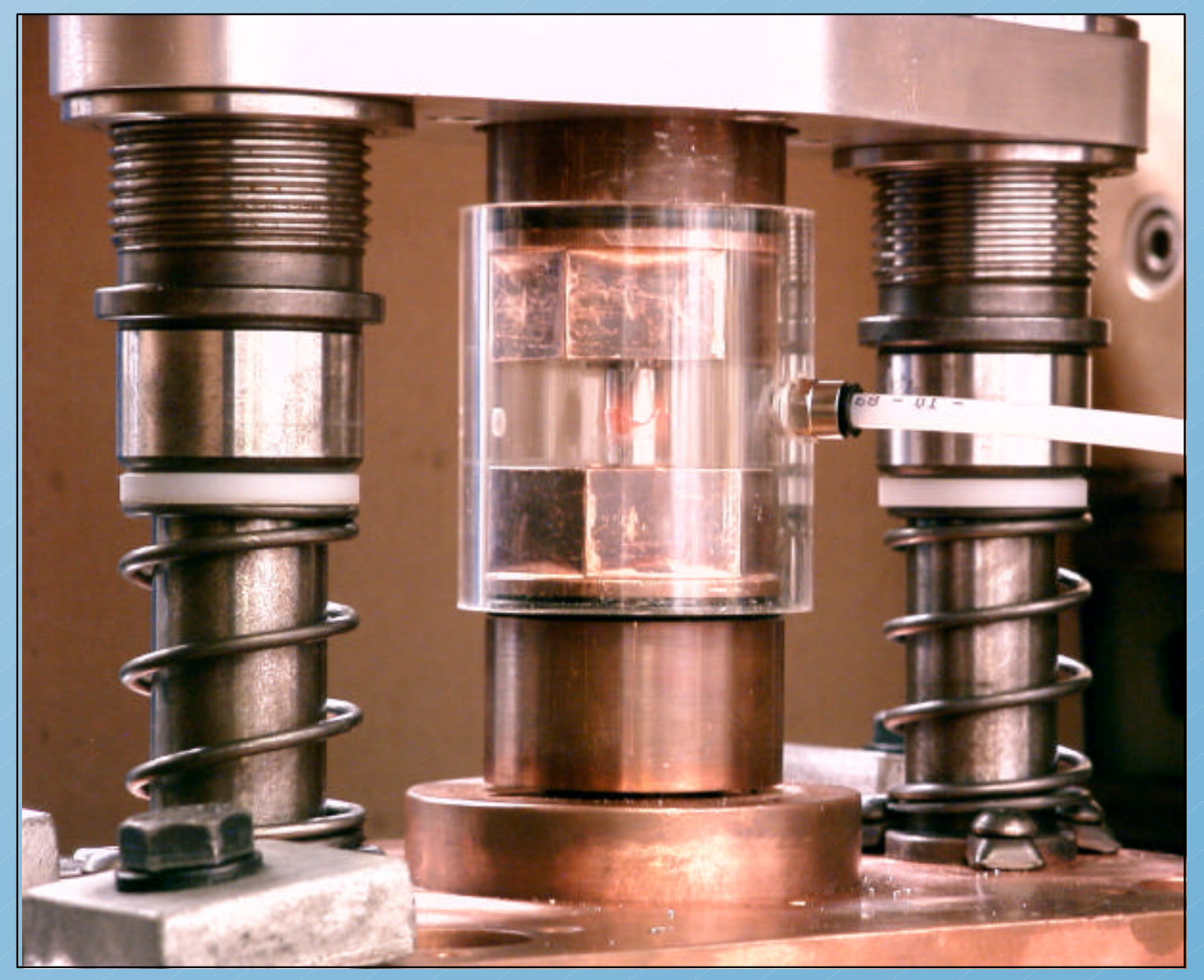

Figure 5. Special welding tool system with lining guides and protective gas usage during the electrical discharge .

Stress relieving heat treatment	
Heat treatment temp. (°C)	**Holding time**
955	1 hour
Precipitation heat treatment	
Heat treatment temp. (°C)	**Holding time**
720	8 hours
621	8 hours

Table 4. Heat treatment for Inconel 718

Stress relieving heat treatment - annealing (*)	
Heat treatment temp. (°C)	**Holding time**
600	1 hour minimum
Solubilisation + ageing (**)	
960	1 hour minimum
540	4 hours minimum

Table 5. Heat treatment for TiAl6V4

Mechanical characterization of the Multipoint CDW welded bars.

The mechanical characterization of the multipoint CDW process applied on Nickel-based superalloy (Inconel 718) and aeronautical Ti alloy (TiAl6V4) is presented.

A certain number of tensile and fatigue tests have been performed onto base metal and as-welded specimens with the same heat treatment either at room temperature, either at working temperature (respectively 650°C and 400°C for Inconel 718 and Ti alloy). Successively, micrographic investigations have been done to relate the welded joint structural capabilities to the material characteristics in the welded zone. All the tests specimens have been designed with the same geometry, according to the standard codes (fatigue specimens roughness below 0.4 R_a).

Tables 2 and 3 show the first set of tensile static test results on welded specimens. V_t is the test displacement speed, R_p is the ultimate stress, R_m the yielding stress.

The tensile tests results show good static behavior of the CDW welded joints in terms of yield and ultimate stresses for Inconel 718 at room temperature, while the Ti alloy specimens reveal the yield stress and ultimate stress to be 20% lower than base material. At working temperature the Inconel 718 welded specimens show sufficiently acceptable ultimate tensile properties (yield strength is below the minimum base material value); the Ti welded alloy specimens have also interesting tensile properties if Heat Treatment (**) is used.

All the CDW-multipoint welded materials exhibit a very low elongation percentage A, according to the fact that the tensile direction is orthogonal to the welded profile. Consequently, all the welded specimens show the yield stress at the same level of the ultimate stress. In Figure 6-10 the fatigue tests results are described. Both the materials in “as welded” conditions show lower fatigue properties with respect of the base material, but longer endurance can be assured with proper load limit calculations and heat treatment improvements. In fact, the CDW welded specimens are capable to reach over 10^6 cycles with applied alternate stresses σ_a = 200-300 Mpa for Inc718 material and σ_a = 150-200 Mpa for Ti alloy material. A greater number of specimens for fatigue tests has to be used in order to better define the achieved results.

	Base material				As welded				
Specimen	I1	I2	I3	I4	I5	I6	I7	I8	I9
T [°C]	25	25	650	650	25	25	650	650	650
$\mathbf{V_t}$ [mm/min]	0.075	0.075	0.040	0.040	0.075	0.075	0.040	0.040	0.040
E [N/mm^2]	204460	206770	220440	243500	201170	195300	184650	223990	175350
$\mathbf{R_p}$ **0.2%** [N/mm^2]	1130÷1140		980÷1000		1160÷1200		800÷1000		
$\mathbf{R_m}$ [N/mm^2]	1430÷1450		1150÷1220		1200÷1270		780÷1100		

Table 2. Static tests data for Inconel 718

	Base material				As welded				
Specimen	T1	T2	T3	T4	T5	T6	T7	T8	T9
T [°C]	25	25	400	400	25	25	400	400	400
$\mathbf{V_t}$ [mm/min]	0.120	0.120	0.075	0.075	0.120	0.120	0.075	0.075	0.075
E [N/mm^2]	105490	103050	98305	90262	105220	105780	94560	86833	88044
$\mathbf{R_p}$ **0.2%** [N/mm^2]	930÷950		600÷620		700÷800		400÷500		
$\mathbf{R_m}$ [N/mm^2]	1000÷1050		730÷750		750÷850		500÷650		

Table 3. Static tests data for TiAl6V4

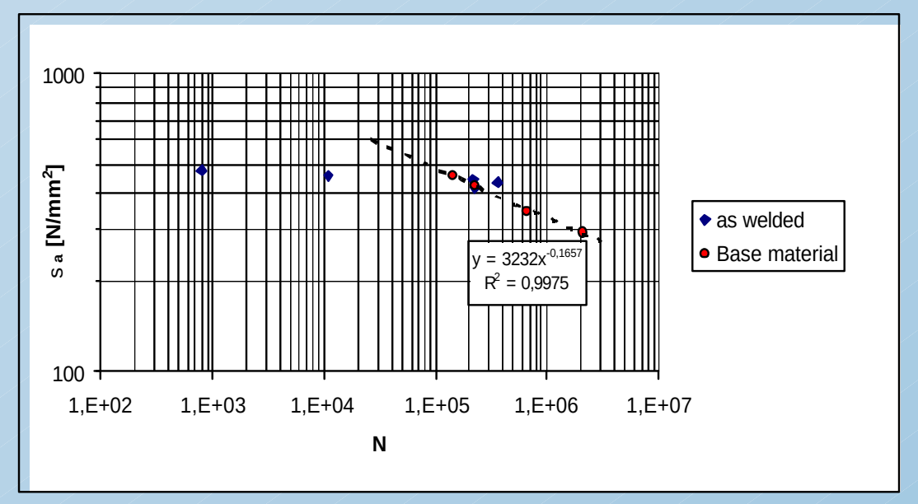

*Fig. 6:*Fatigue tests results for Inc718 welded joints (room temperature).

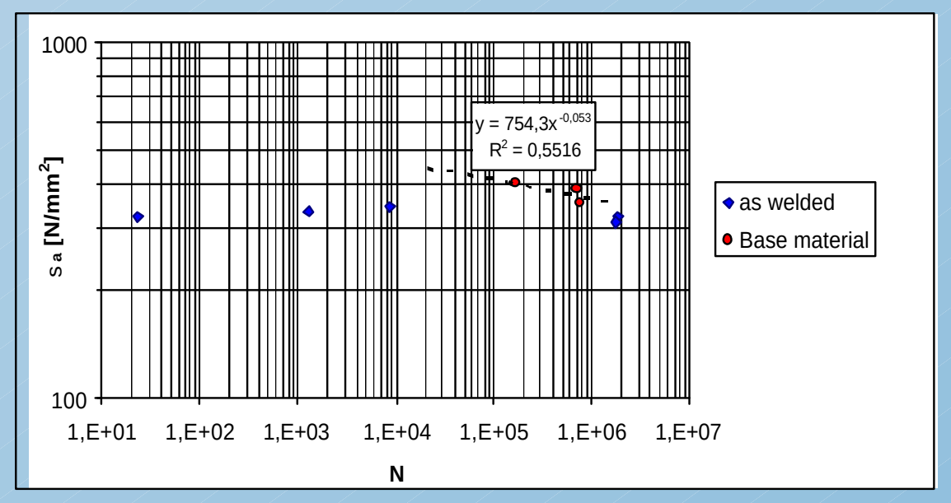

*Fig. 7:*Fatigue tests results for Inc718 welded joints (working temperature).

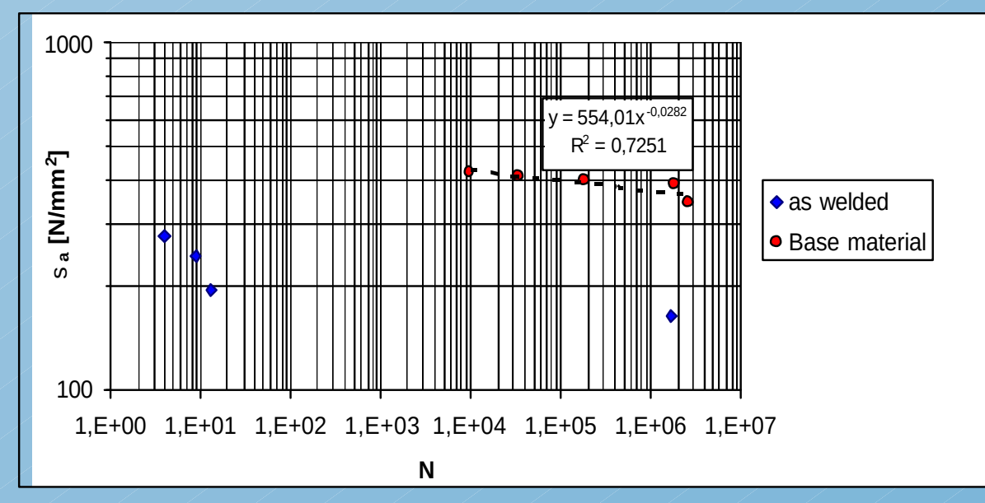

*Fig. 8:*Fatigue tests results for TiAl6V4 welded joints (room temperature).

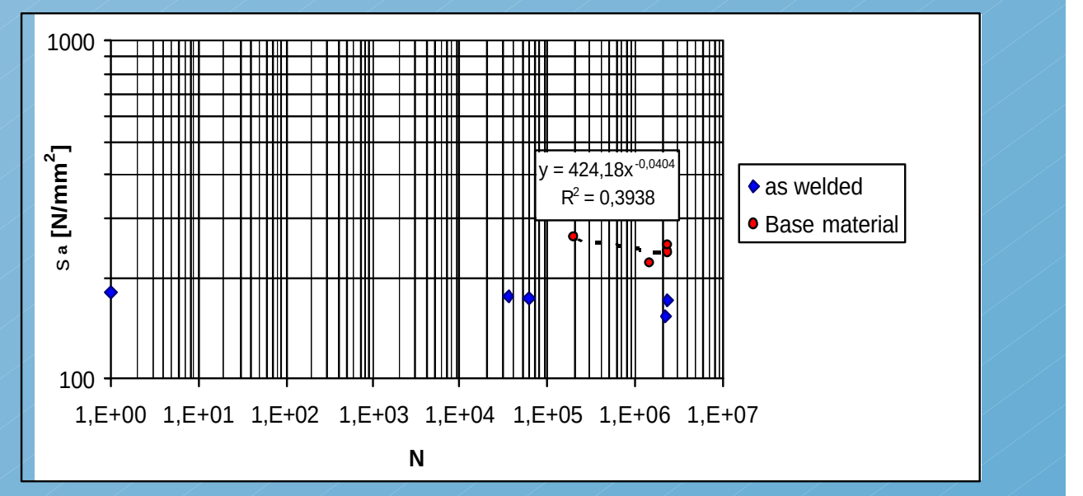

*Fig. 9:*Fatigue tests results for TiAl6V4elded joints (working temperature).

Microstructural characterization of the Multipoint CDW welded bars.

The failure surface follows in all cases the welding profile and appears very smooth and regular; in Fig. 6a-b no cracks and asperities are observed. Ductility is apparently not present since plastic deformations are limited in small layers of the welded metal. The welded metal distribution appears well deposed all over the weld line in extremely thin layers of variable thickness 0.1- 0.3 mm (Figure 7,14) for both the materials; although not uniform molten metal deposition can be observed (Figures 8 and 9) and micro-defects presence is detected in the form of small vain (Fig. 10)localized at the transition point between the peak contact zones and the gaps filled with fused metal, the welded layer appears sufficiently coherent with the base material; for Inconel 718 specimens, the microstructure is characterized by stratified precipitates along the weld border and very fine granulometry with small grain dimension (Figure 10,12) also in the thinner weld zone. Similar considerations can be arisen for the Ti alloy welded specimens and porosity or cracking effects have not been detected. In Figures 11a-b the rupture mechanism is equally recognizable as brittle fracture on the whole surface, but small plastic deformation is sparsely observed in restricted zones where the thin welded metal layer is stretched between the substrates of base material and keeps stuck alternatively to one of the two boundaries giving rise to plastic transition sites. The probable point of initiation of rupture is localized at the weld borders. In Fig. 16,17 the measured microhardness profiles through the weld-base metal are visible.

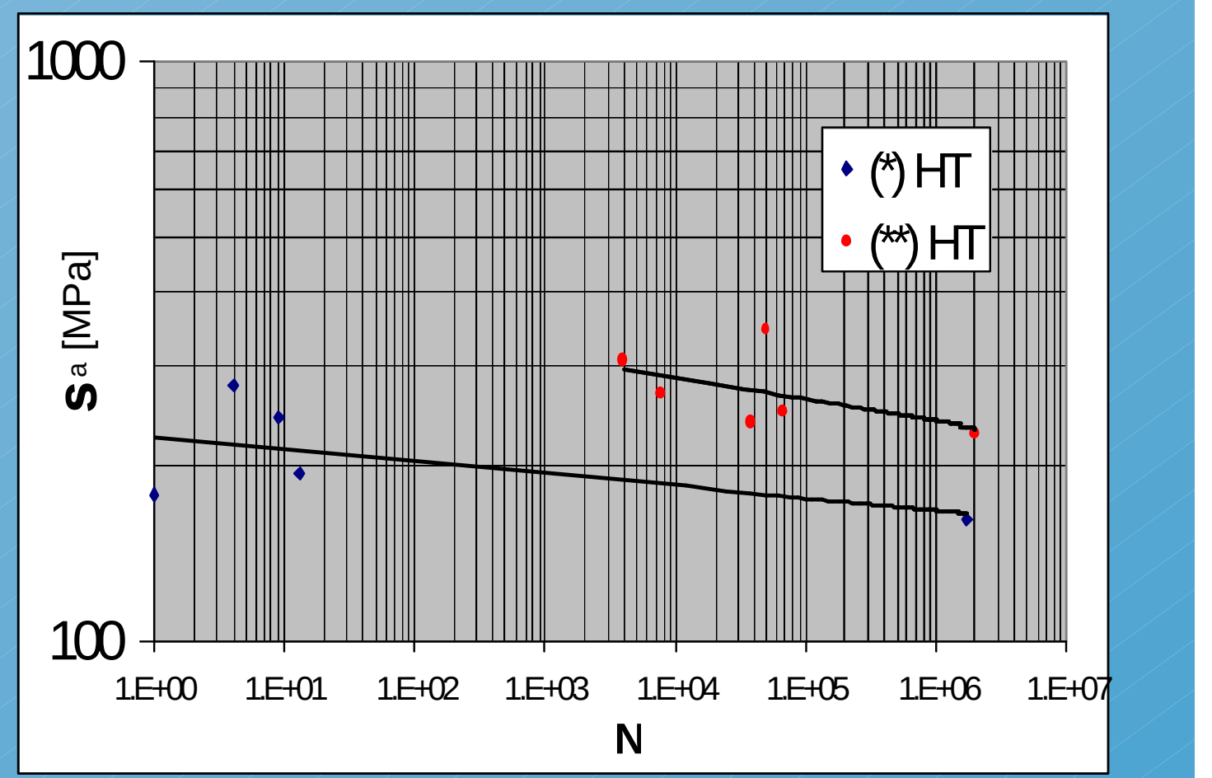

*Fig. 10:*Fatigue tests results for TiAl6V4 welded joints with different Heat Treatment (room temperature).

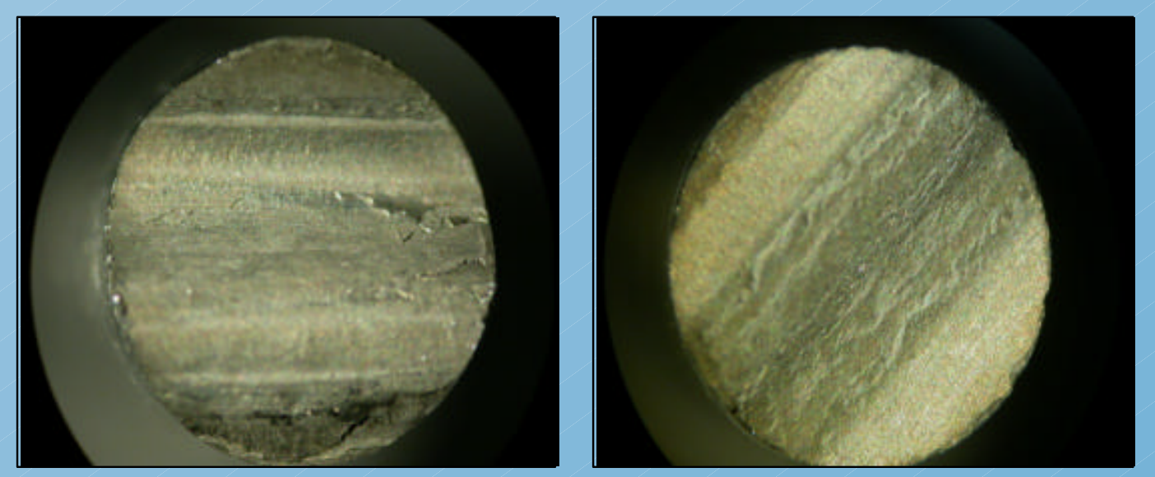

Figure 6. Tensile Rupture surfaces a) Inconel 718, b) TiAl6V4.

Figure 7. Ti alloy welded longitudinal section.

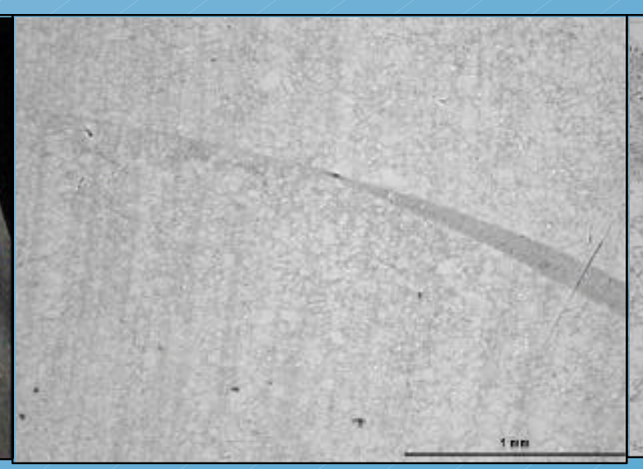

Figure 8. Inc718 welded material distributed along the welding profile.

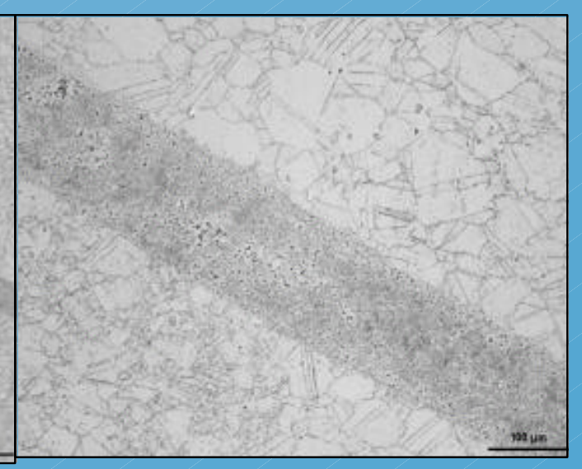

Figure 9. Inconel 718 average welded profile aspect.

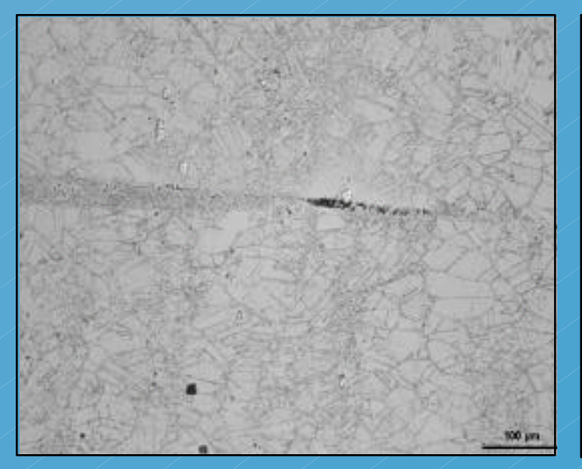

Figure 10. Inconel 718 welded profile discontinuity.

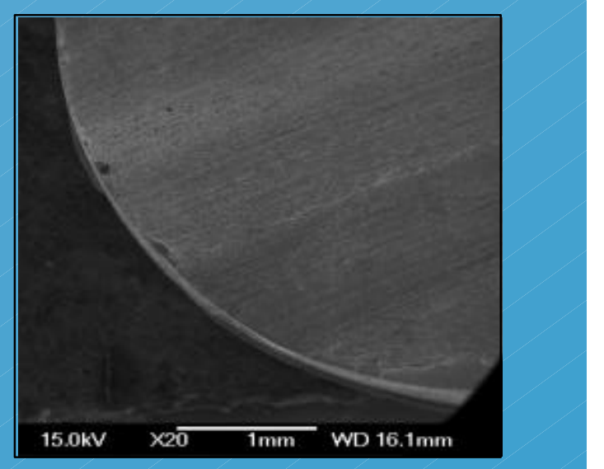

Figure 11a. SEM: Ti alloy surface after rupture.

Figure 12. Inconel 718 welded layer thinner zone.

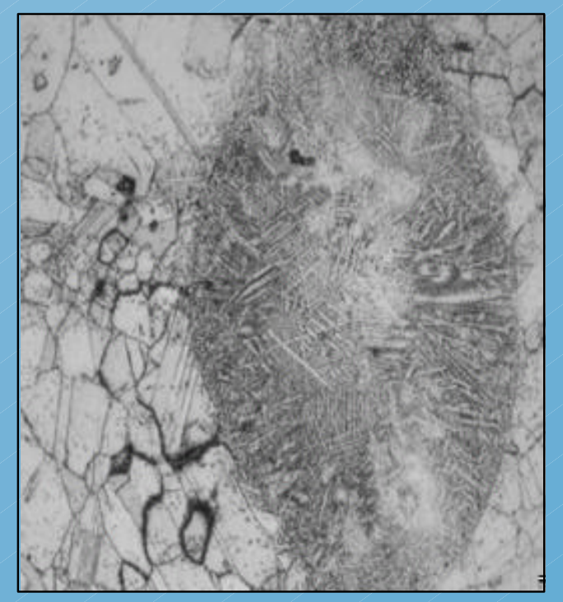

Figure 13. Inconel 718 welding hot spot at the outer region.

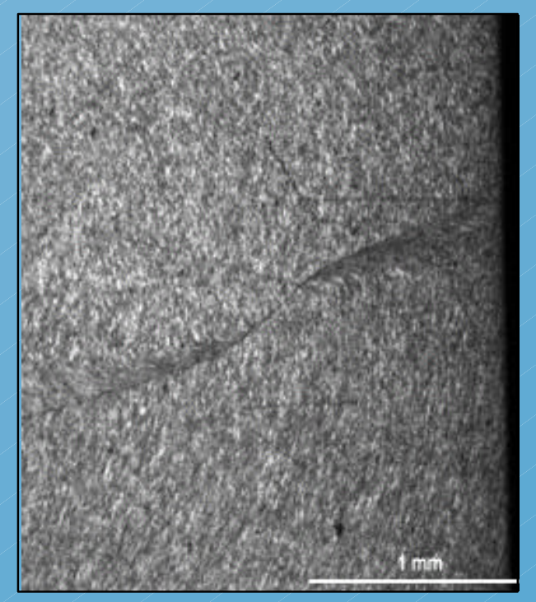

Figure 14. Ti alloy welded profile after CD Welding with the multipoint geometry.

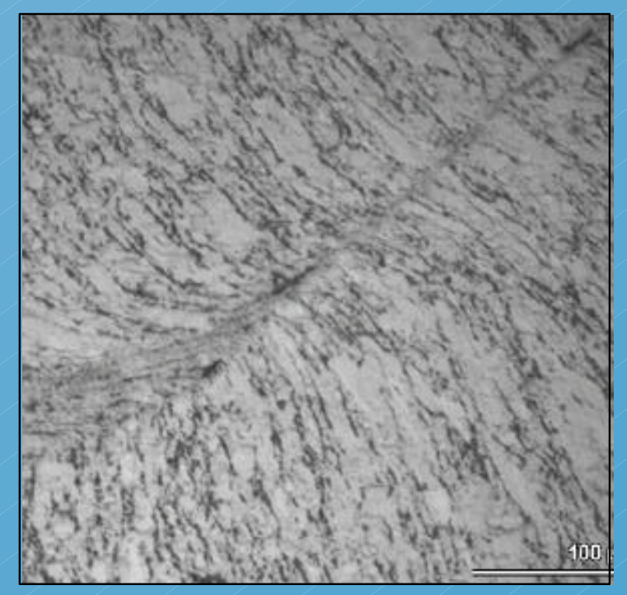

Figure 15. Ti alloy detail of the deformed microstructure of the welded profile.

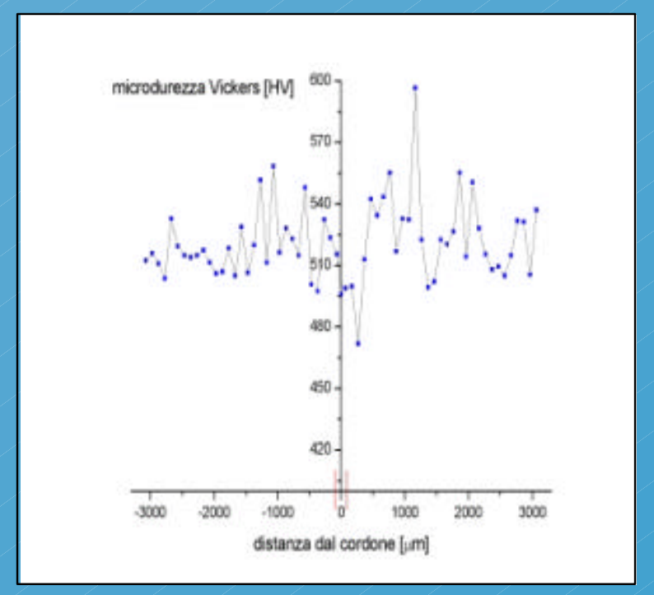

Figure 16. Inconel 718 welding microhardness profile.

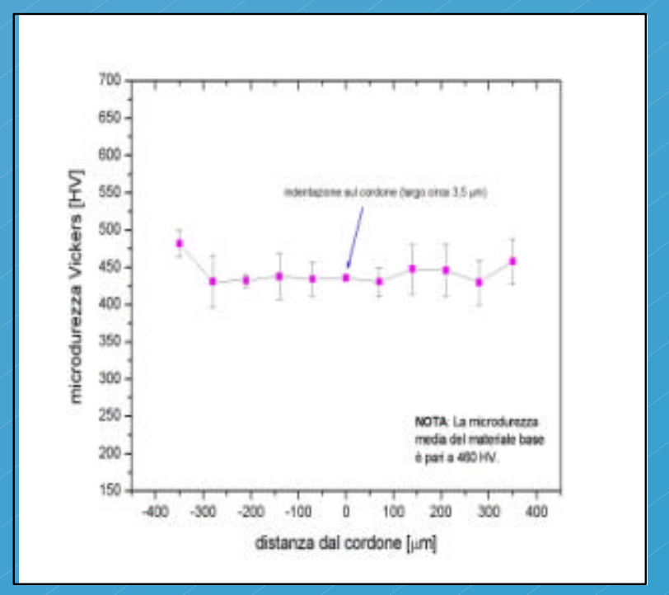

Figure 17 Ti alloy welding microhardness profile.

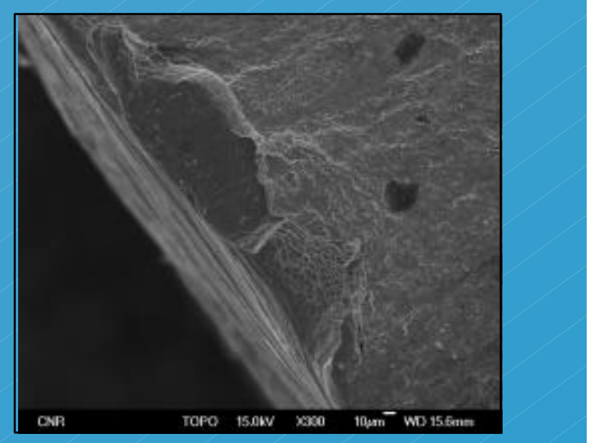

Figure 11b. SEM:probable initiation point of rupture.

Conclusions.

The multipoint CDW Process can be certainly considered for repair and production purposes in several mechanical and aeronautical applications. Nevertheless, in order to validate the potentiality of this technology, the upsetting force, the discharge time and the peak current have to be cautiously selected as well as the joint geometry in the welding contact zone. The mechanical and microstructural characterization of the welded specimens has been done for the CDW technology applied to aeronautical materials, evaluating the static and fatigue properties of the CD Welded joints at room and working temperatures; the presence of elevated precipitates deposition in the welded layer and the thin and discontinuous shape of the molten metal with the subsequent formation of micro structural transition zones produce lower resistance capabilities with respect to the base material.

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