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CHARACTERIZATION OF EXPLOSIVE WELD INTERFACES

N.Raghu, Sanjay K. Rai#, Anish Kumar, T. Jayakumar, K.V.Kasiviswanathan and Baldev Raj

Inspection Technology Group,
Indira Gandhi Center for Atomic Research,
Kalpakkam – 603 102
#Center for Advanced Technology, Indore

ABSTRACT

Explosive welding is a solid state welding process that produces a weld between two components by high velocity impact, aided by controlled detonation of an explosive. In order to produce uniform and consistently good quality welds the welding parameters are to be optimized. The influence of these weld parameters on bond strength and weld quality can be assessed using destructive and non-destructive testing (NDT) methods. Weld joints between Titanium/Steel and Cupronickel/steel, produced by explosive welding technique have been investigated. Mechanical strength of the weld joints has been determined by special tensile testing methods. Novel approach of using ultrasonic testing and XRD technique synergistically for comprehensive characterization of the weld interface is presented in this paper.

1.0 INTRODUCTION

Explosive welding (EXW) offers an excellent alternative for joining dissimilar metals and alloys with varying physical and metallurgical properties. Explosive welding is a solid state metal joining process which produces a weld joint by high velocity impact, aided by controlled detonation with an explosive charge. The requirements that are necessary include sufficient ductility and fracture toughness of the components to be welded to withstand the deformation and to undergo rapid deformation during the process without fracture. Figures 1 shows the component arrangement in parallel plate geometry for cladding very large surface areas and angle bonding for cladding small surface areas. Figure 2 shows the interactions between the base component and the flyer plate during the welding process. The explosive charge when detonated accelerates the metal to a speed at which a metallic bond is formed between the metal components during the collision. This is a near room temperature process as gross heating of the work piece does not occur. The mating surfaces, however, are heated to some extent by the energy of the collision, and welding takes place due to plastic flow of the metals at the surfaces. Welding takes place progressively as the explosion advances from one end of the joint to the other end. Cladding of flat plates and concentric cylinders constitutes the major commercial applications of EXW to combat corrosion and to improve heat transfer characteristics. Explosively bonded interfaces do not exhibit many of the metallurgical characteristics of fusion welding or brazing. The weld interfaces do not reveal heat affected zones and do not have continuous melt bands having mixed chemistry. However, the quality of the bonded component is assured through proper selection of process parameters.

1.1 BONDING PARAMETERS:

The proper bonding parameters for a specific metal combination depend upon the metal types, thicknesses and their mechanical properties. Selection of the proper parameters is critical to assure a strong, high quality ductile bond. The impact conditions during the angle bonding are related by the following equation:

$$V_p = 2V_d Sin(\beta / 2)$$

where, V_p = Impact point velocity; V_d = Detonation velocity; β = Impact angle

During welding, the impact point velocity V_p is equal to the detonation velocity V_d. The collision plate velocity V_p, depends upon metal types, physical and mechanical properties and chemical compatibility. The bond parameters hence are dependent on the explosive detonation rate and standoff distance.

1.2 EXPLOSIVE WELDING MECHANISM

In the explosive welding process, the metal plates are made to collide obliquely with each other at a high velocity with the use of explosive. The impact causes the two metals to come into intimate contact such that metallurgical bonding takes place across the interface. As the detonation of the explosive proceeds, a scavenging action occurs between the two mating surfaces, due to jetting. The jet formation aids metallurgical bonding in two ways: first, it causes the breakup of the contaminant surface film and expels it from the point of collision and it exposes virgin surfaces, which are brought into close contact as a result of collision.

1.3 SELECTION OF EXPLOSIVE

The selection of an explosive that will produce the required detonation velocity is important for obtaining consistently good welds. The explosive must also provide uniform detonation so as to achieve a collision velocity that will be uniform from the start to the finish of the weld. The explosive type and amount per unit area is selected to achieve the necessary detonation energy and detonation velocity.

One of the important process parameters in explosion welding is the amount of explosive used to affect the collision between the plates. For a particular explosive, the collision velocity of the flyer plate is also a function of the quantity of the explosive charge. As the explosive is detonated, part of its chemical energy dissipates in air and part of it is transferred to the flyer plate in the form of kinetic energy. Excessive loading causes the kinetic energy to heat up the interface such that the temperature rise is enough to cause interfacial melting. These solidified melt pockets may have a deleterious effect on the bond strength.

In this paper, detailed experimental studies made for evaluation of the bond strength and its correlation with microstructural observations of the interface in explosively bonded plates are discussed. These bonded plates would then be taken up for i) fabrication of heat exchanger used in the marine environment and ii) fabrication of an electrolytic dissolver cell handling acids of high concentration.

2.0 EXPERIMENTAL

The following two explosively welded specimens are examined in the present study.

a) Explosively welded 155 mm dia, AB2PK Steel/Cupronickel specimen having 21.5/3.8mm thickness to be used in the fabrication of heat exchangers.
b) Explosively welded 160mm dia, AB2PK steel/Titanium specimen having 21.5/3.2 mm thickness to be used in the tanks of the electrolytic dissolver cells.

The explosive bond fabrication has been carried out at Terminal Ballistics Research Laboratory, Chandigarh. The explosion parameters that have been adopted for the fabrication of the weld coupons are proprietary in nature and are not disclosed. However, based on the feedback from the end user, the design parameters are modified so as to produce a sound bond without any delaminations.

2.1 EVALUATION OF SOUND BOND AREAS USING ULTRASONIC TESTING TECHNIQUE

The explosive weld specimens were tested to identify the delaminations / debond areas using the conventional ultrasonic A-scan inspection technique by contact mode and ultrasonic C-scan imaging through immersion technique so as to choose defect free areas for making specimens for further tests. Ultrasonic testing of the explosively welded samples was carried out using EPOCH IV (M/s GE Panametrics, USA) ultrasonic flaw dectector for A-scan based analysis. A 2MHz longitudinal wave transducer was used for defect detection. The defects with size less than the reference defect (1mm flat bottom hole) were considered to be acceptable. Ultima 200 C-scan system developed by Electronics Division, BARC has been used for acquiring the C-scan images. Ultrasonic signals were acquired using a 6 MHz focused immersion transducer and digitized at 200 MHz. The data were collected at 2 mm intervals in both X and Y directions. The weld interface echo was gated and the amplitude in this gated region was plotted in gray scale in XY plane.

2.2 MECHANICAL TESTING

Bond strength evaluation is targeted to assess the quality level of the bonded plates and to detect any deviation in manufacturing process. Mechanical testing is usually carried out to produce data that may be used for design purpose. This data is essential to know the limiting values that a structure can withstand without failure. Adequate control of the material properties is crucial to ensure safety of the product. The ram tensile test is used to provide information that will be used in design calculations or to demonstrate that an EXW material complies with the requirements.

Testing of welds made by EXW process requires special forms of mechanical test specimens, since the primary aim is to establish the quality of bonding along the interface. The problem of assessing the bond strength of an explosively welded joint is due to the thin profile of the bond area. Ram tensile test method ensures failure of the specimen in the bonded zone by a pure tensile load and hence truly represents the strength of the bond.

The ram tensile test is carried out by compressing the ram into the annular space drilled out of the base metal and testing the bond strength of the flyer plate in a suitably prepared standardised test piece. Figure 3A shows the schematic the sketch of the fabricated specimen used in determination of the bond strength. The compressive stress applied on the flyer plate generates tensile stress at the bond interface and would try to separate the clad from the weld interface. The test is carried out in a servo hydraulic testing machine by applying a continually increasing uni-axial load until such time as failure occurs. The load (stress) acting on the ram can be easily measured through a load cell fitted on the tensile testing machine. Figure 3B shows the schematic arrangement of this testing jig, designed and developed at our Centre. The cross sectional area of the specimen is the annulus between the outside and inside diameters. The specimen has a small bonded area which is intended to cause failure at or immediately adjacent to the weld interface. During the test, the specimen is placed on the base block with the ram in the flat bottom drilled hole. Compressive load is applied through the ram and the base. Load at failure is recorded and the bond strength and relative ductility are evaluated.

Ram tensile tests were carried out to determine the ultimate tensile strength of the bond in the as welded condition. To determine the bond strength of the weld interface, ram tensile specimens are required to be fabricated in the size of 25 x 25 mm given in Fig. 3A. The samples were wire cut to extract specimens for fabricating test specimens for ram tensile tests and for metallographic tests. The tests were carried out in a 10 T servo hydraulic testing machine, in the compression mode. The strain rate of 0.5mm/min was used for testing.

2.3 METALLOGRAPHY EXAMINATION

Metallographic studies were carried out on the sound weld as well as on the debonded areas. The samples for metallography were obtained by spark erosion wire cutting method. This method ensures that the sample is not damaged during its slicing. Samples from the sound bond area as well from the debonded area were carefully mounted in epoxy resin so as to preserve the edges. Sequential polishing was carried out using various grades of silicon carbide abrasive paper sheet. Final polishing was achieved using diamond paste. The samples were subsequently etched to reveal the microstructure. The etched samples were observed using Olympus PMG3 metallurgical microscope. The wavelength and the amplitude of the wavy pattern of the interface region were measured using scale graticule. The photomicrograph of the bond region was obtained. The samples were also observed in Philips X-30 scanning electron microscope having EDAX facility for revealing finer aspects of the bond region at higher magnification, including compositional variation across the bond. Microhardness variation across the weld interface has also been obtained using Leitz microhardness tester at a load of 100 g.

2.4 X-RAY DIFFRACTION

X-ray Diffraction (XRD) is a powerful technique for characterizing crystalline materials. It provides information on structures, phases, preferred crystal orientations (texture) and other structural parameters such as average grain size, crystallinity, strain and crystal defects. X-ray diffraction peaks are produced by constructive interference of monochromatic beam scattered from each set of lattice planes at specific angles. The peak locations are determined by the placements of atoms within the lattice planes. Consequently, the X-ray diffraction pattern is the fingerprint of periodic atomic arrangements in a given material.

The XRD profiles of the samples in the sound weld area and in the de-bonded area were recorded using MAC Science MXP18 X-ray diffractometer with the line focus as the source of Cu K_α radiation. The scan was performed in the angular range of 24 to 90 degrees with a step size of 0.02 degrees with a dwell time of 4 sec, with X-ray generator power set at 4 kW (40 kV and 100mA). The instrument was set up in the Bragg–Brentano geometry with a graphite monochromator in diffracted beam arm. The acquired data was suitably corrected for background and $K_{\alpha 2}$ subtraction was carried out before making a peak data file. This data file was used in the Hanawalt search method based software with due weightage for standards matched, peak position match and intensity match to look at the materials found in the interface.

3.0 RESULTS

3.1 ULTRASONIC EXAMINATION

i) AB2PK Steel/Cupronickel specimen

A debond measuring around 40mm dia, was identified in the central portion of the weld, in one of the samples. Minor debonding was also observed in the 10 'O' clock to 11'O' clock position for a small length and isolated defects were noticed in the 1'O' clock position. (The reference hole is located in the 12 'O' clock positions). The debonded areas which were detected in this plate are shown in Fig. 4A.

ii) AB2PK Steel/Titanium specimen

A debond measuring 28mm in diameter was observed at a location 5mm away from the center of the specimen with reference to flat bottom hole at 12 'O' clock position. Other areas were found to be sound. The debond areas in this welded plate is shown in Fig.4B.

3.2 RAM Tensile test

A. AB2PK Steel/Cupro Nickel Welded Specimen

The average tensile strength during the ram tensile test results obtained from steel-cupronickel weld specimens was 210 MPa. During testing, it was noticed that the bond did not detach during compression testing. Cupronickel clad plate was not able to sustain the applied load due to its low tensile strength and failed by cupping.

B. AB2PK Steel/Titanium welded Specimen

The average tensile strength determined during the ram tensile test results from steel-titanium weld specimens was 316 MPa. During testing, the titanium bond detached from the AB2PK steel sample. The scatter in the results can be attributed to the presence of wavy interface at some locations and flat bond interface at the other locations.

3.3 Metallographic examination

i) AB2PK Steel/Cupronickel specimen

In the sound bond areas, wavy interface, characteristic of explosive bond was observed during metallographic examination. The wavelength of the wave was found to be 0.2 mm and the amplitude of the wave was 0.1 mm in the defect free area. The interface was also found to have a highly deformed band, extending for about 250 microns, the same is easily identifiable in the photomicrograph given in Fig.5A. Some molten pockets of the jetted materials were also observed in the front slope of the wave. EDAX analysis was carried out on the line profile across the interface and was found to be a mixture of Fe/Cu/Ni with different compositions. The amount of Fe was rich in the steel side and Ni and Cu being rich in the cupronickel side. The molten jetted materials that were seen in the front slopes were also found to be a mixture of metals with a non-specific combination.

The microstructure near the defective location was also examined in the microscope. The wavelength of the wavy interface was fast decaying and it varied from a few micrometers to almost a flat area. The amplitude has also correspondingly decreased from a few micrometers to zero.

ii) AB2PK Steel/Titanium specimens

Metallographic examination revealed wavy interface as well as flat interface on the sound bond areas. However, interface had a very large wavelength and low amplitude. The bond interface was also found to be associated with a mixture of molten and solidified metal. This molten metal interface was also found to have broken or cracked across the weld interface. At the debonded area, the presence of this solidified layer was not prominently observed. The photograph of the weld interface is given in Fig.5B.

3.4 Microhardness measurements

a) AB2PK steel/Cupronickel interface

Figure 6A shows the variation in microhardness profile across the weld interface for the steel-cupronickel weld joint. The weld interface hardness in the steel side is of the order of 326 VHN, whereas on the cupronickel side the hardness is 146 VHN at the interface and drops down to 134 VHN after 0.1mm. The parent metal hardness in cupronickel is 107 VHN and in steel is about 261 VHN. A high hardness band measuring 0.25 mm on either side of the interface is noticed.

b) AB2PK steel/Titanium interface

Figure 6B shows the variation in microhardness profile across the weld interface for the steel-titanium weld joint. The interface hardness in the steel side is of the order of 378 VHN, whereas on the titanium side the hardness is 252 VHN at the interface and drops down to 225 VHN after a distance of about 0.25mm. High hardness band is seen on either side of the interface for a distance of 0.12 mm. The parent metal hardness is 215 VHN in the case of titanium and 266 VHN for the steel.

3.5 XRD testing

The XRD spectrum on titanium-steel interface is given in Fig. 7A. The search match on the sound bond Titanium-steel interface revealed only peaks of Titanium and Fe-Cr. The Titanium peaks matched well with the ICDD data file 44-1294 and the Fe-Cr with the data file 34-0396. However the debonded interface revealed additional peaks corresponding to Titanium Nitride (TiN) with PDF card number 38-1420 along with Titanium peaks as shown in Fig.7B. Minor peaks of Iron-oxide Phosphate $Fe_2(PO_4)O$ were also observed during the analysis.

The search match on the sound bond of cupronickel –steel interface revealed only peaks of Iron Nickel (FeNi) and Copper Nickel. The peaks matched very well with the ICDD data files 37-0474 and 47-1406. The XRD pattern on the cupro-nickel – Steel interface is given in Fig. 7C. However, intermetallics were not found to form at the interfaces in any of the samples that has been investigated.

4.0 DISCUSSIONS

Ultrasonic A-scan examination was found to be very precise in detecting the presence of delamination in the weld joints. This has also been imaged and confirmed using C-scan technique. The presence of the delamination has been confirmed through metallographic examination as well as by physical methods of separation. The bond strength of the steel-cupronickel EXW was found to be above 200 MPa whereas the tensile strength of the cupronickel was below this value causing extrusion of the material from the ram and resulting in the formation of cupping during the ram tensile testing. The sound bonded areas showed well defined wavy interface with a large wavelength and amplitude. Since the yield strength of the flyer plate (Cupronickel) is lower, well defined wavy pattern has been observed. The presence of a small wave with low amplitude was noticed in the defective area. The X-ray diffraction studies did not indicate presence of any intermetallics at the weld interface in the sound bonded areas and in the defective areas.

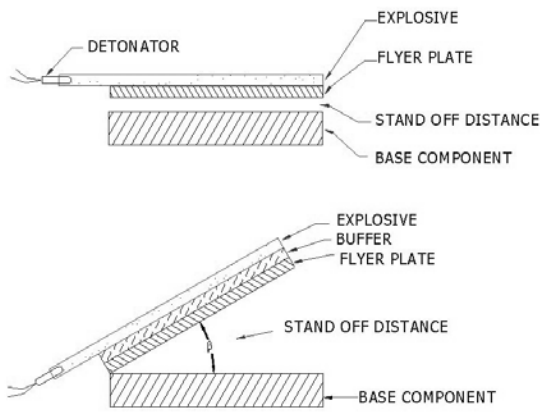
In the case of steel-titanium EXW, the interface bond strength was 310 MPa, whereas the tensile strength of the Titanium was higher than this value. As the bond strength of the interface was lower than the tensile strength of the clad plate, the bond has got detached in the ram test. In the metallography studies, very large wavelength of the wave could be observed with low amplitude. The presence of low amplitude wave is due to the fact that the yield strength of the flyer plate (Titanium) was much higher and the plate was not able to deform during the explosive weld formation. Hence, some molten and solidified metal with the combination of both the plates has been formed in the interface. The presence of this layer has in no way affected the quality of the weld. From the X-ray diffraction studies, Ti-Fe and Fe-Cr peaks were found at the interface of the sound weld zone and presence of Ti-N and Iron-oxide Phosphate $Fe_2(PO_4)O$ was also found in addition to the Ti-Fe and Fe-Cr peaks at the defective areas. The presence of nitrogen compounds has been reported earlier and found not to be detrimental to the quality of the interface. However, the presence of Iron-oxide Phosphate $Fe_2(PO_4)O$ is reported for the first time. This compound could have formed with the base metal during the welding process. When the velocity of explosion is more either due to non-uniform distribution of the explosive charge or due to excessive loading of the charge, the jetting materials gets entrapped at the bond interface and produces a lack of bond area. From these results it can be inferred that the formation of Titanium nitride and Iron oxide phosphate $Fe_2(PO_4)O$ may facilitate delamination.

In the case of steel-cupronickel EXW samples, peaks corresponding to Iron- Nickel and Copper-Nickel have been observed at sound bond area. In the samples having delamination, no additional peak containing compound from the explosive traces was observed during the analysis. The absence of any additional peaks in the defective locations should be possible either due to very low yield of the compound or due to non-adherent nature of the compound at the interface.

5.0 CONCLUSION

The quality of the explosive bonds that have been fabricated is found to be acceptable for the fabrication of heat exchanger and the electrolytic cells in terms of bond strength. However, the presence of delamination in the bond zone at the central region is due to some deviation in the quantity of explosives that has been used which has favored high detonating velocity. Proper standardisation of the explosive content for welding with resultant changes in the impact parameter would produce defect free sound bonded plates.

FIGURES



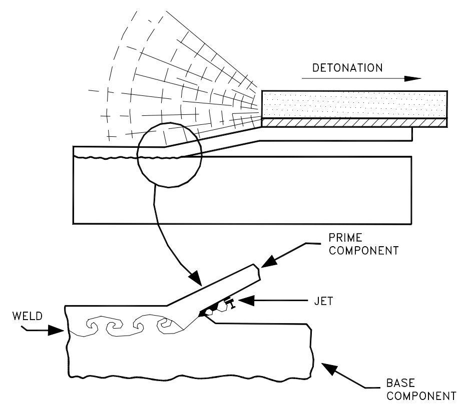


Figure 2: Component arrangement in two geometries during EXW

Figure 1: Interaction between components during EXW

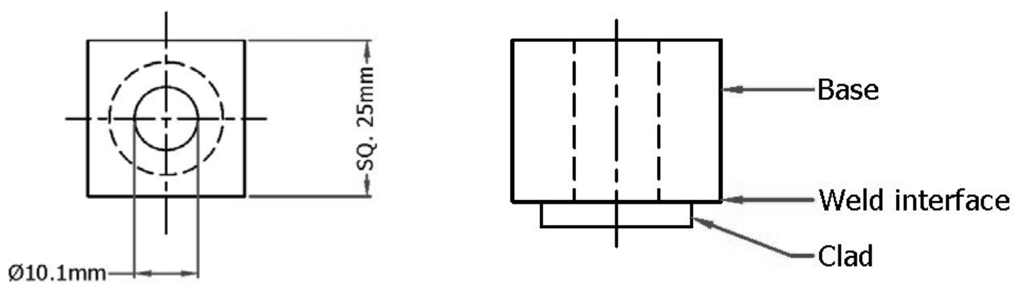


Fig.3A. Schematic sketch of the ram tensile specimen used in testing

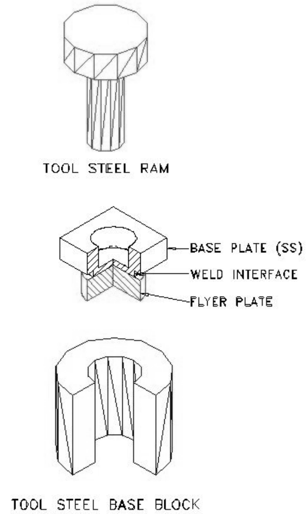


Fig.3B: Schematic sketch of the ram tensile testing jig

Figure 4A: Photograph of the Steel/ Cupronickel sample after ultrasonic testing identifying debond locations

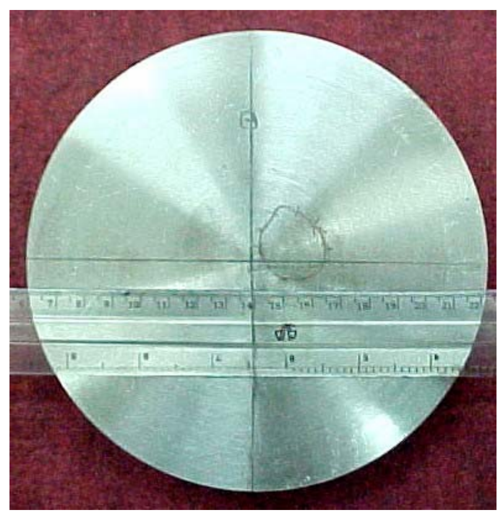


Figure 4B: Photograph of the Steel/ Titanium sample after ultrasonic testing identifying debond locations

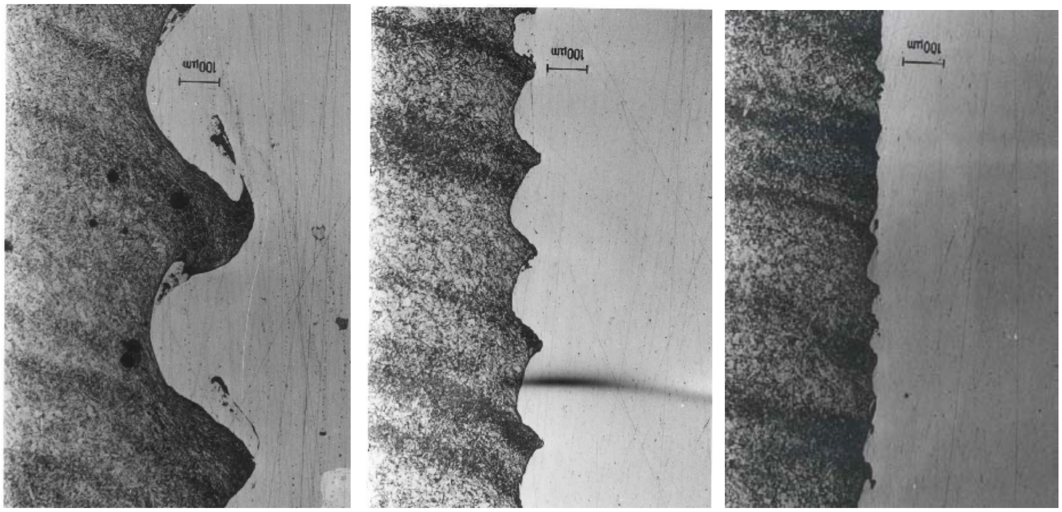


Figure 5A : Photomicrograph of Steel/cupronickel weld interface

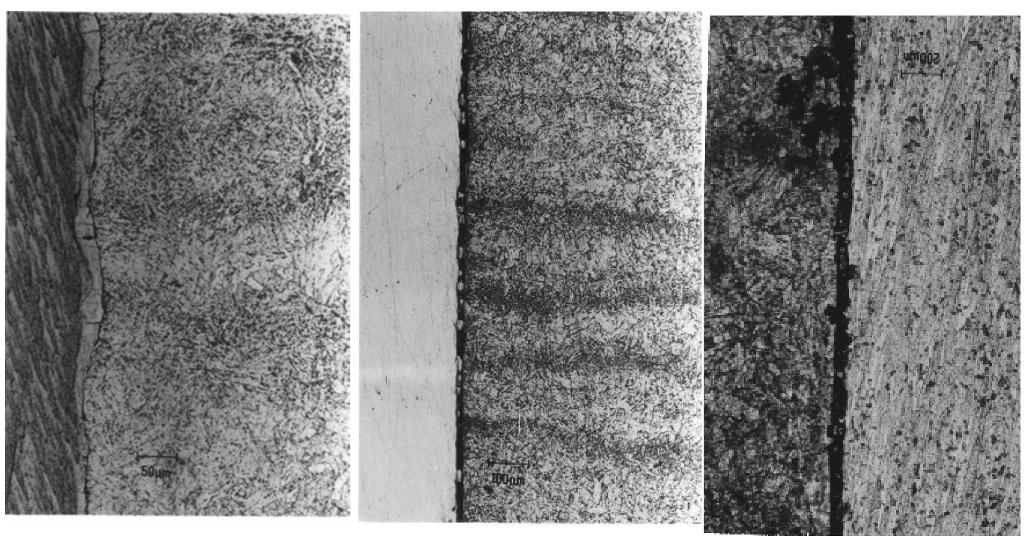


Fig. 5B : Photomicrostructure of the steel/Titanium weld interface

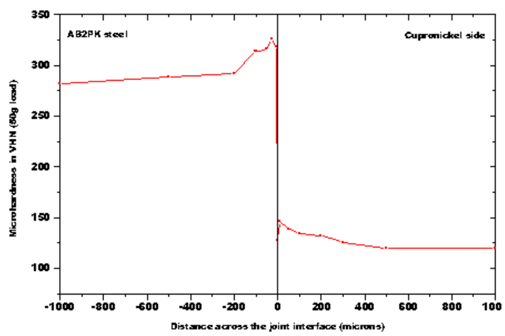


Fig.6A: Microhardness profile across the cupronickel-steel weld interface

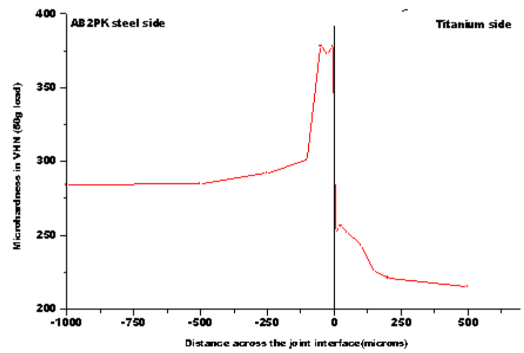


Fig. 6B: Microhardness profile across the Titanium-steel weld interface

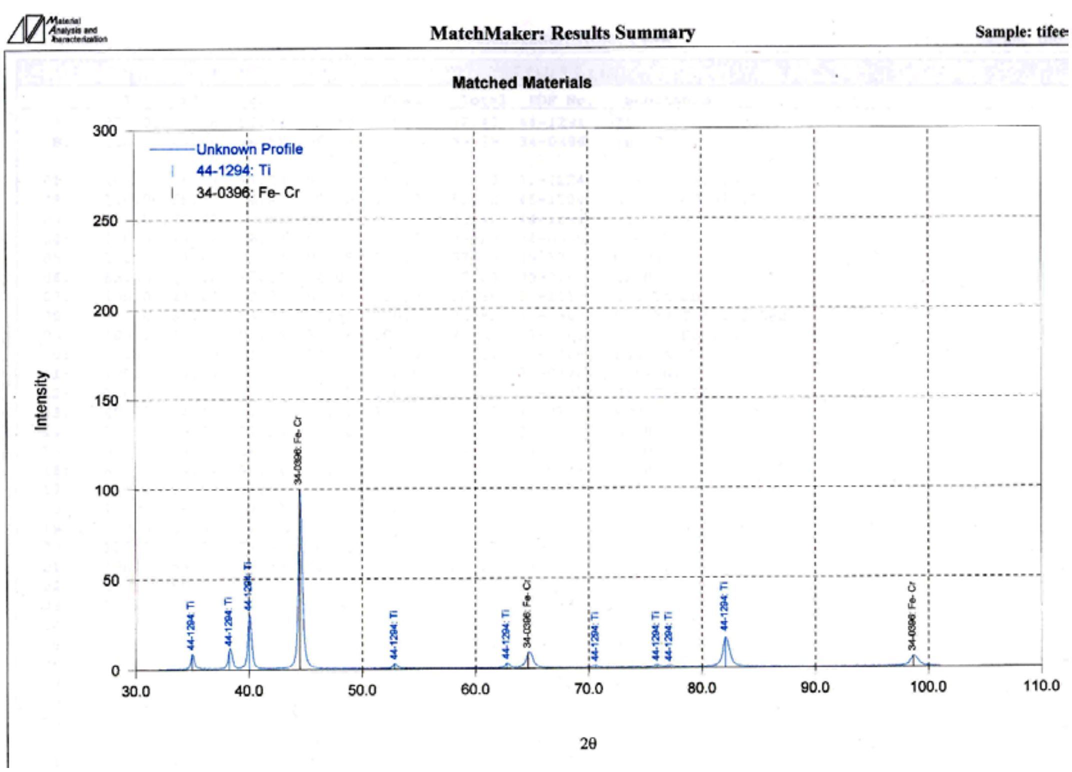


Figure 7A: XRD spectrum of steel-titanium EXW weld interface in the sound bond area

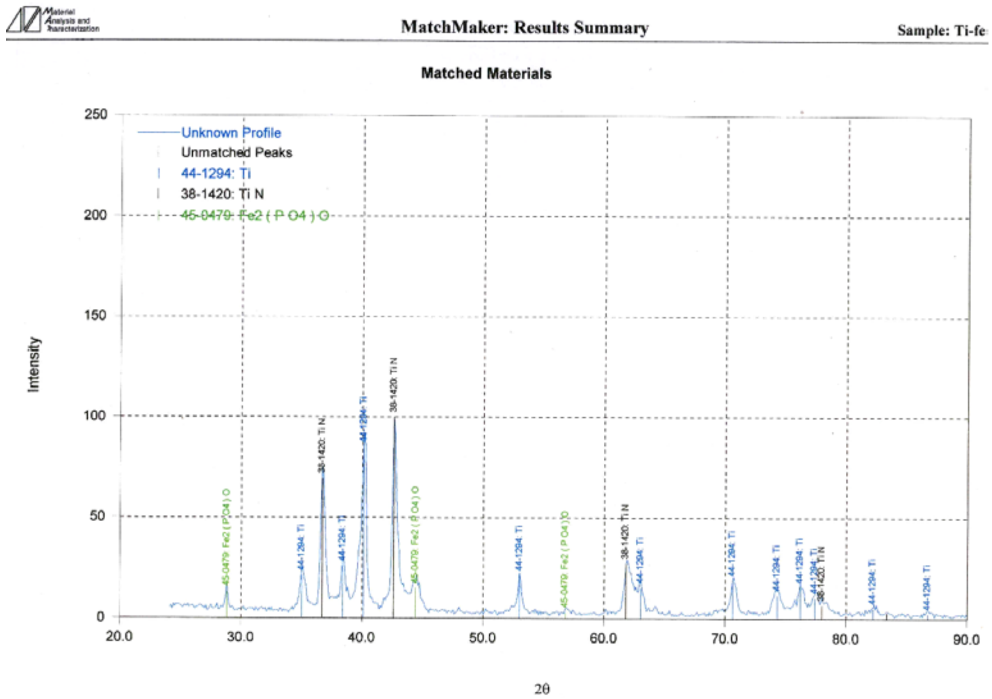


Figure 7B: XRD spectrum of steel-titanium EXW weld interface in the debond area

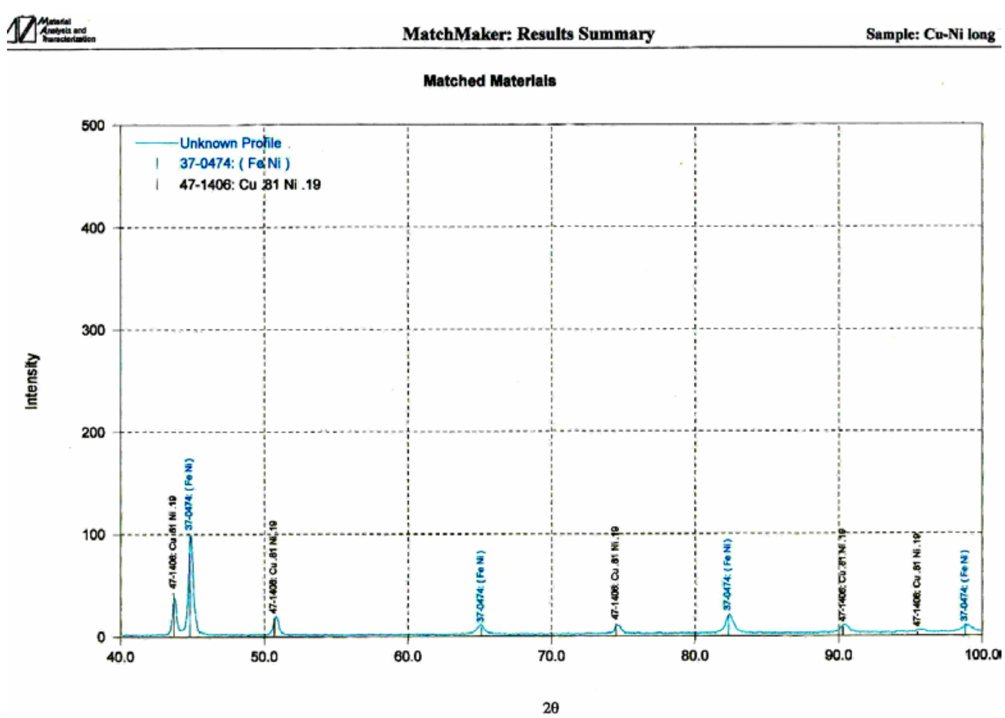


Figure 7C: XRD spectrum of steel-cupronickel EXW weld interface