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CONVENTIONAL RADIOGRAPHY : A FEW CHALLENGING APPLICATIONS

S.P. Srivastava, T.G. Unni, S.P. Pandarkar,
K. Mahajan, R.L. Suthar
Centre for Design and Manufacture
Bhabha Atomic Research Centre

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Abstract

Conventional radiography, which uses X-ray machine and radioactive isotopes such as Iridium-192 and Cobalt 60 for generating penetrating radiation, is used for recording the internal defects of an object on a radiographic film. Advance radiography methods such as Micro Focal Radiography, Digital Radiography, and Real Time Radiography have been developed to offer an edge over conventional radiography for better definition and detectability of small defects, quick result and image processing. However, with all its limitations, conventional radiography can give results beyond expectation, provided the technique selected is proper and adequate. At the Centre for Design and Manufacture (CDM) capability of conventional radiography was explored for the examination of Boron Carbide Pellets and Friction Stir Welded Aluminium plates, having challenging requirements.

Boron Carbide (B_4C) is an extremely hard ceramic material used in tank armor, bulletproof vests and numerous industrial applications. Control rods of nuclear reactors contain pellets of Boron Carbide, which act as neutron absorber. Pellets of Boron Carbide are manufactured by sintering process in which objects of different shapes are formed by heating metal powder at temperature below its melting point. Pores and microscopic imperfections in ceramic give rise to cracks, which can lead to potentially dangerous equipment failure. Radiography technique was developed to detect cracks, micro pores and local density variation in pellets of various sizes, as an effective quality control tool.

Friction Stir Welding (FSW) is a solid state welding process, in which metals are joined together without fusion or filler metal. The welds are created by the combined action of frictional heating and mechanical deformation due to rotating tool. This process is primarily used on Aluminium and most often on large pieces which cannot be easily heat-treated post weld, to recover tempering characteristics. To establish the FSW process for welding of 5mm thick aluminium plates, number of trials using different parameters were carried out at CDM. In one of the welded pieces, it was a tricky task to detect lack of penetration under the Titanium foil, which was sandwiched between two Aluminium plates butting each other.

This paper presents a brief description of these two applications, radiographic technique developed for their examination and analysis of the results.

Introduction

Centre for Design and Manufacture (CDM) at Bhabha Atomic Research Centre is involved in the development of engineering products required for nuclear applications and various R & D activities. Jobs are designed and manufactured as per quality control requirements of the referencing codes, applicable for nuclear components. During manufacturing, components are subjected to various interstage nondestructive tests, such as Radiography Test (RT), Ultrasonic Test (UT), Liquid Penetrant Test (PT), Magnetic Particle Test (MT), Helium Leak Test (HLT), etc. to achieve the required quality, stipulated for the final product. Jobs are innovative in nature, therefore for each job, new NDT technique has to be developed depending upon the material, design, shape, manufacturing process and expected defects. Radiography testing of Boron Carbide pellets and Friction Stir Welded Alminium plates, using conventional X-ray machine, proved to be a very powerful quality tool as it revealed discontinuities even at micro level. This paper presents the detail of radiography testing of these two components developed at CDM.

Boron Carbide Pellets

Boron Carbide (B_4C), a black crystalline compound of Boron and Carbon is a ceramic material and is used in cutting tools, abrasive, bulletproof vests, nuclear power plants and in composite structural materials as a reinforcing filament. It is an extremely hard material and with a hardness of 9.3 on Mohs scale it is the fifth hardest material known. Its ability to absorb neutrons, without forming long-lived radionuclides, makes the material attractive as an absorbent for neutron radiation, arising in nuclear power plants. Nuclear application of B_4C also includes shielding. It is used in the form of pellets in control rods and shut down rods for controlling the power of nuclear reactor.

Ceramic-based materials are manufactured by sintering process in which objects of different shapes are formed, by heating the metal powder at a temperature below its melting point. When the powder is compacted into desired shape and heated i.e. sintered for up to three hours, the particles of powder join together to form a single solid object. Ceramic materials are usually ionic or covalently bonded materials and can be crystalline or amorphous. A material held together by either type of bond will tend to fracture before any plastic deformation takes place and this is responsible for the low toughness of such materials. Additionally, because these materials tend to be porous, the pores and other microscopic imperfections act as stress concentrators, decreasing the toughness further and reducing the tensile strength. These combine to give catastrophic failures as opposed to the normally much gentle failure modes of metals.

Radiography Testing Procedure

Boron carbide pellets of various diameters and lengths are being manufactured by sintering process at the Bhabha Atomic Research Centre for nuclear applications. It was necessary to develop a reliable NDT method to check and control the quality of pellets. Normally ultrasonic and radiography are common methods for detailed examination of ceramic components. Because of small size of pellet and in-homogeneity of the material, low inspection rate and restriction for using couplant, ultrasonic testing was not found suitable and therefore radiography was used as an NDT tool to check the internal details of B_4C pellets. Number of trials were performed, to establish the technique and radiographic parameters for a good quality radiograph. For complete coverage and detection of defects having different orientation, it was decided to radiograph each pellet in two mutually perpendicular directions : axial and radial. Because of cylindrical shape, proper masking was required to avoid undercut. Choice of masking material and its thickness depends upon few factors – a) Masking materials must be able to stop undercut and b) it should not produce very low density image surrounding the image of the pellet to restrict glare on the eyes while viewing the film on the illuminator. Steel and Aluminium plates of 2 mm thickness, having circular holes of diameter equal to that of pellet were used for masking the pellets in axial direction. As far as radiography in radial direction was concerned, it was observed that, pellets kept close to each other offered better solution for preventing under cut and scatter than using any external masking material. To assess the quality of radiograph it was necessary to use Image Quality Indicator (IQI). Since IQI for B_4C is not available it was manufactured out of the same pellets as given in Fig. 1. Slots having depth equal to 1% or 2% of the thickness penetrated by X-ray were machined on curved as well as flat surface. While taking radiograph IQI were placed at extreme edges to occupy most unfavourable conditions. Radiographic parameters were optimized in such a way that radiographs were able to record the image of 2% slot of IQI (Fig. 2), however, even 1% slot was visible on the radiograph.

After receiving the sintered pellets, first of all visual inspection is carried out to segregate the damaged and broken pellets. Acceptable pellets are ground to achieve the required dimensions and after grinding, pellets are subjected to radiographic examination.

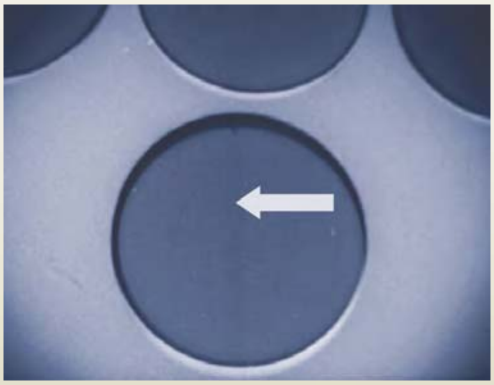

Fig. 2 : IQI (2% slot) image in axial direction

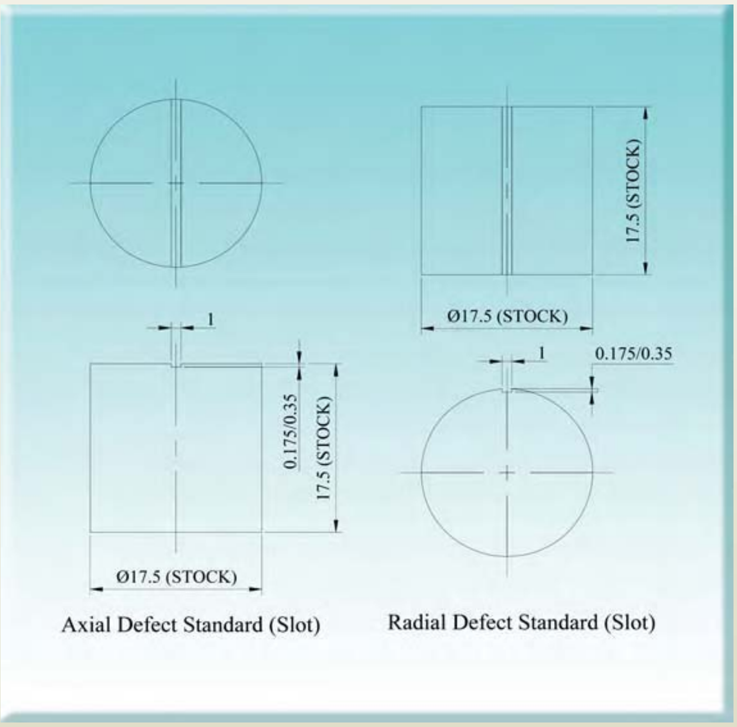

Fig.1 : Slot type IQI (Axial and Radial) for pellets

Result and Analysis

Radiograph of pellet in axial direction with Steel sheet masking was found to be better than with Aluminium sheet because back ground density was less than that of pellet image in case of steel masking. In axial direction, slight undercut between the pellets was observed, however it did not pose any problem during interpretation. Radiograph was able to detect porosity, crack, inclusion, in-homogeneity, density variation etc. (Figs. 3 & 4).

Even improper compactness was revealed in the radiograph and the feedback was utilized to improve the manufacturing process for the next lot of pellets.

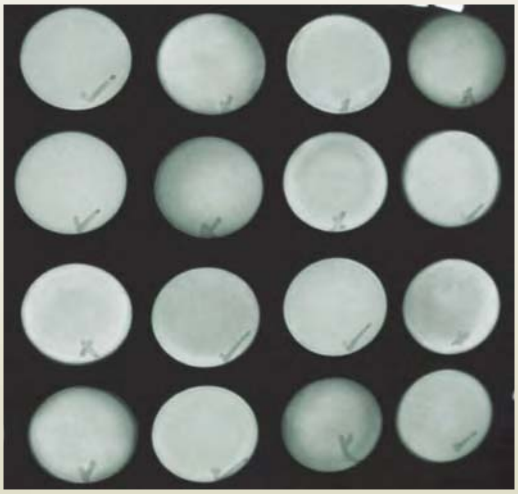

Fig. 3 : Inadequate sintering and compactness in few pellets

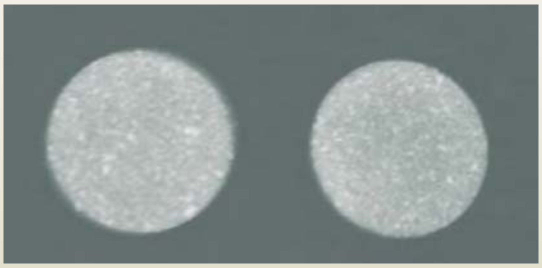

Fig. 4 : Inclusions and different phases seen in the pellets

Since no radiography standard is available for the acceptance and rejection of pellet, acceptance criteria were established by us based on our past experiences. Any type of crack, porosity and inclusion were cause for rejection. As far as local density variation within the pellet was concerned, reference radiographs were prepared. Initially, based on the radiographic image, few pellets having no defect and less density variation were selected for finding out their mass density. Since higher the mass density, better the compactness and lesser the porosity/void, pellets having higher mass density were considered as standard pellets. Radiographic image of these standard pellets were used for comparison in case of local density variation. Till now more than 500 pellets have been radiographed and the feedback has helped in improving the quality of pellets, which in turn has reduced the rejection.

Friction Stir Welding (FSW)

Friction Stir Welding is a type of friction welding which has been used by the automotive industry for manufacturing different parts used in vehicles.

Friction welding is carried out by moving one component relative to the other (linear or rotational motion) along a common interface, while applying a compressive force across the joint. The frictional heat generated at the interface, softens both the components and when they attain plastic state the interface material is extruded out of the edges leaving clean soft material of each component along the original interface. The relative motion is then stopped, and a higher final compressive force is applied before the joint is allowed to cool. The key to friction welding is that no molten material is generated, the weld being formed in the solid state [1].

Friction Stir Welding also produces a plasticized region of material, but in a different manner. In FSW, a cylindrical shouldered tool, with a profiled threaded/ unthreaded probe (nib or pin) is rotated at a constant speed and fed at a constant traverse rate into the joint line between two pieces of sheet or plate material, which are butted together (Fig. 5). The parts are clamped rigidly onto a backing bar in a manner that prevents the abutting joint faces being forced apart. The length of the nib should be slightly less than the weld depth required and the tool shoulder should be in intimate contact with the work surface.

The heat is generated primarily by friction between a rotating-translating tool, the shoulder of which rubs against the work piece. There is volumetric contribution to the heat generation from the adiabatic heating (due to deformation and relative motion around the pin), due to which the stirred material softens without reaching the melting point temperature. The tool traverses along the weld line containing the plasticized tubular shaft of metal. The leading face of the pin forces plasticized material to the back of the pin whilst applying a substantial forging force to consolidate the weld metal joint. The welding of the material is facilitated, by severe plastic deformation in the solid state, involving dynamic re-crystallization of the base material.

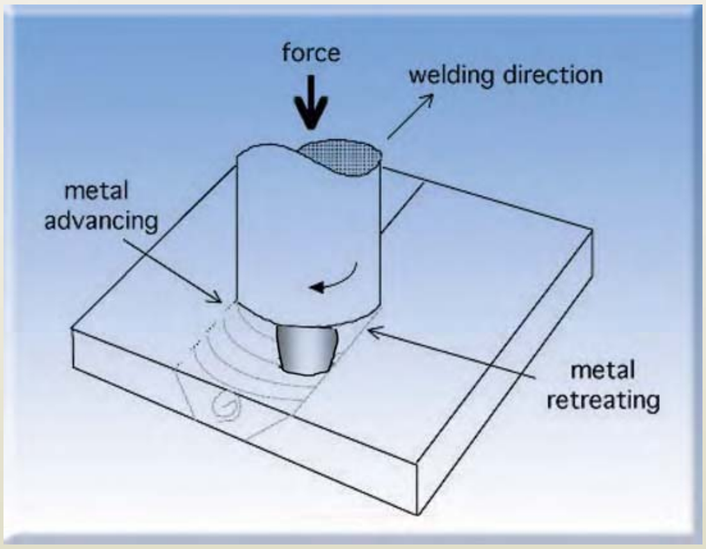

Fig. 5 : Principle of Friction Stir Welding

Application

It is already used in routine as well as critical applications, for joining of structural components made of Aluminium and its alloys, where the original metal characteristics must remain unchanged as far as possible. The process is most suitable for components which are flat and long (plates and sheets) and most often on large pieces which cannot be easily heat-treated post weld, to recover temper characteristics [2]. However, the process can be adapted for large pipes, hollow sections and positional welding. Ability to join dissimilar material makes it popular for the fabrication of components made of two different materials, each one suitable for different duty cycles in service. In the automotive sector the drive to build more fuel-efficient vehicles has led to the increased use of Aluminium in an effort to save weight. Friction stir welding is being used increasingly to replace fusion welding techniques where Aluminium alloys are involved mainly in aerospace, ship building, railway industries, automotive sector, space shuttle, launch vehicles etc.

Advantages

Since it is a solid state welding process, any problem associated with cooling from the liquid phase is immediately avoided. FSW can offer low distortion and lower shrinkage. Problems like porosity, solute redistribution, solidification and liquification cracking are not an issue during FSW. It is suitable for joining dissimilar materials. The process is environmentally friendly, because no fumes or spatters are generated and there is no arc glare. Generally, good weld appearance and minimal thickness deposit under/over the joint minimizes the need for expensive machining after welding.

Defect Associated with FSW

FSW is associated with a number of unique defects. Insufficient weld temperatures due to low rotational speeds or high transverse speeds may result in long, tunnel defects running along the weld, which may be surface or subsurface. If the pin is not long enough or the tool rises out of the plate then the interface at the bottom of the weld may not be disrupted and forged by the tool, resulting in a lack of penetration defect. The light contact between the materials has given rise to the name 'kissing bond'. This defect is particularly worrying since it is very difficult to detect using non-destructive methods such as radiography or ultrasonic testing. Steel can be friction stir welded but the essential problem is that tool materials wear rapidly and the wear debris from the tool can frequently be found inside the weld.

Process Development

Process of Friction Stir Welding of Aluminium plate is being jointly developed by the Materials Science Division (MSD) and the Centre for Design and Manufacture (CDM) of Bhabha Atomic Research Centre (BARC), Mumbai. Trial weld of 5 mm thick Aluminium 6061 plates (Fig. 6) have been carried out using tools of various geometry and various welding parameters such as tool rotation, (rpm-revolution per minute), transverse speeds (mm per minute) and tool tilt (degree). Following qualifying tests have been incorporated in the process to find the soundness of the weld:

a) Tensile test to check the mechanical properties of the joint.
b) Liquid penetrant test (PT) and Radiography test (RT) to detect surface and subsurface defects respectively.
c) Micro-structural characterization to identify the nature of microstructure in the nugget zone, heat affected zone, thermo-mechanically affected zone and the base metal.

NDT of Friction Stir Welding

To study the nature of defects, each welded piece was subjected to Liquid Penetrant Test (PT) and Radiography Test (RT). PT was carried out on face as well as on root side of the weld using solvent removable visible dye penetrant method. Mostly indications on root side corresponding to lack of penetration were observed in PT (Fig. 7). After PT, joint was radiographed using parameters given in Table 1. Result of RT was in agreement with that of PT. Other than Lack Of Penetration (LOP) no other defect such as porosity, lack of fusion, crack etc. was observed in the radiograph. Weld was considered to be of good quality except for LOP, which could be eliminated simply by increasing the length of the nib and controlling its relative position during welding. Further, radiograph was free from mottling effect, which is very common in fusion welding of Aluminium plates.

Fig. 6 : Friction Stir Welded Plate

Fig. 7 : LOP revealed by PT

In one of the experiments 0.2mm thick Titanium foil was inserted between the interface of the butting plates, to study the behavior of material transport in the stir nugget region, where material is heavily deformed giving rise to appearance of several concentric rings commonly known as 'onion-ring' structure. During PT of root side

Table 1: Exposure Detail

S. No.	Parameter	Value/Detail
1	Type of Source	X-Ray
2	Focal Spot	1.5 x 1.5 mm
3	Tube Voltage	80 kV
4	Tube Current	4 mA
5	SFD	750 mm
6	Exposure Time	40 second
7	Film	Agfa D7
8	Lead Screen	0.1 mm front & back
9	Developing Time	5 minute
10	Developing Temp.	20 degree C
11	Developer	Agfa NDI 230
12	Fixing Time	10 minute
13	Fixer	Agfa NDI 305

of the sample weld, lack of penetration was observed, throughout the weld and it was expected that RT would also reveal the same. However, to our surprise, radiograph did not show any lack of penetration. A continuous thick white line was seen throughout the length of the joint at the weld center. Matter was further investigated and effort was made to detect the LOP by RT in the welded plate having Titanium foil. Since the density of Titanium (4.5 g/cm^3) is higher than that of Aluminium (2.9 g/cm^3), image of the Titanium foil appears white in comparison to the parent metal, which is Aluminium. LOP being just below the Titanium foil could not be revealed as kilo voltage (80 kV) used was appropriate for Al and not for Ti. Since the low kV X-ray was not able to penetrate the Ti foil the detail of LOP under it was not seen on the radiograph. Considering the high sensitivity requirement to detect the fine image of LOP a new radiograph was prepared with following modifications: (a) Kilo voltage was increased from 80 to 110, suitable for Ti and (b) Fast and low contrast film (Agfa D7) was replaced by slow and high contrast (Agfa D4) film. Result was encouraging, since LOP was revealed as an intermittent dark line at the center of white image of Ti foil on a radiograph prepared using these new parameters. Distribution of Titanium, near the interface, indicates the transportation of the material under the influence of force applied by the rotating tool (Fig. 8).

Results and Analysis

Most common defect for friction stir welding is lack of penetration, which is more likely to exist at the start of the weld where nib plunges or at the end of the weld where tool is withdrawn due to inadequate frictional force. For this reason, additional material is removed from both the ends. However, if the nib is shorter than the required length, LOP may occur throughout the weld, which is difficult to detect by low sensitivity RT, if interface contains foil of some high-density materials such as Titanium or Copper. Therefore, for such joints in addition to RT, PT must be carried out from the root side which will ensure the detection of LOP. High sensitivity radiography developed by the authors, is able to detect complete internal details of the weld including LOP, material transportation and effect

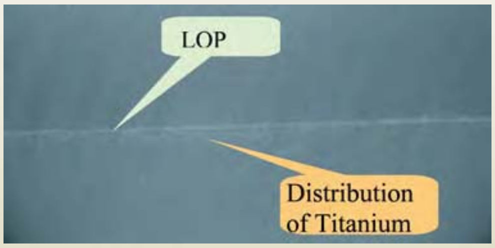

Fig. 8 : Radiograph of FSW Aluminium plates with Titanium foil at the interface

of inadequate force applied by the tool. Fig. 9 is a radiograph showing LOP and circular pressure mark at the start of the weld. The pressure mark in Fig. 9 indicates the change of microstructure of the material, under the shoulder of the tool at the beginning of the welding process, where as Fig. 10 indicates severe deformation of the material without reaching the plastic state.

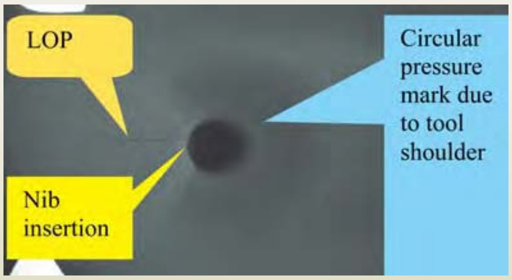

Fig. 9 : Defects at the start of FSW

Fig. 10 : Severely deformed material

Conclusion

An attempt has been made, to establish RT as a quality control tool, for the development work of Boron Carbide pellets and Friction Stir Welding at BARC. Radiographs prepared, using conventional X-ray machine are capable of revealing density distribution, inclusions, porosities, improper compactness and cracks in case of Boron Carbide Pellets and LOP, material deformation and material transport in case of Fiction Stir Welding. Feedback of NDT methods has been utilized, for improving the manufacturing process to get superior quality products with less chances of rejection.

References

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2. Thomas W M, Nicholas E D, Needham J C, Murch M G, Temple-Smith P, Dawes C J, "Friction Stir Butt Welding", GB Patent No. 9125978.8, International Patent No. PCT/GB92/02203, (1991).

External Links

Friction Stir Welding- Wikipedia, the free encyclopedia (www/Friction stir welding/wikipedia.html).

Friction Stir Welding a process invented at TWI, Cambridge (www.msm.ac.uk/phase-transe/2003/FSW/aaa.html).

About the Authors

Mr. S.P. Srivastava obtained his degree in B.Sc. Engineering (Mechanical) from B.I.T., Mesra, Ranchi in 1984. After completing one year course of BARC Training School (29th Batch) he joined Non-destructive Unit of CDM in 1986. In the capacity of Engineer-In-Charge of Material Testing Laboratory, he is responsible for Non-Destructive Testing, Mechanical Testing, Quality Control Activities and Organization of Training and Certification Programme at CDM. He has developed various NDT techniques and systems for the examination of critical components required for nuclear power plants and research equipment. He has obtained certifications in Ultrasonic Testing Level 3, Radiography Testing Level 3, Leak Testing Level 2 and Eddy Current Testing Level 2.

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Mr. T.G. Unni is Engineer-In-Charge, of Non-Destructive Testing Unit of CDM. He is involved in testing of various equipment and accessories manufactured at CDM for nuclear power plants & research activities. He has specialized in the field of Radiography Testing, Ultrasonic Testing, Liquid Penetrant Testing, Hydrostatic Pressure Testing and Magnetic Particle Testing. He has passed Ultrasonic Testing Level 3, Magnetic Particle Testing Level 3, Radiography Testing Level 2 and Eddy Current Testing Level 2 Certification Examinations.

Mr. S. P. Pandarkar joined CDM, BARC in 1978. Since then he is involved in Non-Destructive Testing of nuclear components manufactured at CDM. He is also responsible for third party QS activities for jobs manufactured by private companies. His field of specialization is Radiography Testing, Liquid Penetrant Testing, Helium Leak Testing and Mechanical Testing. He has passed Radiography Testing Level 2 and Ultrasonic Testing Level 1 Certification Examinations.

Mr. K. Mahajan, after obtaining his B.E. (Production Engineering) degree from Punjab Engineering College, Chandigarh in 1973, joined CDM (Centre for Design & Manufacture), (then CWS), BARC in the year 1974. Subsequently, he did his Postgraduate Degree [M.Tech. (Production Engineering)] from the Indian Institute of Technology, New Delhi in 1984. He has been associated with manufacture of Fuelling Machine Head assemblies, Special purpose machines, Precision instruments for various Nuclear Power Stations & Research Reactors for the last 33 years. Guide Tube Cutting Machine was successfully used to cut the bend tube into two parts and brought out of the FBTR and the new guide tube installed in the reactor. In order to study/determine earth's magnetic characteristics accurately, 1 Axis and 2 axis Barker Coil Systems were manufactured in CDM under his supervision and installed at the Indian Institute of Geomagnetism, Alibagh. He was also involved in refurbishing the old imported electrical & pneumatic control systems of Food Package Irradiator (FTD) using indigenous components and the system was upgraded incorporating additional safety features. At present, Mr Mahajan is functioning as Head, Human Resource Development & Industrial Engineering (HRD&IES), Maintenance and Quality Management Sections (QMS) in CDM.

Mr. R. L. Suthar, after obtaining his B.E. (Mechanical Engineering) degree from the University of Jodhpur, joined CDM (then CWS) in the year 1971. He has been associated with design and development of Special Purpose Machines and Precision Instruments & Equipment for Nuclear Power & Research Reactors for the last 32 years. Boring & Grooving Machines developed by him under MAPS Rehabilitation Project have been successfully used under his supervision. Power generation of these reactors then could be raised from 75% FP (Full Power) to 100% FP. Mr Suthar is now heading the Centre for Design and Manufacture and is involved in development of SPMs, Precision Instruments for INDUS-I & II Beam Lines at RRCAT, Indore, and other users of BARC; manufacture of equipment for AHWR Critical Facility, Sub-Critical Facility for RPDD and RED and 5 Axis Mechanism for Sub-reflector of 32 Meter DSN Antenna for ISRO under MoU with ECIL, etc.