Welding Research in India : Present Status and Future Directions

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ABSTRACT

Welding Science and Technology is a continuously growing field thanks to its multi-disciplinary character. There is so much happening in the connected fields like Arc Physics, heat transfer, electronics of power sources, digitisation drive, low cost and robotic automation, materials science, Nano-technology, high energy beams, materials development, stress analysis and so on, that welding has blossomed in many directions. There is no dearth of challenge to the welding professional today and the opportunity is aplenty to learn and improve every day. Welding is also the heart and soul of the fabrication technology and so with the growth in the manufacturing sector, there is an irresistible pull on the welding industry to improve and meet the challenge of the day. Hence, it is no wonder the welding technology is growing, amply contributed by the academia, research centres and the industry in India. While there is great satisfaction that the research in this field in India has advanced to a certain level, there are still several areas, where India is looking up to the outside world for support, and very little of efforts is taking place within the country due to resource and other constraints. This paper is an attempt to look at the various areas, and a self-introspection on where all we in India should be. The areas of research in welding can be broadly categorised as material development, consumable development, establishment of weldability, development of new processes which will improve the quality and productivity while minimizing cycle time of welding, improved non-destructive testing, development of welding procedures to minimize any distortion, characterisation of weldments for their service behaviour etc. The research activities that are currently under progress are discussed in the paper. There is no doubt that the technology is well poised to take large strides in the years ahead, but the research in India should take some strong steps to be in the forefront of such strides.

KEY WORDS: Wave Form Controlled Technologies, Welding Engineering, Advances in high energy beam processes, Advanced Arc Welding processes, Simulation

1.0 INTRODUCTION

Research in Welding does occupy a significant slot among the fraternity in Academia, Research Centres and Industry in India. The reason is simple: the industry needs to have that edge in ensuring sound and consistent quality of the weldments and product, the speed and ease with which the fabrication is done and the cost reductions that can be achieved on a continual basis.The other challenge of the industry is that they are working on newer frontiers in terms of materials, material strength, higher temperatures and pressures, tougher environmental conditions (cycling, corrosive, joining in site conditions etc.). The Academia and Research Centres in India are working to meet these challenges of the industry. This is true of all the sectors, where fabrication plays a key role. Some of the research work related to welding being taken up in the strategic sectors is indeed outstanding, though this paper may not cover these.

The research cycle starts with the development of materials and establishing their consumables and weldability aspects. Choosing and conducting appropriate and select few weldability studies from the available 300 plus such tests is called for at this stage. It then moves into looking at the ideal welding processes, considering the material behaviours. It looks at the fabrication ease of the newer designs and how the human factor could be minimised in ensuring sound weld joints. Narrower grooves, appropriate edge preparation and methodologies, are given a thought. It looks at the NDE that can give confidence on the serviceability of the product. There is also a research needed to study the static and dynamic characteristics of the power sources, especially so as the newer breed of power sources from across the globe are flooding the market, as otherwise they remain a black box. The research also extends to a host of on-site fabrication issues that are envisaged. Simulation of anticipated service issues, modeling of the fabrication sequence to study distortion and residual stress aspects, fracture mechanics studies to examine the influence of defects are certainly part of the research content.

Let us look at some of the above aspects in greater depth to see what the trends are like today and some directions in which we could be working further.

2.0 NEWER MATERIALS FOR FABRICATION

The world of materials is enlarging. The need for increased strength, increased ductility, enhanced creep strength, fatigue strength, erosion resistance, corrosion resistance, thermal shock resistance, oxidation resistance, resistance against interaction between the damage mechanisms and so on, have put huge demands on the materials developers. It would not be far from truth if we were to say that more new materials have been invented in the last quarter century as compared to the entire past history of the world. The Codes of today are also accommodative of these developments and have been willing to take in these materials after about 30,000 hours of creep tests, with a progressive view to absorb the learning from the long term tests. But then what about India? Research on the development of new materials has not been Indian researchers' forte. At best, we can say India has not been shying from using some of the new developments across the globe. There is a need to have more committed research in the country to bring out materials that excel in some properties and do serve the needs of specific segments of the industry.

3.0 CONSUMABLES DEVELOPMENT

The consumables industry has flourished over the years in India and the most common consumables for the industry are available today in India. The ingenuity has been in full bloom to devise consumables that can deliver excellent strength after multiple heat treatments, good and consistent impact toughness at low temperatures are all made in India. FCAW wires for many materials including SS are available from Indian market.

Fig 1: Dia 6.3 mm High Performance Electrode developed at WRI

There are some areas, where the Indian consumables industry has not put a strong foot on. The consumables for Creep Strength Enhanced Ferritic Steels need to be established with a good back up of the creep data. High performance coatings, moisture resistant coatings are some areas where WRI is working on currently. **Fig 1** shows a high performance version of E7018 developed with higher efficiency of 140% with high strength properties and toughness even after multiple stress relief heat treatments.[1]

The industry has been able to understand the nuances of SAW fluxes and wire combinations, and many combinations are working quite well. The need for higher productivity and necessity for welding high alloy steels using SAW process demands the development of special purpose welding fluxes. Basic agglomerated fluxes are more suitable for high alloy steel welding, since alloying and production costs are affordable. Fluxes which can withstand higher heat input levels are to be developed for pipe welding applications where there is a demand for multi-wire SAW technique.

Additional areas for R&D include development of special consumables like backing fluxes, which will eliminate the need for any purging gas and shape the back side of the root weld bead in pipe joints, special fluxes which will improve the penetration in arc welding, backing materials which will enable one side welding etc.

4.0 WELDABILITY STUDIES

When new materials are developed, the ability to weld the materials must be assessed as welding is the main fabrication tool. The conventional carbon steels have excellent weldability, and the operating window for a fabricator is rather wide. But the new generation materials pose many challenges and can be satisfactorily welded only under very narrow welding conditions. Thus the weldability studies establish the welding conditions which give a satisfactory weldment free from any cracks. There are several mechanisms which lead to cracking in the weldment and the study of the welding procedures which will overcome the cracking tendency in the weldment is an on-going programme.

Fig 2 : Implant Test Facility

Fig 3 : Varestraint Test Facility

Many different weldability tests have been developed in the past few decades, though very few are being used in the industrial application regularly. Selection of weldability test is dependent on material, welding process, and environment conditions. Weldability of a material is strongly influenced by the metallurgical phases and mechanical properties of the weld metal and HAZ, the build-up of distortion and residual stresses, segregation of elements etc. These phenomena are primarily caused by the localized heat input during welding and the subsequent rapid cooling of the weld metal. The interpretation of the results with real welding condition is very important. While the conventional tests are adequate for establishing the weldability of commonly used materials, newer tests are required for advanced materials. The conventional tests ensure the freedom from hot cracking and cold cracking tendencies, but the cracking behavior in advanced materials are different like stress relief crack, liquation crack, lamellar tearing etc. Hence research is required to develop special weldability tests to address these issues.

The **Fig. 2** and **Fig. 3** show the Implant Test and Varestraint Test facility at WRI, which are very commonly used. There would be an increased usage of Physical and Software simulation for assessing weldability, especially for development of new materials and welding consumable development, and there is a huge unexplored potential. [2] Perhaps, in the times to come, the AWS definition of weldability tests would need to be revisited to include the simulation aspects as well.

5.0 DEVELOPMENT OF SPECIAL PROCESS VARIANTS

The arc welding processes that are classified under Gas Shielded Arc Welding are Gas Tungsten Arc Welding and Gas Metal Arc Welding. The need for variants within these established and time tested welding processes is necessitated by the special requirements in terms of quality (in terms of heat input control, spatter control, penetration control, weld width control, better fit-up tolerance, energy efficiency and so on), feasibility for easy automation, and overall cost control. For example, in multi-pass welding situations, the quality of the root pass is most critical and conventionally TIG welding is employed which can give high quality welds. But after the root pass, TIG is not suitable for further filling due to the lower deposition rates. Thus there is a need to switch to an alternate process after the root pass. But the developments in MIG welding have eliminated this switch over. The latest wave form controlled processes can tolerate large root gaps and poor fit up conditions and can still produce good quality welds. They effectively take away the skill requirement from the welder and are most suitable for site applications. The research trends in each of these processes are presented in the following paragraphs.

5.1 Research Trends in Gas Tungsten Arc Welding:

5.1.1 Energy input control through pulsed current :

GTA welding is known for its high quality clean welds due to the absence of flux. Also the arc is not disturbed by the droplet transfer as in the case of consumable arc welding processes such GMAW, FCAW etc. Hence, GTAW is the welding process of choice for Aerospace, Nuclear and Power sectors. In GTAW, arc energy input control is critical to the success of the technology. This arc energy input control is sought to be achieved through pulsing the current between high and low levels at varying frequencies. The arc pressure/stiffness is reported to increase with pulse frequency up to 5Hz, and beyond which it remains constant. The interaction between pulse current, background current & pulse frequency on the bead geometry has been an area of active research in the academic institutions. The development of pulsed GTAW power source and technology is an important area of research.

5.1.2 Hot Wire GTAW to improve productivity:

Lower deposition is one of the limitations of conventional GTAW process. This is sought to be overcome through Hot Wire GTAW technology. Development of suitable power source for main arc, hot wire power source, wire feeder, torch for hot wire GTAW and most importantly, avoidance of arc deflection due to hot wire has been the focus area of research in GTAW. With increasing applications for newer breed of Creep Strength Enhanced Ferritic Steels and Ni-base alloys for high temperature application, the technology offers the best solution for tube and pipe joints, more so in the case of dissimilar weld joints. [3,4] The **Fig. 4** and **Fig. 5** show the HWTIG facility and a typical dissimilar weld using the process.

5.1.3 Narrow Gap Hot Wire GTAW :

To further enhance the productivity of Hot Wire GTAW, the Narrow Gap Hot Wire GTAW process has been developed as a high productive technology. In Narrow Gap GTAW, consistent side wall fusion is very difficult to achieve and therefore it requires special torch, power source and controller. Therefore, the design of Narrow Gap GTAW torch, power source, process controller, establishing the technology for heavy wall thickness jobs such as Turbine Rotor Shaft is another focus area of

Fig 4 : Hot Wire TIG Facility at WRI

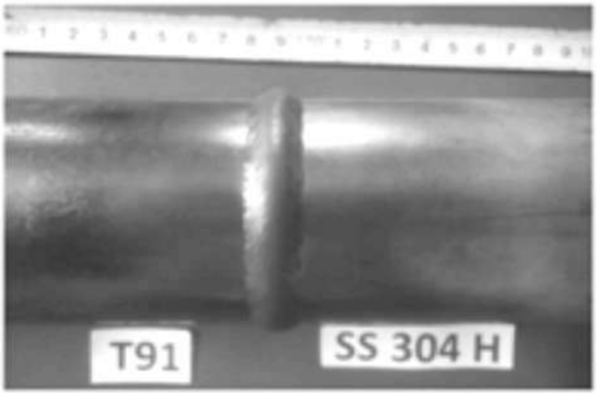

Fig 5 : A typical dissimilar weld by this process

Fig 6 : Narrow Gap Hot Wire TIG Facility

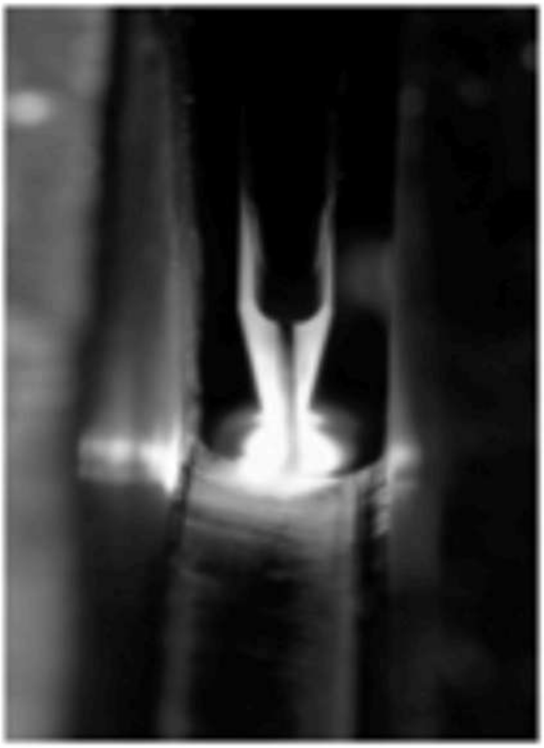

Fig 7 : Welding in progress (Courtesy: Polysoude)

research in GTAW. **Fig. 6** and **Fig. 7** show a welding in progress.

5.1.4 Introduction of automated wire feeding in GTAW process:

GTAW with automated wire feeding known by trade names viz., TipTIG / TopTIG have been developed to overcome the directional limitation posed by the cold/hot wire GTAW process on Robot welding automation. TipTIG enable robotic automation of cold/hot wire GTAW process. Additionally Tip TIG also attracts manual applications of the process for pipe welding. Process capability analysis is one area of research currently progressing.[5]

The **Fig. 8** shows the root pass welded by Tip TIG process and Tip TIG is found to give much uniform bead shape at 3 times faster welding speed.

5.1.5 Inter Pulse TIG Welding:

Inter Pulse TIG is a patented technology from VBC Group, UK. The specially designed Inter Pulse TIG power source provides a highly constricted, fine welding arc which enables welding of "difficult to weld" materials such as super-alloys of gas turbine components. It also allows out of chamber welding of titanium with minimal trailing shield protection. WRI has added this facility recently and is trying out some potential applications. [6] One such is shown in **Fig. 9**.

5.1.6 Orbital TIG Welding Process:

Orbital TIG welding (**Fig. 10** and **Fig. 11)** was developed as a superior joining technique to meet the aerospace welding requirements. A method was developed in which the arc from the tungsten electrode is rotated around the tube weld joint. The arc welding current is regulated with a control system thus automating the entire process. Orbital TIG welding boiler tubes at power plant erection sites is a demanding application due to limited radial/axial clearance and environmental conditions. Development efforts are on to develop and establish the orbital TIG process for site application [7].

5.1.7 Activated TIG Welding:

Enhancing the penetration in GTAW process through active flux coating of the weld joint is an idea patented by PWI Ukraine during 1960s. However, this technology has gained momentum now. Research work is going on to develop suitable active fluxes for different types steels such as alloy steel, stainless steel and even for non-ferrous metals such as aluminum, monel, titanium etc. Work has also to proceed concurrently to improve the consistent delivery of the activated flux on the surface to be welded, so that uniform penetration is

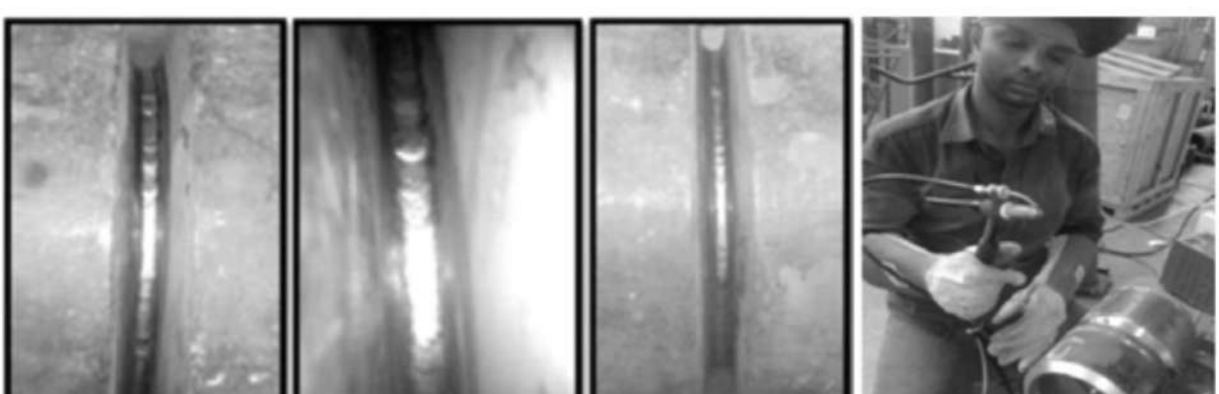

Fig. 8 : Root pass welding by Tip TIG Process

Fig 9 : SS 347H tube welded by Inter Pulse TIG process

Fig. 10 : Orbital TIG welder

Fig. 11 : A typical boiler tube butt weld made by Orbital TIG

ensured. WRI has developed an activated flux suited for stainless steel tube welding applications, which can weld upto 7 mm thickness in one pass, in an orbital TIG welding system. **Fig 12** shows the welds of carbon steels using the activated flux.[7]

5.1.8 K-TIG welding :

After years of research & development at the CSIRO Labs in Australia, the K-TIG welding process has been developed. It has capability to penetrate up 9 mm thick stainless steel plate / pipe in single pass without any edge preparation. Now the K-TIG process capability is being investigated for possible applications in industries. Some trials have been done at WRI for some potential applications, but there is a need to fine-tune

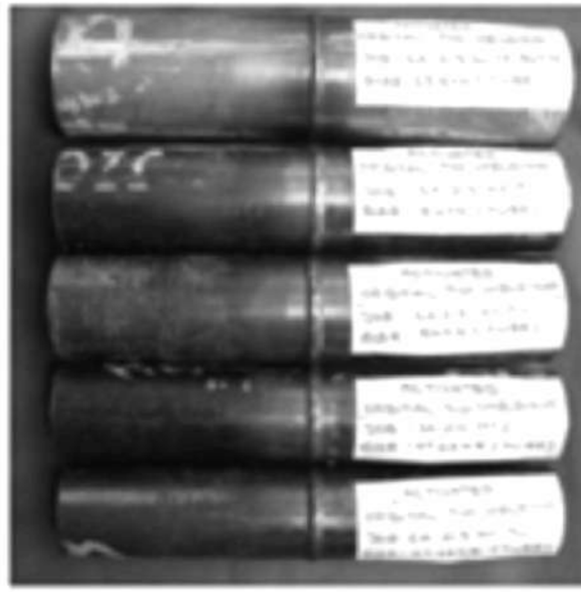

Fig. 12 : Orbital Activated TIG tube butt joints

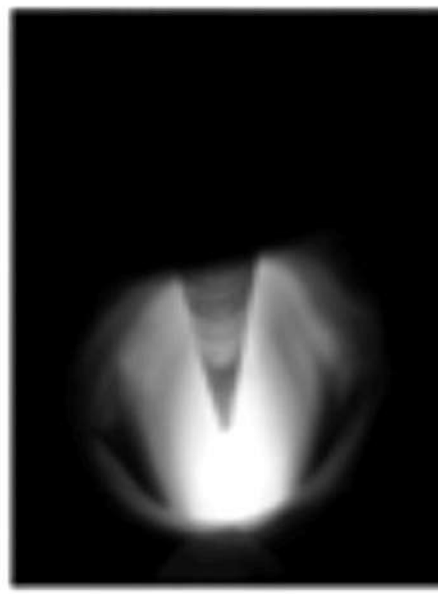

Fig 13 : K-TIG arc

to suit specific applications. **Fig. 13** and **Fig. 14** shows the arc and a macro section of a weld.

5.2.0 Research Trends in Gas Metal Arc Welding:

5.2.1 Waveform controlled GMAW:

Waveform controlled GMAW technology has been developed primarily to control spatter in short circuit transfer GMAW and to also improve plate fusion, thereby avoid lack-of-fusion problems. A large number of waveform controlled GMAW equipment such as STT, RMD, CMT, Fastroot, Welbee are commercially available. The research continues to develop better algorithms & hardware to increase communication speed between the controller and the power source to further improve the performance of the process. Process capability of these waveform controlled power sources for various applications is also being investigated. [8] WRI is currently working with many of these power sources for specific end applications. **Fig. 15** and **Fig. 16** show a pipe root pass welding by Orbital Pipe Welding by RMD process.

5.2.2 Deep penetration GMAW :

Forced short circuiting mode of transfer in GMAW offers deep penetration as compared to conventional short circuit transfer and spray transfer. However, if the power source dynamics is not proper, it will lead to heavy spatter and poor performance. Development of inverter power source with dynamics fulfilling the requirements of deep penetration mode has been a focus area and still continues, based on the feedback from the fields and end customers. Many equipments with different trade names such as forcearc, rapidarc, steel dynamics etc., are commercially available. Performance evaluation in different applications is underway with all these equipments.[9] **Fig. 17** shows a deep penetration weld made for a header stub weld joint for a power plant application.

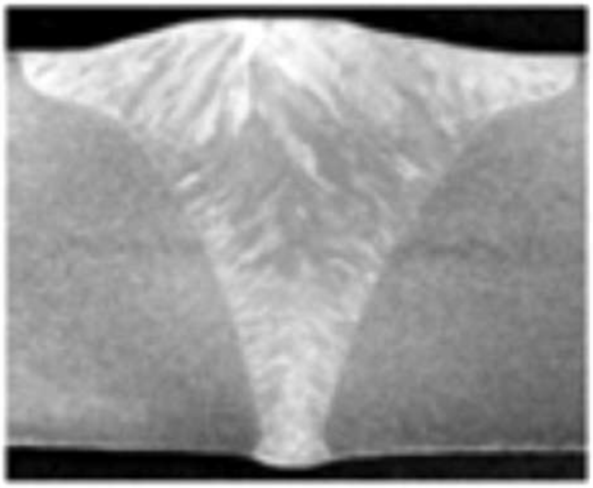

Fig. 14 : K -TIG Weld (Courtesy : K-TIG Australia)

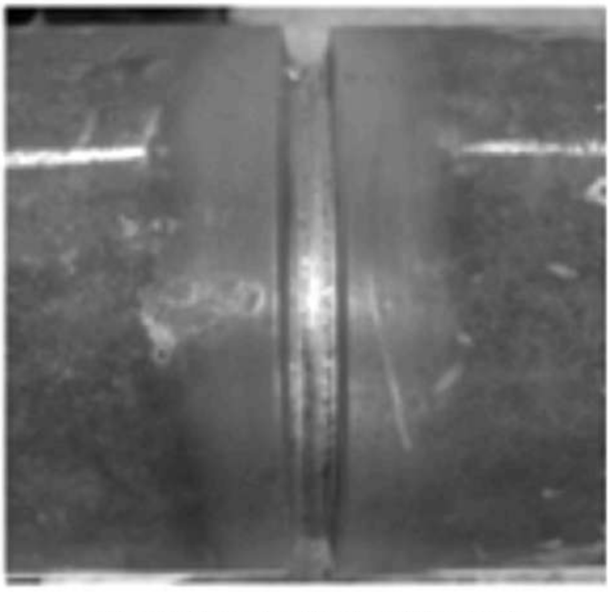

Fig. 15 : Pipe Root pass by RMD process

Fig. 16: Orbital Pipe Welding by RMD process

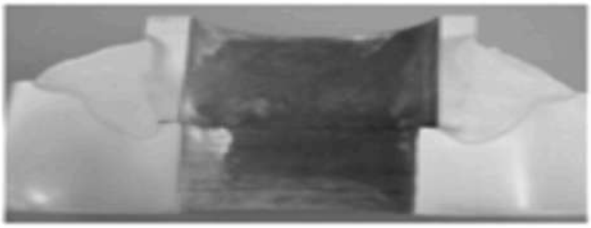

Fig. 17 : Macro of a header stub joint

5.2.3 Pulsed Current GMAW :

Pulsed current GMAW has been established (**Fig. 18**) for a long time with rectangular and trapezoidal waveforms. A lot of research is being pursued to optimise the pulse waveform structure with shoulder, to ensure smooth droplet transfer and to avoid the fine spatter associated with pulsed spray transfer.

Double-pulse alternately known as "pulse on pulse" is recently introduced as a new feature to improve the performance of pulsed GMAW on aluminum welding. The impact of this double pulse GMAW on weldmetal properties is being investigated for various applications including stainless steel.

5.2.4 GMAW with Alternating Shielding Gases:

GMAW with alternating shielding gases involve supplying inert

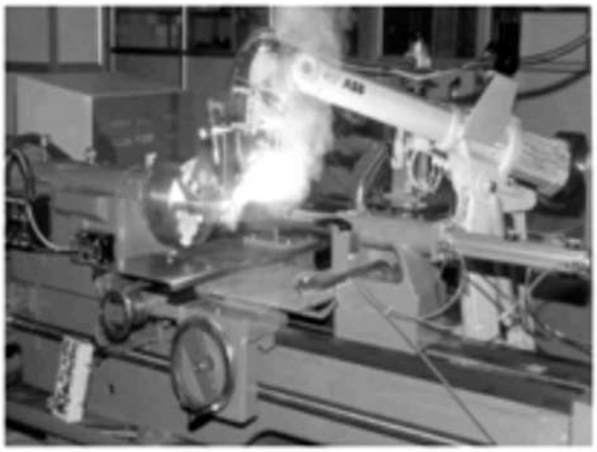

Fig 18 : Pulsed GMAW of a Valve component

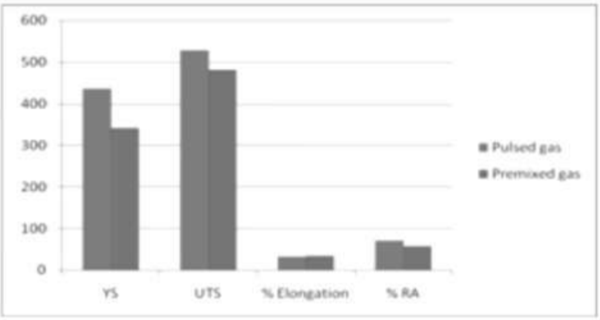

Fig. 20 : Advantages of using gas alternator

and active gases successively one behind the other like a train and thereby influencing the arc behaviour favourably. The alternating shielding gases influence the arc shape and mode of transfer depending on the nature of the gases. It is an emerging technology in GMAW, wherein a pulsing effect can be created with a normal Constant Voltage power source. The studies conducted at WRI have shown that the weldmetal properties are improved as compared to pre-mixed gases, while significantly reducing the consumption of argon gas. [10] (**Figures 19, 20**) WRI is pursuing further studies needed before establishing the technology for industries.

5.2.5 Special Gas Mixtures :

Shielding gas mixtures such as 80% Argon+20% CO_2 is commonly used for GMA welding of carbon and low alloy steels. However, the shielding gases used for stainless steels differ from those used in GMAW of unalloyed steels since they contain much less active gases, such as oxygen and carbon dioxide. This is necessary to prevent excessive oxidation of the passive layer responsible for the corrosion resistant properties of these metals. It is important to remember that the oxidation properties of oxygen are much greater than those of CO_2. However, welding in an inert atmosphere, for example, with argon, is not recommended either since the pure argon arc is unstable and penetration is significantly decreased. The carbon content of the weld metal is a key factor in ensuring resistance to inter-granular corrosion. In stainless steels with particularly low carbon contents, referred to as ELC steels, the carbon content also of the weld metal should not exceed 0.03%. To prevent unacceptably high carbon pickup from the shielding gas, the CO_2 content of the above-mentioned products should be limited to a maximum of 2.5%. If welding is performed correctly, this prevents sensitisation to inter-granular corrosion. In the same way, every other alloy steel require special gas mixture as appropriate for that particular alloy, which requires to be studied and established.

5.2.6 High performance GMAW:

The double wire GMAW is considered as high performance GMAW, (**Fig. 21**) because it offers deposition rate and welding

Fig. 19: WRI developed Gas Alternator

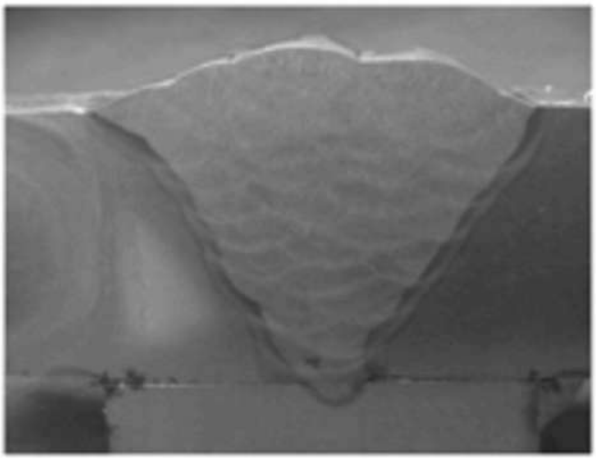

Fig 21 : Conventional GMAW

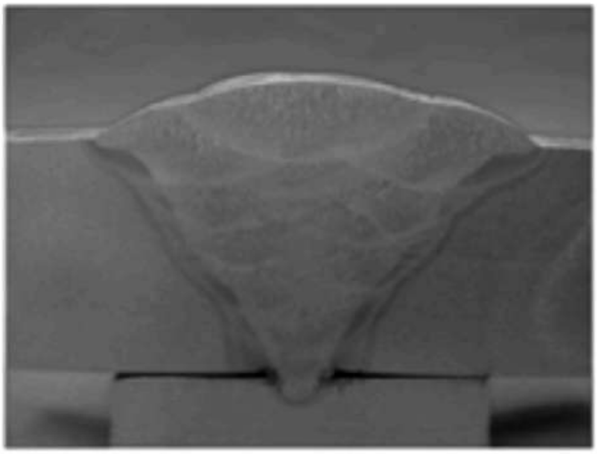

Fig. 22 : TIME Twin GMAW

approaching that of Submerged Arc Welding. Equipments such as TIME Twin, (**Fig. 22**) Tandem GMAW etc., are commercially available. However, further fine tuning is on to redesign the torch for better accessibility. The techno-economics and industrial readiness of the process is being investigated in application labs and industries, though there are quite some applications already in place.[11]

5.3.0 Research Trends in Submerged Arc Welding:

Submerged Arc Welding (SAW) is one of the most versatile joining methods for thin and thick sections for the fabrication industry. With its inherent process tolerance, availability of welding consumables from a large spectrum of suppliers and the ability of the process to ensure high quality weldments, SAW is increasingly patronised by fabricators in power sector, ship building, process industries and infra sector segments. The productivity of SAW process can be increased either by increasing the deposition rate or by reducing the volume of weld metal required for the joint by adopting narrower groove designs of the joints in comparison with the conventional wide groove joints.

5.3.1 Productivity through number of wires

Deposition rates can be improved by about 50 to 60% with tandem SAW technique, wherein the main/leading wire connected to DC is supported by an auxiliary/trailing wire connected to AC to impart higher melting rate. In tandem (**Fig.23**), both the wires are powered. In cold wire SAW technique, the auxiliary wire will not be powered and is being fed as an extra additional filler to effectively utilise the superheat available in the main molten pool. In cold wire SAW (**Fig.24**), the deposition rates can be enhanced by about 50 to 80%. Also, investigations at WRI have showed that the

Fig. 23 : Tandem SAW of Boiler Drum Long Seam

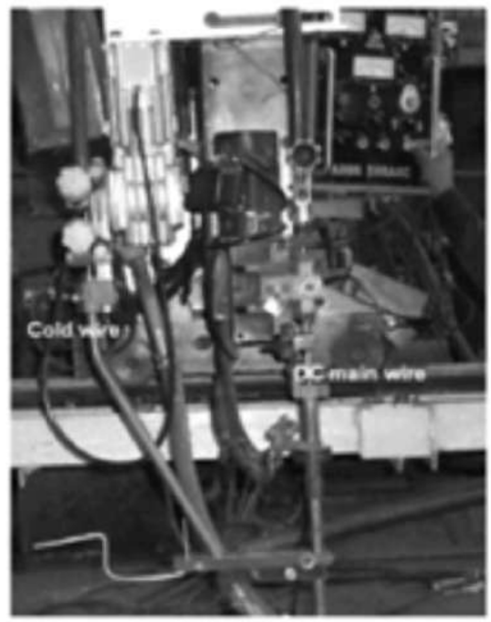

Fig. 24 : Cold wire addition in SAW

mechanical properties, especially impact properties of cold wire SAW is better than conventional or tandem SAW due to lower heat input with cold wire addition. This technique is to be further studied in detail for welding of high temperature materials.

Hot wire addition technique in SAW was also used in industries to enhance productivity. Further increase can be obtained by multi-wire technique. For achieving higher productivity, multi-wire SAW is practiced for welding of pipes of larger diameter with high wall thickness. In ID welding, pre-stressed booms as well as welding heads for up to four wires are commercially available. [12] During ID welding, cross slide mounted laser sensor guides the welding head. Video camera observation for

Fig. 25 : Pulsed GMAW of a Valve component

accurate guiding of the welding process is widely used. For OD welding, a column and boom solution with a very stable cross-slide to adapt to different pipe diameters is used. The welding head, consisting of five wire system, having independent wire feeding arrangement is mounted on a rainbow fixture (**Fig. 25**). With the advent of feedback systems to control the parameters dynamically, more efforts are needed to make these high-end systems more economical.

5.3.2 Productivity through narrow joint design

On the other hand, Narrow Gap SAW technique is capable of reducing the weld metal volume by about 40 to 50% with narrow HAZ, resulting in better mechanical properties. Narrow Gap Welding has long been viewed as a very promising welding technique, which could meet today's requirements for heavy wall fabrication in terms of quality and cost. Narrow Gap Welding offers many advantages over conventional welding methods such as higher mechanical properties of the welded joints, higher productivity and cost effectiveness.

The main reasons for reluctance and caution by fabricators in applying narrow gap welding are the non-availability of indigenous welding system, lack of information on technical and economic aspects and exorbitant cost of imported special purpose equipment. WRI has developed a special torch for NGSAW which can be readily fitted on to the available commercial systems, as shown in **Fig. 26**. This technique will be sought more for welding of thick section alloys in future. The main focus will be to develop suitable welding fluxes for such applications and understanding the unfavourable microstructures during cooling cycles and the ability to deliver a very clean weld metal.

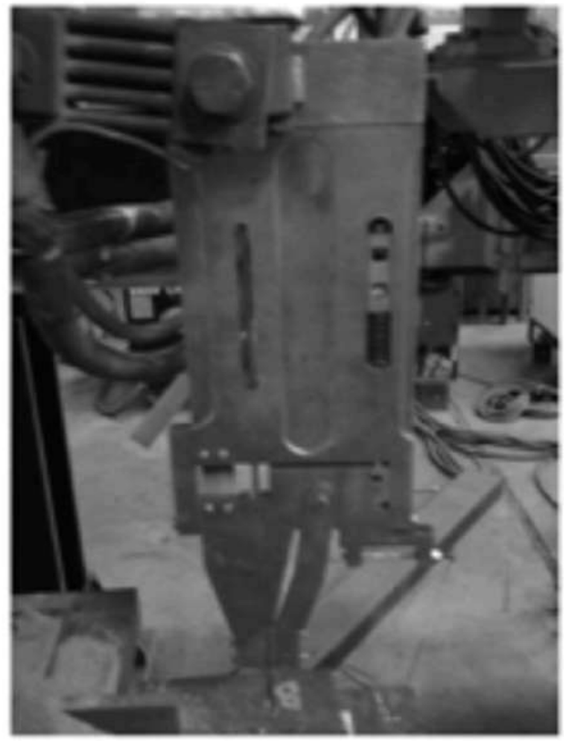

Fig. 26 : Narrow Gap SAW

5.3.4 Quality and Productivity through power source technology

Recent developments in power source technology has resulted in the introduction of invertor based AC/DC variable polarity sources for SAW process, wherein the balance and the offset of wave form is adjusted to control the deposition and penetration. This technique enables the use of single power source for the root requiring deeper penetration (DC characteristic) and for further filling up passes requiring higher deposition (AC characteristic) and also to avoid the necessity of using a backing in most of the cases. In surfacing and hard facing applications where the dilutions levels are to be very closely controlled, this type of power sources can be employed with great advantage to reduce the number of layers required for achieving lower levels of dilution.

5.3.5 Productivity through manual/hand held SAW systems in profile and short welds

The need for profile welding with difficult to follow contours in the structural welding of beams embedded with stiffeners is made easier with hand-held SAW systems. In this technique, the wire and flux pass through a common conduit enabling a continuous and effective shielding of the profile and during interruption due to stiffeners and reinforcing arrangements. The system does not require any sophisticated moving or rotating mechanism and the operators can be trained in a short period of time. However, special purpose machines are also available for pipe/vessel to nozzle welding and robotic SAW is

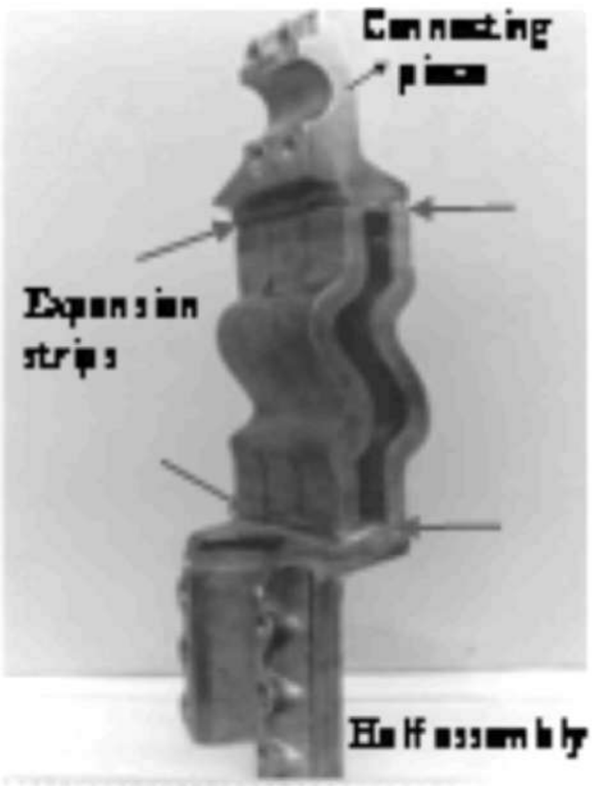

Fig. 27 : An EBW application

being commercialised for curved profile welding applications.

5.4.0 Research in High Energy Welding Processes:

5.4.1 Electron Beam Welding:

Electron Beam Welding (EBW) is a promising process for joining of thin and thick materials of different combinations. Research is on at Paton Welding Institute for depositing different material composition in micro and nano-layering. WRI has successfully developed EBW technology for joining of thick section Al-Cu alloys for space applications upto 100mm thickness. Also, EBW of flexible copper terminal assemblies for 500MW generators [13] have been successfully developed as shown in **Fig. 27**. Each assembly consists of 4 connecting pieces & 12 expansion strips. The Ag coated connecting pieces are made of Cu-Cr-Zr sand casting. Expansion strips are made of Oxygen Free Copper, in which 2 Cu strips of 0.5x58x265mm & 49 Cu strips of 0.3x60x265mm are diffusion welded together. EB welding has been carried out between the connecting piece and the expansion strips as shown in the **Fig. 27**. It is necessary to concentrate on indigenous design of EB gun and accessories to make this technology more affordable, even with the private sector fabricators.

Fig. 28 : LAM product

5.4.2 Laser Materials Processing

5.4.2.1 Laser Additive Manufacturing (LAM)

Lasers are being increasingly used for welding, cutting, surface engineering applications. Based on laser cladding, Net Shaping applications have been developed in the past and it has come to be known as laser additive manufacturing (LAM), which started making inroads not only in engineering, but also in medicine and jewellery. LAM is predominantly used in dental implant making due to its cost effective and quality advantage for titanium implants. [14] At present, this is known as 3D printing technology, which is one of the hottest manufacturing trends. Firing of a liquid oxygen and gaseous hydrogen rocket injector assembly demonstrated the integrity of a highly critical rocket engine component, as per NASA. In this case, the injectors fabricated using traditional processes would take more than a year as against only four months, at a 70% cost reduction, for 3D-printed components. In addition to cost reduction, LAM components for aerospace applications may have another significant benefit, weight reduction. In a case study reported by additive systems manufacturer EOS (Novi, MI) and conducted by EADS Innovation Works (EADS IW; Bristol, England), traditional Airbus A320 steel-cast nacelle hinge brackets were compared to titanium brackets with optimized topology using EOS DMLS technology (see **Fig. 28**). The EADS IW energy consumption analysis included not only the production steps, but also the sourcing and transport of raw materials, and argon consumption and waste produced for the atomisation process of the metal powder material. For the whole lifecycle of the components, including static manufacturing and operational phases of the brackets, the study revealed a 40% reduction in energy consumption, a 25% reduction in raw material consumption, and a potential weight savings per plane of around 10 kg. It is heartening that IIT Mumbai has taken a few steps in 3D Printing technology.

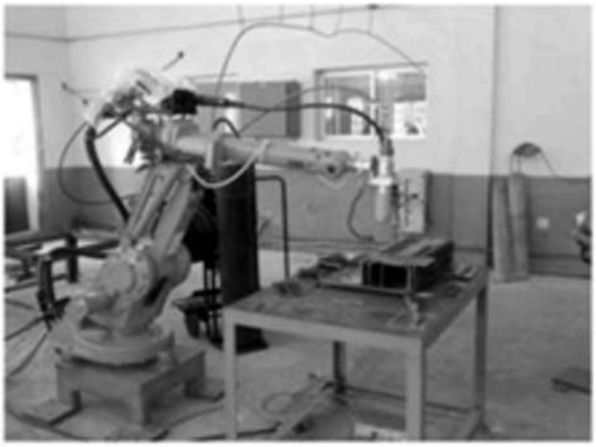

Fig 29 : Laser Hybrid welding at WRI

5.4.2.2 Laser Hybrid Welding (LHW)

The ease of automation and repeatable quality of laser welding was predominantly exploited in micro joining and thin section welding. However, due to exacting fit-up requirements of laser welding, it could not penetrate in mass production, mainly in automotive manufacturing. With the introduction of Laser Hybrid Welding (LHW), wherein a filler wire is being fed into the laser puddle, the gap filling efficiency of laser welding became a reality. LHW is also being investigated for welding of High temperature alloys with thick sections using high power lasers at WRI (**Fig.29**).

Already, the advantage of LHW is exploited by ship builders for fabrication. The shipbuilding industry was the pioneer in adopting laser hybrid, especially in the fabrication of cruise and passenger ships, which are dominated by the large amount of deck-structures made of 5-8 mm thick plate thickness. [15] **Fig.30** shows the installation at Odense Steel Shipyard which mainly builds very large commercial ships, in particular very large container ships. The amount of laser hybrid welds in a large cruise ship is now about 50% of the total weld and the total length which may be in the order of 400 km. The majority of the plates welded are 'thin' plates i.e. in the order of 5-8 mm.

5.4.3 Variable Polarity Plasma Arc Welding (VPPAW)

Variable Polarity Plasma Arc Welding (VPPAW) is a valuable arc welding process for aluminium alloys. In the keyhole mode VPPAW process, a high-energy density and high velocity plasma jet are generated to melt and penetrate through the work piece. The plasma jet momentum allows the jet to completely penetrate the welding pool to form a symmetric, funnel-shaped cavity called a keyhole and a similarly shaped liquid–solid metal phase boundary. Metal fusion takes place when the molten metal flows around the keyhole and solidifies following the jet passage. The VPPAW technique has been successfully used in production, such as in the fabrication of the space shuttle external tanks and space station. VSSC, Thiruvananthapuram, has been using this facility.

The stiff high-velocity constricted arc of VPPAW makes the welds less sensitive to deflection by stray magnetic fields and VPPAW's lower heat input reduces work piece distortion. Cleaning during the reverse cycle minimizes weld pool contamination from surface oxide or hydrocarbons. Welding in the keyhole or fully penetrating mode allows hydrogen to be dissolved in the thin layer of weld metal surrounding the keyhole and be flushed out the backside of the weld. Thus, porosity free welds are obtained.

5.5 Research in Solid Phase Joining Processes:

5.5.1 Deformation Resistance Welding:

Conventional spot welding is suitable only for lap joints of thin sheets. Welding of thin walled tubes to sheets becomes difficult by normal spot welding. Deformation Resistance Welding [DRW] is patented spot welding technique of Delphi,

Fig. 30 : Laser Hybrid welding at WRI

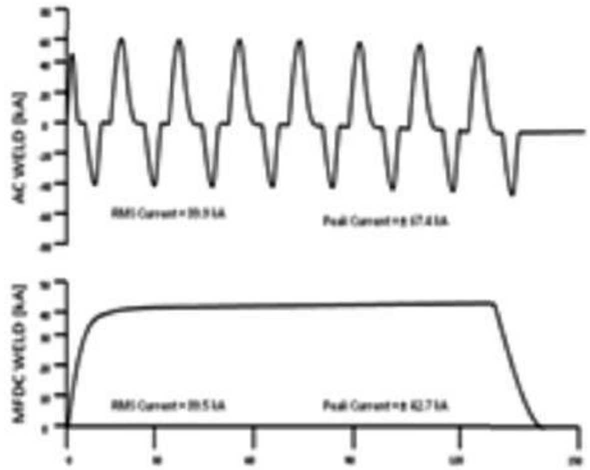

Fig. 31 : AC versus MFDC welding

USA, which facilitates welding of tube to solids, sheet metal and other tubes. DRW applies the heat and force of resistance welding to generate heat, with tooling designed to create the necessary deformation. This creates atomically bonded, solid-state joints through the heating and deformation of the two surfaces to be joined. Melted and solidified weld nuggets may also be obtained through the use of more weld pulses. This process is easily automated and creates near instantaneous, leak-proof joints with uniform circumferential strength capable of holding fluids and gases. Research is underway to extend the application of the DRW process for different automotive components.[16]

5.5.2 MFDC Power Source for Resistance Welding Applications

MFDC (Medium Frequency Direct Current) Resistance welding systems offer an excellent solution to spot welding needs. Due to higher operating frequencies (400 to 2000Hz), the MFDC welding transformer can be as much as 74% smaller than the traditional AC weld transformer (50 / 60 Hz). MFDC utilizes IGBTs for switching. By controlling both the turn on and turn off, the MFDC can use a deterministic approach to controlling weld current. Conventional AC (**Fig. 31**) controls utilize SCRs for switching. These are turned on by the weld control but then remain conducting until the line voltage crosses the zero point during the base frequency line cycle.

Because of this, conventional AC controls must use a predictive algorithm rather than a deterministic approach. Also, if an under or over compensation occurs on one of the cycles, the AC control will have to wait until the next period of the base frequency whereas the MFDC need only wait a fraction (1/20th nominal) of that time. Welding current time can also be decreased since there is no inter-cycle cooling period. This additional benefit would contribute to more energy savings, better production cycle times.[17]

5.5.3 Solid Phase Tube Joining Processes:

Magnetically Impelled Arc Butt Welding (MIAB) (also known as magnet arc welding) is a solid state method of joining pipes and tubes, having similarity with Flash butt welding in terms of resultant welds. In this process, heat is generated prior to forging by an arc generated between the two components, i.e. tubes. This arc is made to rotate along the peripheral edges of the tubes to be welded by the electromagnetic force resulting from the interaction of the arc current and the magnetic field in the gap. This rotating arc heats up the faying surfaces of the tubes to cause localized melting and adjacent softening in the heat affected zone. Finally, the parts are forged together to obtain an acceptable weld. MIAB welding is predominantly used in automobile manufacturing for the tube thickness of less than 3mm and the surface area of faying edges are between 150 to 400 sq. mm. At WRI, experiments have been conducted to establish the MIAB welding technology for welding of high wall thickness tubes ranging from 4 to 6.5mm and having weld surface area of maximum 1100 sq. mm. and welding of tubes of size 2mm for automotive application.

5.5.4 Friction Stir Welding Processes

Friction Stir Welding (FSW) is a solid-state process which involves the plunging of a cylindrical shouldered tool rotating at a constant speed with a pin, with a desired configuration, into the abutting surfaces of a joint to be welded. The parts have to be suitably clamped rigidly on a backing bar to prevent the abutting joint faces from being forced apart. The length of the pin is slightly less than the required weld depth. The plunging is stopped when the tool shoulder touches the surface of the job. The tool shoulder should be in intimate contact with the work surface. The heat generated between the contacting surfaces of the tool, in addition to the heat generated by the mechanical mixing process and the adiabatic heat within the material, cause the stirred materials to soften and quickly raises the temperature of the material being joined to its plasticising temperature. This allows the traversing of the tool along the weld line by displacing the plasticised metal. As the pin is moved forward along the direction of welding, the leading face of the pin, assisted by a special pin profile, forces plasticised material to the rear side of the pin. Here a substantial forging

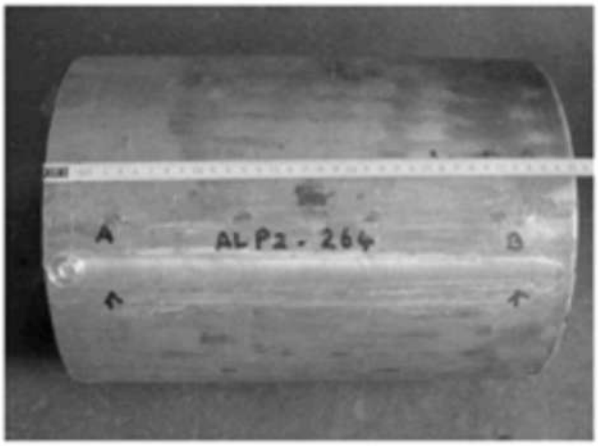

Fig. 32 : FSW of Al 12 mm thick long seam

force is applied by the tool to consolidate the plasticised metal behind the tool. The welding of the material is facilitated by severe plastic deformation in the solid state involving dynamic recrystallization of the base material. The tool is then moved along the seam of the joint to create the desired joint. The process is very useful for applications where the original metal characteristics are required to remain unchanged to the extent possible. This process is currently used extensively on non-ferrous metals & their alloys, and on large components which cannot be easily post weld heat treated to recover material properties. Although this technology is currently commercially applied for materials like Al, Cu, Mg etc., extensive research and development work is in advanced stages for welding of high temperature materials in research centers around the world.

It is to be noted that Academia have shown a great interest in this process, possibly encouraged by the simplicity and the possibility of converting simple machine into an FSW equipment. Annamalai University has done considerable work with different materials. At WRI, we have successfully established a long seam welding of an Aluminium shell, with suitably developed fixtures. See **Fig. 32**. WRI has also successfully introduced FSW for automatic welding of palm assemblies of aluminium bus duct, replacing the less productive GMAW process, at a BHEL Plant. [18]

5.6.0 Research in Understanding Arc Behaviour Through Signature Analysis

5.6.1 Evaluation of Dynamic Characteristics of Welding Power Sources/ Consumables

The arc welding power source is electrical equipment and almost all the international standards talk about type tests like insulation class test, load test and temperature rise tests. The above tests are not adequate to evaluate the performance of the arc welding power source. To evaluate the arc welding power source with regard to its welding performance, the dynamic characteristics of the power source needs to be investigated. The study of the current/voltage transients cannot reveal the true picture, as it is only a small segment of the total event. Computer based high speed data acquisition and data analysis through statistical processing is considered to be a more accurate method to evaluate the dynamic characteristics of the power source/consumables as well as the process. A statistical method to process the captured transient raw data of current/voltage and the probability density distributions of instantaneous welding current and voltage, as well as class frequency distributions of short-circuiting times, arcing and cycle time could help determine the process behaviour while evaluating the power source and the consumable.

Efforts are on at WRI to establish a scientific methodology using Analysator Hannover to objectively evaluate the performance of welding power sources through high speed data acquisition and statistical analysis. [19]

5.6.2 Correlation of Weld Defect with the Signature Analysis

There is an increasing demand in industries to automate the welding process to reduce cycle time as well as to improve the quality through monitoring and control of the welding process. However, monitoring weld quality in real time is important, especially in manufacturing shops, where defective welds lead to loss in production and necessitate time-consuming and expensive repair.

With the existing NDT methods, the nature of defect or the quality of welds cannot be determined directly during welding. However, experts are of the opinion that the analysis of current and voltage signatures of welding arc can provide a means to detect the defect as it occurs during arc welding. But reaching that level of technological maturity requires great volume of welding trials to be carried out before establishing a reliable correlation between the nature of defect and the current /voltage signature coming from the arc welding process.

WRI is attempting to establish such a correlation between different types of defects namely lack-of-fusion and burn-through and the current, voltage signatures in Pulsed Spray Gas Metal Arc Welding process for carbon steel with 80% Argon+20%CO_2 shielding gas mixture. Analysator Hannover has been used for acquisition of current and voltage signatures of GMA welding process and a signal processing tool for

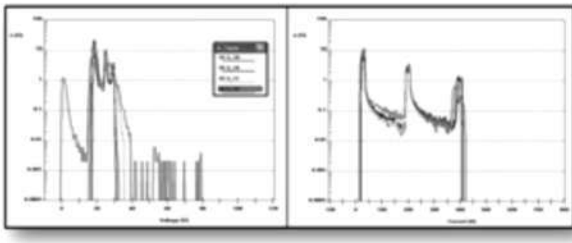

Fig. 32a : Signature Analysis for defects

analyzing the recorded data. **Fig. 32a** shows a typical signature of a defect.[20]

6.0 RESEARCH IN WELDING ENGINEERING

Welding is the metal joining process which can produce a metallurgical bond and hence welding is the only process which can give a joint efficiency of 1.0. Welding process is widely used in a variety of sectors for achieving joints which are required to perform as good as the base metal. The unique capability of welding process is due to a variety of phenomena viz., localized heat input, which causes melting of the abutting edges and thorough mixing of the materials, solidification of the molten pool resulting in good penetration into the base metal, controlled chemical reaction in the short duration through the addition of fluxing material, which gives rise to required level of chemical composition of the weld metal etc.

In spite of the several advantages, welding has some limitations which lead to rework, which is time consuming and expensive. For traditional components, the limitations of welding can be tolerated and may not pose challenges. But as technology advances and newer components are introduced in the market, the limitations of welding must be overcome. Newer demands are placed on welding, which requires that newer capabilities be developed or the existing limitations be overcome to produce a high quality joint consistently.

6.1.0 Weld Characterisation and Analysis

The components for various industries are required to undergo different operating conditions, which causes a degradation of the material properties. Some of the operating conditions, which cause damage in materials, include creep, fatigue, corrosion, erosion, oxidation etc. When the components are fabricated by welding, the weldment is also made to undergo the damage mechanism and in the case of weldments, the rate of damage will be higher due to various mechanical and metallurgical reasons. Hence, there is a need to assess the behaviour of the welds under various operating conditions and

Fig. 33 : Gleeble Simulator

wherever needed, an additional strength reduction factor for weldments must be established and used in the design calculations.

With the developments in material technology, newer materials are being introduced for higher and more stringent operating conditions and in such cases, the rate of damage of weldments must be established for the conditions of the various damages occurring individually and in combination.

6.2.0 Gleeble Thermal Cycle Simulation

The physical simulation is a powerful tool which can be used to study the property changes in components with very steep temperature and stress gradients. Due to the steeper gradients, the property is expected to vary drastically in a small region and this precludes the extraction of test samples from the component. The problem is overcome by the use of a simulation specimen which can be made to undergo the expected temperature and deformation conditions at any point of interest in the component. This tool enables the researcher in establishing the optimum combination of parameters which can give satisfactory quality of the material after fabrication. [21] **Fig. 33** and **Fig. 34** shows the equipment and a typical application.

6.3.0 Use of Simulation Tools

The FEM which was hitherto employed for the analysis of welds in simple geometries has grown to be a major tool for the holistic analysis of welding phenomena. With the improvements in computing power and the data handling facility of the order of terabytes, the tool can be effectively employed for the analysis of actual industrial components containing multiple welds. The material behaviour can be closely represented and the resulting dimensional changes,

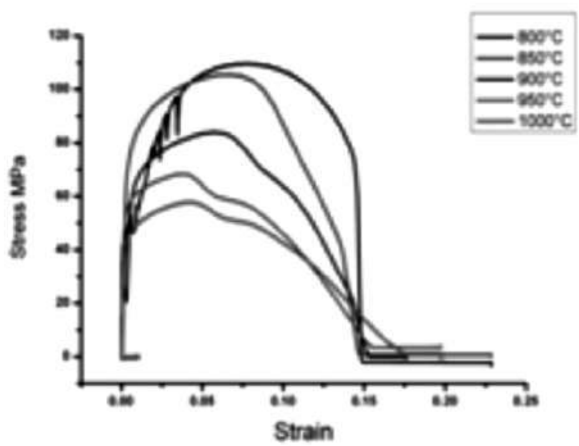

Fig. 34 : An application

Fig. 35 : Simulation of crank bar

residual stress build up, changes in microstructure and mechanical properties etc., can be evaluated. For newer materials whose behavior changes drastically with restraints, the analysis needs to be holistic and the combined influence of the microstructure changes, mechanical property changes and build-up of residual stress etc., as a function of the localised heat input and physical restraints need to be analysed. The optimum combination of welding conditions, which can give defect free welds conforming to the metallurgical and dimensional requirement, can be arrived at for the materials of construction. **Fig. 35, 36** show some examples.[22]

7.0 NON DESTRUCTIVE EXAMINATION OF WELDS

The canvas of ultrasonics in NDE of welds is widening. From conventional systems, the world has moved into Phased Array Ultrasonic Testing (PAUT) Systems, coupled with Time of Flight

Fig. 36 : Simulation of a labyrinth component

Diffraction (TOFD) techniques. It appears the day is not far off when Radiography will be replaced by these, at least in sites; considering the hazards and limitations of radiography. There is considerable work in progress to see how this can be used for evaluation of tubular butt joints.

In the case of thick-walled complex geometry welds, using ultrasonic beams has a serious limitation as there are likely to be multiple reflections from the walls as well as from the defects. Thus there is a possibility of improper interpretation of results. The use of special software which pictorially displays the ultrasonic wave propagation in the complex geometry can effectively minimize the possibility of improper interpretation of results. In addition, the use of special UT waves can enable the non-destructive evaluation of the component in hot condition resulting in time saving.

There may be no match for a good visual testing in NDE. However, sustained R&D is needed to introduce the concept of machine vision for the visual testing of components with large dimensions. This minimizes the need for human element and ensures consistency of the inspection. However, the challenge is in imparting artificial intelligence to the computer system to make it perform like a human being.

8.0 UNDERSTANDING WELD DISTORTION / STRESSES

The residual stresses are internal stresses induced in a material by the nature of the manufacturing operation which is performed on it. The residual stresses will have a highly detrimental effect under certain operating conditions. The stresses are relieved after a successful post weld heat treatment. But in the case of new generation materials, the PWHT parameters must be established based on experimental trials. [23. 24] Thus there is a need to measure the residual stresses in a non-destructive fashion in different materials. The

Fig. 37 : MBN System

Fig. 38 : Magnetic Coercivity Meter

conventional method of measurement using electrical resistance strain gauges is destructive in nature and expensive.

The research activities linking residual stresses in a material and some physical parameter are undertaken all over the world. Physical phenomena like neutron diffraction, ultrasonic wave propagation etc. have been studied for their suitability. But of late, more studies involving magnetic properties are being undertaken. When an external magnetizing field is applied to a ferromagnetic material, the various magnetic domains get aligned to the external field and the resulting movement of the domains emits a noise, which is popularly known as Magnetic Barkhausen Noise (MBN). This noise has been found to have a correlation with residual stress in the material, the metallurgical structure of the material and the bi-axiality of the stresses. Thus, for a given material of a particular structure experiencing a bi-axial stress field, the magnitude of the residual stress has a good correlation with the MBN. Refer **Fig. 37**. [25, 26]

Similarly, the Magnetic Coercive Force (MCF), which is the magnetic force needed to nullify any retained magnetism in a ferromagnetic material, has a good correlation with the level of plastic deformation in the material. This can be used for studying the effectiveness of heat treatment in large components and for studying the residual life of certain industrial components like cranes. Studies are being under-taken at WRI for establishing the correlation for different conditions so that the prediction is fool proof. Refer **Fig. 38**. [27]

The electrical resistance strain gauges are used for experimental measurement of the stresses at a point and are widely used for room temperature applications. But when attempts are made to measure the stresses at elevated temperatures, phenomena such as thermal strain in the material, variation of properties with temperature etc. must be accounted. Studies are undertaken in WRI to assess the applied stress in a component at elevated temperatures. (**Fig. 39**)

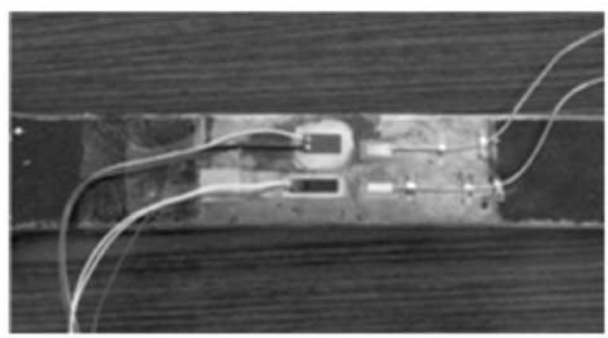

Fig. 39 : High Temperature Strain Gauging

9.0 WELDER TRAINING

9.1 Welding Simulators

The scarcity of skilled welders is felt across the world. As envisaged by National Skill Development Council, urgent steps are to be taken to improve the skill set of young people in the area of welding. The need for skilling ITI trained people and unemployed youth can be fulfilled only by introducing changes in the way skill training is imparted to welders in India. For this, welding simulators are a boon to accelerate this process at least by about 20%. Simulators can be employed in the initial stage of training to impart the instructional portion and also to teach the technique of welding positions and filler feed angle and feed rate. This would also help steady their hand. This will result in saving of materials and power requirement to the tune of around 20% in training costs. The simulator available at present are mostly imported at exorbitant cost and the need for continuous upgradation. Some of the simulators use independent screen for visual observation by the trainees and some of them are equipped with costly and fragile welding helmets with visualizing facility. In most cases, the trainee is aiming his holder in air, which may not help simulate the feel of holder weight and positioning in a joint. However, the recent foray of Indian developers in weld simulators is a welcome change. They need to concentrate on simulating on a material/ model joint and make the visual more user-friendly for the trainee. The simulators need to be very cost effective, since the training institutes can ill-afford costly training tools. They ought to be designed for handling SMAW, GMAW and GTAW on a single platform with possibilities for the user to create his own library.

10.0 WELDER HEALTH AND SAFETY

In the welding shop floors, there are a number of hazards specific to welding or cutting. In addition, there may be other hazards of a more general nature present in the fabrication environment. All potential hazards need to be identified, measured (where appropriate) and assessed. It is essential that remedial measures are put in place wherever necessary. Perhaps, this is one way to make welding an attractive profession for the young population of India. The discipline with regard to the use of appropriate Personal Protective Equipment (PPE) is something that needs improvement in India. There is no dearth of PPE availability in India, but it appears wearing some of them does not provide the comfort levels the welder is looking for. It appears a psychological research to see how this could be done in India would not be out of place. It takes a little more than making the employers and employees fully aware of the dangers that can arise to ensure that they take all reasonable care to ensure the health and safety of all.

The short term and long term health issues connected with welding fumes, dust, heat, noise, arc energy and so on are a matter of continuous study. The pioneering Occupational Health Services of BHEL, Trichy, has carried out several shop floor and welder health studies for better understanding and improvements. The health issues connected with the welding environment must certainly be addressed, but at the same time undue fears of welders should also be clarified through scientific studies. There is a pride of place for medical doctors in the welding profession.

11.0 CONCLUSIONS

Welding technology is certainly progressing in various fronts, and there is considerable research that is going on in the country. There are several good examples of applied research being done to take a new technology to the industry without hiccups. However, the question haunts, are we doing enough of fundamental work in our research? India needs to step on the accelerator in the areas like advanced materials and consumables development, manufacturing state of the art power sources, look into automation as a way of life, carry out simulation and modeling to understand welding situation, train a new breed of welding professionals who would love to take on challenges, improve the welding gear in sites, introspect into the safety and health aspects of our welding. India is on the right track; all it needs to do is take to the faster lanes of progress, aided by sound welding research in the country.

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