Welding Research in Indian Universities

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Although the importance of welding as a specialized branch of engineering science was realized in India only by the late 1950s, much progress has since been made in welding education and research. The first postgraduate programme in the area of metal joining was introduced at the Indian Institute of Technology (IIT) Madras in 1969 and the early welding research was also commenced in that institution. Subsequently, postgraduate and research programmes with speciali-zation in welding emerged in other universities as well, notably the Regional Engineering College (now National Institute of Technology or NIT) at Tiruchi, the University of Roorkee (now Indian Institute of Technology Roorkee) and M.S University in Baroda. It is worth mentioning that National Institute of Technology Tiruchy is working in close collaboration with Welding Research Institute of Bharat Heavy Electricals, a plant fabricating heavy equipment for the power sector. The Master's degree programme in Welding Technology at the M.S University, Baroda is sponsored by Larsen and Toubro, whose Heavy Engineering Division manufactures pressure vessels, reactors, etc. for petrochemicals, refineries and power generation equipment. Because of the close industry-institute collaboration, the research projects from these institutions have a strong industrial orientation and relevance. In addition to these, welding research is being conducted at several universities and laboratories across the country. An overview of the research work pursued currently and during recent years at the Universities in India is presented in this report.*

PROCESS-RELATED RESEARCH

Research in conventional fusion welding, understandably, is only pursued in a few institutions. Wide-ranging studies in the area of pulsed gas metal arc welding have been undertaken at the Welding Research Laboratory, Indian Institute of Technology, Roorkee for several years. This effort has led to some unique applications of this process including narrow-gap pulsed GMA welding of thick steel plates. Research in the development of fluxes for submerged arc welding, as also of covered electrodes/ fluxes for shielded metal arc welding and hard-facing electrodes for sugar mills and agricultural implements, has been conducted at IIT Delhi. One research programme at the M.S. University, Baroda has been concerned with the design and development of a narrow-gap gas metal arc welding system, an important feature of which is a torch oscillation device that was incorporated to ensure sidewall fusion. Flux-activated gas tungsten-arc (GTA) welding for joining of low-activation ferritic-martensitic steel for nuclear applications is being examined at the Deendayal Petroleum University at Gandhinagar. The same group is also working to develop metal cored arc welding for various applications. Flux-activated GTAW has also been studied at M.S University Baroda for tube to tube-sheet welding in austenitic stainless steel.

Several research projects under the industry-sponsored programme at M.S University Baroda have been concerned with the joining of thick plates of Cr-Mo and Cr-Mo-V steels for high-temperature, high-pressure hydrogen reactor service. Similarly the fabrication of low-alloy quenched and tempered steels for pressure vessel applications has also received a great deal of attention. One of the objectives in the former case was to examine if, by adjusting other welding parameters, the preheat temperature could be decreased (which would result in significant savings in cost). In the latter case, the necessity, desirability or

*A great deal of welding research in dedicated areas is under way in several renowned laboratories in the country. Notable among these are the Indira Gandhi Centre for Atomic Research, Kalpakkam, Bhabha Atomic Research Centre, Mumbai, Defence Metallurgical Research Laboratory, Hyderabad and Welding Research Institute, Tiruchi. This report, however, does not cover the work being done in those laboratories.

otherwise of postweld heat treatment (PWHT) (not mandatory under the relevant codes) was studied by determining weldment mechanical properties under various conditions of welding and PWHT.

Fabrication of high-temperature reactors of heavy wall thickness for refinery service often involves a great deal of overlay welding. Welding of austenitic stainless steel overlays on carbon steel and low-alloy substrates is, therefore, a sustained ongoing activity at M.S University Baroda. The use of several alternative technologies is being actively investigated. These include electroslag strip cladding, hot-wire gas tungsten-arc welding, flux-cored arc welding (FCAW) and shielded metal arc welding (SMAW). Deposition of Monel and cupro-nickel overlays for marine service, as well as Inconel overlays for nuclear steam generator applications has also been investigated. In one of these projects, a detailed comparison has been made of the available technologies based on performance and economics. In another project, the development of interface microstructures during cladding and subsequent heat treatment has been examined. The variation in 'ferrite' indication and related formation of strain-induced martensite in austenitic stainless steel overlays during postweld machining operations has been studied in another project. The effect of various shielding gas mixtures ($Ar+CO_2$) on the properties of FCAW stainless steel overlays has also been studied.

Vacuum brazing of an aluminium alloy for defence application has been developed at IIT Madras. Active metal brazing has also been studied there on dissimilar material combinations including alumina to stainless steel, metastable beta-titanium alloy to stainless steel and zirconia to stainless steel. A Jadavpur University project is concerned with the development of gas metal-arc brazing for coated steel assemblies. Transient liquid phase bonding of aluminium metal-matrix composites has been investigated at Jadavpur University using copper foil/powder as interlayer. IIT Roorkee has been engaged in many projects in the areas of metal-ceramic brazing and joining of metal-base particulate composites.

Use of ultrasonic seam welding for producing monotapes of titanium-matrix fibre-reinforced composites is being developed at IIT Madras. Currently, these are made by vacuum plasma spraying of titanium on to a fibre mesh. Ultarsonic seam welding would be a significantly more economical option.

Resistance spot welding is a major issue in the use of automotive grade steel sheets, especially coated steel sheets. Various problems related to spot welding of zinc-coated interstitial-free steel sheets are being addressed in a project at Jadavpur University. Both mechanical properties and corrosion susceptibility receive attention. The Centre for Materials Joining and Research at Annamalai University has also studied the resistance spot welding characteristics of IF steels for automotive applications. The resistance spot welding of Al-TiC composite sheets (synthesized in-situ, cast and rolled) has been investigated at IIT Kharagpur for potential automotive application.

In the last fifteen years, many laboratories have embarked on developmental programmes in friction stir welding. Most of these involve aluminium alloys, but increasing attention is also being paid to the joining of harder materials. The Annamalai group is investigating the application of friction stir welding to magnesium alloys, high-melting materials like ferritic stainless steel, and also dissimilar combinations of Al-Mg and Al-Cu alloys. The Jadavpur University team is studying the application of friction stir welding to the joining of aluminium alloy to zinc-coated steel sheet. At the Deendayal Petroleum University, friction stir welding of aluminium alloys for space applications and the dissimilar combination of copper to stainless steel are being investigated. Use of friction stir processing for producing ultra fine-grained materials in bulk, as well as for producing high-strength, ductile, particle-reinforced aluminium-matrix composites is being investigated at IIT Madras. Friction stir welding of aluminum-titanium boride metal-matrix composite has been investigated at Coimbatore Institute of Technology.

Considerable research effort has been directed into adapting the friction stir process to surfacing applications. IIT Madras has successfully used friction surfacing for developing corrosion and wear resistant coatings on various substrate materials. These include deposition of austenitic stainless steel and martensitic stainless steel surfaces on carbon steel substrates and hard-facing of tool steels such as H13, D2 and M2 on steel, magnesium and aluminium alloy base metals. Further, the feasibility of applying solid state coatings of materials including copper, titanium, nickel-based alloys, cobalt-based alloys and different types of stainless steels on a variety of substrates has been demonstrated. In another programme of work, using powder trace and annular ring methods and monitoring temperatures using infrared thermography, the heat flow characteristics during friction stir surfacing have been modeled. Currently, this group is developing solid-state stellite coatings on steel substrates for industrial valves using friction stir processing. Another group at IIT Madras is examining the use of friction welding and friction surfacing for additive fabrication of three-dimensional metallic parts.

Much work is also being done on the application of friction stir welding to produce spot welds in lap joint configurations. At IIT Madras, one group is looking to develop friction stir spot welding for high-strength aluminium alloy sheet metal structures which are currently made by riveting. It may be noted that, because of the high thermal conductivity and the oxide problem, resistance spot welding is not an attractive option in this case. Friction stir spot welding procedures are also being developed in a project at Jadavpur University for high-strength steel sheets.

Work on friction welding is also being pursued at IIT Madras, particularly for joining dissimilar materials. One of these projects has studied friction welding titanium to austenitic stainless steel for nuclear applications and found that the use of Ta-Ni or V-Ni interlayers resulted in optimum bond strength and bend ductility. Another project is concerned with joining dissimilar aluminium alloys and other combinations of industrial importance, also with interlayers.

Diffusion bonding has been an active area of work in several University laboratories. For example, a project at Jadavpur University has looked at diffusion bonding of alumina to austenitic stainless steel, using different interlayers such as Ni, Nb, Ti and Mo. Complete bonding was obtained only with a nickel interlayer; the shear strength of the bond, however, decreased with increasing nickel foil thickness. Programmes at PSG College of Technology Coimbatore have studied diffusion bonding of similar and dissimilar materials involving Ti alloys, Ni-base superalloys and stainless steels and also bonding of INVAR with magnetic materials. The Centre for Materials Joining and Research at Annamalai University has been engaged in diffusion bonding studies (with and without interlayers) applied to several dissimilar combinations including Al to Mg, Cu to Mg and Ti-6Al-4V to 304 stainless steel.

Plasma transferred arc (PTA) surfacing has been receiving much attention from various research groups. In a project at IIT Madras, cobalt-based hard-facing alloys with addition of boron carbide (B4C) have been deposited on a 316L austenitic stainless steel substrate using PTA surfacing. The use of cobalt-based deposits is, however, not desired for nuclear applications on account of the induced activity from the transmuted Co60 isotopes formed in the nuclear reactor environment. Ni-base and Fe-base alloys are possible alternatives. Another project at IIT Madras has made a detailed study of a nickel-based hard-facing alloy deposited by the PTA process on an austenitic stainless steel substrate. The work included microstructural characterization, study of galling wear and high-temperature sliding wear and thermal aging tests. Plasma transferred arc surfacing for depositing cobalt-based hard-facing compositions on valve seat rings has been studied in detail at Coimbatore Institute of Technology. They have also examined the hard-facing of valve seat rings using gas tungsten arc welding. The materials joining group at Annamalai University is actively involved in improving the ballistic performance of armour-grade quenched and tempered steel with a hard-facing interlayer produced using SMAW and PTAW.

Plasma nitriding and laser hardening have been used in an IIT Madras research programme for surface modification of a 13Cr-4Ni martensitic stainless steel used for hydro-turbine and water pumps. The objective was to improve the resistance to erosive wear due to excessive silt content in the flowing medium. A similar programme by the same group has focused attention on laser surface alloying for surface modification of a martensitic stainless steel. Ni-based and Co-based coating powders were pre-deposited using polyvinyl acetate solution, followed by laser heat treatment. Another group at IIT Madras is engaged in developing spark plasma sintering for joining dissimilar materials, such as titanium to stainless steel with suitable interlayers.

Several university laboratories have been engaged in process modeling, computer control and related work. At IIT Madras, a project has been concerned with finite element analysis of transient heat transfer in the HAZ of pulsed current GTA weldments. This has been used to model transformation behaviour in a mircoalloyed steel. In another project at IIT Madras, microstructural evolution during friction welding is sought to be understood through finite element modeling. The use of a high-speed data acquisition facility for temperature profile monitoring has enabled correlations between microstructure and in-situ thermal profiles. The same group is also involved in modeling using FEM for friction stir processing and using computational fluid dynamics and heat transfer for fusion welding processes. Heat distribution in electron beam welding is also being studied by an IIT Madras group, using equipment with rastering and pulsing possibilities. Solidification modeling in dissimilar metal welding is another activity at IIT Madras. This is coupled with thermodynamic databases for application to technical alloys. The group hopes to evolve a model for understanding phase transformations and microstructure evolution in dissimilar metal welding.

Three-dimensional finite element analysis of heat transfer in arc welding and thermo-mechanical finite element analysis of angular distortion and weldment characteristics have been actively pursued at IIT Kharagpur. The group has extensively used soft computing tools such as artificial neural networks, generic algorithms and fuzzy logic techniques to model weld bead geometry and microstructure in arc welding and electron beam welding. Another major area of their theoretical and experimental work is concerned with temperature distributions and related effects in resistance spot welding.

MATERIALS-RELATED RESEARCH

Many university laboratories have also embarked on research programmes related to the metallurgical aspects of welding. These have involved weldability issues as well as property and performance evaluation.

In one of the programmes at IIT Madras, done in collaboration with the Indira Gandhi Centre for Atomic Research, Kalpakkam, fundamental studies on hot cracking in austenitic stainless steels were undertaken. As a result of this study, a model could be established for correlating the results of the longitudinal and transverse modes of Varestraint testing. Other important aspects of this study were concerned with the effect of titanium in stabilized fully austenitic stainless steel and the effect of nitrogen in unstabilized grades. The work had useful implications for the fabrication of stainless steel components for the fast breeder reactor programme.

Weld fusion zone toughness is a matter for concern in the joining of modified 9Cr-1Mo steel (P91). Flux-shielded welding, especially with rutile-based fluxes, can result often in inadequate toughness under the relevant specifications. A project at IIT Madras showed that the use of synthetic SMAW electrodes (with much of the alloy content in the flux coating) could lead to inhomogeneities in composition and structure and, consequently, areas of ferrite that decrease the toughness. Another research programme at IIT Madras has made a detailed study of possible ways in which the toughness of P91 weld metal in FCAW could be improved.

As a critical issue in the fabrication of power plant components, the joining of low-alloy Cr-Mo ferritic steel to austenitic stainless steel has always been a major research interest. Some of the research programmes have examined in detail the possibilities of using a tri-metallic configuration involving the use of an insert piece of a material such as Alloy 800 (with intermediate thermal expansion co-efficient) between the ferritic and the austenitic steels, so that the thermal stresses can be mitigated. One project at IIT Kharagpur studied the joining of 2.25Cr-1Mo steel to AISI 304 and another at IIT Madras the joining of modified 9Cr-1Mo steel to AISI 316 LN, both employing Alloy 800 as the intermediate piece. The programmes encompassed filler material optimization and performance evaluation under a variety of simulated service conditions (including long-term aging, thermal cycling under load and stress rupture testing).

Carbide-free bainite is an exciting, new concept to produce a very strong, but still adequately tough steel for several applications including rails and protective armour. The formation of cementite between the ferrite plates in conventional upper bainite is prevented by adding sufficient silicon to the steel. The microstructure then consists of bainitic ferrite plates and carbon-enriched residual austenite. Such materials are already in use for laying railway lines. One of the current research projects at IIT Madras aims to develop carbide-free bainitic microstructures in weld fusion zones of high-strength steels for improving ballistic performance of armour plate. Since toughness would improve, as well as strength, the problem of hydrogen-induced cracking would be largely overcome.

Some of the fundamental problems in joining ferritic steel to austenitic stainless steel are also encountered when cladding carbon steel or low-alloy steel with an austenitic stainless steel surface layer. These were addressed in detail in a research project under the industry-sponsored programme at M.S University Baroda. Electrosalg strip cladding was used to deposit 347 austenitic stainless steel on a 1Cr-1/2Mo steel substrate (using 309L as barrier layer) - a joint encountered in the fabrication of high-temperature hydrogen reactors for refinery service. The research project was essentially concerned with the development of interfacial microstructures between the ferritic and austenitic steels as a result of the weld thermal cycle and PWHT. This is an important issue because the hard martensitic zone produced in the transition zone can eventually lead to the serious problem of hydrogen disbonding during service.

Several aspects of the welding problems in duplex stainless steels were investigated in one of the projects at IIT Madras. Currently, work on duplex steel welding (including overlaying duplex steel on other base metals and dissimilar welds involving duplex steel) is being actively pursued at National Institute of Technology, Tiruchi and at M.S. University Baroda.

Work on the mechanical behaviour and corrosion performance of welded joints has received attention in several university laboratories. Fatigue crack growth and fracture toughness characteristics of alpha-beta titanium alloy weldments have been evaluated in a programme at IIT Madras and correlated with the microstructures resulting from GTA and electron beam welding and postweld heat treatment. Jadavpur University is currently engaged in studying and improving the fatigue characteristics of spot-welded, laser-welded and adhesive-bonded high-strength steel sheet joints under different modes of loading. They are also evaluating the corrosion fatigue behaviour of the different regions of high-strength steel weldments in 3.5% NaCl solution with and without cathodlc potential. The welding of boiler grade steel using different processes has been investigated at NIT Tiruchi from the point of view of their mechanical properties and high-temperature corrosion behaviour. A group at IIT Madras has been active for long in the area of weldment corrosion. They are now looking at developing highly corrosion-resistant coatings on aluminium alloy welds applying a relatively new coating technique, viz., micro-arc oxidation. This overcomes a persistent problem of high corrosion sensitivity in the partially-melted zone of some aluminium alloy welds.

Many laboratories have been conducting research programmes on the joining of non-ferrous metals and alloys. Much work has been done at IIT Madras on improving the mechanical properties of weld fusion zones in high-strength aluminium alloys including Al-Mg-Si, Al-Cu, Al-Zn-Mg and lithium-containing aluminum alloys. A related objective in these projects was to reduce the hot cracking tendency of the age-hardenable alloys. These projects have demonstrated the benefits of Ti+B and Zr additions to the filler materials commonly used for high-strength Al alloys. Techniques such as using pulsed welding current in GTAW, imposing magnetic oscillations on the arc and planishing of the welds have also been examined in detail. These have resulted in refining the microstructure, which in turn served to reduce hot cracking tendency and also increase mechanical properties by improving postweld ageing response. Using electron beam welding, beam oscillation and a novel bead-over-bead technique have been developed, which were demonstrated to reduce porosity in Ti-6Al-4V welds. This has since been adopted by ISRO for gas bottle fabrication for space applications. Work by the same group on the high-strength Al-Cu alloy AA 2219 has shown the remarkable improvement conferred by scandium additions to the filler material, both in enhancing mechanical properties and reducing solidification cracking.

One of the projects at M.S. University Baroda has been engaged in the development of welding procedures for aluminium alloys, including an age-hardened Al-Si-Mg alloy, for marine applications. The objective was to maximize the mechanical properties.

The weldability of a beta-titanium (15-3-3-3) alloy has been examined in detail at IIT Madras using GTAW and EBW. The project also involves the study of microstructure evolution using a Gleeble-type thermomechanical device for simulating weld thermal cycles in the heat-affected zone. Another research programme at IIT Madras is concerned with the cutting and welding characteristics of borated stainless steel for fusion reactor applications. Since boron has a relatively high neutron absorption cross-section, boron-en-riched stainless steel finds use for spent fuel storage. Establishing cutting and welding characteristics would enable the use of welded designs for the component.

The welding characteristics of the Ni-based alloy Inconel 718 have been studied in detail at IIT Madras. Although developed to improve weldability by reducing strain age cracking, the 718 alloy is susceptible to hot cracking due to segregation of eutectics containing a Nb-rich Laves phase. The research programme was aimed at refining the Laves phase and dispersing it by using current pulsing in GTA welding. The project also addressed HAZ micro-fissuring caused by the constitutional liquation of the Nb-rich phase and boron segregation to the grain boundaries. Significant improvement in stress rupture life was realized by the application of advanced techniques in GTA and laser welding.