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Future Trends for Joining of Advanced Materials - A Report on Research Activities in Advanced Materials and Processes at Ohio State University

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Abstract

The 21st century offers a challenge to industry to effectively utilize the newer advanced materials and processes to produce better, more economical welded and bonded products at reduced costs. This paper is a report on some of the welding and joining research activities currently underway in the laboratories of the Department of Welding Engineering at The Ohio State University aimed at using advanced materials and advanced joining processes.

KEY WORDS: (Advanced Materials) (Advanced Processes) (Joining) (Welding)

1. Introduction

The welding and joining industry has seen considerable growth over the latter part of the 20th century. As new steels and non-ferrous materials were developed, new arc welding processes were developed in order to fabricate them. Now, as we approach the 21st century, many new advanced materials are appearing. And, newer welding processes such as electron beam, laser, ultrasonics, microwaves, and robotic applications are likewise coming of age.

The Department of Welding Engineering at Ohio State University plays an important part in that growth, both from a teaching and from a research standpoint. The Department is the only accredited welding engineering department in the United States offering a full range of degrees including the B.S. in welding engineering, the M.S. and the Ph.D. As part of its graduate program, the Department also conducts basic research programs on a range of advanced materials and processes.

From the early 1930's, the Department has been a leader in this welding research and development. Many extensions and improvements on the early arc welding processes and welding flux developments were the direct result of department research professors. In addition, many of the early non-destructive testing techniques were developed at OSU (ref.1).

More recently, the Department was the recipient of one of the first National Science Foundation's Industry-University Research and Development Centers called the Center for Welding Research. This Center began serving the welding research and development needs of industry in 1979.

In 1984, the Department played the lead roll in the expansion of this university/industrial cooperation by promoting the establishment of the Edison Welding Institute. This non-profit industrial membership-based application research and development-based organization has grown to over 170 member companies since its opening in January 1985. The Department of Welding Engineering still serves as the major basic research source, via subcontracted research, for the Edison Welding Institute.

In addition, the Department conducts a significant amount of basic and advanced applications research for industrial and governmental sponsors such as General Electric, IBM, Chrysler Corporation, Alcoa, Naval Research Laboratory, National Science Foundation, Department of Energy, Air Force Materials Laboratory, Army Research Office, DARPA, and NATO, just to mention a few.

The research conducted within the Department is divided into four major divisions. These are: a) materials research associated with welding and bonding of all major structural and electronic materials, b) non-destructive testing of materials, c) engineering research including design, property testing, and fitness-for-service assessment, and d) process and process control developments (ref.2).

This paper is a report on some of the welding and joining research activities that are currently underway in the Department's laboratories which are aimed at improving the use of advanced materials. Efforts specifically reported are those which will lead to a better understanding of the joining characteristics of advanced materials and the better utilization of advanced processes and systems to handle these materials in unique environments. The objective of this paper is to provide an overview of the research activities in the hope of stimulating further in depth associations between the various research centers and industry. It is only through this in-depth technology transfer that the innovative links between advanced materials and the processes for their fabrication will meet the challenges of the 21st century.

2. Weldability Research in Some Advanced Materials

2.1 Plain Carbon HSLA Strip and Plate Steels

The developments in the production of plain carbon steels over the past 15 years have concentrated on the production of strip and plate products which are stronger and tougher than previous materials, yet possess improved weldability. This is being accomplished by additions of microalloying elements coupled with complex thermo-mechanical treatments during rolling and accelerated cooling to produce significantly improved properties. The most recent advances have been to produce alloys with much lower carbon content than previously needed to get equivalent properties (ref.3). Applications for these steels range from automotive to pipeline to large ship and offshore platform construction.

The outcome of this development effort is an improvement in the weldability particularly related to hydrogen or delayed cracking susceptibility. Over this time period, research work at OSU and EWI has concentrated on tests to determine moisture content and hydrogen distribution while using various processes (ref.4,5). Also included is an evaluation of implant weldability testing to determine susceptibility of these newer steels to hydrogen cracking and the determination of the amount of preheat required to eliminate this cracking (ref.6). It has been found that these newer steels require less preheat than predicted by older formulas. The most recent effort is to update prediction formulas to more accurately represent these newer steels (ref.7). This should broaden their use into newer applications.

The thermo-mechanically processed microalloyed steels do, however, tend to suffer serious embrittlement when stress relieved. Recent efforts have concentrated on determining simulative tests to better understand the kinetics of embrittlement. Preliminary temperature-time stress relieving procedures for reduction of embrittlement have been determined (ref.8).

2.2 Coated Plain Carbon and HSLA Strip

An area of interest, particularly for automotive applications, has been the development of coatings which improve corrosion resistance. In general, the coatings have been a zinc (galvanized) coating which was applied by hot dipping. The newer forms, however, are electro-galvanized, electro-alloy coatings or coatings applied by paint-baking lines.

A considerable amount of concern about weldability, particularly spot weldability, is being expressed. These coatings tend to reduce electrode life and limit the useability of the materials. Work to develop monitoring systems for spot welding has progressed to the point where the statistical variation in resistance welding of these materials can be determined. In addition, the interaction of these coating with the sheet and electrode during nugget development is becoming clear (ref.9). This is leading to the development of a new generation of coatings and electrodes which will dramatically improve resistance weldability.

In addition, a spot weld nugget growth model, based on heat flow concepts and the interaction of the surface physical properties, is being developed (ref.10). Use of this model will aid in the establishment of weld parameters when unusual materials or coatings are being resistance welded.

2.3 Stainless Steels

In the stainless steel area, argon-oxygen decarbonization (AOD) melting furnaces have been applied to melt production (ref.3). This process is capable of reducing impurities and interstitial elements to extremely low levels in all grades including austenitic, ferritic and martensitic stainless steels. In general, the low levels of carbon nitrogen and sulfur result in steels with reduced hot and cold cracking, and improved toughness and corrosion resistance. The low interstitial levels are causing loss in weld bead shape control (ref.11), however.

Efforts in modelling heat and fluid flow during welding and the relationship of this flow to both temperature gradients and material compositional variables are beginning to shed new light on weld bead shape and penetration control (ref.12,13).

2.4 Duplex Stainless Steels

The duplex ferritic/austenitic stainless steels are beginning to find some applications particularly for their higher strength and stress corrosion cracking resistance. Weld control, however, depends on the ability to develop filler metal with controlled balance of ferrite and austenite and development of weld procedures to preserve properties in the heat-affected zone (ref.3).

The fundamental mechanisms of weld hot cracking in the austeno-ferritic duplex stainless steel alloys have been evaluated using the varestraint test and Gleeble hot ductility testing. Evaluation of weld structures was accomplished using optical and transmission electron microscopy. This information will rapidly be extended to the development of new compatible filler material and the associated development of welding procedures (ref.14).

2.5 Titanium Alloys

Advances are being made in the titanium alloys through improvements in processing techniques, most notably, powder metallurgy and rapid solidification techniques. Unique rapidly solidified microstructures and fine dispersions of stable second phase particle such as rare earth oxides, sulfides and oxy-sulfides, are producing alloys with greater high temperature strength and creep resistance (ref.3). One of the main blocks to the use of these alloys is, however, the lack of engineering data, including welding and weld repair data.

Programs to investigate and characterize the rapidly solidified structures in eutectoid and hypereutectoid titanium alloys has been performed (ref.15). In addition, welding data related to the welding of dissimilar titanium alloys has been completed. These have shown the need to maintain fine grain structures within titanium joints. Work on the implantation of microcooler additions into welds to promote refined grain structure is continuing (ref.16).

2.6 Aluminum-Lithium Alloys

Several grades of lightweight Aluminum Lithium alloys have recently been developed to meet the needs of the aerospace industry. These alloys are being produced by both conventional ingot metallurgy and by advanced rapid solidification/power metallurgy processing. These alloys possess a remarkable combination of light weight and strength with high modulus. Some alloys can be super-plastically formed (ref.3). But these alloys have had considerable difficulty in welding. Most grades are quite sensitive to weld and heat affected zone hot cracking, and very little is know about the stress corrosion cracking susceptibility of weldments in these alloys. Extension of applications to automotive, light shipping, tankers and light weight armor will require the solution to the welding problems.

Work has started to develop a fundamental understanding of the hot cracking mechanisms and stress corrosion cracking in Al-Li alloys (ref.17). Work comparing the various hot cracking testing mechanisms developed in the U.S., England, and Japan using these unique alloys is underway (ref.18). These results are showing that the testing techniques are somewhat material dependent and a direct comparison of results is not possible without consideration of material and test technique. And, a program to determine stress corrosion cracking data has just been initiated (ref.19). These programs will lead to the formulation of more weldable alloys.

2.7 Powdered Metallurgy Aluminum Alloys

Special aluminum alloys made by advanced powder metallurgy techniques are being considered for high strength and in some cases, elevated temperature applications (ref.3). Here again, the development of welding procedures is the stumbling block to application.

Early welding development work centered around the use of gas tungsten arc welding processes for these materials. Recently, however, some acceptable welds have been made with rapid solidification processes such as electron beam and laser welding (ref.20), and solid state techniques such as inertia and diffusion brazing (ref.21). The fine tuning of procedures is now required.

2.8 Metal Matrix Composites

Particulate and fiber reinforced metal matrix composites are beginning to make in-roads into production. The use of vapor deposition is aiding the bonding of fiber to matrix and a number of new products are being tested (ref.3). The most common matrix is aluminum or aluminum alloys reinforce with silicon-carbide, although titanium and magnesium MMC are appearing. Each of these composites offer substantial improvements in strength and stiffness over unreinforced alloys. Although applications have been predicted in the aerospace industry for some time, newer applications in automotive engine components are under consideration (ref.3). As with most of the newer materials, the lack of engineering data, including weldability, has slowed the use of these materials.

Welding studies have concentrated on demonstrating the feasibility of bonding metal matrix composites. Several processes have been tried including arc welding, high energy beam welding, resistance welding and solid state bonding. Of these, the capacitive discharge process (ref.22) and the transient liquid phase bonding processes appear to be the most promising (ref.23).

2.9 Thermoplastics and Thermoplastic Composites

Thermoplastic resins are currently being developed that offer ease of molding with properties of improved strength, heat resistance, ultraviolet resistance, chemical resistance and good impact. Increased use of these thermoplastics and composites is predicted for both automotive and aerospace applications (ref.3).

Welding techniques for these thermoplastics and composites are currently being developed. To date small scale test samples have been successfully joined using hot plate, vibration, ultrasonic and implant welding. The main topic still requiring further work is scaling up the welding techniques to permit joining large components in a single operation (ref.24).

2.10 Thermoset and Thermoset Composites

A brisk effort in development of thermoset and thermoset composites is also occurring.

At present, thermoset composites cannot be welded. Joints can only be achieved using adhesive bonding. Work is currently being carried out by adhesive producers to develop suitable materials. Working closely with these groups, trials are being conducted to assess tolerance to part fit-up, adhesive dispensing systems, and effect of material surface condition.

2.11 Hybrid Materials

Hybrid materials are those composed of two or more distinct materials. An example would be a thermoplastic composite bar or tube with a thin outer coating of aluminum sheet. Hybrid materials are being considered for some space application because the atomic oxygen present in low earth orbits has a marked detrimental effect on some organic-based materials. Therefore, these materials cannot be used where they will be exposed to this environment. To overcome this, hybrid materials are currently being developed which have an organic composite core and then are either clad or coated on the outside with aluminum.

The feasibility of joining these materials using welding and adhesive techniques are currently being determined. An important consideration is the effect of the various joining processes on the parent material and the coating in the region of the weld (ref.25).

2.12 Ceramic Materials

The development of structural ceramic materials over the past 10 years has indeed been impressive. Proposed applications include engine components and other high temperature service, and applications for energy absorbing armor. Some of the latter applications will require bonding.

The most common methods being considered for bonding ceramics and ceramics to metals include the vapor deposition of compatible material on the ceramics and brazing the parts (ref.26). Recent work designed to investigate the feasibility of electrostatic assisted diffusion bonding of ceramics to metals is now underway (ref.27,28). The results should lead to an increased use of structural ceramics.

2.13 Lunar Materials

The construction of lunar bases ia a challenge for the future. The cost of transporting construction materials to a lunar base may preclude early construction of these bases. The use of lunar soil, on the other hand, may present a cost effective alternative (ref.29). The compacting of lunar soil and the effectiveness of microwaves in sintering of lunar soil simulants for primary production of structural components has already been demonstrated (ref.30). These developments imply that this technique may also be effective for joining of lunar structural components.

3. Welding Innovation in Some Advanced Environments.

Effective utilization of the material advances describe above requires that these materials can efficiently be incorporated into structural components. In many cases, consideration of the materials and the material properties is not enough. A consideration of the fabrication process and the fabrication environment is required.

3.1 Robotic Cell Environment - Computer Aided Welding Manufacture

The robotic cell in a welding operation consists of all the components necessary to produce the fabricated part from any of the representative advanced materials described above. This includes all the materials preparation equipment, materials handling equipment, fixturing equipment, any necessary computer programming equipment, and the robot itself. One of the significant problems with programming robotic cells for arc welding is the necessity for on-line teach programming of the robot, fixtures, materials handling and other equipment. This on-line, point-by-point, teaching is tedious, displaces productive use of the robot, and in many instances produces a weld strategy which is far from optimized (ref.31). In fact, unless the unique welding procedures developed for some of the advanced materials are followed exactly, inferior or defective welds will result.

Computer Aided Welding Manufacturing (CAWM) is rapidly becoming a viable solution to this problem. CAWM links all of the vital components of the robotic system together in an off-line programming mode. This is accomplished via a real-time interactive graphical simulation of a robot, tooling and the weldment itself on a CRT based work station. The work station is linked with all of the appropriate materials and welding procedure databases. Computer expert systems sort and select all of the necessary materials and procedure information and combine these with the appropriate welding cells to develop the entire manufacturing strategy.

Current research efforts (ref.32) are defining the structure and strategy required for Computer Aided Welding Manufacture and the implementation of this strategy into existing robotic work cells via off-line programming has begun. In addition, a considerable amount of effort is underway to develop the numerous material property and welding procedure data bases necessary for the complete system. Finally, the development of robotic expert systems has just started.

3.2 Robotic Instrumentation and Control for Harsh Environments

One of the applications for the use of robotic welding systems is where the surrounding environment is too harsh or dangerous for humans. Applications such as the repair of nuclear reactors or repair of underwater systems are excellent examples. In such repair application, however, the area to be repaired is often not exactly the same as the original construction schematic because of the damage necessitating the repair or long term corrosion or other factors. Thus, a rather extensive robot sensing and feedback control system is required.

Some recent sensing work has centered on the development of a real-time sensory vision system for use in automatic control of arc welding robots. A system which views the weld area during gas tungsten arc welding supplies the robot system with vision for seam tracking and bead shape control. An extension of this system using a laser diode-based structured lighting system allows the simultaneous sensing of joint geometries. Additional work to examine infrared spectrometry to allow sensing of pool and heat-affected zone temperatures is underway (ref.33). Finally the extension of this technology to other types of welding processes has begun.

Weld sensing of the weld pool penetration is also important during remote robotic welding. A system for sensing weld pool vibrations to obtain information on weld bead geometry for real-time feedback control has also been developed (ref.34).

Systems such as these will extend the useful life of the advanced materials particularly in hazardous environments by enabling their repair.

3.3 Welding in the Space Environment

Many of the advanced materials described above are under development for use in the aerospace industry. Some may even find applications in the space environment. Processes that are successfully used to weld materials on earth cannot necessarily be applied if the same structure were to be fabricated in space. Process concerns are outgassing during welding, size of equipment, power requirements, distortion, time and ease of operation, carrying out the process by a person in a space suit, automation and joint properties. To overcome these difficulties processes and procedures specifically for use in space need to be developed (ref.25).

The most extensive process modification will be required for the metals joining techniques, particularly those involving arc welding. Some space arc welding efforts, closely linked with that already being conducted in industry, are currently underway. Other metals joining techniques will need to be studied in detail. These include electron beam and laser welding, diffusion bonding and brazing. The joining process modifications required for some of the other advanced materials, i.e. polymeric and ceramic, have already been described above.

One area of concern that will require special emphasis is repair. During the operating life of any structure in space, some form of maintenance and repair operation will be required as a result of component failure, impact damage or general wear and tear. Damaged structures will require both quick and simple repairs as well as techniques to bring the structure back to full design specification.

The aim of a temporary repair program is to develop generic repair techniques that can be applied to a wide range of materials. These processes must permit rapid repair to allow continued use of the structure or prevent further massive damage. It is not intended that the structure be brought back to the original design specification. The equipment must be small, portable and operable by nonspecialized staff.

On the other hand, permanent repair procedures will be designed to bring the damaged structure back to full operating specification. It is envisioned that different processes will be required for different materials and areas of the structure. In addition, specialized equipment and staff might be required. These techniques will probably be based on equipment similar to that used in manufacturing the structure.

4. Conclusions

The development of advanced materials and the development of new manufacturing processes to encourage the use of these advanced materials has continued at an ever increasing rate. Research conducted in the Department of Welding Engineering at the Ohio State University has been aimed at a) developing the necessary materials property data bases for effective use of the newer advanced materials in joining applications, b) developing procedure data bases required to join these materials, and c) developing new welding systems which can utilize the information generated, even in some rather unusual environments.

The welding and joining industry indeed has a challenge for the 21st century. That challenge is to absorb the abundance of information being generated worldwide on advanced materials and processes, and to convert that information into new product designs and production. A fitting strategy for the next century should be to establish the links between industry and the independent and university research centers that allows abundant technology transfer to occur so that speedy utilization of the advanced materials and advanced processes can proceed.

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