Strategic Vision of Materials Joining in Japan†

Yukio UEDA* and Akira MATSUNAWA (Editors)**

Abstract

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1. Overview of the Present State of Materials Joining in Japan

by Yukio UEDA*

The basic and practical objective of materials joining is to promote efficient manufacture and economical production of high quality and high reliability. Cutting and welding are key technologies, and selection of the kinds of materials, welding methods, etc. are completely dependent upon the expected functions of the products. Relevant research is proceeding to cope with these demands.

First, in this report, the present activities and movements of technology in Japanese industries will be outlined in relation to welding and joining. Then, the present status and future direction of research in several fields will be described.

In the ship and offshore construction industry, higher qualification and multi-function capability of conventional structures are basic demands, e.g. double hulled ship-structures for prevention of oil spillage, low fuel consumption ships, and so on. Even with a constant low level of activity in the ship-building industry, development of new kinds and types of products are considered necessary, such as passenger ships, LNG carriers, jet-foils, Super-Techno Liner, super-conducting ships, etc. A particular challenge to the present technology, was the construction of a manned deep sea submersible-Shinkai 6500.

Generally, a lack of skilled workers and shortage of young labor in the shipbuilding industry made it increasingly important in recent years to speed up automation and mechanization and, eventually, to construct computer-aided-manufacturing systems. This stimulas introduces new subjects to develop component technologies. One specific exapmle is the use of new materials instead of conventional structural steels: Al alloys and 9% Ni steel for LNG carriers, Ti alloy for deep sea explorer submersibles, Al alloy and thin HT steel for weight saving and strengthening for high speed ships. A good appearance for passenger ships and extra-high reliability of deep-sea explorer submersibles bolt require strict control of welding deformation. This requirement is also applied to higher levels of automation in the construction of conventional ships.

The height of land structures in Japan is increasing and will result in ultra-high buildings in the 21st century. To achieve this goal in a country where earthquakes are frequent require the development of welding methods for thick TMPC and 590 N/mm^2 steel of low yield stress ratio for land buildings, and thick 780 N/mm^2 steel. Fire-resistant steel and stainless steels for corrosion resistance and cosmetic appearance are used.

Large bridges have been constructed using thick 780 N/mm^2 steel. Their main structural components are girders and box sections of large sizes, which are

† Received on 25, November 1994
* Professor and Director General
** Professor

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fabricated in very efficient production lines. The legs of bridges may be covered by Ti-cladded plates which are joined by TIG welding. These land structures, including bridges, are often constructed in the open air and improvements in efficiency and quality of welding are constantly expected.

Concerning energy-related industries, the construction of new nuclear power stations and fossil fuel power plants is very difficult in Japan. Consequently, repair and enlargement of the capacities of the existing power plants are performed in a manner which will extend the life and increase the reliability. This requires the development of advanced, higher strength materials with good toughness in the HAZ to resist SCC at high temperatures with high pressure and the corresponding welding technology.

In the electric machinery industry, the demand for electric generators of various sizes stimulates the construction of production lines for small lots of various sizes. In hydroelectric systems, replacement by larger sizes of water-wheels is undertaken. In this case, since the casting of such large wheels is difficult, the assembly of cast parts by welding or fabrication of the entire structure by welding on site may be essential. The success of these methods is completely dependent upon the control of reliable welding and accurate fabrication of the structure by welding on site.

In the automobile industry, international trade friction and conservation of environments forces change from the expansion of quantity to quality. To improve fuel efficiency, Al alloy and thin HT steel plate have started to be used for lighter cars. For higher quality, surface-modified plates for anti-corrosion are also adopted. Almost 90 % of welding in fabrication of automobiles is by spot welding and life extension of the electrode is of concern. Weldbonding is also adopted for weight-saving and greater rigidity. Development of efficient robots for spot welding and effective utilization of lasers for welding are expected.

In the electronics industry, fast and reliable microsoldering is a keen issue. Excellent soldering alloys without lead (Pb) and accurate joining methods are under development.

Automation of arc welding is a vital subject of common interest across a variety of industries. It requires optimum systematization of element technologies such as sensing, controlling of welding process, etc.

Usage of high energy density welding methods such as EB and laser is also expanding in various industries in order to increase reliability, accuracy and productivity of production.

In the above, the present status of technology and development in Japanese industries has been outlined and a number of important items are listed below to illustrate the directions of present and future research and development:

1. Highly efficient and low cost welding for conventional products
2. New cutting and joining technologies employingultra-high energy density methods.
3. Technology for life extension of the existing structures with sufficient reliablity
4. Thick higher tensile strength steels with good weldability
5. Joining technology for new materials such as Al alloys, stainless steel, new kind of HT, etc.
6. Precision cutting and strict control of welding deformation for automation
7. High standard component technology for computer-aided-manufacturing

In the following sections the present state of the art of materials joining in various fields of welding and joining in Japan will be described.

2. Arc Welding Processes

by Masao USHIO and Katsunori INOUE****

2.1 Introduction

Manufacturing technology in Japanese industry has been facing a number of serious problems, such as, aging of the work force, shortage of skilled welders, progress of NICs with low production costs and so on. Under these circumstances many industries have made great efforts to systematize production processes. In the welding, industry, a variety of automatic welding systems and allied processes have been developed successively, which can provide a high quality of weld and highly efficient productivity.

In this chapter we shall summarize the recent developments and future prospects in Japan of necessary technologies for the promotion of automation, such as improvements of welding consumables and welding power sources, development of arc welding robots, and advancement of welding sensors and welding systematization.

2.2 Automation of arcc welding processes

Figure 2.1 shows trends in the production of welding materials over the past 10 years. The proportion of GMA welding wire (solid wire and flux-cored wire) to total production has continued to increase, attaining 65% in 1992.

Figure 2.2 shows the changes in annual consumption of various types of wire and gases in various industrial fields. In the areas of car production and industrial machinery, where welding automatization is at an advanced level, solid wire is extensively used, while in the shipbuilding the usage of flux-cored wire is growing.

Since the introduction of invertor control technology into arc welding power sources in 1982, it has been extended across all gas shielded arc welding processes in Japan. The introduction of invertor sources has been based upon the advancement of welding performance due to high-speed control of current, rather than improvements of other functional aspects such as miniaturization

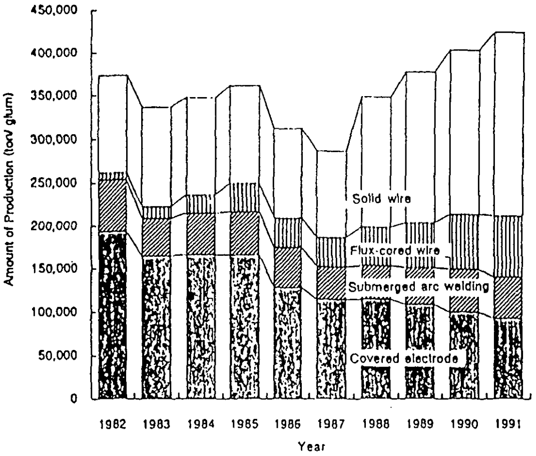


Fig.2.1 Change in annual production of welding material in Japan

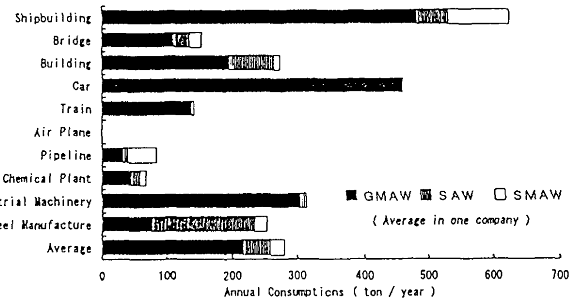


Fig.2.2 Annual consumption of welding electrode in various industries,estimated by sum of deposited material

weight reduction and saving of electricity consumption. Efforts have for the most part focused on the analyses of welding arc phenomena and the control of phenomena with external parametes. Consequently various waveform control power sources have been developed.

Around 1970, the thyristor was adopted in DC power supplies for the first time as an output control device in place of the magnetic amplifier, and thus the function of the welding power supply was greatly improved. In 1982, a GMA welding power supply with a transistor invertor capable of much higher-speed control of current was developed with BJT, and its application has also advanced, particularly in pulsed GMA welding. Since then, with advancement in its function and performance, invertorized power sources have come into wide use all over the fields of gas shielded arc welding. With respect to GTA welding power supplies, the change from thyristor control to invertor is similar to that of GMA welding. Its diffusion exceeded 50 % toward the end of 80's, and nowadays reaches to nearly 80%.

The major part of GMA welding wire in Japan is designed for carbon dioxide gas arc welding and solid wire is more widely used than flux-cored wire. This is quite different to the situation in U.S.A.

Ar-CO2 mixture gas shielded arc welding is gaining high popularity because of low spatter and fumes as well as the good appearance of the weld bead, and its advantages have been further recognized by its combination with pulsed-current power sources. On the other hand, in CO2 gas shielded arc welding, the "spattering" problem still remains unsolved, although many studies have been conducted on this particular problem.

Figure 2.3 shows an example of controlled waveform of welding current in short arc welding. Current is decreased immediately after detection of the bridging of wire and weld pool, which results in smooth bridging.

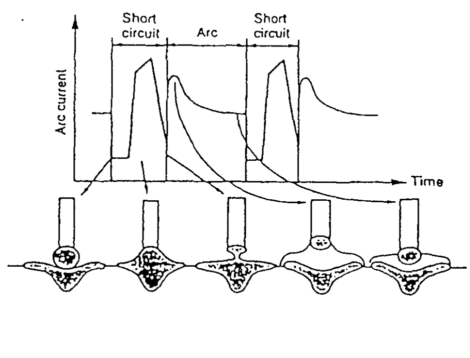


Fig.2.3 A typical current waveform control in short-circuiting transfer mode in CO_2welding

After that, the current is increased to excite the pinch effect, and subsequently is reduced again before the detaching of wire metal from the pool and restriking arc. When the arc restrikes, *V-I* characteristics of the power supply are adjusted to one which to promotes stability and regularity of droplet formation and arc length.

A number of fundamental researches on spattering have been made in the research centers of steel makers and JWRI of Osaka University. The effects of minor elements contained in the wire on the specific mechanism of spattering are becoming clear and the combined conditions of wire feed procedure and current wave-form are being investigating for perfect spatter-less CO2 welding.

According to production statistics of industrial robots in Japan, the accumulated number of arc welding robots since 1978 amounts to approximately 55 thousands. A welding robot is defined as an automatic welding machine having more than three degrees of free movement with teaching, programming and play-back functions controlled by micro-computer.

Figure 2.4 shows the ratio of consumed metal weight deposited by robotic or automatic welding to that deposited by semiautomatic and automatic welding. This is one of the measures of automation and robotization in each industrial field. As for the robotic welding ratio, 76% in car production, 55% in industrial machinery and 39% in rolling stock industry are examples of highly robotized fields. But in other industries, the ratio has not reached even 10% and the automatic welding ratio is also under 30% except for chemical plant.

As mentioned above, GMA welding is the key process in automatic arc welding. All of the major efforts have been concentrated on the improvement of GMA welding process to provide high quality welds with high efficiency and low cost.

One of the important successes of the JWRI deserving special mention is the development of tungsten

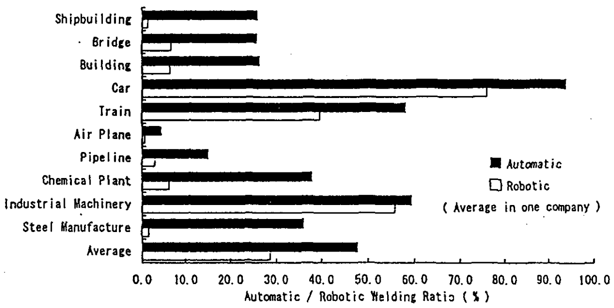


Fig.2.4 Comporsion of rations of automatic and robotic welding to all of GMA welding, estimated by sums deposited metal

electrodes activated with small amount of LA2O3, Y2O3 and LaB6 and their combinations. These electrodes have a high durability and allow long operation in fully automatic welding.

2.3 Present needs for research and development and future prospects.

In the future, it seems that automation and robotization in various industrial fields, particularly in shipbuilding and steel construction fields, will be continue to grow. Characteristically, the requirement for the development of the GMA welding process will be focused on 1) low spattering, 2) better pit resistance and 3) higher efficiency. Increased efficiency and high quality of welding can be achieved more effectively by an approach utilizing the combination of the factors, that is, wire, shielding gas and power supply, instead of wire or power supply alone.

Because of the shortage of skilled welders, the development of new welding power systems for semiautomatic welding, have been urgently required so that inexperienced welders can produce proper welds.

In order to meet to the user's demands described above, a new welding power supply having waveform control of current as well as new system based on fuzzy control theory have been developed. A skilled welder has been steadily adjusting the output parameter (output voltage and wire feed speed) by observing the changes in arc length, wire extension, arc and weld pool behavior, arc sound and so on. New welding power systems based on above concept aims to take in the know-how of skilled welders to control the output parameters of the power supply.

The demand for developing welding system which allows even inexperienced welder to weld easily will continue to grow, and be accompanied by a requirement for automation of the welding operation.

Application of the arc welding robot in the factory are increasing steadily, in spite of the changes in production character from a few kinds of mass production to diversified small quantity production. At present, however, the practical use of robotic welding is limited largely to the very simple case of the flat position welding of a linear joint.

Automated welding machines and welding robots used in the automobile industry are mainly the articulated and stationary type, but in the heavy industries other mechanisms (which is regarded as Cartesian types with carriage) are mostly applied.

To promote automation and robotization in arc welding, it is necessary to use adaptive control of the welding process, which provides seam tracking of the

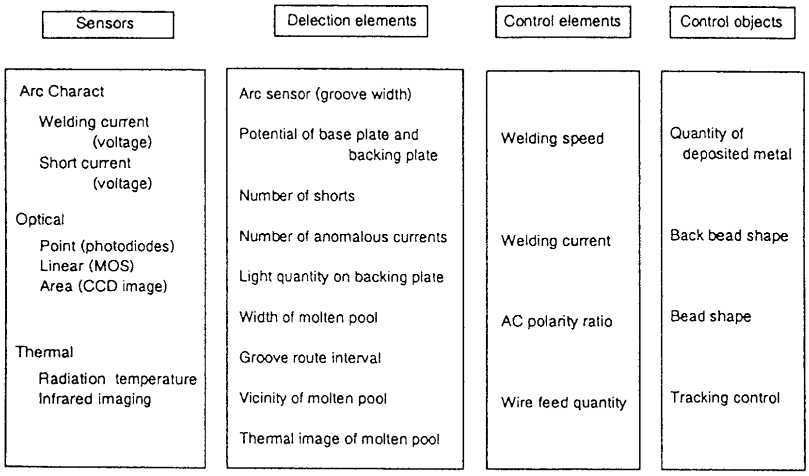


Fig.2.5 Sensor for adaptive control systems and combinations of control elements

weld line and adjustment of welding parameters to cope with changing groove conditions.

At present, sensors are mainly used for seam tracking and detecting joint-end, and their application to the adaptive control of welding parameters are remarkably few. Through-the-arc sensors and electrode contact sensors are widely used and almost all robots are equipped with those sensors. The problems of these sensors are their reliability and accuracy, and reproducibility of the sensor signal is most important. A cheap system of optical sensing and its processing are urgently required.

There is a lot of research and development in the area of processing sensor data and controlling welding conditions to obtain high quality welds. Available combinations of adaptive control systems are generally divided into the components; 1) sensor, 2) detection element, 3) control element, and 4) objects controlled. These are shown in **Fig. 2.5.** The optimization of these combination may be the most important research work. However, this system is still in the conceptual stage for ideal automation. The more fundamental researches are indispensable to develope the system more completely.

3. The State of The Art of Laser Welding

by Akira MATSUNAWA**

3.1 Introduction

As a heat source, a laser is characterised by the highest power density among various heat sources ever developed. Only an electron beam (EB) has competitive power density. It is well known that EB welding is the most advanced process in its sophisticated control and it is widely used in industries as an accurate and reliable joining method. In contrast, laser materials processing has various restrictions for industrial applications because of poor process controllability, easy formation of defects, insufficient development of laser and peripheral systems such as the beam delivery and focusing units, NC control systems, insufficient accuracy of work table and robot and so on. Presently, no laser technology has employed process monitoring or adaptive control, which leads to a lower penetration of laser materials processing in production sites. These are mainly brought by the 1) poor understanding of process phenomena, 2) slow temporal response of laser for power control, 3) lack of practical sensors and detectors for process control, 4) thermally induced optical distortion of lenses and mirrors, 5) slow speed of NC control system for process control, 6) poor accuracy of robotics, and so on.

In spite of these circumstances, many scientists and engineers believe the potential capability and flexibility of lasers as the promising production tools in industries in the next century. In Japan, laser cutting of thin sheet metal has spread widely since the late 70's even in small scale industries as a very flexible cutting method. Laser welding, on the other hand, has been less extended, but there are many industries which successfully utilize laser welding in production lines. Laser surface modification is not widely used at the moment in Japan except in a few cases, but is regarded as one of the near future technologies.

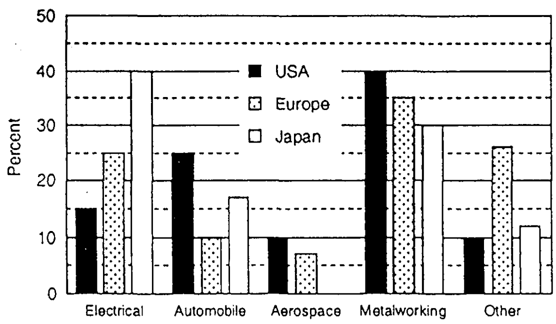
3.2 High power lasers for industrial use and application areas

High power lasers used for materials processing are mainly the infrared CO_2 and YAG lasers at present. The maximum powers of industrial lasers are 45 kW for CO2 and 3 kW for YAG.

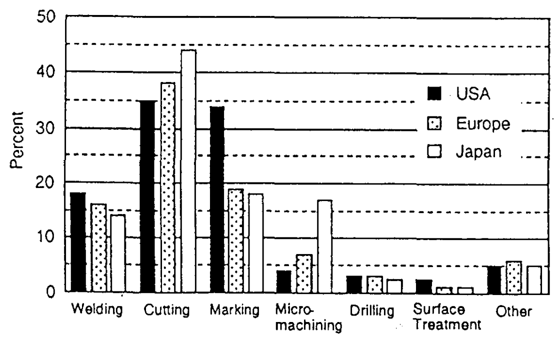
There are three areas in the world where lasers are intensively used in industry, i.e., North America, EC countries and Japan. However, about half of the high power lasers in the world are installed in Japanese industries. In **Fig. 3.1**(a) and (b) are shown the distribution of infrared lasers used in various industries and application areas in the above mentioned three areas.[3.1] The use of lasers in industries and their applications are slightly different in each area, perhaps due to the differences in industrial structures. In Japan lasers are used intensively in electrical, metalworking and automobile industries, and mostly used in cutting. However, the applications in marking, micro machining and welding are increasing in recent years.

Another important laser is an ultraviolet Excimer laser and this is gradually increasing in applications such as ablation hole drilling of organic materials used for electronic devices and stripping of insulation of thin wires.

Other new infrared lasers are also under development in Japan. They are high power CO and Iodine (COIL) lasers. A CO laser (5 μm wavelength) has been developed by Institute of Renovation and Innovation



(a) Industrial Distribution



(b) Applications

Fig.3.1 Distribution of industrial lasers and their applications in the world [3.1]

(IRI) and Mitsubishi Heavy Industries (MHI) for application in the dismantling of nuclear power plant. A prototype 5 kW CO laser was developed in 1989 and installed at the Applied Laser Engineering Center (ALEC) in Nagaoka City in 1992. In 1991, a 20 kW machine was developed by MHI and IRI. A 1 kW prototype iodine (COIL) laser, on the other hand, was developed by Kawasaki Heavy Industries (KHI) in 1990 and the first machine (Max. 2 kW) was installed at ALEC in 1992. This laser is a chemical laser and has the wavelength of 1.3 μm which allows beam transmission through quartz optical fibers.

3.3 Laser welding

In contrast to the laser cutting, the laser welding has been employed in limited areas since the early 80's in Japan. There were several reasons that restricted the introduction of laser welding in industries. One of them was the cost and unstable performance of high power lasers. The second and more important reason is that no sophisticated process control nor adaptive control is employed in laser welding. For example, a weld seam tracking that is suitable for the very high speed and tiny spot laser process has not yet been developed, and hence a heavy and rigid fixing equipment is required for laser welding. Laser welding is thus not a flexible process, and has been partly used in mass-production lines at the moment. However, the performance of high power lasers has greatly improved in the last decade and laser welding is spreading slowly but steadily in recent years in spite of inadequate means of process control.

Table 3.1 shows the present states of laser welding applications in various fields in Japanese industries together with the adopted reasons and merits of laser welding.[3.2] Major reasons for adoption of laser welding are quoted as low distortion, deep penetration, high speed and precision welding, and the usage of laser has brought many merits such as greater improvements in workability, productivity, reliability and preciseness. In the following sections outline the state of the art of innovative laser welding ineach industrial area.

(1) Automobile

The first introduction of laser welding was perhaps to the manufacturing of automotive parts in the early 80's in Japan. **Figure 3.2** shows the historical changes in the welding method for a stator core for a power generator used in a car.[3.3] The stator core used to be fixed at first by arc welding then by resistance projection welding to increase the production efficiency. In these processes, however, an extra degreasing procedure was required prior to welding in order to reduce weld

Table 3.1 Applicatons of laser welding inJapan [3.2]

Industrial Field	Materials Used	Features of Laser Welding	Purposes of Laser Welding Adoption	Advantages of Laser Welding	Applications Examples
Steel Making	Low C-Steel Medium C-St. Stainless Steel Silicate Steel	Low Strain Deep Penetration	Eliminate Postheat Treatment Replace MIG Wg. Replace Resistance Wg. Replace Plasma Wg.	Improvements of Workability, Productivity, & Reliability	Steel Coil Pipe
Machinery (Car) (General Machine)	Zn-coated Steel Low C-Steel Medium C-St. Low Alloyed Steel	Low Strain High Speed	Replace Seam Wg. Eliminate Post-Machining	Improvements of Productivity, & Reliability Reduction of Size, & Weight	Fuel Tank Mission Gear Automatic Trans-mission Engine Parts Wheel
Precision Machinery	Copper Alloys Stainless steel	Precision Wg. Low Strain	Min. Distortion after welding	Improvements of Accuracy, Productivity, & Reliability.	PAA Antenna Aerospace Parts Parts of Measure-ment Equipment
Heavy Structure	Stainless Steel Low C-Steel	Deep Penetration Low Heat Input	Eliminate Post-Machining	Improvements of Productivity, Workability, & Reliability.	Pressure Vessel Vacuum Chamber Mechanical Parts

defects, but it was no sufficient to eliminate defects and distortion. In 1982 the first CO2 laser welding line was completed in Nippon Denso (ND) and reduced the production costs because the degreasing and rinsing processes could be eliminated. As the oil completely evaporates with a laser beam and a clean surface appears before the metal melts, and thus a sound weld can be obtained without any preliminary treatments. Presently, many other automotive mechanical parts are laser welded and many production costs are greatly reduced by simpler design of machined parts and elimination of post-weld machining.

In the preparation of car body parts, too, innovative laser welding has been applied since mid 80's. The method is called "Laser Tailored Blank Welding" and was first attempted by Toyota. As illustrated in **Fig. 3.3**, a part of the body is initially prepared by pieces of blank materials and these are laser welded linearly in the flat position, and then press formed after into 3D- shape.[3.4] The method is advantageous both in the reduction of unnecessary materials and the selection of different thicknesses depending on the necessary strength at each part. It is also important to mention that straight welding in the flat position makes the system much simpler and welding speed faster than those employing 3D laser welding. Therefore, adoption of the tailored blank welding concept leads to cost saving as well as to the production of lighter weight vehicles, and many automobile makers in the world presently employ this efficient method to produce car bodies.

(2) Steel making

In 1982 Kawasaki Steel (KS) employed the laser welding process for coil to coil connection in the rolling mill .[3.5] KS first introduced the process in the line for grain oriented magnetic steel by using a 5 kW CO2 laser, and proved its reliability. The process is presently used in other thin strip mills using the 5 and 10 kW machines in KS.

Also in mid 80's, a unique process was developed by Nippon Steel (NS) for the production of medium thickness steel pipe. The pipe used to be made by the high frequency (HF) pressure welding, but the heating of middle part of the plate thickness is likely to be insufficient due to the nature of HF induction heating. In order to obtain the uniformity of heating along the plate edges, a high power CO2 laser beam was used in the middle part of the joint with multiple reflection on the wall as illustrated in **Fig. 3.4**, and uniform heating of the weld joint was successfully achieved.[3.6] This process might be the first attempt at hybrid welding

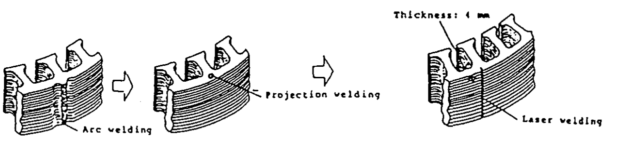


Fig.3.2 Chanfes in welding method of stator core [3.3]

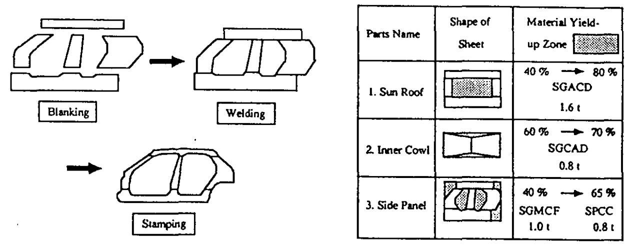


Fig.3.3 Laser tailored blank welding [3.4]

technology combining HF with laser in Japan.

Presently, a small diameter stainless pipe of thin thickness is 100 % produced by the HF combined laser fusion welding.

(3) Power plant

Laser welding is not used in production of power plants except for small mechanical parts. However, very important application of laser to power plants is the repair welding of existing facilities. In particular, the damage of heat exchanger tubes in the steam generator of a nuclear power plant (PWR) is a serious problem from the aspect of safety and preservation of the environment. Repair of such damaged parts used to be carried out by inserting inner sleeves and Gold brazing to the main tube from the inner side of pipe, but the repairing efficiency was poor and more efficient fusion weld methods were intensively sought.

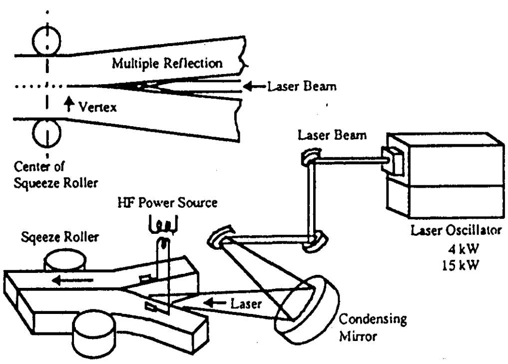


Fig.3.4 Combined HF and laser welding for production ofpipe [3.6]

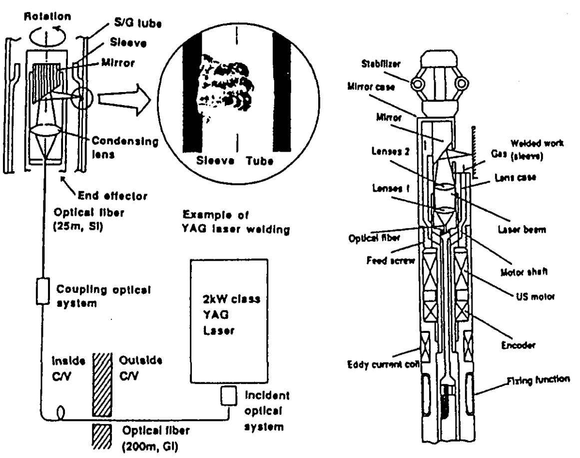


Fig.3.5 YAG laser repair welding of steam generator of nuclear power plant [3.7]

There was a revolutionary technological development in 1989 by Mitsubishi Heavy Industries (MHI) when they repaired a damaged tube by a fiber delivered YAG laser as shown in **Fig. 3.5**.[3.7] Quartz optical fiber of 0.8 mm diameter can easily transmit the YAG laser wavelength of several kW for long distance without significant attenuation of power. Also the welding torch can be minimized in size by adoption of laser. MHI developed 2 kW class YAG laser in collaboration with NEC and Toshiba, and completed a sophisticated YAG laser repair welding system. As the repair system must be operated in a radioactive environment, all operations of pre-inspection, insertion and expansion of sleeve, welding, and post-inspection are remote-controlled, and the laser power is transmitted from the outside of the plant by an optical fiber of 250 m in length. The technology is also applicable to ordinary power plants, chemical plants, and so on. The life extension of existing structures is one of the most important issues in modern welding engineering.

(4) Heavy manufacture (Indoor)

In heavy industries, the main welding procedure is arc welding and laser welding is only applied to mechanical parts, parts of small vessels and so on. However, there will be a trend to replace some arc welding by laser welding if the power of the laser can be increased. For example, if a high power YAG laser over 4 - 5 kW is developed, it is expected that all position TIG welding of pipe to pipe will be replaced by laser robotic welding.

There is a general trend to reduce the weight of rolling stock and transport ships to save the fuel consumption. In order to achieve this, the use of light weigt honey comb plates or corrugated plates made from thin sheet may be one of the solutions. Steel makers and heavy industries are interested in making new materials by laser welding in order to increase the welding speed and reduce weld deformation, and intensive R & D is in progress at present. There is a big project called "Techno-Super Liner Plan" which is to construct a high speed cargo ship moving at 100 km/hr, and large amounts of honey comb plates of aluminum alloys or stainless steels are necessary to realize the project.

Another potential application of laser welding to shipbuilding is in the construction of fishing and pleasure boats using aluminum alloys. These small boats are presently made of fiber reinforced plastic, but they are causing a serious environmental problem in Japan because there is no adequate means of disposal.

Therefore, boats made of recycled materials are the general trend in the future. However, aluminum alloys are typically difficult materials for welding because of the high heat conductivity as well as ease with which of various weld defects such as porosity, cracking and residual distortion occur. To overcome these difficulties, a possible solution is the use of high power density heat sources like EB and lasers. Thus, the importance of laser welding among heavy industries and material suppliers will continue to increase.

3.4 Future trends of laser materials processing and the necessity for basic research

Today, the role of laser technologies in materials processing is becoming more important than before, because there exists a global need to save natural resources and protect the environment of the earth. Therefore, structures of the next generation must be designed to be lighter in weight and with sufficient strength and more accurate assembly to maintain their functions and lives. In such situations, the use of thin sheet welding or complex shape welding in narrow areas will be increased, and the laser is the only heat source that can cope with these demands.

However, as described in the Introduction, laser materials processing does not at present employ the adaptive control. To raise the laser materials processing to the level of a sophisticated technology, it is absolutely necessary to conduct fundamental researches to clarify the processing phenomena and to establish new prediction control systems based on mathematical models. The establishment of non-equilibrium material science and evaluation methods of residual functions of materials and structures are future subjects to develope laser technologies in the next century. At present, intensive and comprehensive researches are undertaken at the Welding Research Institute and Department of Production and Welding Engineering at Osaka University, the Advanced Materials Processing Institute (AMPI) which was recently established in Amagasaki, and Applied Laser Engineering Center in Nagaoka.

References

3.1) Industrial Laser Review: January (1993), p.14.

3.2) S. Hiramoto: Joy Tech, March (1989), p.32 (in Japanese).

3.3) Y. Iwai & others: Proc. of LAMP'87, May, 1987, Osaka, High Temperature Society of Japan [HTSJ], p.517.

3.4) F. Natsumi and others: Preprints of Spring Meeting, JSAE Review, Paper No. 901, May (1990), p. 245.

3.5) M. Ito and others: Proc. of LAMP'87, May, 1987, Osaka, HTSJ, p. 535.

3.6) K. Minamida and others: Proc. of ICALEO'86, Arlington, USA, Nov. (1986), Laser Institute of America (LIA), p. 97.

3.7) T. Ishide and others: Proc. of LAMP'92, June, 1992, Nagaoka, HTSJ, p. 957.4.

4. High Energy Heat Sources and Allied New Areas for Materials Processing

by Shoji MIYAKE**

4.1 Introduction

It is well known that high energy sources such as electron and laser beams as well as various arc plasmas are playing key roles for the high performance welding and cutting. With the exception of arc plasmas, high power electron and laser beam welding machines have been developed within the last 30 years, and the Welding Research Institute (JWRI) at Osaka University has made internationally recognised contributions in this area.

Present day Japanese scientific research and industrial technology continues to search for, various new high energy sources to develope for highly qualified new materials and their fabrication.

In this chapter the development and application of various high energy heat sources are described which have been applied to joining and other allied areas of materials processing in Japan.

4.2 Development of high power electron and laser beams for welding and cutting

As for the development of high power electron beam (EB) welding machines, a very high voltage and power, 600 kV/300 kW machine, the biggest in the world, was developed at the Research Center for Ultra High Energy Density Heat Source of JWRI about 10 years ago. [4.1] Using this machine it has been demonstrated that a high speed (300 mm/min) one pass weld in a very thick (200 mm) SUS 304 steel is possible at a beam power of 120 kW. [4.2]

At present various machines up to 100 kW are working in the commercial base in Japan, and several industries or companies are making research and development studies for more refined welding processes with high quality control.

Welding by laser beams has a great advantage in comparison with that by EB in the point that the process is possible at atmospheric pressure. In turn it possesses a lower penetration depth. For welding of a steel plate with a thickness larger than 10 mm, usually a high power CO2 laser over several 10 kW is necessary in the CW mode operation.

A 15kW high power CO2 laser machine was developed in the United States and installed at JWRI in 1980 for the first time in Japan. In the 1980's a 20kW machine was developed in Japan in a large project by the Ministry of International Trade and Industry (MITI). [4.3] Quite recently a very high power machine of 50 kW output developed in the United States has been installed at an institute in Japan [4.4], where its application to thick plate welding and cutting, as well as to surface modificatrion technology is being investigated.

YAG laser is known to be one of the most important heat sources applied to welding, cutting and other allied areas of materials processing, but its development is limited to a power level of several kW. This laser is usually pumped by arc lamps. While development of high power laser diodes (LD) is quite rapid in these days, and we can expect to obtain a low cost LD in near future, in whcih case on LD pumped YAG laser will have the possibility to compete with the CO2 laser. At our institute we are planning to develop and equip a high power LD system as one of the new and very compact sources of high quality energy density, which can be applied also to LD pumped YAG lasers with high efficiency and controllability.

4.3 Excimer lasers, ion beams and other high energy sources for allied materials processing

CO2 and YAG lasers emit infrared radiations which are efficient for thermal processing. Excimer lasers (XeCl, KrF, ArF, etc.) have radiations in the ultraviolet region in the pulsed mode, so that strong photo-chemical effects are available for materials processes . Drilling by excimer laser ablation is one of the non-thermal processes based on this effect and is different from those offered by CO2 or YAG lasers.

In our country development of high power excimer lasers have been undertaken again by a national project AMMTRA (Advanced Material-processing and Machine Technology Research Project, 1986-1993) under the leadership of MITI. For instance, the development of a high power XeCl laser with an average power of 2 kW and a repetition rate of 1 kHz has been targetted in this project.

Practical application technologies of excimer lasers based on the ablation process are drilling, etching, surface modification including cleaning, thin film synthesis and so on. They are not directly connected with the present day welding, but deeply correlated with the study of joining at nano or atomistic scale in the future, which should be one of the key technology in the microelectronic industries in Japan.

As another example of high energy sources for materials processing, the development of high current and/or high energy ion beams is also concerned with joining and surface modification of materials. Typically, ion beams are known to have high controllability of the process similar to electron and laser beams.

Development of high power ion beams have been undertaken also in AMMTRA by MITI. This project is promoted 1) to realize materials processing technology using excimer and ion beams (which is necessary in the advanced technology industries such as energy, fine machinery, electronics, aviation and space technology, etc.,) and 2) to obtain highly precise and highly functional parts of machinery and electronics by ultra-precise nano scale processing.

In this project the development of high current Al ion beams of 100 mA and 100 keV has been targetted, for instance for the surface modification of materials over the wide area of 100 cm^2 by a one pass implantation process.

In a typical ion implantation the modified layer is limited by the range of the ions and it is usually very thin, below 1mm even at an ion energy higher than 100 keV. To overcome this limitation, ion beam dynamic mixing method has been developed by Japanese researchers. In this method various materials are evaporated and deposited by simultaneous bombardment of ions on the base materials. By this method thick modified layers are obtained with very good adhesion between the base material and the modified layer. A future trend of ion beam technology will be for the surface modification of materials, as well as for new materials sythesis.

The JWRI is extensively studying ion beam dynamic mixing [4.5] and recently has installed equipment by which metal ion implantation and ion beam dynamic mixing can be conducted to study the formation of functional surface layers in connection with joining problems of new materials.

Besides electron, laser and ion beams, our institute has also studied high energy density millimeter-wave radiation source for materials processing. Using a high power pulsed source of 60 GHz gyrotron we have succeeded in obtaining an energy density reaching to a value of 100 kW/cm^2 [4.6] and applied it to the rapid sintering of pure Al2O3 [4.7] and ZrO2 without any binder and with a very small grain size. As for CW sources for industrial application, a 28 GHz system with an output of 15 kW is now operating in Japan. [4.8]

The application of high power microwave or millimeter-wave energy to materials is becoming one of the processes for synthesis, sintering and joining of various fine ceramics, and it has been extensively studied, especially in the United States.[4.9] Recently it is also attracting great attention in our country, and we are now planning to have joint research on this process with Australian researchers.

Arc plasmas are the main high energy sources applied to welding and cutting, and these thermal plasma sources, including RF and microwave plasmas, are also being applied to the field of surface modification and new materials synthesis. Thermal spraying is one of the popular technologies of surface coating, and JWRI has been making extensive studies on this process from the scientific point of view at Research Center for High Energy Surface Processing.[4.10]

Another example of surface modification using arc plasmas is the forming or overlaying of metal alloyed thick layers on base materials. For instance Al and its alloys are widely used in various industrial areas, but one of the recent demands for these materials is the improvement of their wear resistance. This problem has been studied as a project "Development of Thick Surface Layer Hardening Technology of Al and Al alloy Products (1991-1993)" sponsored by MITI. For instance, hardfacing of Al alloys was successfully achieved [4.11] using the plasma transfered arc (PTA) overlaying process with various metal and ceramic powders.

Various non-thermal, physical and chemical vapour deposition (PVD and CVD) processes using low pressure plasmas, ion and laser beams are also acknowledged to be key technologies in Japanese industry, and they are always concerned with joining problems at nano or atomistic scale interface. Our institute is also conducting extensive studies on these problems. In the advanced materials processing of complex, layered and/or functionally graded materials, it is inevitably important to study joining problems from the scientific point of view in collaboration with researchers engaged in new materials synthesis as well as those in the field of micromachining or microelectronics.

4.4 Summary

Development and application of various high energy heat sources in Japan for materials joining have been described briefly. The present state of high power electron beam, CO2 laser and YAG laser for welding and cutting was described first. Secondly new trends of materials processing in Japan, using other high energy sources such as UV Excimer lasers, ion beams and/or millimeter-wave radiation, as well as thermal arc plasmas are discussed. The contribution and activity of our Welding Research Institute in the development and application of these high energy sources are also emphasized for the future stratelgic vision of materials joining.

References

4.1) Y. Arata, M. Tomie: J. High Temp. Soc. 18 (1984) 10 (in Japanese).

4.2) M. Tomie, N. Abe and Y. Arata: J. High Temp. Soc. 19 (1993) 119 (inJapanese).

4.3) N. Tabata et al.: Proc. ICALEO'84 (1984) 238.

4.4) Kousai, No. 1 (AMPI, Osaka, 1994) 8.

4.5) S. Miyake: ISIJ Int. 33 (1993) 907.; in Proc. Pre Assembly Symp. of 47th Ann. Assembly of IIW, Sept. 1-2, 1994, Dalian, China.

4.6) S, Miyake,O. Wada, M. Nakajima, T. Idehara and G.F.. Brand: Int. J. Electronics 70 (1991), 979.

4.7) Y. Setsuhara, Y. Tabata, R. Ohnishi and S. Miyake: Trans. JWRI 21 (1992) 181.

4.8) For example MRS Symposium Proceedings Vol. 269 "Microwave Processing of Materials III" Ed.by R.L.Beatty, W. H. Sutton and M. F. Iskander, (MRS,Pittsburgh, 1992)

4.9) T.Saji: Seramikkusu 29 (1994) 383 (in Japanese)

4.10) A. Ohmori: Proc. Symp. '93 of Research Center for High Energy Surface Processing (1993) 33.

4.11) K. Nakata, T. Hashimoto and F. Matsuda: Proc. 2nd Japan-China Joint Symp. on Surface Engineering (1993) 143.

5. Joining of Conventional Mateials

by Fukuhisa MATSUDA**

5.1 Introduction

In compliance with the current demand for lighter, stronger and more reliable structures and products, conventional materials have been improved and advanced rapidly. Since most such materials are ultimately employed in welded constructions, weldability is an important factor in their development. Therefore researches into the weldability of these materials have been continued without any interruption in research institutes and industries.

This chapter will be concerned with the present situation and the future trends of materials researches in

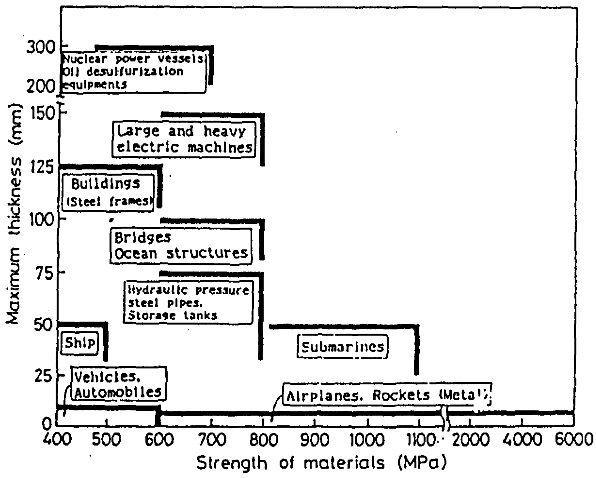


Fig. 5.1 Relation between strength and thickness for constructional steels used in individual industries in Japan

relation to welding in the respective industrial fields in Japan. The utilization of constructional steel in Japan is shown in relation to strength and thickness in **Fig. 5.1** [5.1]

5.2 Automobile and vehicle industries

The main research subjects in this field are described as follows :

1) Life extension of the electrode in spot welding for zinc-coated, organic matter-coated steel or aluminum sheet: The tip of the Cr-Cu electrode is easily eroded by formation of intermetallic compounds during spot welding.
2) In order to make lighter automobiles, the use of aluminum and its alloy is expected. High speed welding of aluminum without any defects is investigated by the laser welding process.
3) Surface modification of aluminum and its alloys with a hard and thick layer is under research for the fabrication of anti-abrasive engine cylinders made of aluminum alloy [5.2].
4) Improvement of weldability in the fusion welding of aluminum to steel is expected by developing specific filler materials or processes. Due to the formation of brittle intermetallic compounds there is no successful fusion welding process without any filler material .
5) The problem of deterioration of fatigue strength is not yet solved for welded joints of high tensile strength steel. The superiority of TMCP high tensile strength steel is almost lost in welded joints because of decrease in the yield strength due to the weld thermal cycl

5.3 Aircraft and aerospace industries

In this field the research and industrial development in concentrated on the following items:

1) Development of weldability of high strength Al-alloys such as Al-Li, Al-Cu and Al-Zn- Mg systems is expected. These alloys have high crack susceptibility in fusion welding. Therefore development of crack insusceptible alloys by adding a minor alloying element is expected.
2) In relation to the development of rocket engines, prevention techniques for microfissures are required for the root of the weld in heat resistant nickel alloys with GTAW and EBW.
3) The effect of minor or residual element on hot crack susceptibility is not completely clarified yet and further research is expected, especially for fully austenitic stainless steel and for high nickel alloys.
4) The development of ultra high tensile strength steels, such as maraging steel, which have excellent weldability in EBW: Especially, prevention of strength loss in the as-welded condition is expected for heat -treated steel.
5) Application of plasma spraying of heat resistant ceramics to engine parts for protection, coating or repair Improvement and development of ceramic powders are expected.

5.4 Electronics industries

Microprocessing techniques for electronics are already much advanced. Bonding techniques will be further improved in future. The following items are under investigation.

1) Development of advanced soldering alloys can be expected for high temperature and long time duration: Specific brittle intermetallic compounds are formed in the boundary zone between Pb-Sn solder and base metal after long service.
2) In order to prevent formation of the intermetallic compound in the bonding boundary of Au/Al/Si, Au/Sn and Au/Sn/Cu in service for long times, the effect of alloying elements in solder on the formation of the compound should be investigated in detail.

5.5 Chemical plant industries

The following items need to be examined from a material point of view;

1) Continuous development of non-susceptible low alloy steels to cold cracking during welding and stress relief cracking after PWHT.
2) Prevention of hydrogen embrittlement of weldments during long service at high temperatures and high hydrogen gas pressures. This is especially necessary for Cr-Mo steels used in desulphurizer vessels.
3) Development of non-susceptible stainless steel and weldments to SCC. The effect of additive elements in stainless steel on SCC is expected to be investigated.
4) Technical establishment of fusion welding processes for Ti- or Al-clad steel. Formation and prevention of brittle intermetallic compounds are not yet fully understood.
5) Prevention of microfissuring and hot cracking in weld metal and HAZ of stainless steels and high nickel alloys. In multilayer weld metals, this is currently an important research subject. The effect of additive alloying elements on microfissuring will be continuously investigated.
6) Improvement of the weldability of refractory metals and alloys, such as Cr, Mo, and W [5.3]; The weld metal and HAZ of these metals becomes brittle due to crystallization and precipitation. The effect of residual and additive elements on the brittleness will be investigated.

5.6 Power plant industries

Welding technologies are expected to be further advanced in the following items;

1) Prevention of SCC for carbon steel and high nickel alloys in high temperature , high pressure water environments [5.4]; Especially for life extension of nuclear power plants this subject is strongly stressed. More fundamental investigation is expected for SCC.
2) Development of low alloy pressure vessel steels whose weld metals with EBW have high toughness [5.5]: Ductility deterioration occurs in the weld metal of thick steel plates. The cause of ductility deterioration is due to upper-bainitic structures including M-A constituent. The role of alloying element in structural changes is expected to be clarified in detail.
3) Development of temper-bead welding processes for repairing large-sized pressure vessels. The effect of the weld thermal cycle on toughness of welded zones is expected to be analysed.
4) Prevention of deterioration of HAZ toughness in thick HT 80 and HT 100 steels during high heat input welding [5.6]. The role of the M-A constituent on toughness and the prevention of formation of M-A is expected to be investigated in.

5.7 Shipbuilding industries

The following items are subjects for continuous development from the material point of view;

1) Development of weldable high tensile strength steels (HT 60 and HT 80) by means of TMCP: In succession to HT50, production of a higher grade steel is expected with a low cost process.
2) Improvement of the weldability of aluminum alloy and 9% Ni steel in thick plates, and 36% Ni Invar alloy: Porosity-free welds for aluminum alloy up to 250mm in thickness, high ductility welds with 9%Ni filler wire for 9%Ni steel and hot crack free welds for thin 36%Ni Invar alloy are expected to be developed for LNG vessels.
3) Development of HY 150, and 180 steels together with related welding electrodes having resistance to SCC in sea water environments: Increase in hardness of weld metal decreases the resistance to SCC. Development and improvement of both welding electrode and process parameters are expected for the welding of these steels.

5.8 Bridge and architecture industries

In this field the following items are under investigation and development ;

1) Development of weather-proof steels and their welding materials which do not cause any defects by conventional welding: The problems of porosities and hot cracking are not yet completely solved.
2) Development of high tensile steels and electrodes which have a high toughness in the weld metal with the high heat input electroslag welding process [5.7]: Effect of additive and residual elements on microstructural changes in the weld metal will be more carefully investigated.

5.9 Research and development in the future

In order to develop higher quality materials and relevant technologies for industrial use, wider and more profound knowledge about welding technology is neccessary. Then technology and science need to advance simultaneously.

Welding technologies related to conventional materials have been developed and advanced to a great extent, but at the same time many new subjects have arisen. The following main subjects will be continuously investigated and relevant problems tackled.

1) Use of TMCP for steel making in order to avoid cold cracking and toughness degradation.
2) Utilization of useful elements in welding materials as well as in steel making.
3) Development of high tensile steels against toughness degradation during high heat input welding.
4) Solution of SCC problems and development of new materials.
5) Prevention of hot cracking in the welding of high alloy steels and metal
6) Improvement of ductility in weldment of refractory metals.
7) Improvement of weldability in joining dissimilarmetals and materials.
8) Development of new reliable solders.
9) Development of surface modification processes and materials
10) Development of repair welding processes and materials for life extension of nuclear and chemica plants,bridge, ships etc.
11) Investigation of the weldability of heavily irradiated steels and materials.
12) Investigation of bacterial corrosion of metal weldments.

References

5.1) F. Matsuda ;Science of high temperature, Nikkan kogyou Shinbun, (1988), in Japanese

5.2) F. Matsuda et al ;Development of hard surface modification with thick layer for Al and its alloys, 1st int'l conf. on Processing Materials for Properties, TMS, Nov. 7-10, 1993

5.3) F. Matsuda et al ;Weldability of Mo and its alloy sheet (Report 1), Trans. JWRI,Vol.8, No.2, (1979)

5.4) F. Matsuda et al ;SCC susceptibilities of carbon steels in high temperature and high pressure water, TransJWRI, Vol. 22, No.2, (1993)

5.5) G. Takano et al ;EB weld metal toughness for heavy section low alloy steel, Sep.(1993), IIW Doc. IX-1710-93

5.6) F. Matsuda et al :Toughness improvement of embrittled HAZ of HSLA steels welded with high heat input by means of low temperature PWHT, PACRIM WELDCON'92 (1992.6), Darwin Australia

5.7) S. Fujihira eta al : An investigation on toughness characteristics of weld metal of 50Kg/mm2 class constructional steels by high heat input ESW PACRIM WELDCON' 92

6. Joining of Advanced Materials

by Masaaki Naka**

6.1 Role of advanced materials in the technology revolution

Figure 6.1 shows the general trends of materials used historically. The structural materials such as steels and high alloying steels supported the industrial and technological revolution in a variety of fields up to the 21th century. Aluminum, titanium and plastic materials advanced engineering applications such as modern transportation system, automobile and aircraft The need to use materials in severer environments demands advanced materials such as structural ceramics and composites with superior heat and corrosion resistance. The key to further technological advance ties in the use of advanced materials.

One of the advanced materials is ceramic. **Figure 6.2** represents the estimated commercial consumption for ceramics in Japan [6.1]. The economic size of the ceramic industries in Japan [6.2] expanded from 300 million dollars in 1981 to 600 million dollars in 1983. The types of ceramic changed from oxide ceramics, such as Al_2O_3 and MgO, to non-oxide ceramics such as Si_3N_4 and SiC since these possess superior mechanical strengths.

Another class of advanced materials is composites, which are polymers metal reinforced with dissimilar materials. Typical fiberes for reinforcement are carbon and boron. Composite maaterials are classified as FRP (Fiber Reinforced Plastics) and FRM (Fiber Reinforced Metals). FRM attract special interest, since the composite metals will exhibit superior strength at elevated temperatures.

The engineering application of advanced materials requires new joining technologies. For instance, the

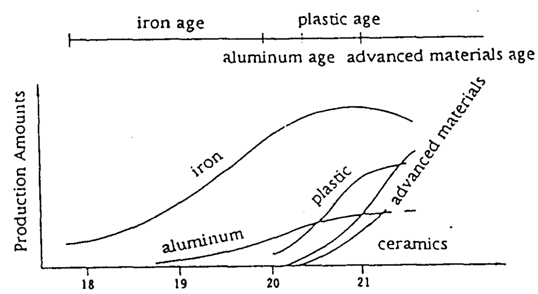


Fig.6.1 Trend materials used in engineering fields

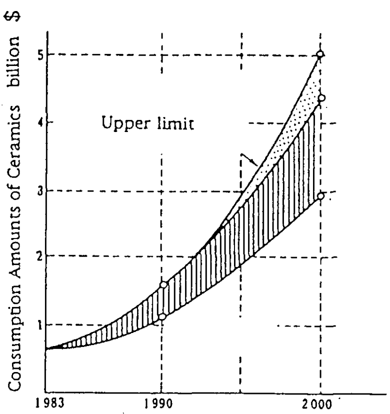


Fig.6.2 Consumption amounts of ceramics in Japan

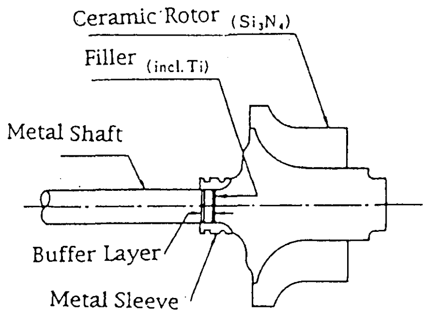


Fig.6.3 Structure of ceramic turbocharger

characteristics of ceramics which involve covalent or ionic bonding give difficulties in the joining of ceramics, compared with the joining of metals. This section describes the present state of joining in advanced materials technology.

6.2 Joining of ceramics

Successsful joining of ceramics to metals extends the practical range of application of ceramics. The highre producibility of brazing process among the various joining processes leads to its common usage in practical engineering applications. In the brazing process, molten filler between the dissimmilar materials has to form a sound bond after cooling. In the joining of ceramics, the fillers must have high wettability against ceramics during brazing, and high mechanical stength themselves after joining. Molten metals, which are often used as filler metals, in general do not wet oxide and non-oxide ceramics at though they will wet metallic materials such as steel. If the wetting ability of molten metals is improved by adding alloying elements to the metals, molten metals can be used as the filler for joining ceramics to metals. The alloying of titanium to fillers improves the wettability against ceramics [6.3]. Further the formation of compounds such as nitride and carbide resulting from reactions of titanium with ceramics also increases the strength of the joining layer [6.4].

Ag-Cu eutectic filler with 60 at% Ag containing Ti that possesses the lower melting point is used in practical applications. In order to suppress the excess reaction of titanium with Si_3N_4, the titanium content in the Ag-Cu filler is decreased to 4.5 at% [6.5], although the wetting of molten copper is improved at the titanium content of 20 at% or more. The joining mechanism of Ag-Cu-Ti alloy is similar to that of Cu-Ti alloys, and TiN and Ti_5Si_3 are formed at the ceramic/metal interface [6.6].

Filler metals containing Sn and In have also been reported in order to reduce the brazing temperature and titanium content. The precoating of Ti on SiC lowers the Ti content to 3.8 at% in the brazing of SiC [6.6]. In order to improve the heat-resistance of brazed ceramic joints, nickel instead of copper is used as a matrix element [6.7]. The SiC joint with Ni-Ti alloy shows a different dependency on Ti content, compared with its joint with Cu-Ti alloy. The higher brazing temperature in the SiC joint with Ni-Ti alloy causes the uniform distribution of TiC carbide in the Ni matrix, compared with that in SiC joint with Cu-Ti alloy [6.8]

The species and the distribution of compounds formed are important in the interface strength of ceramic/metal joint.

6.3 Application of ceramic/metal joints

Joining of ceramics, especially to metals, is applied in a variety of engineering fields from electronics to automobiles. IC substrates are metallized by the Mo-Mn process in which molybdenum powders containing manganese oxide are bonded to the surface of Al_2O_3 substrates in a H_2-H_2O atmosphere at high temperatures. A recent example of the application of silicon base ceramics to structural components is the turbocharger in an automobile to improve the fuel consumption ratio. Since the temperature of exhaust gas is high and the temperature of blade is around 1273 K, a ceramic rotor is used. [6.9]

The details of the rotor are represented in **Fig. 6.3** [6.9]. The stainless shaft is brazed to the ceramic rotor with Ag-Cu-Ti filler metal.

6.4 Joining of composites

Though elemental materials possess their characteristic properties, the combination of the dissimilar materials may display superior characteristics to those of the individual materials.

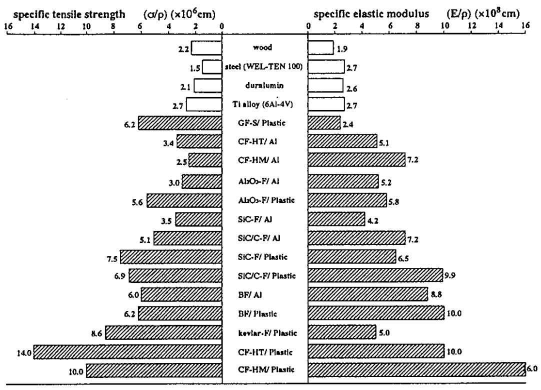


Fig.6.4 Comparison of specified strength andspecified modulus of materials

The properties of the glass fibre reinforced composite, which was first developed as a structural materials for aircraft, has attracted much interest elesewhere.

Figure 6.4 compares specific strengths and the specific elastic modulus of elemental materials and of composite materials [6.10]. Reinforcement with fibres of high strength and high elastic modulus in composites produces an improvement in the specific properties. Composites are, in general, categorised as FRP and FRM.

Metal matrix composites(FRM) possess high strength and high elastic modulus. A well known ponents in a space application is B/Al composites in the tubular components in a space shuttle,where the B/Al composites in the tubular components in a space shuttle, where the B/Al composites are joined to Ti tubes with a taper scarf join. An Al composite is easily jointed to Ti alloy by diffusion bonding [6.11] . Since the bonding of thecomposite to Ti-3Al-2.5V is good, the fracture of the joint takes place in the composite.

The Al composite can also be brazed to Ti alloy using Al-Si-Mg filler [6.11]. The C/Al plate is also joined to super plastic ally formed Ti plate by brazing. The joining of composites to Al base components is also employed during construction a piston for an automobile engine. The molten aluminum is cast to an Al composite preformed ring which possesses good wear resistance.

6.5 New joining technology

The joining of Al to Al at room temperature can be achieved in a high vacuum condition of 10^{-9} Pa, when the joining surface are impacted by ion beams[6.12]. Recent results show that two processes are involved in the room temperature joining. First, the cleaning of the joining surface and appearance of a fresh joining surface. Second, the ion beam irradiation leads to activation of the joining surface. The second process occures at vacuum pressure of 10^{-5} Pa [6.13]. This new joining technology has been applied to the microbonding of Cu balls to Ag in microelectronics applications.

6.6 Summary

The development of engineering fields requieres the use of advanced materials such as engineering ceramics and composite materials. The new joining technologies allowes the advanced materials to be used in practical enginnering applications.

References

6.1) H. Koizumi and H. Yanagida, Fundamentlls of Ceramics,Ohrmu Co.,1987,3.

6.2) ibid., 19.

6.3) M. Naka, Trans. JWRI.,21(1992), No. 1,1.

6.4) T. Tamai and M. Naka, Tenth Int. Conf. on The Strength of Metals, Japan Inst. Metals, 1994 Sendai.

6.5) M. M. Schwartz, Ceramic Joining, ASM Int.,(1990),107.

6.6) S. Ishida, Bull. Japan Inst. Metals, 29(1990), 880

6.7) M. Naka, M. Tsuyoshi and I. Okamoto, ISIJ Int 30(1990), 1108.

6.8) M. Naka and T. Taniguchi, Brazing, High Temp. Brazing and Diffusion Welding, 1992, DVS, 254.

6.9) A. Koyamada and S. Fujii, J. Japan Weld. Soc. 55(1986), No. 8, 23.

6.10) M. Moriya, Advanced Composite Materrials, K Books, 1986, 101.

6.11) C. Fujiwara, J, Japan Weld. Soc., 60(1991), No. 1, 43.

6.12) T. Funakubo and M. Akaike, J. Japan Inst. Metals, 46(1982), 935.

6.13) T. Suga, J. Japan Weld. Soc. 61(1992), No. 2, 98.

7. Welding Mechanics in Fabrication and Repair

by Yukio UEDA*

7.1 Introduction

A statistical survey of Japanese papers and reports related to welding mechanics appeared for 6 years from 1987 to 1993 is summarized according to 9 categories. During the recent economic depression in Japan, research activities have slowed down and the number of papers decreased slightly, except for works on fatigue strength.

Research on ductility, static strength and fatigue strength of joints increased suddenly in 1991. One of the main reasons was the expansion of research areas toward joining of dissimilar materials and compound materials. Another, is due to the recent ecological concerns. The idea of life extension of structures especially such as ships, bridges, nuclear power plants, etc. has been recognized and related researches have been promoted.

The technological and also social circumstances surrounding research activity are changing. As is well recognized, the development of computer technology, such as high power and speed, large storage, and low price work-stations, applied to numerical methods of analysis, such as the finite element method, the boundary element method and has enabled us to perform, eassily and rapidly, detailed analyses of complicated phenomena. This new tool has also been applied also to welding. By analyzing very complex nonlinear mechanical behavior which could not be observed directly, new valuable information has been provided.

The shortage of skilled workers and young labor in the shipbuilding industry has made it increasingly important to speed up automation and mechanization. At the same time, attention has also been given to the subject of establishing suitable new working processes, because only through appropriate working processes can the advantages of mechanization be fully utilized. To achieve automation and mechanization in the shipbuilding industry it is necessary to maintain high precision in all the assembly processes, such as cutting, bending and welding.

Another effort is exerted to substantiate the CIM (Computer-integrated-manufacture) system which requires further development in all stages of its component technologies.

These issues demand a new role from welding mechanics: For precision cutting and welding, evaluation of the influences of various factors including those hidden behind workmanship, and the prediction of deformations in advance so as to control them. In this chapter, special attention is paid to the basic subjects of welding mechanics in fabrication and repair welding.

7.2 Simulation for mechanical behavior of structural components during welding by thermal elasto-plastic analysis

In 1971, Ueda and Yamakawa published a paper [7.1] which proposed a method of thermal elastic-plastic analysis of metals during welding by a finite element method. On of the examples was bead-on-plate welds under a moving heat source. Thereafter, this new method was used to deal with phase transformation, creep

STRESS STATES	h'_{cr}/ℓ	PATTERN OF RESIDUAL STRESS DISTRIBUTIONS	PATTERN OF PLASTIC STRAIN DISTRIBUTIONS	PATTERN OF RESTRAINT STRAIN DISTRIBUTIONS
(1)	$h'_{cr}/\ell < \sigma_1^*$	elastic ($\lvert X \rvert \le 0.9$)	no plastic strain	
(2)	$\sigma_1^* \le h'_{cr}/\ell < \sigma_2^*$	elastic-plastic		
(3)	1) $\sigma_2^* \le h'_{cr}/\ell < 0.25$	full plastic		
	2) $0.25 \le h'_{cr}/\ell < 0.35$		approx. ellipse	
	3) $0.35 \le h'_{cr}/\ell \le 1$			

$$\sigma_1^* = \frac{\zeta}{(10.5 - c_1')}\frac{\sigma_Y(h_w/h)}{(E/\pi)\alpha(T_m - T_f)} \; ; \; \sigma_2^* = \frac{\zeta}{(2 - c_1')}\frac{\sigma_Y(h_w/h)}{(E/\pi)\alpha(T_m - T_f)}$$

Fig.7.1 Restraint intensity and restraint stress-strain in it weld

behavior for annealing, etc. This approach enabled us to simulate the mechanical behavior of metal during welding and annealing and provide detailed information on stress-strain in the metal which could not be observed

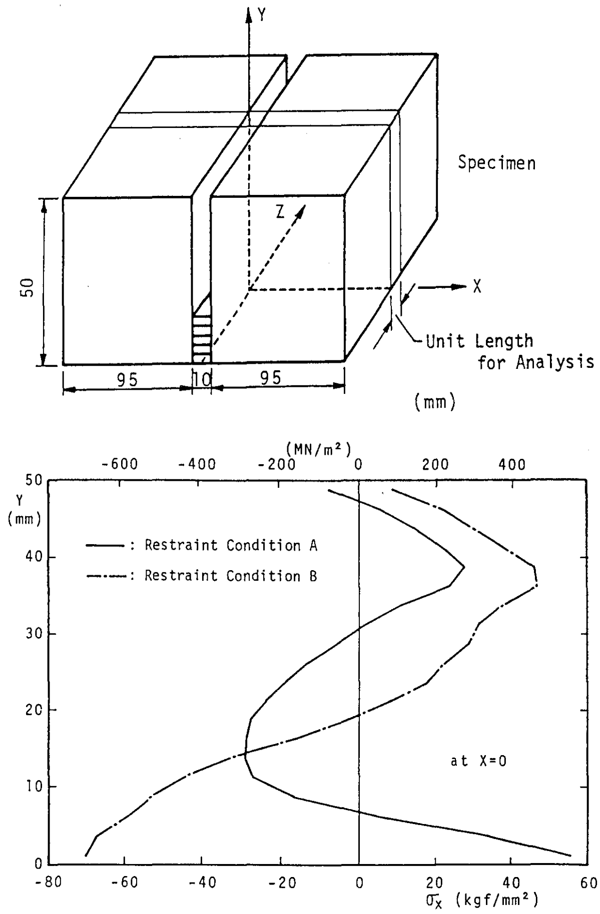


Fig.7.2 Transverse welding residual stresses produced by multi-pass welds

by experiment.
In 1988, this approach has been applied to real three-dimensional objects such as repair welds of thick plates [7.2], as a result of the low cost of calculation by super-computer. But an analysis on a large structural member by this method is still not in daily use. In order to make it possible, further advancement of high speed computers is necessary and the cost of computation mast be low. On one other hand, recent engineering work stations are very powerful and very efficient for simulation of thermal elasto-plastic analysis of small welded joints.

In the following, examples of the application will be shown.

(1) Restraint intensity and welding stress-strain

In one dimensional members, restraint intensity R is defined as $R = P/d$ where d is the shrinkage due to welding and P is the corresponding restraining force. This implies that R is a spring constant.

Restraint intensity was used widely as a measure to predict welding residual stresses before the thermal elasto-plastic analysis by FEM became a practical tool. Many examples of the FEM analyses of the relationship between the restraint intensity and restraint stress-plastic strain for two and three dimensional stress states indicate that the applicability of restraint intensity is limited but it can be used for rough estimation of the resulting residual stresses [7.3]. As advanced computers can now be used economically, research along this line will not be promoted in the future.

(2) Local stress-strain in reference to weld cracking

By the FEM analysis, detailed and fairly accurate information about thermal elasto-plastic behavior, below the mechanical solidification temperature, of a welded joint can be obtained. This method is as a powerful tool has been used to investigate the mechanism of production of welding stress and strain which may cause cold and hot cracking of a welded joint. Several examples are listed below.

a) Butt joint of plates under a moving heat source (in reference to end cracking, control of transverse shrinkage)
b) Multi-pass welding[7.4]
c) Heat-sink method for prevention of SCC[7.5](to weld the circumferential jointof pipe under water-spraying from the inside)
d) Repair weld of bridges under service condition (in reference to weld cracking to be described in [7.6]
e) Thermal and residual stress at the interface of dissimilar material.

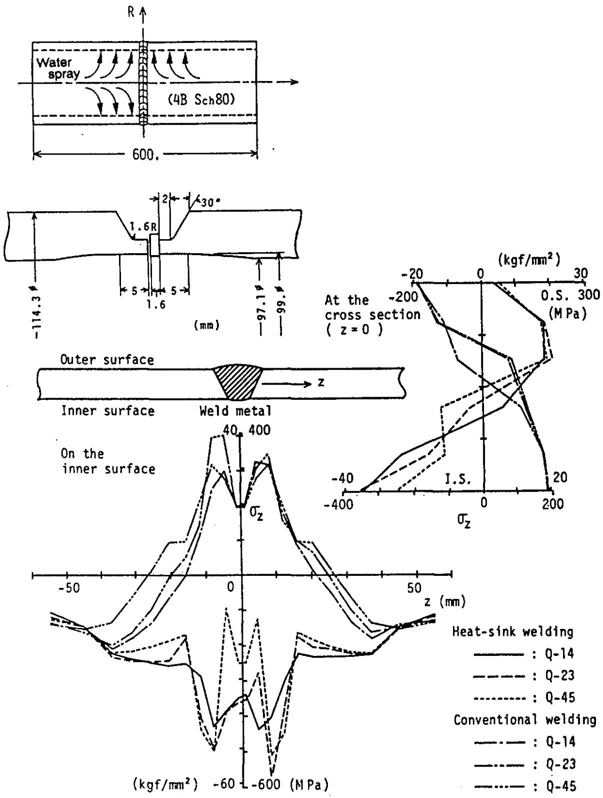


Fig.7.3 Mechanism of production of welding residual stress(Heat-sink method)

(3) Deformation

The same FEM analysis as for stress-strain can be applied to deformation. For deformation analysis, not only the limited portion including the welded portion but also the remaining large elastic part can be included in the analysis, since the deformation of the remaining part is also important consideration. Strict requirements of accuracy of the deformation means that a large portion should be analysed, sometimes in three-dimension, to deal with the effect of large deformations. The deformation analysis used to be very expensive for these reasons before the cost of powerful computers had become low, but very recently it has carried out on many examples. At present, a new concern is how to improve the accuracy of solution. To realize automation and mechanization in shipyards, it is necessary to maintain high precision in all assembly processes, such as cutting, bending and welding. Specific relevant examples can be found in all the following items:

a) Gas and plasma cutting
b) One-sided automatic welding
c) Stiffened plates due to fillet weld
d) Plug welding of machinery parts

7.3 Measurement of three-dimensional residual stress by the inherent strain Method

In spite of so many reports on two-dimensional welding residual stresses, in practice, welding residual stress is three dimensional and this is especially obvious in the case of thick plate. Actual measurement is essential,not only for verification of thermal elasto-plastic analysis, but also on real welded joints. After Ueda and Fukuda proved that the Rosenthal - Norton method was an approximate method, they proposed a new measuring method [7.5] of three dimensional residual stress by using inherent strain as a parameter (in 1975). This enabled us to measure the entire distribution without any approximation at the first time.

Inherent strain is regarded as the source of residual stress. Its important characteristics arise from the fact that inherent strain in a specimen does not change by cutting the specimen if this is performed without producing any new plastic strain. Therefore, a three dimensional welded joint can be cut into several thin specimens without introducing new plastic strains. The measurement of two dimensional residual stresses in the these specimens is then performed. With the information, conversely, the inherent strains can be calculated. The sum of these inherent strains constitutes the entire distribution. Once the inherent strains are available for the original stress-free body, the three dimensional residual stress distribution can be calculated at any point of the body. This method was later applied for the prediction of residual stress.

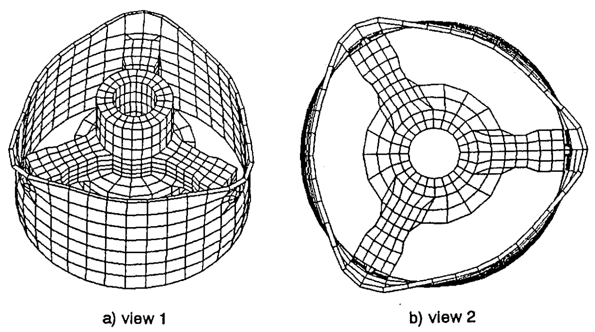


Fig.7.4 Welding deformations of machinary parts

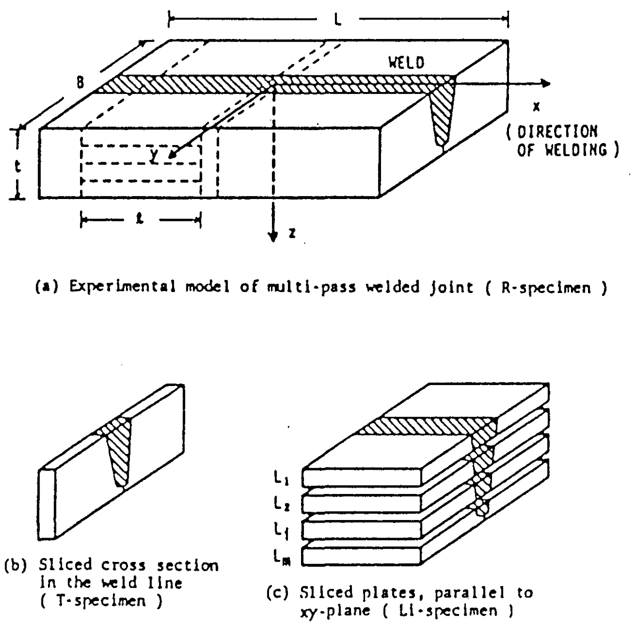


Fig.7.5 Measuring method 3-d residual stresses induced by multi-pass welds

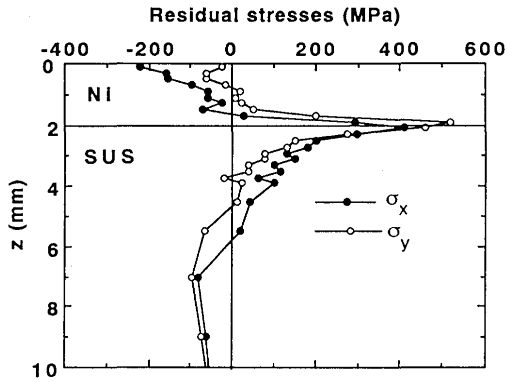


Fig.7.6 Measurement of residual stresses in claded plate

Some recent successful applications of this method to the measurement of local 3-D residual stress are as follows:

a) Multi-pass welds in thick plate [7.7]
b) Fillet welds [7.8]
c) Clad plate [7.9]
d) Thermal sprayed plate [7.10]

7.4 Prediction of residual welding stress in plate-structures by the inherent strain method

For predicting residual welding stress, the thermal elasto-plastic analysis by FEM is a powerful tool. However, it is not economical and sometime impossible to use for large-size structural members. To over comethis difficulty the characteristic of inherent strain is used for prediction of residual welding stress.

Residual welding stress may be expressed in terms ofa so-called inherent strain which exists only in the vicinity of the weld. The pattern of its distribution in plate structures is rather simple, and regardless of the kind of material and its magnitude, is rather insensitive to the first step is to decide what type and how much inherent strain should be given and in which part of the plate. The second step is to find the appropriate heating and cooling condition to produce the desired inherent strain. A method to determine the necessary inherent strain using FEM has been proposed [7.13].

7.6 Repair welding of steel structures under the service condition

The background and the problems of repair welding are discussed and several studies on repair welding under the static loads are reviewed [7.14].

On the other hand, repair and reinforcement work by welding on steel structures in service condition are often performed under pulsating loads. The hot crack, which was classified into that occaring in the solid-liquid state (called the solidification crack) and that occaring in the solid state (called the HS-type crack), initiating at comparatively high temperatures, sometimes occurs during welding under pulsating loads.

For solidification cracking, the accumulation strain, repeatedly applied to the weld metal in the short time from the liquid phase to the solid phase was proposed as a measure for deciding the solidification crack initiation under the pulsating loads [7.15]. The solidification crack initiates when the accumulation strain is larger than a critical value, which is depend on materials characteristics. The accumulation strain was expressed as the relative root gap opening displacement, Δd, whih can be easily measured before welding.

Next, for HS-type cracking, an equation which describes the initiation of the HS-type crack under pulsating loads was derived [7.16]. Based on this, a practical equation to decide the initiation of the HS-type crack was also developed, in which Δd can be easily measured before welding and then used as a measure for the crack intiation.

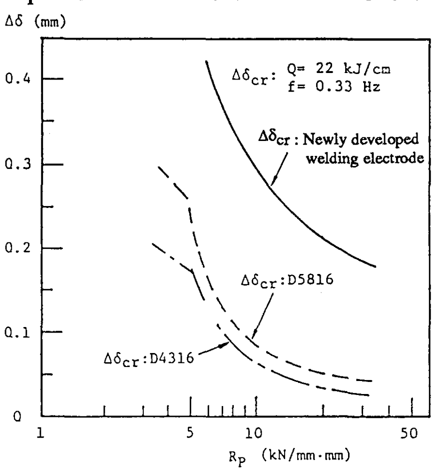


Fig.7.10 Critical root gap opening displacement, $\Delta\delta_{cr}$, for three kinds covered electrode and judging theadvisability of welding in service.

Concerning the solidification crack initiation, the main factor was the product of Δd by the external loads and repeat number. The main factor for HS-type crack initiation was the maximum strain rate (the root gapopening rate) produced by the external loads in a cycle.

By these means, a new welding electrode was developed[7.17]. From the results of weld cracking tests, the critical value of Δd of the newly developed welding electrode could be made three or four times as large as that of commonly used welding electrodes and the welding under the pulsating loads could be easily performed.

7.7 Future prospects

A variety of materials are used for products and structures of higher quality and reliability. Consequently, joining of these materials between similar and dissimilar ones becomes necessary. In order to promote automation of production processes, precision cutting and welding are also necessary. In order to find optimum conditions to satisfy these requirements, one of the key technologies is computer simulation. To achieve this aim, in every field of welding engineering, a great deal of effort is exerted. So far, the thermal elasto-plastic analysis by FEM has been well used and many new findings have been provided. For accurate simulation, one of the essential pieces of information relates to material constants in various conditions. These should be provided for realistic simulation in parallel with the advancement of fast and economical large computers.

For prediction of residual stresses and deformation in large size structures, the inherent strain method is a very powerful technique and reasonably accurate if the data of inherent strains are accumulated. So far, the entire distribution of three dimensional residual stress can be measured by the inherent strain method even for local stress of a fillet weld. Although this is destructive, it is the only rational method. This must be compared with neutron measurement.

References

7.1) Y. Ueda, T. Yamakawa, Trans. of JWS(The JapanWelding Society), 2-2(1971), 186-196.

7.2) Y. Ueda, Y.C. Kim, K. Garatani, T. Yamakita, Welding International, 2-1(1988), 33-39.

7.3) Y. Ueda, K. Fukuda, Y.C.Kim, R.Koki, Trans. of the JWR(Welding Research Institute,Osaka Univ.) 11-2, (1982), 105-113,

material and its magnitude, is rather insensitive to the size of a specimen. So residual stress can be predicted only by the elastic analysis using inherent strain as an equivalent load, as will be described in the following. As the measurement of local three-dimensional inherent strains for other types of welded joints (mentioned in 7.3) has become possible, the prediction of the residual welding stresses can also be performed using these inherent strains.

In the case of a butt-welded plate, inherent strain exists in the vicinity surrounding the weld line and its distribution is simple. In actual plate structures, such as ships, the length of plate is long in comparison with the width so that the important longitudinal component of residual stress is caused only by the longitudinal inherent strain, whose cross-sectional distibution is trapezoidal. This can be predicted from a simplified formula which was derived and is applicable to certain variations of heat input, plate sizes and material properties. Consequently, the residual stress in a butt-welded plate can be obtained by an elastic analysis of two-dimension using the predicted inherent strain [7.11].

The residual stress distribution in an I-joint can also be calculated by imposing the inherent strain predicted for a butt-joint in the same sequence as the actual welding process, by adjusting the effective heat inputs of fillet welds to be equivalent to butt welds [7.12]. Therefore, this method may be applied to predict the entire distribution of welding residual stresses in a large structure.

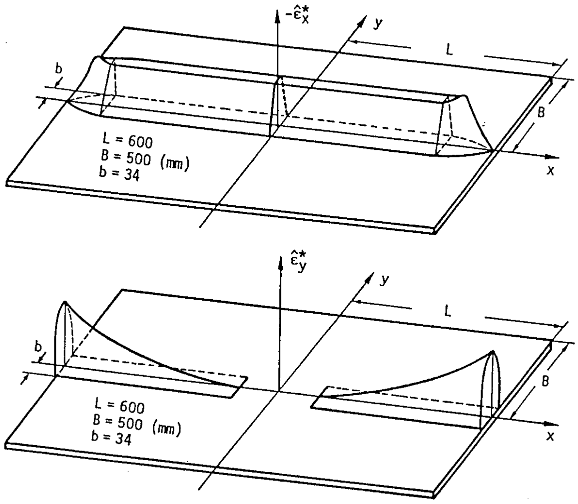


Fig.7.7 Longitudinal and transverse inherent strains (ε^*_x and ε^*y)

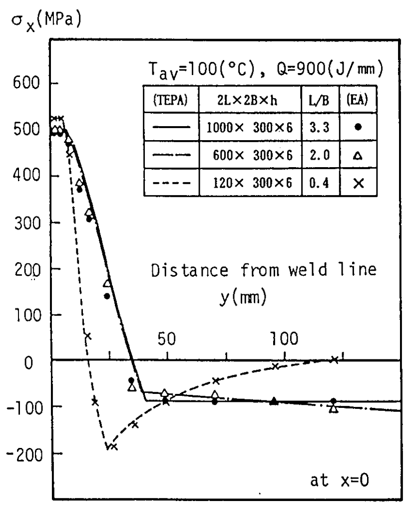
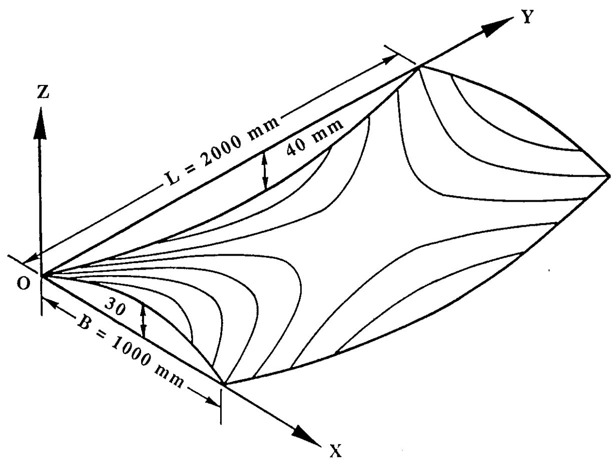


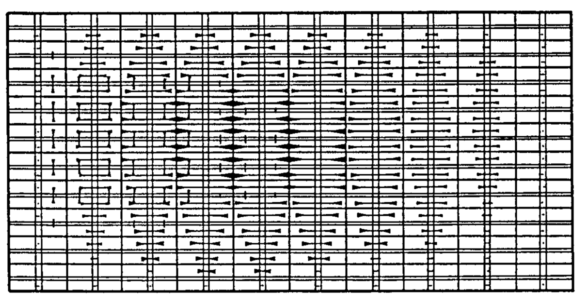
Fig.7.8 Residual stresses by proposed method and TEPA.

7.5 Development of a computer aided process planning system for plate bending by line heating

Plate bending by line-heating can be considered as a process in which plates are bent to the three dimensional form by the inherent strain (plastic strain) caused during the gas heating and the water cooling. The inherent strain can be divided into the bending and the in-plane components. Therefore, the task of process plan making for plate bending can be separated into two steps. The



(a)Geometry to be achieved



(b) Generated orthogonal compressiveinplane inherent strain

Fig.7.9 Plate bending by line heating

7.4) Y. Ueda, K. Fukuda, K. Nakacho, E. Takahashi, K. Sakamoto, 3rd Int. Conf. on Pressure Vessel Technology (ASME), Part II, Materials and Fabrication (1976), 925-933.

7.5) Y. Ueda, K. Nakacho, T. Shimizu, Trans of the ASME,J. of Pressure Vessel Technology, 108(1986), 14-22.

7.6) Y. Ueda, K. Fukuda, K. Nakacho, S. Endo, Trans. of the JWRI,4-2,(1975),123-131 and Theoretical and Applied Mechanics, 25(1977), 539-554

7.7) Y. Ueda, K. Fukuda, Trans. of the JWRI,8-2(1979),224-256 and Trans. of the ASME, J. of Engineering Materials and Technology, III(1989), 1- 8.

7.8) N.X. Ma, Ph.D. Dissertation, Osaka Univ., (1944) (in Japanese).

7.9) Y Ueda, N.X.Ma, Trans. of the JWRI,23-2, (1994),1

7.10) Y.C. Kim, T. Terasaki, T.H. North, ASM, Proc. of 4th National Thermal Spray Conf., (1991), 221-227.

7.11) Y. Ueda, M.G. Yuan, Trans. of the ASME J. of Engineering Materials and Technology, 115(1993), 417-423.

7.12) Y. Ueda, M.G. Yuan, Trans of JWRI, 22-1,(1993), 157-168.

7.13) Y. Ueda, H. Murakawa, A.M. Rashwan, Y. Okumoto, R. Kamichika, Trans. SNAME, J. of Ship Production, 10-1(1994), 59-67.

7.14) K. Horikawa, H. Suzuki, Trans. of JWRI, 14-2(1985), 375-383.

7.15) Y.C. Kim, I. Imoto, Y. Nakanishi, H. Suzuki, K. Horikawa, Trans. of JWRI, 21-2(1992), 293-298.

7.16) Y.C. Kim, I. Imoto, Y. Nakanishi, K. Horikawa, Trans. of JWRI, 22-2(1993), 315-320.

7.17) I. Imoto, Y.C. Kim, Y. Nakanishi, K. Horikawa, Quarterly J. of JWS, 9-2(1991), 294-298 (in Japanese).

8. Computer Aided Fabrication of Steel Construction

by Kohsuke HORIKAWA**

8.1 Introduction

Automation or robotization are being rapidly introduced into fabrication of steel construction. This has been considered as hard to do because of the variety of structural components and the small size of production units. The aims of automation, in general, are as follows;

1) To increase profits through lowered cost, and market-enlargement by more mass-production.
2) To allow certain work under extreme environments such as in vacuum, space, under nuclear radiation as well as in areas too small for a human being to work. In this case, the expenditure to introduce the new systems becomes a secondary factor.

As for steel construction, however, the main purpose of automation is not the above, but is to compensate for the shortage of skilled labor. Therefore, automation ha to compete in cost with un-mechanized labor-intensive fabrication.

It is interesting that the introduction of robots began from the fabrication of building structures where investments are around US$ 1 million, then in bridge fabrication where it costs US$ 10 million and lastly in ship building, where it is estimated US$ 100 million, are invested.

8.2 Fabrication of steel structures for buildings

Automation by welding robots has been developed steadily over the last 10 years, and has removed the difficulty caused by a wide variety of components and small quantity production units through generalization of sensing techniques and off-line teaching methods.

More than 20 robot makers now produce welding robots for corner welding of columns and beam-column connections.

Simple linear slide robots and specialized robots for beam-column connections with the combination of multi-axial manipulators and positioners are extensively used.

Table 8.1 shows the types of robots and their applications. **Figure 8.1** shows a linear slide multi-pass welding robot system for core assemblies.

For fabrication of built-up box columns, mechanization is rapidly developing and at each stage of assembly, welding (corner joints and diaphragm setting) as well as drilling comes in to the production line,

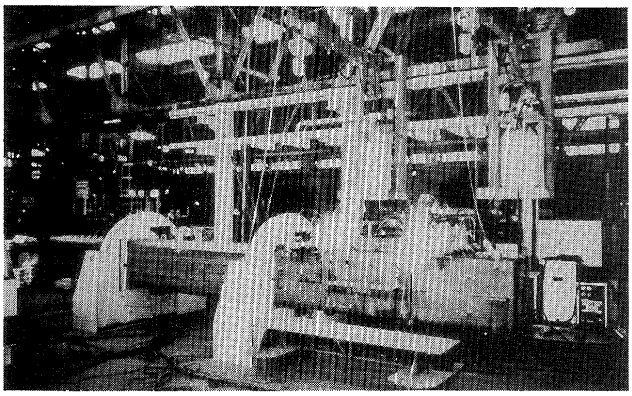


Fig.8.1 Liner slide multi-pass welding robot system for core assembly

Table 8.1 Type of Robots and application

Application	Type of Joints	Welding process	Type of Robot	Structure of Robots
Corner joint of box column	Butt	MAG SAW	Stationary	Cartesian-axes Multiaxes+Manipulator
Built-up H	Fillet	MAG	Stationary	Cartesian-axes Multiaxces+Manipulator
Beam-column connections	Butt	MAG	Stationary	Cartesian-axes Multiaxes+Positioner
Bracket	Butt	MAG	Portable Stationary	Linear slide+Carriage Multi-axes+Positioner
Diaphragm of box column	Butt	MAG & Electroslag	Stationary	Cartesian-axes+Carriage

systematized under numerical control (N.C.).

The welding method many users need to put into practical use, is probably that for Steel-Reinforced Concrete (hereafter: SRC) connections. Welding robots have been used in many fields, but most of the SRC connections have not been welded by robots.
have been used in many fields, but most of the SRC connections have not been welded by robots.

A critical reason is that it offers little benefit for engineers to teach the robots how to weld like usual systems. In other words, a high by functionalized system of robots is expected to be developed to cope with the variation of shape and size of SRC connections. Efforts have been made to introduce new technology, for example, the welding system which provides control data of welding robots automatically, taking advantage of the CAD data which the fabricator possesses.

8.3 Fabrication of steel bridges

Table 8.2 shows the automation needs and introduction processes for the fabrication of steel bridge components, prepared by the Construction Division, Japan Welding Engineering Society. The present system is still transitional from the second stage to the final. **Figure 8.2** shows a vertical fillet welding robotfor transverse rib of steel deck structure.

The fabrication process of a steel bridge can be divided into the fore-stage and the rear-stage. The fore stage is to work on the steel plate. The main processes of this stage are cutting, welding, pressing for straightening and drilling. The feature of the fore-stage process is that it is not influenced by the variety of the components. The problem is that how to connect it to the automated system of design and full size drawing, especially through on NC-device.

Rationalization is also important. It is, for instance, important to decrease the work of turning and shifting of steel plates, and the dynamic connection by conveyer line in each process and introduce a production line which synchronizes contact-time.

The rear-stage is the process of assembling, welding, straightening, and finishing of the structure after the fore-stage fabrication. The feature of the rear-stage is that the automation is restricted by the size and shape of structural components. Especially in welding, the type of weld joints and spatial constraint conditions are different according to whether plate girder, box girder, steel deck, truss and steel pier are involved, so that general and systematic automation and robotization of welding has been almost impossible.

However, efforts have been made. First, from the view point of assembling and welding, spatical constraint conditions of each component are grouped into plate-panel component, open-section component and closed-section component.

Plate-panel components relate mainly to the steel deck. They have a welded joint on one side and few spatical constraints, so it is easy to adopt an automated system of welding, and these are widely used.

An open-section component occures in a plate girder. It has welded joints on both sides of the plate. Automation will be possible when a device for turn-over is provided in the automatic welding system.

Closed-section components occar in box girders or piers. As most welded joints are in a closed section, spatial constraint is strict, and automation of welding is extremely difficult. However the amount of welding is overwhelmingly large in rib joints on flanges or stiffener joints on webs. So, welding of closed-section components are also included in welding systems for plate panel components. If welding of ribs and stiffeners are finished before assembling, and if erection methods are adopted where flange and web are assembled like panels, then the closed section component resembles the plate panel one.

Table 8.2 Automatization needs and introduction processes

Automitization Needs	Introduction Processes
[Pre-liminary stage] •To improve deposit efficiency •To supply welding consumable automatically •To decrease fatigue of welders •To weave automatically	SMAW ⇓ Semiautomatic GMAW ⇓ Automatic GMAW&SAW
[1st stage] •To trace groove automatically •To operate multiple welding torch by one operator •To improve quality of welds	Simple carriage ⇓ Mechanical sensor ⇓ Touch sensor with feed back system ⇓ Monitoring of welding conditions ⇓ Multi-torch welder on gantry
[2nd stage] •To control starter and crater automatically •To weld multi-layer continuously by automatic setting of torch angle,location and layers •To set welding conditions automatically •To weld different positions continuously •To set welding condition for multiple joints on-line (monitor-free operation)	Traveling carriage with location detector ⇓ Sequence robot ⇓ Play-back robot ⇓ Off-line teaching robot ⇓ On-line teaching robot ⇓ Numerical controlled robot
Final stage] •To operate welding and operate simultaneously •To feed in and feed out of works synchronized with welding •To achieve human less fabrication	Systematization of multi-stage processes ⇓ Automatized line assembly ⇓ Human-free shop

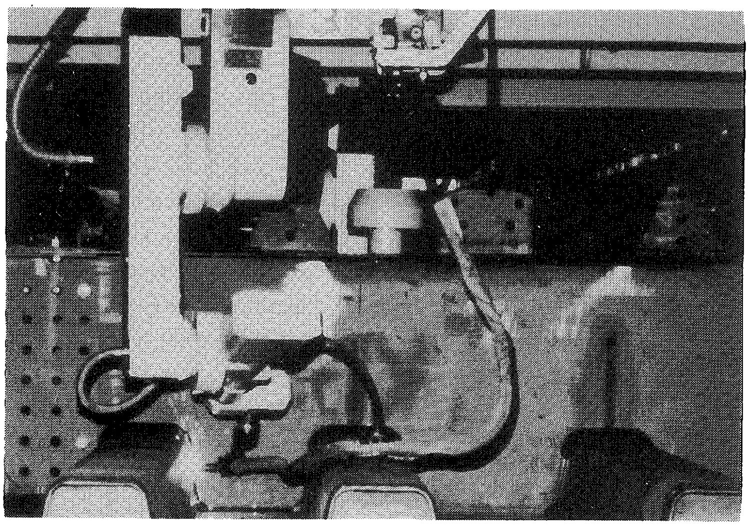


Fig.8.2 Vertical fillet welding robot for transverserib at steel clack

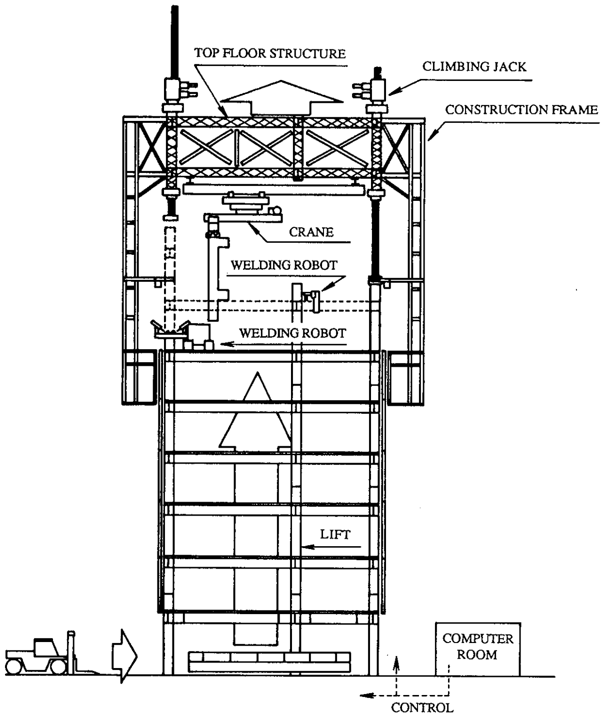


Fig.8.3 Computer aided system for building construction

panels, then the closed section component resembles the plate panel one.

The designs are given to the fabricator as a book and the data are input again in order to use NC-data.Computers are also used in the design stage, whether it is CAD or not. So, if these data can be delivered to the fabricator by appropiate means, like diskette etc., it will be compatible with CAD/CAM, and it may be the first step towards FA or CIM.

8.4 Computer aided systems for building construction

Several construction groups are now developing a computer aided system for building construction on site.

The main concept of the system is as follows (Fig. 8.3);

1) Top floor structure with the roof is constructed by the conventional techniques.
2) This structure is raised by means of climbling jacks.
3) Structural members of the subsequent floors are)at first installed by lifts and cranes.
4) The members are connected by welding robots.

All climbing jacks, lifts, cranes and welding robots are controlled by a host computer.

By using these systems, building construction on site is expected to be possible under any weather conditions.