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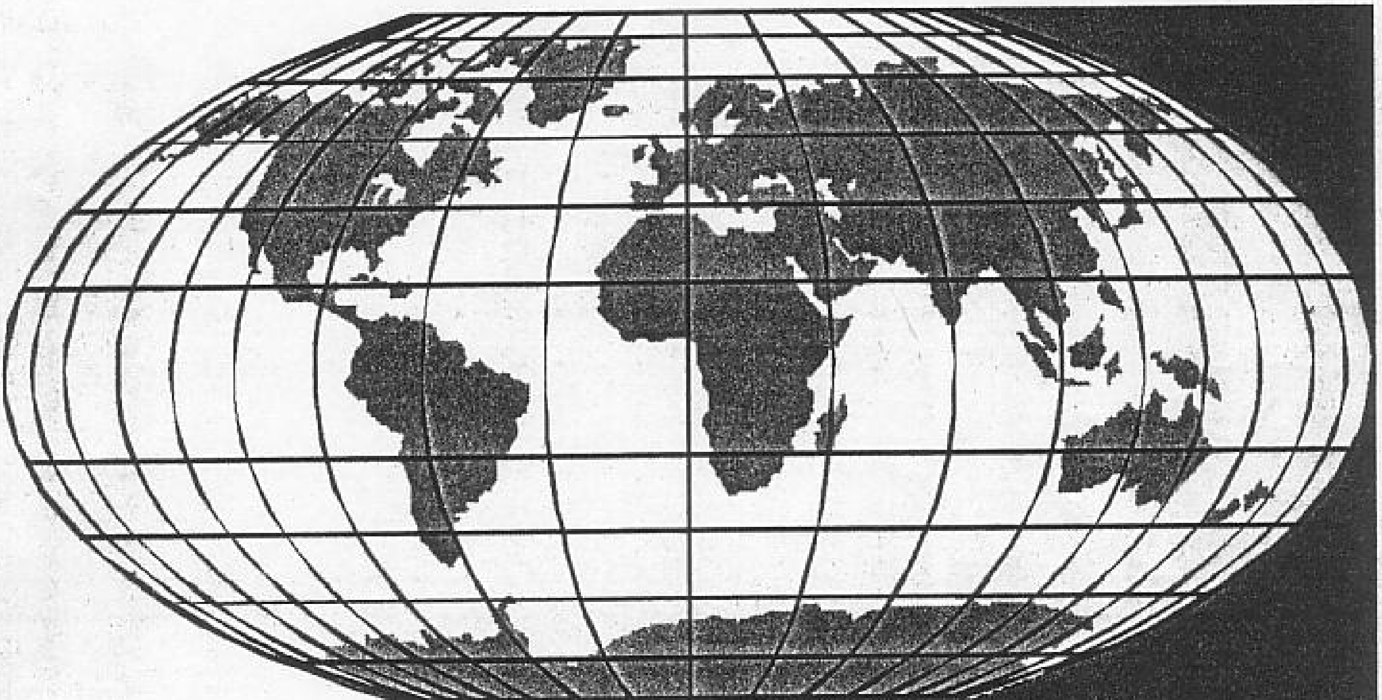
Prague, Czech Republic, 14 – 15 July 2005



Development of Advanced Laser Integrated Manufacturing System (ALIMS) and Laser Roll Welding of Dissimilar Metal Joint

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Abstract

High power lasers, including CO2 laser, Nd:YAG laser, Excimer laser, Diode laser, LD pumped YAG laser, LD pumped Disk laser, LD pumped Fiber laser and Femto second laser are now used as a modern tool for industries as well as a computer in 4th wave of modernization (21 century). Lasers are currently used for welding, cutting, drilling, cladding, direct fabrication, marking, cleaning, micro-machining peening and forming of materials in modernized factories. The joining speed (= welding speed x penetration depth) of 45,000mm2/min for steel sheet can be obtained by a 10kW Yb doped fiber laser and is the same as that of 50kW electron beam welding, which require the vacuum chamber. As a result of large numbers of research and developments, the Advanced Laser Integrated Manufacturing System (ALIMS) has been developed and used for modernization in many industrialized countries.

The laser materials processing is now penetrated as a manufacturing tool into many industries. In the present paper, high power laser manufacturing systems and its applications to industries such as automotive, electronics, ship building and steel making industry are introduced. In addition, development of advanced laser integrated manufacturing systems using 2kW fiber lasers for welding a car panel and Laser Roll Welding system for dissimilar metal joint of mild steel/high strength steel to aluminium alloys is described for modernization of industries. It will be a magnificent tool for the industries. And the 4th wave of modernization/civilization will be promoted more by laser/photon technology with electronics and mechatronics.

KEYWORDS

Advanced laser integrated manufacturing system(=ALIMS),High power lasers, Remote welding, Hybrid welding, Laser roll welding, Dissimilar metal joint, Joining of Steel to Aluminium

1. Introduction

In the book " The 3rd wave " by Alvin Toffler, the information intensive society and mecha-tronics was closed up in 1980s. After laser development in 1960, the spectrum of laser technology and the applications in our society has considerably been enlarged from information technology to medical uses. For instance, laser materials processing, including hardening, drilling, cutting and welding to cladding, micro removal marking, cleaning and soldering, has been introduced to automotive industry since 1971.

Nowadays, new high power lasers for materials processing are developed day by day. 100W-10kW Yb doped fiver laser with good beam quality (0.4-13mm/mrad) was developed for materials processing including micro and macro fabrications). Research and development of the laser technology is now taken place in China, South East Asia, South Africa, Mexico and Egypt for modernization of their industries and society. It is well known that the attractive features of lasers for materials processing are as follows;

(1) High power density
(2) Wide range of wavelengths from ultraviolet to far infrared and of pulse duration
(3) Precision machining with fine beam
(4) Low heat input and minimum distortion
(5) Easy to transfer the beam for FA and LA

(6) Clean power source without mass

(7) High productivity with short interaction time

(8)High flexibility using an optical fiber .

The author can suggest the 4th wave of manufacturing system which will be promoted by laser (photon) and electron for 21 century.

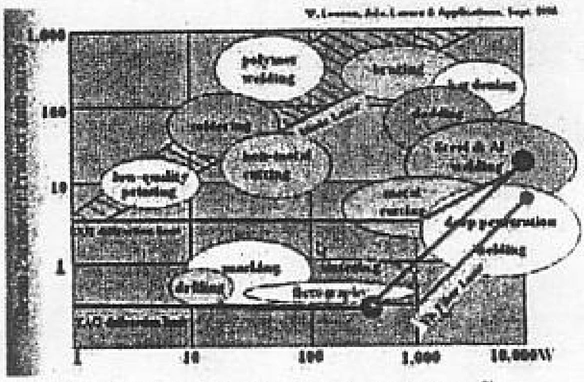


Fig.1 Beam quality of different lasers [2)]

2. Developments of new high power lasers

2.1 High Power Diode Laser

In last decay, great advancements on high power laser facilities and systems for laser materials processing have made in development of high power diode laser and LD(laser diode) pumped solid laser including Nd:YAG laser, Yb doped Disk and Yb doped fiber laser. Commercial 4kW diode laser, 6kW LD pumped YAG laser, 4kW Disk laser and 10kW Fiber laser, which are available now for production line. The relation between beam quality(Beam Parameter Product) and laser power is shown in Fig 1. Diode laser has low quality beam. However, recently, high power diode laser with high quality beam was developed by effective optical accumulation of laser arrays as shown in Fig.2. The beam spot size is 0.8mm in dia. Two sheets of 0.7mm thick steel can be lap welded at a welding speed of 2.7m/min[3)]. The laser is available for welding, cutting, cladding and surface treatment such as paint stripping using a robot as shown in Fig.3[4)]. The advanced laser integrated manufacturing system is small like a welding robot system.

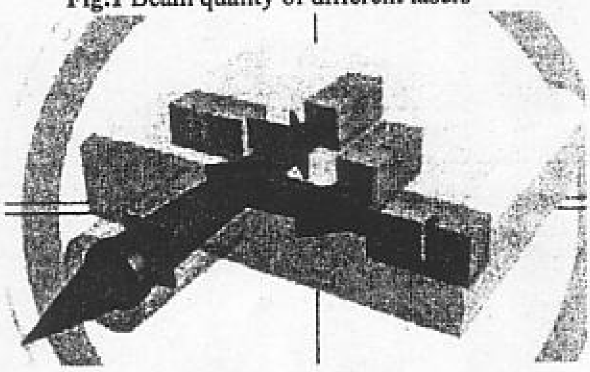


Fig. 2 High power, high quality diode laser [3)]

Fig.3 Diode laser on a robot [4)]

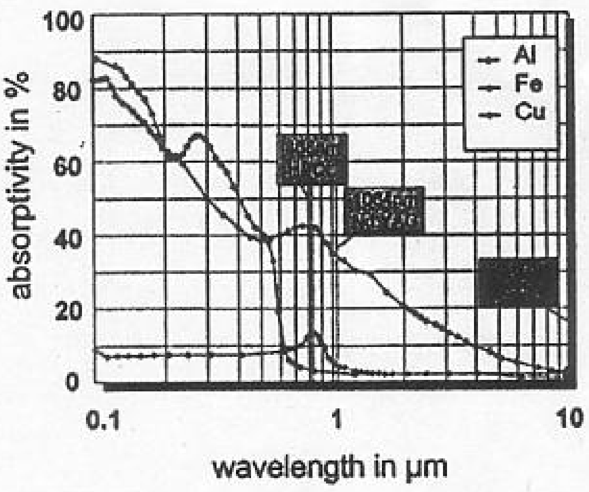
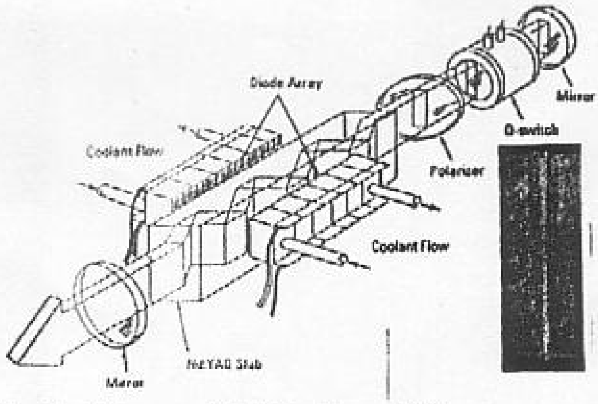


Fig.4 Laser absorption to metals at different wave length [5)]

2.2 LD pumped YAG laser

LD pumped Nd:YAG laser are now in production line. the laser has high efficiency of 20% - 30%. The life of laser diode is about 20,000hours. The absorption of laser to metal is higher than those of CO2 and YAG lasers as shown in Fig.4. 4-6kW LD pumped YAG laser is developed by national project in Germany, USA and Japan. 6kW LD pumped slab type YAG laser was developed in US project of Laser Precision machining for future production system as shown in Fig.5[6)]. 65mm thick steel plate can be welded in one pass at the travel speed of 3cm/min [7)]. The bead width is about 2mm and the distortion is very small. Precision welding is available by this type of laser in heavy industry.



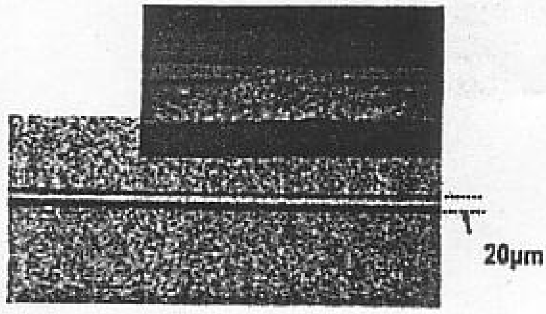


Fig. 5 LD pumped slab YAG laser [6) 7)]

Fig. 6 Micro welding of stainless sheet (t=10 +40 μ m)by 10W fiber laser[8)]

2.3 10W-10kW Yb Fiber laser

A low power fiber laser has developed in1961 and used for communication. Recently 10-100W small power Yb fiber has been rapidly developed for micro fabrication like micro soldering and micro joining as shown in Fig.6 [8)]. High power Yb doped fiber laser has been rapidly developed since 2001. The mechanism of new fiber laser has two core fibers as shown in Fig. 7. Diode laser beam was introduced into inner core fiber in which Yb was doped for excitation.

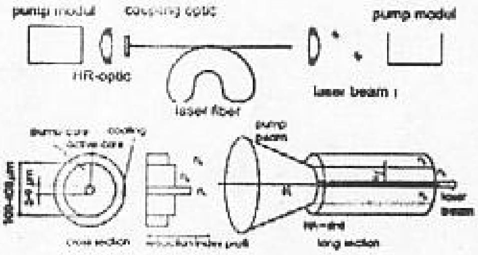


Fig. 7 Mechanism of high power fiber laser [9)]

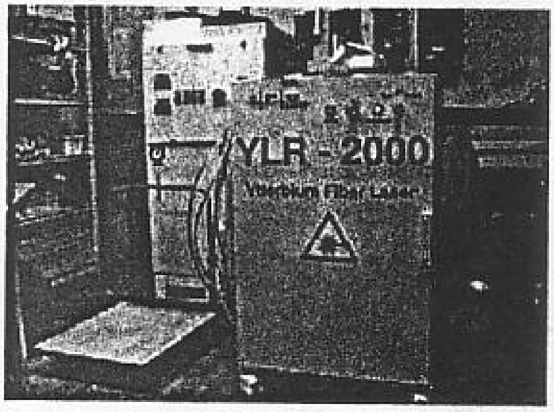
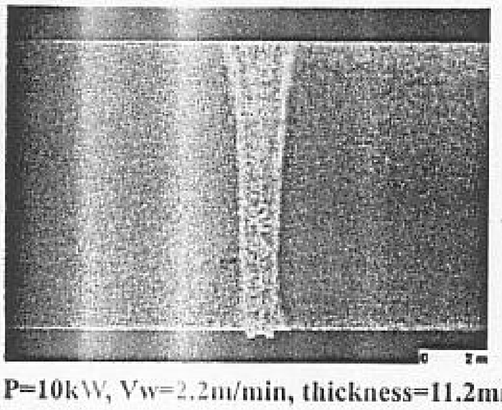


Fig. 8 2kW Fiber laser facility and chiller[10)]

The diameter of inner core is 100 nm – 200nm for 1-10kW power [2)]. Fig.8 shows 2kW Yb Fiber laser which was installed in Nagoya University last year. It is very small size,630wx808Lx1036h(mm). . The core diameter is 100 μ m and the BPP is 4.4 mm/mrad. The life time is about 10,000hours. The penetration characteristics of high power fiber laser is better than that of diode laser or Nd:YAG laser as shown in Figs.9and 10 [2)11)].



P=10kW, Vw=2.2m/min, thickness=11.2mm

Fig.9 Full penetration welding of carbon steel by 10kW Yb fiber laser [2)]

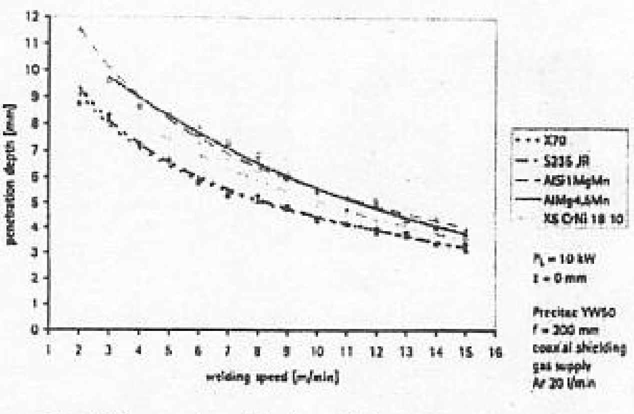
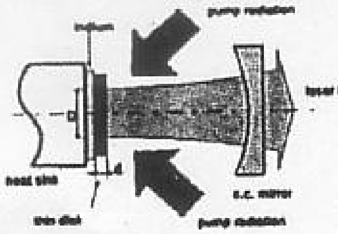
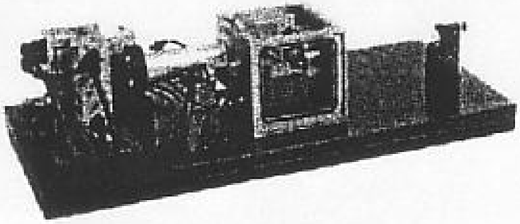


Fig.10 Penetration depth at different welding speeds in welding of steel by fiber laser[2)]

2.4 High power disk laser





(a) Mechanism of high power disk laser (b) 1.5kW disk laser

Fig.12 High power disk laser [12)13)]

High Power disk laser was developed by Dr Giessen of Stuttgart university in 2001 using diode laser beam as shown in Fig.12. This laser has a small and thin (0.2mm) disk of YAG doped with Yb. Diode laser was reflected between the disk and special mirror to generate the high quality beam. The quality is the same as that of fiber laser. High power beam was generated by several units as shown in Fig.12(b). 4kW Disk laser was developed and tried to use for scanner welding of car panel. Fig.13 shows the " Joining Speed "(= welding speed x penetration depth) of different welding processes[14]. The joining speed of a 10kW fiber laser welding is 45,000mm^2/min. It is the same as that of 50kW electron beam welding, which require a vacuum chamber.

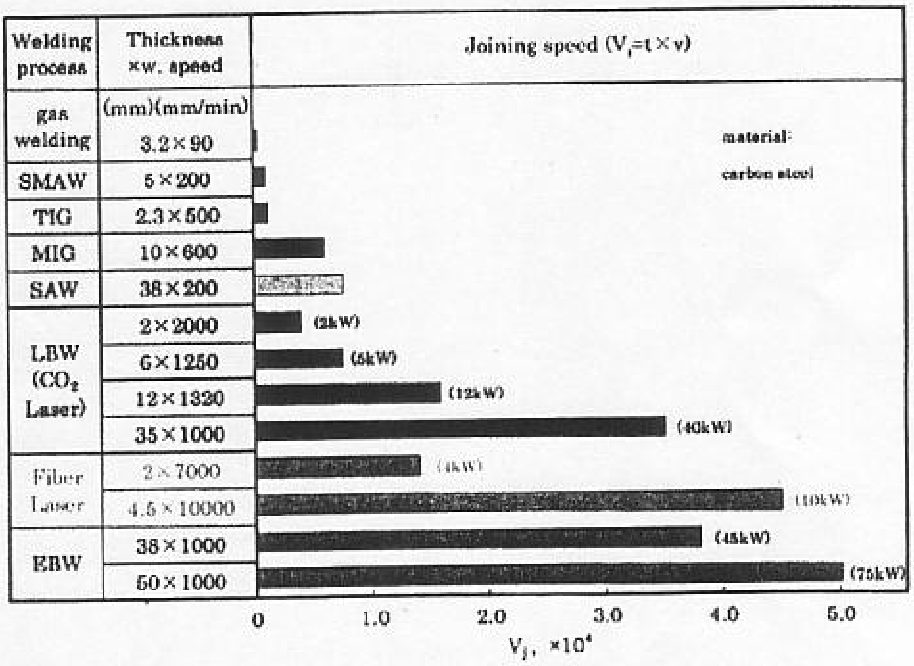


Fig.13 Joining speed of different welding processes

2.5 Ultra-short (fs) pulse laser and excimer laser

In the field of semiconductor industry and microelectronics, nano technology and micro fabrication (MEMS) are important. Ultra-short (20-50fs,femto second) pulse laser and excimer laser are available for micro-fabrication and MEMS. Micro-fabrication of inorganic materials such as diamond, glass and silicon is possible by ultra-short pulse (or Femto second) laser. In this process, no thermal stress and crack are caused during the process, because of lack of time for heat

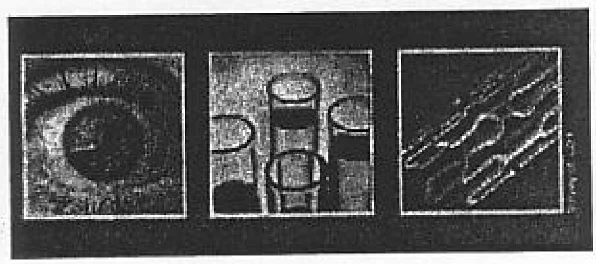


Fig.14 Examples of applications of femto second laser [15)]

transfer. Fig.14 shows the applications of femto second laser.

3. Applications of laser materials processing

3.1 laser applications to automotive industry

In automobile industry the first application of laser processing was laser cutting of coil paper for motor in 1971 and second one was laser hardening of gear housing of diesel engine by General Motors, Saginaw plant in 1973[16]. Tyssen Steel Co. started to supply under body panel of zinc coated steel to Audi Motor Co. after laser welding of the panel since 1986. Many application of laser processing were developed as follows since 1971:

(a) Laser welding: automatic transmission parts (gear, planet carrier, tappet housing), stator core of motor, and pulley, tailored blanks for door panel (shown in Fig.15), underbody panel, sun roof and center pillar, 3D on-line welding of roof to door panel (shown in Figs.16 and 17) and of trough panels, fuel tank, muffler, injector and break plates, plastic parts (key holder, intake manuhold) (shown in Fig.18)

(a) Laser cutting and drilling: cutting of proto-type car body panel, steel panels/parts and polymer parts, antenna hole for radio antenna , drilling of cum shaft and locker room

(b) Laser surface treatments: hardening of rotor shaft, cladding of engine valve and valve seat (shown in Fig19)[21]

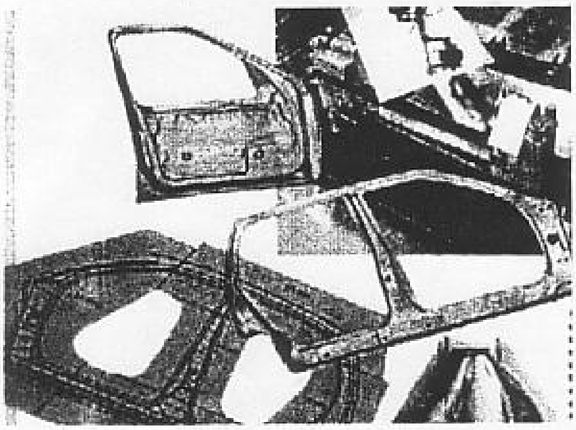


Fig.15 Welding of tailored blank for car(TWB Co)[17]

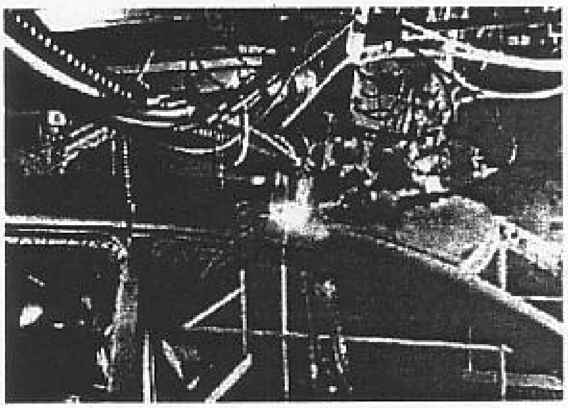


Fig.16 3D laser welding of car body on-line[18]

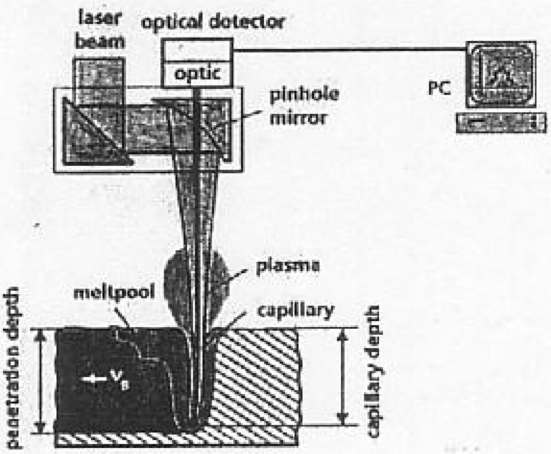


Fig.17 Monitoring system for laser welding using Coaxial Optical Control or CMOS camera[19]

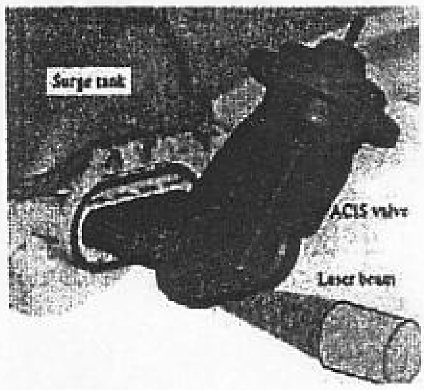


Fig.18 Laser welding of intake manuhold[20]

Fig.17 shows the monitoring system for laser welding called as coaxial optical control which was developed by Fraunfoher Laser Institut Aachen. This system is available for detecting penetration depth, weld defect and seam tracking[19].

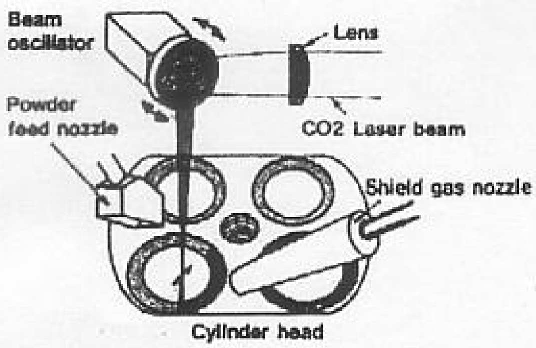


Fig.19 Laser cladding of valve seat for engine (Toyota Motors Co)[21)]

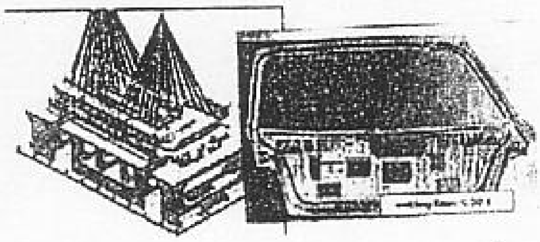


Fig.20 Remote laser welding of rear swing door (Clysler -Utica, Us 2000) [22)]

Remote laser welding has great advantages of high speed welding and ultra short space-cutting time using X-and Y- galvano mirrors. The welding speed is about 7m/min to 15m/min. The welding time are less than 30 seconds for welding of swing rear door shown in Fig.20 and 5 seconds for welding of small car parts (20 welding seams) shown in Fig.21, respectively. The shielding gas is required for good quality of welds. If welding time is compared, remote welding has advantage in total welding time. Especially in welding of complex part like heat exchanger. No robot is required for remote welding. Mirrors are enough for moving the laser. beam. In our laboratory, a remote welding system using fiber laser and robot is under developing as an ALIMS for future.

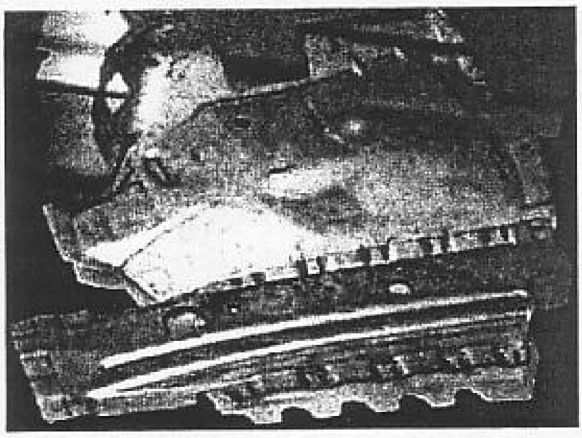
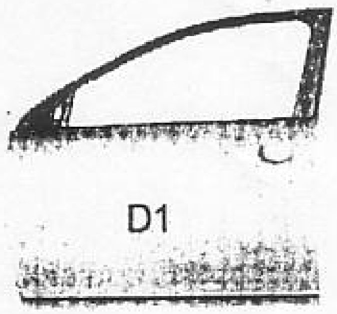


Fig. 21 Remote laser welding of car parts(BMW) [23)]

Laser-MIG/MAG hybrid welding is convenient for welding of stamped panels which have large amount of joint gap. Because allowable joint gap is increased by adding the filler wire into the key hole. 0.3 mm or 0.5mm gap can be allowed for 2 or 3mm thick plate. Hybrid welding has following advantages;

1) High welding speed due to deep penetration
2) Low distortion due to low heat input
3) Smooth bead appearance
4) Large allowance for joint gap
5) Control and modification of weld metal to decrease weld defects (crack and porosity)

Volkswagen has developed CO2 laser-MIG hybrid welding for joining car door of aluminum alloy in 2000 as shown in Fig.22 . Laser-Arc hybrid welding is introduced to weld door panel in weld length of 3.57m per door instead of MAG arc weld length of 0.38m per door. And Volkswagen AG are converted from spot welding to laser welding in their assembly line of under body also.



Process	amount of seams	welded length
MIG	7 seams	(380 mm)
Laser	11 seams	(1030 mm)
Laserhybrid	48 seams	(3570 mm)
Σ		4980 mm

Fig. 22 Hybrid welding of car door panel [24)]

3.2 The applications to ship building industry

In May 1996 at Glasgow in Scotland, an international conference on "Exploitation of Laser Processing in

Shipyards and Structural Steelwork" was held . A draft of guidelines for the approval of CO2- laser welding for ship construction was presented by five European ship bureaus which permit the use of laser welding of ordinary butt and fillet joints.

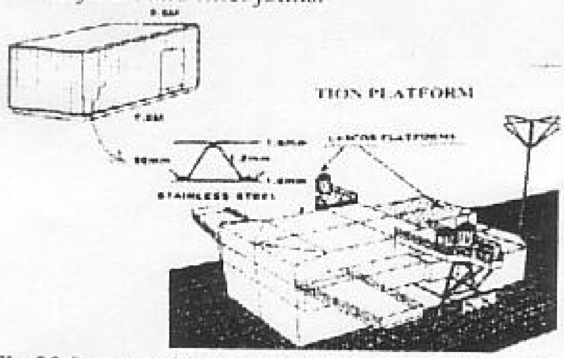


Fig.23 Laser welded sandwich panel structures of stainless steel for frigate ship (UK Navy) [25]

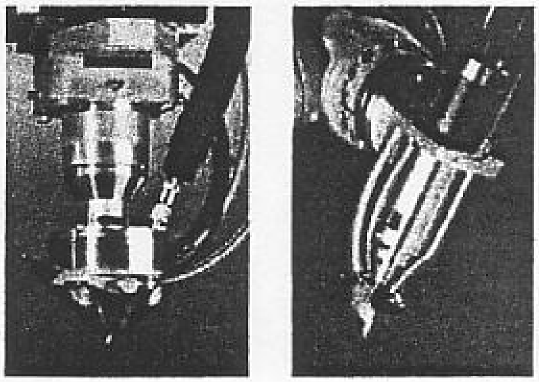


Fig. 24 Hybrid welding torches for fine and heavy duty (Frauhofer Laser Inst.) [26]

Recently Light panel is used to decrease the weight of high speed ships (cruising and frigate ship etc) as bottom and upper deck panels. These sandwich light panels are now laser welded because of thin steel sheet. Fig.23 shows the upper structures of frigate ship which was constructed by laser welded sandwich panel walls. Hybrid welding can be used for manufacturing of sandwich panel. Fig.24 shows the torches.

There are many types of hybrid welding such as CO2 laser –MIG hybrid, CO2 –MAG hybrid, CO2 – TIG hybrid, YAG – TIG hybrid, YAG - GMA hybrid, CO2 laser – Plasma hybrid, etc. Mayer Werft Shipyard AG applied CO2 laser- MAG hybrid welding using 4 set of 12kW CO2 lasers as shown in Fig. 25.

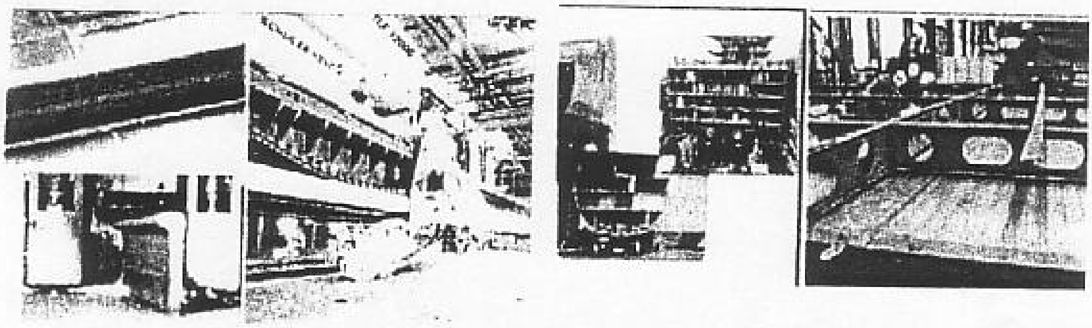
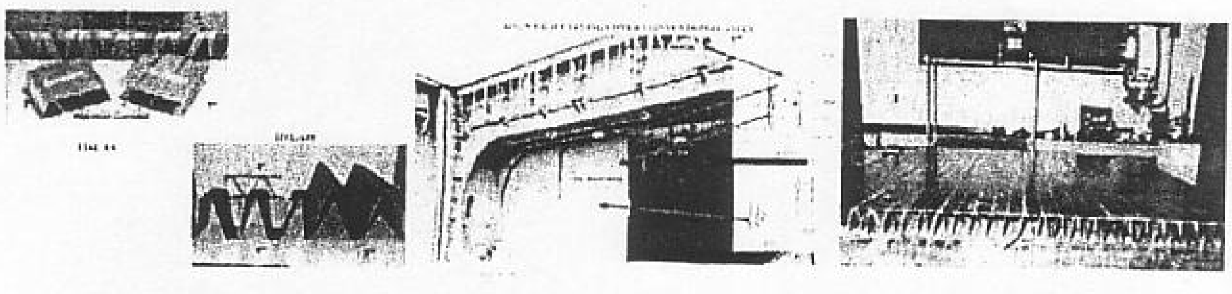


Fig.25 Hybrid welding of ship structures(MayerWerft,Germany) [27]



(a) Laser welded sandwich panels (b) Door using sandwich panels (c) Flight deck using sandwich panels.

Fig.26 Sandwich panels and its applications for reducing weight of ship structures [28]

Sandwich panel of ship structures are welded by laser for US Navy ship now. As shown in Fig.26 [28]
It includes fleet applications for flight deck, door/wall/floor panels and hatch cover. 40% weight reduction was possible in hatch cover. Automated system for laser forming of hull segments was also developed by Applied Research Laboratory of The Pennsylvania State University[29]

3.3 The applications to aircraft industry

Today riveting is the standard process to join the parts in manufacturing aircraft.. But Airbus Co has developed new manufacturing system to join the stringers to skin plate using laser welding with filler (Al-12%Si) after changing the Dualumin to A6013HDT-H4 alloy as shown in Figs.27 and 28. The cost saving is 40% of fabrication cost.

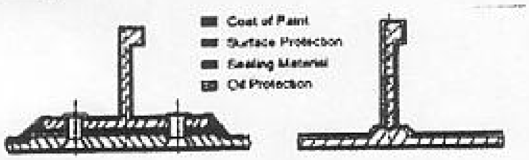


Fig.27 Joint design of A380 passenger cargo (Airbus) [30]

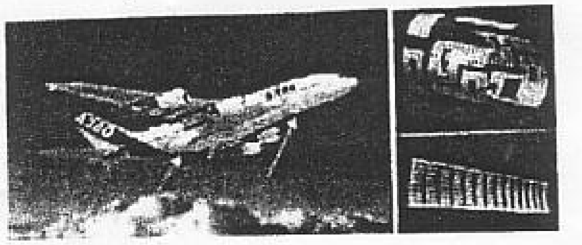


Fig.28 Airbus A380 with 8 laser welded panels [31]

Airbus Co will put largest flight; A380 (passenger :550) into the market from 2006. For joining of the seat track made of dissimilar metals, i.e. aluminum alloy and titanium, laser soldering is investigated as shown in Fig.29 [32] for next generation of A380 airplane.

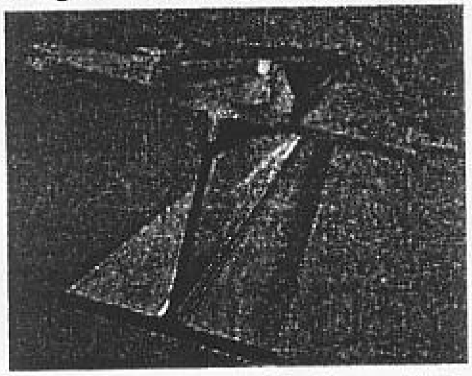


Fig.29 Seat track welded by laser soldering [32]

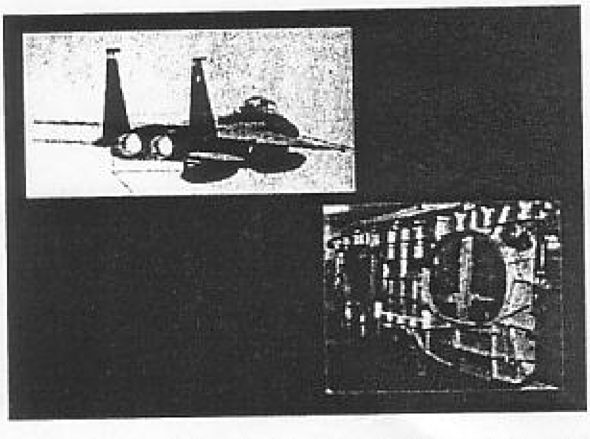


Fig.30 Laser Direct fabrication of Ti alloy structures (AeroMET co.) [33]

Recently in US, laser direct fabrication, laser powder deposition and rapid prototyping are used to high quality parts for jet fighter(F-15,F-18) and racing car. The Ti-6Al-4V titanium alloy structures as shown in Fig.30 are fabricated directly using CAD data, 18kW CO2 laser or high power fiber laser and laser powder deposition system in Argon atmosphere (3.6m x 1.2m x 1.2m). The advantage is cut of manufacturing time, cost saving, no need of die and tools and getting high quality [33].

3.4 The applications to electronics industry

Various kinds of laser materials processing is Introduced to electronics industry. It includes micro-welding, soldering, marking, repairing, cutting, trimming, via-hole drilling, scribing, wire striping, cutting of metal mask and stent, balancing, micro-machining, micro-bending. Laser based MEMS will be important for the near future.

4. Promotion of Advanced Laser Integrated Manufacturing System (ALIMS)

Laser integrated manufacturing mentioned the above is very attractive for modernization of our future production. Therefore, the advanced laser integrated manufacturing system, called as ALIMS, are proposed now as a national project for tomorrow. It includes the following laser materials processings;

1) Laser - arc hybrid welding
2) Remote laser welding
3) Femto second laser processing
4)Welding of polymers by diode laser

5) Water jet guided laser processing
6) Laser roll welding of dissimilar metal joint (steel – aluminum, steel- titanium, aluminium-titanium)
(7) Laser based MEMS, micro-fabrications
(8) Laser Direct Fabrication and rapid proto-typing.
(9) Laser drilling of via hole or through hole (1600 holes per second)
(10)Laser marking by low power laser with low price

5. Laser Roll Welding of Dissimilar Metal Joint

Joining of carbon steel to aluminium alloy dissimilar metal combination has many problems such as poor strength and cracking due to brittle intermetallic compound formation shown in Fig 31. By controlling laser power and interaction time with the material, there is a possibility of achieving joints with reduced thickness of IMC and formation of ductile IMC shown in Fig 32. In the present work, laser roll welding of aluminium alloys and low carbon steels (mild steel and high strength steel) was fundamentally investigated. As a basic study on mutual diffusion of iron and aluminium atoms, the interdiffusion coefficient of aluminium to iron is estimated very high at elevated temperature above 1000℃ as shown in Fig.33. So, if the interface between steel and

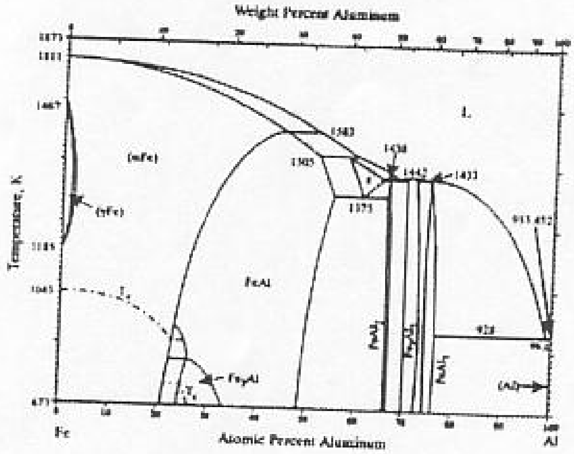


Fig.31 Aluminium – Iron Phase diagram

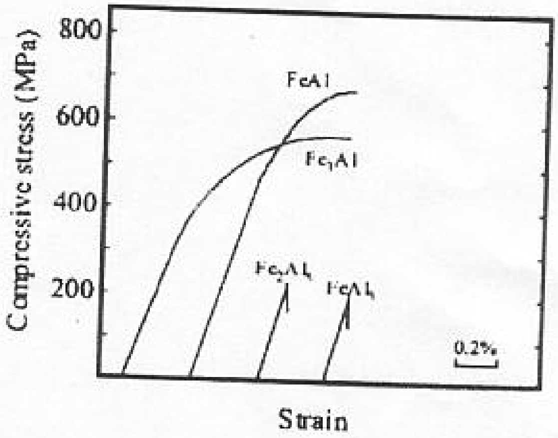


Fig.32 Compression test of intermetallic compound[34]

alunium is heated up to 1200 ℃ rapidly by laser and cooled down rapidly by metal plate, ductile intermetallic compound can be formed. Using a developed laser roll welding facility shown in Fig.34, a sound dissimilar joint was prepared and it has shown that the joint strength can be improved by controlling the interface layer thickness between 4 and 9 μm and its composition balanced with Fe-rich and Al-rich intermetallic compounds. The welded joints were broken in the base metal of carbon steel during tensile test as shown in Fig.35. And the welded joints were broken in the base metal of aluminium during Erichsen test, which was also performed to judge formability of the joints. This new process can be applied to car panels to reduce the weight and production cost. Fig.34(b) shows the schematic drawing of laser roll welding of dissimilar metal joint such as low carbon steel to aluminum alloys (A5052)[34] This new process was developed by the author. The joint was failed at the

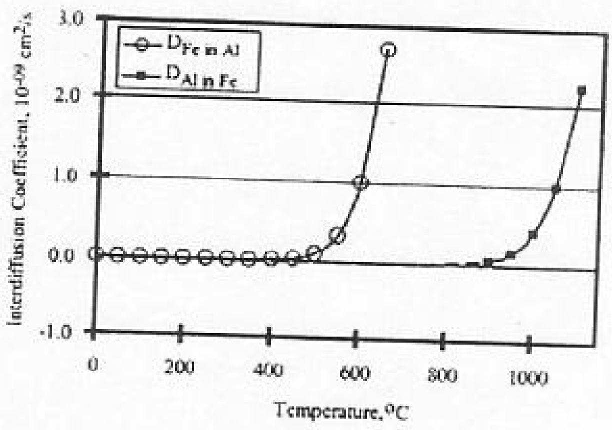
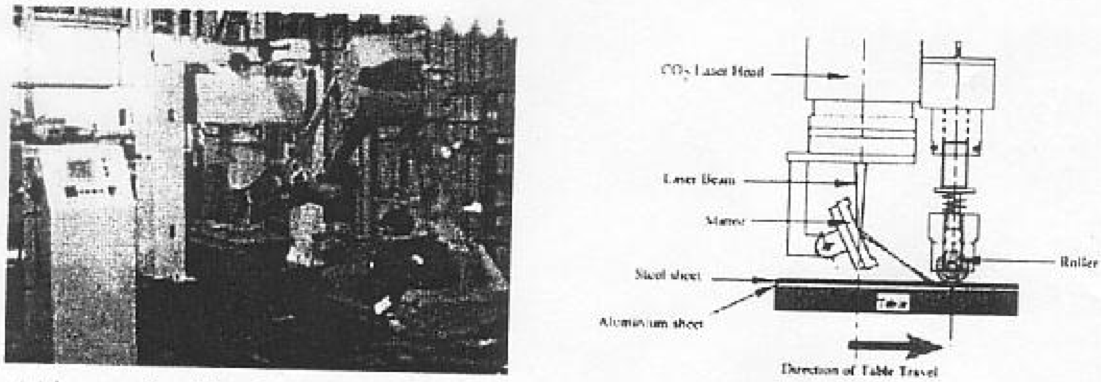


Fig. 33 Effect of temperature on interdiffusion coefficient[36]

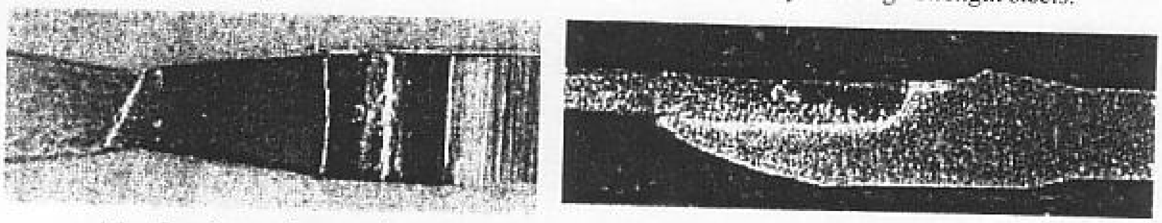
base metal of mild.



(a) Laser roll welding facility using diode laser (b) Experimental setup of laser roll welding

Fig.34 Developed Laser Roll Welding Facility (Nagoya Univ. and Fineprocess Co) [35][36]

steel tensile strength is 430 N/mm2) in tensile test. Hybrid structure for car body is now studies to get high strength, low weight and low cost for car body using aluminum alloys and high strength steels.



(a) Specimen after tensile test (b) Overlap-Butt joint of dissimilar joint

Fig.35 Specimen of laser roll welded dissimilar metal joint of steel and aluminum alloy

6. Summary

Laser technology and the materials processing are still young and growing at the growth rate of more 10% for our human society. A new knowledge, new lasers and new processing are still developed for future. It is seemed that " the 4^{th} wave of modernization" can be created by laser (photon) technology and electronics/mechanics.

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"The Application of Electron Beam Welding in Heavy Industries"

Shuzo SUSEI*, Shigetomo MATSUI*, Muneharu KUTSUNA*
and Hiroyoshi NAGAI*

1. Introduction

Progress in science, technology and engineering after World Wal II was remarkable. The structures or components which are manufactured in heavy industries have been increasingly enlarged, high qualified and diversified. Mammoth (50,000 DWT) oil carriers, jumbo jet planes, large (1,100 MW) nuclear power plants, high quality jet fighters, and space rockets have been constructed in last decade. Trend of this nature will be continued even in this decade, 1980's.

In the field of welding as one of fabrication processes, new problems associated with joining technology have been arised as follows :

(i) Welding the materials of high strength, corrosion resistance and heat resistance
(ii) Welding materials diversified
(iii) Welding thick sections
(iv) Less distortion of weldments
(v) High productivity

Table 1 shows the problems above, the engineering solutions and the available welding processes. Consequently, we can see from Table 1 that EB process is closed up as a future joining process in which the problems above can be solved.

Focusing our research and development into the application of EB welding to structures and its parts in heavy industries, practical work has been carried out in last decade.

In present paper an introduction to application of EB welding in heavy industry is described.

Table 1 Problems associated with welding technology

Problems	Technological solutions	Available welding process
Welding high strength, corrosion resisting, heat resisting materials	i) to reduce heat input ii) to reduce thermal strain iii) to reduce diffusible hydrogen	a) EB welding b) laser welding c) automatic TIG welding d) diffusion bonding
Joining materials diversified	i) welding in vacuum	a) EB welding b) diffusion bonding c) vacuum brazing
	ii) welding with inert gas	a) TIG b) MIG c) laser welding
	iii) welding at the temperature which bass metal is not melted	a) explosion welding b) pressure welding c) friction welding
Joining thick sections	i) to get narrow bead ii) to get deep generation	a) narrow gap arc welding b) EB welding
Less distortion of weldments	i) to select the welding process which shows low distortion	a) diffusion bonding b) EB welding c) laser welding d) TIG e) brazing
High rate of joint production	i) to increase joining speed i)-1) increase heat input	a) high current MIG b) multi-electrode submerged arc welding c) electro-slag welding
	i)-2) to get high energy density	a) EB welding b) laser welding
	ii) to weld multi jointing areas	a) multi spot welding b) diffusion bonding c) brazing

2. Its characteristics in feasibility study

2.1 The characteristics as a welding power source

Energy density of electron beam is very high as well

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as laser welding, comparing with conventional arc welding as shown in Fig. 1 (2).

Defining the mean power density of joining heat source as a ratio of beam power (P) to effective area of heat source { $S = \pi \left(\frac{do}{2}\right)^2$, do = effective diameter of heat source } , mean power densities in welding of various kind are shown in Fig. 2.

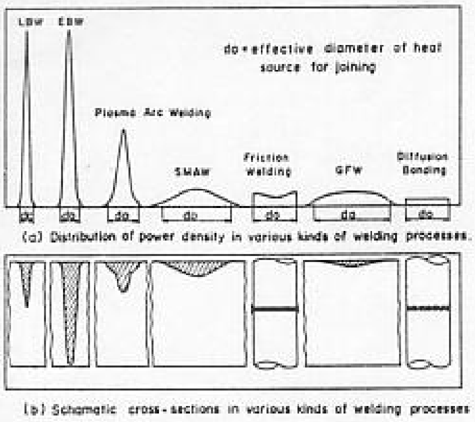

Fig. 1 Comparison of power density in a variety of welding processes

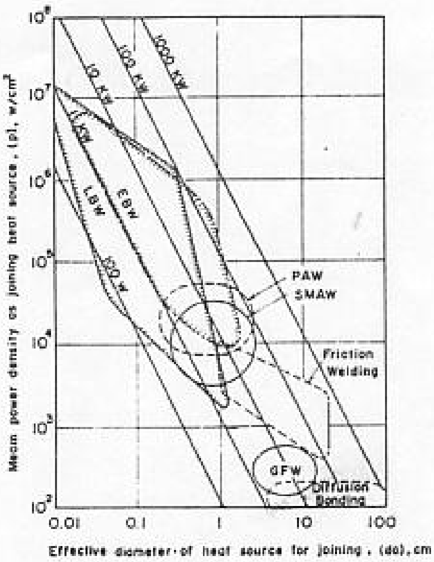

Fig. 2 Relationship between mean power density and effective area of heat source

EB welding has not only high power density, but also the applied power density in wide range chosen by changing the beam power and beam diameter. Therefore, it is possible to apply EB welding to either thin sheets of 0.1 ~ 2.0 mm in thickness or thick sections of 150 ~ 250 mm in thickness. EB welding is different from laser welding in penetration depth at same beam power, although penetration of key-hole type is gotten in both processes with high power density ($10^6 \sim 10^9$ watts/cm^2) at focus point. In the case of key-hole penetration, it is possible to make welds that are deeper, narrower, and less tappered than arc welds. In addition, a total heat input per unit joint area in EB process is much lower than that in any other joining processes as shown in Fig. 3.

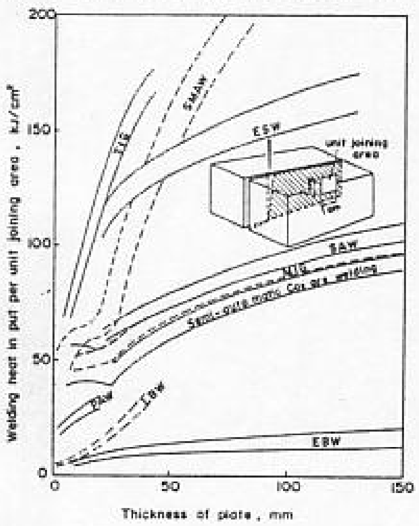

Fig. 3 Total heat input per unit joint area

2.2 Three major characteristics as welding technology

(a) A single pass process with deep penetration and high joining speed

The EB process make very deep narrow welds for which the ratio of depth to width is typical 10 :1. A dense stream of high-velocity electrons (electron beam) has a extremely high energy density, and therefore it has a ability to make welds that are deeper, narrower and less tappered than arc welds. The highest power EB welding machine developed by our laboratory members and collaborators can penetrate up to 320 mm in steel and to 590 mm in aluminum alloy.

The shape of groove for this process is usually I-butt independent of the thickness of work. However, the joint gaps must be kept to a minimum and precision joint preparation and precision tooling with high cost are required to get good alignment of beam and joint. The allowable joint gap which depends mainly on the thickness of work and beam parameters is usually less than 1.0mm.

The EB process has a very high joining speed (i.e., welding speed x penetration depth of each pass) as shown in Fig. 4. The joining speed of high power EB welding is forty times more than that of shielded metal arc welding (SMAW).

This high rate of joint production makes EB welding very attractive for joining thick sections.

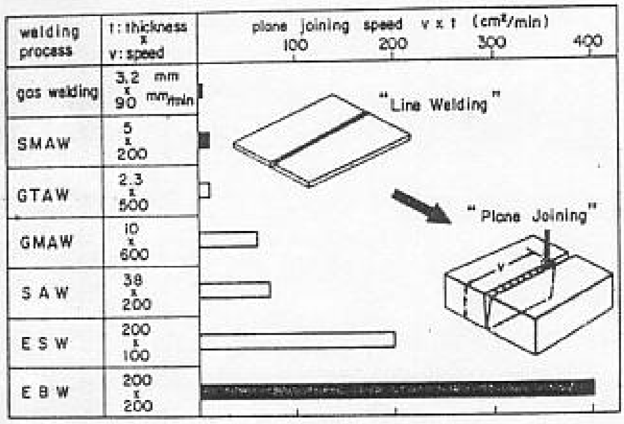

Fig. 4 Joining speeds in various welding processes

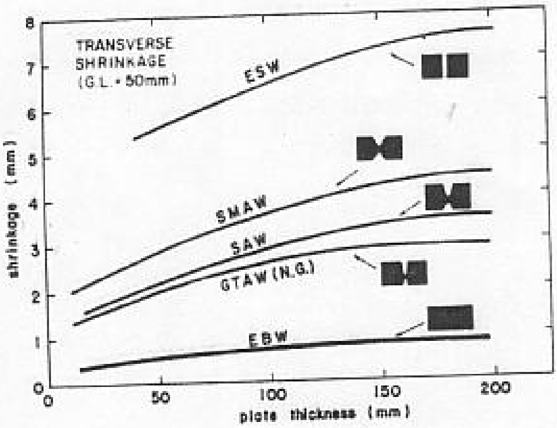

Fig. 5 Transverse shrinkage of butt welding

(b) A mechanised process with low heat input and resulting low distortion of weldments and good toughness

The total heat input per unit weld length in EB welding is lower than that in arc welding. Therefore, the heat affected zone of parent metal is very narrow and the deformed area is small. These characteristics make possible minimizing distortion and shrinkage of weldments. The measured transverse shrinkages on top surface of welded joints are shown in Fig. 5. EB process has lower shrinkage than those of SMAW and submerged arc welding. When 100mm thick plates are EB welded, the transverse shrinkage is about 1.0mm. In this case, the angular distortion is also very low. This reason comes mainly from a single pass process with I-butt.

The measured residual stress is low. Therefore intermediate stress relief annealing can be sometimes cut down, or reform after welding is always almost unnecessary.

(c) A non-contamination process in a vacuum

EB process is carried out in a vacuum chamber in which the pressure is below 5×10^{-2} Torr except non-vacuum EB welding that is not subject to the limitations of the vacuum chamber. The process in a vacuum makes possible welding of refractory and reactive metals (i.e., Ti, Aℓ, Mg, Zr, Ta, Mo, etc.), and welding of combinations of dissimilar metals not usually joinable by arc welding. Non-contamination EB process makes welds of good joint properties without the effect of atmospheric temperature and moisture. The joinability for welding of combinations of dissimilar metals is good. Many combinations of dissimilar metals is used for fabrication in aircraft industry. On the other hand, disadvantages of vacuum EB welding are as follows:

(i) Limitation of the vacuum chamber
Work size is limited by the chamber dimensions, and the need to pump down the work chamber for each load affects the welding cost.

(ii) High cost of equipment including vacuum chamber, vacuum pumps, and welding jigs.

(iii) Difficulty of welding of metals easily vapourized i.e., Mg, Sn, Zn, Pb, S, Cd.

2.3 The other characteristics as welding technology

(a) EB equipment is a well-controlled and mechanized system and is expensive one.
(b) EB welds is subject to quick heating and rapid cooling.
(c) Filler metal is usually unnecessary. We can save the cost of filler metal.
(d) EB welding is a energy saving process. EB process has the lowest cost of electric power especially in joining of thick plate.
(e) EB process is a healthy and safe welding process without welding arc. But it is necessary to protect from the X-ray by the chamber wall.

3. Research and development on high power EB welding thick walled components

Some of large pressure vessels, large castings, and large machinery parts have sections greater than 100 mm thick to be welded. At present these structures are welded by either manual or mechanized arc processes which are essentially multipass for the thicknesses involved. However, welding man hours for the fabrication are enormous especially in joining ultra-thick sections. To reduce the welding man hours, we have made efforts on the development of high power EB welding.

Fig. 6 shows a high power EB welding equipment developed by The Welding Institute in the United Kingdom, and now in use by Kawasaki group. A high voltage type gun of 75 kW power is mounted on a large vacuum chamber (the dimension: 3x3x2.5 m). Gun ports are provided in the horizontal, 45° (diagonal), and flat positions with ready location of the gun at each port. The highest power (120 kW) EB gun was developed by KAWASAKI and the collaborators in 1976 and the deepest welds penetrated by the equipment are shown in Fig. 7.

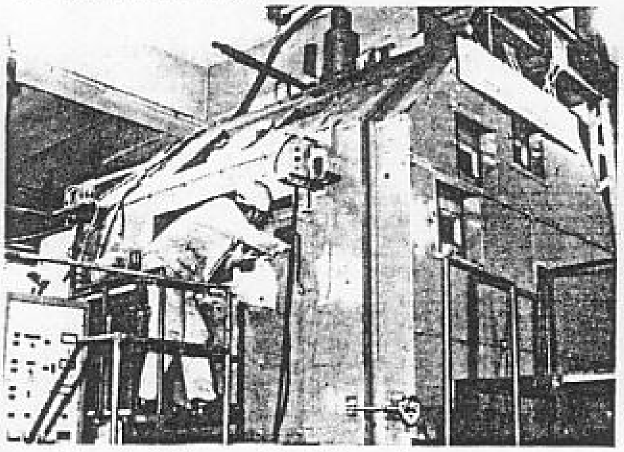

Fig. 6 High power EB welding equipment

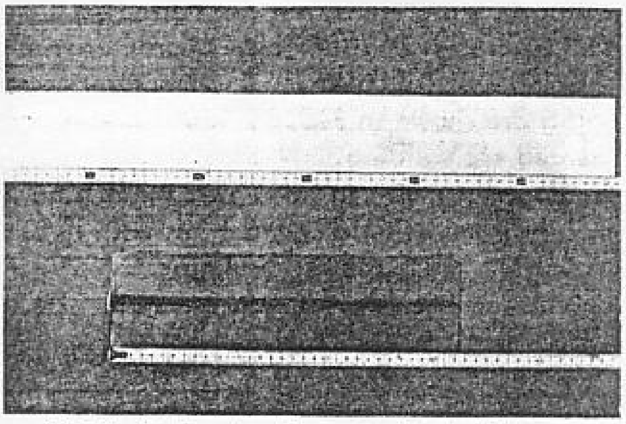

Fig. 7 The deepest welds penetrated by the highest power EB welding machine
top : aluminum alloy, dp=590 mm
bottom : steel, dp=320 mm

The problems of applying high power EB welding to large thick walled components are mainly expected as follows:

(i) Problems associated with materials
- Weldability of metals (prevention of weld defects)
- Service performance

(ii) Engineering and welding technology problems
- Joint fit-up
- Vacuum requirement
- Alignment of beam and joint
- Seam Tracking
- Weld profile control
- Demagnetization
- Repair of weld defects in deep welds

These problems have been studied by using 75 kW EB welding equipment.

For example, the electron beam can be deflected by magnetic fields at joint. Therefore, components to be welded must be demagnetized to an acceptably low level before welding. The level of magnetic flux density is usually 5 Gauss.

Joint fit-up problem is particularly serious in EB welding, and the profile of the narrow weld produced by the process is distorted by a joint gap or mismatched surface. Such fit-up defects can be more easily tolerated in manual welding. In addition it should be noted that because the focused beam is generally only 0.25 ~1.0mm dia. it can pass through relatively small joint gaps without heating the work on either side. Since it is difficult to produce very good close butt joints between two large components, new techniques must be developed to permit welding with the largest gaps between faces. Filler wire technique and pricision jig system must be developed to improve considerably on present practice in general engineering.

4. Developments of local vacuum EB welding

To remove the limitation of the vacuum chamber, local vacuum EB welding process, whose mechanism is illustrated in Fig. 8, is developed first by the Nuclear Agency of France and Clover Co.. With this system, the EB gun mount is moved over the workpiece to be welded and only the small volume between the gun and the workpiece is maintained at a partial vacuum. This equipment has a slit in the welding frame above the joint which is covered by a metal tape or silicone rubber.

Modifications carried out by Kawasaki, however, have improved the stability and

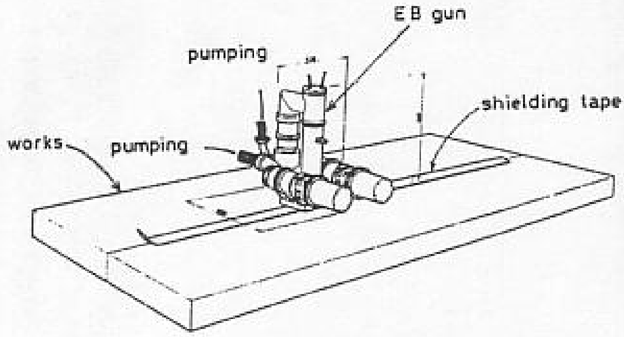

Fig. 8 Mechanism of the local vacuum EB welding

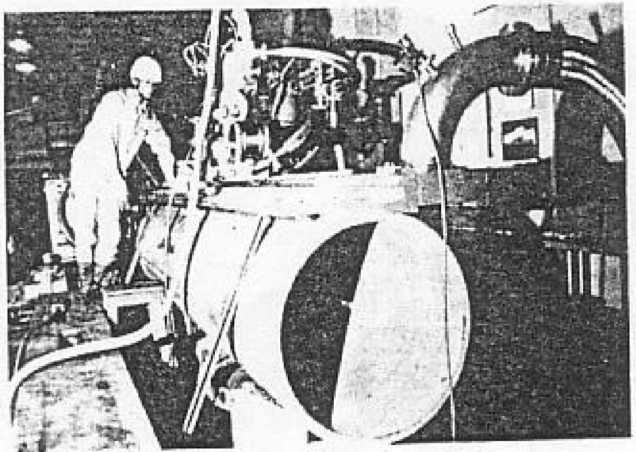

Fig. 9 Linear type local vacuum EB welding equipment modified

applicability of the equipment. The EB gun is usually of the low voltage type and the use of the unit is restricted to flat plates or cylindrical structures as shown in Fig. 9. The pressure below the EB gun is usually $10^{-1} \sim 10^{-2}$ Torr, and in the pumping system for the local chamber rotary pumps and mechanical boosters are used.

From the view point of the application, this process is a epoch-making joining process in which the applicable field of EB welding is enlarged from welding parts to welding large structures. Many modifications have been devised in Japan and France in last decade, 1970's.

5. Approaches to large components

An approach to boiler drums was carried out by using a local vacuum EB welding equipment in manufacturing shop as shown in Fig. 10. To overcome misalignment of electron beam and the work or stopping of the carriage, hydraulic jack system and chain driving system was devised. In this case, sealing bead was previously deposited. The macrosection of the bead is given in Fig. 11.

In the case of a Moss-type LNG tank constructed of aluminum alloy, shown in Fig. 12, it would require more than 100 passes to complete the 200mm thick aluminum ring members using conventional MIG process. The enormous number of man hours are required. If EB welding process can be applied to this equatorial ring, the productivity could be increased. In our approach, vertical type local vacuum EB welding equipment was used. As a result of the trifurcated section of the ring, the joint is difficult to weld even using EB welding. Therefore, a special frange was used to fit tightly over the ring to provide a weld of equal thickness and removed by machining after welding as shown in Fig. 13.

6. Conclusions

The application of EB welding to large components in heavy industries is now at dawn. It is necessary to carry out further development and evaluation work covering the items which are either described or not described in present paper.

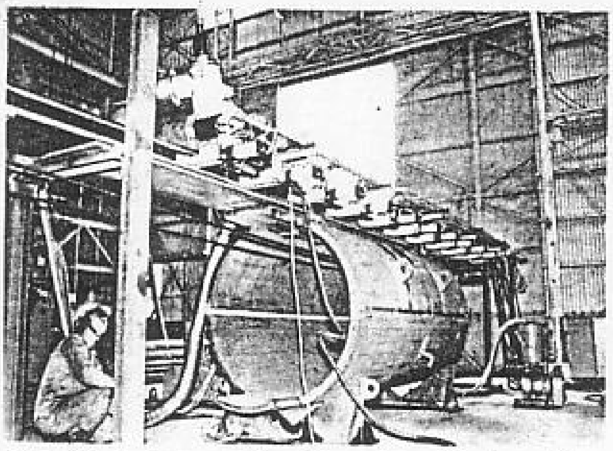

Fig. 10 Local vacuum EB welding equipment for long welds (linear type, max. weld length = 6 m)

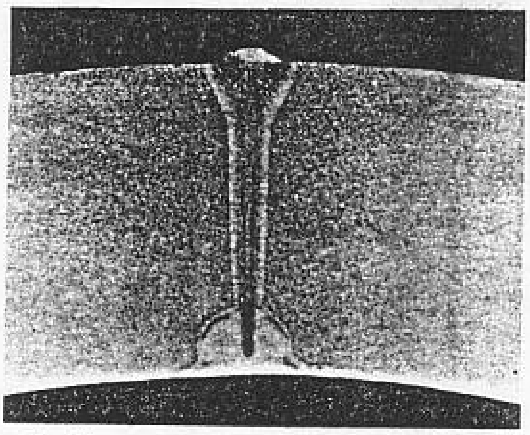

Fig. 11 Macrosection of EB welds of boiler drum

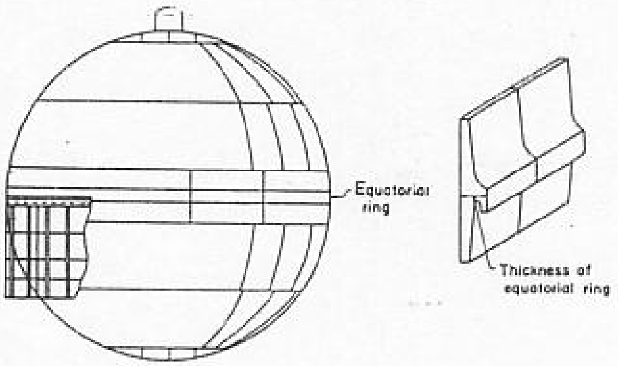

Fig. 12 Spherical tank for LNG carrier

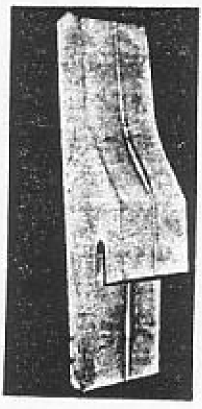

Fig. 13 Equatorial ring members welded by vertical type local vacuum EB welding