Modern Laser Technology and Metallurgical Study on Laser Materials Processing

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ABSTRACT

Laser has been called a "Quantum Machine" because of its mechanism of generation since the development on July 7,1960.by T.H.Maiman. We can now use this machine as a tool for manufacturing in industries. At present, 45kW CO2 laser, 10kW Nd:YAG laser, 6kW LD pumped YAG laser and 4kW direct diode laser facilities are available for welding a heavy steel plate of 40mm in thickness and for cutting metals at high speed of 140m/min.

Laser Materials Processing is no longer a scientific curiosity but a modern tool in industries. Lasers in manufacturing sector are currently used in welding, cutting, drilling, cladding, marking, cleaning, micro-machining and forming. Recently, high power laser diode, 10kW LD pumped YAG laser, 700W fiber laser and excimer laser have been developed in the industrialized countries. As a result of large numbers of research and developments, the modern laser materials processing has been realized and used in all kinds of industries now. In the present paper, metallurgical studies on laser materials processing such as porosity formation, hot cracking and the joint performances of steels and aluminum alloys and dissimilar joint are discussed after the introduction of laser facilities and laser applications in industries such as automotive industry, electronics industry, and steel making industry. The wave towards the use of laser materials processing and its penetration into many industries has started in many countries now. Especially, development of high power/quality diode laser will be accelerate the introduction of this magnificent tool, because of the high efficiency of about 50%, long life time and compact.

KEYWORDS

Laser materials processing, High power laser, Welding, Cutting, Metallurgical aspects.

1. Introduction

During the last decade, the spectrum of laser technology and the applications in industries has considerably enlarged from hardening, drilling, cutting and welding to cladding, micro removal marking, cleaning, soldering, forming, and peening This has led to two digit market growth and increasing number of technical papers dedicated to laser applications underline the strong interest for this " Quantum machine". Lasers have shown their versatility in all sectors of materials: metals, ceramics, stone, polymers, paper, & composites.

Attractive features of high power lasers for materials processing are considered as follows;

(1) Wide range of power density for materials processing as shown in Fig.1
(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

Table 1 shows the historical aspects of laser science and materials processing. It is indeed quite attractive for us to use this photon energy as a laser beam with high power for manufacturing in the future.

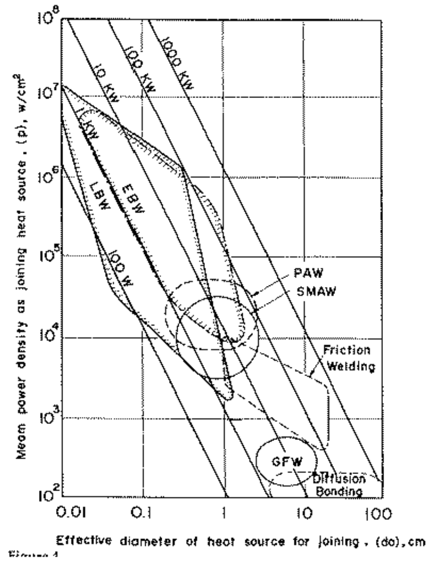


Fig.1 Power density of different heat sources for welding

2. Developments of high power lasers for materials processing

Nowadays, a powerful CO2 laser facility of 45 kW is available for industry. Two of them are used to weld heavy hot slab in steel making plant. Nd:YAG laser

Table 1 Historical aspects of laser science and materials processing

Year	Topics in laser science	Topics in laser materials processing
1900	"Quantum hypothesis of energy" by Max Plunk, FRG	
1917	"Emission and Absorption of Radiation in Quantum Theory" by Albert Einstein, FRG	
1951	"Idea of MASER by microwave" by C.H. Townes, USA	
1954	"Microwave Amplification by Stimulated Emission of radiation" presented by C.H. Townes,USA	
1957	Patent application of semiconductor MASER by J.Nishizawa,Japan	
1960	First generation of Ruby LASER by Theodore H.Maiman,USA	
1960	He-Ne laser by A.Javan,USA	
1961	Glass laser by Switzer,USA	
1964	1.72 W CO2 laser by C.K.N.Patel at Bell L. Nd:YAG laser by Bell Laboratories,USA	
1965		Coherent Co. marketed 100W CO2 laser system First application of laser for drilling of diamond die
1966	Die laser by Lempicki,USA	
1967		Development of 8 kW CO2 laser by Raytheon Co.USA
1969	CW Chemical laser by COOL,USA	
1970	Generation of Ultraviolet laser using liquefied Xenon by D.G.Basov, USSR	Fast axial flow type CO2 laser by Tiffany,FRG
1971		First application of laser cutting. in automotive industry
1972	Excimer laser by J.J.Yuing, USA	Cross flow type 20kW CO2 laser was developed by UTRC,
1973		Laser transformation hardening of gear housing of car,G.M. AVCO marketed 10kW CO2 laser
1976	X-ray lithography(SOR) by IBM,USA	Quanta-Ray introduces the first reliable YAG laser
1977		Laser hardening of cylinder liner of diesel engine for car Starting of Japan national project" Flexible manufacturing system using high performance lasers
1981		Laser welding of steel on line by Kawasaki Steel,Japan
1983		CAD/CAM system for cutting of electricmachine panels, Toshiba,
1984		Laser robotics cutting of car body at the stage of assembly line, Toyota Motor,Japan
1986		Thyssen Stahl supplied laser welded underbody panel to Audi , Toyota and Aisan Ind. produced laser cladded valve
1987		UTIL marketed 25kW CO2 laser , 1.4kW Nd:YAG laser ldeveloped by NEC and Toshiba, Japan
1988		3kW CO laser developed by LRI and MHI Toyota Motors Co. started tailored blank welding by laser
1990		20kW CO laser developed by LRI and MHI
1991		Benz Motors applied laser for 3D on-line welding of roof panel to door panel
1990's		R&D of Femto second pulse laser
1993		Toyota Motors started laser cladding of engine valve seat
1996		10kW COIL developed by Kawasaki H. I.. R and D of micromachining by femto second laser
1999		2.5kW diode laser developed by Rofin Sinar Dimler Benz used diode laser for welding of pllastic part
2000		4kW diode laser developed by Nuvonyx,US Volks Wagen intdocued laser-arc hybrid welding for car.
2001		700W Yb doped fiber laser developed by IPG photonics
2002		10kW LD pumped Nd:YAG laser by Japan national project

was developed in 1964 by Geusie. Now, 10kW lamp pumped Nd:YAG laser developed and in Japan and are used in heavy industries. Recently, 4kW high power diode lasers and 6kW LD pumped Nd:YAG laser are developed in US and Germany. And 10 kW LD pumped Nd:YAG laser have been developed by Japanese national project of "Photon technology". Fig.2 shows 4kW diode laser developed by Nuvonyx in US[1]. High power excimer laser is also used mainly in semiconductor industry. 700 W Yb(Yttbium) doped fiber laser was developed last year in US. 5kW fiber laser will be designed for the industrial use in the near future. 10kW Chemical Oxygen Iodine Laser (called as COIL) was developed by Kawasaki Heavy Industries for welding and cutting heavy steel plates of 10-15 mm in thickness. These high power lasers are useful for material processing like welding, cutting, drilling, surface treatment/processing, marking, forming, ablation and so on.

3. Developments of new technology for materials processing

Since 1960, many researches on laser technology have been carried out through the world. For example, One of the master thesis titled as " Study on Application of Laser for Surface Alloying" has been prepared by F.E.Cunningham at MIT in 1964. First application of laser material processing was the laser drilling of diamond die in 1965 using a Ruby laser. US Navy has started their R & D on welding and cutting of high strength steels like HY-110 and HY-130, aluminum alloys and titanium alloys in the thickness range of 5 to 20 mm using 15kW CO2 laser end of 1960's. First application of laser materials processing in automotive industry is laser cutting of coil paper at GM in 1971.

Nowadays, laser material processing is used mainly in automobile industry, steel making industry, electric and electronics industry, and heavy industries. In addition, new materials processing and technology are developed as follows;

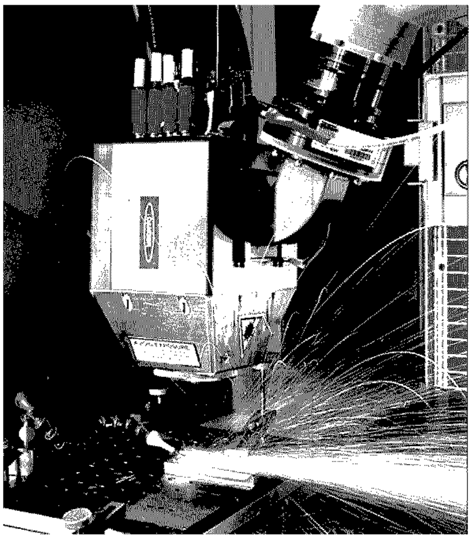


Fig.2 4kW diode laser on robot (Nuvonyx Co)

Laser – Arc hybrid welding
Underwater laser welding.
Laser welding of hot steel slab
Laser welding of plastics by diode laser.
Laser Roll Bonding of Steel to Aluminum alloys
Laser drilling of via hole or through hole
Laser cutting of shin silicon steel at a speed of 140 m/min.
Laser marking and engraving

Combinations of Laser and Arc can make the another possibilities for welding. Many types of laser –arc hybrid processes are studied and used now[2-4]. Fig.3 shows the setup of CO2 laser and MAG hybrid welding[4]. The advantages are as follows;

(1) To get deeper penetration,
(2) To increase the travel speed,
(3) To get a wide allowable joint gap,
(4) To control the chemical composition of weld metal
(5) To control the bead shape and appearance

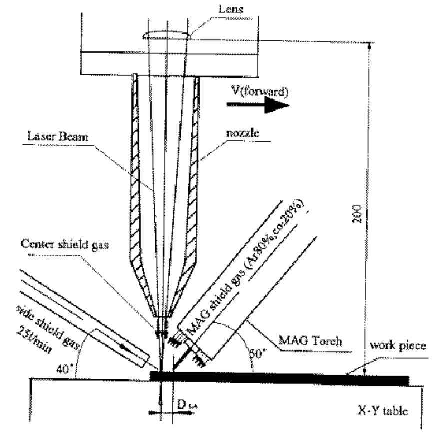


Fig.3 Setup of laser-arc hybrid welding

Fig.4 shows the schematic drawing of laser roll bonding for dissimilar metal joint such as steel (thickness:t=0.5mm) to aluminum alloys(t=1.0mm). [5,6] The joint was failed at the base metal of mild steel tensile strength is 430 N/mm2) in tensile test as shown in Fig.5 Hybrid structure for car body is now studies for reduction of car body using aluminum alloys and high strength steels. This laser roll bonding is available for the purpose.

High speed and precise laser drilling for hybrid LSI for moving telephone is possible using excimer laser, YAG laser and CO2 laser. The maximum speed of drilling of 50 μ m hole is 700 holes per second[5]. During the last decade, following new laser materials processing have developed;

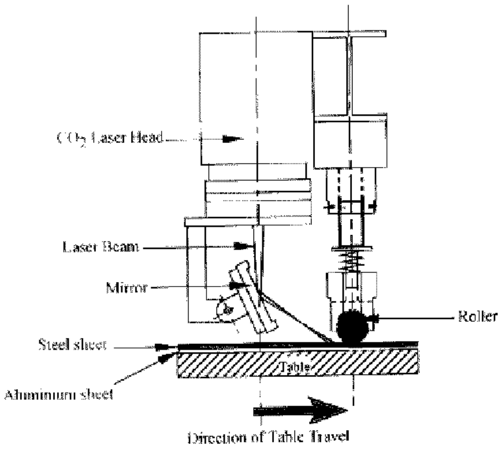


Fig.4 Schematic drawing of laser roll bonding

Laser cleaning of statues in church, machinery parts, heating roll of printer and potato.

Laser peenning for preventing Stress Corrosion Cracking(SCC) in nuclear power plant
Laser desensitization of stainless steel welds
Laser Forming and Bending of plate
Laser atomizing to get nano-particles
Laser cladding of engine valve seat
Laser ablation of polymer and ceramics
Laser paint stripping and wire stripping
Laser 3D drawing in glass (=Laser art)

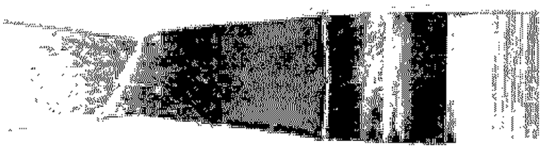


Fig.5 Laser roll bonded dissimilar joint of carbon steel and aluminum alloy(A5052)

4. Researches for materials behaviors in laser processing

4.1 Weldability of carbon steels

(1) Rapid Heating and Cooling

The thermal cycles during welding of carbon steels showed a rapid heating rate of 10^5k/s and a rapid cooling rate of 10 4 k/s [6]. For example, in CO$_2$ laser welding of low carbon (0.23mass%) steel at a travel speed of 6 m/min(100mm/s), the heating rate from 500℃ to 1200℃ is in the order of 10^5℃/s, and the cooling rate is in the order of 10^4℃/s in the thermal cycle measured using a Pt-PtRh thermocouple of 0.1 mm in diameter[6]. Therefore, the microstructures of HAZ in laser welds of carbon steels are different from that of arc welds as shown in Fig.6 which shows martensite/pearlite colonies in ferrite matrix. The grey/ white lamellar structure was observed in the martensite colonies in HAZ of laser-welded 0.36%carbon steel. The solid state transformation from pearlite to austenite during the rapid heating up to above A3 temperature make the carbon distribution inhomogeneous in the transformed austenite at elevated temperature and make the inhomogeneous martensite colonies during the rapid cooling. Because of lack of time for carbon migration from cementite flake in pearlite colony to austenite matrix. The distance of carbon migration in HAZ during laser welding at two travel speeds of 4m/min(66.7mm/s) and 2m/min(33 mm/s) have been measured using EPMA analysis. It was 2 μm~8μ m.as shown in Fig.7[7]

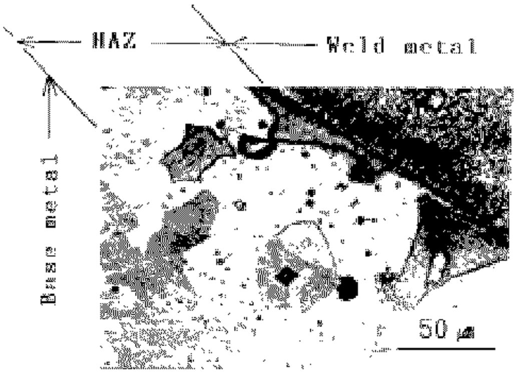


Fig.6 Heat affected zone of laser weld of steel (0.36%C)

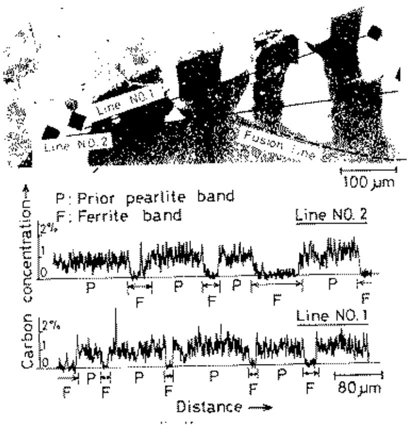


Fig.7 Carbon distribution across the pearlite colonies in HAZ of laser weld

In the case of pulsed YAG laser welding of carbon steels, the heating- and cooling rate were higher than that in CO 2 laser welding of the same steel. The width of HAZ are very narrow. For example, it was about 70 ~80μ m in laser weld at a travel speed of 1.8 m/min (30 mm/s).

(2) Microstructure and hardness

The microstructure in HAZ consists of ferrite matrix and hard martensite colonies with high carbon content. The martensite colonies have high hardness of 593 and 677 in the HAZ of mild steel weld. On the other hand, the hardness of ferrite matrix are about 257 Hv.

In the case of ultra low carbon steel weld, the polygonal ferrite and bainitic ferrite mixture, which hardness was 195 Hv, was observed at a travel speed of 1.8 m/min (30mm/s)[8]. In the laser weld of 0.014% carbon steel, polygonal ferrite, bainitic ferrite and small amount of martensite with hardness of 240 Hv were observed. as shown in Fig.8.

The microstructures of laser steel welds depend on the carbon content/equivalent and cooling rate or welding speed as shown in Fig.9. Hardness of laser welds of steel depends on the microstructures. The hardness distribution are different from that of arc welds. For instance, the maximum hardness is obtained at the center of fusion zone or in the HAZ closed to unaffected base metal in laser welds of carbon steel. In arc welds

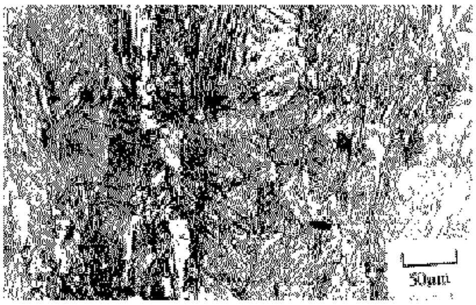


Fig.8 Microstructure of laser weld of low carbon steel

the location of max. hardness is usually in the coarse grain zone. The max. hardness of laser welds increases with the carbon equivalent which is proposed for laser welds. The following Carbon Equivalent is an example;

$CE_{laser} = C + Si/50 + Mn/25 + P/2 + Cr/25$

This CE was proposed by S.Kaizu et al [9] .

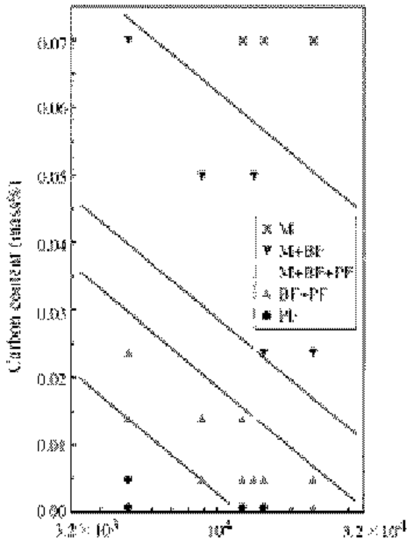
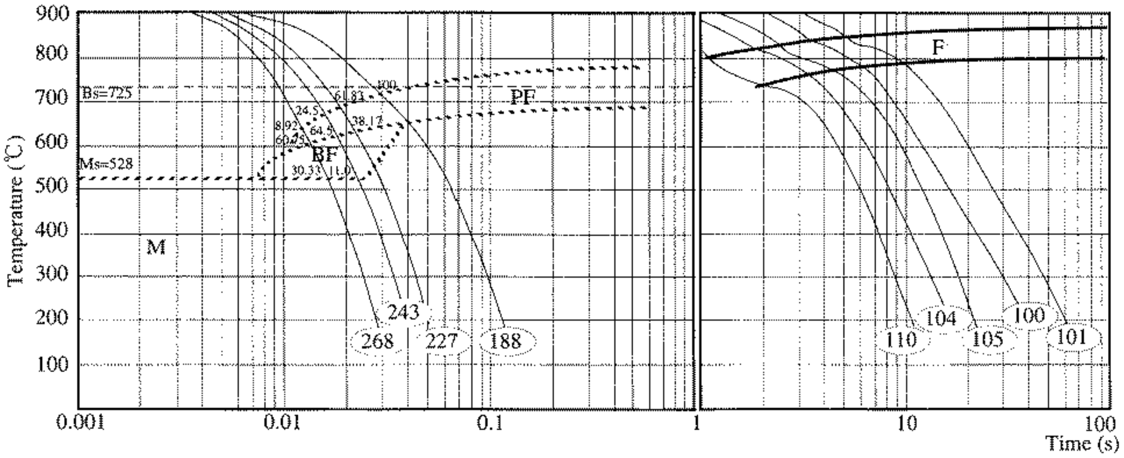


Fig.9 Microstructures of weld metal in laser welding of carbon steels

(3) CCT diagram for laser steel welds

The CCT diagram is useful for welding engineer to recognize the microstructure and hardness of steel welds. Fig.10 shows an example of CCT diagram for estimation of microstructures and hardness for laser steel weld metal developed by M.Kutsuna and K.Uetani[8]. In the research work, the estimated CCT diagrams were compared with the conventional CCT diagram for arc welds of low carbon steels. The characteristic value such as Ms (starting temperature of martensite formation) and Bs (starting temperature of bainite formation) were calculated with the formulas proposed by W. Steven, A.G. Haynes [10] and by T.Kunitake et al[11]. The cooling curves, hardness and microstructure compositions are experimental values.



(a) Estimated CCT diagram for laser welds

(b) CCT diagram for arc welds

Fig.10 Estimated CCT diagram for laser welds (0.014% carbon steel)[8]

(4) Mechanical properties of laser steel welds

Laser welded joint of ultra low carbon steel has a relatively high strength and elongation. The effects of carbon content on tensile strength of laser welded joints and microstructure composition are shown in Fig. 11. The laser welded joints of 0.006 mass%C steel showed the tensile strength of 403 N/mm^2.and 450 N/mm^2at a welding speed of 8.3mm/s and 16.7mm/s, respectively. The tensile strength of welded joints increases with increases of carbon content, bainitic ferrite and martensite in weld metal. It is obvious that bainitic ferrite and martensite increase the tensile strength of weld metal. The Steel E(0.051%C)specimen obtained at a welding speed of 16.7mm/s showed the tensile strength of 620N/mm 2 . Elongations of welded joints decrease with the increase of carbon content.

4.2 Hot cracking of stainless steel welds

Recent advances in laser materials processing have made the laser welding of various kinds of metals. However hot cracking and porosity formation are still problems. Even in welding of stainless steel, hot cracking is a problem. Fig.12 shows the experimental result of hot cracking test in laser welding and TIG welding of different solidification modes of stainless steels. In laser welding, the weld metal is easier to get austenite at room temperature than that in arc welding due to rapid cooling. The border of solidification mode from primary austenite solidification to primary ferrite solidification mode is shifted to higher Cr and lower Ni equivalent. As a result, primary austenite

Solidification range is enlarged and apt easy to make hot crack in laser welding.

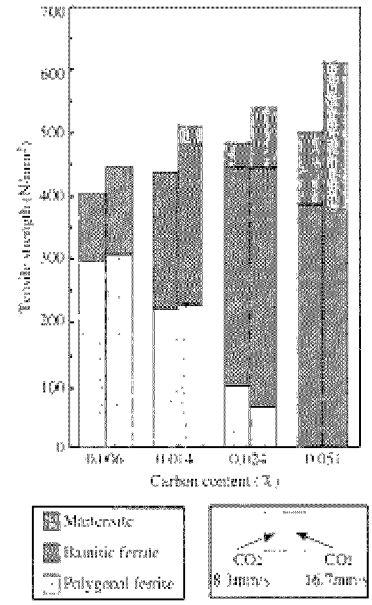


Fig.11 Tensile strength of laser welded joint of ultra low carbon steels

4.3 Porosity formation in laser welding of aluminum alloys

Porosity formation in laser welding of aluminum alloys is still problem in production because of effects on the quality of welds. It has been generally accepted for TIG and MIG welding of aluminum alloys that the hydrogen being highly soluble in liquid aluminum is the dominant cause of porosity in aluminum alloy welds[12]. But the mechanism of porosity formation in laser welds of aluminum alloys has not been cleared yet because the behaviors of molten pool and keyhole during the rapid cooling and of metal vapor and hydrogen are not clear. Thus, more complicated phenomena during this process should be considered to clear it. Three possible considerations shown in Fig.13 have been suggested by the researchers to state the mechanism of porosity formation during laser welding of aluminum alloys. The porosity formation of laser welding of aluminum alloys might be attributed to dissolved hydrogen in molten pool[13], formation of an unstable keyhole due to evaporation of the alloying elements with low vapor pressure, such as Mg and turbulent flow of the molten metal, respectively.

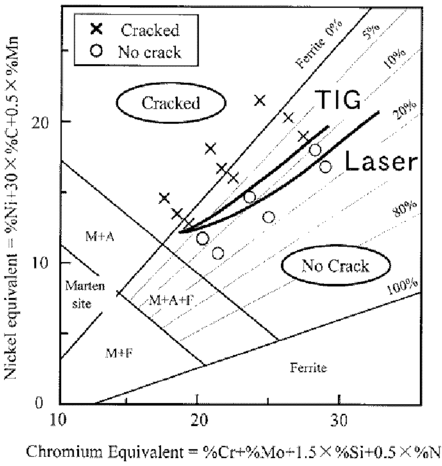


Fig.12 Hot crack susceptibility of stainless steel

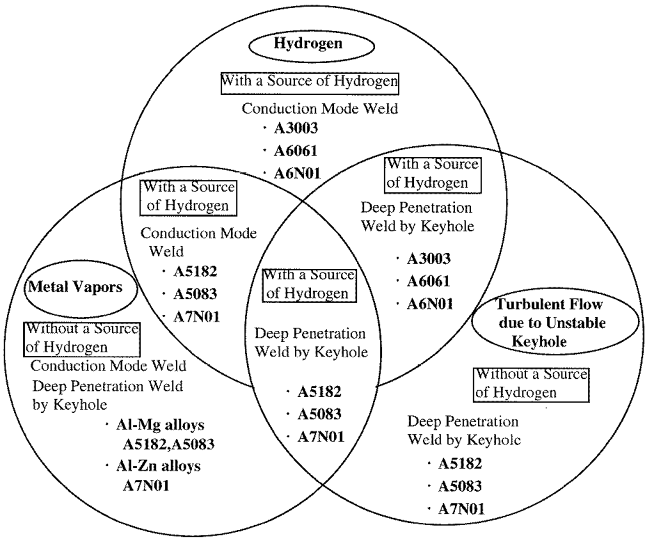
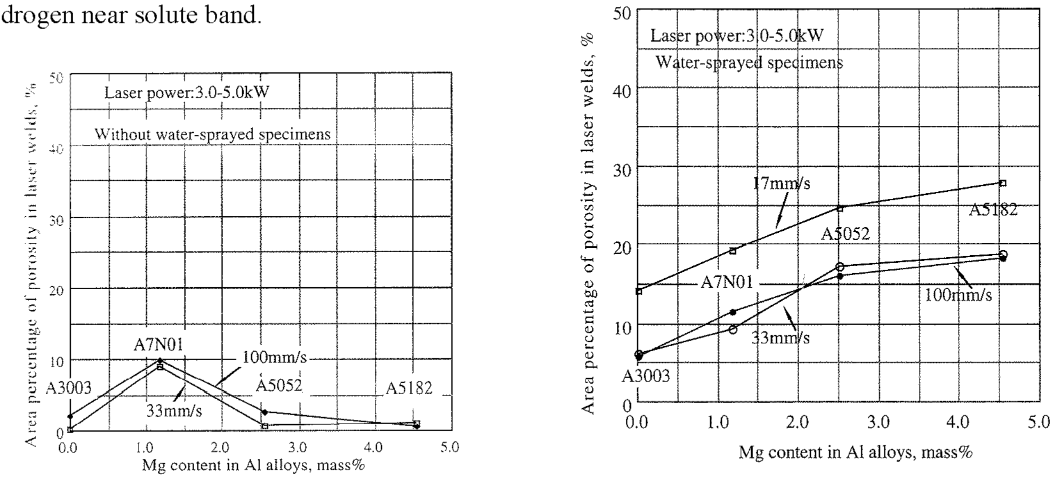


Fig.13 Three main factors affect porosity formation

Porosity was readily produced in laser welding of aluminum when shielding was insufficient. According to analysis of porosity gas in laser welds of A3003, A6061, A6N01 and A5052, hydrogen was about 90vol% of total porosity gases and the rest of it was nitrogen. And for A5083 and A5182 alloy welds which had deeper penetration, helium as a shielding gas was also detected.

Porosity formation is greatly influenced by solidification rate, e.i. welding speed and magnesium and hydrogen as shown in Fig.14[14]. Magnesium in aluminum alloys strongly influences the behavior of porosity formation not only by its evaporation but also by segregation of Mg alloying element with hydrogen near solute band.



(a) without water spraying (b) with water spraying

Fig.14 Effect of Mg and Hydrogen on porosity

Fig.14(a) shows no effect of Mg content on porosity formation when water is not sprayed on the specimen. However, the strong effect of Mg content on porosity formation is remarkable only when water is sprayed on the specimen.

5.Applications of laser processing in automotive, steel making and heavy industries

5.1 In automotive industries

In automobile industry the second application of laser processing was laser hardening of gear housing of diesel engine by General Motors ,Saginaw plant in 1973. 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 (Fig.15), sun roof and center pillar, 3D on-line welding of roof to door panel and of trough panels(Fig.16), fuel tank, steel wheel, injector and break plates, plastic part

(b) Laser cutting and drilling: cutting of proto-type car body panel, steel panels/parts and polymer parts, antenna hole for radio(Fig.17), drilling of cum shaft and locker room

(c) Laser surface treatments: hardening of rotor shaft, cladding of engine valve and valve seat (Fig.17)

(d) The others: marking, rapid prototyping for making a original mold.

Recently, most car manufacturers and their part suppliers are using so many laser systems including LD pumped YAG laser and direct diode laser.

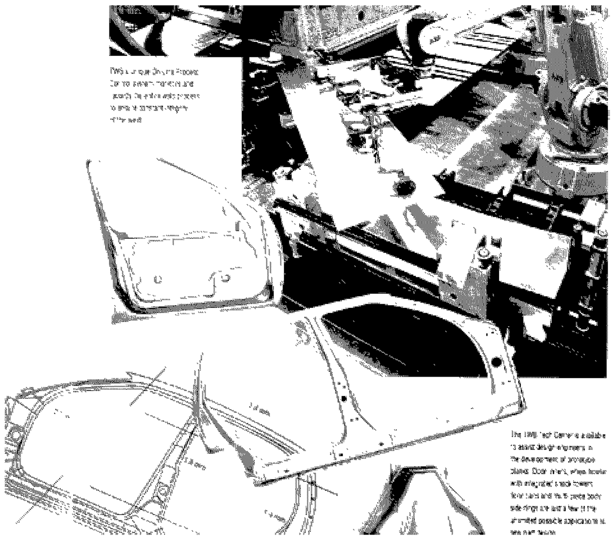


Fig.15 Welding of tailored blank for car(TWB Co)

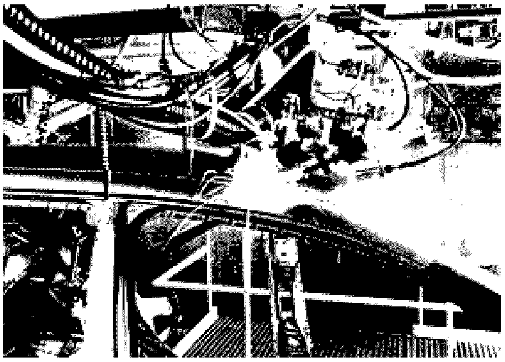


Fig.16 3D laser welding of car body on-line

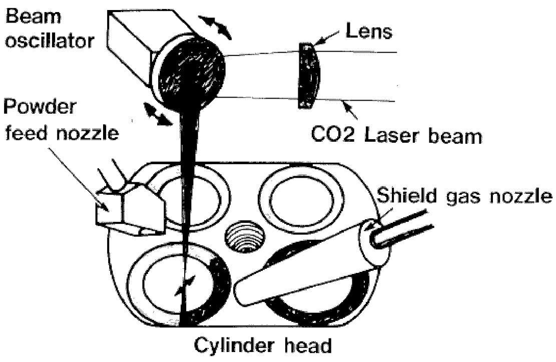


Fig.17 Laser cladding of valve seat for engine (Toyota Motors Co)

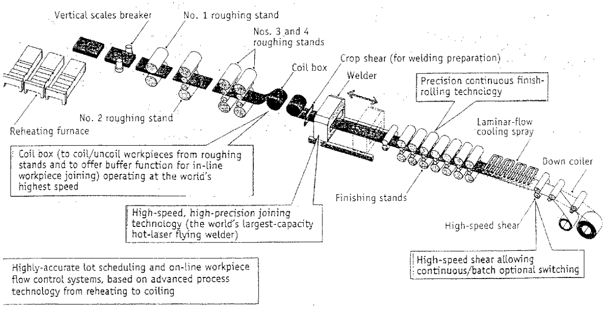


Fig. 18 Laser welding of heavy hot slab (Nippon Steel Corp)

5.2 In steel making industry

Laser welding and cutting are commonly used in steel making industry. For instance, two 45 kW CO$_2$ laser facilities are used now for joining hot slab in Japan as shown in Fig.18. The 40-50 mm thick hot slab is running at a high speed of about 10m/min and high temperatures (1000℃-1100℃) for the continuous hot rolling

Laser welding of stainless steel is used in pipe production line in Germany and Japan since 1991.

Light structural panels such as honey com panel and sandwich panel (Fig.19) are now laser welded for the parts of vehicles and constructions like high speed ship with hydrofoil and TGV car floor. Laser surface treatments for steel and non ferrous metals are used for metallurgical and physical modification of surface.

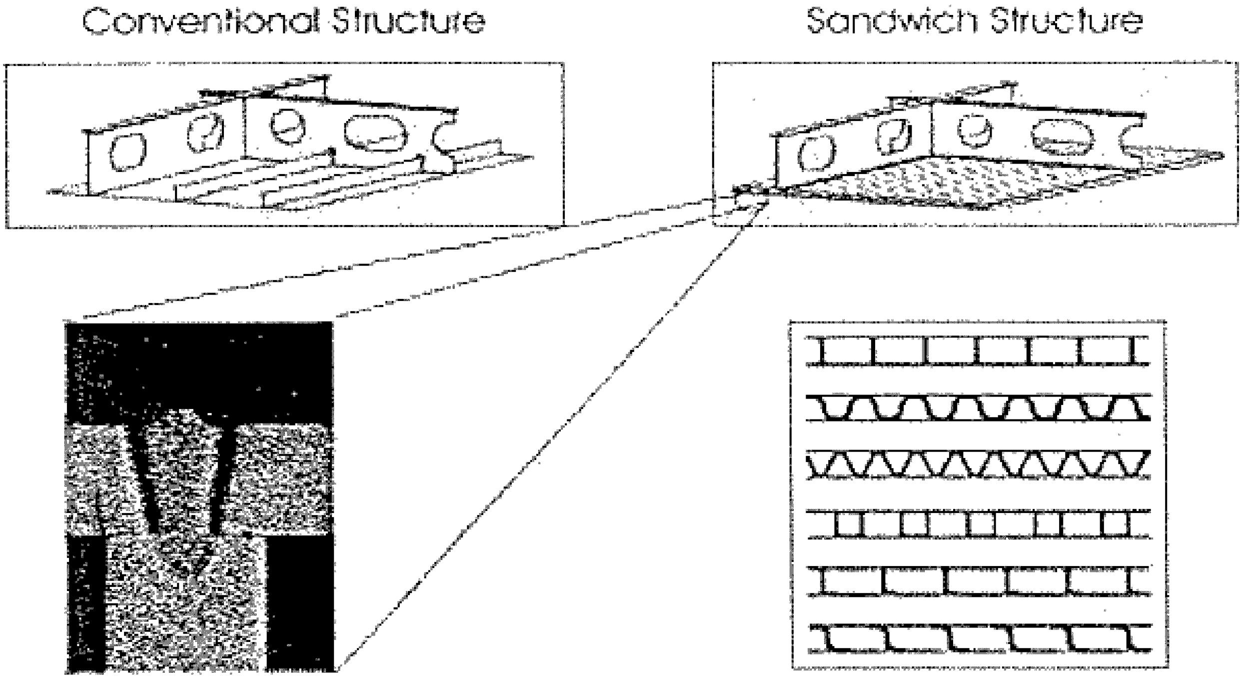


Fig.19 Principles of Sandwich panel for passenger ship and vehicles (Meyer Werft Co)[16]

5.3 In heavy industries

In nuclear energy plants control rod of nuclear reactor, tube plate and tube are laser welded Under water laser welding and cutting system was developed for nuclear power plant. Recently laser peening process was applied to prevent stress corrosion crack of stainless steel pipe.

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 T-joints in ship construction. In ASME Code Section IX, laser welding is permitted as one of the welding processes for pressure vessel and pipe.

6. Laser materials processing for tomorrow

Laser technology is growing, and new laser materials processing are developed for tomorrow. The followings are the example:

(1) Laser and arc hybrid welding
(2) Dissimilar metal joint of steel and aluminum alloy using laser[15]
(3) Presition welding and cutting by ultra high peak power diode laser
(4) Ultra fast (femto second) pulse laser processing
(5) Welding of polymers by diode laser(Fig.20)

Fig.20 Welding of key holder for car using 80W Diode laser[17]

7. Summary

Laser technology and the materials processing are still young and growing so fast for our human society.
A new knowledge bear many new processing in this field.
Laser give our industries a new convenient tool which have higher possibility and flexibility.

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