특 집 : 고에너지 응용기술의 최근 동향

The Latest Trend of Laser Materials Processing

Akira Matsunawa and Jong-Do Kim

1. Introduction

The laser is regarded as the greatest scientific and technological invention in the 20th Century. Since Theodore Maiman succeeded the world first oscillation of Ruby laser in 1960, many scientists and engineers have paid great attentions to this artificial light that never exists in the nature. Though many applications of laser were proposed, the laser measurements were only realized in those days because of the shortage of power. However, various kinds of lasers were invented since then, and areas of laser applications were gradually expanded as the laser power was increased.

The first laser material processing was realized in 1967 at AT&T Co. to make a hole in diamond dies for drawing fine metal wire. This was an epoch-making technology because the processing time was shorted less than 1/15 than that of conventional electrolytic method. There still left, however, many problems and barriers until the lasers were introduced to industries in full-scale.

The artificial term of "LASER" came from "Light Amplification by Stimulated Emission of Radiation". Large amount of money was invested to develop lasers and their applications, but good results were hardly obtained. It was thus called ironically that "LASER" was the abbreviation of "Lucrative Acquisition Scheme for Expensive Research".

In 1970's, technological developments of laser welding, laser cutting, laser hardening and so on were undertaken in earnest. And laser technologies began to penetrate gradually into industries. At present, there are three areas where laser materials processing are intensively and widely used in industries. They are North America, Japan and EU countries. In recent years, however, Korea, Taiwan and China are getting active to employ laser technologies in industries.

The features of laser applications in Japanese industries are little bit different from those in US and EU. Lasers applications in US and EU are mainly concentrated in the automotive and military industries. In Japan, on the other hand, lasers are spread in wide industrial areas such as the electric and electronic, automotive, mechanical, bridge, heavy structural and steel making industries.

The development of high power lasers were greatly accelerated since early 1990's, and the commercial 45 kW CO_2 laser and 10 kW YAG laser appeared in the mid-1990's. Particularly in Japan, the laser welding of medium and thick plates attracted interests in many industries such as the heavy industries and heavy electric industries. Responding to the industrial demands, the MITI (Ministry of International Trade and Industry) organized a big project called "Advanced Photon Processing and Measurement Technologies" for 5 years from 1997. The project was composed of 3 areas, i.e., 1) Photon Applied Measurement (In-Situ and Non-Destructive Measurements), 2) Photon Applied Processing (Macroscopic and Microscopic Processing), and 3) Photon Beam Generation (High Power and Tightly-Focusing All Solid-State Lasers). The target values of Macroscopic Processing were the full penetration welding of 30 mm thick steel and 20 mm thick aluminium alloy at the speed of 1 m/min with no imperfection. Also, the development of 10 kW LD-pumped solid-state laser was aimed. All target values in the project were cleared, but unfortunately the achievements have not been reflected to industries.

In recent years, the new lasers with extremely good beam quality such as the disk and fiber lasers have been developed in Europe and United States. Also, a high power Laser Diode is presently commercially available. At the beginning of 21st Century, the laser materials processing technologies are now entered into the new Renaissance age. In this paper will be described the new trends laser Materials processing.

2. New Industrial Lasers

2.1 Problems of High Power Lasers

An ideal laser in physics is defined as the temporal and spatial coherent electro-magnetic wave (EMW). In a word though it is not theoretically correct, the temporal coherence means monochromatic wave, and the special coherence is a strong wave with uni-phase. This kind electro-magnetic wave does not exist in the nature and only possible to produce by the laser or maser.

From the view point of energy concentration, the spatial coherence is important. The EMW in phase can be tightly focused by the lens or mirror, and thus the extremely high concentration of energy is achievable. A laser is a heat source that can produce the highest power density more than 10^7 kW/cm^2 that the mankind has ever used. The beam mode is an important factor which governs the focusing capability. Beam mode is defined as the pattern of standing wave in the radial direction in the laser cavity. As shown schematically in Fig. 1, there are numberless modes of standing wave in the cavity. The white part in the figure shows where the beam intensity is high. The beam mode is expressed by TEM$_{mn}$ (Transverse Electro Magnetic Mode), and TEM$_{00}$ is called as the basic mode, single mode or Gaussian mode. The intensity at the beam center is the highest in TEM$_{00}$ mode. The modes with higher values of m and n are called the higher order mode or multiple mode. If the beam power is the same, the peak intensity becomes lower in higher order mode. The Gaussian mode is the ideal case of laser, however, it is only achievable up to several kW CO$_2$ laser and several W lamp pumped solid laser.

The focusing capability is the highest in the Gaussian beam, and it is getting worse as the indices m and n are increased when the same optics is used. In Fig. 2 is shown the propagation characteristic of Gaussian beam. Though a laser has the superior directionality, it is not the perfect parallel beam (plane wave) but has a

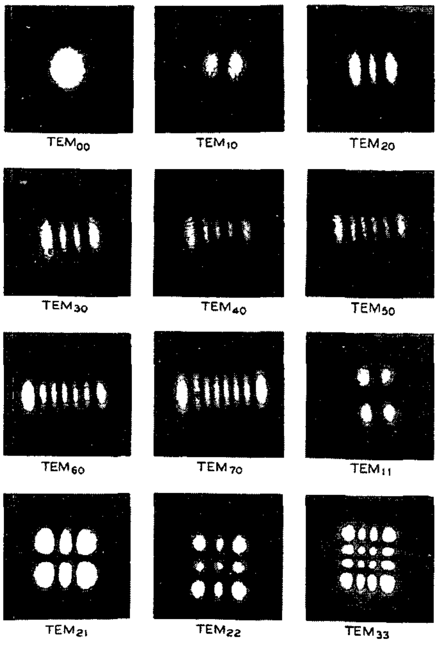


Fig. 1 Pattern of beam mode[1]

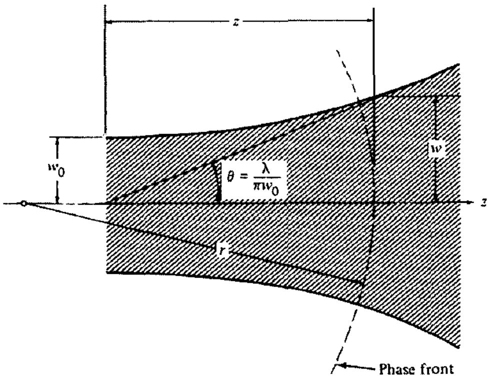


Fig. 2 Propagation characteristic of gaussian beam[1]

slight divergence angle(spherical wave). The angle is called as the beam divergence angle Θ, and the part with minimum beam diameter is called the beam waist w_0.

The beam radius w at the distance z is expressed by the following equation, when the origin of axis is taken zero at the position of beam waist.

$$w^2(z)=w_0^2\left[1+\left(\frac{\lambda z}{\pi w_0^2}\right)^2\right] \tag{1}$$

From this relation, the beam divergence angle Θ is obtained as follow.

$$\theta=\lim_{Z\to\infty}\frac{dw}{dz}=\frac{\lambda}{\pi w_0} \tag{2}$$

If the Gaussian beam is focused by an ideal lens, a new beam waist is formed. The radius of new waist w_1 is given by;

$$w_1=f\theta_1=\frac{f\lambda}{\pi w_0} \tag{3}$$

where, f is the focal length of condensing lens.

The beam radius $W(z)$ of multiple mode is increased by the constant ratio M at any position of z.

Thus,

$$W(z)=M\cdot w(z) \tag{4}$$

is obtained. The magnification M is different depending on the order of mode, and becomes larger as the order is higher. Also, the divergence angle Θ of higher order beam is $\Theta=M\Theta$. Therefore, the beam radius of multiple mode $W(z)$ is expressed by the following equation.

$$W^2(z)=W_0^2\left(1+\left(\frac{M^2\lambda z}{\pi W_0^2}\right)^2\right) \tag{5}$$

As described above, the dimensionless quantity M^2 is a measure of expressing beam quality. In Gaussian beam, $M^2 = 1$, while $M^2 > 1$ for multiple mode beam. In practical high power lasers, M^2 value usually ranges from10 to 100. Therefore, the spot size at focal point become larger as the laser power is higher, which has been the problem in laser materials processing with high power lasers.

Another index BPP (Beam Parameter Product) is also used widely to evaluate beam quality. BPP is expressed by the dimension of [mm mrad], and higher the BPP, the lower the beam quality. The definition of BPP and its relation to M^2-value is shown in Fig. 3.

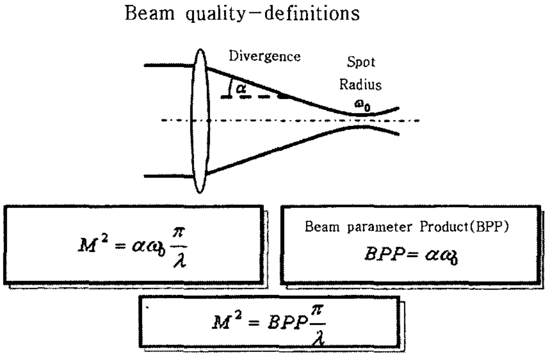


Fig. 3 Definition of BPP[2)]

2.2 Appearance of High Quality-High Power Solid Lasers

A solid-state laser has an advantage that the size of laser oscillator is much compact compared with that of gas laser with same output power. However, there is a big problem that the beam quality of solid laser is much worse than that of gas laser due to the thermal distortion of solid crystal. Also, the electric-light conversion efficiency is extremely low. For example, the conversion efficiency of lamp pumped YAG laser is as low as 1/10 of CO_2 laser.

In recent years, new solid-state lasers are developed and the beam quality as well as conversion efficiency has been greatly improved. In particular, the disk and fiber lasers have attracted attention from the view point of beam quality. These lasers employ the LD pumping and the conversion efficiency exceed 25 %, which is much better than that of conventional CO_2 laser. As to the conversion efficiency is concerned, a laser diode is the highest, more than 40 %, however there is a problem of bad focusing ability.

In a disk laser, a very thin disk of 0.1-0.3 mm in thickness is used to avoid the thermal distortion. Figure 4 shows the schematic structure of disk laser. The Yb^{3+} doped YAG disk (10 mm in diameter) is directly soldered to water cooled copper heat sink to minimize the thermal distortion. A fiber delivered LD light is obliquely irradiated on the disk for pumping laser as shown in Fig. 5.

As the disk hardly receives thermal effect, the beam quality is greatly improved much more than that of conventional lamp pumped YAG laser as seen in Fig. 6. The actual beam mode is the near single mode. One disk can produce 1 kW output, and a 4 kW machine is commercially available at present.

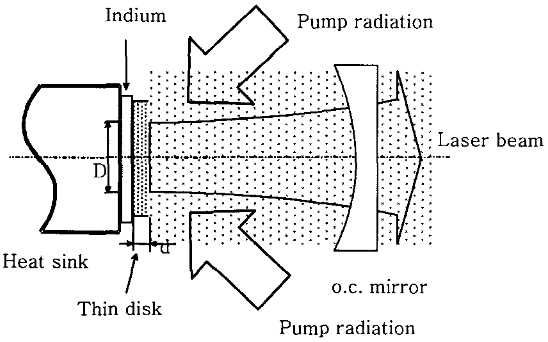


Fig. 4 Basic structure of disk laser (Courtesy of Dr. A. Giesen)

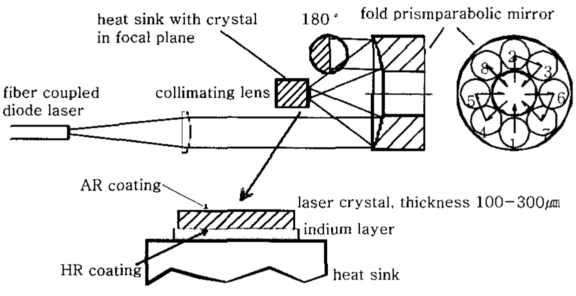


Fig. 5 Pumping method in disk laser (Courtesy of Dr. A. Giesen)

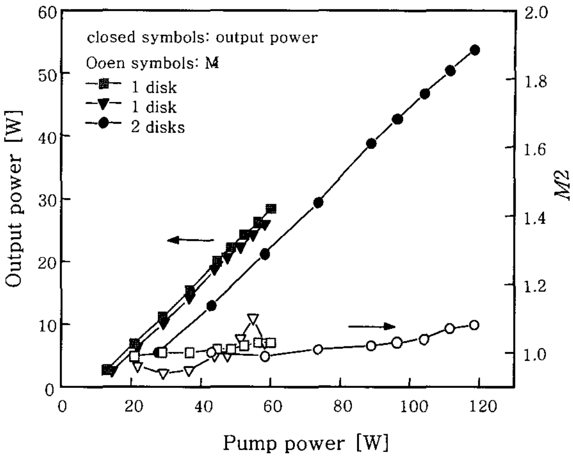


Fig. 6 Power and beam quality of disk laser (Courtesy of Dr. A. Giesen)

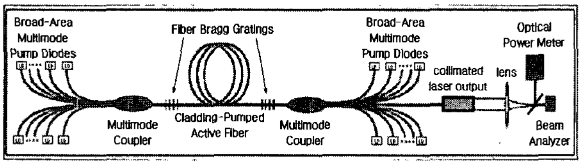


Fig. 7 Basic structure of high power fiber laser (Courtesy of IPG Co.)

Another solid-state laser that is more attracted attention is a fiber laser. The basic structure of fiber laser is shown in Fig. 7. The core part of fiber is doped with Yb^{3+} or Er^{3+}, and the LD pumping light is

Introduced into the clad layer which is thicker than that of conventional optical fiber. Here, the Bragg gratings located at the both end of active fiber play the role of mirrors in the conventional laser cavuty.

The features of fiber laser are;

1) Simple structure,
2) Extremely good beam quality (M^2 〈 2 or BPP 〈 10 mm mrad),
3) High electric-light conversion rate (〉 30 %),
4) Easy to increase power.

Presently, a 17 kW fiber laser is commercially available.

Figure 8 shows the comparison of beam quality in various lasers. It is obvious that a fiber laser has the best beam quality among all practical lasers. Figure 9 illustrates the historical trend of power increase of CO_2, YAG and fiber lasers. It is noted that the power increase of fiber laser has been achieved within a short period.

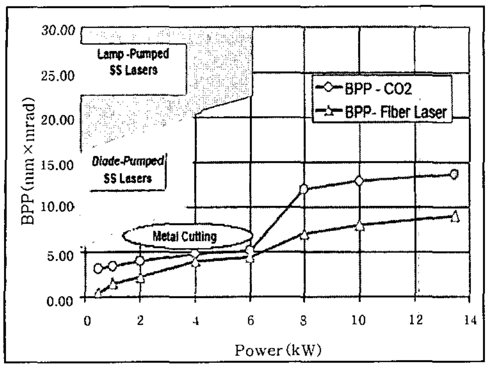


Fig. 8 Beam quality of various lasers (Courtesy of IPG Co.)

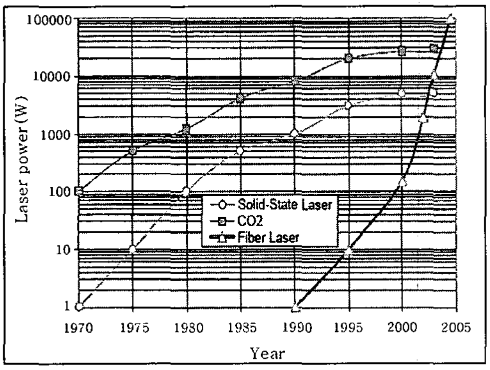


Fig. 9 Historical power increase of various laser (Courtesy of IPG Co.)

A laser diode (semi-conductor laser) has been also attracted industrial attention. The biggest feature of laser diode is that the electric-light conversion efficiency is the highest, more than 40 %, among all lasers. The compactness and light weight is also attractive. A drawback of LD is the poor beam quality which leads to a large focal point.

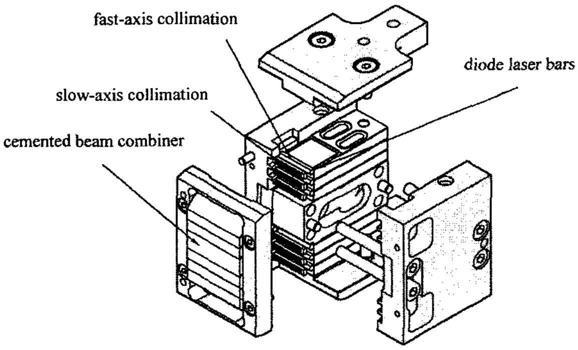


Fig. 10 Array module of laser diode[3)]

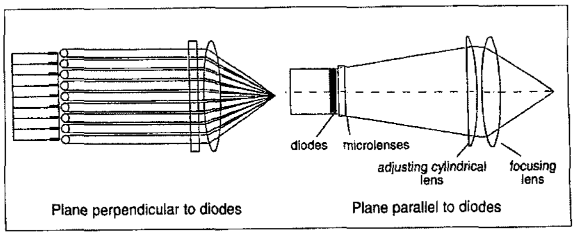


Fig. 11 An example of beam combining in laser diode[4)]

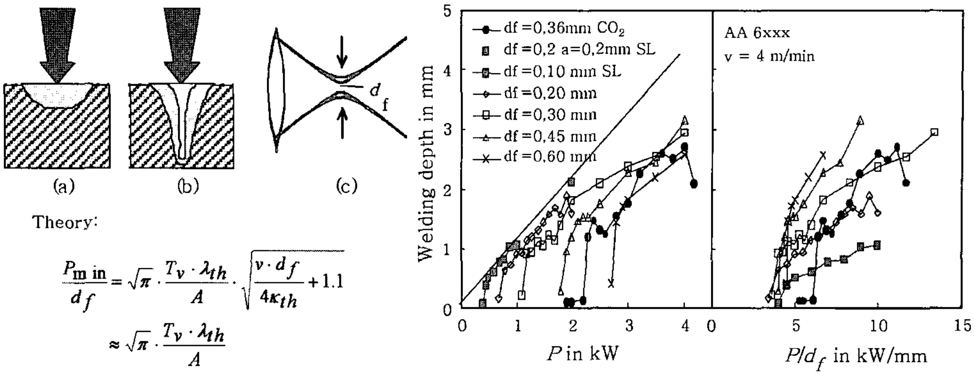
Figure 10 shows the array module of laser diode. The module is set LD bars of several 10 W in array, and it is possible to achieve high output power. Each LD bar emits a rectangular beam from the end of bar, and beams are combined to single beam using special micro-optics as shown in Fig. 11. However, the emitted rectangular beam has the large divergence angle and thus the beam focusing capability is not good enough. Presently, a 6 kW class laser diode is available commercially.

Other attractive lasers are also available in recent years. They are the pico-second and femto-second lasers, which can be applied to non-thermal micro-fabrication. However, these lasers will not be described here due to the limit of papers.

3. Materials Processing by High Quality Lasers

3.1 Deep Penetration and High Speed Welding

As the power density at focal point is increased, the evaporation from laser irradiated part is enhanced and a deep keyhole is formed due to the recoil force of evaporation. In laser welding, a conduction mode penetration is obtained when the laser power (strictly, power density) is low, as shown in Fig. 12(a). However, when the laser power exceeds a certain threshold value, a deep keyhole is formed by the intense recoil force of evaporation and a deep penetration is achieved as seen in Fig. 12(b). This type of welding is called keyhole mode. Figure 12(d) shows the effect of beam power on the transition from conduction to keyhole mode welding using various lasers with different beam size. As seen

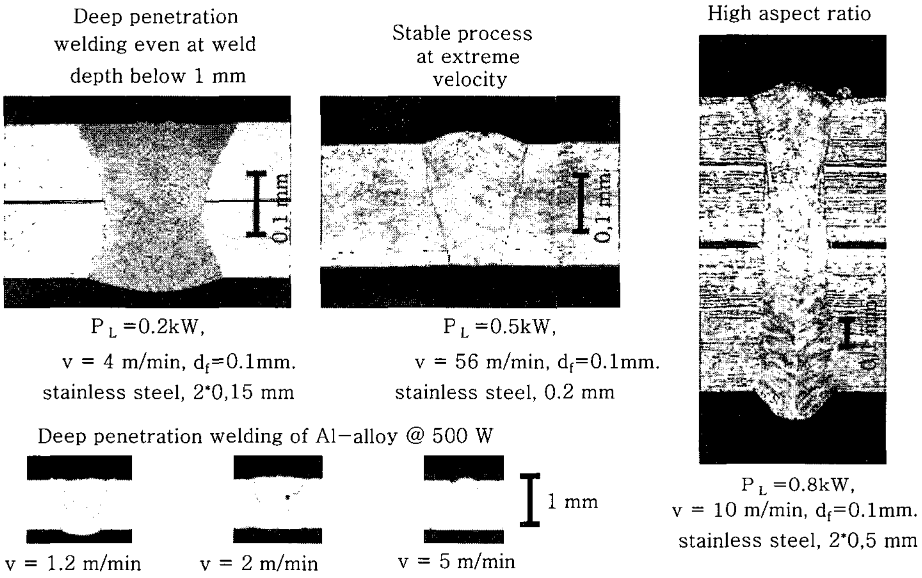


Theory:

$$\frac{P_{\min}}{d_f} = \sqrt{\pi} \cdot \frac{T_v \cdot \lambda_{th}}{A} \cdot \sqrt{\frac{v \cdot d_f}{4\kappa_{th}} + 1.1}$$

$$\approx \sqrt{\pi} \cdot \frac{T_v \cdot \lambda_{th}}{A}$$

Fig. 12 Transition from conduction mode welding to keyhole mode welding[5)]



Deep penetration welding even at weld depth below 1 mm

P_L =0.2kW,
v = 4 m/min, d_f=0.1mm.
stainless steel, 2*0,15 mm

Stable process at extreme velocity

P_L =0.5kW,
v = 56 m/min, d_f=0.1mm.
stainless steel, 0.2 mm

High aspect ratio

P_L =0.8kW,
v = 10 m/min, d_f=0.1mm.
stainless steel, 2*0,5 mm

Deep penetration welding of Al-alloy @ 500 W

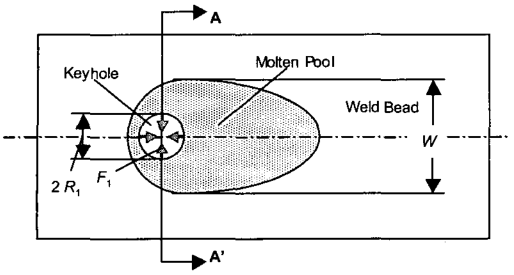
v = 1.2 m/min v = 2 m/min v = 5 m/min

Fig. 13 Weld bead shape by disk laser (Courtesy of Dr. A. Giesen)

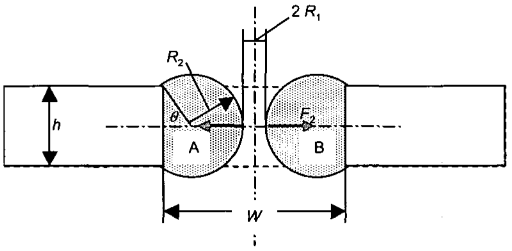
in the figure, the threshold powers of transition are quite different depending on the lasers used. F. Dausinger and others[5)] found that a new parameter P/d_f can reasonably arrange the threshold value of bead formation transition as shown in Fig. 12(e). Here, d_f denotes the beam diameter at the focal position (Fig. 12 (c)). As seen in Fig. 12(e) the threshold value of bead formation transition is more converged to a certain value of P/d_f. They conducted a theoretical analysis on this point and obtained a relation shown in the figure. However, they did not give the physical meaning of quantity P/d_f.

The above results shows that the threshold power of bead transition becomes smaller as the beam quality is better, namely, as the focal spot size is smaller. Figure 13 shows the welded results of thin plates with a low power disk laser. Beads with high aspect ratio (ratio of penetration depth to bead width) are obtained at very high welding speed.

A keyhole welding of thin plate is rather difficult because the surface tension instability is likely to occur. Figure 14 shows the liquid configuration during keyhole welding. A keyhole with curvature radius R_1 tends to shrink by the surface tension F_1 because of negative curvature. While, the liquid attached to base metal with curvature radius R_2 causes to widen keyhole by surface tension F_2. Therefore, if the gravity is ignored, the static capillary pressure balance of keyhole is given as;



(a) Top view of keyhole welding



(b) A-A' cross section

Fig. 14 Bridging condition of liquid droplets in keyhole welding

$$p_\sigma = \sigma\left(-\frac{1}{R_1}+\frac{1}{R_2}\right) \tag{6}$$

If $p_\sigma < 0$, the keyhole tends to close, and if $p_\sigma > 0$, the keyhole tends to widen.

In sound keyhole welding, the liquid droplets A and B must bridge again behind the keyhole. The critical bead width W_B for bridging is given as follow;

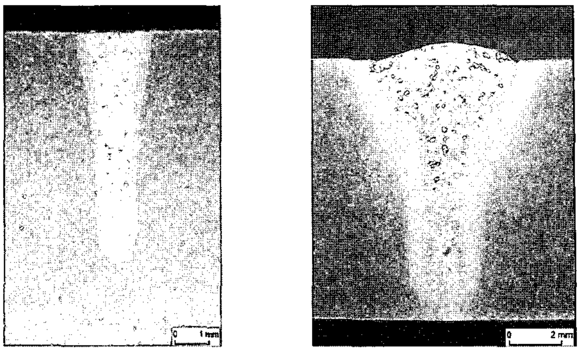
$$\frac{W_B}{h} = \frac{\pi-\theta+\cos\theta \bullet \sin\theta}{2\sin^2\theta} = \frac{1+\cos\theta}{\sin\theta} \tag{7}$$

Therefore, the critical plate thickness that can weld by keyhole process is roughly given as follow.

$$W_B / h_c = 1.84 < 2 \tag{8}$$

It is, therefore, necessary to achieve a narrow bead width, i.e, narrow keyhole diameter, to avoid the surface tensional instability in keyhole welding of thin plate.

Figure 14 shows the weld configuration by a fiber laser which has further better beam quality than that of fiber laser. Reflecting the excellent beam quality, a deep and narrow weld is obtained at high welding speed. A fiber laser is a very promising laser for welding.



(a)
Mild steel
P = 6.9 kW
v = 4 m/min

(b)
Mild steel
P = 6.9 kW
v = 1 m/min

Fig. 14 Bridging condition of liquid droplets in keyhole welding

In deep penetration welding by high power lasers, the porosity formation and solidification cracking are the serious problems. The present author and his coworkers[6-8], and Tsukamoto and others[9,10] have revealed the mechanisms and preventive measures, and many papers have been published.

As described above, the new disk and fiber lasers have much superior beam quality than the conventional solid-state lasers, and a deep penetration welding is possible at rather high speed. Furthermore, these lasers employ LD for pumping, an thus the electrical-light conversion efficiencies are much higher than CO_2 laser. Also, the fact that the life time of LD is much longer than flash lamp is important from the view point of actual production.

Among all lasers, a LD has the highest conversion efficiency as high as 40-50 %. Noting this fact, the direct use of LD is increasing in industries. However, due to the poor beam quality, a LD is mostly used for conduction mode welding of thin sheet. The feature of direct LD welding is the smooth bead surface comparable to TIG welding. Also. the welding speed is higher than in TIG welding. As the focused beam has a rectangular shape, the welding performance is different depending on the beam traverse direction as shown in Fig. 15.

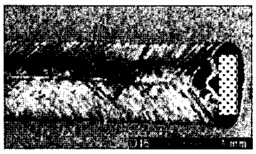
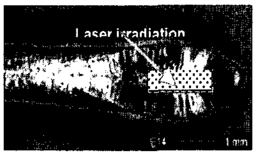
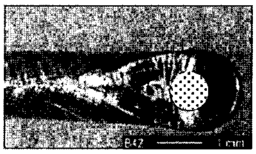
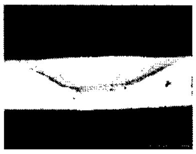
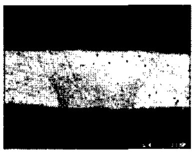
Rectangular spot perpendicular to joint line	Rectangular spot parpallel to joint line	Round spot
		
		

Fig. 15 Direct LD welding performance depending on beam traverse direction11) (Material: Type 316L, Laser Power: 1.38 kW, Welding Speed: 5 mm/s)

3.2 High Efficiency Welding (Remote Welding or Scanner Welding)

In the Laser stitch welding which is widely used in car body assembly, the conventional method is that the welding torch moves continuously and laser power is repeated on and off operation. Namely, the off-time is a loss of processing time. To overcome this problem, a new welding method called remote welding (or scanner welding) has been developed in Europe. As shown in Fig. 16, a laser beam is scanned quickly to the next position by the 2 mirrors, and thus the off-time can be reduced considerably. The beam focal point can be also quickly changed by moving focusing unit along the *z*-axis. In order to cover the wide scanning area in x- and y-directions, it is required to use a long focal length optics. However, as stated at previous eq. (3), the focal spot size becomes larger as the focal length is longer. Therefore. It is necessary to employ a laser with good beam quality. At the moment, a 4 kW class CO_2 laser with $M^2 < 2$ is actually used in industries. In near future, the disk and fiber lasers will be used in remote welding.

Figure 17 shows an example of remote welding applied to floor panel of car. The remote welding is not only used in automotive industries but also used in other industries. Figure 18 illustrates an example of remote welding of tubes to tube plate of heat exchanger[12].

The idea of remote welding may have a possibility to reduce the rigidity of high speed moving robot. In conventional robot, the tip of robot must be quickly decelerated and accelerated at the corner part during its motion along the *x-y* trajectory shown by dotted line in the figure.

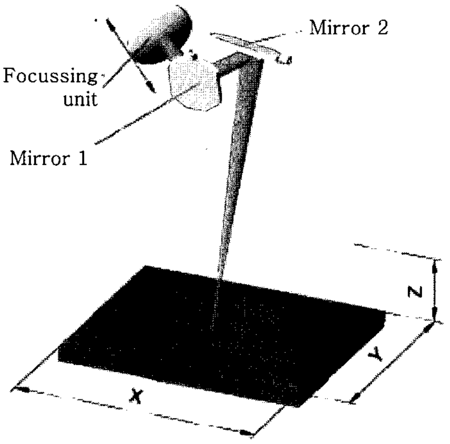


Fig. 16 Remote laser welding (Courtesy of Trump Co.)

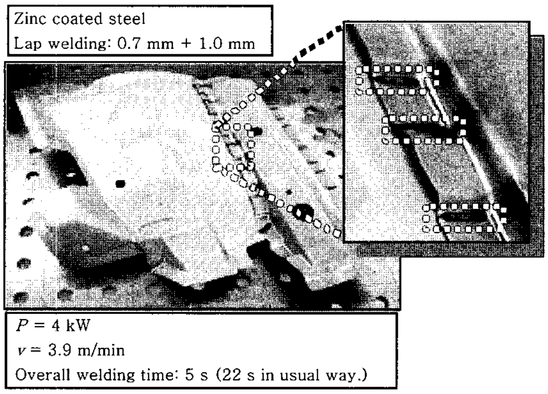


Fig. 17 Remote laser welding of floor panel of car (Courtesy of Trump Co.)

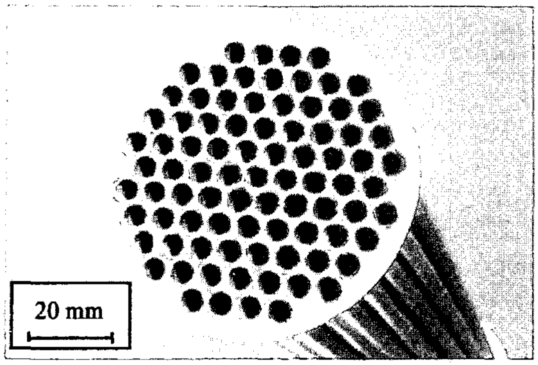


Fig. 18 Remote welding of tube to tube plate He at exchanger[12)]

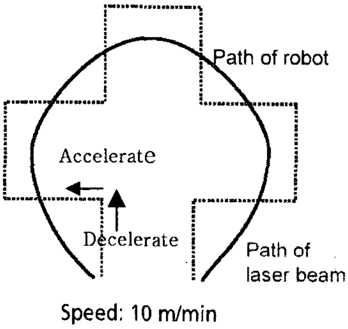


Fig. 19 Trajectory of robot and required pass (Courtesy of Dr. E. Beyer)

The present laser cutting machine receives the maximum acceleration of 4G and extremely high rigidity is required to robot structure. This leads to a heavy and expensive machine. However, if the idea of remote welding could be applied, the robot itself could move along a smooth trajectory at high speed, and the scanner mirrors could describe the required trajectory. If realized, the weight of robot might be reduced considerably. This is still in the stage of idea, but may be worthy to consider.

3.3 Laser Brazing

Recently, laser brazing is actively employed mainly in automotive industries in Europe. The features of laser brazing are;

1) Narrow heat affected zone,
2) Minimal thermal distortion,
3) High speed processing,
4) No post treatment required,
5) Increase in design freedom and
6) Applicable to dissimilar joints.

Figure 20 shows the cross-sectional view of laser brazed joint and application to the rear part of car body.

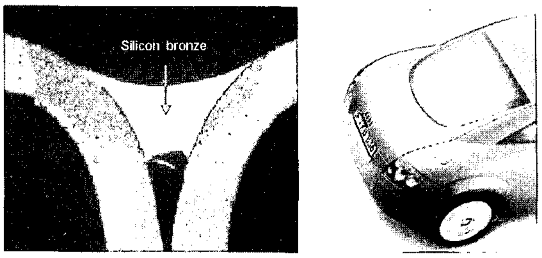


Fig. 20 Laser brazing and its application to car body (Courtesy of Dr. E. Beyer)

3.4 Laser Welding of Plastics

Use of adhesive is the major joining technique of plastics, though there has been a welding method of thermo-plastic materials using a hot air jet. However, welding of some kind of plastics with YAG laser or LD is spreading in practical manufacturing in recent years. The principle of laser welding of plastics is illustrated in Fig. 21. A plastic plate which is transparent to the wavelength of laser beam is placed on the opaque plate and pressure is applied from the top. When a laser beam is irradiated from the transparent plastic side, the laser beam is absorbed at the surface of opaque material and surface melting occurs. The heat generated on the surface of opaque plastic is transferred to the upper transparent material and both plates are melted at the interface and welding is completed. In practice, the both plastic materials

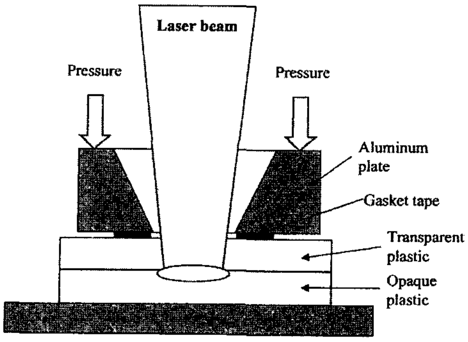


Fig. 21 Principle of laser welding of plastics[13)]

are principally the same kind. However, in order to enhance the laser beam absorption, the opaque plastic is prepared by adding beam absorbing materials such as carbon. Today the technique begins to use intensively in manufacturing plastic products of automotive use. Figure 22 shows the laser welded air-intake manifold used for car. The product used to be joined mechanically, but the number of parts and processes can be greatly reduced as shown in the figure. The laser welding of plastics will be applied in various field in near future. TWI in UK has demonstrated to use this technology to sewing T-shirts.

3.5 Three Dimensional Forming by Metal Powder Deposition (Direct Metal Deposition)

DMD (Direct Metal Deposition) is a method to pile up metal layer by melting and solidifying metal powders at the laser irradiated part and form a complex shape which is unable to make by machining. Also, the method is applicable to produce the structures of gradient materials and compound materials by controlling the amount of several metal powders. Figure 22 shows the concept of FMD and Fig. 24 illustrates a demonstration sample of complex 3D structure of steel on the copper base. The method is not suitable for mass-production but is intensively used for trial manufacturing of weapon parts and metal moulds in US and Europe. There is a movement to apply this technique to repair the broken turbine blade made of single crystal.

J. Mazumder and his coworkers[15] are conducting a notable R&D on DMD. All metals expand at elevated temperature. However, their new idea is to laminate two different metals with different thermal expansion coefficient in cell structures as shown in Fig. 25, the overall structure does not expand at higher temperature by generation

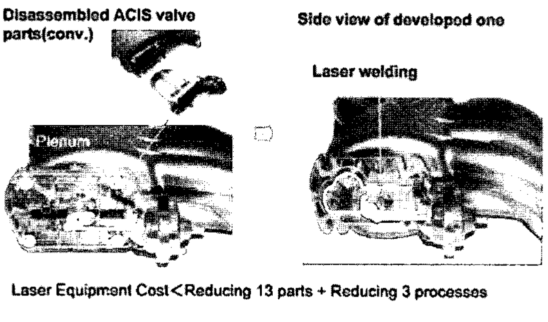


Fig. 22 Laser welded plastic air intake manifold used for car (Courtesy of Toyota Motors)

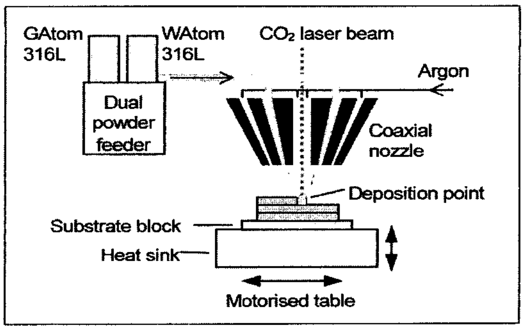


Fig. 23 Basic concept of DMD[14]

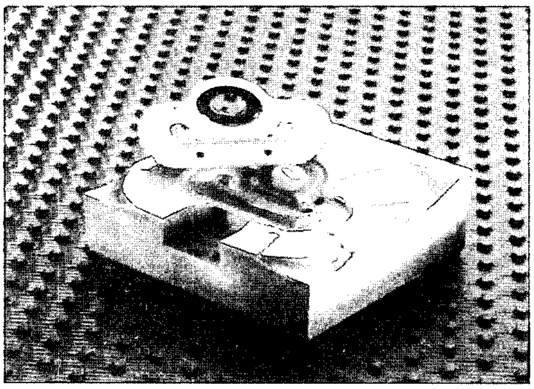


Fig. 24 3D steel structure deposited on copper[16]

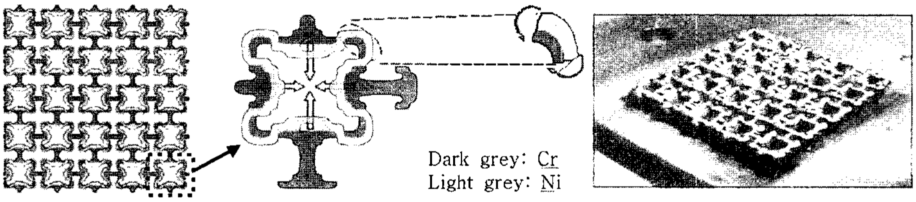


Fig. 25 Temperature independent bed made by DMD with 2 metals with different thermal expansion[15]

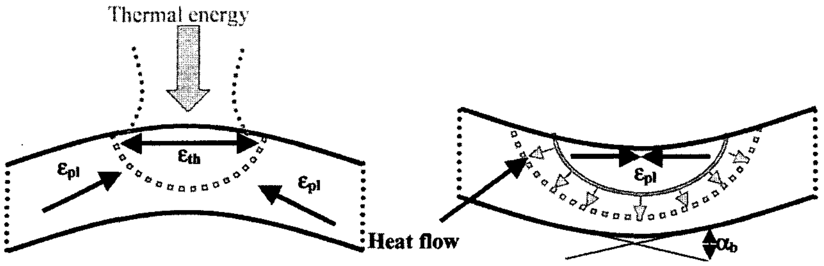


Fig. 26 Principle of laser forming[16)]

of compressive stress according to the bi-metal reaction at the cell corner. Moreover, even the shrinking structure at higher temperature is possible to make by proper selection of materials and design.

3.6 Three Dimensional Laser Forming

As seen in Fig. 26, when a metal plate is irradiated by laser beam, it is expanded at the surface side during laser heating and is contracted during cooling, and the permanent deformation remains finally. Forming a 3D shape using this phenomenon is called Laser Forming. The idea of laser forming was proposed by Namba[17)] in the late 1980, but it has not been noted in industries. However, the technique is attracting attentions in many fields.

Figure 27 shows an example of 3d laser forming of thin mild steel. In accordance with the development of simulation technology, the number of papers on elasto-plasto analyses of laser forming is increasing. Fig. 26 was also formed based on simulation by scanning beam along a part of elliptical arch.

3.7 Laser Peening (Laser Shock Hardening)

When a nano-second short pulse laser is shot on a metal, an extremely high pressure laser plasma is induced and a shock wave propagates in the solid metal as shown in Fig. 28. Particularly when a laser is irradiated in water environment, the plasma pressure reaches to several GPa which exceeds the yield stress of metal.

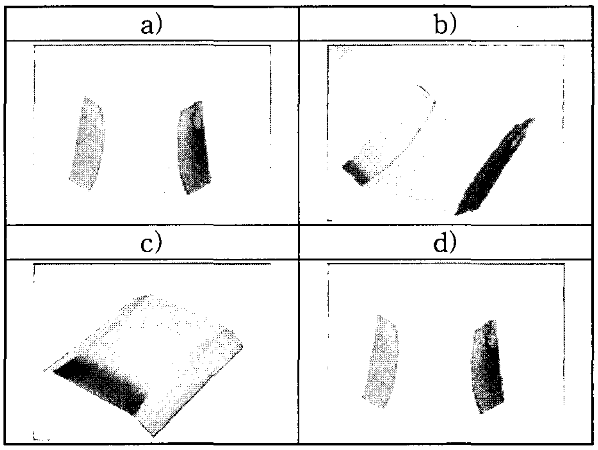


Fig. 27 3D forming of thin metal sheet by laser[18)] (Mild steel: 152 x 152 x 0.2 mm, Elliptical scan)

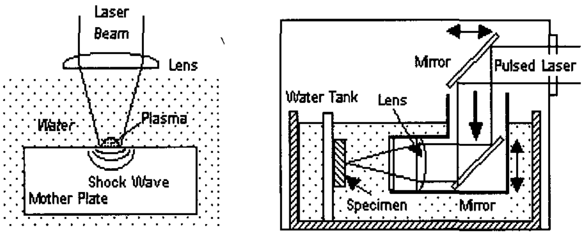


Fig. 28 Laser peening[19)]

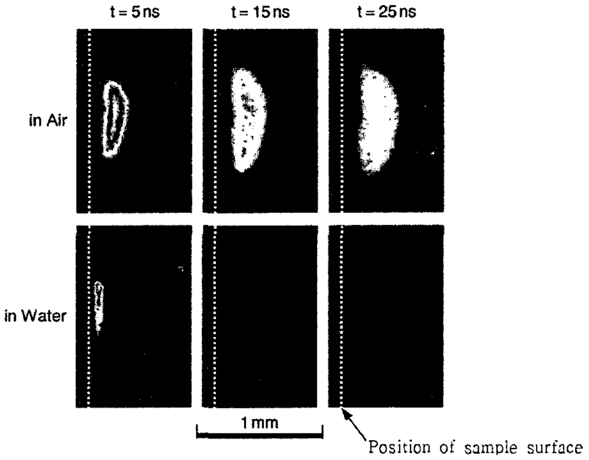


Fig. 29 Plasma evolution in air and water after laser shot[19)]

Figure 29 shows the plasma evolution in air

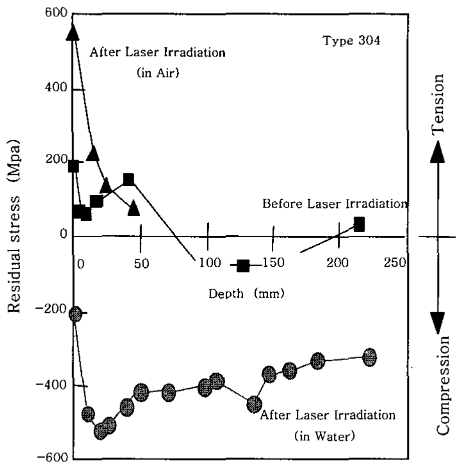


Fig. 30 Stress distribution before and after laser peening (Type 304)[19]

and water by the shot of a Q-switched YAG lase (Pulse duration: 5 ns). In air environment, the plasma expands quickly and the estimated plasma pressure at 20 ns is 70 Mpa. While in water environment, the plasma is confined by surrounding water and does not expands as is in air. The estimated pressure at 20 ns after laser shot reaches as high as 2 Gpa, which is considerably higher than the yield stress of metal.

Figure 30 shows the stress distribution in metal (Type 304) before and after the laser irradiation. The initial tensile stress distribution near the surface turns into the compressive stress distribution after laser peening in the water. The depth of laser peened is much deeper than that obtained by conventional shock peening.

In nuclear power plant, the stress corrosion cracking of welded part is a serious problem. In order to prevent the stress corrosion, the laser peening has been applied to actual nuclear power plants (BWR) since 2002 by Toshiba.

4. Problems to be Solved in Laser Materials Processing - Reduction of Photon Cost and Process Stabilization by Hybrid Technologies-

Laser materials processing have been gradually improved their performances by the advances of laser power and its quality. Presently, laser technologies are widely recognized as the useful measures in many industries. From the view point of present author, however, the industrial applications of laser materials processing, particularly laser welding technologies are not sufficient yet when considering the potential of lasers. There may be many factors that hinder the wide use of lasers in industries. Among them, the following factors are important:

1) Photon cost of lasers is too high.
2) Increase in accuracy of joint preparation that can cope wit the high speed movement of tiny laser beam,
3) Spatial and temporal increase in precision of seam tracking devices,
4) Requires heavy and rigid jigs, and
5) Insufficient development of adaptive control systems.

These factors are naturally causing the high cost of laser materials processing.

In order to reduce photon cost, development of hybrid welding is a recent topics in the world. The idea is to combine laser energy with other heat sources such as arc discharge and high frequency induction heating. Laser hybrid welding is not a new idea. In late 1970's a laser/arc hybrid welding process was first examined by W. Steen's group[20]. After that Kosuge and others conducted the experimental works using CO_2 laser and TIG arc. However, their pioneering works did not attract attentions in industries because the laser welding technologies were not matured enough. In 1994, E. Beyer and his group[21] published a paper on YAG laser/TIG arc hybrid welding and showed the effectiveness of hybrid process, particularly significant increase in gap tolerance and bead formation stability. Since then the development of laser/arc hybrid welding has become a hot topic worldwide. Another important progress of hybrid welding is the laser/induction heating hybrid welding. The technology was established by Japanese steel industries and intensively used in production of stainless steel pipe.

In Fig. 31 is described the concept of laser/arc hybrid process. Many combinations of lasers

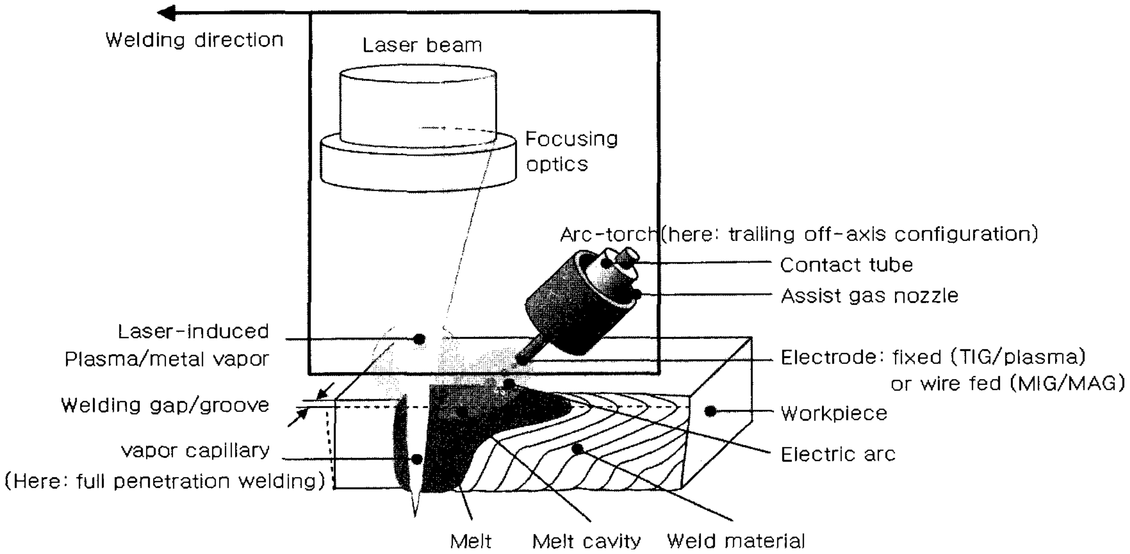


Fig. 31 Concept of laser/arc hybrid welding[22)]

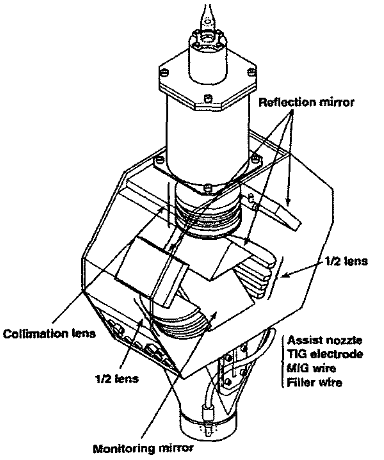


Fig. 32 Coaxial type laser/arc hybrid welding torch[23)]

such as CO_2 and YAG lasers, LD, and fiber laser with various arcs such as TIG and MIG/MAG arcs are investigated. In principle, the laser/arc hybrid welding can be classified into two types, i.e.,

1) Laser assisted arc welding, and
2) Arc assisted laser welding.

Purposes of these two processes are different each other and phenomena are also slightly different. Generally, the laser and arc torches are set off-axis but there is also an attempt to develop a coaxial torch that can use for contour or 3D welding as shown in Fig. 32.

The advantage of laser arc hybrid welding are that the tolerance to gap and misalignment of joints is increase remarkably as well as bead formation stability is increased very much at high welding speed. There are also several reports that porosity formation is successfully reduced in hybrid processes[23.24)]. In Fig. 33 is shown the effect of gap tolerance in but joint welding by the single laser welding and YAG laser/MIG arc

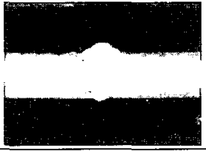
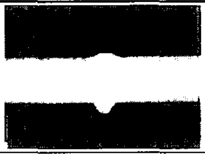
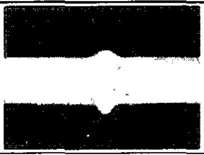
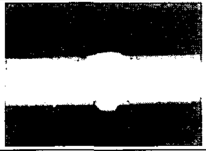
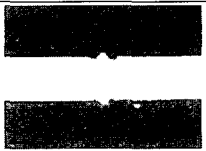
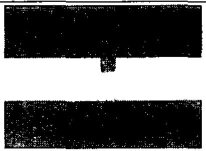
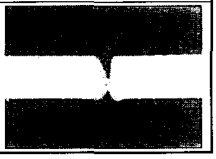
Gap(mm)	0	0.5	1.0	1.5
MIG-YAG 5kW, 125A, 18V 0.8m/min Ar				
YAG only 5kW 0.8m/min Ar				

Fig. 33 Gap tolerance of single laser welding and YAG/MIG hybrid welding of but joint[23)]

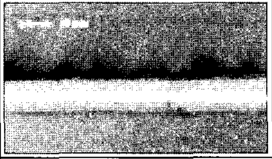
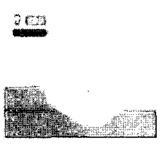
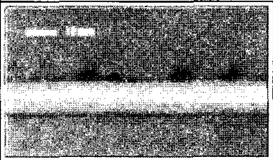
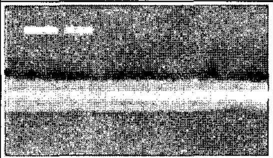
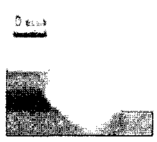
Welding speed: 4m/min wire feeding:13m/min ACMIG: 135A 16.9V EN ratio: 30% Diode laser power at workpiece: 1925W		
Gap	Bead appearance	Cross section
0.0mm		
0.5mm		
1.0mm		

Fig. 34 Gap tolerance in TAG/AC MIG hybrid welding of lap joint[25] (A5052, 1.2 mm + 1.5 mm, Wire: A5356, Laser Power: 2.5 kW, Welding Speed: 4 m/min, Arc Current: 139 A, EN Ratio: 30 %)

hybrid welding. It is obvious that the hybrid process has wider gap tolerance. Figure 34 shows the gap tolerance of fillet welding of lap joint. Here, a special AC MIG arc is used. AC MIG arc is featured by wide range controllability of penetration of base metal br choosing EN (Electrode Negative) ratio. In general, the gap tolerance in single laser welding is about 10 % of upper plate thickness. However, as seen in the figure, the gap tolerance is extremely enlarged in laser/MIG hybrid welding.

Another important hybrid process is the laser/HF induction heating hybrid welding. High frequency welding has been widely used in production of pipes in steel industries. HF welding is a solid state pressure welding. However, due to the skin effect of high frequency current, the heating at the middle part of plate thickness is likely to become unstable when the plate thickness becomes thicker. To overcome this problem, arc/HF hybrid welding is sometime employed.

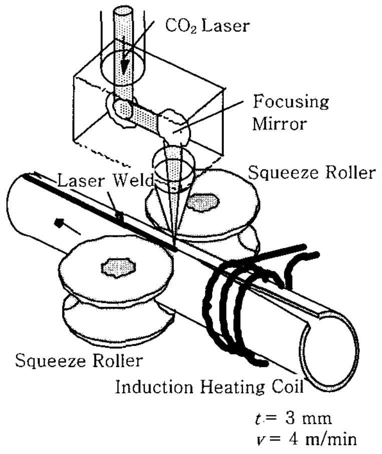


Fig. 35 Laser/HF induction heating process in production of pipe (Courtesy of Sumitomo Metal Works)

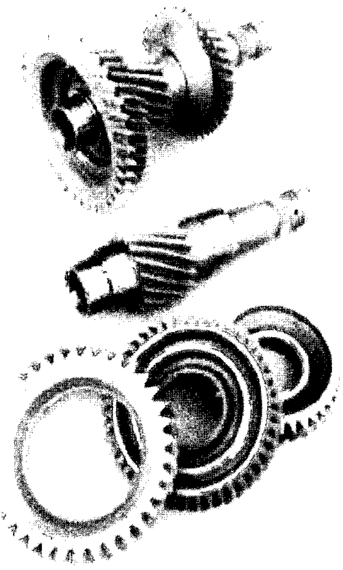


Fig. 36 Laser/HF hybrid welding of gear for automotive use (Courtesy of Dr. E. Beyer)

Laser/HF induction heating process has been introduced since early 1990's in production line of stainless steel pipe in Japan. Fig. 35 shows a schematic diagram of the process. In this process, the welding speed could increase four times faster than that of single HF welding and stability of weld bead formation was considerably improved.

Similar method is recently introduced in German automobile industries to produce power train parts as shown in Fig. 36. The very hard materials are used in these parts, and cracking is likely to occur in single laser welding. However, a laser/HF process can successfully avoid this problem as well as to improve the productivity.

5. Concluding Remarks

In the above were described the latest topics of laser materials processing. In particular, the appearance of high power-high quality lasers will open the new era of laser technologies. In this sense, laser materials processing technologies has just entered into the new Renaissance. However, there still left many scientific and technological barriers that hinder the further expansion of laser technologies in industries. Many problems have been gradually solved by the efforts of scientists and engineers. The personal opinion of present author is that the developments of the adaptive control system, exploitation of materials suitable for laser welding, establishment of evaluation technologies of laser welded joints, and so on are the key issues to be overcome.

References

1. S. S. Charschan: Lasers in Industries, Van Nostrand Reinhold Company, New York, 1972, 14-20, 139-143
2. W. O'Niel, M. Sparkes, M. Varnham, R.Horley, M. Birch, S. Woods & A. Harker: "High Power High Brightness Industrial Fiber Laser Technology", Proc. of ICALEO 2004, Oct. 4-7, 2004, San Francisco, CA, USA, Paper No. 301
3. A. Knitsch, B. Seme, D, Hoffmann, D. Petring, P. Loosen & R. Poprawe: "Diode Laser Systems for Cutting Applications of Thin Materials", Proc. of ICALEO 2003, Oct. 13-16, 2003, Jacksonville, FL, USA, Section D, Paper No. 203.
4. D. Boisselier, O. Freneaux, J. P. Gaufillet, J. Hamy & D. Marchand: Laser Welding, Air Liquide, June, 1998,10
5. F. Dausinger P. Berger & H. Hugel: "Laser Welding of Aluminum Alloys-Problems, Approaches for Improvement and Applications-", Proc. of ICALEO 2002, Oct. 14-17, 2002, Scottsdale, AZ, USA, Section A.
6. N. Seto, S. Katayama & A. Matsunawa: "Porosity Formation Mechanism and Suppression Procedure in Laser Welding of Aluminum Alloy", Quarterly Journal of Japan Welding Soc. (JWS), 18 (2000), 243-255. (in Japanese)
7. N. Seto, S. Katayama and A. Matsunawa: "High-Speed Simultaneous Observation of Plasma and Keyhole Behavior during High Power CO_2 Laser Welding: Effect of Shielding Gas on Porosity Formation", Journal of Laser Applications, LIA, 12-6 (2000), 245-250
8. A. Matsunawa: "Science of Laser Welding- Mechanisms of Keyhole and Pool Dynamics -", Proc. of ICALEO'02, Oct. 14-17, 2002, Scottsdale, AZ, USA, (CDR)
9. S. Tsukamoto, I. Kawaguchi, G. Arakane & H. Honda: "Suppression of Porosity using Pulse Modulation of Laser Power in 20 kW CO_2 Laser Welding", Proceedings of ICALEO 2001, Oct. 15-18, 2001, Jacksonville, FL, USA, Section C, Paper No. 1702
10. S. Tsukamoto, G. Arakane , I. Kawaguchi & H. Honda: "Keyhole Behaviour in High Power Laser Welding of Thick Plates - Formation Mechanism and Suppression of Weld Defects-", Proc. of ICALEO 2003, Oct. 13-16, 2003, Jacksonville, FL, USA, LMP Section A, Paper No. 1007
11. N. F. H.Kerstens, O. M. Richardson & B. T. J. Stoop: "High Power Diode Laser Welding of AA2024 and AISI316L", Proc. of ICALEO 2003, Oct. 13 - 16, 2003, Jacksonville, FL, USA, Section D, Paper No. 207, LMP Section A, pp. 55 - 64
12. F. Vollertsen & T. Seefeld: "Remote Welding at High Laser Power", Proc. of ICALEO 2003, Oct. 13-16, 2003, Jacksonville, FL, USA, Paper No. 1405, LMP Section E, 376 - 385
13. A. Jansson, S. Kouvo, A. Salminen & V. Kujanpaa: "The Effect of Parameters on Laser Transmission Welding of Polymers", Proc. of ICALEO 2003, Oct. 13 - 16, 2003, Jacksonville, FL, USA, Paper No. 609, LMP Section A, 124-133
14. A. J. Pinkerton & L. Li: "A Comparative Study of Multiple Layer Laser Deposition using Water and Gas Atomised 316L Stainless Steel Powders", Proc. of ICALEO 2002, Oct. 14-17, 2002, Scottsdale, AZ, USA, Section B
15. J. Mazumder: "Designed Materials by Direct Materials Deposition", Proc. of ICALEO 2003, Oct. 13-16, 2003, Jacksonville, FL, USA, LMP Section E, 451 - 460
16. J. P. Shackel, J. Sidhu & P. B. Prangnell: "The Metallurgical Implications of Laser Forming Ti-6Al-4V Sheet", Proceedings of ICALEO 2001, Oct. 15-18, 2001, Jacksonville, FL, USA, Section D, Paper No. 601
17. Y. Namba: "LaserForming of Metals and Alloys", Proceedings of LAMP 1987, 21-23 May, 1987, Osaka, Japan, 601-606
18. K. Bartkowiak, G. Dearden, S. P. Edwardson & K. G. Watkins: "Development of 2D ans 3D Laser Forming Strategies for Thin Section Materials using Scanning Optics", Proceedings of ICALEO 2004, 4-4, Oct., 2004, San Francisco, CA, USA, Section Laser Forming, 68-77
19. Y. Sano, N. Mukai, M. Yoda, K. Ogawa & N. Suezono: "Underwater Laser Shock Processing to Introduce Residual Compressive Sress on Metals", Materials Science Research International, Special Technical Publication - 2, (2001), 453

20. W. M. Steen & M. Eboo: "Arc Augmented Laser Welding", Metals Constr., III-7, (1979), 332-336..
21. E. Beyer, U. Dilthey, R. Imhoff, C. Maier, J. Neuenhan & K. Behler: "New Aspects in Laser Welding with an Increased Efficiency", Proc. of ICALEO'94, 183-192
22. D. Petring & C. Fuhrmann: "Recent Progress and Innovative Solutions for Laser-Arc Hybrid Welding", Proceedings of PICALO 2004, April 19-21, 2004, Melbourne, Australia, PLEN 7-10
23. T. Ishide, S. Tsubota, M. Watanabe & K. Ueshiro: "Development of YAG Laser and Arc Hybrid Welding Method", IIW Doc. XII-1705-02
24. Y. Naito, M. Mizutani & S. Katayama: "Observation of Keyhole Behavior and Melt Flows during Laser-Arc Hybrid Welding", Proc. of ICALEO 2003, Oct. 13-16, 2003, Jacksonville, FL, USA, LMP Section A, 159 - 167
25. T. Ueyama, H. Tong, I. Yazawa, M. Hirami, K. Nakata, T. Kihara & M. Ushio: "High Speed Welding of Aluminum Alloy Sheets with Laser Assisted AC Pulsed MIG Process", IIW Doc. XII-1707-02

- 마쯔나와 아키라(松縄　朗)
- 1938년생
- 오사카(大阪)대학 명예교수
- 레이저 재료가공, 용접물리, 아크물리
- e-mail: matunawa@jwri.osaka-u.ac.jp

- 김종도(金鍾道)
- 1963년생
- 한국해양대학교, 기관시스템공학부
- 레이저용접, 플라즈마해석, 실시간모니터링
- e-mail : jdkim@hhu.ac.kr