Laser Advanced Materials Processing

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Abstract

This paper presents studies on the development of science and technology of laser beams and its application to advanced materials processing. After some topical review for laser advanced materials processing, fundamental phenomena in laser materials processing are discussed together with the electron beams which is very similar to laser beams from the viewpoint of high energy density beams.

KEY WORDS: (Laser Materials Processing) (Fundamental Phenomena)

1. Introduction

Any currently known form of energy including electromagnetic energy, mechanical energy and chemical reactive energy can be employed as a heat source for materials heat processing. Although a wide variety of processing heat sources are available through various technologies, from the practical viewpoint they should be studied basically from two major points of power and energy density. Recently, laser beams and electromagnetically accelerated particle beams with a strong focusing system such as electron, ion, neutral and special type plasma beams with large outputs have been developed. These beams are unified as "High and/or Ultra-High Energy Density Beams (HEDB)" because they inherently have a potential of high energy density heat sources. Heat sources of such large output and high energy density are capable of opening new application particularly if employed for materials processing and will not only contribute greatly to industry but also help to develop new academic areas of science and technology. In this report, among these high energy density beams "laser beams" will be mainly discussed for their application capability and their fundamental processing characteristics.

2. Laser Advanced Materials Processing

When we discuss laser advanced materials processing, there are two major standpoints as shown in Fig. 1. The first is concerned with the problems on "laser facilities" and the other is on the "laser application technologies".

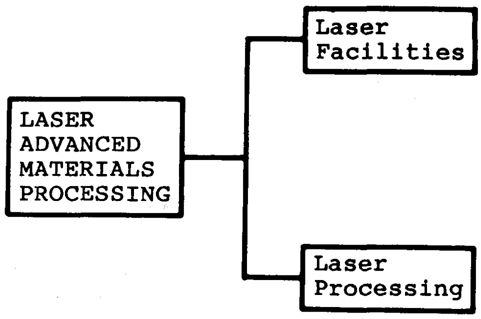

Fig. 1 Laser Advanced Materials Processing.

The author has long been studying laser advanced materials processing on these two major standpoints for about 20 years.

2.1 Laser facilities

Problems on laser facilities are connected with three items as shown in Fig. 2. The first is to obtain a high quality apparatus with good controllability including robotics and strong focusing system The second is how to develop a high power machine with high stability and efficiency. The third is to select an appropriate laser apparatus favorable to each processings such as CO_2 laser or excimer laser and so on. Among them the author mainly discusses on the development of a strong focusing system for a high power laser processing, as well as the development of high power laser facilities.

After the invention of the first CO_2 laser by Dr. C. N. K. Patel in 1964[1)], the author developed in 1966 1 kW

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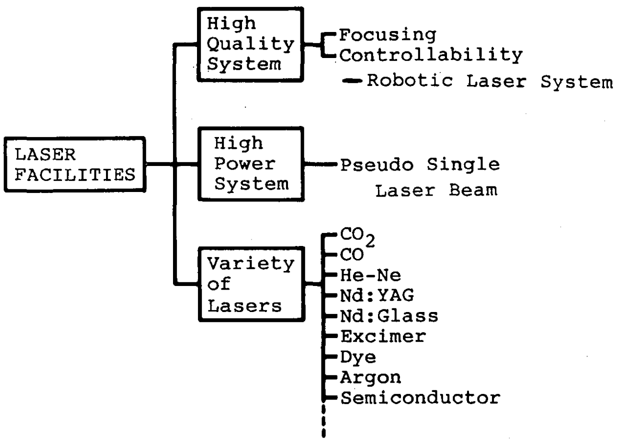

Fig. 2 Laser facilities.

CO_2 laser device as a heat source and introduced it to the world's first large output continuous CO_2 "laser welding" and "laser gas cutting"[2].

To utilize a laser beam in a state of high energy density, how to focus strongly the laser beam is extremely important. Since a focusing lens is damaged by the laser beam, systems using conventional optical lens cannot be used long time in high power laser materials processing. In general, the conventional system using a metallic concave or parabolic mirror has very large aberration. Therefore, the author invented a new focusing system[3]. System (a), (b) and (c) in Fig. 3 are well known as "Arata Laser Focusing System" using concave and plane mirrors developed 21 years ago. Compared with other systems, the greater the laser output the more effective its function becomes in this system.

Recently the author has succeeded in making this system work efficiently as a device to gather "plural beams" into a simple very intense laser beam and named it "Pseudo Single Laser Beam System (PSLB)" for ordinary single laser beam "LB".

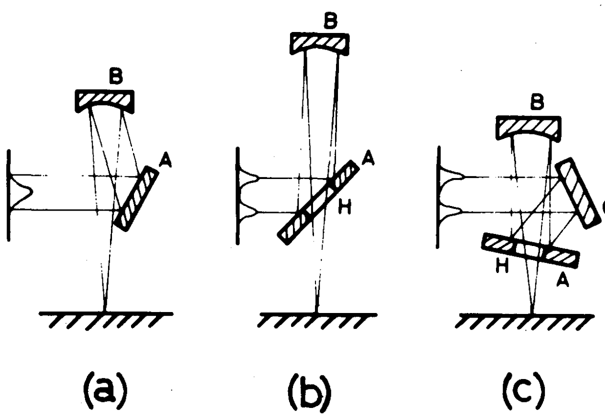

Fig. 3 Arata Laser Focusing System.

Now it is generally accepted that CW CO_2 laser apparatuses with the maximum output of about 10 kW are guarantied in industry. This means, at the same time, that to obtain stably a higher output is very hard and too expensive. By applying this new laser focusing system, the author has made it possible to obtain a very high power and high energy density "pseudo single beam" due to the efficient and simultaneous focusing of a couple of laser beams. It is possible, for example, that with the actual use of guarantied 10 kW-class laser beams, over 50 kW ~ 100 kW-class output "pseudo single beam" is available with a high quality assurance as if it is a single beam. Figure 4 shows schematic diagram of this system. There are two types; the one is the coaxial collection type against the optical axis as shown in (a) and the other is based on the collection system with very low values of aberration in the optical axis for each beam within "several degrees", which was discovered by the author 20 years ago as shown in Fig. 5[3]. In Fig. 6(a) is shown the bead cross section of a welded plate by a "single" 12 kW CO_2 laser beam, while in (b) the cross section by the "pseudo

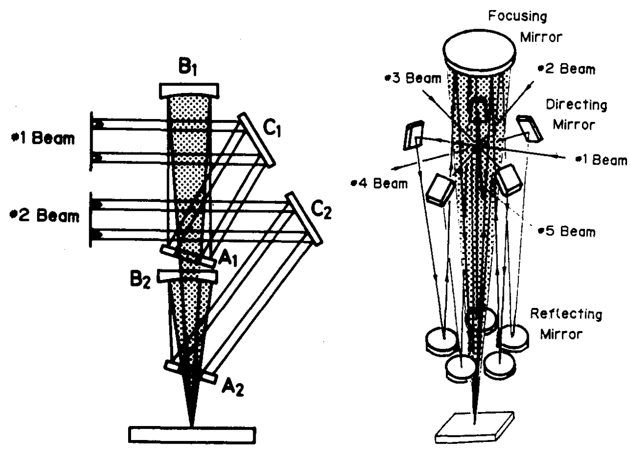

Fig. 4 High Power Pseudo Single Laser Beam System.

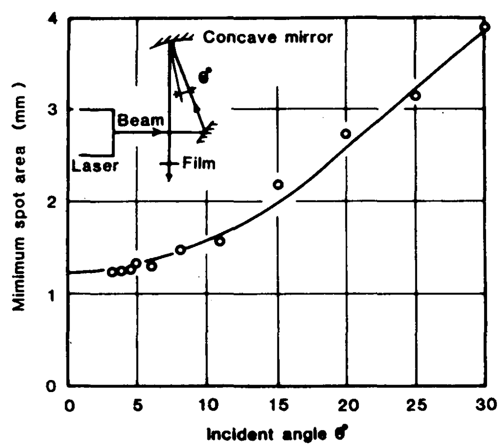

Fig. 5 Minimum spot area vs. incident angle.

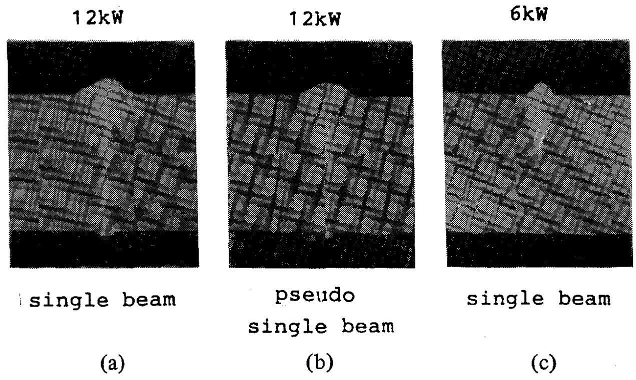

Fig. 6 Comparison of bead cross section. (a) 12 kW single beam, (b) 12 kW PSLB, (c) 6 kW simple beam

single beam" of 12 kW (=6 kW + 6 kW) output. It is clear that both figures show almost the same result. In (c) is given the bead cross section in the case of a "simple" 6 kW laser, by which we can understand well the great ability of the High Power "Pseudo Single Laser Beam System (PSLB)". Of course this newly developed High Power "Pseudo Single Laser Beam System" is available not only to CO_2 laser facilities but also other various high power facilities such as "CO" or "excimer laser" etc. Other big advantage of this system is to be able to obtain "Tandem Laser" just as the so called "Tandem Electron Beam"[4)] by separating each focusing points of the plural beams. Indeed a variety of merits will be expected by the further application of this system to different kinds of lasers and/or materials processing. At present the author believe that even the excimer laser, for which it is considered to be very hard to obtain a high power output by the single beam, can be produced as "pseudo single beam" with the output of 1 ~ 10 kW. Furthermore, we are planning to develop extremely high output laser facilities by using "Compound Laser Beam Generator" system. Fig. 7 shows a schematic drawing of this system. It has 12 pieces of 5 kW CO_2 lasers arranged on the same plane. They can generate 12 laser beams parallely within about 10 cm in diameter. These beams are also easily focused as single 60 kW laser beam of about 1 mm in diameter by using "Pseudo Single Laser Focusing System". If one gathers more 24 or 48 beams as shown in Fig. 7, one can obtain 360 kW of 1000 kW CO_2 laser as pseudo single beam. Indeed "Pseudo Single Laser" might be a dreamful system to produce high power laser facilities.

2.2 Laser processing

Figure 8 shows a classification of "laser processing". It is divided into four major categories with regard to the

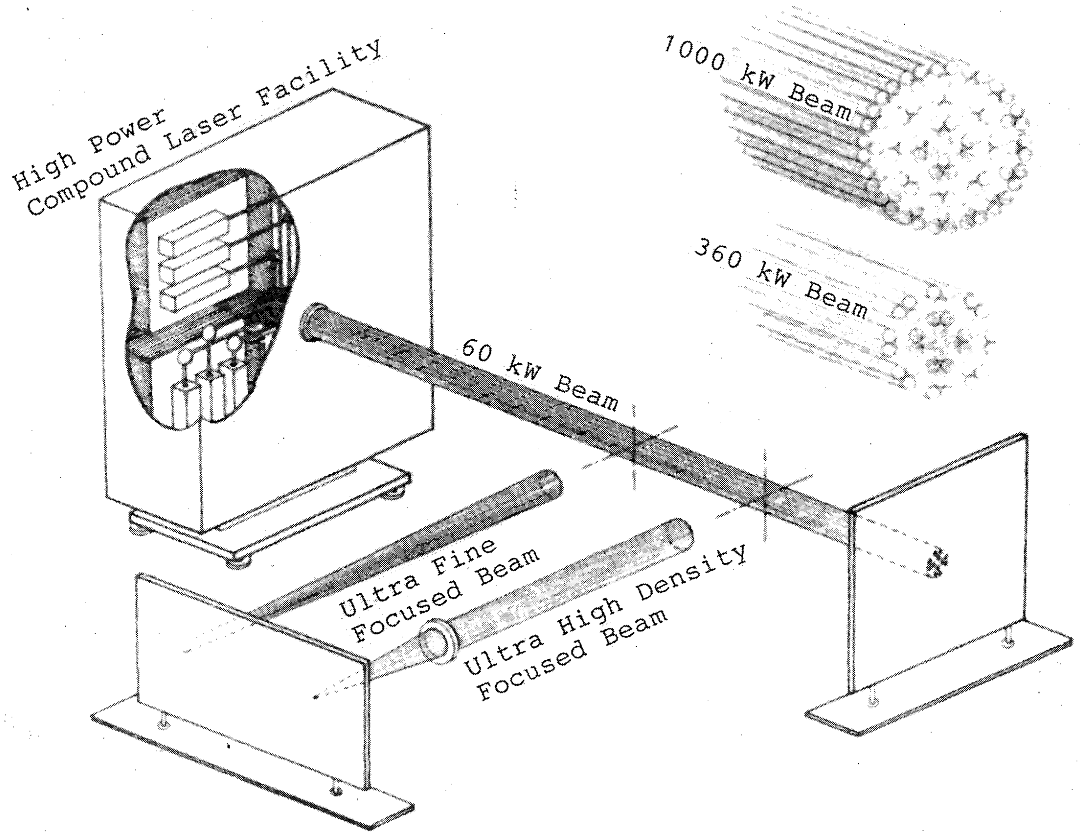

Fig. 7 Composed Laser Beam Generator.

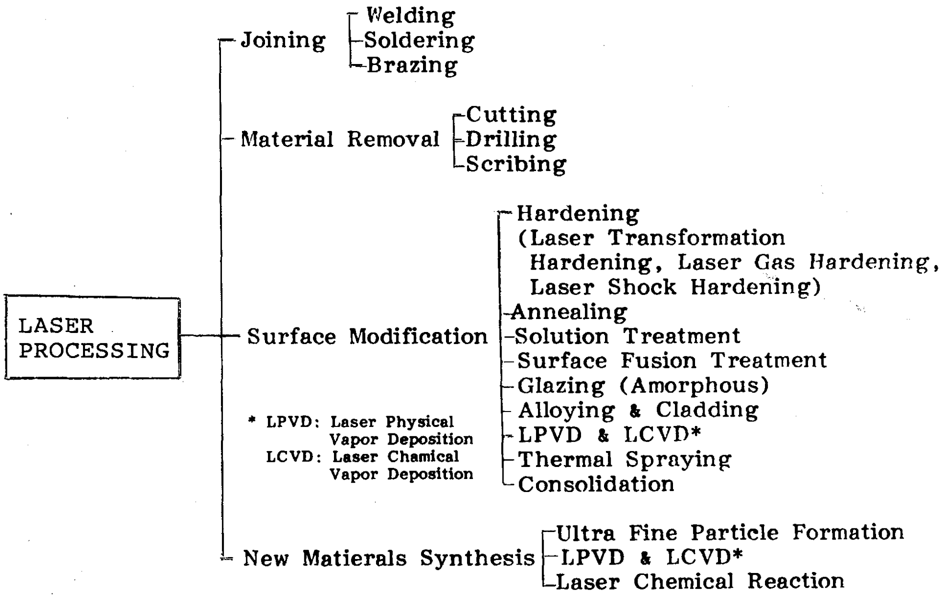

Fig. 8 Laser processing.

interaction type of laser and materials. When the bulk of material is melted, the joining of material takes place. This category includes *welding, soldering* and *brazing.* When the melted material is removed, *cutting, drilling* and *scribing* are possible. If the interaction is limited around the surface of the material, "surface modification" is achieved. Surface modification is classified into two subcategories, melted and non-melted. When the surface is not melted, *hardening, annealing, solution treatment* and *thermal spraying* take place. When the surface is melted, *surface fusion treatment, glazing, alloying, cladding* and *consolidation* are possible. Other application is "new materials synthesis" which utilizes laser power as chemical reaction energy. It includes *ultra fine particle formation, LPVD, LCVD* and *laser induced chemical reactions.* Some examples of these applications of laser advanced materials processing are reviewed below.

2.2.1 Cutting

Laser cutting is the most popular application of laser to materials processing. It started from very early period of history of laser materials processing. The author has succeeded in developing "Laser Gas Cutting" (Fig. 9) by a high power CO_2 laser beam and "Electron Beam Gas Cutting" (Fig. 10) for the first in the world at nearly the same time 20 years ago[3]. In 1966, they were named as "High Energy Density Beam Gas Cutting (HEDB Gas Cutting)" by clarifying systematically various common but characteristic phenomena. In this study we have analyzed in detail their characteristics using the newly developed special observation method with 16 mm films[5]. Meanwhile in the EB gas cutting, the beam arc or

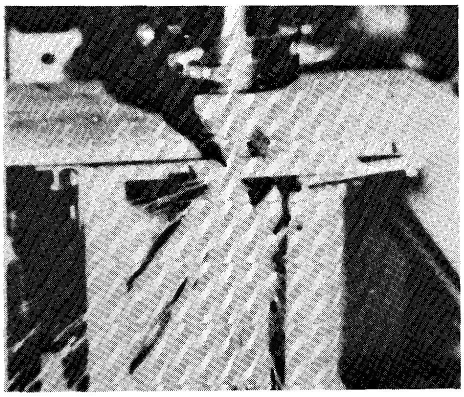

Fig. 9 Laser gas cutting.

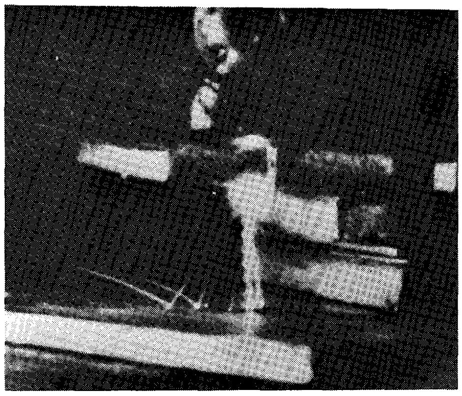

Fig. 10 Electron beam gas cutting.

beam-plasma beam which is sustained in the existence of the electron beam is obtained by the superposition of arc discharge or plasma beam, and a more efficient cutting is possible[6].

To know clearly which is better between electron and laser beams as HEDB gas cutting, the most important factor to be considered is the degree of the beam-plasma generation, but other factors such as the state of the surrounding gas, the variety of the materials used and its configuration have also remarkable influences. That is to say we needed to select a better way judging the optimum conditions "case by case".

Generally the HEDB Gas Cutting process seems superior giving good results for thick plates by the development of plural nozzles. Especially in the laser gas cutting this method was successfully developed in 1979 and their overall review was published later[7, 8]. Several years later many kinds of laser gas cutting torches were presented by some researchers and put into practical use[9]. In these days laser cutting is used not only for small parts but also very large parts such as concrete for "dismantling" of nuclear power plants. Figure 11 shows concrete cutting by laser[10]. These method will employ laser robot system for remote control.

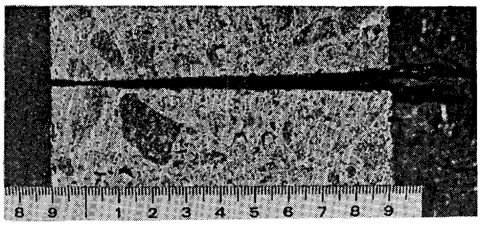

Fig. 11 Concrete cutting by laser.

2.2.2 Welding

Laser welding is the second major application of laser beam for materials processing, because the laser is very easily focused to small spot to become very high energy density. This property is similar to electron beam. However, usually the electron beam is operated in the vacuum and the laser in the open air. So that, even though comparison between EB and laser processing was studied by many researchers so far, it has essentially been incorrect and has brought various mistakes in the understanding of their characteristics.

The author has compared systematically the HEDB processing by studying the correlation of beam and processing characteristics at arbitrary pressure from high vacuum to atmospheric one. That is, although one is electromagnetic wave and the other is charged particle beam, beam hole profile and its behavior in the welding process has been found to be almost the same, if they are utilized as a heat source having the same power and the same energy density. Indeed these two beams could be unified as HEDB not only in the cutting but also in the welding processes. Figure 12 shows the comparison of the beam hole profiles by the electron and the laser beam welding in the vacuum condition. It should be noted in this figure that the same welding conditions (power, energy density, welding speed and the gas pressure) are selected for the two beams. It is clearly seen that quite similar beam holes were obtained[11].

As already described previously the laser beam welding is usually performed in the open air. In this case the penetration depth becomes shallow and wide as like non-vacuum EB welding. This is because the laser plasma prevents the efficient irradiation of the beam to the specimen. To avoid the plasma efficiently, "Laser Spike Seam Welding (LSSW)" method was developed by the author as shown in Fig. 13[12]. Another way of directly avoiding the formation of the plasma was succeeded by the development of the "Vacuum Laser Welding", by which a very similar bead profile with the EB welding was obtained also in the laser welding[11].

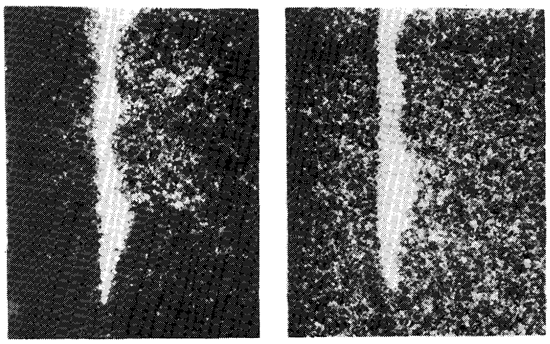

Fig. 12 Comparison of beam hole profile between laser and electron beam welding both in vacuum condition. (11kW, V_b = 10 cm/min, HT80, p = 10^{-4} Torr, 300 frames/s) (a) laser welding, (b) electron beam welding

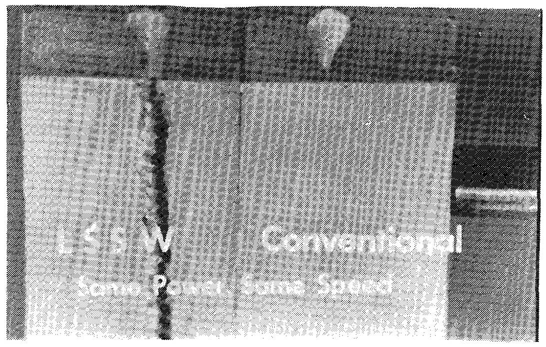

Fig. 13 Comparison of bead between LSSW and conventional method of the same power and welding speed.

2.2.3 Other challenging areas

Titanium was irradiated with laser in a nitrogen atmosphere to form a TiN layer or Ti layer containing a high concentration of nitrogen at the fusion surface. Figure 14

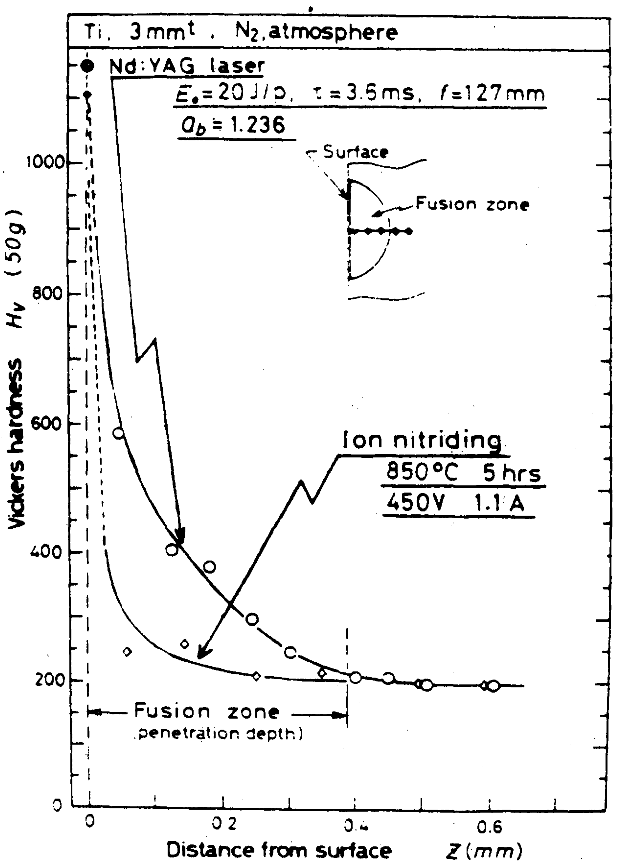

Fig. 14 Comparison of hardness between laser gas hardening and ion nitriding method.

shows a comparison of hardness distribution between "Laser Gas Hardening" and conventional "Ion Nitriding" method. Laser gas hardening can harden titanium surface more rapidly and deeply than conventional method, though the laser nitrizing zone is so small[13]. This "Laser Gas Hardening" technique employs the "Gas-Liquid Reaction" occurring at high temperature and is characterized by the direct formation of ceramic coating on the base material.

When the cooling speed of molten metals is very high, "amorphous" materials sometimes created. Figure 15 shows an example of "Laser Glazing" by YAG laser irradiation[14]. Amorphous ($Pd_{78}Cu_6Si_{16}$) layer of 200 μm in thickness is formed as shown in Fig. 15(a). Figure 15(b) shows its X-ray diffraction pattern.

Laser irradiation improved the quality of thermal-sprayed metallic and ceramic films, that is, the consolidation of the films is performed. For instance, the hardness of thermal-sprayed Ni base film, $Ni_{75}Si_{15}B_{10}$ (Hv = 210) is increased to the value of Hv = 520 by the laser irradiation. The porous thermal-sprayed partially stabilized ZrO_2 film in Fig. 16(a) becomes the dense film in (b) after laser irradiation. The hardness of sprayed film (Hv = 870) is improved to the value of Hv = 1500 under the condition

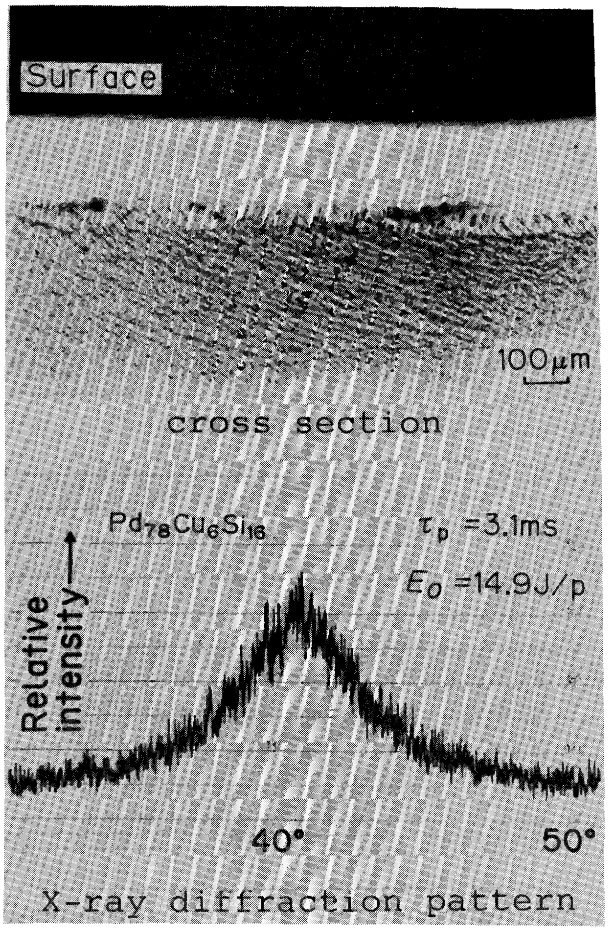

Fig. 15 Laser glazing. (a) cross section, (b) X-ray Diffraction pattern

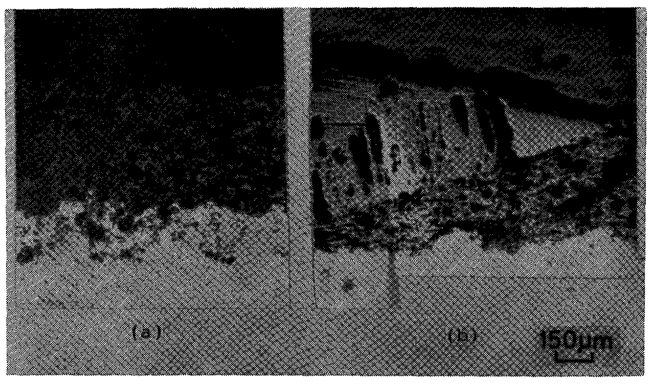

Fig. 16 Laser consolidation. (a) thermal-sprayed partially stabilized ZrO_2, (b) laser-irradiated partially stabilized ZrO_2

of laser power of 2 kW and specimen moving speed of 2 m/min.

Further, the metallizing of ceramics is performed by laser irradiation. In this laser process, even the high melting point metal can easily be melted. For instance, Ni-10 mass% Ti alloy can be metallized to Al_2O_3 under the condition of laser power of 0.5 kW and the specimen moving

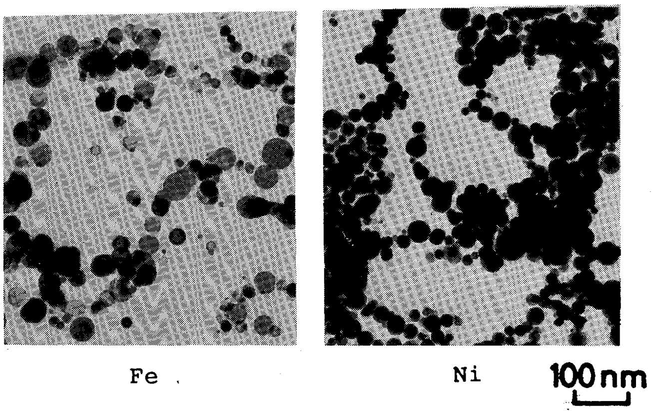

Fig. 17 Ultra fine particle formation by laser. (a) Fe, (b) Ni

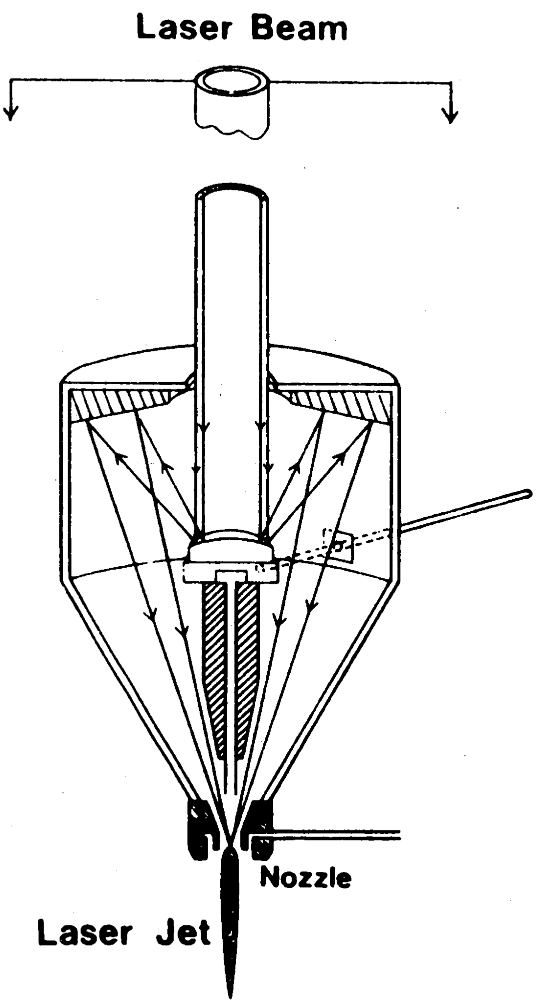

Fig. 18 Plasma Jet.

speed of 1 m/min.

The laser evaporation method using YAG laser can produce "ultra fine particle (UFP)" of metals and ceramics from pure metals in controlled atmospheres. Figure 17 shows an example of TEM pictures of UFP composed from Ni and Fe[15].

A laser beam can also be easily applied to the thermal spraying of metals and ceramics. Due to the high energy density of the laser heat source, the spraying material is easily heated to a high temperature and can be melted effectively. Thickness of coating film can be controlled easily by changing the conditions such as speed of wire supply, traverse of test piece and number of scan[16].

Figure 18 shows an illustration of "Laser Jet Spraying" developed by the author. By using Arata Laser Focusing System effectively, single or plural beams are gathered to the focal point and the materials are fed through the axis to the focal point. These materials instantly becomes heated to a high temperature, forming a strong plasma jet and are rapidly sprayed on the target. In the case of a violent laser jet where materials are evaporated rapidly to the state of atoms and/or molecules, the Laser Jet concept can be applied to other fields such as LPVD or LCVD.

In addition to these examples, many other challenging areas for surface modification and material synthesis have been researching such as alloying, cladding, LCVD, LPVD, the production of superconductive material and so on.

3. Fundamental Phenomena in Laser Materials Processing

Essential phenomena in laser materials processing, especially in laser welding, cutting, drilling and so on are featured by "Violent Evaporation" and "Beam Hole" formation which are caused by its own powerful high energy density.

In order to analyze these phenomena in detail, direct observation of the process was performed with optical method using visible light and X-ray transmission with intensified image converter using a high speed camera. Figure 19 shows the visible observation of laser welding in soda-lime glass. From the film analysis, "periodical dynamic motion" of front wall of beam hole and molten pool were observed. On the front wall, distinguished periodical movement of bright spot happens. This indicates a "shoulder formation" on the front wall, whose behavior determines the welding characteristics[17]. To study further this phenomenon in the actual welding process of metals a transmission X-ray method was utilized. Figure 20 shows the actual beam hole behavior of 10 kW class laser welding of mild steel with assist gas. The shape of beam hole cahnges with gas flow rate of assist gas.

The most important phenomena of laser beam processing are intense laser plasma formation, which obstruct the transmission of the laser power to the specimen. It is an extremely serious problem in case of a high power laser beam. In order to suppress or remove such laser plasma, it

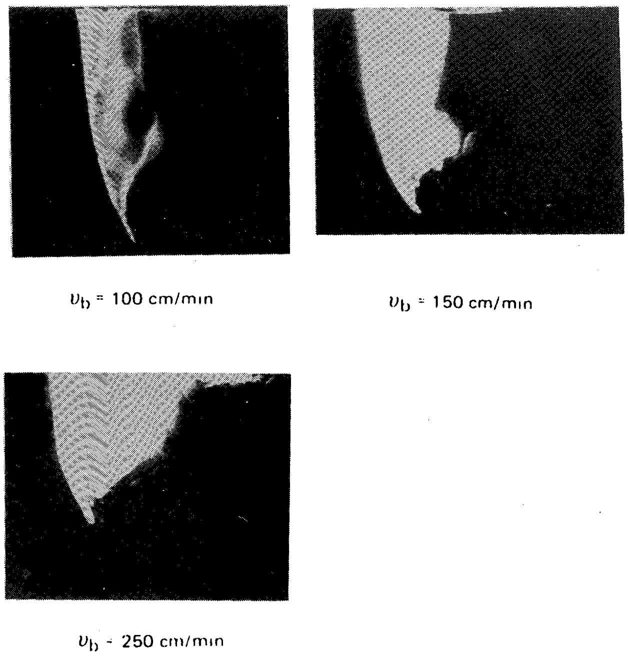

Fig. 19 High speed photographs of beam hole by optical method. (laser beam welding of glass, atmospheric pressure, 8000 frames/s).

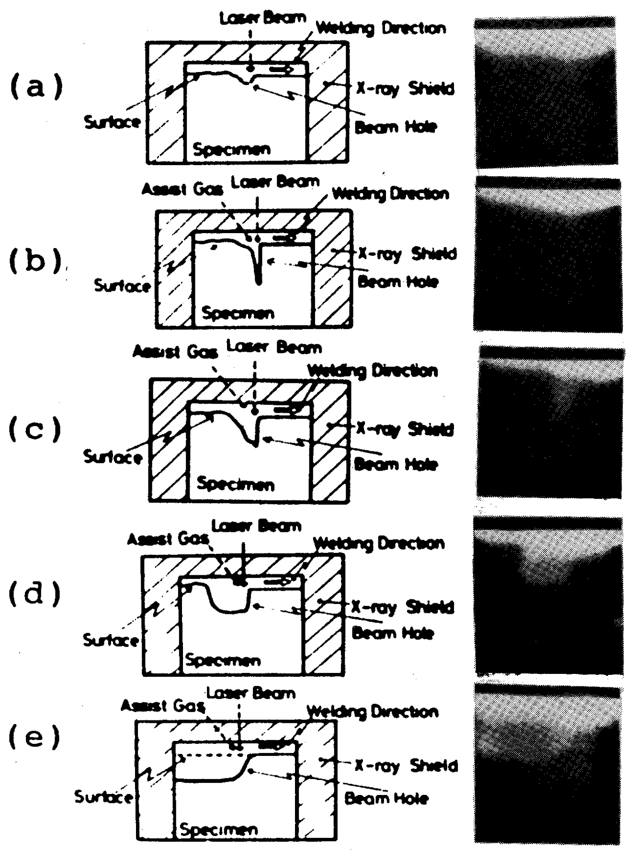

Fig. 20 Typical shapes of beam hole at various gas flow rates. (a) 0 l/min, (b) 36 l/min, (c) 51 l/min, (d) 81 l/min, (e) 120 l/min.

is very important to know fundamental phenomena of the plasma formation and its processing behavior. These characteristics were analyzed in detail using special high speed film technology. Figure 21 shows the formation process of the laser plasma with pink and blue colors. Pink plasma goes upward, while bright blue plasma remains around the opening of the beam hole. Their appearance are repeated periodically. This periodical formation of laser plasma affects the characteristics of front wall behavior as shown in Fig. 22, although the laser beam is continuously supplied. When the plasma is formed the beam cannot irradiate so strongly on the front wall, by which the wall becomes dark. When the plasma disappears, front wall becomes bright and promote deep scrape by the beam. This phenomena appear alternately[11].

Although an "assist gas" is usually employed to reduce the laser plasma, it cannot sufficiently blow away the plasma, especially within the beam hole and cannot increase the penetration depth so much as shown in Fig. 20. Because the strong assist gas also blow away the molten pool to enlarge the beam hole, "Wall Focusing Effect" for the laser beam is reduced and cannot concentrate the

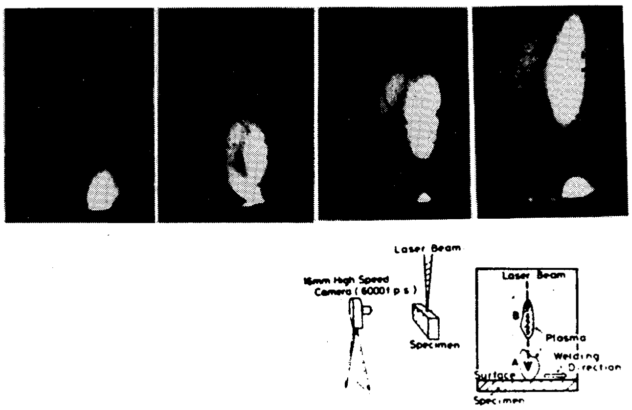

Fig. 21 Laser plasma formation.

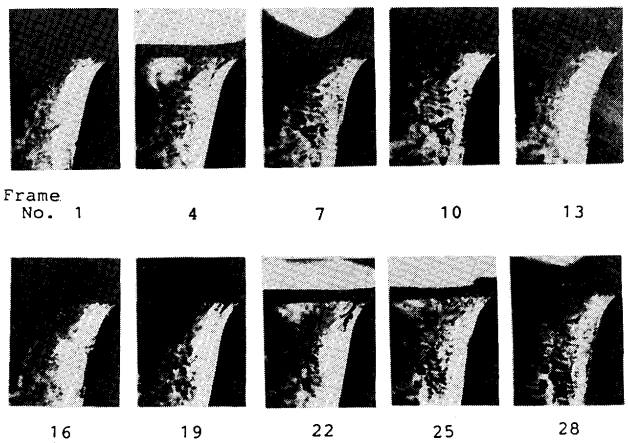

Fig. 22 Periodical change at the upper part of the beam hole during laser welding of glass.

beam to penetrate further with increasing flow rate of the assist gas.

In order to overcome this difficulty, the author have developed "Laser Spike Seam Welding" (LSSW)[12]. It avoids the plasma by shifting the beam forward just before the occurrence of laser plasma burst as shown in Fig. 23. Resultantly, the penetration becomes deep periodically. However, proper shift distance can make continuous bead. It can penetrate twice as deep as conventional laser welding at the same power and same speed.

As another suppression method of the laser plasma, the author developed two types of "Vacuum Laser Welding system"[11], high vacuum type aimed at fundamental research and low vacuum type conveninet for actual application. Figure 24 shows the decrease of the laser plasma with increasing the degree of vacuum. Penetration depth increases with degree of vacuum as shown in Fig. 25. On the view point of materials processing, processing characteristics of laser and electron beams are quite similar each other on the optimum operating condition, because it is resulted by the nature of high energy density itself. Figure 26 shows an essential similarity of the beam penetration in both processes. Clearly in both case, decrease of the pressure caused an increase of the penetration depth in quite a similar manner. In fact, the beam hole behavior in both processes is almost the same as described earlier (Fig. 12).

Besides the importance of the behavior of the front wall and the beam hole, the behavior of molten metal is also very important. However, an X-ray observation method is impossible to distinguish the difference in the image of the base metal and the molten metal. Therefore,

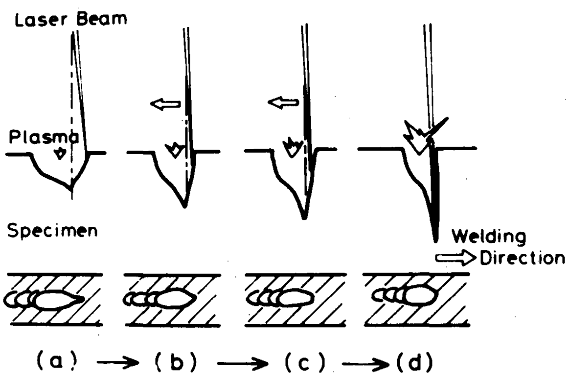

Fig. 23 Mechanism of Laser Spike Seam Welding.

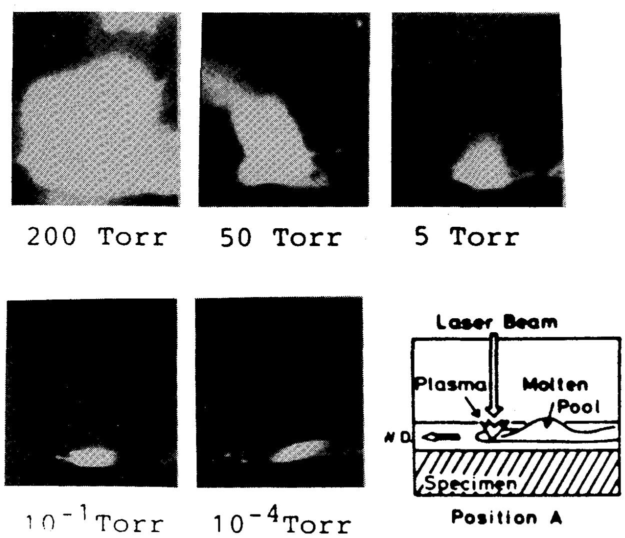

Fig. 24 Typical photographs of laser plasma at different pressures.

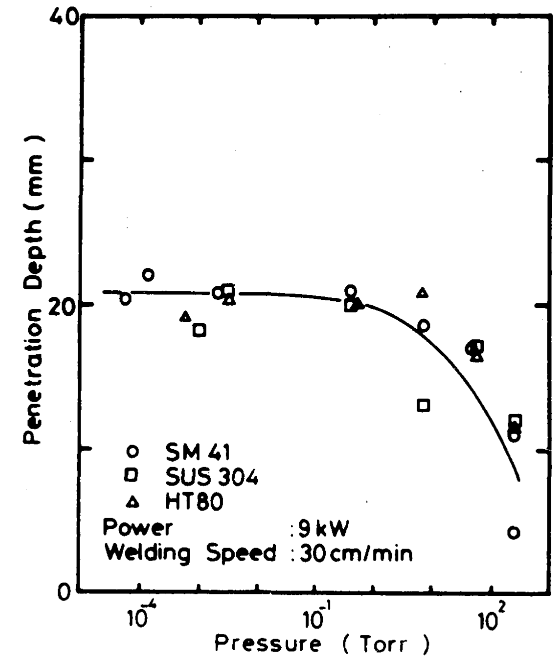

Fig. 25 Pressure dependence of the penetration depth in vacuum laser welding.

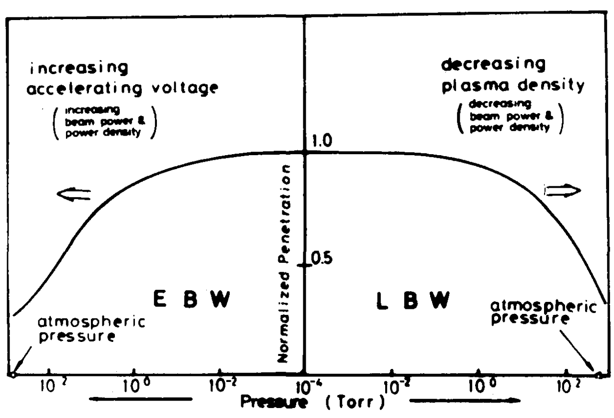

Fig. 26 Comparison of pressure dependence of penetration depth between laser and electron beam welding.

a tungsten tracer was used to trace the molten metal flow. Figure 27 shows the trace of an dropped particle into the molten pool of aluminum alloy. In the upper zone of molten pool, the molten flow is so slow and rather quiet, and in the middle the flow is violent. At the root of the molten pool, melt zone becomes narrow and the particle is trapped there. The particles on or near the rear surface of the beam hole are brown up very rapidly[18].

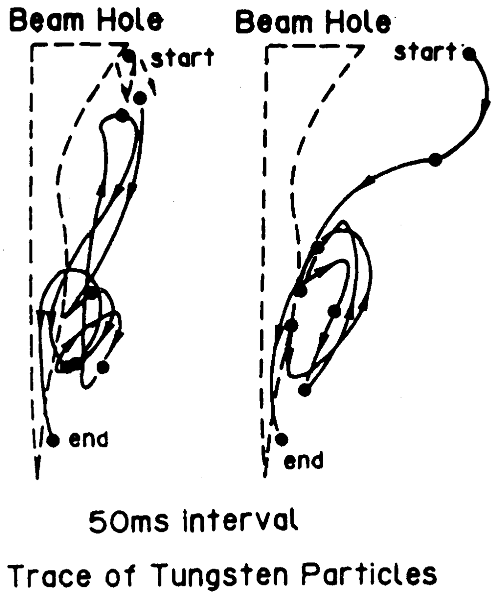

Fig. 27 Examples of trace of tungsten particle.

4. Conclusion

As briefly described above, research of laser advanced materials processing has been promoted in parallel on two major points of facilities and applications. Development in facilities will change from low to high power especially including "pseudo single beam" and from simple automatic controll to automatic robots. Progress in application will turn from cutting and/or welding to surface modification as the high technology for new material synthesis. However, research of fundamental phenomena will be by far the more important. Although the author has long been studying to clarify welding, cutting process and/or surface treatment etc. on this principle, the author believes this is the most essential point of view, and it will develop new revolutional high technology for materials processing. With this point in mind, the author will continue the research work hoping to establish a new academic area with full dream in future.

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