The State of the Arts of Laser Materials Processing and Their Future Subjects

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1. Introduction

A laser is regarded as the greatest scientific and technological invention in the 20th century, because its applicable areas are extremely wide in science, engineering, medicine, etc.. Laser materials processing is only a part of them, but its status in industrial technologies is very important due to the potential capability of laser. As a heat source, a laser is characterized by the highest power density among various heat sources ever developed. Therefore, a laser can bring us processing result of the much better accuracy, higher processing speed and more reliable than that by traditional heat/energy sources, as well as realization of quite new processing technologies which did not exist in the past.

Presently, laser materials processing are widely introduced to industries in North America, EC countries and Japan since early 1980's. The material removal technologies such as cutting, hole drilling, and so on have been the major applications. However, laser welding, and partly laser surface modification technologies, are growing little by little. Many scientists and engineers believe the potential capability and flexibility of lasers as the promising production tools in industries in the next century. However, overviewing the technological and industrial movements in the last several year, the spreading speed of laser technologies in manufacturing seems to be slower than that was expected.

In this article will be described the present state of the arts of laser materials processing in Japan, in particular laser cutting and welding, as well as the subjects to be solved for the wider and more intensive use of laser technologies in near future.

2. Classification and Features of Laser Materials Processing

2.1 Classification of Laser Materials Processing

Laser materials processing can be classified into several kinds by various view points. One of the classification is shown below from the aspect of processing mode based on the usage type of energy.

1) Thermal processing...........................Conversion of photon energy to thermal energy
2) Quantum or non-thermal processing.....Direct action of photon energy onto atoms or molecules without heat generation

Another classification is based on the purpose of processing and is shown as follows.

1) **Materials Removal**..............(Ingenious use of high power density heat source)
   1.1 Cutting....................................Most widely used in industries
   1.2 Scribing...................................Widely used in semi-conductor industry

- 1.3 Trimming..................................Widely used in semi-conductor industry
- 1.4 Marking.....................................Increasing in recent years
- 1.5 Drilling.....................................Fine drilling of super hard/soft materials
- 1.6 Surface cleaning..........................Selective removal surface contamination
- 1.7 Etching.....................................New technology
- 1.8 Production of ultra-fine particles....New technology

2) Joining

- 2.1 Welding.....................................Increasing in recent years
- 2.2 Soldering and brazing...................Increasing in semi-conductor industry

3) Surface Modification

a) Physical Method

- 3.1 Transformation hardening.............Practicable technology
- 3.2 Hardening by melt quenching........Practicable technology
- 3.3 Formation of metastable phase......Near future technology
- 3.4 Surface amorphization.................Near future technology
- 3.5 Shock hardening.........................Near future technology
- 3.6 Cladding...................................Practicable technology
- 3.7 Physical Vapor Deposition...........New technology
- 3.8 Annealing.................................New practicable technology
- 3.9 Doping.....................................New practicable technology

b) Chemical Method

- 3.10 Alloying.................................New practicable technology
- 3.11 Chemical Vapor Deposition........New practicable technology

4) Others

- 4.1 Strain relief...............................New technology
- 4.2 Thermal plastic forming..............New technology

2.2 Features of Laser Materials Processing

General features of laser materials processing is summarized in **Table 1** from the view points of functional and production technological aspects.

Table 1 General features of laser materials processing

	Functional Features	Features from Production Technology
Merits	1) Free selection of power density 2) Non-contact processing 3) Processing in atmospheric pressure 4) Precision processing 5) No X-ray radiation	1) High quality processing 2) Economical processing 3) Flexibility of processing 4) New processing capability 5) Safe processing
Demerits	1) Low energy efficiency 2) Low absorptivity of beam energy 3) Precise optical alignment 4) Hazard by intense radiation	1) Lack of processing data 2) Insufficient reliability and stability of machine 3) Large initial investment cost 4) Matching with existing production lines

2.3 Features from Application Aspects

1) Much wider application areas are expected compared with other heat/energy sources
2) Flexible manufacturing process can be adopted due to better matching characteristics to computer, and the unmanned and energy saving process is easy to achieve.

3) No restriction of work due to non-contact processing, and the multi-station and/or time-sharing processing can be achieved by suitable optical systems.

4) High quality and high productivity processing is possible.

2.4 General Problems

1) Reflection loss is large on metal surface and energy efficiency is low.

2) There are many unknown phenomena left and the adaptive control system has not been established.

3) Laser facilities are still immature.

4) Peripheral equipments such as optics, NC control system, fixing equipments, etc., are far behind to give full play to existing laser's ability.

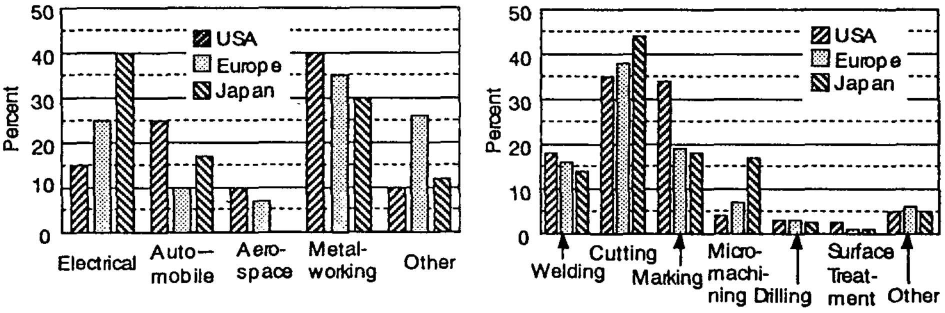
3. Trends of High Power Laser for Materials Processing and Application Areas

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

There are three areas in the world where lasers are intensively used in industry, i.e., North America, EC countries and Japan. Among them, about 40% of the high power lasers in the world are installed in Japanese industries. In **Fig. 1**(a) and (b) are shown the distribution of infrared lasers used in various industries and application areas in the above mentioned three areas.[1] The use of lasers in industries and their applications are slightly different in each area, perhaps due to the differences in industrial structures. In Japan lasers are used intensively in electrical, metalworking and automobile industries, and mostly used in cutting. However, the applications in marking, micro machining and welding are increasing in recent years.

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

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



(a) Industrial Distribution

(b) Applications

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

4. State of the Art of Laser Cutting

The laser cutting is featured by an extremely flexible cutting method and has been widely spread in industries since mid 70's for cutting metals, plastics, ceramics, and so on. In recent years the 5 or 6 axises 3-D cutting robots are intensively introduced in automotive, machining, electric, and heavy industries.

Figure 2 illustrates the comparison of cutting capability of various cutting processes. In the course of development of laser cutting, a great effort has been paid to increase the cutting quality of thin sheet. One goal was to obtain the surface roughness of laser cut equivalent to those of wire cut or EDM. As seen in the figure, the laser cutting has special performance that no other cutting process can achieve. This is the greatest reason that the laser cutting have been widely and quickly spread in industries.

Figure 3 shows the effect of cutting speed on laser cut quality. It is obvious that the laser cutting is intrinsically an extremely high speed process. In laser cutting of stainless steel, Ti-alloys and Al-alloys with oxygen assist gas, the cut quality is not good enough because oxide slag is likely to adhere to the cut edge. In order to overcome this, a high pressure inert gas jet is now used to blow off the molten metal and non oxidized cut with smooth surface is easily obtained.

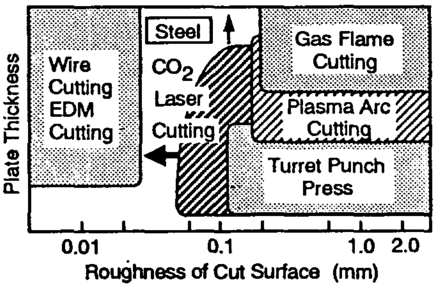


Fig. 2 Comparison of cutting capability of various cutting methods [2]

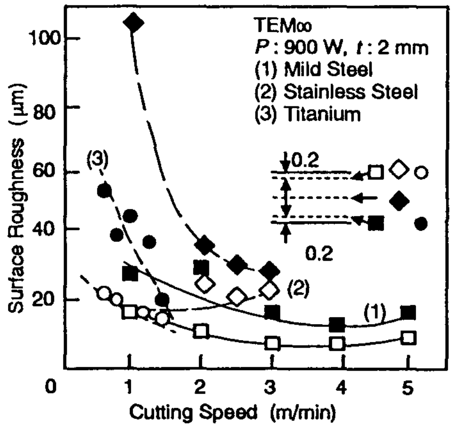


Fig. 3 Effect of cutting speed on quality of cut surface [3]

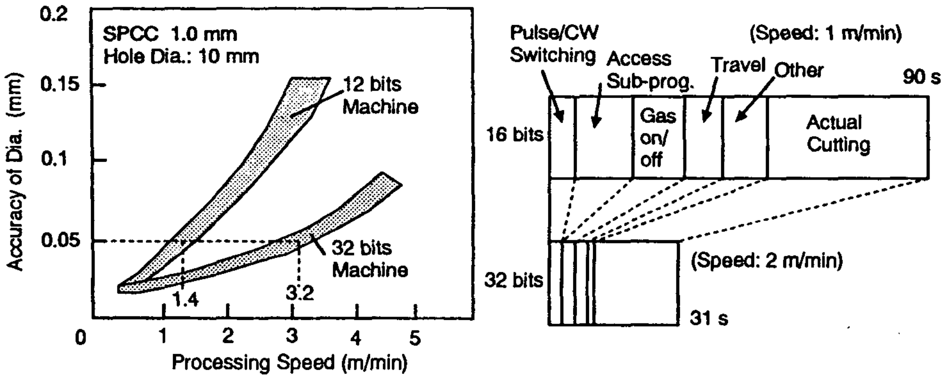


Fig. 4 Improvement of cutting accuracy and reduction of processing time by usage of high speed micro-processor [4]

As described before, the laser cutting is principally a high speed process. However, present laser cutting seems not to give full play to its potential capability. One of the reasons is the lack of stabilities in output power and beam mode. Present lasers have been much improved in long term stability, but a recent study has shown that sub-milli second order instability gives the effect of cut quality. Further and bigger reason is due to the immature peripheral equipments, in particular the work table. In the 2-D or 3-D cutting work table or robot, the travel speed is too slow to obtain the good quality cut. It is strongly required that the development of high speed micro-processor as well as the appearance of light weight, rigid and highly accurate table. Since 1990, the introduction of 32 bits micro-processor has been employed in the commercial laser cutting systems, and the reduction of processing time is greatly reduced as seen in **Fig. 4**, where a circular hole of 10 mm in diameter can cut in higher speed than that of conventional machine to obtain the same accuracy of hole diameter.

5. Laser Welding

5.1 Features and Problems of Laser Welding

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

As the intrinsic problem of materials processing by high power density heat source, the thermal hysteresis of laser welding becomes extremely rapid. The cooling rate in pulsed laser spot welding, for example, is 100 to 10000 times faster than that in arc welding, and the solidification modes and phase transformation are quite different from ordinary solidification. It is not well known that how this kind of metastable phase affects on the mechanical and physical properties of laser welded joints.Therefore, it is necessary to conduct systematic clarification of micro structural and phase changes of each materials.

5.2 Application States of Laser Welding in Various Industries

Table 2 shows the present states of laser welding applications in various fields in Japanese industries together with the adopted reasons and merits of laser welding.[4] Major reasons for adoption of laser welding are quoted as low distortion, deep penetration, high speed and precision welding, and the usage of laser has brought many merits such as greater improvements in workability, productivity, reliability and preciseness. In the following sections outline the state of the art of innovative laser welding in each industrial area.

Table 2 Industrial applications of laser welding in Japan [4]

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

(1) Automobile

The first introduction of laser welding was perhaps to the manufacturing of automotive parts in the early 80's in Japan. **Figure 4** shows the historical changes in the welding method for a stators core for a power generator used in a car[5] The stators core used to be fixed at first by arc welding then by resistance projection welding to increase the production efficiency. In these processes, however, an extra degreasing procedure was required prior to welding in order to reduce weld defects, but it was not sufficient to eliminate defects and distortion. In 1982 the first CO2 laser welding line was completed inNippon Denso (ND) and reduced the production costs because the degreasing and rinsing processes could be eliminated. As the oil completely evaporates with a laser beam and a clean surface appears before the metal melts, and thus a sound weld can be obtained without any preliminary treatments. Presently, many other automotive mechanical parts are laser welded and production costs are greatly reduced by simpler design of machined parts and elimination of post-weld machining.

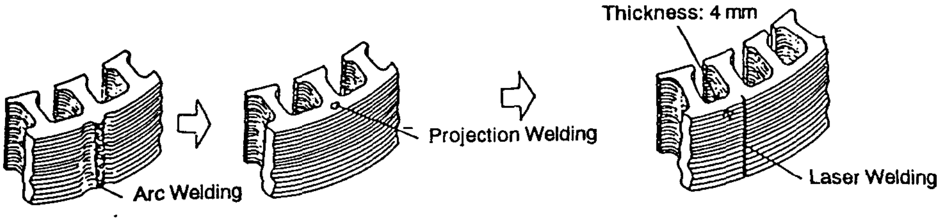
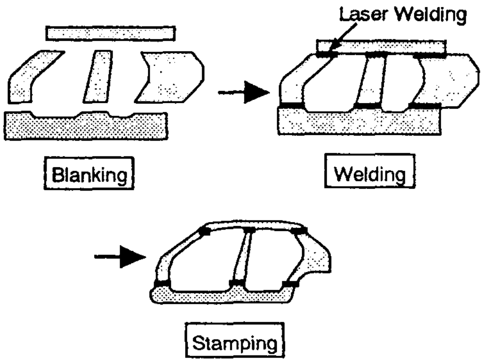


Fig. 4 Changes in welding method of stators core [5]



Parts Name	Shape of Sheet	Material Yield-up Zone ▨
1. Sun Roof		40 % → 80 % SGACD 1.6 t
2. Inner Cowl		60 % → 70 % SGCAD 0.8 t
3. Side Panel		40 % → 65 % SGMCF SPCC 1.0 t 0.8 t

Fig. 5 Laser tailored blank welding [6]

In the preparation of car body parts, too, innovative laser welding has been applied since mid 80's. The method is called "Laser Tailored Blank Welding" and was first attempted by Toyota. As illustrated in **Fig. 5**, a part of the body is initially prepared by pieces of blank materials and these are laser welded linearly in the flat position, and then press formed after into 3D- shape.[6] The method is advantageous both in the reduction of unnecessary materials and the selection of different thicknesses depending on the necessary strength at each part. It is also important to mention that straight welding in the flat position makes the system much simpler and welding speed faster than those employing 3D laser welding. Therefore, adoption of the tailored blank welding concept leads to cost saving as well as to the production of lighter weight vehicles..

(2) Steel Making

In 1982 Kawasaki Steel (KS) employed the laser welding process for coil to coil connection in the rolling mill .[7] KS first introduced the process in the line for magnetic steel by using a 5 kW CO2 laser, and proved its reliability. The process is presently used in other thin strip mills using the 5 and 10 kW machines in KS.

Also in mid 80's, a unique process was developed by Nippon Steel (NS) for the production of medium thickness steel pipe. The pipe used to be made by the high frequency (HF) pressure welding, but the heating of middle part of the plate thickness is likely to be insufficient due to the nature of HF induction heating. In order to obtain the uniformity of heating along the plate edges, a high power CO2 laser beam was used in the middle part of the joint with multiple reflection on the wall as illustrated in **Fig. 6**, and uniform heating of the weld joint was successfully achieved.[8] This process might be the first attempt at hybrid welding technology combining HF with laser in Japan. Presently, a small diameter stainless pipe of thin thickness is 100 % produced by the HF combined laser fusion welding.

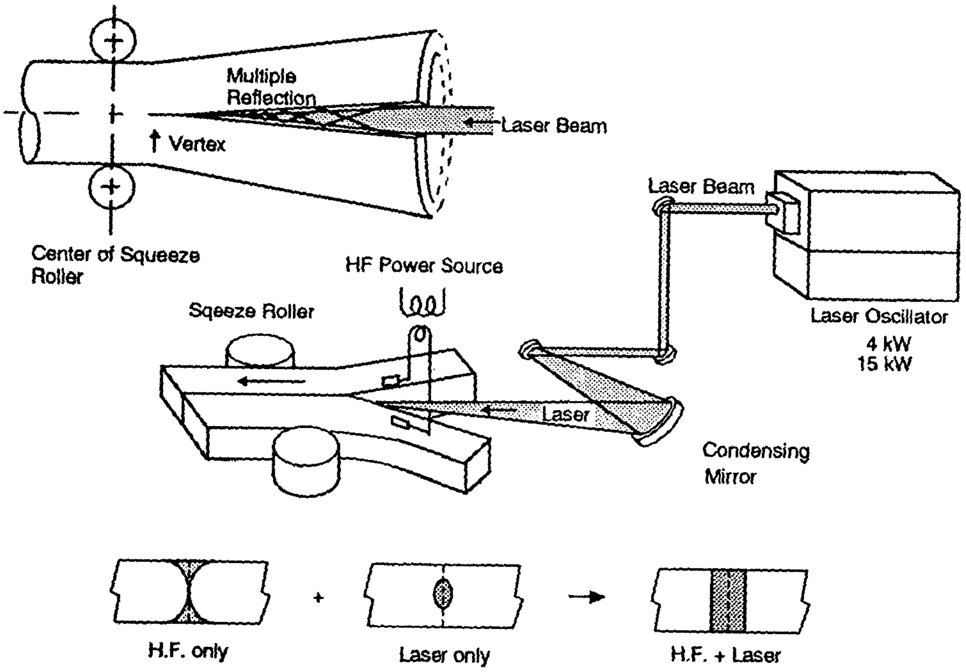


Fig. 6 Hybrid HF and laser welding for production of pipe [8]

(3) Power Plant

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

There was a revolutionary technological development in 1989 by Mitsubishi Heavy Industries (MHI) when they repaired a damaged tube by a fiber delivered YAG laser as shown in **Fig. 7**.[9] Quartz optical fiber of 0.8 mm diameter can easily transmit the YAG laser wavelength of several kW for long distance without significant attenuation of power. Also the welding torch can be minimized in size by adoption of laser. MHI developed 2 kW class YAG laser in collaboration with NEC and Toshiba, and completed a sophisticated YAG laser repair welding system. As the repair system must be operated in a radioactive environment, all operations of pre-inspection, insertion and expansion of sleeve, welding, and post-inspection are remote-controlled, and the laser power is transmitted from the outside of the plant by an optical fiber of 250 m in length. The technology is also applicable to ordinary power plants, chemical plants, and so on. The life extension of existing structures is one of the most important issues in modern welding engineering.

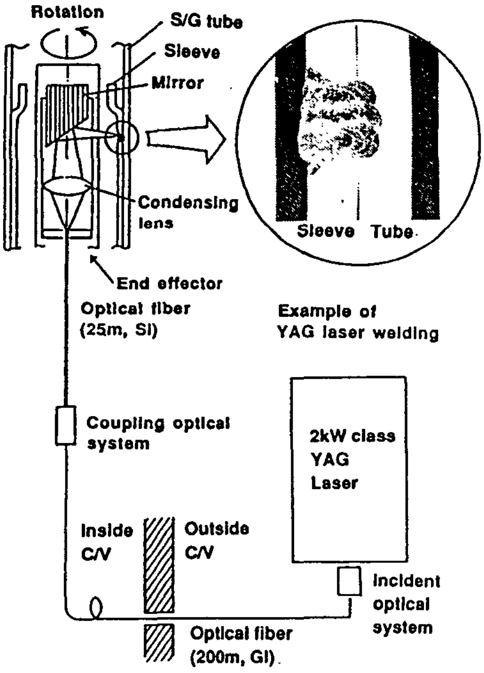


Fig. 7 YAG laser repair welding of steam generator of nuclear power plant [9]

(4) Heavy Manufacture (Indoor)

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

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

Another potential application of laser welding to shipbuilding is in the construction of fishing and pleasure boats using aluminum alloys. These small boats are presently made of fiber reinforced plastic, but they are causing a serious environmental problem in Japan because there is no adequate means of disposal. Therefore, boats made of recycled materials are the general trend in the future. However, aluminum alloys are typically difficult materials for welding because of the high heat conductivity as well as ease with which of various weld defects such as porosity, cracking and residual distortion occur. To overcome these difficulties, a possible solution is the use of high power density heat sources like EB and lasers. Thus, the importance of laser welding among heavy industries and material suppliers will continue to increase.

6. Future Trends of Laser Materials Processing and the Necessity for Basic Research

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

However, as described in the Introduction, laser materials processing does not at present employ the adaptive control. To raise the laser materials processing to the level of a sophisticated technology, it is absolutely necessary to conduct fundamental researches to clarify the processing phenomena and to establish new prediction control systems based on mathematical models. The establishment of non-equilibrium material science and evaluation methods of residual functions of materials and structures are very important future subjects in order to develop laser technologies in the next century.

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