Special Contribution

Advances in Material Processing Technology of Copper Using Short Wavelength Lasers

– The Role of Blue Diode Lasers in The Smart Country Concept –

Professor,
Joining and Welding Research Institute,
Osaka University
Ph. D. (Engineering) *Masahiro Tsukamoto*

*Yuji Sato[*1], Ritsuko Higashino[*2], Nobuyuki Abe[*3], Yoshinori Funada[*4], Yu Sakon[*5], Seigo Ouchi[*6], Kohei Asano[*7], Koji Tojo[*8]*

ABSTRACT Smart Country Concept (SCC) of the "People-friendly town development where people can get together." has been proposed as the "Town Development" that Japan should aim for. "People-friendly" is a society where a smart mobility exists and "People can get together." is a safe and secure society that incorporates the public health environment that reduces the risk of viruses. Since copper has a high electrical conductivity and super anti-bacterial properties, it is a very useful material for the achievement of both societies. The processing range of copper has been expanded because of the higher output and the higher brightness of blue diode lasers. In this report, along with showing the superiority of blue diode lasers, we will introduce the processing machine and the examples of the copper processing that apply the blue diode lasers developed in the NEDO laser project.

1. INTRODUCTION

The SCC has been proposed as the "Town Development" that Japan should aim for. In the SCC, the "People-friendly town development where people can get together." has been the focus.

As far as the "People-friendly", concepts such as a smart city, a woven city, etc. have already been proposed and the SCC in which the autonomous driving systems function is shown. In the smart mobility society, under the Internet of Things (IoT) environment, Artificial Intelligence (AI) will be able to grasp not only the route guidance but also the hobbies, the tastes, and the health status extracted from the large data associated with the personal information of all passengers, just by letting AI know the destination and then AI will do everything such as selecting the rest area on the way to destination, guiding to the favorite restaurant, etc. Such a world is expected to be reached not too far in the future. The core of AI-equipped vehicles that achieve this autonomous driving is a motor. Since a pure copper material with a high electrical conductivity is used for the coil of the motor, the processing technology of pure copper is indispensable. In addition, one of the promising next-generation processing technologies of pure copper to produce the pure copper parts for the high-performance motors is Additive Manufacturing (AM). AM is shown in Figure 1. AM is also called 3D printer. As shown in Figure 1 (a), AM has seven categories. For the metal AM, the powder bed fusion method and the directed energy deposition method are

[*1] Ph.D. (Engineering), Associate Professor, Joining and Welding Research Institute, Osaka University
[*2] Specially Appointed Researcher, Joining and Welding Research Institute, Osaka University
[*3] Ph.D. (Engineering), Specially Appointed Professor, Joining and Welding Research Institute, Osaka University
[*4] Ph.D. (Engineering), Deputy General Manager, Machinery and Metals Department, Industrial Research Institute of Ishikawa
[*5] Manager, Product Development Department, Manufacturing Department, MURATANI MACHINE MANUFACTURE Co., Ltd.
[*6] Deputy General Manager, Advanced R&D Center, YAMAZAKI MAZAK CORPORATION
[*7] Ph.D. (Engineering), Advanced R&D Center, YAMAZAKI MAZAK CORPRATION
[*8] Deputy General Manager, Advanced Analysis Unit, Technology Research Laboratory, Shimadzu Corporation

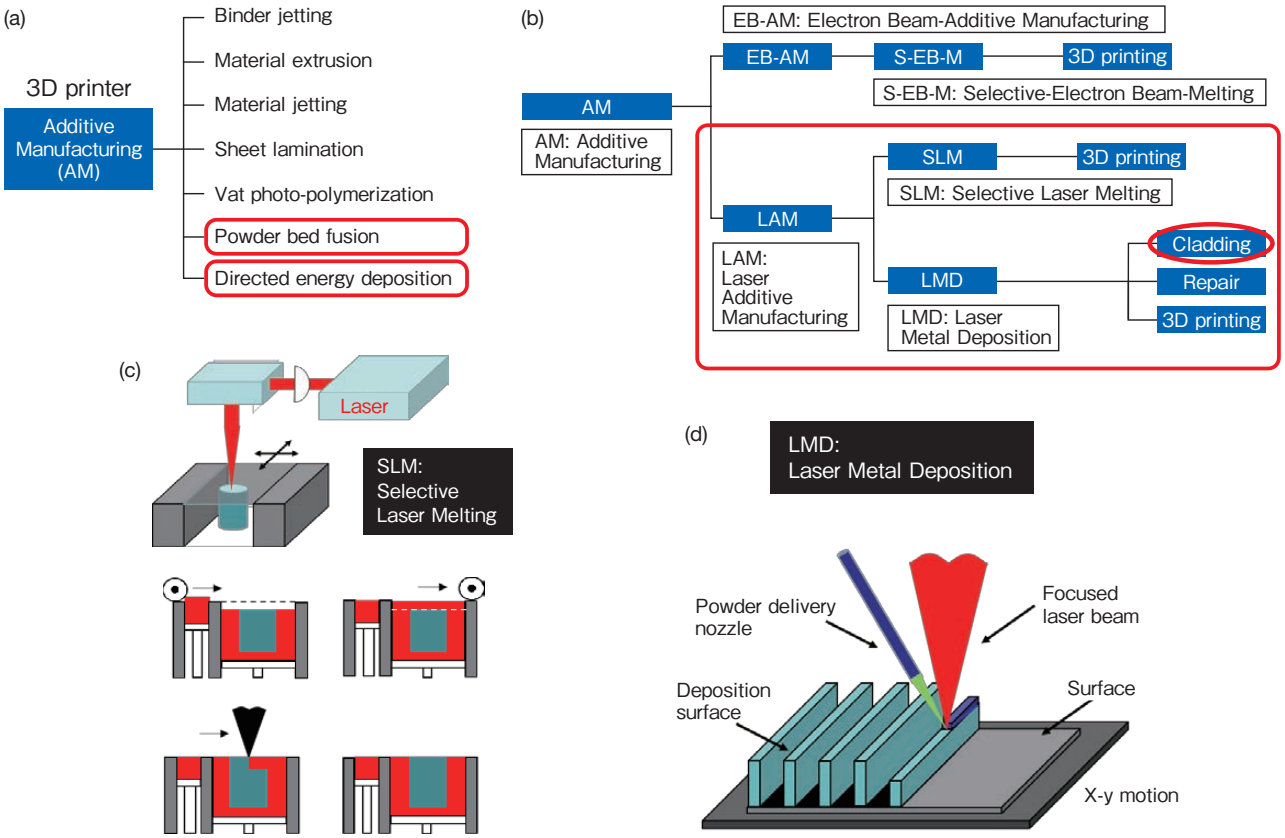

Figure 1 (a) Additive Manufacturing (AM) and 7 categories, (b) Laser Additive Manufacturing (LAM: AM using a laser.), (c) Selective Laser Melting (SLM: Powder bed fusion method using a laser.) , (d) Laser Metal Deposition (LMD: Directed energy deposition method using a laser.)

used. The powder bed fusion method and the directed energy deposition method introduced with the use of lasers are called Selective Laser Melting (SLM) and Laser Metal Deposition (LMD), respectively (Figure 1 (b)). SLM is a 3D printing method in which the metal is spread and irradiated with a laser to form a metal (Figure 1 (c)) and LMD is a 3D printing method in which the supply of the metal powder and the laser irradiation are performed at the same time to form a metal (Figure 1 (d)). As shown in Figure 1 (b), LMD includes the repair and the cladding (film formation) in addition to the 3D printing. We believe that a blue diode laser with a wavelength of 450 nm is suitable for the processing of pure copper and together with showing the superiority of this laser, we have been developing the processing system using this laser and the AM technology for pure copper in addition to the welding of pure copper. The necessity of the pure copper parts in the automobile industry and the laser processing of pure copper including the AM technology have been described above, but there are high expectations for this processing not only from the automobile industry but also from the electrical industry, the space industry, etc.[1), 2)]

"People can get together." was natural in the town (society) of two years ago. However, it is not natural now. The novel coronavirus infectious disease (the COVID-19), which has become a global pandemic since the beginning of last year, is still showing no sign of receding and is changing our lifestyle completely. In Japan as well, a state of emergency has been declared four times and it continues to have a tremendous impact on the social and economic activities. When a viral infectious disease such as the COVID-19 occurs, the technology development that enables the prompt and accurate response and minimizes the impact on the social and economic activities is required. Looking at the trends of the viral infectious diseases in recent years, the virus is brought in from overseas. By stopping the flow of people and goods from overseas, it is possible to prevent the virus from entering the country. However, it is difficult to eliminate the flow of people and goods in today's globalized world. When a virus invades the human body, it is a vaccine that prevents it. Vaccines have been developed to recede this COVID-19, but it has been found that the vaccine development will take more than a year. It is understood that the "public health environment" before a virus from overseas infects humans is the "last bastion" to hold back the virus, in consideration of the situation where "It is impossible to stop the flow of people and goods from overseas." and "Vaccine development takes time.". From the fact that this COVID-19 pandemic has extended, it is clear that the building of the "Public health environment that reduces the risk of viruses" is important and urgent. Another thing to be considered is the existence of the next viral infectious disease, "Next Corona". This is because even after the receding of the COVID-19, it is undeniable that the various viruses may be introduced

from overseas to Japan due to the globalization and cause the new infectious disease. Every time a new infectious disease spreads, it causes enormous damages to the social and economic activities. In order to minimize the damages, it is necessary to build the "Public health environment that reduces the risk of viruses", which is the "last bastion". In Japan, there are various virus-inactive technologies such as ultraviolet rays, titanium oxide, copper[3] and silver and it is thought that by applying each technology, building the "Public health environment that reduces the risk of viruses" is possible. However, this is not the case when a large earthquake occurs. Whenever a large earthquake occurs, a power outage will definitely occur. Then, in the evacuated indoors, ultraviolet rays, ultraviolet lasers, titanium oxide or visible light responsive type titanium oxide will not work. Since the water supply is cut off at the same time, you cannot wash your hands and gargle. The state of the public health will deteriorate at once. It is needless to say that if a large earthquake occurs in the corona crisis, the infectious disease will spread rapidly and a pandemic will occur and the number of beds in the hospital, which is flooded with many injured people, will be insufficient. In such a situation, the components made of copper, etc. that do not require a light source and inactivate the virus will play a major role as the "Public health environment that reduces the risk of viruses", which is the "last bastion". When making the handrails and the handle components using copper, the components become thicker since the virus inactivation, the mechanical strength and the durability are required, so the amount of copper used increases. As a result the production cost will increase. Therefore, the copper coating technology is required. The copper coating reduces the amount of copper used, leading to the cost reduction. The coating methods include the plating, the thermal spraying and the laser cladding. The laser cladding is the best when focusing on the mechanical strength and the durability. As can be seen in Figure 1(b), the laser cladding is belonging to the LMD of the AM technology.

In this report, at first, the superiority of the short wavelength lasers with the oscillation wavelengths in the blue and green wavelength regions in the metal material processing will be shown and the development status of the blue diode lasers and the green lasers by the overseas manufacturers will be introduced. Next, the development of the blue diode lasers in the NEDO project of the "Development of Advanced Laser Processing with Intelligence Based on High-Brightness and High-Efficiency Next-Generation Laser Technologies (TACMI Project)" (from FY 2016 to FY 2020) (the NEDO laser project) will be explained. Moving on, the processing machine, to which the blue diode laser developed in the NEDO laser project is applied, will be shown and finally, the "RESEARCH INSTITUTE FOR JOINING AND WELDING WITH BLUE DIODE LASER" as a future development will be introduced.

2. THE SUPERIORITY OF THE SHORT WAVELENGTH LASERS WITH THE OSCILLATION WAVELENGTHS IN THE BLUE AND GREEN WAVELENGTH REGIONS

Currently, the lasers with a wavelength of 0.8-1.06 μm are mainly used as the high-power lasers for processing. The light absorption rate of copper is shown in Figure 2. As can be seen from Figure 2, in the wavelength range of the near-infrared laser, the absorption rate is as low as 10% or less[4], so that it is difficult to process the copper with this laser. However, the light absorption rate increases sharply when the wavelength is below 500 nm band, which is a green wavelength, and the absorption rate reaches 60% at the wavelength of 400 nm band[4]. By using the laser with a wavelength of 400 nm band, the processing of copper will become easy.

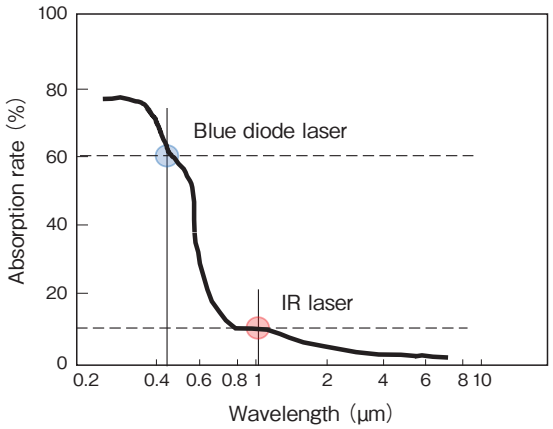

Figure 2 Light absorption rate for copper.

3. THE DEVELOPMENT STATUS OF THE BLUE DIODE LASER AND THE GREEN LASER

3.1 The Development by Overseas Manufacturers

The manufacturers of the blue diode lasers include Laserline GmbH, NUBURU Inc., Coherent Inc., BWT Beijing Co. Ltd., etc.

The blue laser of Laserline GmbH[5] has a fiber core diameter of 600 μm and a power density of 0.7 MW/cm^2 with a wavelength of 445 nm and an output of 2,000 W and the Beam Parameter Products (BPP) is 60 mm·mrad and the NA is 0.2. Also, in the AO series of NUBURU Inc.[6], the AO-650 has a fiber core diameter of 400 μm and a power density of 0.5 MW/cm^2 with a wavelength of 450 nm and an output of 650 W. The BPP is less than 30 mm·mrad and the NA is 0.22. In another lineup of the AI series, AI-1500 seems to achieve a fiber core diameter of less than 125 μm, a power density of 12.2 MW/cm^2, a BPP of less than 11 mm·mrad, and a NA of 0.22 with a wavelength of about 445 nm and an output of 1.5 kW. Coherent Inc. has achieved a high output and high brightness of 500 W using a fiber having a core diameter of 200 μm and also achieved kW class output with a large

diameter fiber[7], and has obtained an power density of 1.6 MW/cm^2.

In recent years, Chinese companies have also been working on the development of the blue diode lasers and the processing technology using the blue diode lasers. It is reported that BWT Beijing Co. Ltd. has achieved a fiber core diameter of 330 μm (NA 0.22) with a wavelength of 450 nm and an output of 1000 W[8]. In addition, United Winners Laser Co. Ltd. has commercialized a fiber core diameter of 800 μm (NA 0.22) with a wavelength of 455 nm and an output of 1000 W[9].

On the other hand, regarding the green laser, TruDisk 3022 of TRUMPF corporation[10] has achieved a fiber core diameter of 200 μm, and a power density of 9.6 MW/cm^2 (BPP 8 mm·mrad, NA 0.1) with a wavelength of 515 nm and an output of 3000 W. Also, TruDisk 2021 has achieved a fiber core diameter of 100 μm and a power density of 25.5 MW/cm^2 (BPP 4 mm·mrad, NA 0.1) with a wavelength of 515 nm and an output of 2000 W. Furthermore, TruDisk 1020 has achieved a fiber core diameter of 50 μm and a power density of 50.9 MW/cm^2 (BPP 2 mm·mrad, NA 0.1). with a wavelength of 515 nm and an output of 1000 W. The TruDisk1020 is equipped in the SLM type AM machine.

3.2 The Development of the Blue Diode Laser in the NEDO Laser Project

In the NEDO laser project, the research and development group of the Joining and Welding Research Institute, Osaka University and the research and development group of Panasonic Corporation have been developing the different types of the blue diode lasers respectively.

In 2018, the group of the Joining and Welding Research Institute, Osaka University has developed the blue diode laser having a core diameter of 100 μm, a NA of 0.20 and a fiber end output of 100 W, in cooperation with Nichia Corporation. This laser achieved the world's highest brightness with a power density of 1.3 MW/cm^2 at the fiber end. In addition, the output was increased from 100 W to 200 W in 2020. Since the core diameter is 100 μm, the power density at the fiber end is doubled to 2.6 MW/cm^2, recording the world's highest brightness as a single blue diode laser light source. Also, in 2020, an output of 500 W for the blue diode laser was achieved. Furthermore, an output of 1500 W was obtained from an optical fiber with a core diameter of 400 μm. The power density at the fiber end is 1.2 MW/cm^2.

The Panasonic Corporation group has announced the development results of the high beam quality (a wavelength of 400-450 nm, an output 135 W and a BPP of 1.5 mm·mrad) blue laser light source (without fiber coupling) using a direct diode laser wavelength synthesis technology at PHOTONICS WEST 2020[11]. Based on these results, from 2020, the final year of the NEDO laser project, the "Mass production development of the high beam quality and high output blue laser processing machine equipped with a pulse drive function" is being carried out in the "Social implementation and popularization acceleration project of members and materials for realizing the innovative CO_2 saving" held by the Ministry of the Environment.

4. THE PROCESSING MACHINE USING A BLUE DIODE LASER DEVELOPED IN THE NEDO PROJECT

4.1 The World's First Multi-tasking Processing Machine Equipped With a Blue Diode Laser

4.1.1 The development of the LMD technology

In the conventional LMD, a high-power laser is irradiated from the center of the processing head, a molten pool is formed on the surface of the base materials and a film can be formed by injecting the material powder into the molten pool from the side. In the conventional LMD, the stable formation of the molten pool is important and a high-power laser of several kW or more is required for stable formation of the molten pool. Therefore, in the processing into the precision part, the influence of the distortion and the dilution of the base material becomes a problem. Cross-ministerial Strategic Innovation Promotion Program (SIP) of the "Innovative Design/Manufacturing Technologies Development of laser coating methods for realization of high value-added design and manufacturing" ("SIP Phase 1 Project"), we have proposed a multi-beam method that replaces the position of the conventional LMD laser and powder flow and have developed a multi-beam processing head. In this processing head, 6 blue diode lasers were superimposed to achieve an output of 100 W[12]. Since this method (Figure 3) is less affected by the distortion and the dilution of the base material, a film formation that can be applied to compact, thin-walled, and highly accurate products has been achieved.

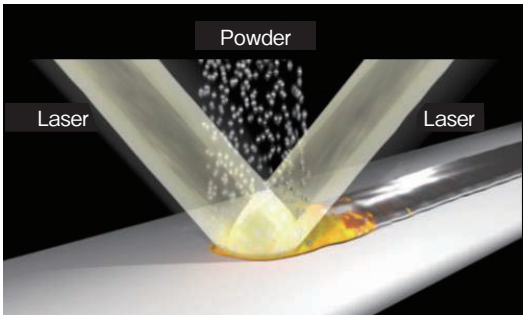

Figure 3 LMD using a multi-beam method.

4.1.2 The development of a multi-tasking machine equipped with 200 W blue diode laser

A power density of 0.1 to 1 MW/cm^2 is required for the copper film formation and welding. Therefore, we have developed a hybrid multi-tasking machine (Figure 4) that incorporates three 200 W blue diode lasers developed in the NEDO laser project into a multi-beam processing head (Figure 4) together with Yamazaki Mazak

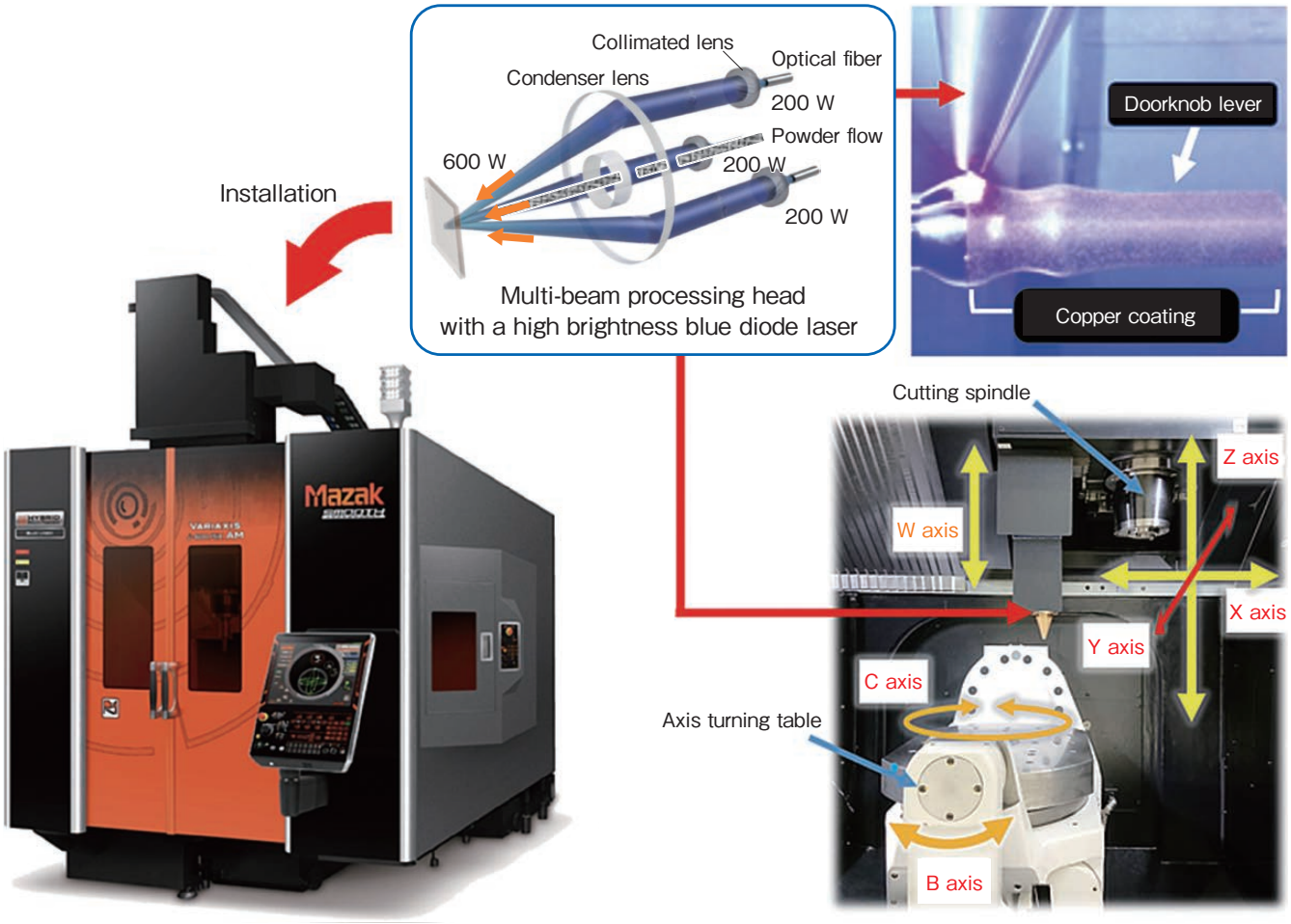

Figure 4 Multi-beam processing head equipped with three 200 W blue diode lasers and hybrid multi-tasking processing machine with a processing head.

Corporation, a company participating in the NEDO laser project[13]. As can be seen in Figure 4, a copper powder beam is supplied along the central axis of the three beams. In the past, the output of the multi-beam superimposition region was about 100 W, but by increasing it to 600 W in the NEDO laser project, a high power density at the laser focusing spot can be achieved and the copper coating speed to the metal materials such as stainless steel, aluminum, etc. can be improved by more than 6 times. In addition, a high-speed and precision coating of copper to the part with the complicated shapes has become possible[14] (Figure 5).

4.2 Galvano Scanner Method SLM Type 3D Printer Equipped With a Blue Diode Laser

We have developed a galvano scanner method SLM type 3D printer equipped with the 200 W blue diode laser developed in this project[15]. Figure 6 shows a schematic view of the galvano scanner method 3D printer and Figure 7 shows an external photograph respectively. The laser focusing spot diameter on the powder bed is 250 μm. By controlling the angle of the galvano mirror and condensing the laser light at a desired position, the pure copper powder at the required part on the stage was melted and solidified and the AM was tried (Figure 8). In addition, by combining CAD software, it becomes possible to freely laminate and form copper shaped objects with a fine structure, which is expected to lead to the development of high-precision technology such as in the copper material parts for automobiles and electronic parts.

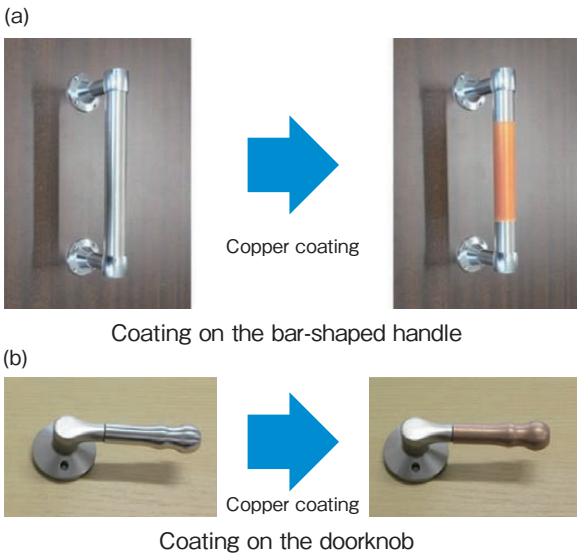

Figure 5 High-speed and precise coating of copper using a blue diode laser.
(a) Coating on the bar-shaped handles and (b) Coating on the doorknobs

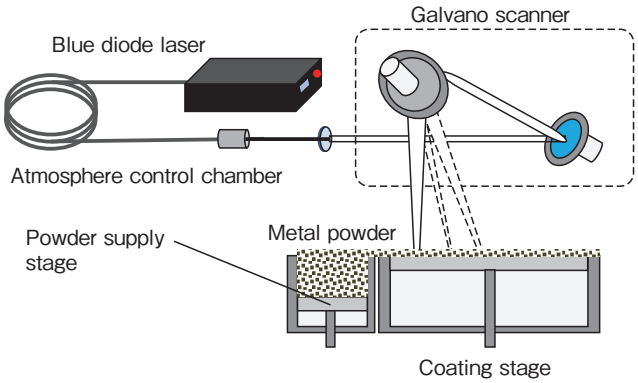

Figure 6 Schematic diagram of a SLM method 3D printer equipped with a blue diode laser.

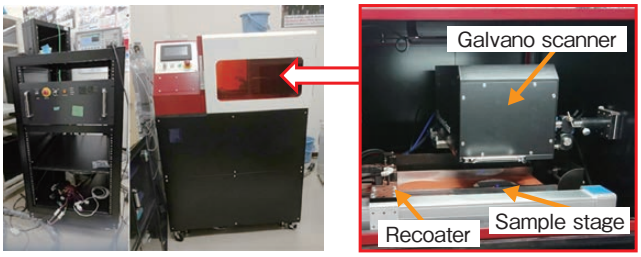

Figure 7 External appearance photograph of a SLM method 3D printer equipped with a blue diode laser.

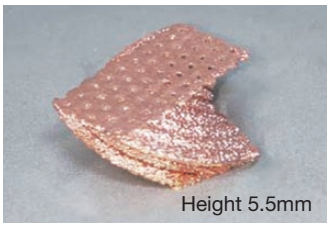

Figure 8 Pure copper laminated molding using a SLM method 3D printer equipped with a blue diode laser.

4.3 The Hybrid Welding Machine That Combines a Blue Diode Laser and a Near-infrared Fiber Laser (Manufactured by Furukawa Electric Co., Ltd.)

We have constructed a hybrid laser system that combines a 200 W blue diode laser with a 1.5 kW near-infrared fiber laser. This system used two pairs of 200 W blue diode lasers combined with a 1.5 kW near-infrared fiber laser. Figure 9 shows a setup diagram of the hybrid laser irradiation optical system and Figure 10 shows a photograph of the exterior. Each laser was coaxially superimposed using a dichroic mirror and focused on the processing point using a plano-convex spherical lens. At this time, the focused spot diameter is 60 μm for the 1.5 kW near-infrared laser and 200 μm for the 200 W blue diode laser. By applying this system, the high-speed welding of the pure copper square wire required for motor coil manufacturing has become possible (Figure 11).

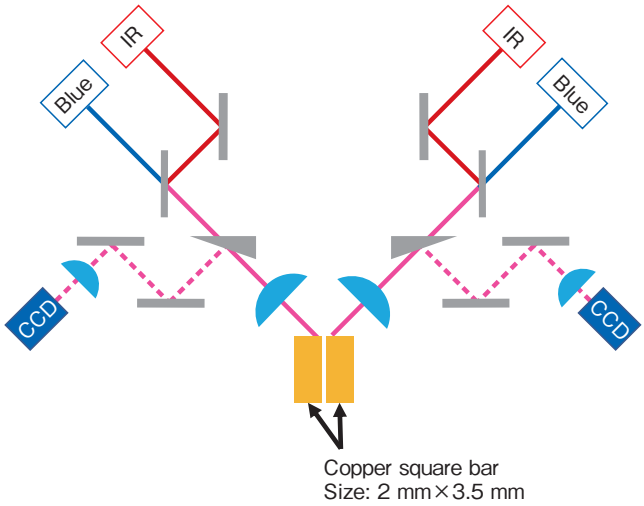

Figure 9 Setup diagram of a hybrid laser irradiation optical system that combines a blue diode laser and a near-infrared fiber laser.

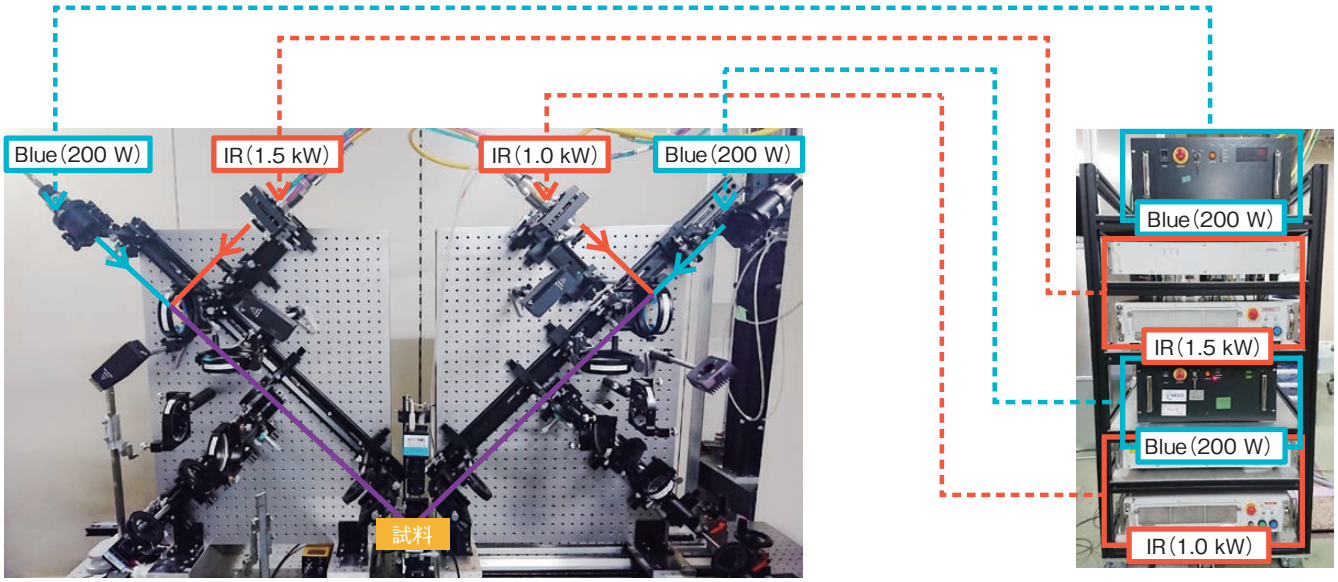

Figure 10 Setup photograph of a hybrid laser irradiation optical system that combines a blue diode laser and a near-infrared fiber laser.

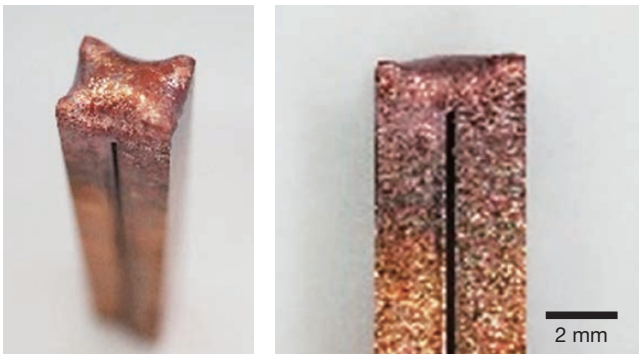

Figure 11 High-speed welding for a pure copper square wire using a hybrid laser system that combines a blue diode laser and a near-infrared fiber laser.

4.4 Multi-beam Welding Machine Equipped With Three 500 W Blue Diode Lasers

Welding experiments were conducted in order to carry out a practical evaluation of the blue diode laser developed in the NEDO laser project and the penetration welding to a pure copper substrate with a thickness of 200 μm was achieved at an output of 200 W. However, at this output, if the thickness of the pure copper substrate is increased, the amount of the heat input is insufficient, so that the penetration becomes small and the welding capacity is limited. Therefore, in order to realize a thick plate welding, we have developed a multi-beam processing head using three blue diode lasers with an output of 500 W. A photograph of the look of this processing head is shown in Figure 12 (a). Three beams of 500 W blue diode laser were superposed at the processing point, and the maximum output measured at the superimposing position was 1.5 kW (Figure 12 (b)). Figure 13 shows a spot image superimposed on the focused spots of each of three blue diode lasers. The beam diameter focused on one point is 300 μm, and it can be confirmed that three beams are superimposed on one point. When the bead-on welding was performed using this processing head, a 1 mm thick copper plate was penetrate-welded at an output of 1000 W (Figure 14). It is thought that by enabling the copper plate welding, it will be possible to use it in various fields such as automobile parts, IC parts, motors, coils and etc.

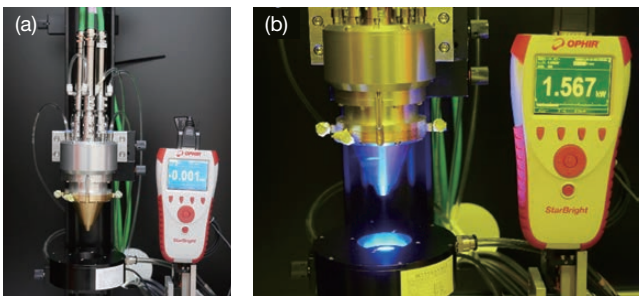

**Figure 12 Multi-beam processing head using three 500 W blue diode lasers has been developed.
(a) Processing head (b) Laser output**

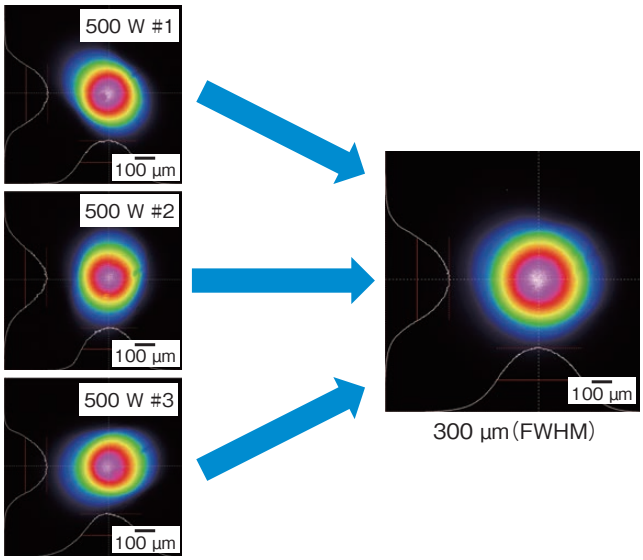

Figure 13 Beam profile superimposed with three 500 W blue diode lasers.

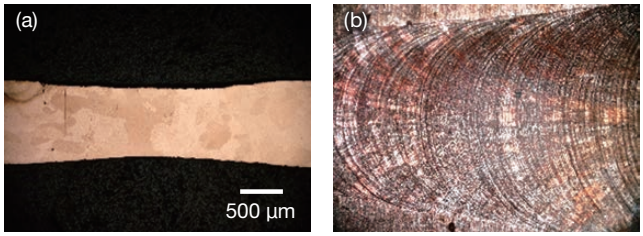

**Figure 14 Bead-on welding experiment results using a multi-beam processing head (output 1,000 W).
(a) Cross-sectional photograph in the direction perpendicular to the scanning direction of the laser focused spot (b) Surface photograph**

5. FUTURE DEVELOPMENT: "RESEARCH INSTITUTE FOR JOINING AND WELDING WITH BLUE DIODE LASER"

The "RESEARCH INSTITUTE FOR JOINING AND WELDING WITH BLUE DIODE LASER" was established on December 1, 2020 in order to accelerate the social implementation of the blue diode laser developed in the NEDO Laser Project[16]. The managing members are Furukawa Electric Co., Ltd., Shimadzu Corporation, Nichia Corporation and Osaka University (Joining and Welding Research Institute) and the general members are 21 companies as of August 1, 2021. The board of directors is composed of representative directors elected from the managing members and this study group is managed by them. Seminars on the blue diode lasers and processing are held regularly for the general members. The general members can receive the technical consultations as necessary. The managing members of this study group mainly engage in research on the copper welding using the blue diode lasers and the AM technology.

6. CONCLUSION

In this report, we explained the development of the blue diode lasers and the development status of the processing machines equipped with the blue diode lasers, along with the role of the blue diode lasers in the SCC of the "People friendly town development that people can get together." With the increasing of the output and the brightness of the blue diode lasers and the expanding range of the processing applications, the copper processing technology using a blue diode laser can be a useful technology in order to realize a safe and secure society that incorporates the smart mobility society indicated by the SCC and the public health environment that reduces the risk of viruses. We look forward to future research and development starting from the "RESEARCH INSTITUTE FOR JOINING AND WELDING WITH BLUE DIODE LASER" introduced at the end of this report.

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