High Quality Processing of Copper Using Fiber Lasers

Keigo Matsunaga[*], *Taro Murayama*[*]

ABSTRACT The fiber laser has the property of a high rate and a low heat effect processing based on the performance of the high beam quality and the high power density. On the other hand, since copper has a high reflectance on oscillation wavelength of fiber laser and a high thermal conductivity, it is a difficult material for a stable welding. Furukawa Electric Co., Ltd. succeeded in high quality processing of the copper material using a fiber laser based on the ultra-fast frequency modulation technology which is irradiation with a laser modulated at high frequency and the beam mode controlling technology which can control precisely the beam intensity distribution at a focal point.

1. INTRODUCTION

In order to achieve carbon neutrality (decarbonization), the activity of reducing of greenhouse gas emission is proceeding in the world. A shift to the Electrified Vehicle (xEV) from the conventional gasoline car is accelerated in the automotive industry. The high capacity battery and the compact motor, which are main construction elements, are necessary before the xEV becomes common and the precise and high quality processing of copper material which is used as electrodes and winding wires are required.

Since the fiber laser has a property of high beam quality and high power density in general, it can get a penetration depth locally on the work piece and a processing merit in suppressing the heat effect on the peripheral irradiated area. However, since the copper has a high reflectance to infrared irradiation of fiber laser wavelength and high thermal conductivity, it is difficult to make a stable processing of the copper with the fiber laser.

Furukawa Electric Co., Ltd. (FEC) continues with the development of an innovative laser processing on copper material focusing our attention on the manufacturing process for battery and motor. In this paper, we introduce the fiber laser products of FEC, and then we report the ultra-fast frequency modulation technology useful for cutting process of copper foil which is used for the electrode of the battery and the beam mode control technology useful for the lap welding of copper material and the welding of winding wire, and also processing application case together.

[*] Industrial Laser System Department, FITEL Products Division, Communications Solutions Division

2. INTRODUCTION OF FEC FIBER LASER

The fiber laser can be roughly classified into the single mode fiber laser which can focus the diameter into several tens of μm with high beam quality and the large output multimode fiber laser combined with multiple units of the single mode fibers. FEC has a lineup of the single mode fiber laser up to 1.5 kW and the multimode fiber laser up to 12 kW and the fiber lasers can be used properly for processed material type or plate thickness. The feature of each laser is introduced in this chapter.

2.1 Single Mode Fiber Laser

An external view and configuration of FEC's single mode fiber laser is shown in Figure 1 and Figure 2 respectively. The fiber laser is optically amplified so that the light oscillated by a pump laser diode is guided into the Yb doped optical fiber, and the light is resonated in two of Fiber Bragg Gratings (FBG) having different reflectance and placed ahead and behind the Yb doped fiber. As seen above, since the fiber laser completes all functions in the fiber, it has the features of unnecessary optical axis adjustment, high quality, high conversion rate and maintenance free. Based on the high device quality and our own combiner structure in the telecommunication field, FEC achieves smaller transmission fiber core diameter rather than in the conventional fiber laser and provides a fiber laser with a more stable and a higher beam quality. The single mode laser fiber manufactured by FEC has a core diameter ∅ of 14 μm, a typical beam quality of M^2 factor at optical output end of 1.06 and a Beam Parameter Products (BPP) of 0.36 mm·mrad. The M^2 factor shows the deviation from the ideal Gaussian beam and its focusing property of laser as shown in formula (1).

$$\omega = \left(\frac{4\lambda}{\pi}\right)\left(\frac{f}{D}\right)M^2 \qquad (1)$$

ω : Light focus spot diameter (μm)
λ : Laser wavelength (nm)
f : Focal distance of condenser lens (mm)
D: Collimated beam diameter before focusing lens (mm)
M^2: Beam quality factor

As M^2 factor of our single mode fiber laser is close to the ideal Gaussian beam of 1, the fiber laser has an excellent focusing property. Since it is easy to get high energy density due to the focusing of the beam radius in tens of μm based on the above performance, a high reflectance of copper material and of aluminum material can be processed, and also a high quality process with less heat effect on the peripheral irradiated area can be achieved.

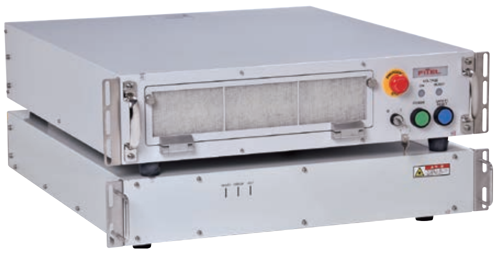

Figure 1 External view of single mode fiber laser.

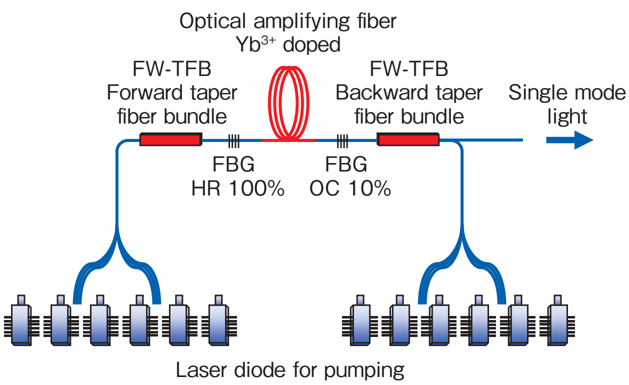

Figure 2 Configuration of single mode fiber laser.

2.2 Multimode Fiber Laser

FEC provides the multimode fiber laser combined with a 1 kW single mode fibers applied low loss and high efficiency beam combiner technology. The external view of FEC's 12 kW multimode fiber laser is shown in Figure 3. We have a line-up of the multi-mode laser with a core diameter ∅ of 50 μm, 80 μm and 100 μm. The typical BPP of the laser is 1.7 mm·mrad (M^2 = 5.0), 3.0 mm·mrad (M^2 = 8.9) and 3.5 mm·mrad (M^2 = 10.3) respectively. We will provide an 18 kW multi-mode fiber laser in 2021 FY having 3.0 mm·mrad which is 25% better than the beam quality of the 4.0 mm·mrad of conventional fiber lasers above 10 kW.

These multi-mode fiber lasers are most suitable for processing on the copper material with thickness of more than 2 mm and the penetration depth on high rate region is obtained due to its excellent beam quality.

Figure 3 External view of 12 kW multi-mode fiber laser.

3. ULTRA-FAST FREQUENCY MODULATION TECHNOLOGY

Lithium-ion battery is used mainly as the battery of the main part of the xEV. The current collector of lithium-ion battery is a copper foil (negative electrode) and an aluminum foil (positive electrode), the electrode foil is necessary to be cut in the shape of tab using a roll-to- roll process in the manufacturing process, as shown in Figure 4. Since cutting with laser does not require maintenance in replacement of consumables, such as the cutlery, the mold, and it is easy to change the cutting locus, compared to machine process with a slitter or a press, it is capable to make an improvement of productivity and cost reduction for specification change and the technology development of laser cutting is proceeding with new processing without cutting instruments. However there is an issue of difficulty to maintain the process quality due to the occurrence of oxidation and dross by heat when cutting with laser because copper foil used battery electrode is very thin with several μm and has a small heat capacity.

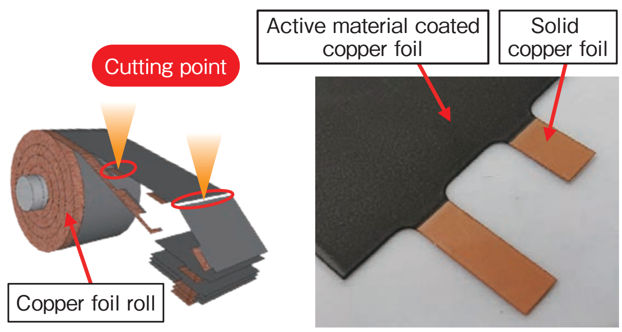

Figure 4 Cutting process of electrode foil and tab-shaped copper foil.

Figure 5 shows laser irradiation surface and cut section image respectively when copper foil with thickness of 8 µm was cut by a single mode fiber laser with focused light beam of less than 50 µm and rate of 2 m/sec. According to Figure 5, it is shown that the molten copper foil solidified dross is occurring and heat discoloration is occurring in the center on the dross. Since the dross of the electrode foil is a cause of a short circuit when building the battery, the solution for the problem of the dross occurrence is needed by introducing laser cutting as a foil cutting process.

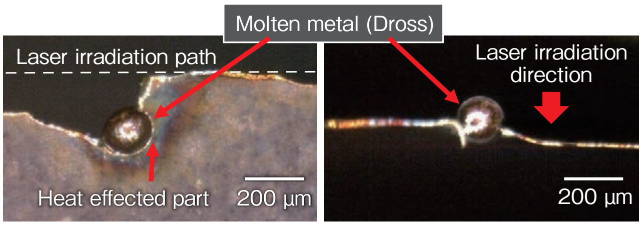

Figure 5 Surface image and cross-sectional image of laser cut copper foil.

As a general method of decreasing heat input on laser processing, the irradiation technology consisting of a laser oscillation signal added with a modulation and a pulse wave control of the continuous oscillation laser is used. However, since the rise time of the laser output to the input pulse of the conventional laser is more than 10 µsec, the repetition frequency of less than 50 kHz is limited. In the case of a low repetition frequency, the pulse does not overlap on high rate processing, and it leads to the problem of not processing continuously. FEC made an improvement of the pulse response and succeeded in the development of the single mode fiber laser with an ultra-fast frequency modulation whose pulse rise time is very short in several µsec and the modulation can be done at a maximum of 250 kHz of the repetition frequency. The difference of oscillation mode between the conventional laser and the ultra-fast frequency modulation fiber laser and schematic diagram of the lasers application on foil cutting are shown in Figure 6.

Based on using the ultra-fast frequency modulation fiber laser, it is achievable to control a suitable input energy while maintaining a micro beam diameter and a peak output power of several tens of kW and is capable of cutting the copper foil under minimum heat effect. The result of real cutting of copper foil using the ultra-fast frequency modulation fiber laser is shown in Figure 7. The laser irradiation condition of Figure 7 is the same as in the case of Figure 5 except for the modulation at frequency of several hundred of kHz. Comparing between Figure 5 and Figure 7, there is no appearance of dross in Figure 7 and it demonstrated that the effect of heat is largely suppressed. As described above, it is capable to make a high quality laser cut of copper foil through controlling the input amount of heat using the ultra-fast frequency modulation technology.

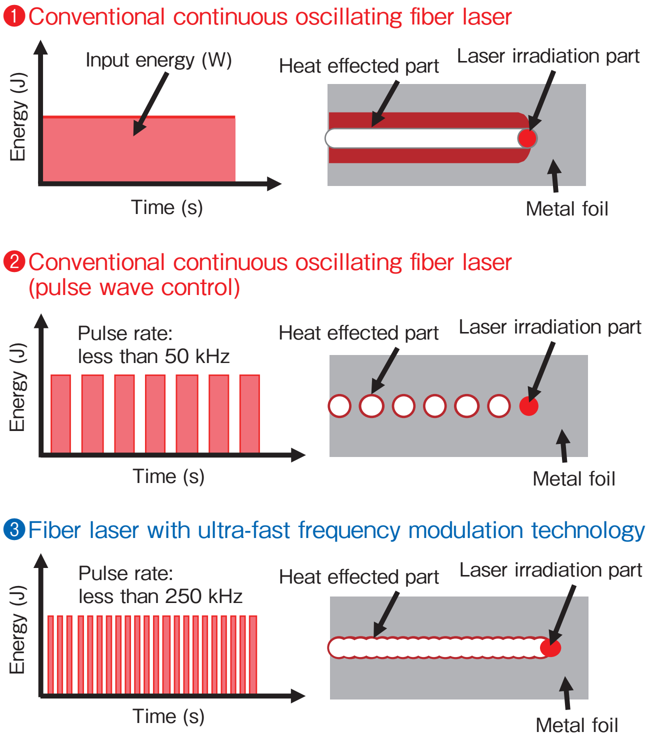

Figure 6 Comparison of laser oscillation mode (left) and applied to cutting foil (right).

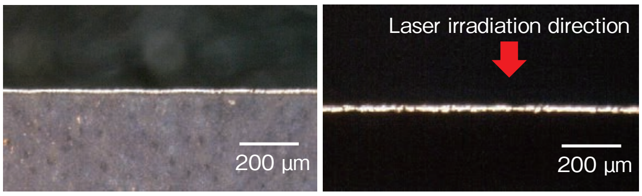

Figure 7 Surface image and cross-sectional image of copper foil cut with an ultra-fast modulation laser.

4. BEAM MODE CONTROL TECNOLOGY

Copper has the property that the laser light absorption rate of 1070 nm of wavelength for solid state is very small at around 5%, but rises significantly on starting of melt due to temperature rising. Dependent on the property, it is needed a high laser power for melting in the beginning, on the other hand, once melting begins, energy is absorbed locally around keyhole which is occurring at laser irradiation part and the molten pool is not stable, and it leads to the defect of spatter of scattered metal and the blowhole of remaining of entrapped air in the molten metal, as shown in Figure 8 (a). If these defects are occurring in the process of laser welding process, they lead to decreasing of the joint strength and increasing of the process for eliminating the spatter. The weld defects are a big issue when applying the fiber laser on the copper welding process.

In order to solve the issue, FEC is carrying out the development of the beam mode control technology which can control precisely the intensity distribution at laser focusing point. The beam mode control technology, as

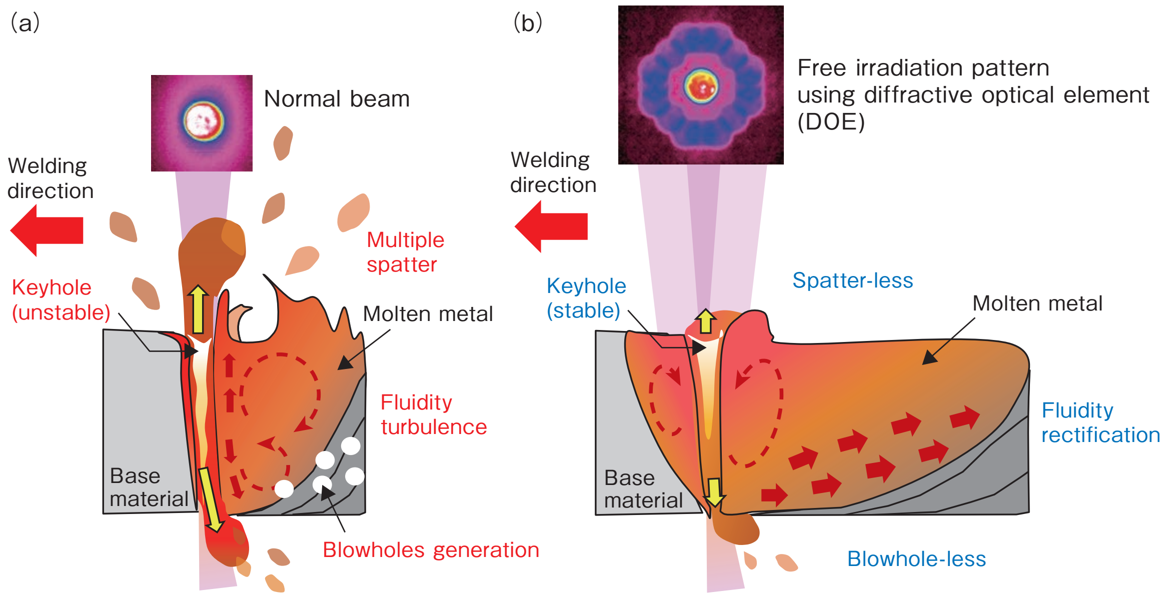

Figure 8 (a) Mechanism of defect generation on laser welding.
(b) Suppression of welding defects by beam mode control technology.

shown in Figure 8 (b), is a method for improving quality of the welding in the form of multiple of sub-beams arranged around a main beam of processing for the purpose of pre-heating and rectification of the molten metal fluidity. Our beam mode control technology can control the arbitrary light intensity distribution due to inserting the beam mode controlling element and has excellent laser power durability and beam conversion efficiency which were not achievable with the conventional beam mode controlling element. FEC's 1.5 kW single mode laser to 12 kW multi-mode laser are applied with a process used by a laser with a wide range, and it is capable of a high quality laser welding using the laser suitable to the processed material.

In this chapter, the actual case of a copper plate welding and a winding wire welding utilizing the beam mode control technology are introduced.

4.1 High Quality Welding of Copper Plate

The single mode fiber laser has an excellent beam quality and can irradiate by focusing on a small beam diameter Ø of 20 to 30 µm. Based on the above feature, a high power density of more than 10^8 W/ cm^2 can be obtained easily and it is effective for fine welding of copper material with high reflectance. On the other hand, the molten pool gets thin on welding in high rate region and it leads to the occurrence of spatter and deterioration of welding strength. In order to solve the above problem, it requires the irradiation with increasing beam diameter based on defocusing of laser light or enlarging of the molten pool with decreasing welding rate. However, since laser irradiation with defocus results in enlarging of heat influenced part and decreasing of allowance for height direction of irradiation position and decreasing of welding rate is directly related to the cycle time, it is needed to investigate the process condition in the focused and high rate region. Then FEC aims at stabilization of the molten pool with the application of the beam mode control technology with single mode fiber laser welding.

Doubled two copper sheets with thickness of 0.5 mm and 1.0 mm respectively were irradiated on by laser with focusing light point settled on the surface of copper, and the appearance of the weld bead is shown in Figure 9. Figure 9 (a) shows the result of a conventional one spot irradiation without beam mode control and Figure 9 (b) shows the result of a beam mode control technology application. According to Figure 9 (a), it demonstrates that the bead width is not stable and welding defects of spatter, pit (hole), etc. are occurring with the conventional one spot irradiation. On the other hand, the result of the beam mode control technology application in Figure 9 (b) shows a high quality welding with a stability of the bead and no occurrence of welding defect. As for the used beam mode for the welding, since the beam with focusing light spot diameter of 21 µm is arranged in micro area of Ø 100 µm and where energy distribution ratio to each spot is controlled precisely, the stability of molten pool and a high quality of processing are achieved.

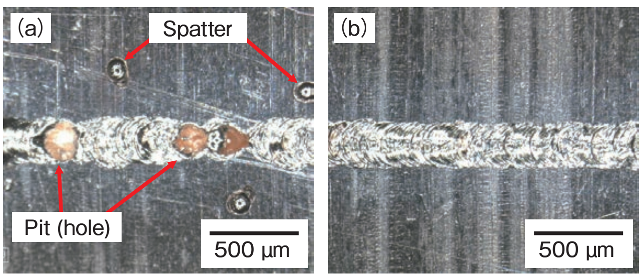

Figure 9 Optical image of laser welding on copper plate.
(a) Conventional focused beam without a beam mode control technology.
(b) Focused beam with a beam mode control technology.

4.2 High Quality Welding of Winding Wire

Toward the miniaturization and the high output of the motor for the xEV, as shown in Figure 10, using of the rectangular wire becomes mainstream due to winding conductor with high occupancy in the motor comparing with the conventional round wire. The Tungsten Inert Gas (TIG) welding was mainstream for welding of the rectangular wire conventionally, but there were many issues for the TIG welding, such as, the necessity of stripping the coating massively to grounding aside from the welded parts, a large heat impact due to long welding time and a difficulty of precise operation for irradiation position. On the other hand, for laser welding, it is feasible to strip coating to minimum because of contactless welding and shortening significantly welding time using high power laser. However, since the fiber laser has another issue, for instance, occurrence of spatter on welding which causes the shortage and occurrence of blowhole in the welded part which it has deteriorating influences on strength and electric resistance, it has been considered difficult to improve in quality.

Figure 10 Difference of compactness between round wires and rectangular wires in the motor.

FEC applied the beam mode control technology to 6 kW multimode fiber laser and reached a suitable welding condition for rectangular copper wires, and it is succeeded to shorten significantly the welding time and made an improvement of the welding quality. X-ray transmission image of two of rectangular wires with cross-sectional surface of 1.5 mm × 3.1 mm used actually in the motor on hairpin welding is shown in Figure 11. A lot of blowholes are found in the wire with the conventional laser welding without the beam mode control technology application as shown in Figure 11 (a), but the blowhole is suppressed significantly for the welding applied with the beam mode control technology as shown in Figure 11 (b). The illustration of the welding is shown in Figure 12 with the comparison of the above two cases. According to Figure 12, it is demonstrated that the application of the beam mode control technology leads to an excellent welding without spatter. The welding is completed with a laser irradiation time of less than 0.1 second and it is possible to shorten the welding time to a level the TIG welding cannot achieve. The heat direction is one way on welding end of the rectangular wire, and the coat burning is occurring in the case of long irradiation time. However, since the process time of FEC's laser welding is short, in the case of stripping short length of 8 mm for thermoplastic resin coat of poly ether-ether ketone (PEEK), the coat burning is not occurring with the laser welding, shown in Figure 13.

Minimum stripping of coat resin leads to the cost reduction and the motor miniaturization, and the shortening of welding time leads to productivity improvement.

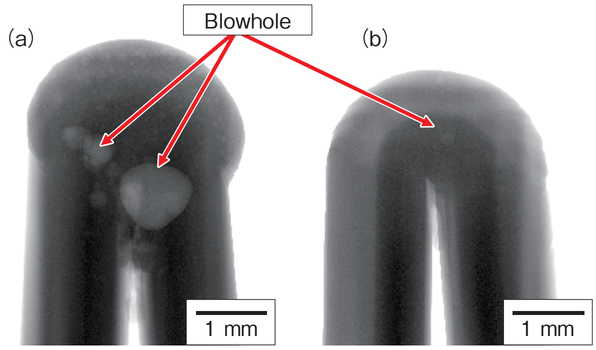

Figure 11 Xray transmission image of hairpin rectangular copper wires.
(a) Conventional focused beam without a beam mode control technology.
(b) Focused beam with a beam mode control technology.

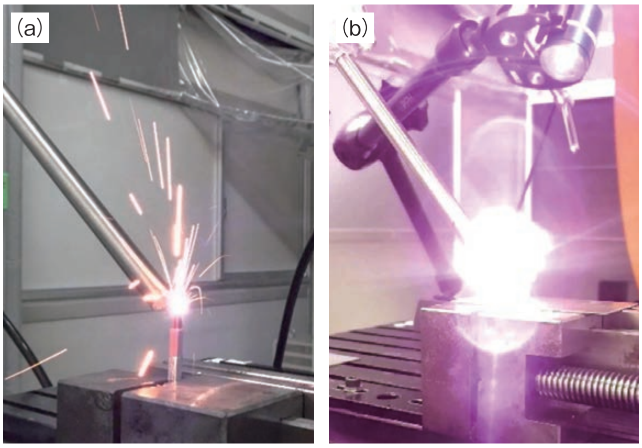

Figure 12 Hairpin welding of rectangular copper wires.
(a) Conventional focused beam without a beam mode control technology.
(b) Focused beam with a beam mode control technology.

Figure 13 Optical image of hairpin welding of PEEK resin coated rectangular wires with a stripping length of 8 mm.

5. CONCLUSION

Increasing of demand for batteries and motors focused on application to the xEV, a process technology with a high speed and a high quality for the copper material, as main material, is required. Furukawa Electric Co., Ltd. has the processing solution combined from its own technologies through various fiber lasers with a high beam quality, an ultrafast frequency modulation and a beam mode control. We would like to further continue the development of lasers with high output power and high quality, and the development of a processing technology, and to propose solutions for the customer demand.