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Author(s)	Jung, Kwang-Woon; Kawahito, Yousuke; Katayama, Seiji
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Laser Direct Joining of CFRP to Metal or Engineering Plastic†

JUNG Kwang-Woon*, KAWAHITO Yousuke**, KATAYAMA Seiji***

Abstract

This study was performed to investigate the joining possibilities, strengths (loads,) and mechanisms of the joint between 3 mm thick CFRP (PA6) and 0.7 mm thick zinc-coated steel or 2 mm thick amorphous polyamide (PA) plastic using a continuous wave (cw) diode laser with a line-shaped beam. The results revealed that strong lap joints with the tensile shear load of 3300 N between CFRP and zinc-coated steel could be produced, and many bubbles of sub-millimeter sizes inside the wide shallow melted zone of CFRP near the joint interface were formed. Also, the joint was tightly bonded on atomic or molecular sized levels between the melted plastic and nanometer thick zinc oxide film on the surface of zinc-coated steel. On the other hand, in the case of laser joining of CFRP to amorphous PA plastic, the PA matrix plastic in the CFRP and the amorphous PA plastic at the joint interface were melted and tightly bonded without gap between two materials, and the amorphous PA plastic of the joints was elongated without fracture.

KEY WORDS: (Laser joining), (Diode laser), (Zinc-coated steel), (PA plastic), (high tensile strength), (nanometer zinc oxide film), (PA plastic elongation)

1. Introduction

Carbon fiber reinforced plastics (CFRP) with high strength-to-weight ratio and outstanding fatigue resistance in comparison with engineering metals are widely applied as one of new light-weight structural materials in various industrial areas such as aircrafts, automobiles and sports[1,2].

The development of manufacturing technologies such as joining, cutting and drilling to use more CFRP materials in the proper positions is rapidly demanded. Among others, the joining technology that can produce hybrid components with high functionality or flexibility utilizing the excellent characteristics of metal and CFRP is necessary. A joining of metal-plastic and metal-CFRP materials has been usually performed using adhesive bonds (glues) or mechanical fasteners such as bolts and rivets, but these joining processes lead to volatile organic compound (VOC) emission and inconvenience in mass production caused by hole drilling process[3,4].

As a solution, recently, several researches for a joining of CFRP to metal using laser direct joining[5], ultrasonic metal welding[6] and friction spot joining[7] have been actively conducted. In particular, laser direct joining of CFRP to stainless steel using a cw disk laser reported that strong lap joints with the tensile shear load of 4800 N (for 20 mm wide CFRP) could be produced by chemical bonding (ionic bonding of oxide film and metal), physical bonding (Van der Waals force) and mechanical bonding (anchor effect) near the joint interface. However, there are few trials to directly join CFRP and different materials such as metal and plastic.

In this research, therefore, with the objectives of investigating the joining possibilities, strengths (loads), characteristics and mechanisms of the joint between 3 mm thick CFRP (PA6) and 0.7 mm thick zinc-coated steel or 2 mm thick amorphous polyamide (PA) plastic using a cw diode laser with a line-shaped beam, laser direct joining experiments were performed.

2. Materials and Experimental Procedures

The materials used in laser direct joining experiments are commercially available zinc-coated steel (namely, hot-dip galvannealed steel), transparent amorphous PA and polyacrylonitrile (PAN) type CFRP purchased. The dimensions of zinc-coated steel sheet and amorphous PA plastic sheet used were 0.7 mm in thickness, 30 mm in width and 70 mm in length, and 2 mm in thickness, 30 mm in width and 70 mm in length, respectively. CFRP

† Received on September 30, 2013

* Professor
** Associate Professor
*** Specially Appointed Researcher

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used consisted of polyamide 6 (PA6) as a matrix plastic and a long fiber pellet type of chopped carbon fibers with the volume of 20 % and manufactured by injection molding. The dimensions of CFRP plate were 3 mm in thickness, 20 mm in width and 100 mm in length. Prior to laser joining experiments, the surfaces of zinc-coated steel sheets and CFRP plates were cleaned with ethanol.

Figure 1 represents a schematic experimental set-up for laser direct joining process of CFRP to zinc-coated steel or amorphous PA. Zinc-coated steel sheet or amorphous PA sheet were lapped on CFRP plate and tightly fixed by pressing two bridge plates with four bolts. About 60 N·cm torque was equally applied to each bolt. The cw diode laser with the maximum laser power of 3 kW, the wavelength of 800/940±10 nm and the focal distance of 100 mm was utilized, and the laser beam used was a line-shaped beam of 0.6×11 mm at the focal point. The incident angle (θ) of the laser head used was 5˚. In the case of laser joining of CFRP to zinc-coated steel, the diode laser beam was directly irradiated on a 0.7 mm thick zinc-coated steel sheet overlapped on a 3 mm thick CFRP plate. On the other hand, in the case of laser joining of CFRP to amorphous PA, the diode laser beam was directly irradiated on the 3 mm thick CFRP plate after transmitted amorphous PA sheet. Laser joining conditions used in these experiments were the laser power of 70 - 700 W, the travelling speed of 5 - 15 mm/s. The N_2 shielding gas of 30 L/min was used to reduce the contamination of the protection glass of the laser head and to cool the surface of amorphous PA sheet.

In order to evaluate the possibility and strengths for the laser lap joints produced, the tensile shear test was conducted at the travelling speed of 0.33 mm/s for the gauge length of about 80 mm. The microstructure near the joint interface was observed by scanning electron microscope (SEM) and transmission electro microscope (TEM). Furthermore, the characteristics and mechanisms of the joints near the joint interface were investigated by SEM-EDS (energy dispersive X-ray spectrometer) and TEM-EDS in detail.

3. Results and Discussion

Prior to, laser direct joining experiments of CFRP to zinc-coated steel was performed by directly irradiating the cw diode laser with the line-shaped beam on zinc-coated steel sheet overlapped on CFRP plate. **Figure 2** indicates the appearances of laser direct lap joints between CFRP plate to zinc-coated steel sheet, and the tensile shear test results obtained under different joining conditions. The results in Fig. 2(a) show that the dissimilar lap joint of CFRP to zinc-coated steel was produced by irradiating with a diode laser, and the weld bead was not observed on the top surface of zinc-coated steel sheet, although the laser-irradiation area was recognized as a slight color change of the zinc-coated steel sheet surface. Also, it is observed that the melted plastic with some carbon fibers of CFRP flowed out towards both start- and end-edges of CFRP plate. This is

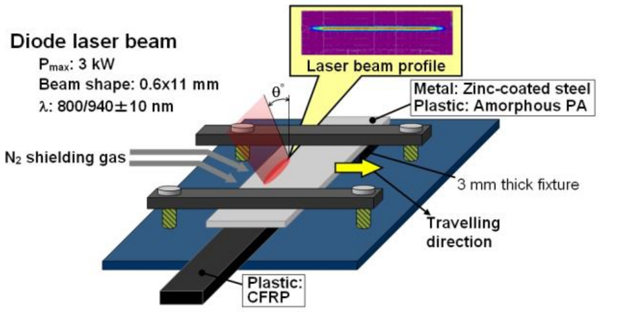

Fig. 1 Schematic illustration of experimental setup for laser direct joining of CFRP to zinc-coated steel or amorphous PA using cw diode laser with line-shaped beam.

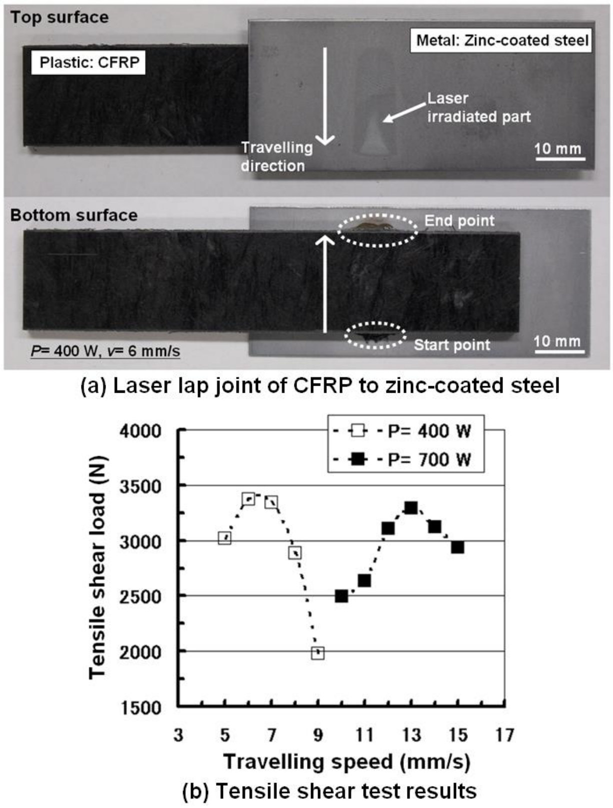

Fig. 2 Appearances of laser direct lap joints between CFRP to zinc-coated steel (a) and tensile shear test results made under different joining conditions (b).

attributed to the activated flow of part of the CFRP (especially, the matrix plastic) during a laser irradiation. In Fig. 2(b), in the case of the laser power of 400 W, the lap joints had the maximum tensile shear load of about 3300 N at the travelling speed of 6 or 7 mm/s. At the speeds faster than 7 mm/s, the strengths of joints decreased with increasing the travelling speed. In particular, at 9 mm/s, the joints had the lowest load of 2000 N. This is attributed to a decrease in the joining area. On the other hand, in the case of the laser power of 700 W, the joints made at 13 mm/s had the highest load of about 3300 N. However, at less than 13 mm/s, the strengths of the joints decreased. It was caused by an

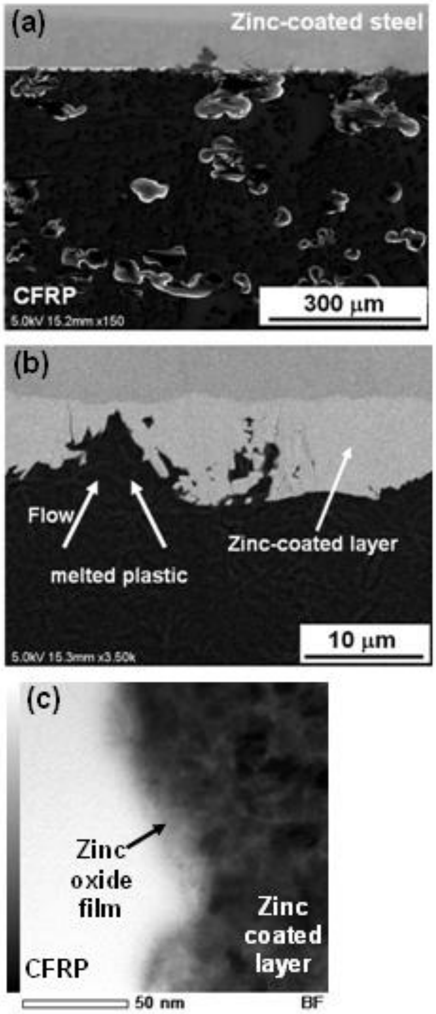

Fig. 3 Cross-sectional SEM photos (a-b) of interface for laser direct lap joint of CFRP to zinc-coated steel and TEM photo near joint interface (c).

increase in thermal damage to CFRP due to excessive laser heat input.

The microstructure characteristics and mechanisms of the joint between CFRP and zinc-coated steel during laser joining were examined in detail. **Figure 3** represents cross-sectional SEM photos of the joint interface for laser direct lap joint of CFRP to zinc-coated steel and a TEM photo near the joint interface. In Fig. 3(a), it is seen that the joint was tightly bonded without gap between two materials, and many small bubbles of sub-millimeter sizes inside the wide swallow melted zone of CFRP near the joint interface were irregularly formed. In Fig. 3(b), the zinc-coated layer on the surface of steel was broken partially with the formation of big grooves. Especially, it is observed that the melted matrix plastic of CFRP entered to closely flow in big grooves. This result suggests that strong mechanical bonding like anchor effect should be achieved near the joint interface. In the TEM photo of Fig. 3(c), it is observed that the amorphous PA plastic was tightly bonded on atomic or molecular sized levels on the nanometer thick zinc oxide film existing on the surface of the zinc coated layer. From these results, it is confirmed that much possibility of strong physical bonding and chemical bonding (ionic bonding of zinc oxide and carbon) should exist.

Subsequently, laser direct joining of CFRP plate to transparent amorphous PA sheet was conducted by directly irradiating a diode laser beam on the CFRP plate after the laser transmitted the PA plastic. **Figure 4** indicates laser direct lap joints between CFRP plate and amorphous PA sheet before and after the tensile shear test. The laser power and the travelling speed used were 100 W and 15 mm/s, respectively. The results show that the joint of CFRP to amorphous PA could be produced by only a laser irradiation, and after the tensile shear test, the amorphous PA plastic of the joint was elongated without any fracture. The tensile shear loads measured were about 3700 N similar to that of the base PA plastic. The characteristics of the interface for the joint were observed by SEM. **Figure 5** shows cross-sectional SEM photos of the interface for the joint of CFRP to amorphous PA. It is

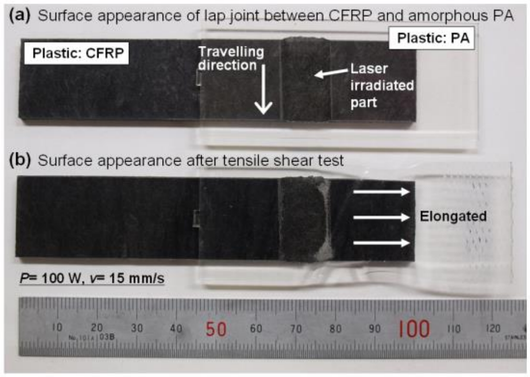

Fig. 4 Laser direct lap joints between CFRP and transparent amorphous PA before and after tensile shear test.

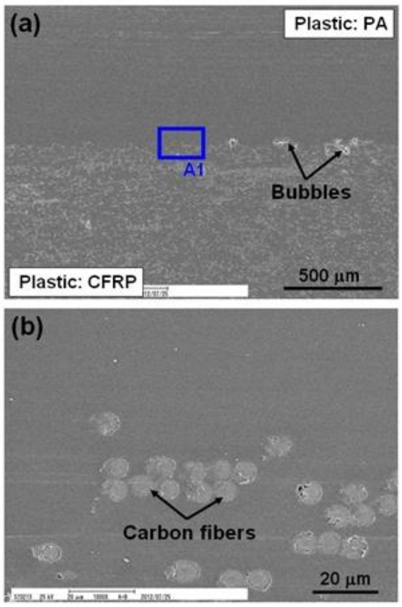

Fig. 5 Cross-sectional SEM photos of interface for laser direct lap joint of CFRP to amorphous PA: lower magnification (a) and higher magnification (b) corresponding to boxed region of A1.

confirmed that the joint was tightly bonded without gaps between two materials, and the matrix PA6 plastic in the CFRP and the amorphous PA plastic were integrated through melting·cooling process during a laser irradiation.

4. Conclusions

Laser direct joining of PAN type CFRP to zinc-coated steel or transparent amorphous PA was performed by a cw diode laser with a line-shaped beam. It was confirmed that the dissimilar lap joint of CFRP and zinc-coated steel was possibly produced by a diode laser irradiation. The tensile shear test demonstrated that strong lap joints with the maximum load of about 3300 N could be produced. Many small bubbles of sub-millimeter sizes inside the melted zone of CFRP near the joint interface were irregularly generated. It was revealed that strong mechanical bonding (anchor effect) should be achieved near the joint interface, since the melted plastic flew into big grooves of the fractured zinc-coated layer. Moreover, the PA matrix plastic was tightly bonded on atomic or molecular sized level on nanometer thick zinc oxide film existing on the surface of zinc coated layer, suggesting much possibility of strong physical bonding and chemical bonding. In addition, it was confirmed that the lap joint of CFRP (PA6) to amorphous PA could be produced by a diode laser irradiation, and the amorphous PA plastic of the joint was elongated without fracture.

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