EVALUATION ON JOINING BEHAVIOR OF UD-CF/EPOXY LAMINATES AND ALUMINUM PLATE USING ULTRASONIC HEATING

A. Urano[1], D. Tanabe[2] and K. Nishiyabu[3]

[1] Advanced Course of Mechanical System Engineering, Kobe City College of Technology, 8-3, Gakuen-Higashimachi, Nishi-ku, Kobe 651-2194, Japan.
[2] Department of Mechanical Engineering, Kobe City College of Technology, 8-3, Gakuen-Higashimachi, Nishi-ku, Kobe 651-2194, Japan, kcct-tanabe@g.kobe-kosen.ac.jp
[3] Faculty of Science and Engineering, Kindai University, 3-4-1, Kowakae, Higashiosaka city, Osaka 577-8502, Japan, nishiyabu@mech.kindai.ac.jp

Keywords: Ultrasonic heating, Phenoxy, CF/Epoxy, Energy director, Joining strength

ABSTRACT

This study aims to reveal the ultrasonic joining behavior and joining strength of aluminium and carbon fiber reinforced plastics (CFRP) by using ultrasonic heating. The material used for experiment was unidirectional carbon fiber reinforced epoxy (UD-CF/Epoxy) laminates and aluminium (Al) plate. In order to improve the tensile shear strength of joining part, polishing and surface-modified phenoxy polymer coating were performed on the joining surface of the Al plates and UD-CF/Epoxy laminates. In this study, UD-CF/Epoxy laminates and Al plates were bonded by the ultrasonic welding method using phenoxy polymer sheet as energy director. The effects of processing conditions such as oscillation time, pressing force and surface treatment methods were investigated to improve the tensile shear strength. In this study, the various processing condition was investigated to improve the tensile shear strength. The contents for evaluation were single lap tensile share strength, cross-sectional and fracture surface observation. From the experimental results, it was found that the joining strength was depended on the difference in the surface treatment of joining surface.

1 INTRODUCTION

Carbon fiber reinforced plastics (CFRP) have been attracting attention as structural members such as aircraft and automobiles and industrial equipment [1]. However, since CFRP has problems in durability, heat resistance, and manufacturing cost, it is expected that various characteristics such as weight reduction and cost reduction will be improved by combining CFRP with other metals and plastics to make it a multi-material. It is necessary to join dissimilar materials such as using thermosetting adhesives, mechanical joining using metal bolts and rivets.

In recent years, several joining methods using laser heating and friction stir welding (FSW) have been proposed as joining methods for metal and CFRP [2]. With laser heating, it is difficult to heat and press the joint at the same time. Also, FSW is difficult to control the temperature of the joining part. A common problem with these joining methods is that heat conduction from the metal side heats the joint, resulting in uneven temperature distribution across the joint. In order to join metal and aluminum with high strength, it is necessary to apply pressure and heat at the same time. It is also required to heat the joint locally and uniformly.

In general, to improve the bonding strength by the anchor effect, surface treatment of the metal side such as anodizing or porous plating is required. Previous studies have also proposed a method of forming unevenness on the surface of a metal plate using laser heating.

On the other hand, ultrasonic heating method has been proposed as one of the fusion joining methods for CFRTP. For ultrasonic joining of CFRTP, there is a method of welding using an energy director [3-

5]. This energy director is manufactured by molding a thermoplastic into a sheet, and by arranging it on the joint surface in order to ultrasonic energy can be concentrated [3-5].

This study aims to development the ultrasonic joining of UD-CF/Epoxy laminates and an aluminum plate using phenoxy polymer as the energy director. The effects of ultrasonic welding conditions and surface treatment of UD-CF/Epoxy and Al plates on melting behavior and joining strength were investigated.

2 MATERIALS AND EXPERIMENTAL PROCEDURE

2.1 Materials

The materials used for experiment were unidirectional carbon fiber reinforced epoxy prepreg sheet (Mitsubishi Chemical Co., Ltd., TR350C150S, 150g/m^2, UD-CF/Epoxy prepreg) and aluminum plate (A6063, thickness t=2.0 mm). The prepreg sheets were laminated in an arbitrary stacking sequence and used as laminates by hot press molding. The surface of the aluminum plate was polished with # 400 water-resistant abrasive paper.

The energy director was made from phenoxy polymer (Mitsubishi Chemical Co., Ltd., jER®, 1256, phenoxy). The result of differential scanning calorimeter (DSC) analysis of phenoxy polymer shows that the glass transition temperature was T_g=93ºC, and result of thermogravimetric analysis shows that the thermal decomposition temperature was T_d=264 ºC.

2.2 Manufacturing process of UD-CF/Epoxy laminates

Fig.1 shows the manufacturing process of UD-CF/Epoxy laminates. The manufacturing process is divided into 2 steps. (a)UD-CF/Epoxy prepreg sheets were cut into a length of 138mm and a width of 138mm, and the stacking sequence of the prepreg was $[0/90]_{19}$. (b) The UD-CF/Epoxy laminated plate was prepared by press forming in a vacuum with a vacuum heating press. The heating conditions were a mold temperature of 200ºC. and holding for 10 minutes. Finally, UD-CF/Epoxy laminates with a thickness of 2 mm was obtained.

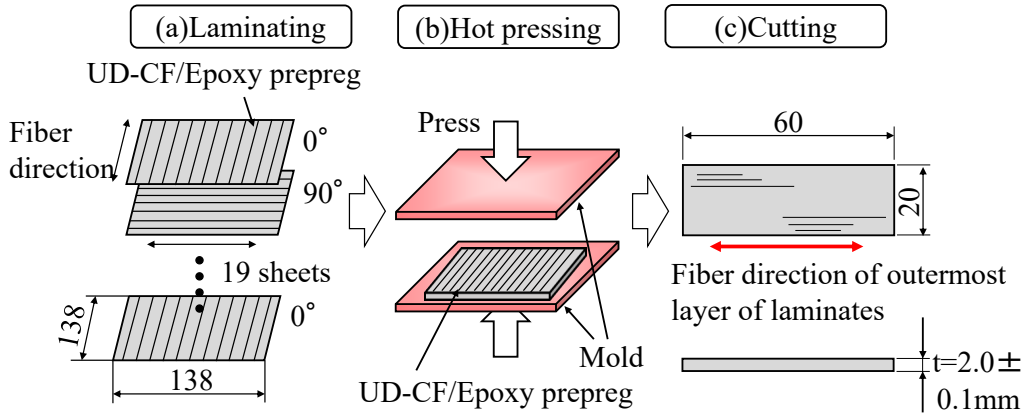


Figure 1: Manufacturing process of UD-CF/Ep laminates by vacuum hot press molding at T=200 ºC, t=10min.

2.3 Manufacturing process of energy director

Fig.2 shows the manufacturing process of phenoxy polymer energy director. The manufacturing procedure is as follows. Since phenoxy polymer has hygroscopicity, phenoxy pellet was dried in a constant temperature bath at 80 ºC. (a)The phenoxy polymer sheet was molded by heat press molding using a vacuum heating press machine. The heating conditions were a mold temperature of 200 ºC, load

of 1 ton and a holding time of 10 minutes. (b) It was cut into a length of 23mm and a width of 23mm using an ultrasonic cutter and used as an energy director.

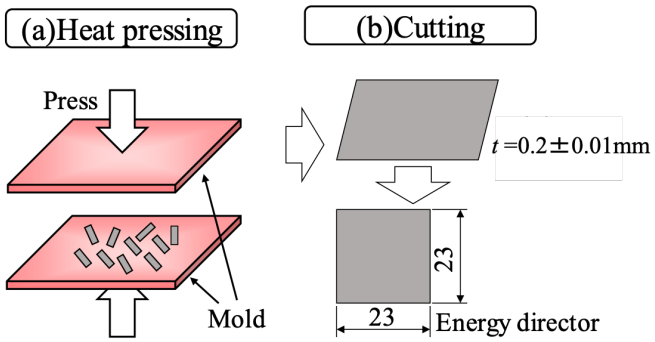
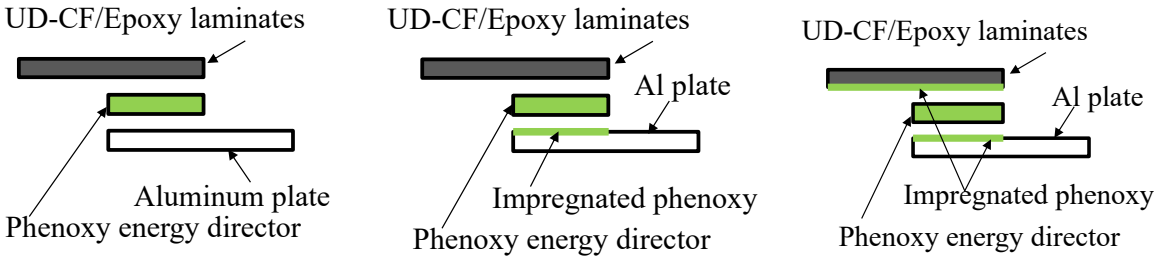


Figure 2: Manufacturing process of energy director by vacuum hot press molding at T=200 ºC, t=10min.

In this study, we investigated the effects of pre-impregnation of phenoxy polymer on the joint surface. Fig.3 shows the configuration of the joining specimens. One is a specimen using phenoxy polymer only as an energy director (Fig.3(a)). Another is made by welding phenoxy polymer to the surface of an aluminum plate by hot press molding (Fig.3(b)). The other is a UD-CF/Epoxy laminated plate and an aluminum plate impregnated with phenoxy polymer by hot press molding (Fig.3(c)). When the UD-CF/Epoxy laminate was impregnated with the phenoxy polymer, it was carried out simultaneously with the curing reaction of the UD-CF/Epoxy prepreg.



(a) Non pre-impreg. (b) Al pre-impreg. (c) CFRP-Al pre-impreg.

Figure 3: Configuration and conditions of joining specimens.

2.4 Ultrasonic welding method

A schematic drawing of the ultrasonic welding equipment is shown in Fig.4. The ultrasonic vibration is generated by applying the ultrasonic output from an ultrasonic oscillator (DUKANE, iQ-Aim®, maximum output power 2600W, frequency 20kHz) to a bolt tightening Langevin-type oscillator, which generates a small amplitude. The ultrasonic vibration was amplified by an ultrasonic horn (horn tip dimension, 27mm×27mm).

The ultrasonic vibration was applied with an arbitrary load using a servo press system (Daiichi-Dentsu Co., Ltd., DSP 3000). The servo press enables constant monitoring of the load and displacement during ultrasonic welding.

The energy director generated heat above the melting temperature of phenoxy polymer (T_m=200°C approx.) due to friction and viscous damping, and the polymer near the fusion welding surface was heated and melted. After that, the polymer was cooled to lower than the glass transition temperature of phenoxy polymer (T_g=93°C) by air cooling under pressure, and ultrasonic welding was performed by solidifying the polymer.

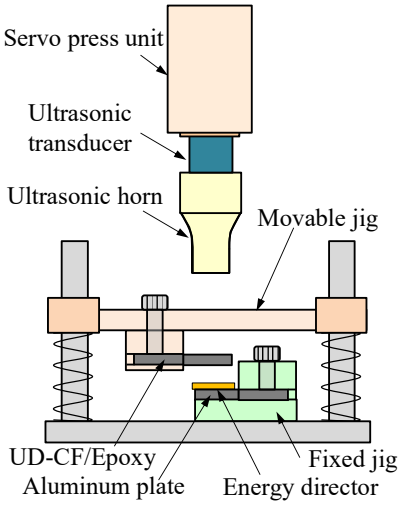


Figure 4: Schematic diagram of ultrasonic joining device for joining UD-CF/Epoxy laminates and aluminum plate.

2.5 Evaluation method

In order to evaluate the joining strength of ultrasonic joining part, the single lap tensile shear test was carried out by using a universal testing machine (Shimadzu, AG-Xplus 100kN). Fig.5 shows the geometry of single lap tensile shear strength test specimen. The UD-CF/Epoxy laminate was bonded to the aluminum plate so that the 0 degree fiber direction of the outermost layer faces the longitudinal direction. The crosshead speed during the tensile shear test was 0.5mm/min. The tensile shear strength was calculated by using this equation:

$$\tau = \frac{P_{max}}{A_w} \tag{1}$$

where τ , single lap tensile shear strength [MPa]; A_w, overlap area [mm^2] and P_{max}, maximum tensile force [N].

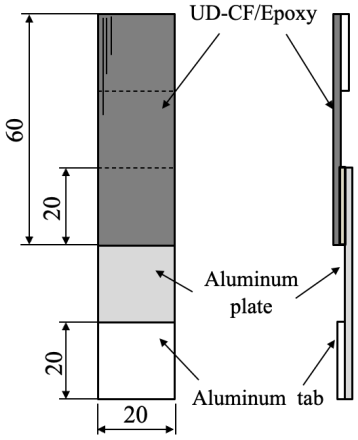


Figure 5: Geometry of single lap tensile shear test specimens.

3 EXPERIMENTAL RESULTS AND DISCUUSION

3.1 Examination of the application direction of ultrasonic energy

In the ultrasonic joining process of UD-CF/Epoxy laminates and Al plate, it is necessary to consider from which specimen ultrasonic energy should be applied. In addition, ultrasonic vibrations can cause specimens to resonate and break. Fig.6 shows the behavior of the ultrasonic output when ultrasonic heating was performed from the Al plate side or the UD-CF/Epoxy laminates side. ED-phenoxy specimens were used in this experiment. When ultrasonic oscillation was performed from the Al plate side, the ultrasonic output was low up to about 0.7s, and then showed unstable behavior. Therefore, it was considered that the ultrasonic energy was not sufficiently absorbed by the energy director at the welding layer. In the case of ultrasonic waves were oscillated from the UD-CF/Epoxy laminates side, the ultrasonic output showed a high value exceeding P_U=1000 W immediately after the oscillation, indicating that the ultrasonic energy was concentrated in the energy director.

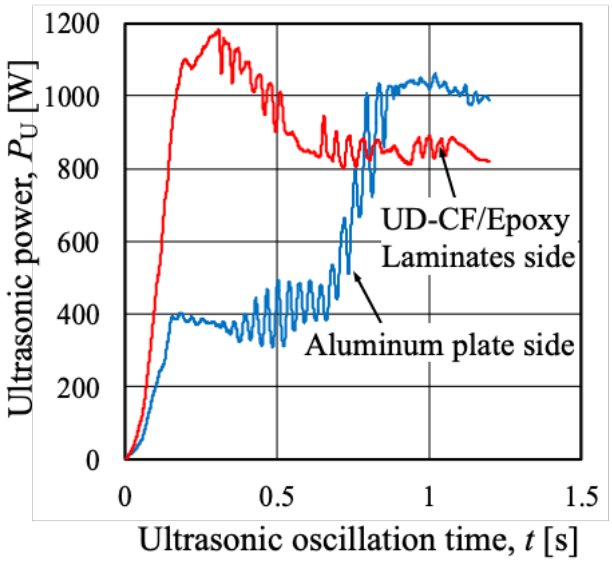
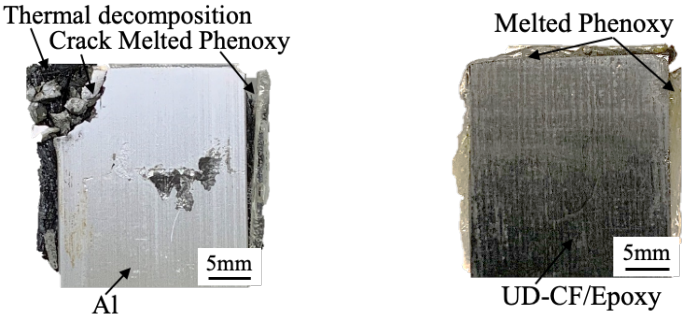


Figure 6: Effects of ultrasonic oscillation time on ultrasonic power (ED-phenoxy specimen).

Fig.7 shows fracture surface observation images of each plate when the application direction of ultrasonic oscillation was changed. As shown in Fig.7(a), damage to the aluminum plate was observed when the ultrasonic wave was oscillated from the aluminum plate side. The reason for this is thought to be that the aluminum plate resonated and fatigue fracture occurred. As shown in Fig. 7(b), when the ultrasonic wave was oscillated from the UD-CF/Epoxy plate, the phenoxy polymer of the energy director was melted and the laminate was not damaged. From these experimental results, we decided to apply ultrasonic energy from the UD-CF/Epoxy laminate side.



(a) Aluminum plate side (b) UD-CF/Epoxy laminates side

Figure 7: Scan images of peeled face (UD-CF/Epoxy laminates and aluminum).

3.2 Effects of heat fusion treatment of phenoxy polymer on the joint surface

Fig.8 shows the effects of pre-impregnation temperature of phenoxy polymer on tensile shear strength using ED-CF/Epoxy-Al-phenoxy specimen. As a general trend, the tensile shear strength was increased with increasing pre-impregnation temperature. The reason for this was thought to be that the higher the pre-impregnation temperature, the lower the melt viscosity of the phenoxy polymer. The tensile shear strength tended to continue to increase until the pre-impregnation temperature reached 200°C, but after that, there was a tendency that there was not much change. The appropriate molding temperature for the phenoxy polymer used in this study was 160°C to 200°C. Therefore, in this study, the pre-impregnation temperature was determined to be 200°C.

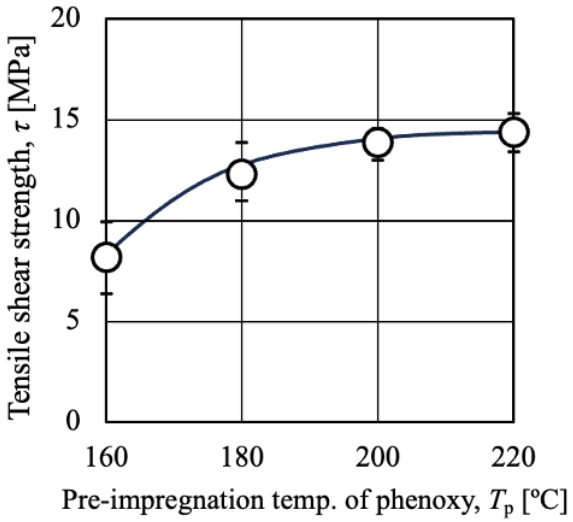


Figure 8: Effects of pre-impregnation temperature of phenoxy polymer on tensile shear strength (ED-CF/Epoxy-Al-phenoxy specimen).

Fig.9 shows the comparison of single lap tensile shear strength of ED-phenoxy, ED-Al phenoxy and ED-CF/Epoxy-Al specimens. In the case of ED-phenoxy specimen, the tensile shear strength showed an extremely low value. It was considered that this is because the phenoxy polymer did not impregnate the rough surface of the aluminum surface due to ultrasonic time was as short as 1s to 2s, and heat dissipation to aluminum plate with high thermal conductivity, and a sufficient anchor effect could not be obtained. On the other hand, in the case of ED-Al-phenoxy specimen, it was considered that the tensile shear strength was improved because phenoxy polymer of energy director melted by ultrasonic heating and phenoxy polymer welded to Al plate were fused and joined.

In the case of ED-CF/Epoxy-Al phenoxy specimen, the tensile shear strength was 14 MPa or more. This is about twice the tensile shear strength when the phenoxy polymer sheet is not integrally molded with the UD-CF/Epoxy laminates. Based on these experimental facts, it was found necessary to pre-impregnate CF/Epoxy laminates and aluminum plates with phenoxy polymer.

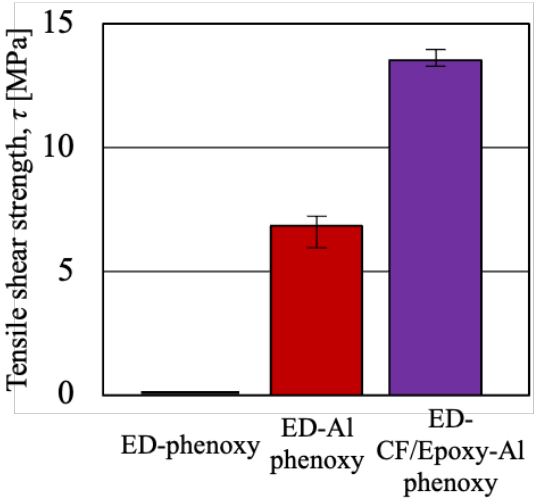


Figure 9: Comparison of single lap tensile shear strength.

4 CONCLUSIONS

In this study, the various processing condition was investigated to improve the tensile shear strength. The contents for evaluation were single lap tensile share strength, cross-sectional and fracture surface observation. From the experimental results, it was found that the joining strength was depended on the difference in the surface treatment of joining surface.

REFERENCES

[1] M. Yamane, “Technologies of Carbon Fiber Reinforced Thermoplastics -Material・Molding・Recycle-”, *Science&Technology Co.,Ltd.*, (2015).

[2] A. Pramanik et al., “Joining of carbon fibre reinforced polymer (CFRP) composites and aluminium alloys – A review”, *Composites: Part A*, vol.101, pp.1-29, 2017.

[3] I.F. Villegas, L. Moser, A. Yousefpour, P. Mitschang and H.E. Bersee, “Process and performance evaluation of ultrasonic, induction and resistance welding of advanced thermoplastic composites”, *Journal of Thermoplastic Composite Materials*, Vol.28, No.8 (2012), pp.1007-1024.

[4] I.F. Villegas and G. Palardy, A comparative evaluation between flat and traditional energy directors for ultrasonic welding of CF/PPS thermoplastic composites, *Composite Interfaces*, Vol.24, No.5, pp.515-528, 2017.

[5] J.C. Yan, X.L. Wang, R.Q. Li, H.B. Xu and S.Q. Yang, The effects of energy director shape on temperature field during ultrasonic welding of thermoplastic composites, *Key Engineering Materials*, Vol.353-358, pp.2007-2010, 2007.