Int J Adv Manuf Technol (2017) 91:2811–2817
DOI 10.1007/s00170-016-9891-7

ORIGINAL ARTICLE

3D printing of carbon fibre-reinforced plastic parts

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Received: 19 June 2016 / Accepted: 13 December 2016 / Published online: 11 January 2017

Abstract Carbon fibre-reinforced plastic parts were manufactured by sandwiching carbon fibres between upper and lower ABS layers made by a 3D printer using fused deposition modelling. Carbon fibre-reinforced plastic tensile specimens were manufactured, and the strength of the specimens was measured. The strength is not increased only by sandwiching of the carbon fibres, and thermal bonding between the fibres and layers is required. The strength for the small diameter of the nozzle is higher than that for the large diameter. The thermal bonding operation is simplified by using a microwave oven.

Keywords 3D printing · CFRP · Thermal bonding · Microwave oven

1 Introduction

As additive manufacturing processes, stereolithography of photopolymer, selective laser sintering using metallic powders, fused deposition modelling using plastics, etc. have been developed. In the selective laser sintering process, high strength parts are made of high alloy powders, whereas the equipment is expensive. On the other hand, the price of fused deposition modelling machines drastically decreases, and the application of this modelling process is expanding remarkably. With the fused deposition modelling process, mechanical parts are manufactured by laying down successive layers of molten plastic without dies [1]. However, the strength of parts produced by the fused deposition modelling process is not equivalent to that by the conventional injection moulding processes. Sood et al. [2] examined the effect of modelling conditions such as layer thickness, orientation, raster angle, raster width, and air gap on the tensile, flexural, and impact strengths. It is desirable to increase the strength of parts manufactured by the fused deposition modelling.

The use of carbon fibre-reinforced plastics increases in aircraft and automobiles industries because of weight reduction. The carbon fibre-reinforced plastics are produced by mixing shortly cut fibres with a resin and by embedding continuous fibres into a resin. In the mixture of cut fibres, injection moulding is available for the production of reinforced plastics, whereas the strength of the plastics is not very high. Miwa et al. [3] investigated the effect of the fibre length on the tensile strength. Fu et al. [4] examined the effect of the distribution of fibre orientation on the tensile strength.

In resin transfer moulding for producing thermosetting carbon fibre-reinforced plastics, a carbon fibre fabric cut into a desired shape is heated in the mould, thermosetting resin is pumped, and is held in several minutes until solidification. In the production of thermosetting carbon fibre-reinforced plastics, the productivity is low and the operations become complicated. Yanagimoto et al. [5] heated a carbon fibre-reinforced plastic sheet by sandwiching between heated metallic sheets during stamping.

To improve the productivity and operations, thermoplastic carbon fibre-reinforced plastics are attractive. Carbon fibre

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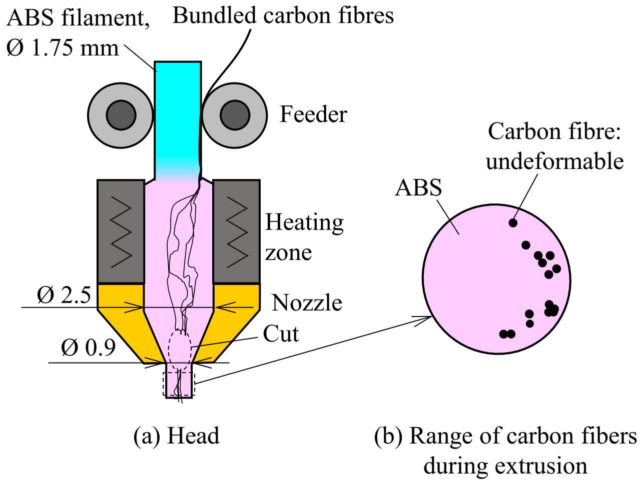


Fig. 1 Inclusion of carbon fibres in molten ABS

sheets composed of fibre fabric and thermoplastic resin are heated in a furnace and then are hot-stamped. The sheets are not heated in the dies, and the holding at the bottom dead centre of a press for cooling the formed sheets is comparatively short, below 1 min. The application of thermoplastic carbon fibre-reinforced plastics to automobile body-in-white parts has begun. Rozant et al. [6] examined deformation behaviour of thermoplastic carbon fibre-reinforced plastic sheets in the tensile test. Davey et al. [7] measured the relationship between the fibre direction and the strain in bulging of carbon fibre-reinforced PEEK sheets. Isogawa et al. [8] obtained the optimum forming temperature and blankholder pressure in deep drawing of the thermoplastic sheets. The produced parts are hollow and not solid because of making of sheets.

To increase the strength of plastic parts produced by the fused deposition modelling, Shofner et al. [9] compounded cut nanofibres into an ABS filament and increased the strength by about 20%. Matsuzaki et al. [10] simultaneously extruded continuous carbon fibres and a resin filament to heighten the strength, while embedding of the carbon fibres in the filament is not easy because of segregation of the fibres. It is desirable to develop a process for compounding a sufficient amount of long carbon fibres in plastic parts.

In the present study, a 3D printing process of carbon fibre-reinforced plastic plates was developed to manufacture three-dimensional mechanical parts. The static tensile and bending strengths of the specimens made of carbon fibre-reinforced plastic manufactured by 3D printing were measured.

2 3D printing of carbon fibre-reinforced plastic parts

2.1 Inclusion of carbon fibres in plastic parts

To increase the strength of plastic parts, bundled carbon fibres were included in the molten plastic as shown in Fig. 1. The bundled fibres were inserted with the ABS filament from the entry of the nozzle and were extruded together. The fibres were bonded with the ABS by heating during passing through the nozzle having 2.5 and 0.9 mm in entry and exit diameters, respectively.

The extruded ABS filament including the carbon fibres without disposition is shown in Fig. 2. Since the carbon fibres are not stretched during extrusion, the amount of the extruded

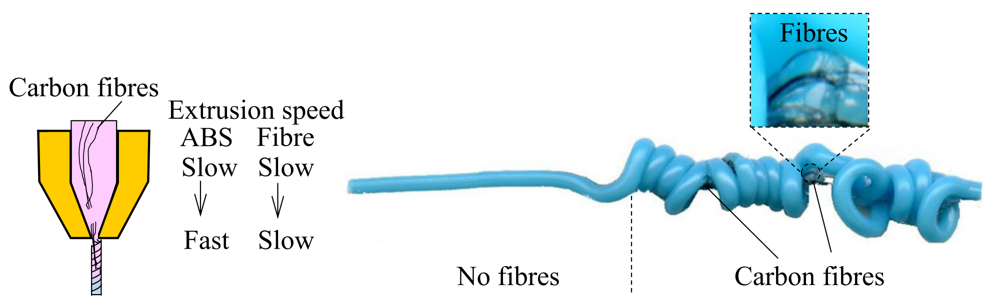


Fig. 2 Extruded ABS filament and carbon fibres without disposition

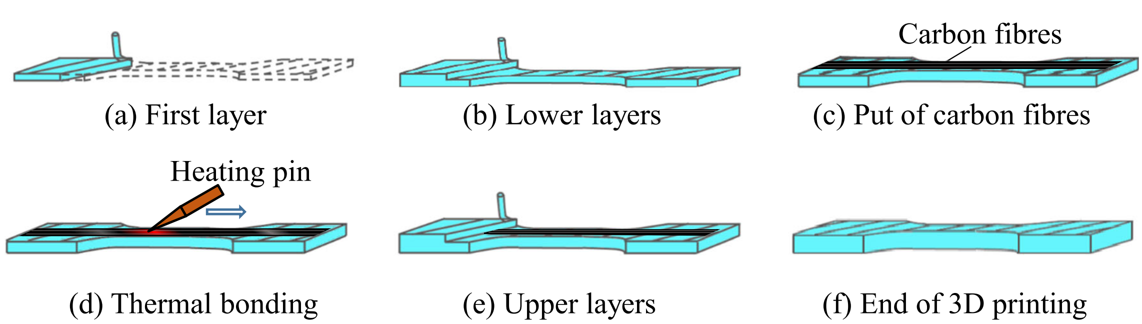


Fig. 3 Sandwiching of carbon fibres between 3D-printed ABS layers

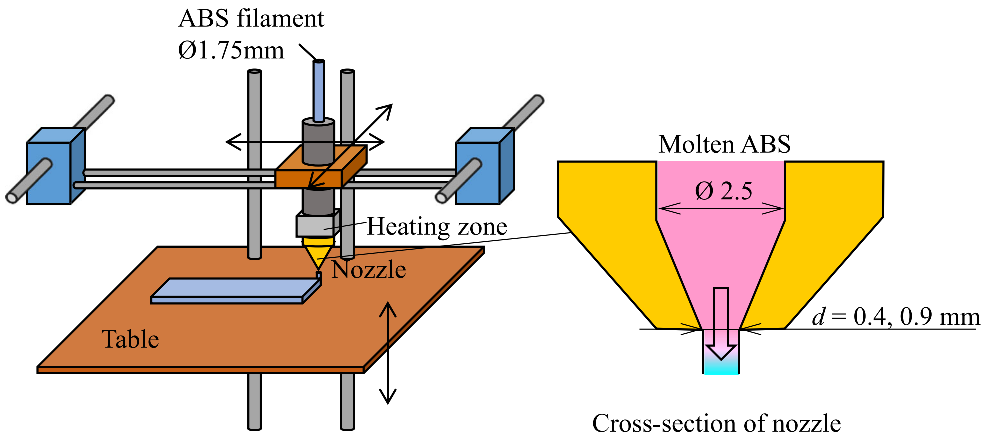


Fig. 4 3D printer for manufacturing carbon fibre-reinforced plastic tensile specimens

ABS from the exit is larger than that of the fibres. By the difference in extruded amount, the extruded ABS is curled and the carbon fibres are out of the ABS. For a severe condition, the carbon fibres are cut by being stretched by the molten ABS during extrusion. In addition, the amount of inserted carbon fibres is limited. It is difficult to extrude the carbon fibres with the molten ABS.

2.2 Sandwiching of carbon fibres between 3D-printed ABS layers

Carbon fibres are embedded by being sandwiched between 3D-printed ABS layers without fibres as shown in Fig. 3. First, the lower layers are manufactured by 3D printing and are covered with the bundled fibres cut into the dimensions of the specimen. The fibres are thermally bonded with the lower layers by the heating pin, and finally the upper layers are deposited on the lower layers.

2.3 Conditions for 3D printing of specimen

Static tensile specimens made of carbon fibre-reinforced plastic were manufactured by the 3D printer shown in Fig. 4, and then the specimens were tensile-tested. The mechanical properties of the ABS filament and the carbon fibre are given in Table 1. The conditions for 3D printing of the specimens are given as Table 2. The ABS filament having a diameter of 1.75 mm was melted in the nozzle, and the molten ABS was extruded from the nozzle having exit diameters of $d = 0.4$ and 0.9 mm. The successive ABS layers were laid down on the heated table. For the deposition of the first layer, the moving speed of the nozzle was reduced to weld the first layer with the table.

Table 1 Mechanical properties of filament and carbon fibre

ABS filament	Tensile strength	30 MPa
	Diameter	1.75 mm
Carbon fibre	Tensile strength	5.3 GPa
	Diameter	6 μm

Table 2 Conditions of 3D printing of tensile specimens

Nozzle diameter d		0.4 mm	0.9 mm
Nozzle temperature		225 °C	190 °C
Nozzle moving speed	Edge of specimen	30 mm/s	30 mm/s
	Inside of specimen	25 mm/s	50 mm/s
	First layer	40% reduction	20% reduction
Length of fibres		145 mm	70 mm
Volume percentages of carbon fibres in parallel sections of specimen		1.45%	0.85%

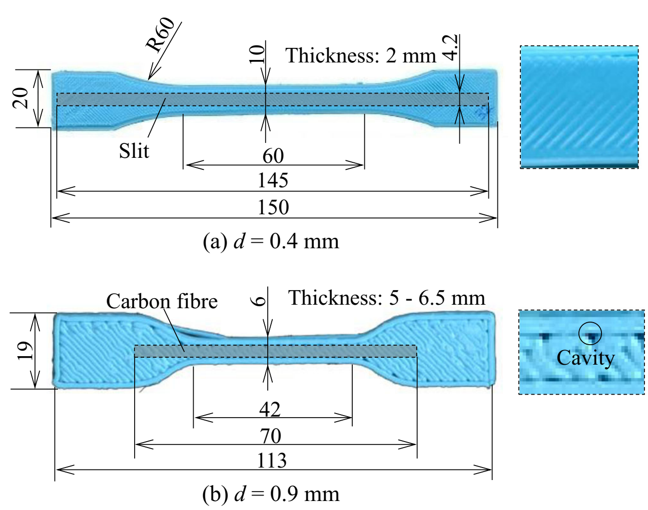


Fig. 5 Carbon fibre-reinforced plastic tensile specimens manufactured by 3D printing for $d = 0.4$ and 0.9 mm

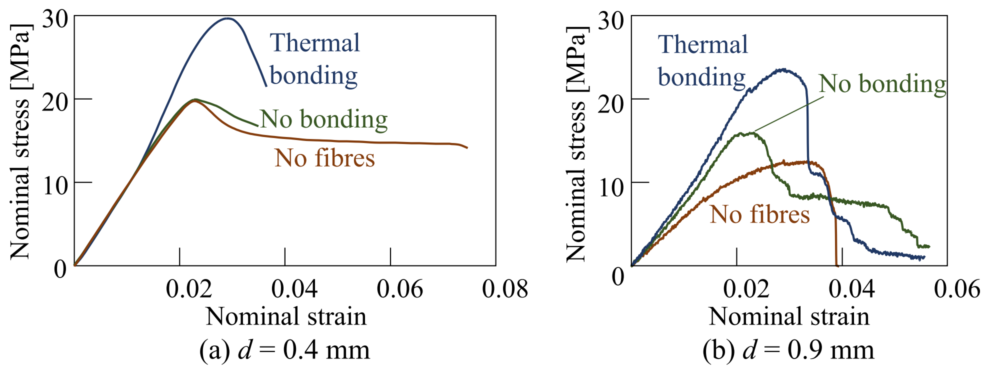


Fig. 6 Nominal stress-strain curve measured from static tensile test of 3D-printed specimen

3 Results of tensile tests

The static tensile specimens manufactured by 3D printing are shown in Fig. 5. The numbers of the lower layers for $d = 0.4$ and 0.9 mm were 3 and 2, and the numbers of the upper layers were 4 and 3, respectively. The number of carbon fibres sandwiched between the upper and lower layers was 9000. The temperature of the heating pin for bonding the fibres with the lower layers was about 400 °C. The extruded ABS is sufficiently bonded together for $d = 0.4$ mm, whereas the cavities are caused for $d = 0.9$ mm.

The nominal stress-strain curve measured from the static tensile test of the 3D-printed specimens is illustrated in Fig. 6. The strength is not increased by only sandwiching of the carbon fibres, and thermal bonding is required. The strength with thermal bonding is 1.5 times higher than that without fibres. The strength for $d = 0.4$ mm is higher than that for $d = 0.9$ mm, because the specimen for $d = 0.9$ mm has the cavities shown in Fig. 5. For $d = 0.9$ mm, the stress considerably drops after attaining the maximum stress due to the cavities.

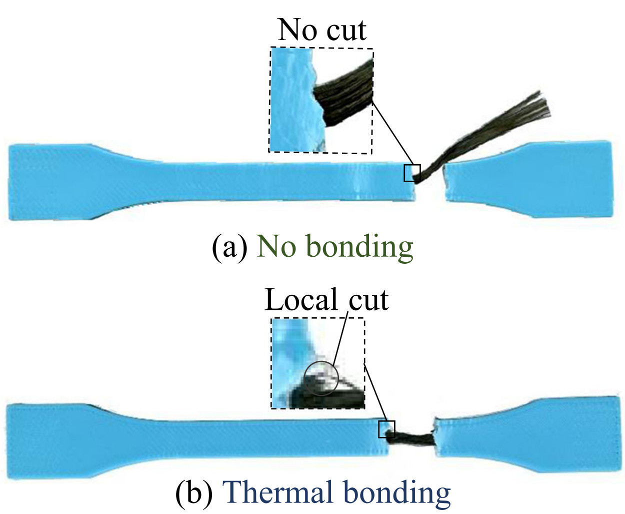


Fig. 7 Ruptured tensile specimens without and with thermal heating for $d = 0.4$ mm

The theoretical tensile strength s_t of the carbon fibre-reinforced plastic specimen is approximately calculated by

$$s_t = \frac{s_c A_c + s_p A_p}{A_c + A_p} \quad (1)$$

where s_c is the tensile strength of the carbon fibre, A_c is the total cross-section area of the carbon fibres in the specimen, $s_{p.}$ is the tensile strength of the ABS, and A_p is the cross-section area of the ABS in the specimen. The theoretical tensile strengths for $d = 0.4$ and 0.9 mm are 103 and 74 MPa, respectively, and these values are considerably higher than those shown in Fig. 6.

The ruptured tensile specimens without and with thermal bonding for $d = 0.4$ mm are given in Fig. 7. For no bonding, the carbon fibres completely slipped from the ABS layers. On the other hand, for thermal bonding, the fibres were locally bonded with the ABS layers, and the bonded fibres were cut.

The cross-sections of the ruptured specimens for $d = 0.4$ and 0.9 mm are given in Fig. 8. The voids tend to occur in the extruded ABS for $d = 0.9$ mm, and thus the strength was

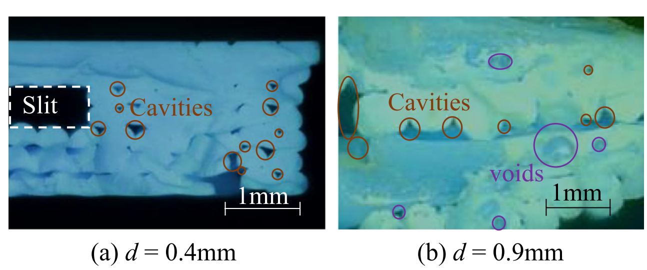


Fig. 8 Cross-sections of ruptured specimens for $d = 0.4$ and 0.9 mm

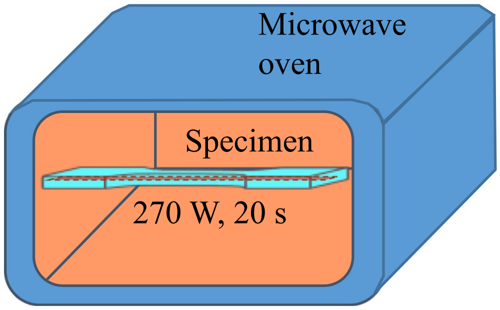


Fig. 9 Thermal bonding using microwave oven

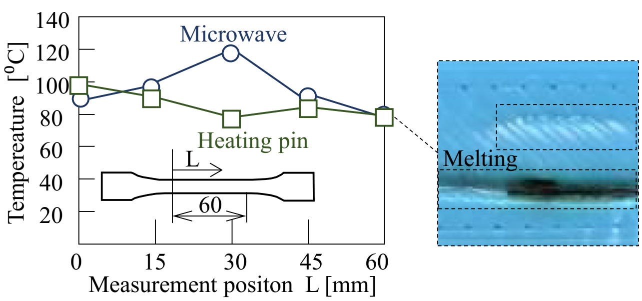


Fig. 10 Distribution of temperature of specimen just after heating

smaller than the specimen for $d = 0.4$ mm due to large numbers of the voids and cavities.

4 Thermal bonding using microwave oven

4.1 Thermal bonding

Although the thermal bonding operation is required for obtaining sufficient strength, the operation using the heating pin shown in Fig. 3(d) is laborious due to local heating. Since carbon fibre-reinforced plastics are heated by a microwave

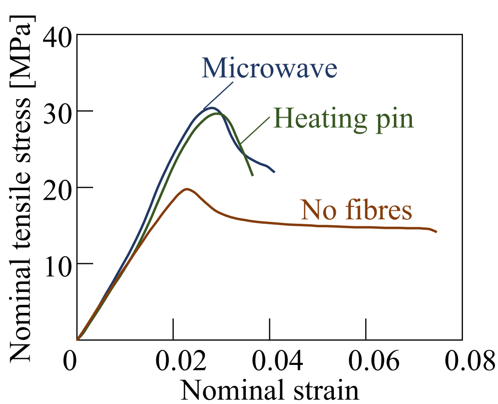


Fig. 11 Nominal stress-strain curve measured from static tensile test of specimen with thermal bonding using microwave oven

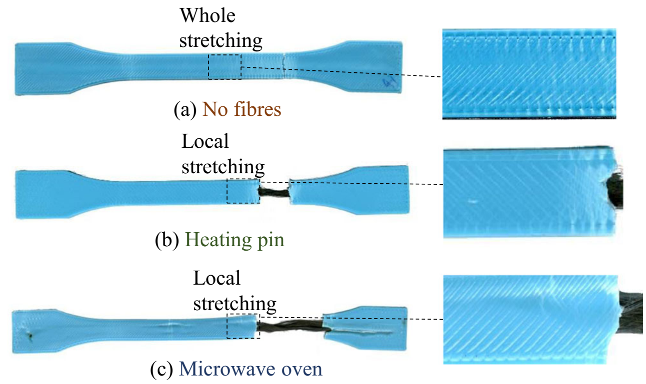


Fig. 12 Ruptured tensile specimens without and with carbon fibres

oven due to electrical conductivity of the carbon fibres [11], the microwave oven was used for thermal bonding. The carbon fibre-reinforced plastic specimen without thermal bonding was heated by the microwave oven for 270 W and 20 s as shown in Fig. 9. The specimen for $d = 0.4$ mm was employed in this experiment because of the high strength.

The distribution of temperature of the specimen just after heating is shown in Fig. 10. The heating temperatures by the heating pin and the microwave oven were almost 100 °C. The surfaces of the specimens were melted above 70 °C in heating using the microwave oven. The heating operation using the microwave oven makes the thermal bonding easy.

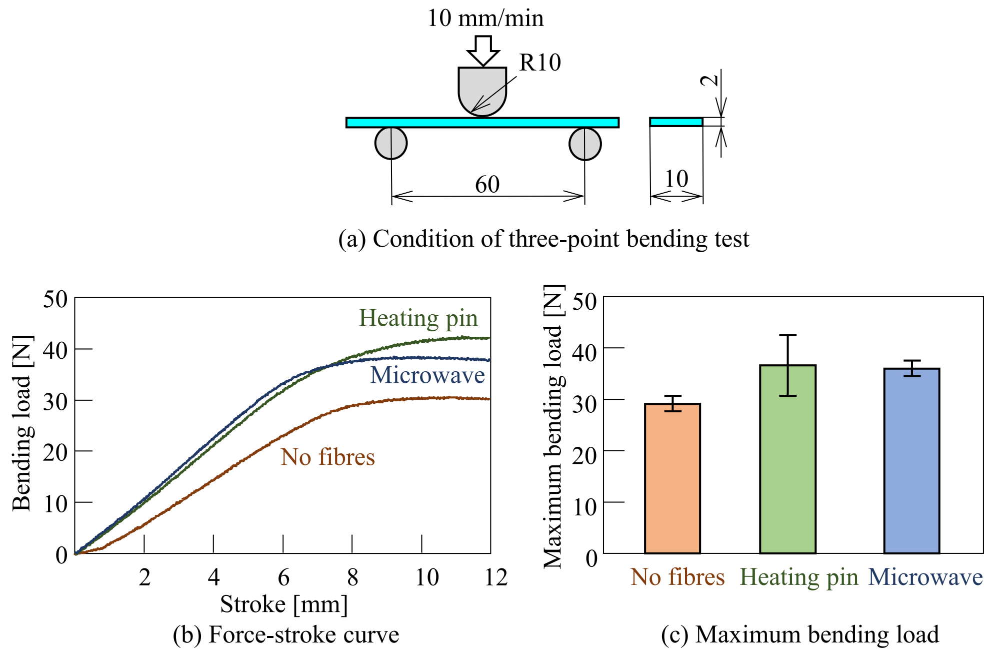
4.2 Results of tensile and bending tests

The nominal stress-strain curve measured from the static tensile test of the specimen with thermal bonding using the microwave oven is illustrated in Fig. 11. The strength of the specimen using the microwave oven is almost similar to that using the heating pin.

The ruptured specimens in the tensile test are given in Fig. 12. In the carbon fibre-reinforced plastic specimens, the ABS layers are ruptured and the carbon fibres are not cut due to the high strength. The strength may be increased by improving bonding the carbon fibres and ABS layers.

The bending force-stroke curve measured from the three-point bending test of the specimen with thermal bonding using the microwave oven is shown in Fig. 13. The specimens were the same with the tensile ones. Due to sandwiching the carbon fibres between the ABS layers, not only the static strength but also the stiffness increases. The maximum bending loads by the heating pin and microwave oven were almost similar. It was found that the strength of the ABS parts is easily increased by the carbon fibres with the microwave oven.

Fig. 13 Bending force-stroke curve and maximum bending force measured from three-point bending test of specimen with thermal bonding using microwave oven



Although the carbon fibres were fully heated with a microwave, bonding of the carbon fibres with the ABS was not sufficient as shown in Fig. 12. Zhou et al. [12] exhibited that the thermal conductivity of plastic is increased by including boron nitride powder. Shimamoto et al. [13] suppressed the thermal degradation at the interface between the carbon fibre and resin matrix using hexagonal boron nitride. Bonding of the carbon fibres with the plastic would be improved by the boron nitride.

4.3 Application to 3D thin parts

The plane specimen was dealt with in the present paper. This technique can be extended to increase the strength of thin parts manufactured by 3D printing as shown in Fig. 14. The lower shell is first produced by 3D printing, then is covered with the carbon fibres, and the upper shell is 3D–printed. Using the fibres in two directions, the strength of the parts is almost isotropic. For long parts such as propellers and wings, the fibres in one direction are effective because of the increase of strength only in the longitudinal direction. Tailored parts are manufactured by a partial cover with fibres.

5 Conclusions

The 3D printing processes are suitable for small-lot and flexible production. Particularly, the application of fused deposition modelling using plastics rapidly expands due to the low cost of the machines. The strength of plastic parts produced by the fused deposition modelling process is increased by being reinforced with carbon fibres. Although the produced tensile specimens were flat, curved parts can be produced by sandwiching the carbon fibres between curved plastic layers. In addition, 3D solid parts can be produced by repeating the sandwiching operations. In this case, the heating operation using a microwave oven makes thermal bonding easy. It is desirable to develop advanced production processes using 3D printing.

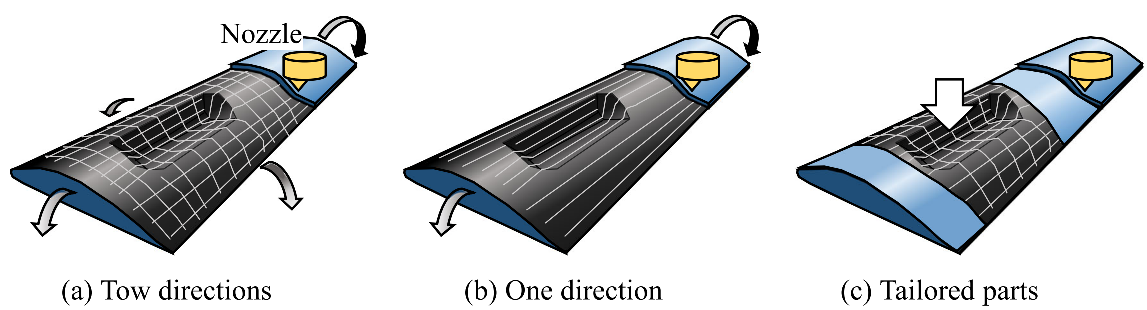


Fig. 14 Application to 3D thin parts for improving strength

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