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Parametric study on design of composite–foam–resin concrete sandwich structures for precision machine tool structures

D.I. Kim, S.C. Jung, J.E. Lee, S.H. Chang *

School of Mechanical Engineering, Chung-Ang University, 221, Huksuk-Dong, Dongjak-Ku, Seoul 156-756, Republic of Korea

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Abstract

In this paper, sandwich structures for micro-EDM machines are optimized by using parametric study varying composite geometries and parameters like stacking sequence, thickness and rib geometry. The structures are composed of fibre reinforced composites for skin material and resin concrete and PVC foam (Closed cell, Divinycell) for core materials. Column structure was designed by a beam with cruciform rib and performance indices such as static bending stiffness (*EI*) and specific bending stiffness (EI/ρ) for dynamic stability are examined by controlling the thickness and stacking sequence of composites. For the machine tool bed, which usually has a plate shape, was designed to have high stiffness in two directions at the same time controlling stacking sequence and rib geometry; that is, rib thickness and number of ribs. The sensitivity of design parameters like rib thickness and composite skin thickness was examined and the optimal condition for high stiffness structure was suggested. Finite element analysis was also performed to verify the static and dynamic robustness of the machine structure. L-shaped joint for combining bed and column of the micro-EDM machine was proposed and fabricated using adhesive bonding. The dynamic performance such as damping characteristics was investigated by vibration tests. From the results optimal configuration and materials for high precision micro-EDM machines are proposed.

Keywords: Sandwich structure; Foam; Micro-EDM; Specific bending stiffness; Rib configuration; Parametric study

1. Introduction

The precision of machine tool components and electronic devices has been being demanded for the better function and performance of final products. As manufacturing technologies develop machine components and parts of electronic devices tend to become smaller for getting multi-function and precise operation of the machines or devices. In special fields like MEMS and nano-scaled manipulation devices, which are needed to guarantee sub-micron precision of motion control, some parts are demanded more complex shapes and smaller size to cope with the requested function. The conventional machine tools such as milling machines come to face their limit to process small size with high precision components because the machining process inevitably has contact condition between tools and work pieces, which induces vibration and heat during the machining causing dimensional changes of the final product. On the other hand, non-contact machining such as EDM (electrical discharge machining) and ECM (electrochemical machining) has strong advantage to get complex and precise products with sub-micron precision. Many researches on the non-contact machining and development of EDM/ECM machines were carried out to enhance the precision and machining quality of various mechanical and electronic components. Masaki et al. [1] succeeded to machine micro hole and shaft with 5 μm diameters and they controlled the precision by 0.1 μm level using micro-EDM machine. Kim et al. [2] developed micro-EDM machine system to manufacture 3-D micro-structures under the size of 300 μm. Lee et al. [3] enhanced the precision of micro-EDM process to fabricate 3-D micro-structures and also reduced processing time for machining by new tool path algorithm. Kim et al. [4] machined various micro shapes like holes, slots and pockets in a few

* Corresponding author.
E-mail address: phigs4@cau.ac.kr (S.H. Chang).

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micrometer sizes using micro-EDM machine. Chae and Lee [5] calculated the wire vibration of WEDM (wire electrical discharge machining) and correlated the relation between the natural frequency and tension of the wire during machining. Because micro-EDM machines are vulnerable to vibration the robustness of the machine structure is one of the essential requirements. In order to improve the dynamic robustness of machine tool structures the polymer based fibre reinforced composite materials, which have high specific stiffness and damping characteristics, have been successfully applied to design machine tools and robot structures with higher performance. Chang and Lee [6,7] developed composite-steel hybrid column and headstock for ultra precision grinding machine. Lee et al. [8] designed and manufactured hybrid boring bar whose dynamic stiffness is 30% higher than that of conventional tungsten boring bars. Jeong et al. [9] analyzed dynamic characteristics of carbon/epoxy composites with respect to the stacking sequence using thin beam-type specimens.

Sandwich structures, which are composed of high stiffness skin materials and lightweight core materials, have higher specific stiffness (E/ρ) and they were verified to have a high specific bending stiffness (EI/ρ) and high damping characteristics by many researchers [10,11]. In order to apply sandwich structures to machine tool bodies successfully several parameters such as thickness of skin material, density of core materials, rib configurations should be considered [12]. In this paper, sandwich structures composed of fibre reinforced composite materials, polymer foams and resin concrete were investigated to design and manufacture micro-EDM machine structures. Parametric study was carried out to find out the sensitivity of each parameter and to determine the appropriate shapes and dimensions of the structures. The prototype of the machine was also manufactured and then vibration tests were carried out to verify the dynamic rigidity of the sandwich structures.

2. Micro-EDM machine structure

Micro-factory, which is composed of several precision micro-machines (see Fig. 1), is designed to process and fabricate ultra precision elements for MEMS and nano-scale manipulation components. Therefore, every part of the system structure including feed mechanism like stages requires high positioning accuracy and machining precision.

The major machine tools composing the micro-factory are micro-EDM and micro-ECM because those machine tools have non-contact condition during the machining, which guarantee high precision machining. But there are several vibration sources like spindle system and wire transfer unit for WEDM. In order to design robust structures for micro-EDM machine sandwich structure which is composed of fibre reinforced composites, polymer foams etc. is proposed. The major structural elements of micro-EDM machine structure are a bed and a column whose configurations are shown in Fig. 2.

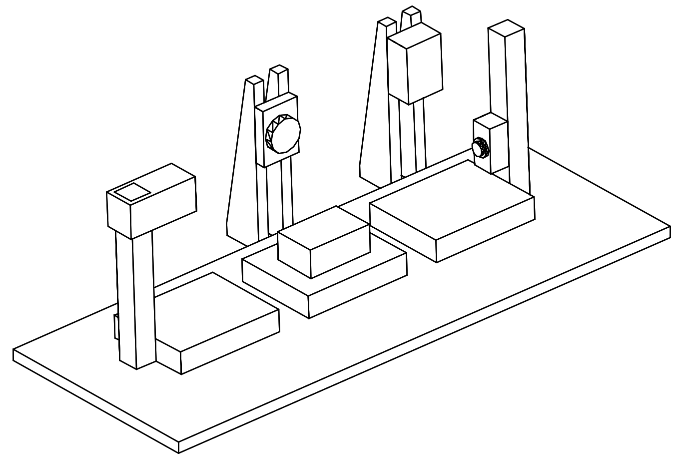

Fig. 1. Concept of a micro-factory system.

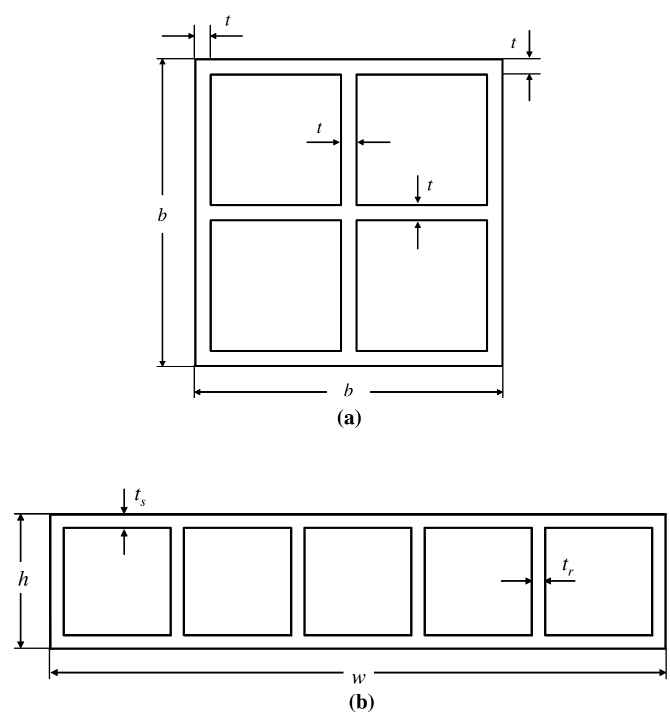

Fig. 2. Proposed sandwich structures for micro-EDM machine: (a) column and (b) bed.

The sandwich structures are composed of fibre reinforced composite as skin material and foam or resin concrete as core materials. The proposed column and bed have cruciform rib or several vertical ribs to enhance bending stiffness. The materials used for design of the sandwich structures and conventional metal materials for comparison are listed in Table 1.

The ply thickness of the prepreg is 0.125 mm and the Young's modulus of carbon fibre/epoxy prepreg used as skin material with respect to the stacking angle was calculated by CLPT as shown in Fig. 3.

Table 1
Major material properties for sandwich structures

Materials	Density (kg/m^3)	Young's modulus (GPa)
USN 125 (carbon/epoxy prepreg, UD)	1550	E_L: 130 E_T: 10
Resin concrete[a]	2207	15
PVC foam (HT90)	90	0.062
Cast iron	7480	138
Aluminium	2800	70

[a] The resin weight fraction of the resin concrete above is 7.5%.

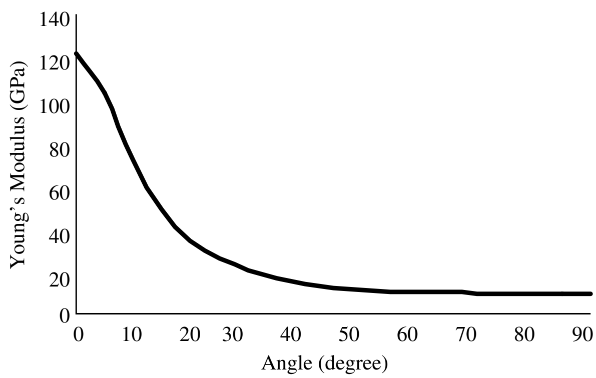

Fig. 3. Young's modulus of carbon/epoxy prepreg with respect to the stacking angle.

3. Parametric study

3.1. Sandwich column with cruciform rib

The bending stiffness (EI) and the specific bending stiffness (EI/ρ) were investigated with respect to the stacking sequence of composites, composite thickness and various core materials to select appropriate materials and their conditions. The PVC foam and resin concrete were considered for core materials and hollow column with cruciform rib was also investigated and compared with others. Several stacking sequences of composites are considered but $[\pm 5]_{nT}$ was selected by taking into account the stiffness of the prepreg and manufacturing efficiency. The equivalent bending stiffness (EI) and the equivalent specific bending stiffness (EI/ρ) of the sandwich column with respect to the composite thickness (t) can be expressed as the following equations:

$$EI(t) = E_s I_s(t) + E_c I_c(t) \tag{1}$$

$$E_s I_s(t) = \frac{E_s}{12}\left[b^4 - (b-2t)^4 + (b-2t)(t)^3 + (t)(b-2t)^3 - t^4\right] \tag{2}$$

$$E_c I_c(t) = \frac{E_c}{12}\left[(b-2t)^4 - (b-2t)(t)^3 - (t)(b-2t)^3 + (t)^4\right] \tag{3}$$

$$\frac{EI(t)}{\rho(t)} \tag{4}$$

$$\rho = \frac{m_s + m_c}{V} \tag{5}$$

$$m_s = [b^2 - (b-2t)^2 + (2t)(b-2t) - (t)^2] \times l \times \rho_s \tag{6}$$

$$m_c = [(b-2t)^2 - (b-2t)(2t) + (t)^2] \times l \times \rho_c \tag{7}$$

where the subscripts s and c represent skin material and core material, respectively. The variables used the above formulae are listed below;

m	mass (kg)
ρ	equivalent mass density (kg/m^3)
V	total volume (m^3)
t	composite thickness (mm)
b	column width (mm)
l	column length (mm)

Figs. 4 and 5 show the bending stiffness and specific bending stiffness of the sandwich column with respect to the thickness (t) of the skin material and sort of core materials when the column width (b) is 20 mm and finally they were compared with those of the conventional metals.

The column made of fibre reinforced composites had the higher bending stiffness (almost two times higher than that

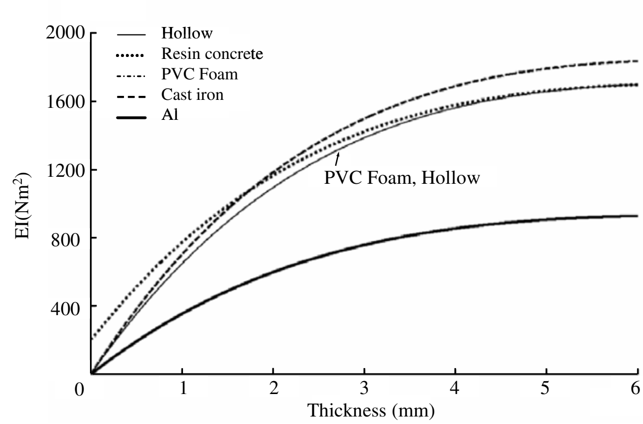

Fig. 4. Bending stiffness of columns with respect to the composite thickness and various core materials.

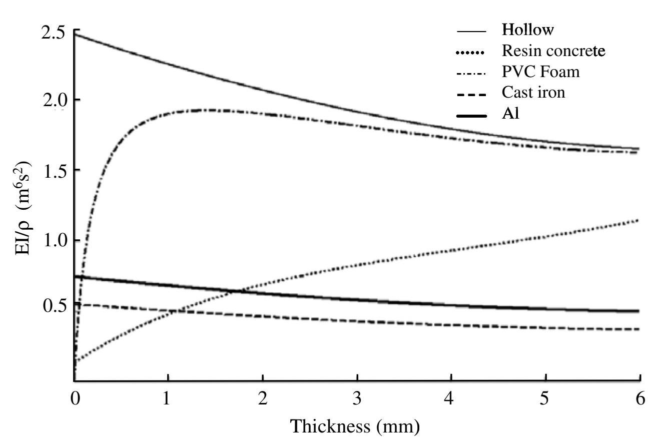

Fig. 5. Specific bending stiffness of columns with respect to the composite thickness and various core materials.

of conventional aluminium column) but it has slightly lower bending stiffness than that of cast iron column. On the other hand, the specific bending stiffness of the composite hollow column had the highest value thanks to the lowest mass density but the hollow beams may generate the lateral surface deformation when they support surface loads. The specific bending stiffness of the composite–foam sandwich column had peak value (more than three times higher than those of the conventional metal columns) around the composite thickness of 1 mm and then decreased slightly because of mass increment. The additional composite thickness does not contribute to the enhancement of specific bending stiffness because the column width (b) is fixed to 20 mm. The specific bending stiffness of composite–resin concrete sandwich column increased monotonously as the composite thickness increased but its value is quite low when the thickness is below 10% (2 mm) of the column width (b). The composite–foam sandwich column was selected because the micro-EDM machine supports relatively small static load but needs to be robust in vibration environment for ultra precision machining; that is, the specific bending stiffness is the most important specification.

In order to find out the natural frequency and mode shape of the composite–foam sandwich column with respect to the column length (l) modal analysis was carried out using ANSYS 9.0. Solid 186 and Shell 99 were used for foam and composite parts, respectively and free–free boundary condition was used for the analysis. When the composite thickness (t) and width (b) are 1 mm and 20 mm, respectively it was found that the vibration mode were changing as the column length increased; that is, diagonal bulging in/out mode ($L \leqslant 100$ mm), twisting mode (100 mm $< L \leqslant 210$ mm) and finally bending mode ($L > 210$ mm). This means the cruciform rib effectively suppresses the lateral surface vibration and bending mode vibration. Fig. 6 shows the twisting mode shape of the model and the natural frequency variation with respect to the column length (l).

Considering all the parametric study and finite element analysis results the column configuration was determined; that is, composite thickness and length are 1 mm and 110 mm, respectively.

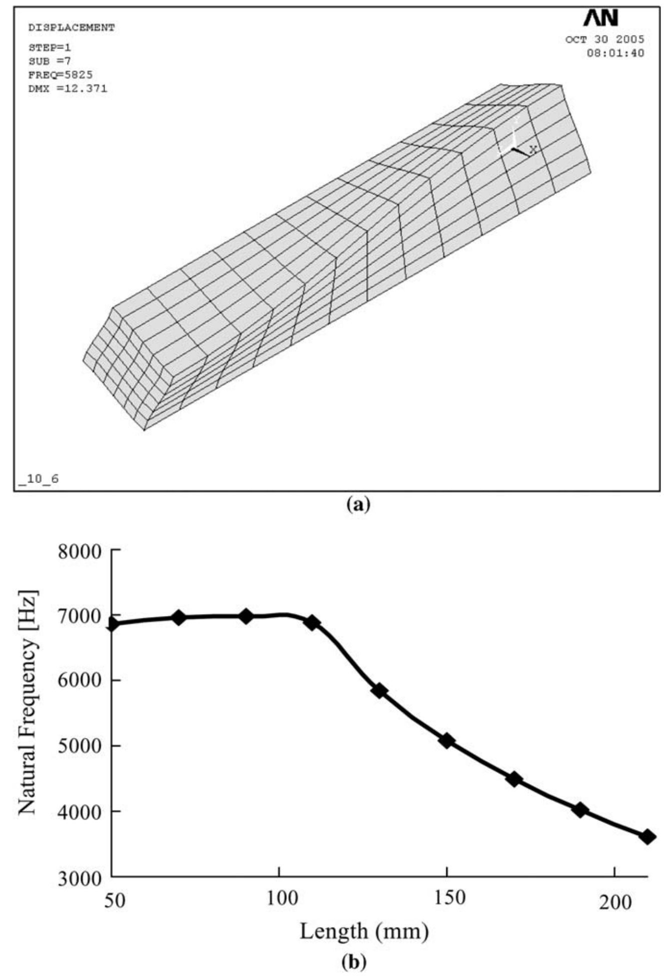

Fig. 6. Modal analysis of the sandwich column: (a) mode shape and (b) the first natural frequency with respect to the column length (l).

3.2. Sandwich bed with vertical ribs

Because beds generally support out-of-plane static load by work piece or working tables the compressive stiffness is important as well as high dynamic stiffness. In order to design a bed structure with high specific stiffness and appropriate compressive stiffness a sandwich thick plate with several vertical ribs was proposed as shown in Fig. 2(b). Being different from slender beams plates should be reinforced in two directions at the same time. The surface plates were designed to have stacking sequence of $[\pm 85]_{nT}$ to resist y-directional deformation and x-axis bending moment and the ribs have stacking sequence of $[\pm 5]_{nT}$ to support y-axis bending moment and out-of-plane compression as shown in Fig. 7. The width (w) and length (L) of the bed were set to be $100 + \alpha$ mm (α is very small and depends on the number of plies stacked) and 120 mm, respectively considering the travelling route and sizes of the machines comprising the micro-factory.

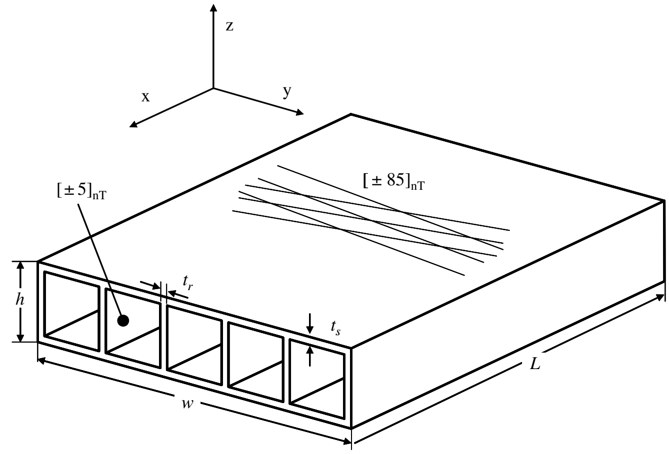

Fig. 7. Sandwich bed structure with several ribs.

In order to determine the number of ribs and rib thickness a preliminary modal analysis assuming that the composite skin thickness (t_s) is 2 mm was carried out. From the analysis it was found that the vibration mode of the first natural frequency was twisting mode and the frequency was mainly affected by rib thickness when the bed has a few ribs ($\geqslant 3$) as shown in Fig. 8. Considering the calculation result four ribs were proposed for the sandwich bed.

The thickness of rib (t_r) and composite skin thickness (t_s) were determined by investigation of the natural frequency and deflection under out-of-plane compressive force (50 N). Fig. 9 shows the first natural frequency with respect to the rib thickness and composite skin thickness. The twisting mode was found to be the first mode and it was found that the rib thickness affected more on the dynamic stiffness of the structure. From the analysis results the first natural frequency of the sandwich bed almost saturated at the region between 1.0 and 2.0 mm of composite skin thickness (t_s) for all the rib thicknesses considered in this analysis.

For the case of thin composite skin ($t_s \leqslant 0.5$ mm) the first natural frequencies decreased as the rib thickness (t_r) increased because the thicker ribs are hardly able to resist the twisting vibration properly but increases mass of the structure.

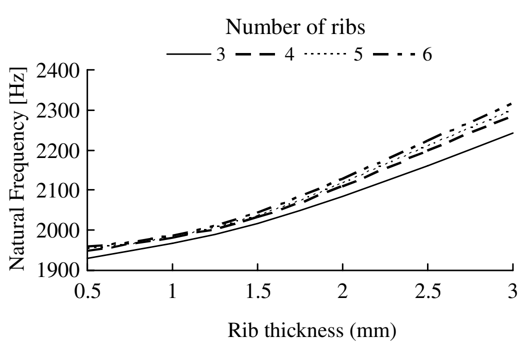

Fig. 8. The first natural frequency of the sandwich bed with respect to the rib thickness and number of ribs.

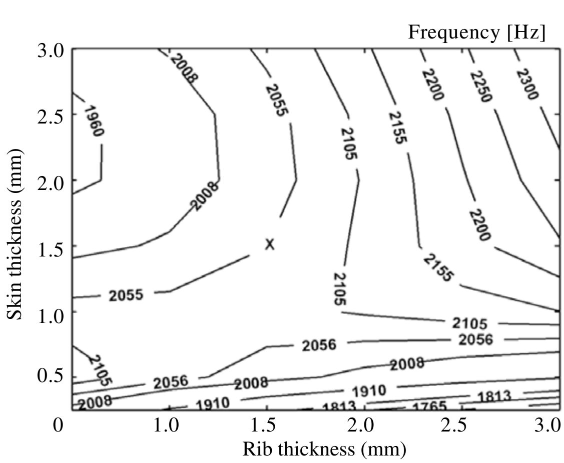

Fig. 9. The first natural frequency of the sandwich bed with respect to the rib thickness and composite skin thickness.

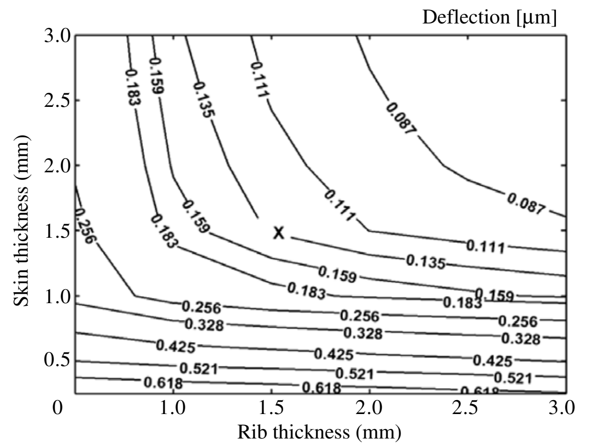

Fig. 10. The deflection of the sandwich bed with respect to the rib thickness and composite skin thickness.

The maximum deflection due to the out-of-plane force with respect to the rib thickness and composite skin thickness was also calculated. As shown in Fig. 10, the deflection of the sandwich bed abruptly decreased after the thickness of composite skin of 1.5 mm and then saturates for all the rib thicknesses. And the deflection was also saturated when the rib thickness is around 1.5 mm for relatively thick composite skins ($t_s \geqslant 1.0$ mm).

With the results of the above finite element analysis the composite skin thickness (t_s) and rib thickness (t_r) were determined as 1.5 mm and 1.5 mm, respectively.

4. Manufacturing of the structures

Composite–foam sandwich column and bed were fabricated using PVC foam (HT90) and carbon/epoxy prepreg

Fig. 11. Fabrication of the sandwich column with a mould.

by autoclave de-gassing moulding. After stacking prepregs with the stacking sequence of $[\pm 5]_{2T}$ on the foams, whose cross section was machined in size of $9 \times 9\ mm^2$, those four beams were stacked together in 2 by 2 array and then prepregs whose stacking sequence is $[\pm 5]_{2T}$ was wrapped around the beams and put it into the mould (see Fig. 11) and cured in an autoclave.

The composite–foam sandwich bed was also manufactured. After curing 5 sandwich beams, which are composed of PVC foam and composites with the stacking sequence of $[\pm 5]_T$ for top and bottom surfaces and $[\pm 5]_{3T}$ for side surfaces (see Fig. 12), and then they were bonded in a row to construct vertical ribs. The prepregs with the stacking sequence of $[\pm 85]_{5T}$ were stacked on the outer surface of

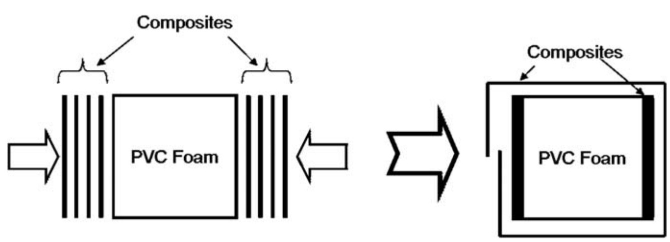

Fig. 12. Stacking process of sandwich beams for sandwich bed fabrication.

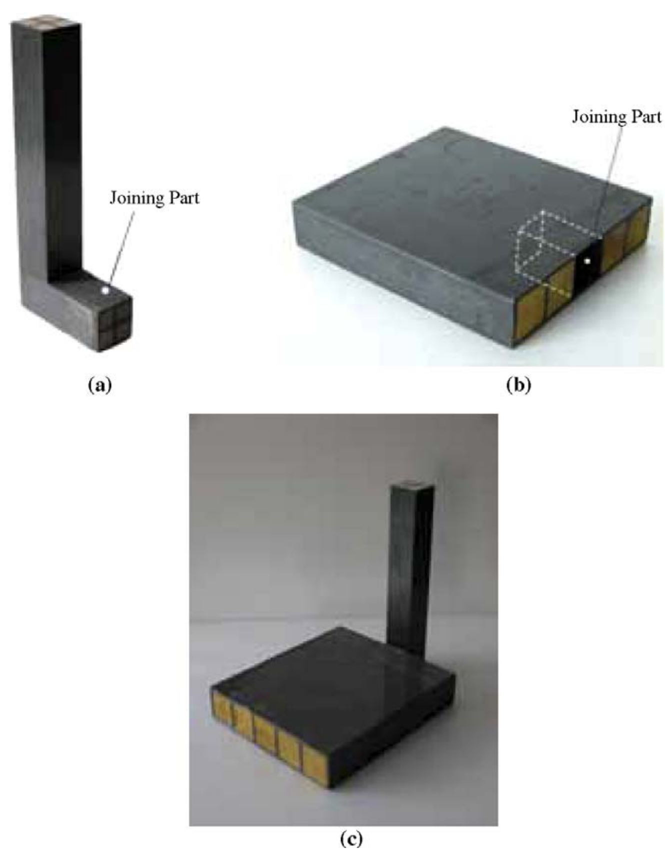

Fig. 13. Sandwich structures for micro-EDM machine: (a) column, (b) bed and (c) assembly.

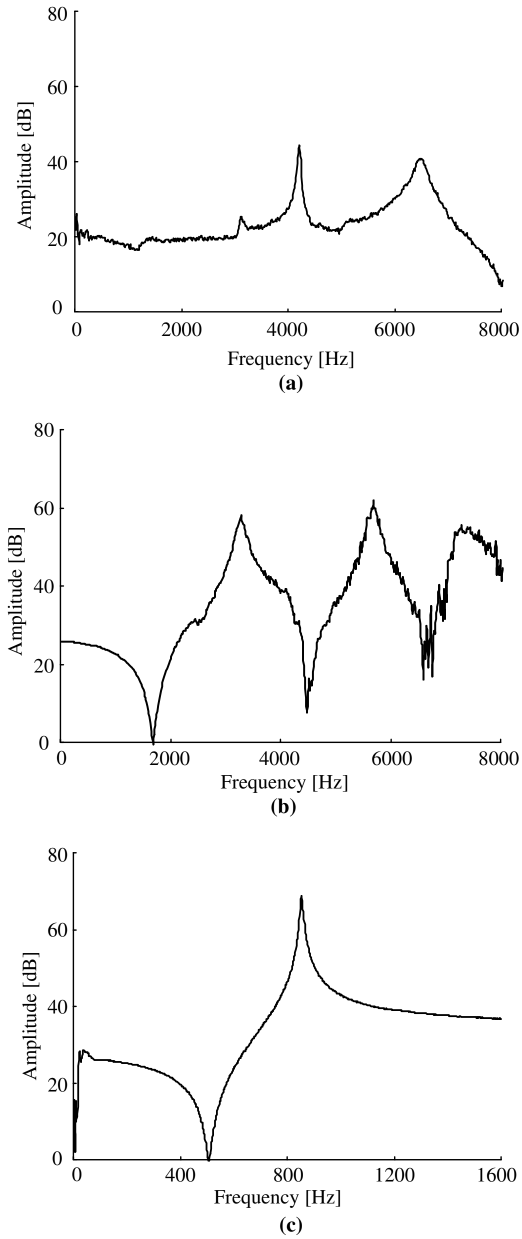

Fig. 14. FRF of columns and beds: (a) column, (b) bed and (c) assembly.

Table 2
The first natural frequencies and damping ratios of sandwich structures before and after assembly

		1st natural frequency (Hz)	Damping ratio
Before assembly	Bed	3280	0.0086
	Column	4208	0.0051
After assembly	Bed	856	0.0106
	Column	856	0.0060

the combined beams to complete the sandwich bed with four vertical ribs and then cured using aluminium mould.

In order to assemble the column and bed structures the column was modified to have L-shaped joint at one of the ends of the sandwich column by adhesive bonding with a short sandwich beam. To overcome the stiffness degradation at the bonding part composite laminates were reinforced

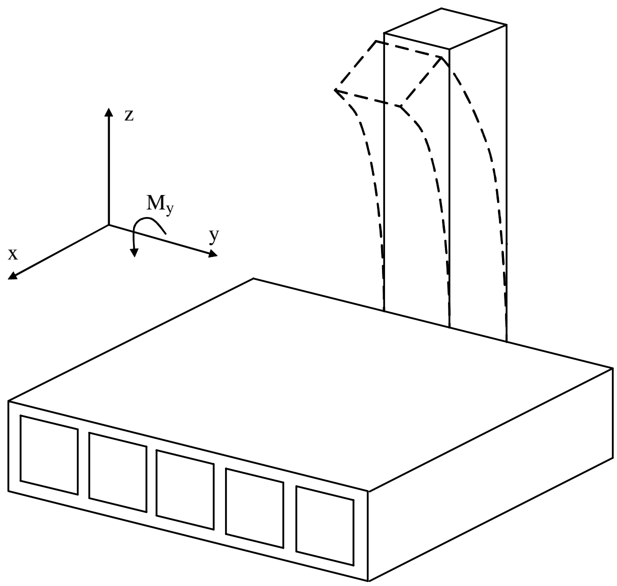

Fig. 15. Mode shape of the assembled structure.

over the joint part and then the L-shaped column was assembled with the bed structure by adhesive bonding. Fig. 13 shows the fabricated sandwich structures for micro-EDM machine structure. The total system mass composed of sandwich column and bed structures is 167 g.

5. Vibration tests

In order to investigate the dynamic characteristics of sandwich structures vibration tests with free–free boundary condition of the composite sandwich structures were carried out. The natural frequencies and damping ratios were measured and compared with each other. Fig. 14 shows the FRF (frequency response function) of the composite sandwich column, bed and the assembled structure. The first natural frequencies and their damping ratios of the sandwich structures are listed in Table 2.

The measured first natural frequency, which is y-directional bending mode (M_y; see Fig. 15) of the column, are lower than those from the components before assembly (see Table 2) because the boundary conditions have changed (free–free to semi-clamped) for the assembly but the damping ratios increased due to the adhesive bonding.

6. Conclusion

In this paper, a micro-EDM machine structures were designed and manufactured with composite–foam sandwich structures. The stacking sequence and specifications of composite skin material of the sandwich column with cruciform rib were determined by investigating of the specific bending stiffness (EI/ρ) and so on. Machine tool bed, which is also composed of carbon/epoxy prepreg and polymer foam, was designed to have high stiffness in two principal directions in x–y plane controlling the stacking sequence of the skin material and vertical ribs. The number of ribs and rib thickness were determined by considering the first natural frequency and the maximum deflection due to the out-of-plane compressive force using finite element analysis. The sandwich structures were fabricated using appropriate moulds by autoclave de-gassing moulding and the fabricated sandwich column and bed were assembled by adhesive bonding using L-shape joint part. The vibration tests were also carried out to verify the dynamic stiffness and damping characteristics of the sandwich structures.

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