ÓBUDAI EGYETEM
ÓBUDA UNIVERSITY
A MAGYAR TUDOMÁNY ÜNNEPE
Az MTA programsorozata
Engineering Symposium at Bánki
(ESB 2025)

A multifunctional and modular drill-measuring fixture for testing the machinability of fibrous polymeric composites and their sandwich structures

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Abstract

Fibre-reinforced polymer (CFRP, GFRP, BFRP) composites and their sandwich structures are very popular due to their outstanding specific strength and low weight. Many high-tech industries apply these composites, such as the ship, aerospace, military, and automotive. Although these fibrous composites are widespread and frequently used, there are many shortcomings and challenges in their machining, compared to metals. Considering that the machinability investigations require special fixtures, there is no suitable commercially available fixture that is capable for collecting multiple datasets. Therefore, the main goal of this work was to systematically design a multifunctional and modular drill-measuring fixture capable of performing cutting force, cutting torque, cutting temperature, burr, and vibration measurements. As a result of this study, a multifunctional and modular drill-measuring fixture is proposed to support further machinability investigations in fibrous composites and their sandwich structures.

Keywords: Fixture, Drilling, Design, Composite, Sandwich panel

1 Introduction

Carbon fibre-reinforced polymer (CFRP) composites are widely used in several industries with great preference [1]. A few areas where fibre-reinforced materials are playing an increasingly important role are automotive, aviation, and space technology [1]. Good specific mechanical properties, such as an excellent weight-to-strength ratio, make these fibrous composites suitable for use in high-end industries [1][2]. The composite elements can be shaped almost completely ready at the end of the pre-manufacturing operation (*e.g.,* by lamination or compression moulding), but holes, fitting surfaces, and other advanced geometrical features have to be machined to meet required dimensional tolerances [1]. These machining operations are difficult to plan and require a lot of time to implement, and are also expensive [1][2]. Undesirable damages such as delamination, burrs, or fibre pulled-outs of the composite structure may occur during the machining processes [1][2][3]. These machining-induced defects need to be eliminated or at least minimised.

Influences of machining parameters have already been investigated in numerous studies [4][5], [6][7][8][9]; however, the response parameters (*i.e.*, cutting force, cutting temperature, tool vibration, *etc*.) are usually not measured in-situ because of the lack of an appropriate fixturing setup. The in-situ measurement of these parameters would make the cutting process monitorable, thus the probability of machining-induced geometrical defect formation can be minimised.

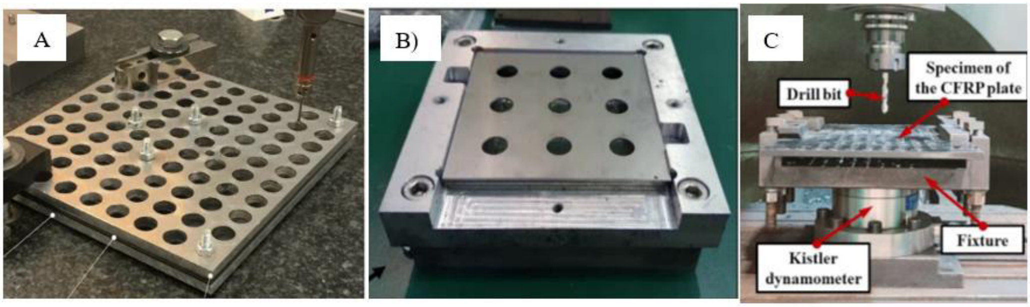

Figure 1. Fixtures applied by researchers: A) support plates below and above the composite workpiece [4], B) back-up support of the composite workpiece [5], C) General fixture [6]

Geier et al. [4] applied a drilling fixture capable of fixing a composite plate and supporting the top and bottom layers of composite against buckling (see **Fig. 1A**). This fixture was also used to measure macro geometrical properties by using a coordinate measuring machine (CMM). Although this fixture is multi-functional, it fails to allow collecting cutting temperature and vibration raw data simultaneously. Although the fixtures used by Seo et al. [5] and Xu et al. [6] (illustrated in **Fig. 1B** and **Fig. 1C,** respectively**)** are capable of measuring cutting force and torque, they neither allow to capture images from the bottom side of the composite plates, thus making these setups inappropriate for cutting temperature measurement through a thermal camera. Considering that the hole entry is visible, the entry delamination can be measured accordingly.

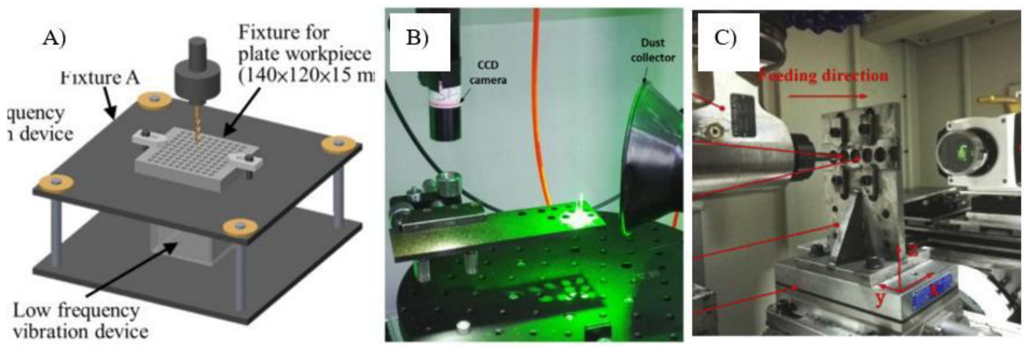

Figure 2. Fixtures applied by researchers: A) Fixture for force and vibration measurement [7] B) Experimental setup for CCD camera data collection [8] C) Experimental setup for measureing cutting force and cutting temperature through thermo camera [9]

The fixture illustrated in **Fig. 2A** [7] is able to detect and interpret force and vibration signals. The fixture is equipped with a dynamometer and a low-frequency vibration device. The main examined parameter is the vibration depending on the thrust force. Only thin structures can be measured due to thickness limitations. Although the vibration can be measured, but only in one direction. The experimental setup illustrated in **Fig. 2B** [8] was applied to test CFRP drilling-ability with a picosecond laser and double rotation technique. The picosecond laser cuts holes in the specimen and collects the respirable dust. After the machining, a CCD camera inspected the holes. The fixture illustrated in **Fig. 2C** [9] was applied to measure the drill-exit temperature and the cutting force. The machining directions are also different from the previous ones, which in this case is horizontal.

Considering that the reviewed composite fixtures fail to be able to collect multiple information on the machinability of composites, the main goal of our work is to develop a multifunctional and modular drill-measuring fixture for testing multiple indicators of machinability in sandwich structures, such as cutting force, vibration, cutting temperature, and machining-induced damages through visual inspection.

2 Description of the novel multifunctional and modular fixture

Considering the advantageous features and solutions of the reviewed fixtures, and their lacks, a list of requirements was collected first. These conditions are ranked based on importance and risk. We selected the list of requirements from among the prepared ideas. We discarded or transformed inappropriate concepts.

2.1 List of requirements

The main design parameters and the requirements based on the risk and severity/priority were collected in Table 1. We made seven main requirement categories, such as geometry, load, measure, safety, installation, transport, and maintenance. All the main categories contain at least one requirement. After careful consideration, seventeen points of requirement were made. Most of the requirements are in the geometry category. The strictest requirements were given by geometric and economic aspects. During the design phase, the device was designed in such a way that it could not cause damage to users easily. It is necessary to close the door of the machining center to start the machining, thus also helping to increase safety.

Table 1. List of requirements

Category	ID	Requirement Name	Description	Information	Priority
Geometry	Req 1	Test specimen thickness	The ability to test more specimens with different thicknesses	2-40 mm	High
	Req 2	Fixture size	Maximus dimension of the fixture, because of the measuring range	100x170 mm	High
	Req 3	Maximum high	The maximum height of the fixture	510 mm	High
	Req 4	Orientation	Orientation for machining	Vertical milling/drilling	High
	Req 5	Weight	Need to be optimal for better manageability and operation		Medium
	Req 6	Connection	Connection with the machining	M8	High
Load	Req 7	Z-axis normal pressure	The ability to resist the load, the specimen can't be deformed or destroyed	19 MPa	High
	Req 8	Z-axis rotation	The specimen needs to be fixed correctly in the fixture	2 Nm	High

Category	ID	Requirement Name	Description	Information	Priority
Measure	Req 9	Vibration measure	The ability to attach vibration measurement sensors	Brüel & Kjaer 4518-001	High
	Req 10	Temperature measure	During the milling necessary to monitor the temperature	VarioCAM HDx	High
	Req 11	Force measure	During the milling, the force needs to be registered	Kistler 9257B	High
	Req 12	Microscope	to make pictures and check the surface quality	Dino-Lite AM4013M(Z)T	High
Safety	Req 13	Touch protection	The fixture cannot be touched during the machining process	Instructions	Low
	Req 14	Cut resistance	The safety of the operation crew	Instructions	Medium
Installation	Req 15	Easy to assemble	The fixture needs to be easily assembled	Geometry and instruction	High
Transport	Req 16	Move by hand	The fixture must be lightweight for manual movement	Optimalization	Medium
Maintenance	Req 17	Durability, maintenance	The used materials guarantee long life and low maintenance	Material usage and surface treatment	Medium

2.2 Presentation of the fixture

The optimised and finalised geometry of the developed multifunctional and modular drill-measuring fixture can be seen in **Fig. 3.** This solution proved to be suitable in all conditions listed in **Table 1.**

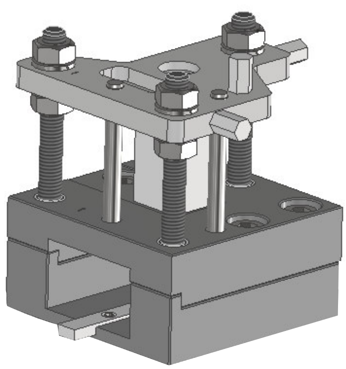

Figure 3. Final geometry of the developed multifunctional and modular drill-measuring fixture

Machining the base structure (*i.e.,* **No 2** and **No 3** parts in **Fig. 4**) would be expensive if it was conventionally machined, so it is necessary to split it into two parts so it can be easily produced in a machining centre by conventional milling technology. In **Fig. 4,** we marked the parts of the fixture. In **Table 2,** the names of the marked parts were collected.

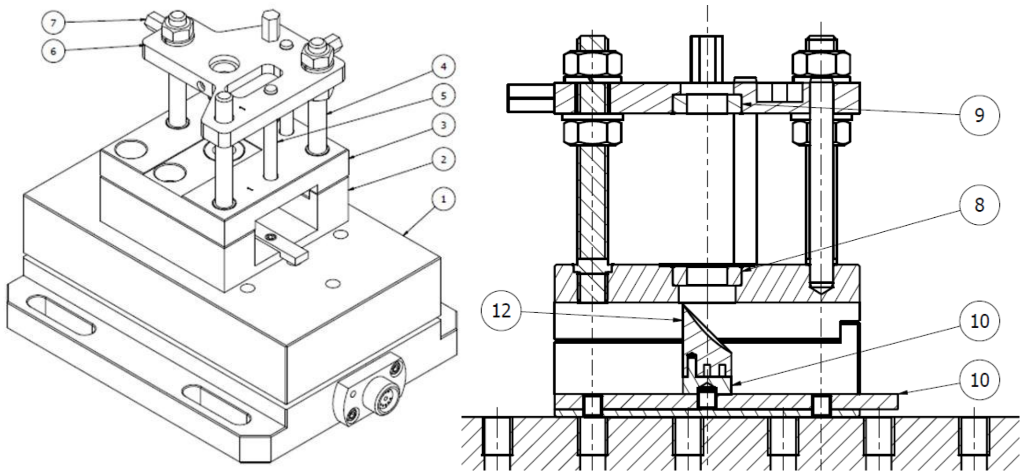

Figure 4. Drilling components, where the marked component names are listed in Table 2

Table 2. Marked components

No	Name
1	Force measure cell
2	Lower fixture
3	Middle fixture
4	Threaded spindle
5	Leading pin
6	Upper fixture
7	Axial vibration sensor
8	Lower delamination ring
9	Upper delamination ring
10	Lens stand
11	Lens holder rail
12	Infrared lens
13	Support frame
14	Spindle
15	Led track
16	Led buffer
17	Lower led wand
18	Upper led holder

The multifunctional and modular drill-measuring fixture is composed of 12 parts and structured as follows. The lowest part (**No 2**) of the fixture is assembled into a KISTLER dynamometer (**No 1**) with four M8 bolts. The dynamometer is responsible for measuring the machining force. The middle fixture (**No 3**) is screwed through the lower fixture (**No 2**) connected to the force measure cell. These two parts are geometrically centered. The top of the middle fixture will hold and position the specimen. The upper fixture part (**No 6**) is responsible for the transmission of clamping force, which is applied with the threaded spindle (**No 4**). The leading pin (**No 5**) centralizes the moving upper fixture to the middle fixture to ensure identical fixturing of the upper and lower parts of the composite specimen. The axial vibration sensors (**No 7**) are positioned on the upper fixture. Sensors collect data from all three directions of the space during the machining, which we process with the help of a computer. The fixture contains delamination rings (**No 8-9**) aiming to hold the specimen and keep the laminated fibres in and minimise the delamination. A lens (**No 12**) and its holder (**No 10-11**) are positioned below the composite specimen. The infrared lens has a special coating on its surface, and it changes the light path of the infrared camera, which is out of the machining station for safety. The lower fixture has a groove to guide the lens holder component. The assembly contains ISO 4032 M8 nuts and ISO 7089 8 washers to move the upper fixture and apply the preload force.

The LED measurement set-up can be seen in **Fig. 5,** and its components are in **Table 2**. We disassemble the preparation until only the base remains (**No 1-3**). Place the support frame (**No 13**) on the force measure cell (**No 1**) and make it abut against the base components (**No 2-3**). Fix the spindles (**No 14**) in the frame (**No 13**) with the help of the flattening, then put the M8 screws on them. The led track (**No 15**) can be attached to the screws on the spindles (**No 14**). The LED buffer (**No 16**) can also be installed using the groove in the lower fixture (**No 2**). Once everything is installed, the only thing missing is the units holding the two LEDs (**No 17-18**).

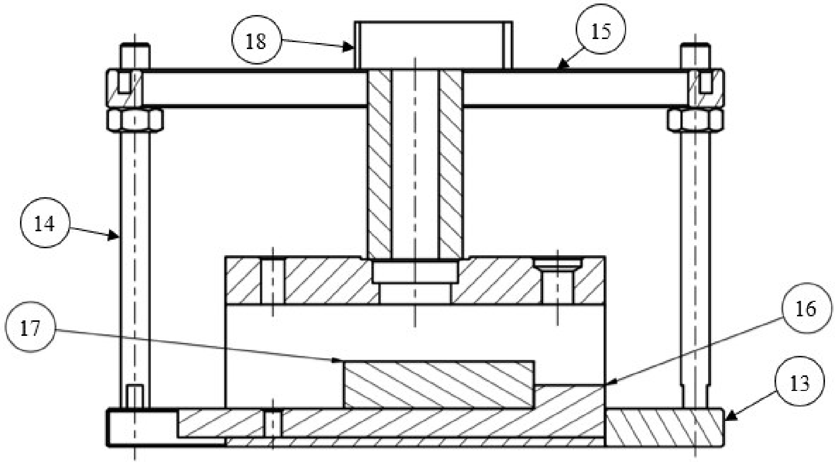

Figure 5. LED assembly components

2.3 Application of the development fixture

The fixture operation workflow can be seen in the **Fig. 6**. The fixture has to be applied according to this workflow in order to minimise error.

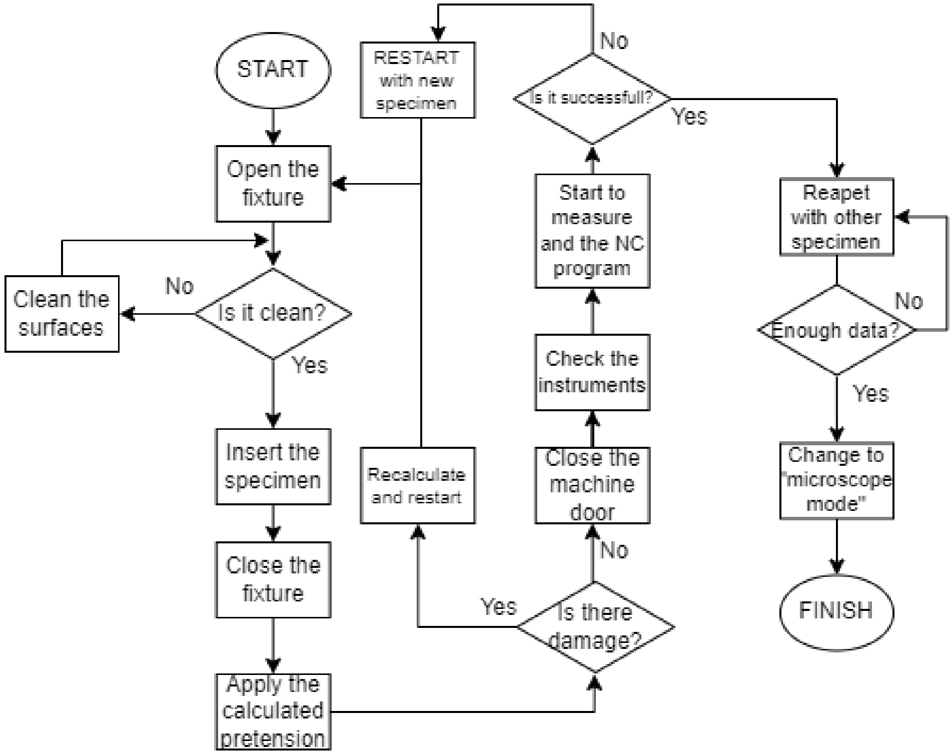

Figure 6. Operation workflow

The first step is to open the fixture. If the surfaces are dirty (*i.e.,* contain shavings, emulsion, or other kinds of contamination), it is necessary to clean them. After cleaning, check the cleanliness again; if it is not adequate, repeat the cleaning process. In the case that they are clean, the test specimen can be inserted into the device with the help of the grooves in the position to be fixed. After insertion, the pre-calculated pretension force (expressed by **Eq. (1) and (2)**) must be applied for fastening.

$$F_{max} = \sigma_{allowed} \cdot A \tag{1}$$

$$M = F_{max}\left[\frac{d_2}{2} \cdot tg(\alpha + \rho') + \frac{d_a}{2}\mu_a\right] \tag{2}$$

Where the notations are defined in **Table 3**. It is worth checking the instruments. If everything is in order, the NC program required for machining the specimen can be started. If the program has run correctly and the data has been recorded, the measurement can be performed on other samples. If an error has occurred, the entire process must be restarted with checks and calculations. With sufficient processing data, the fixture can be converted to a microscopic assembly for further examination. After taking the microscopic images, the fixture must be cleaned and disassembled for safe storage.

Table 3. Calculation symbols

Notation	Name	Current values
A	Contact surface	331.41 mm^2
d_a	Nut center diameter	10.175 mm
d_2	Thread center diameter	7.188 mm
F_{max}	Maximum force	-
M	Torque	-
α	Pitch angle	3.168°
μ_a	Coefficient of friction	0.6
ρ'	Apparent friction half-cone angle	3.168°
$\sigma_{allowed}$	Permissible tension limit	Material catalogue

3 Discussion of limitations and future scope

We are capable of measuring multiple machinability indicators of different composite structures using the proposed fixture. The fixture is able to collect three types of machining parameters (force, temperature, vibration) at every specimen in-situ.

The developed fixture is suitable for determining, testing, and optimizing machining parameters in a wide range. The assembly is capable of high-precision measurement of several parameters (*i.e.,* cutting force, vibration along each axis, cutting temperature, machining-induced delamination, microscopic analysis, *etc.*). The collected data also make it possible to compare different material structures and laminates. The fixture enables data collection of this level and quality with one capture. However, the presented fixture is not suitable for testing structures larger or smaller than specified in the list of requirements (**Table 1**). Below the defined lower limit, the captured sample could resonate, while the larger specimen would exceed the capacity of the system. Furthermore, the effect of environmental influences (environmental temperature, humidity) on the test specimen cannot be controlled; considerable attention has to be paid to keep them at a constant level/setup.

One of the main advantages of the developed fixture is that the device is highly complex and suitable for collecting a large amount of machining data. The modularity of the device allows it to be used in the environment of drilling, milling, coordinate measuring devices, and microscopes. The instruments in the fixture can be replaced with a range of measurements. A considerable disadvantage is the speed of use when it comes to changing test specimens. The production cost of the fixture exceeds the price of conventional fixtures. The device will only be suitable for carrying out measurements; it will not be able to produce products.

In order to function properly, a lot of emphasis must be placed on maintenance. The instructions for use must be strictly followed to avoid personal and property damage. Due to page limitations, these regulations are not presented; however, they can be provided upon request. In the future, considerable attention should be done on the improvement of handling/operation time and own weight. Furthermore, its automation (*e.g.,* hydraulic, electric motor clamping and fixing) would be helpful to spread the use of the fixture in industry.

4 Conclusion

In the present study, a novel multifunctional and modular drill-measuring fixture is introduced that is capable of testing the machinability of sandwich structures. According to the present study, the following conclusions can be drawn:

- The developed multifunctional and modular drill-measuring fixture is suitable for determining, testing, and optimizing machining parameters in a wide range. The fixture makes an appropriate environment to collect cutting force, cutting temperature, and vibration data simultaneously. Furthermore, it provides a uniform mechanical support of the entry and exit sides of the workpiece.
- The application of the novel multifunctional and modular drill-measuring fixture was proposed for determining the machinability indicators of composite materials, especially carbon fibre reinforced polymer (CFRP), glass fibre reinforced polymer (GFRP), basalt fibre reinforced polymer (BFRP) composites; and for sandwich structures (*e.g.,* Al/CFRP, Ti/CFRP) no thicker than 40 mm.
- Although the developed multifunctional and modular drill-measuring fixture can be widely used, its drawbacks and limitations have to be considered and become the focus of further research, *e.g.*, minimising the own weight of the fixture elements, automatization of the fixturing operations by applying pneumatic or hydraulic systems, and analysis of the effect of environmental temperature on the applicability of the fixture.

Acknowledgements

This research was implemented thanks to the support of the 2021-1.2.4-TÉT-2021-00050, which encourages scientific and technological cooperation between USA and Hungary; and the 2021-1.2.4-TÉT-2021-00051, which encourages scientific and technological cooperation between China and Hungary. The development is also supported by the New National Excellence Program of the Ministry for Innovation and Technology No. ÚNKP-23-5-BME-409.

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