NOVEL CONCEPT OF THREE-DIMENSIONAL (3D)
THICK COMPOSITE STRUCTURE FROM PITCH BASED
CARBON FIBRE FOR MACHINE TOOL APPLICATIONS

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SUMMARY
A new composite structure has been developed particularly for thick walled or nearly solid beams with a maximized bending stiffness (e.g. spindle beam for machine tool application). The structure is based on 3D axially oriented cells with up to 80 % axial fibres. Their properties against unidirectional composites are improved significantly especially in transverse directions. The structure has been applied to the prototype of a machine tool spindle beam

Keywords: three-dimensional composite structure, pitch based carbon fiber, ultra high modulus, graphite fiber, beam, bending stiffness, machine tool.

INTRODUCTION
Research and development work for the application of composites in the area of machine tools is not new. Different research centres like VCSVTT Prague [1], RWTH Aachen [2], Republic of Korea [3] or Cambridge University [4] started to work on application developments with the increased availability of high modulus fibres over last 15 years. The first motivation to apply composites in the machine tool or machine building industry is to increase machine performance. This is achieved by weight reduction of machine parts and by increasing stiffness in the main load direction by using high modulus fibres. The improvement of these two properties will transform the vibration characteristics of the machine part and using the high modulus fibres it is possible to significantly increase the natural bending frequency over conventional materials.

CompoTech has a long experience in the application of carbon-graphite high modulus fibres in the machine building industry, especially in the area of light automation. CompoTech has developed a technology to design and manufacture long square beams with high bending stiffness. These beams (see Fig 1) are made conventionally by automated lamination of thin layers around square mandrel and then consolidated in press mould. The wall thickness of such beams varies from 3 to 15 mm. These beams
are then integrated to the machine systems, like linear guides, flanges to connect with other parts, power lines for pneumatics, hydraulics and control electronics. All these systems are conventionally requiring extensive drilling in the composite structure of the beams and this requires detailed engineering and analysis so that life time of the product is properly designed. All this has an effect on product cost.

The same problems which were overcome by the application of graphite fibre beams in the area of machine building in the automation market sector can be seen in the machine tool applications. There is however, one big difference. The parts are considerable bigger in size and there is greater need for overall precision and quality of integration with other parts, for example linear guides.

A good case is, for example, the spindle beam of a heavy vertical CNC lathe (see Fig 2). This is generally a long simply supported beam. The overall machine performance is a function of the dynamic bending stiffness and stability of this beam. To design and manufacture such a part from graphite fibre composites and using conventional production technologies there will be two basic problems. 3D stresses in the thick walled laminate and problems with joining to other, mostly steel, parts.

CompoTech illustrates here a solution for both problems..

**INTEGRATION TECHNOLOGY FOR JOINING**

CompoTech has been developing integration techniques for many years. One of the first parts developed using this technique was a hydraulic cylinder (see Fig 3). It is a nice example to explain the philosophy of this technology: i.e. to integrate the connection of other parts (usually of isotropic material) using the fibres so that any fibre cutting or a pure shear adhesion joint is avoided.
In the case of a hydraulic cylinder, the fibre loops were made in one process at the end of the carbon fibre cylinder tube. Steel bolts were used for pinning the cylinder to the steel or titanium end. This technique produces a high performance joint that has twice the holding strength of an equivalent glue joint, as well as delivering a smart solution produced in one operation.

In the case of the spindle beam for a CNC machine tool, the critical parts to join are the linear guides at the corner of the beam. The CompoTech solution (see Fig 4) is based on integration of a composite tube in the beam structure and holes formed in the process for screwing on the linear guides. Fasteners are screwed in to a steel bar, which is inserted in to the corner tubes after curing. This steel bar has enough surface area to
distribute loads from beam to linear guides or vice versa. There is another composite tube integrated into the structure for systems like power for the spindle or cooling oil for the tool.

**Figure 4: Integrated joint – linear guide in composite beam.**

**3D CELL STRUCTURE**

CompoTech has developed a 3D cell structure as an answer to the problems of transverse and inter-laminar stresses especially in thick walled structures. This structure has cells containing unidirectional fibres coaxial with the centreline of the beam whose cell walls are made from fibres wrapped around the cells at one or more selected angles, usually somewhere between 45° and 89° to the cell direction.

**Figure 5: 3D cell structure.**

This 3D cell structure has been used for the first time in a prototype of a spindle beam made for the Centre of Manufacturing Technology at Czech Technical University in Prague. The use of the 3D cell structure enables the integration of corner tubes for connecting with linear guides. The transverse loads from the threaded bar (see Fig 4) at
the beam corners are dissipated into the beam structure via the cell borders of off axial layers, thus allowing there to be a high volume of axial fibres inside the cells.

**SPINDLE BEAM APPLICATION**

The spindle beam prototype was built to replace an existing steel beam of cross section 350mm x 350mm to achieve a maximum dynamic bending stiffness. In the case of a longer spindle beam, where the length is approx. 8 times section dimension, the optimum laminate for such beam would consist of approximately 80 per cent of axial fibers of the maximum possible elastic modulus and 20 percent of off-axial directions, mostly combinations of ± 45° layers. Trying to use a conventional layer laminating process would be extremely expensive and probably impractical.

Production of the spindle beam (Fig. 6.) starts with the filament laying of a base tube. It is a laminate of axial fibre layers and cross-wound ± 45° layers all from high modulus pitch graphite fibres. Next the 3D cells and corner tubes are positioned, then the outer surface is laid, forming the fixing holes for the linear guides in the process and finally the whole structure is consolidated in a mould under pressure. The 3D cells consist of tows of high ultra high modulus graphite fibres with axial orientation and thin hoop wrap of HS carbon fibre.

![Diagram of spindle beam](image)

Figure 6: Scheme of cross section of spindle beam for machine tool.
EXPERIMENTS AND PROTOTYPE VERIFICATIONS

The prototype of the spindle beam was tested at the Centre of Manufacturing Technology at Czech Technical University in Prague. The first test was done to determine natural frequency by free vibration impact test (Fig. 7.). Results for the first three vibration mode shapes were measured as 721 Hz, 553 Hz and 535 Hz.

Figure 7: Free vibration impact testing of composite spindle beam.

Figure 8: Natural frequency determination of supported spindle beam thorough linear guides.
The spindle beam prototype was then fixed on a testing bed (Fig. 8.) using the linear guides in order to simulate a realistic situation in the CNC machine tool. The natural frequency at different vibration mode shapes was measured. The comparison with a geometrically equivalent steel spindle beam can be found at Figure 10. An FEM simulation of the significant vibration mode shapes were done in order to verify the numerical and parametrical model of the prototype spindle beam (Fig. 9.).

Figure 9: 10th vibration mode shape of realistically supported spindle beam.

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Figure 10: Natural frequency comparison between steel and graphite beams.
CONCLUSION

The prototype spindle beam was successfully manufactured and tested.

The prototype spindle beam with weight of 110 kg was produced as one operation, one cure cycle product (Fig. 11.).

Using the 3D cell structure it was proven that it is possible to significantly reduce the production time.

The 3D cell structure is out performing conventional unidirectional laminates from ultra high modulus pitch fibre, especially in transverse properties.

Interlaminar shear strength, transverse modulus and transverse strength is increased significantly (see [5]).

A weight saving of over 54 % was achieved.

The dynamic stiffness was increased on average by a factor of 1.9 in comparison with the equivalent steel beam.
References


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