Advanced composite materials in precision machine tools sector – Applications and perspectives

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SUMMARY

The most recent R&D activities and applications of advanced materials for designing and fabrication of light and damped structures of precision machine tools (MT), are here presented. These new solutions include carbon fibres reinforced polymers (CFRP), hybrid sandwiches and novel multifunctional smart structures.

Keywords: machine tools; composites; multifunctional materials; smart structures.

1. INTRODUCTION

The ever growing competition on the international markets pushes manufacturers towards shorter design cycles and decreasing manufacturing times and costs for their products. This trend generates a demand for smart and faster machining systems which are able to drastically reduce machining time, while improving the final accuracy. Machine Tools (MT) axis acceleration 2 to 3 times higher than conventional ones together with machining accuracy in the sub-micron range will be the most probable targets of the new generation of machining systems inside manufacturing shops. Strong mass reduction of mobile machine parts together with the increasing of their stiffness and damping to get excellent static, dynamic and thermal stability of the structures are then becoming a "must", to ensure a technological and cost-effective achievement of such an ambitious goal. Typical examples of machine structures are the mobile parts of milling machines, grinding machines, coordinates measuring machines, etc. Conventional materials for building MT are cast iron, welded steel and, in some cases, Aluminium-alloys. Although these materials represent a very consolidated technology for MT engineers, the need to ensure such high performances requires the investigation of a new class of materials with improved inherent properties in terms of specific stiffness and structural damping and dimensional stability. The materials selection strategy is based on the evaluation of two parameters which can be considered merit indexes: the structural index [1] and the damping coefficient (loss factor). The structural index is given by $E^{1/3}/\rho$, where E is the Young's module and ρ is the density of the material. This index links the material mass and stiffness. In particular, for a prescribed stiffness, materials with the same structural index have the same weight. The weight is minimised (and the stiffness is increased) by selecting materials with large values of structural indexes. The loss factor represents the attitude of materials to damp vibration.

The values assumed by the structural index $E^{1/3}/\rho$ and the damping coefficient η for the following materials:

- Cast iron
- Steel
- Aluminium alloys
- Mg alloys
- Aluminium foams
- CFRP (Carbon Fibre Reinforced Polymer, considering three types of carbon fibres: HS (High Strength), HM (High Module), and UHM (Ultra High Module, that is with a Young's module higher than 700 Gpa).

are reported in the table below.

Table 1. Materials structural index and damping coefficient

	$E^{1/3}/\rho$ [Gpa$^{1/3}$/(Mg/m^3)]	**η**
Cast iron	0.63	$1.2\cdot10^{-3}\div1.7\cdot10^{-3}$
Steel	0.77	$6\cdot10^{-4}\div10^{-3}$
Aluminium alloys	1.5	$2\cdot10^{-4}\div4\cdot10^{-4}$
Mg alloys	1.9	$10^{-3}\div10^{-2}$
HS CFRP (unidir)	≈ 3.3	$1.5\cdot10^{-3}\div3\cdot10^{-3}$
HM CFRP (unidir)	≈ 4.0	$1.5\cdot10^{-3}\div3\cdot10^{-3}$
UHM CFRP (unidir)	≈ 4.4	$1.5\cdot10^{-3}\div3\cdot10^{-3}$
Al Foams	≈ 3	$4\cdot10^{-3}\div10^{-2}$

As it can be seen from the above table, the material characterised by the highest values of the structural index is the UHM CFRP. Aluminium Foam shows both a pretty high value of structural index and very good damping property. Actually, also Mg alloys have a high value of damping but this material is extremely expensive, especially due to the high manufacturing costs.

In the case studies described in Chapter 2 and 3, CFRP-based solutions are used to design and produce MT structural (mobile) components. In the first case-study, a HM CFRP unidirectional layer is used as an external skin of a sandwich multi-material structure. Basically, in comparison with the monolithic CFRP-UHM solution (second case-study), the proposed sandwich structures are cheaper because the nobler material is employed just to realise the sandwich skins. Selecting the materials for the core and the skins of the sandwich structure appropriately, an hybrid solution can be obtained whose structural index is higher than that of its two constituents. Moreover, there are further advantages in terms of damping thanks to the presence of bonded joints.

On the other hand the CFRP-UHM as monolithic solution in some case is extremely advantageous in terms of weight reduction while the cost-effectiveness strongly depends on the fabrication process selected for the composite part.

As already pointed out another strict requirement that the MT design engineers have to fulfil to improve the accuracy of machine is the thermal stability. In particular, a well-known problem is the thermally-induced errors arising from thermal deformations of the machine elements caused by internal/external heat sources. There are several methods to solve this problem [2], including: temperature control, thermally stable structural designs and errors compensation. In this context two novel approaches for thermal errors reduction, which are based respectively on an “active” and a “passive” (self-adaptive) strategy, are proposed and described in Chapter 4 and 5:

- a new class of ‘smart adaptronic structures’ based on integration of passive materials, e.g. CFRP, with smart sensors (optical fibres) capable of measuring in real time the ‘deformed’ states of the structure itself, and then, through proper thermo-structural model and algorithms, predicting the displacement at tool tip.
- a new class of multifunctional materials based on metallic (Aluminium) foam impregnated with PCM (Phase Change Materials) material. This foam, used either as filler or core of sandwich structures provides high stiffness-to-weight ration together with good vibration damping property and high thermal-stability.

All the above mentioned solutions will represent a great challenge in MT sector and could open interesting perspectives for industrial applications of advanced materials technologies within this sector.

2. CASE STUDY 1 - HIGH SPEED MACHINING CENTRE

The here presented case study is related to the applications of a hybrid multi-materials sandwich to design novel MT parts of a linear motors horizontal (3-axis) machining centre for prismatic component machining. To select the most effective structural part to be redesigned using new technologies, a FE multipurpose analysis has been carried out. The aim of this application is the increasing of the dynamic stiffness in order to get the advantages described in the previous chapters. Figure 1 shows the FE design flowchart. The static sensibility analysis is based on the evaluation of the contribution of each single structure/component of the machine to the global compliance at the tool tip, while the particularity of the dynamic sensibility analysis is related to the evaluation of the percentage contribution of each machine part to the dominant modes in terms of strain energy percentage and kinetic energy percentage of the total.

$$E_S = \frac{1}{2}[u]^T[K][u]$$

$$E_C = \frac{1}{2}[\dot{u}]^T[M][\dot{u}]$$

It can be seen that the strain energy E_s is directly proportional to the stiffness while the kinetic energy E_c to the mass. From this analysis it is possible to evaluate some critical design indexes on which to individuate the critical elements and so to concentrate the effort design only on the elements where the modification is more effective. According to this analysis the Ram (Z-axis) and the Column (X-Axis) resulted as the most critical components.

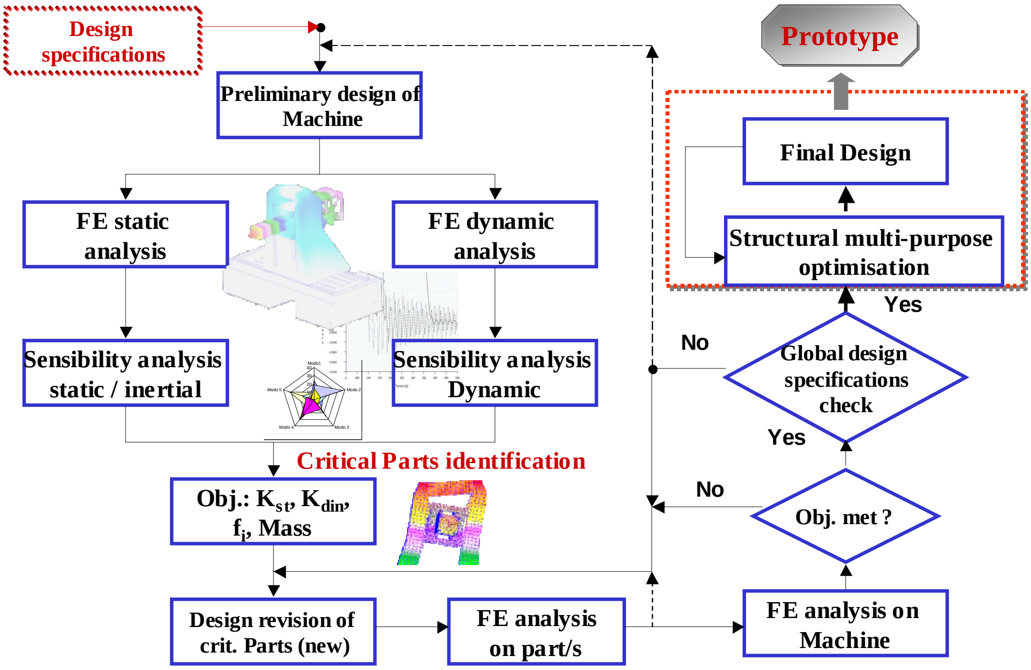
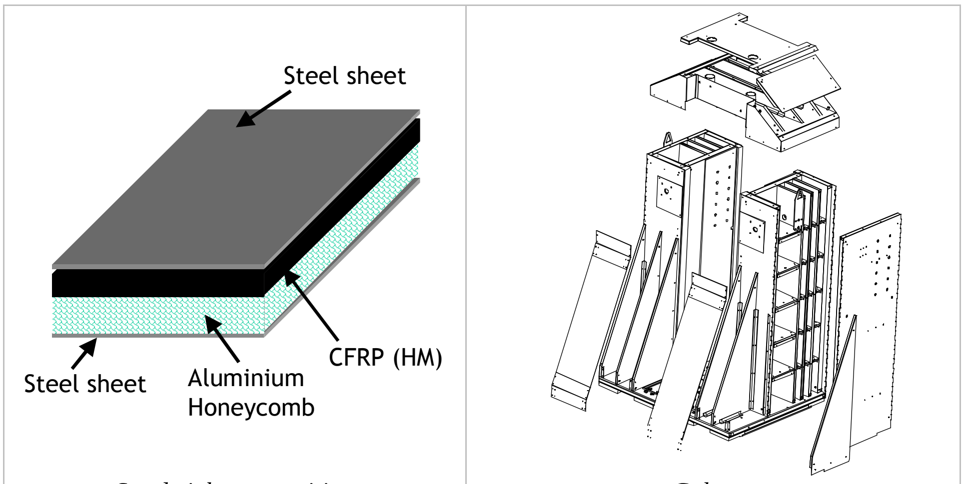
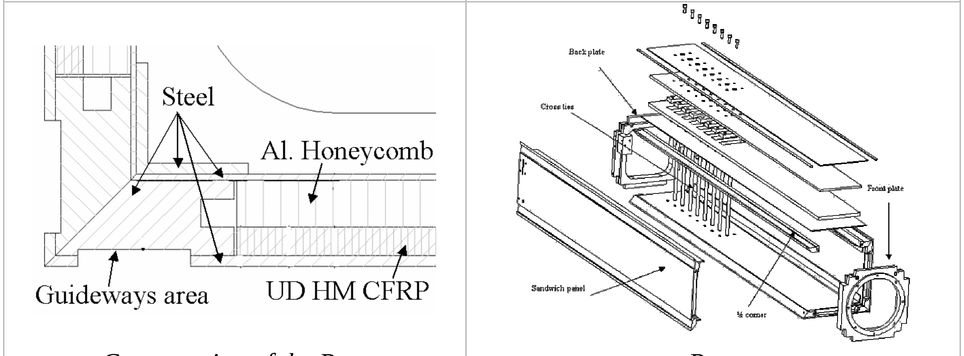


Figure 1: The FE design flowchart

Therefore, starting from an existing conventional High Speed Machining Centre, the Ram and the Column have been substituted with novel ones.



Sandwich composition *Column*



Cross section of the Ram *Ram*

Figure 2: Sandwich hybrid material and applications

The electro-welded steel structures have been substituted with an hybrid sandwich structure (steel/CFRP/Al-honeycomb/steel) as shown in Figure 2.

Panels have been joined through gluing technology. The actual damping has been increased up to 3 times for the Ram and 8 times for the Column. The saving in mass for both the components has been the 20 %.

3. CASE STUDY - ULTRA HIGH SPEED MODULE

This second case study regards an Ultra High Speed Module (the morphology is the similar to the previous one but with smaller size), where the steel RAM has been substituted with another one made in a hybrid material structure. The external skin is in thin steel plates glued on an internal tube fabricated through filament winding technology (the material is UHM carbon fibres for the square tube and HM fibres for the inner corners, used as local stiffeners).

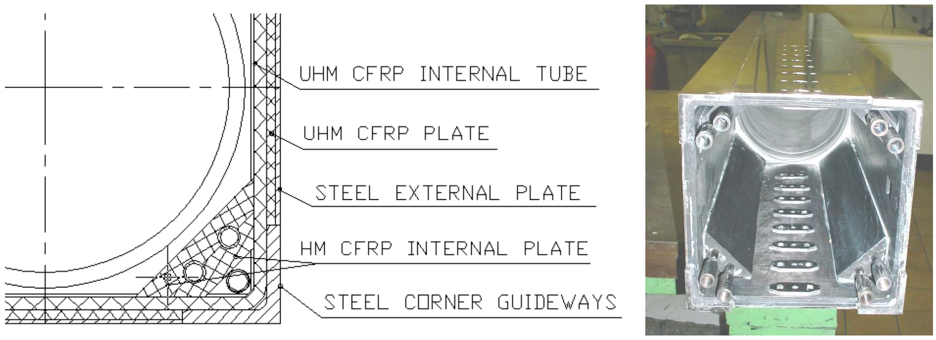


Figure 7: Ram cross section - Ultra high speed module

The inner corners include also aluminium pipes used for cooling and thermo-conditioning of the part.

The fibre orientations of CFRP tube has been optimised in order to minimise the mass and maximise the stiffness and the first modal bending frequency. The achieved results are very good with a mass reduction of 40 % and the damping increased by 2.5 times. The advantages in terms of weight saving are greater than the solution described in the first case-study while the damping increasing, as expected, is a little bit lower than the previous one (due to less number of glued layers).

4. CASE STUDY 3 - SMART STRUCTURES

A strict requirement that the machine tool design engineers have to fulfil in order to drastically reduce machining time while improving the final accuracy is the thermal stability. In particular, a well-known problem is the thermally-induced errors arising from thermal deformations of the machine elements caused by internal/external heat sources and differential coefficients of thermal expansion (CTE) between CFRP material and metallic end-fitting, inserts, etc.

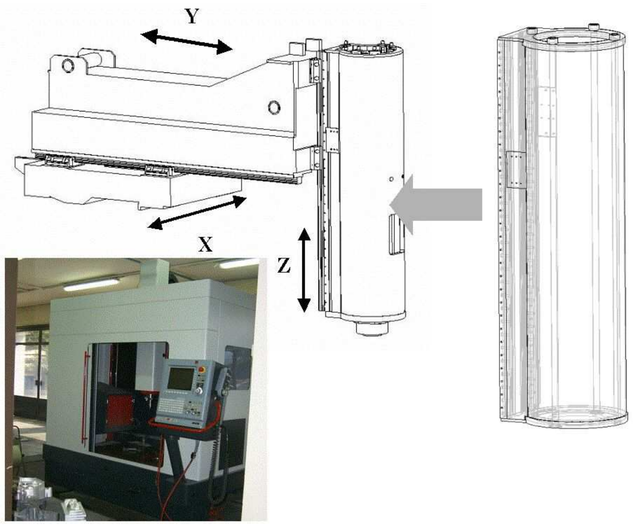


Figure 3. Precision Milling machine for dies & moulds machining

The SMART structure here proposed consists of an innovative machine tool part, the ram (Z-axis) of a milling machine made of CFRP-UHM material (Figure 3 and 4), which integrates a set of the Fibre Bragg Grating (FBG) displacement sensors (Figure 5a) to measure the overall elongation (integral effect) of some critical point-to-point dimension of the part geometry.

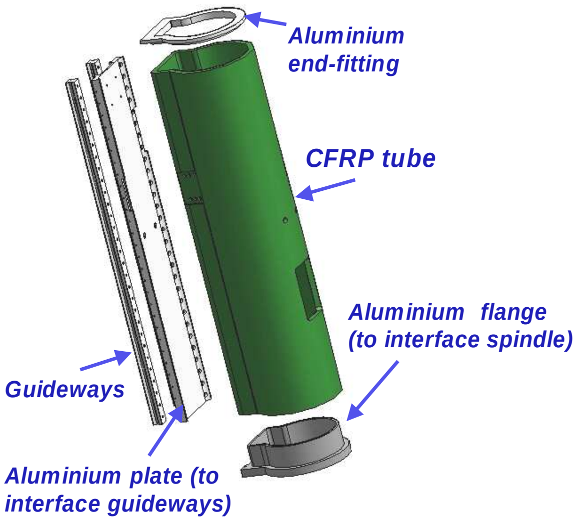


Figure 4. Machine tools part (Ram) made in CFRP with metallic end-fittings

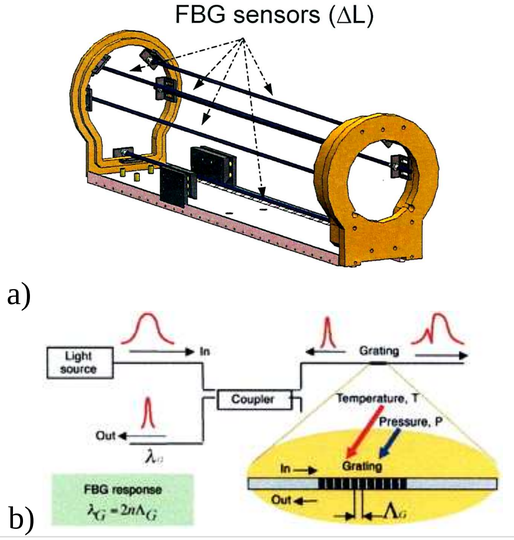


Figure 5. a) Ram with FBG sensors;
b) Principle of FBG sensor

A uniform FBG includes a segment in which a periodic modulation of the core refractive index is implemented (Figure 5b). When an external mechanical or thermal deformation is imposed onto the grating area, the grating periodic spacing and consequently the effective reflective index will be altered [3]. Then the Bragg wavelength will shift because of changes in either the refractive index or the periodicity of the grating. An optical spectrometer can thus provide a measure of the total strain affecting the grating.

Five FBG sensors have been placed in the ram structure in order to measure the total axial elongation of each side of the structure. These on-line measures will be used as input in a structural mathematical model of the part — based on MRA (Multiple-

Regression Analysis [4]) — that will predict the drift of the tool tip in the three spatial directions.

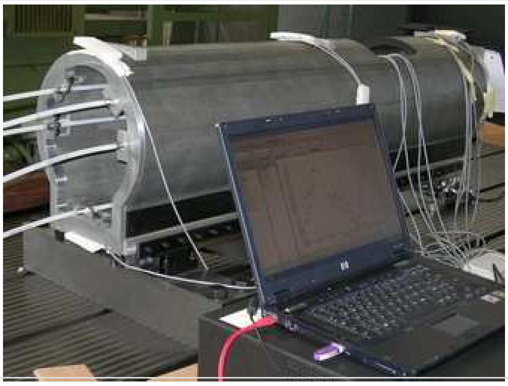
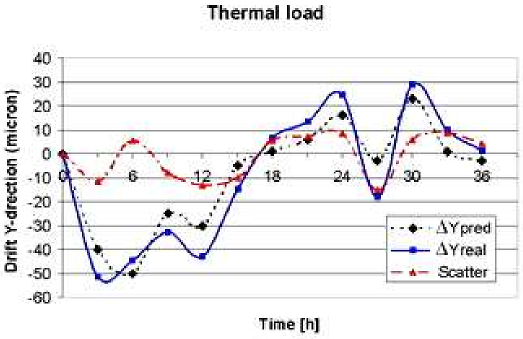
	

Figure 6. Test-bench setup of Ram with FBG sensors	Figure 7. Test results - actual tool tip displacement vs. predicted one.

To validate the model, a test-bench has been set-up (Figure 6). During the experimental tests, the thermo-structural effects due to thermal loads application (changing the ambient temperature) over a prescribed time period have been monitored. The results (Figure 7) showed that in the compensated case the maximum residual drift error at tool tip can be potentially reduced within a window of approx. ± 10 µm by the proposed model and algorithms, while without compensation the drift due to thermo-structural distortions would be approx. ± 50 µm.

5. CASE STUDY 4 - MULTIFUNTIONAL STRUCTURE

This third case study regards the same high precision milling machine for dies & moulds machining presented before where the electro-welded steel RAM has been here redesigned and prototyped using an hybrid sandwich solution based on steel skins (calendered and welded tubes/profiles) filled in with aluminium metal foams (closed cells) by direct foaming fabrication technique (using welded tubes and profiles as a skeleton structure). The thickness of skins/ribs and the proper density has been optimised through FE calculation. Experimental test has been then carried out.

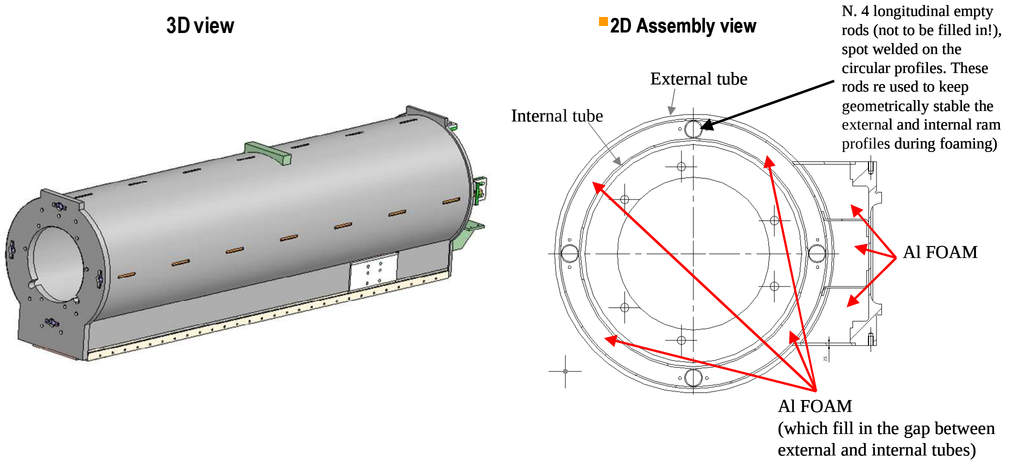


Figure 8. Aluminium foam sandwich structure

The results in term of static stiffness and vibration damping has been reported in the following table where a comparison with other material technologies (electro-welded steel, CFRP) used to realise the same component is showed as well.

Table 2. Results comparison for different materials

	Weight [kg]	Experimental Stiffness (X – direction) [kg/μm]	First Vibration Frequency (bending) [hz]	Modal Damping [%]
STEEL	97	2.2	596	0.1
CFRP	50	2.1	1206	0.23
Al FOAM	116	2.5	667	1.7

It can be seen that the CFRP solution offer great advantages in terms of weight reduction (-40%) respect to the conventional steel solution (with approx. the same static stiffness) while the Al-foam sandwich solution shows very good damping properties (the best one) but does not offer any advantages in term of weight reduction. This is due to the fact that for process fabrication constraints it was not possible to use skins thickness and foam density under a specified value. Anyway an increasing of stiffness respect to the steel solution has been achieved. Metal foams core (especially open-cells) offer also potential for designing self-adaptive thermal stable component.

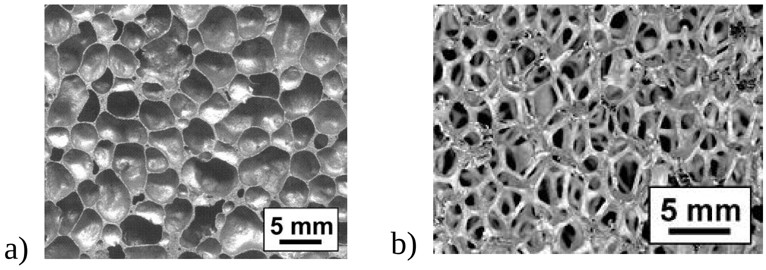


Figure 9. Aluminium Foam – a) Closed cell; b) Open-ceel

In fact the particular micro-cellular interconnected structures permit to be impregnated by PCM. PCM are latent heat storage materials [6]. As the temperature rises, the chemical bonds within the PCM break up as the material changes phase from solid to liquid. The phase change is isothermal process and therefore the PCM absorb heat keeping constant the temperature of a machine component [7] in a defined time range. This impregnated Al-foam, used either as filler or core of sandwich structures provides high stiffness-to-weight ration together with good vibration damping property and high inherent thermal-stability. Authors have designed, simulated, fabricated and tested (thermal trials) a sample prototype (Figure 9) made of sandwich with steel skins and multifunctional foam core. The thermal trials consisted to expose the sample at an environmental temperature variation (from 20°C to 50°C) in order to assess its capability to absorb heat and maintain thermal stability in a defined time range.

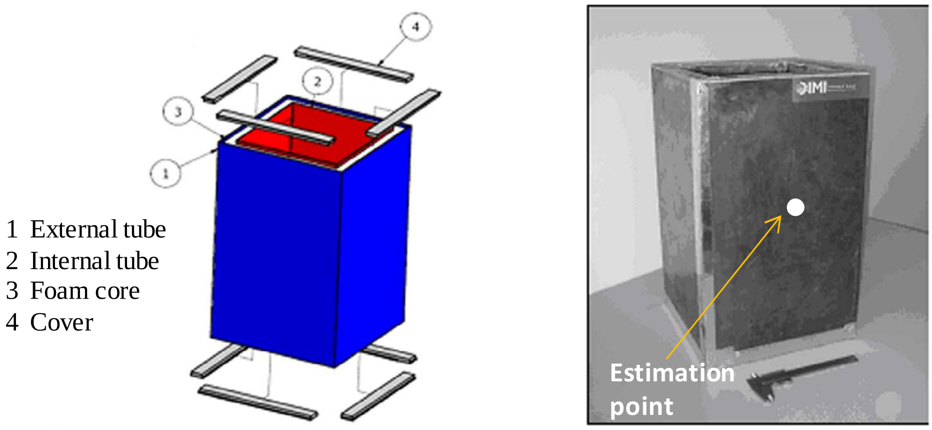


Figure 9. Multifuncional foam sample (Al-foam, open cells, densitity = 40 ppi; PCM wax melting temperature = 31° C)

The results are reported here below.

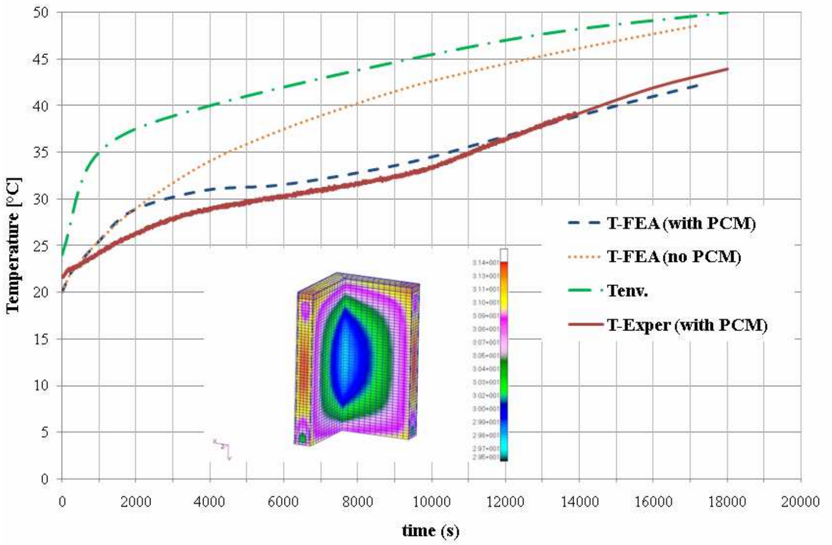


Figure 10. FEA results – numerical experimental comparison at the estimation point

The Figure 10 refers to the FEA results aimed at evaluating the temperture viariation of the estimation point considering a sample model with PCM based core and without PCM. As it can be seen the thermal stabilisation effect of PCM is relevant, especially in the time range 4000-12000 sec where an average temperature decreasing of about 10°C is got. In Figure 10 is also plotted the comparison between FEA numerical results vs. experimental ones. As it can be seen a good prediction is achieved through the proposed FE model. The mis-matching of curves within the 0-5000 sec time range could be mainly attributed to the glue modelisation which does not take into account for the changing in the gap size (due fabrication issues), filled by the glue, between core and skins.

6. CONCLUSION

The reported case studies of novel light-damped machine tools structures show the big potentiality offered by the application of advanced materials in high performances machine tools. Firstly the combination of hybrid materials (steel, CFRP, Al honeycomb) and an intensive use of gluing technology allows to increase damping and, at the same time, to get a consistent mass reduction (up to 40%) without reducing the overall stiffness. Moreover the integration of FBG sensors into a CFRP structure allows a compensation of geometrical distortions (due to differential CTE between CFRP material and metallic end-fitting, inserts) through a thermo-structural prediction model based on real-time sensors measurements. A comparison study regarding structural performance of a machine tool component (of a precision milling machine) realised with different competing material technologies has been done as well. Results showed as a significant increasing of damping can be achieved by Al-Foam sandwich structures. Finally the authors have studied the thermal stability of MT structures considering multifunctional materials based on Al-foam impregnated with PCM. The thermal tests performed on a beam sample highlighted a significant thermal behaviour improvement due to this novel solution.

The effectiveness of the described solutions has been confirmed by experimental tests which have validated the design methodology as well.

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