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Machine Tools thermostabilization using passive control strategies

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Abstract. The aim of this study is to investigate passive control strategies using Phase Change Materials in Machine Tools (MTs) thermostabilization. By considering the main issues related to the thermal stability, authors presented the application of novel multifunctional materials to Machine Tools structures. A set of advanced materials are considered: aluminium foams, corrugate-core sandwich panels and polymeric concrete beds. The adopted solutions have been infiltrated by phase change materials (PCMs) in order to maintain the thermal stability of MTs when the environmental temperature is perturbed. The paper shows the results of simulative and experimental tests.

Introduction

The design of innovative machine tools reflects the behaviour of the modern competitive markets, where the customers' expectations rapidly increased [1]. Many researches aim to apply innovative materials and effective solutions to obtain high machining performances and quality of products [2,3], reducing costs at the same time. There are many aspects that affect the accuracy and precision of machining or operation performance [4-6]. Relevant problems are related to thermal, static, dynamic and mechatronic behaviour of the machines and manufacturing systems [7-10]. In particular, important considerations deal with the evaluation of thermal errors during the machining operations. Thermal errors can be classified in two main categories: errors that effectively alter the linear positioning of the machine and errors that change the machine offsets [11]. These errors can be caused by different heat sources (i.e. bearings, drives, pumps, motors, cutting action or external sources) and they have to be analyzed to avoid possible effects on machine accuracy.

These preliminary considerations suggest to study particular structural materials (i.e. cement concrete, fibre reinforced plastics) able to minimize the deformation due to temperature changes, and evaluate advanced techniques to compensate thermal errors monitoring temperatures of machine critical points. This study aims to investigate novel multifunctional materials applied to Machine Tool (MT) structures (mobile and fixed parts) useful to reduce the thermal errors effects using passive strategies. Authors present a set of solutions based on the use of Phase Change Materials (PCMs) in MT structure building in order to absorb heat, keeping constant the temperature of a machine component in a defined time range when temperature is perturbed. PCMs are latent energy storage materials that use their phase change to absorb heat and maintain constant the temperature for long duration ("plateau"). In particular a PCM temperature remains constant during the phase change. This is useful for keeping the object (i.e. MT components or structures) at a uniform temperature. In this study a paraffin wax, a heat capacity (latent heat) of 130 kJ/kg and a density close to 0.89 kg/l (solid state at 25°C) is considered, nevertheless other solutions can be adopted in based on environmental conditions. Paraffin wax is an ecological heat storage material that uses the processes of phase change between solid and liquid (melting and congealing) to store and release large quantities of thermal energy at nearly constant temperature. Other important proprieties are long life product, with stable performance through the phase change cycles, ecologically harmless and non-toxic and chemically inert. To achieve the declared goals, different MT structural materials have been studied and assessed (metal foams, corrugated core materials, polymeric concrete) able to host PCMs. The proposed solutions also provide a significant contribution to solve other related problems, for example the application of light-weight materials, without impacting on the element stiffness, guarantees high mechanical damping ensuring machining accuracy, especially in the submicron range. To study the proprieties and advantages of these classes of materials, authors have designed, realized and tested prototypes of MT mobile (Figure 1) and fixed structures and compared the results with the conventional materials.

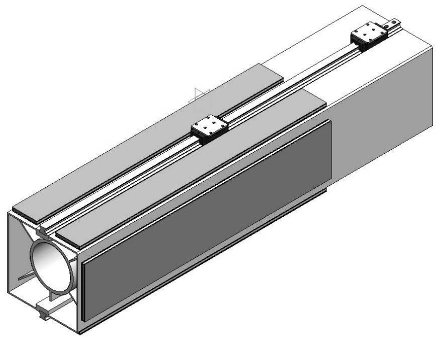


Fig.1. Z-axis of a milling machine.

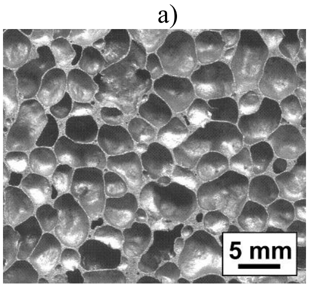
Application of multifunctional materials to Machine Tools mobile parts

The approach developed for thermal error reduction of MT mobile structures is based on the "passive" (self-adaptive) strategy. This method consists on hybrid multifunctional materials based on Aluminium foam sandwich (AFS) and corrugate-core sandwich panels impregnated with PCM (Phase Change Material) materials. These configurations provide high stiffness-to-weight ratio together with good vibration damping property and high thermal-stability. The novel structures can represent solutions in MT sector and could offer benefits for industrial applications of advanced materials technologies.

Metal foams represent a new class of materials with low density and novel physical, mechanical, thermal, electrical and acoustic proprieties. They guarantee potential for lightweight structures, for energy absorption and thermal management with low costs [12]. These performances can be achieved thanks to their exceptionally high properties in term of stiffness-to-weight ratio and low density with good shear and fracture strength. A further advantage of these materials is the damping capacity that is larger than that of solid metals by up to a factor of 10.

In this study authors have considered open celled foams, while evaluations and possible applications of closed cell materials are currently under testing. Open celled foams are porous structures consisting of an interconnected network. They are a cellular structure constituted by a solid metal (aluminium) containing a large volume fraction of gas-filled pores. Their particular structure permits to be impregnated by other materials (liquid state) as a PCM wax. The main features of these types of materials are the pore size and the relative density. The pore identifies the polygonal opening through every open window while its size defines the number of pores per inch (ppi), as shown in Figure 2. The relative density is a fundamental property in order to understand the density of a foam divided by the density of the solid parent material of the struts. Therefore while pore size controls the number and nominal size of the foam structure, the relative density defines the ligament cross-section shape and actual size. By using this information it is possible to choose the most suitable type of foam and calculate the quantity of the PCM material that can be infiltrated into the metal foam cells. The second considered class of materials is a structure based on sandwich panels with an Aluminium corrugated core. This material guarantees light-weight proprieties without impacting on the MT element stiffness. Corrugated core structures provide less efficient and highly anisotropic load support, and enable opportunities of incorporating a number of different functions in the same structure. In particular their shape features permit to be easily realized and impregnated by a PCM material. The corrugation approach is often preferred for low relative density structures made of alloys with high formability. Triangular, flat topped, square or sinusoidal corrugations represent different effective solutions to adopt in sandwich realization. Selected prismatic topology structures can be manufactured by sheet bending or progressive rolling operations or by extrusion techniques.

a)



b)

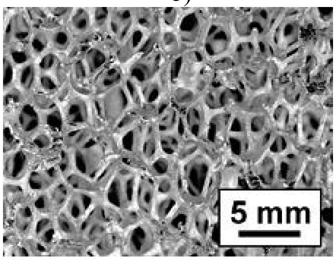


Fig.2. Al Foam a) Closed cell; b) Open-cell.

In order to evaluate the properties of the selected materials (metal foams and corrugated core structures) a comparison with conventional materials to realize structural components is shown in Table 1. The selection strategy is based on the evaluation of two indicators: the structural index and the damping coefficient. The structural index is given by the ratio between the cube root of the Young's module E and the density of the material ρ. This index regards the material mass and stiffness. The weight is minimized (and the stiffness is increased) by selecting materials with large values of structural index. The materials characterized by the highest values of the structural index and damping coefficient are the Aluminium Metal Foam and Aluminium Corrugated panels. In the same way, Mg alloys have a high value of damping but it is extremely expensive, especially due to the high manufacturing costs. In the light of these considerations authors considered metal foam and aluminium corrugate materials as excellent candidates to reduce problems of static, dynamic and mechatronic behaviour in MT structural building.

Tab. 1. Selecting material indicators.

MATERIAL	$E^{1/3}/\rho$ [$GPa^{1/3}/Mg/m^3$]	η
Al alloys	1.50	$2\cdot10^{-4}\div4\cdot10^{-4}$
Mg alloys	1.90	$10^{-3}\div10^{-2}$
Steel	0.77	$6\cdot10^{-4}\div10^{-3}$
Al Corrug. Sandw	2.52	$4\cdot10^{-3}\div10^{-2}$
AFS	2.67	$10^{-4}\div10^{-3}$

To demonstrate the thermal accuracy capability, authors have infiltrated the lightweight materials with a PCMs wax (melting point about 31°C). In particular authors have designed, realized and tested prototypes of a MT mobile structure (Z-axis of a precision milling machine) and compared the results with the conventional materials. The first prototype consists of a structure of sandwiches with core made of metal foam (open cells, density 20 ppi) material impregnated by the PCM wax. The second considered 3D beam is a PCM-filled structure based on sandwich panels with an Aluminium corrugated core. The prototypes have been tested in controlled environmental conditions, reducing the noise variability as a consequence. Thermal conditions have been obtained and maintained by one thermal source (2 kW), and measured using an infrared thermo-camera and a series of a thermocouples strategically positioned on the prototypes. Figure 3 shows the comparison between the AFS and corrugated core structures prototypes. The environmental conditions at the beginning of the experiment are close to 17°C. The tests ended after 18000 seconds and, in any case, after the melting completion of the PCM. The experiment is monitored since the external temperature of the beams impregnated with PCM reaches 40°C. Data collection is permitted by an accurate data acquisition system (sampling frequency of 9Hz). Environment achieves 55°C after 25 minutes and maintains constant the temperature for 6 hours. A conventional material shows a similar trend. Instead, the multifunctional structures, impregnated by the PCM materials, present an important plateau trend. The Al corrugated core structure plateau ends after completion of PCM phase transition in time close to 67 minutes, then a linear increasing (VarT equal to 0.039 °C/min) of the temperature is correctly observed. It is noted that AFS multifunctional structure has a plateau duration of 87 minutes limiting the thermal noises. A considerable thermal gain due to the multifunctional material is evident. From a MT point of view this effect would lead to undesired shape errors on the workpiece. The thermal gain is proportional to the temperature accumulated by the wax, quantifiable by the area included between the environment and plateau curves (Figure 3).

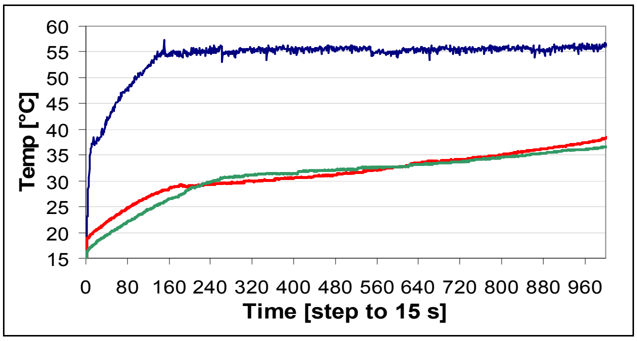


Fig. 3. Comparison between AFS structure (green line), Al corrugated structure (red line) and enviroment temperature (blu line).

Application of multifunctional materials to Machine Tools fixed parts

At the same time, the main functional requirements of MT fixed structures are high structural stiffness, high damping and thermal inertia. Advanced composite materials can give an important contribution to satisfy these requirements. In particular polymeric concrete, based on epoxy resin and quartz, is one of the new materials, that offers potential application in the machine tool industry. Table 2 shows a comparison between properties of MT structure conventional materials and synthetic granite materials.

Tab. 2. Material properties of Cast iron vs. Synthetic granite [13].

Properties	Unit	Synthetic granite	Cast iron
Density	kg/dm^3	2.30 to 2.50	7.20
Compressive strength	N/mm^2	120 to 150	500
Tensile strength	N/mm^2	10 to 15	150 to 250
Modulus of elasticity	kN/mm^2	30 to 40	90 to 120
Coefficient of linear thermal expansion	10-6/°C	9 to 13	10 to 13
Thermal conductivity	W/m °C	1 to 3	50

In the light of these considerations, authors proceeded using a theoretical model and develop a FEA analysis to investigate the effect of PCM applications to a polymeric concrete MT bed. It has been supposed to fill a MT element (dimensions – 300x300x500 mm, Figure 4) using a paraffin wax as phase change materials (melting point at 22°C). Neumann's Model [14, 15] is useful to study the melting process of PCM at solid/liquid interface. Using a dedicated software the PCM solid/liquid interface has been estimated and prototype thermal behaviours have been analyzed. Table 3 points out the different FEA simulated configurations to study the impact of the polymeric concrete and PCM thermal conductivity on the structure stability. In the FEA simulation the temperature has been perturbed from 20°C to 30°C instantly. The configuration ∅ is not PCM filled. Figure 5 states T_{Ae} behaviour of the beam when the temperature changes. It is noted that the plateau exists (a logarithmic scale of x-axis can better highlight the thermostabilization) and it depends on the material and PCM thermal conductivity. In particular the PCM conductivity plays a fundamental role in the thermostabilization of the structures. The results confirm the excellent potentialities of these advanced materials in MT structures design and building. Nevertheless further studies are necessary to improve the advantages and practical applications.

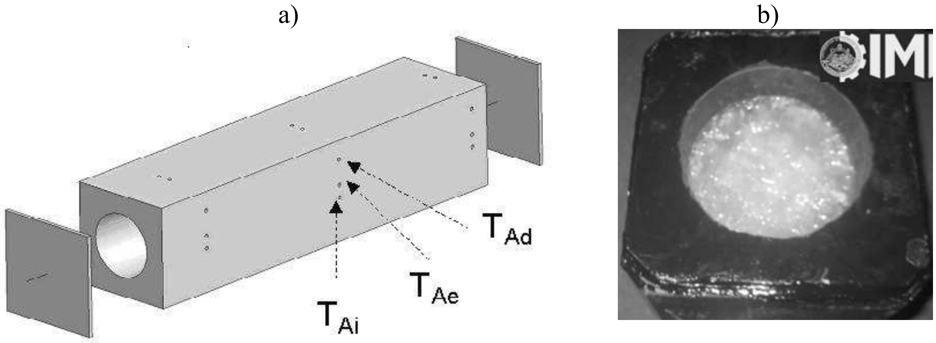


Fig.4. Multifunctional Polymeric concrete sample (a-b).

Tab. 3. Summary of simulated configurations.

Configuration	PCM	Polymeric Concrete Thermal Conductivity [W/mK]	PCM Thermal Conductivity [W/mK]
∅	N	2.00	-
1	Y	2.00	0.20
2	Y	20.00	0.20
3	Y	0.20	0.20
4	Y	2.00	2.00

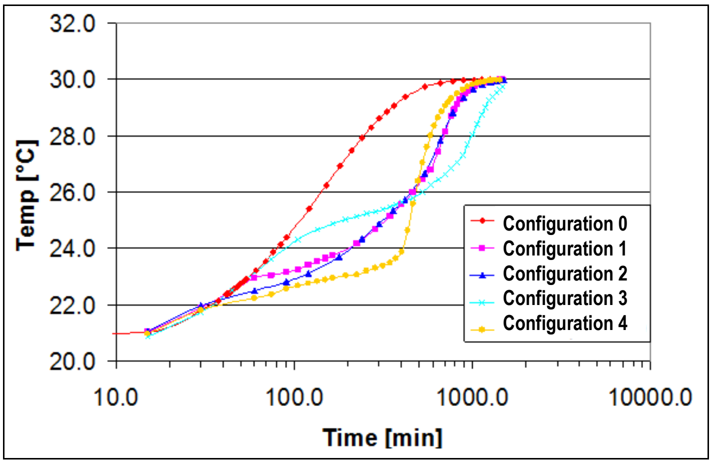


Fig.5. The simulated thermal behaviours.

Conclusions

This paper presents the application of novel multifunctional materials to MT design and building. The proposed case studies show the potentialities offered by the utilization of these advanced materials in manufacturing sector. Authors attempted to study the thermal stability of the MT structures considering Phase Change Materials to impregnate the structural parts of a MT. Thermal properties and behaviours of the multifunctional material prototypes have been investigated experimentally. The thermal tests performed on the beams (Al foams and Al corrugated core structures) highlight a considerable thermal gain due to the multifunctional materials. Considering these thermal tests, developed in an appropriate room where the temperature was perturbed in a specified range, the temperatures measured on the external surfaces of the innovative prototypes do not exceed 40°C, during the plateau phase and for long duration time. Instead the beams without the PCM infiltration rapidly reach 50°C, causing potentially serious consequences in terms of distortions and shape errors during manufacturing. In the same way authors investigated the possibility to apply

PCM to MT fixed part (beds) design. Prototypes based on polymeric concrete have been studied. Due to the particular configuration of prototypes (dimensions) and economical constraints, only a theoretical study was performed to validate the initial hypothesis. The analysis (FEA) highlights that the plateau exits and the MT fixed parts can be also maintained under control if the temperature is perturbed. In particular the PCM conductivity plays a fundamental role in the thermostabilization of the structures. Following this way it possible to design innovative elements for MT mobile or structural parts that are able to maintain constant their temperature for long duration, even if there are many heat sources. It is clearly necessary to improve the process realization of these structures nevertheless these solutions can represent a good milestone to develop further studies.

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