International Journal for Quality Research 10(1) 143–158
ISSN 1800-6450

Giuseppe Lucisano [1]
Miladin Stefanovic
Cristiano Fragassa

ADVANCED DESIGN SOLUTIONS FOR HIGH-PRECISION WOODWORKING MACHINES

Article info:
Received 14.12.2015
Accepted 02.02.2016

UDC – 54.061
DOI – 10.18421/IJQR10.01-07

Abstract: *With the aim at performing the highest precision during woodworking, a mix of alternative approaches, fruitfully integrated in a common design strategy, is essential. This paper represents an overview of technical solutions, recently developed by authors, in design of machine tools and their final effects on manufacturing. The most advanced solutions in machine design are reported side by side with common practices or little everyday expedients. These design actions are directly or indirectly related to the rational use of materials, sometimes very uncommon, as in the case of magnetorheological fluids chosen to implement an active control in speed and force on the electro-spindle, and permitting to improve the quality of wood machining. Other actions are less unusual, as in the case of the adoption of innovative anti-vibration supports for basement. Tradition or innovation, all these technical solutions contribute to the final result: the highest precision in wood machining.*

Keywords: *wood processing, machining, design of machine, machine tools*

1. Introduction

Many industrial machinery manufacturers find themselves facing an increasing number of new requirements, such as the demand for more flexible machine tool designs that can be rapidly adapted to new products, as well as for machines that can be easily integrated into existing plants. In addition, increasing global competition, market demands and regulatory mandates require industrial machinery companies – who serve multiple industries – to continuously innovate and optimize their products (Dimic and Pavlovic, 2016). The market not only expects maximum uptime on a day-to-day basis, but also to remain productive for years. In addition, with the introduction, there now lies the challenge of manufacturing with decentralized, autonomous machines that communicate with one another and the products they are manufacturing, so production can be optimized. This adds a whole new level of technology integration requirements (Siemens, 2016).

The realization of machine tools and in particular of machining CNC centers with high performance has made required in recent times to enable a strong increase in productivity and a consequent decrease in the product piece costs. According to Monno and Mussi, (2007), the available strategies to make possible this increase in productivity are essentially two. The first is a sharp

[1] Corresponding author: Giuseppe Lucisano
email: glucisano@scmgroup.com

increase of speed in material removal, made possible by the appearance on the market of cutting tools made by high performance materials such as cubic-boron-nitride (CBN) or polycrystalline diamond. To reap the full benefit of these tools is necessary to perform the machining with high removal rates and high depth of cut. As a consequence, machine tools require a structure capable of withstanding the elevated dynamic stress that these working conditions carry on. Their design solutions are characterized by high stiffness and large ability to dampen vibrations. In fact, the vibrations of the machine tool structure are among the other causes that restrict high speed operations or degrade the cutting precision (Slocum, 2006).

The second strategy is the reduction of the so called "air cutting time". This dead time represent the period in which the tool is not in contact with the workpiece since required to bring the machine tool in the working position and with the correct tool. The impact of these dead times on the entire cycle is not negligible in the case of modern work center, especially when used for manufacturing complex parts. According to (Shu *et al.*, 2004) it is can reach *70%* of the overall cycle. To reduce the "air cutting time", it is essentially necessary to design very fast machines, up to *2 m/s* of speed against the *0.5 m/s*, typical of a conventional machine. Obtaining these high speed on very small distances (usually few meters) is possible only if the mobile parts of the machine can move under very high accelerations, over $10\ m/s^2$. The related design solutions aims at obtaining such high accelerations without penalizing other aspects (as stability and precision).

The positioning accuracy is feasible only by using machine tools with moving parts characterized by high stiffness and low mass. In fact, one of the primary reasons for low productivity is large mass of the moving parts of machine tools, which cannot afford high acceleration and deceleration encountered during operation. A historical technical study estimated that a proper design solution reduce the weight of the vertical and horizontal slides by 34% and 26%, respectively, and increased damping by 1.5–5.7 times without sacrificing the stiffness (Tobias, 1965).

In general, both approaches highlight the need to design machine tools characterized by structures with high dynamic stiffness and reduced mobile masses. The realization of this kind of machines is almost impossible using structural materials traditionally employed, namely the cast iron and steel. It is therefore necessary to consider classes of materials innovative that the achievement of these objectives will make it possible with the least possible impact on the machine costs. Typically, composites materials, as carbon or glass fiber reinforced composites offer a good compromise between alternative requirements (as weight, manufacturability, costs, etc.). This is also evident in the case of the substitution of the traditional metals with light composites materials, as carbon fibre reinforced plastics (CFRP), for the realization of machine structures and parts. Several other investigations demonstrated that, in fast moving components, as in the case of the supporting frame (Lee *et al.*, 1985) or cover (Suh *et al.*, 2001) in the electro spindle, a reduction in weight permits to improve speed and productivity thanks to the reduction of inertial masses (Shu *et al.*, 2004). Several other investigations describe the effect of a material substitution, in the case of changing of traditional alloys with fiber reinforced composites. In Choi and Lee (1997), for instance, it is reported the use of carbon fibre-epoxy composite as constitutive material for a spindle-bearing system, used in a machine tool. On the contrary, in Hwang *et al*. (2004) it is analyzed the clamping effects on the dynamic characteristics of machine tool when the whole structure is realized in composites.

Whichever is the preferred approach that drives a material redesign action, the general aim of obtaining the highest precision in woodworking obliges the designer to follow several common considerations. In particular, it is noteworthy that the degree of accuracy of a machine tool, allowing to obtain high quality surfaces in wood pieces, depends on two basic factors (Rossi *et al.*, 2002):

1) static and dynamic stiffness of the structure, particularly relevant with respect to bending and torsion solicitations. The specific characteristics of the material that have a greater impact on these aspects are: the Young's modulus and its internal damping.
2) dimensional stability with respect to mechanical stress related to working and physical stresses related to the environment in here the machine has to operate.

The demands on the material are therefore:

- very low internal tensions
- very low coefficient of thermal expansion
- large thermal conductivity so as to enable rapid heat transfer inside of the whole structure by minimizing the thermal gradients and thus the thermal deformations that follow.

Table 1. Relation between machine tool features and material properties

Machine Tool Features	Material Property	Value
Static and dynamic stiffness	Elastic Modulus	High
	Internal Dumping	High
Dimensional stability	Internal Stress	Low
	Thermal dilatation	Very Low
	Heat conductivity	High

The relation between machine tool features and material properties are summarized in Table 1.

2. Material Design

The designer of any product, other than software, must get involved with material selection. The designer must understand the materials and their properties as deep as possible, to be able to design a competitive product. This consideration is also valid in the case of designing machine tools (Mohring *et al.*, 2015).

There are an incredible large range of materials on the market; adding, contrary to what a common opinion might be, a lot information about these material is already available and easy to collect. As first step, it is necessary for the designer to focus the attention on the product's function and, from this, to preliminarily define the class of materials to be selected. A very famous chart, used for material selection was proposed by *Ashby* and reported in (Figure 1). This specific diagram permits to select the material on the basis of density and Young modulus, but many others are available. The modulus spans 5 orders of magnitude, from *0.01 GPa* for foams to *1000 GPa* for diamond, also the density, from *100* to *20.000* kg/m^3, giving evidence of large range of materials available.

In addition of that, these materials must possess other important technological characteristics as:

1) wear resistance, impact and fatigue
2) low coefficient of friction
3) great resistance to chemical attack by aggressive liquids, in particular lubricants and refrigerants that are used during mechanical machining.

According to Weck (1980), particularly important are also economic factors as:

1) traceability on the market
2) price per unit mass
3) cost of processing
4) ability to obtain complex structures by casting and welding
5) possible rates of curing and / or thermal treatment

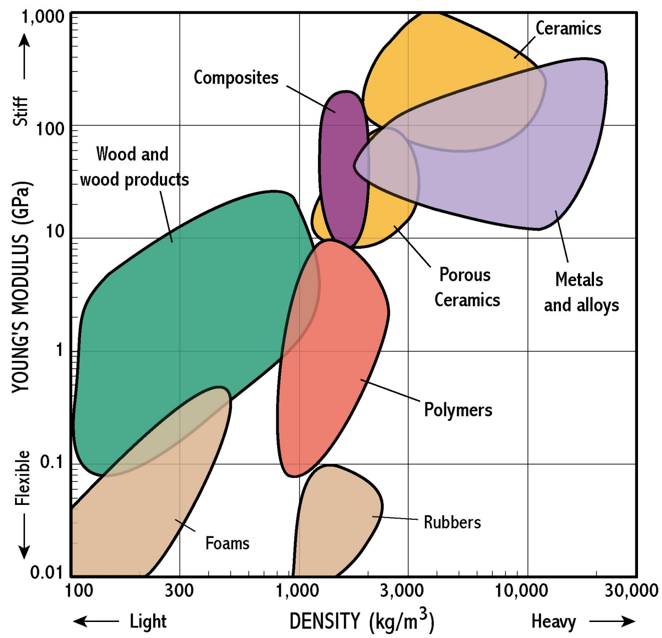

Figure 1. Material selection chart (Ashby, 2004)

Specifically, in Blaszczyk and Melone*,* it is summarized that for a correct material design in the case of machine tools considerations have to include aspects as: strength, brittleness, hardness, weight, machinability, weldability, cost, corrosion resistance, conductivity, wear resistance, thermal conductivity. All of them assume a specific relevance in design and manufacturing of machine tools for precise woodworking. A synthesis of constructive materials used in machine tools and their main features is reported in Table 2.

Table 2. Main materials in machine tools

Material	Features
Steel and Cast Iron	strong, stiff, heavy, cheap
Aluminum	weaker, lighter, more expensive than steel
Composite (CFRP)	strong, stiff, very light, but expensive

This paper deals with solutions of redesign involving a material changes and permitting to improve the performances of machine tools during woodworking. Cast irons, polymers and rubbers are considered as case-study. These solutions were already implemented on industrial applications proving their benefit and are here presented in an integrated form.

3. Cast iron

Wherever a change in material is proposed, it is quite common to refer that this change would involve metal alloys and fiber reinforced plastics. At the same time, it is unusual to consider that cast iron represents an important material, appreciable for properties and production techniques (Angus, 2013; Elliott, 1988, Oswald *et al.*, 2015). Adding, it is noteworthy that every change in materials that regards the selection of a totally different one, typically from metals to reinforced plastics (Simoes *et al.*, 2014), is a technologically complex task. Such action also implies, sometimes, a real change of paradigm in design. Several investigations demonstrated that, even if marginal improvements could be obtained by using advanced materials, with high specific stiffness in a direct substitution of the traditional ones, it is not the right way to operate, especially when a cost-effective approach is also considered (Ribeiro *et al.*, 2008). On the contrary, relevant advances in mechanical design, are possible even with apparently marginal changes in materials. This is exactly the case of cast iron.

Nowadays, the cast iron is still one of the most used materials in several industrial sectors. In particular, in design of woodworking machines, it is used for the realization of parts and frames in consideration of aspects as (Slocum, 2006):

- high dimensional stability
- high vibration damping
- high thermal conductivity
- limited cost
- good heat transfer
- well established design solutions

These positive features characterizing the cast alloy can be also reinforced by treatment of thermal relaxation, vibration or an appropriate period of natural aging (ASM, 1996). These benefits are demonstrated by the large variety of components realized in cast iron and used as parts for machine tools: from little inserts to enormous basements (Figure 2).

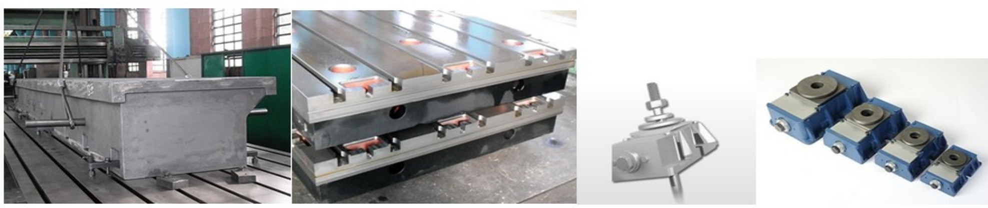

Figure 2. Elements in cast iron used in machine tools (Je.Com)

But "cast iron" is a generic term representing a large gamma of iron-carbon alloys. According to the microstructure and, in particular, to the specific shape that the carbon assumes inside the material (as shown in Figure 3, the families of cast alloy are conventionally identified in (Campbell, 2008):

- white cast iron
- grey cast iron
- malleable cast iron
- ductile cast iron

Figure 3. Example of microstructures

Actually, the only grey and ductile cast irons present a significant commercial use. Most of the production of white cast iron is reprocessed for obtaining malleable or ductile cast irons. Adding, the malleable cast iron is declining since it presents a higher complexity in processing, not justified by lower improvements properties. Comparing grey and ductile cast irons (also shorted in SGI considering the alternative name of Spheroidal Graphite Iron), this second one is preferable wherever superior mechanical characteristics are necessary. Several interesting dissertations are available with the aim at comparing the properties or in specific the fields of applicability of these different cast alloys (Lampman, 1996; Baicchi *et al*., 2007; Tiedje, 2010).

Another possibility is represented by the Vermicular Graphite Iron. Also in this case, its peculiarities are in net relation with the specific "vermicular" shape of the graphite particles. While grey cast iron is characterized by randomly oriented graphite flakes and in ductile iron graphite exists as individual spheres, in Vermicular Iron graphite flakes are randomly oriented and elongated as in grey iron, but they are shorter, thicker and with rounded edges, in some aspects more similarly to the ductile cast iron (SGI). In Dawson and Schroeder, (2000), a complete description of the Vermicular Graphite Iron is reported. *Dawson* considered this material, sometimes also called Compacted Graphite Iron (CGI), as a "viable alternative" to the traditional cast irons in practical applications, describing potential benefits. Even if the practical applications of CGI, as reported in Dawson and Schroeder (2004), are mainly limited to preliminary researches or to market sectors far away from the design of machine tools (e.g. motors), the list of opportunities invited to further investigations on this material. Specifically, in Fragassa *et al.* (2016), the main mechanical properties (as Tensile Strength, Elastic Modulus, Elongation) of compacted and spheroidal graphite irons were determined. By Fragassa and Pavlovic (2016), information regarding the Poisson's ratio was also obtained by a direct experimental evaluation, unusual for this materials. In Fragassa *et al*. (2016) the fracture toughness of cast iron was experimentally determined, while Fragassa *et al.* (2016) investigates the fatigue behaviour. All these very recent studies permit to enlarge the experienced knowledge on compacted graphite iron toward a comparison with the spheroidal graphite iron. A summary of the most relevant mechanical properties cast iron is reported in Table 3.

According to this table, in terms of mechanical properties, it is possible to consider CGI in the middle between Grey and SGI, perfect for specific applications of design of machines. Respect to the use of SGI, in fact, CGI is able to provide:

- an improved castability, useful in the realisation of complex components;
- lower accumulated stress due to lower elastic modulus;
- an improved machinability due to lower hardness

Table 3. Summary of the most relevant mechanical properties cast iron

Property		Grey	CGI	SGI
Tensile Strength	MPa	250	337	549
Elastic Modulus	GPa	105	270	340
Elongation	%	0	3.4	10
Transversal Modulus	-	0.21	0.22	0.24
Fatigue Limit	MPa	110	128	212
Thermal Conductivity	W/mK	48	37	28
Damping Capacity		1	0.35	0.22
Hardness	HB10	190	145	235

During the tests, it was also verified the possibility to obtain complex castings without integrity defects (low percentage of residual magnesium in the molten metal) and in a simpler way respecting the nodular cast iron. Moreover, it was verified that the production in CGI of castings, currently produced in grey cast iron, reduce problems of breaches or cracks during working and handling.

4. Composites

In the case of composites, the correct use of these light and reinforced materials cannot ignore the fact of being in presence of anisotropic microstructures and alternative manufacturing processes. As a consequence, with the aim at obtaining industrially sustainable results by a change in materials, mechanical designers should also abandon the traditional way to design machine tools (mainly by metal sheets and castings), including the necessity of acquiring specific competences regarding these new materials and advanced processes.

On the contrary, as reported in (Monno and Mussi, 2007), the realization of structures or parts for machine tools characterized by lightness, stiffness and damping is almost impossible without using materials such as steel, cast iron, or light alloys characterized by similar specific stiffness and scarce if not negligible features damping. The use of polymer matrix composite materials reinforced with fibers, however, can allow to obtain parts with these features apparently discordant between them, in fact, if on one side the reinforcing fibers are characterized by high specific rigidity (ratio of elastic modulus and density), the other the matrix of polymeric material guarantees high damping. Materials of this type, also permit the construction of sandwich structures with skins of composite polymer matrix reinforced with fibers with filling materials in the foam or honeycomb that can be designed so as to optimize the response to specific stresses.

In (Lee, 2004), for example, analyzes the design of the horizontal and vertical guides of a machining center with numerical control using multi-layer panels composed of layers in composite carbon fiber-epoxy resin, and inside honeycomb or foam nest. The choice of the particular type of material is linked to the intent to exploit the high modulus of elasticity of the carbon fibers and simultaneously high damping characteristic of the epoxy resins in which the fibers are embedded and the foam fills or honeycomb. Otherwise, considering the benefits offered by these advanced materials, their introduction has not been limited to the design of machine tools, but also involves other categories of production plants (as reported by (Minak *et al*. 2011) in the case of packaging).

Figure 4. Use of flexible curtains in machine tools (Schmersal, 2016)

Another and totally different example of clear advantages for wood manufacturing that are possible to be achieved by the use of reinforced polymers, is represented by the case of flexible curtains adopted for the protection of personnel from the ejection of blunt objects from the working area (as slivers from wood or broken segments of tools). Alternative to the traditional plastic boxes, rigid and bulky, a flexible barrier can be realized by overlapping several dangling slices of Kevlar reinforced textiles. These curtains, when correctly dimensioned, permits an efficient protection of workers from every ballistic risk, as demonstrated in (Pavlovic and Fragassa, 2016; Djapic *et al.*, 2016). At the same time, their flexibility better safeguards all the necessities related to the productive process as, for instance, the rapid introduction or way out of wooden semifinished products under manufacturing. In Figure 4 the use of flexible curtains with the aim at dividing the working area of a machine tool from the environment is represented (Schmersal, 2016).

5. Rubber

The increased performance demands on machine tools is a steady trend of recent years. It can be translated in terms of cycle time reduction along with the increase of the material removal capacity and the obtaining of a surface finish of higher quality piece. In this context, issues related to vibration control appear to be of major importance as they represent a limiting factor to the increase in performance. From these considerations the following activities focus on a study of vibration damping pin systems from a state of virtual modeling. The causes of vibration for machine tools can vary depending on the underlying cause. They can be induced by a not desired external forcing or following a self-regenerative phenomena (chatter). In the first case, the machine oscillates at the frequency of the source of vibration. For impulsive sources or step, as the workpiece to be machined or discontinuity of the trajectory, oscillations are manifested also to the natural frequencies of the machine. In the second case, instead, the oscillatory phenomenon is related to the interaction piece-tool and is capable of self sustaining. In this case it is essential to avoid or at least block the instability generated that devalues in a more visible that the workpiece surface finish and is reflected in the sanding capacity, up to possible breakage. Moreover, the variability of the generated from processing chip thickness can generate an oscillatory phenomenon that puts the machine into resonance.

These oscillations can be contrasted by:

- a passive approach that provides for the introduction of the vibration damping systems calibrated theoretically or experimentally measured resonance frequency,
- an active approach, which involves the use of sensors which measure the extent of oscillations and actuators that relying on measurements performed control the force in amplitude and frequency on the basis of a predetermined control algorithm.

This part of research aimed to understand and simulate the behavior of the system and of the base of the legs as the objects that are able to lower the magnitude of the oscillations. Specifically it started from the fact of studying the vibrations which were due to the cutting process, in order to be able to have a reference vibration range. At the end of the cutting process and the analysis of the reference machine tool was identified, the tool and the machining parameters that, according to the simulations, were able to send machine in chatter at frequencies between *50Hz* and *200Hz*.

The damper of any machine tool is an intermediary component able to absorb all the vibrations of the machine itself during a work cycle (Figure 5). These components are used to provide a levelled, stable base for the machinery or equipment, creating the limit of tilting, vibration, wear and noise.

In the selection of the shock absorbers, it is necessary to ensure that all support a load proportional to their size or, in other words, that they may all be loaded with the same specific load. Consequently, for a correct loading of the shock absorbers it is relevant to know:

- weight machine
- machine's center of gravity position
- media position relative to the center of gravity
- permissible load on cushion
- number of supports.

Then, it is possible to calculate the load distribution weighing on different supports and provide to select the proper dumper.

In today's market there is an excellent selection of different types of damper, between the classic ones up to those auto-leveling to accommodate every type of application. Each damper has an upper part for connection to the basement and a lower section to lean on the floor. Usually these dumpers are entirely made of steel, permitting highest resistance and lowest cost, but losing the possibility to optimize the dynamic behaviour of machine toll. Differently, dumpers can be also realized with the base in plastic or rubber and the central part in steel. Even in this case, the selection accommodates a wide range of size and weight requirements.

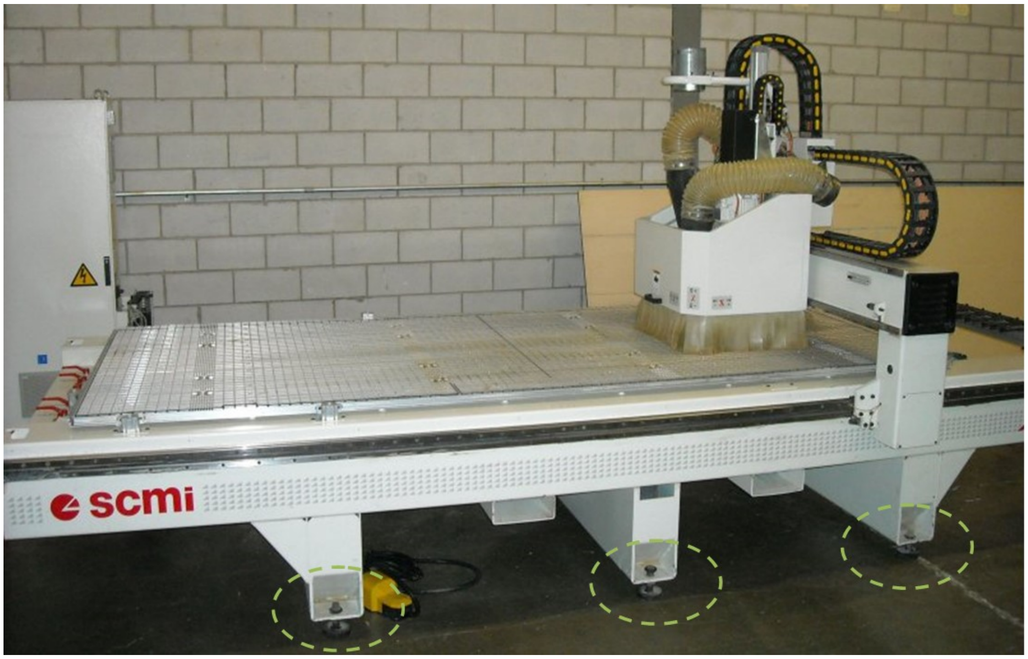

Figure 5. Machine tool with antivibration damper

In the present study three different types of vibration dampers, were investigated and compared by Finite Element (FE) simulation. These dampers are different both in terms geometry or materials. In Fiugre 6, the CAD simplification of these dampers is reported. It is possible to note:

1) the linear geometry of a rigid damper, made in steel, cheap, reliable and very common;
2) the intermediate shape of an unusual damper, characterized by a cast iron disk.
3) the multifaceted profile of a traditional shock absorber, in steel/rubber.

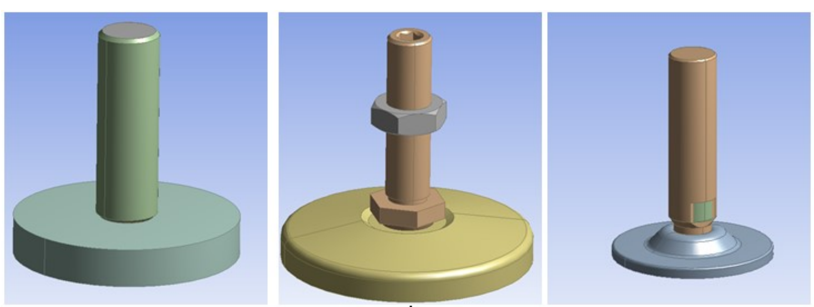

Figure 6. Antivibration dampers in the case of steel, steel/cast iron and steel/rubber

In Table 4, the mechanics properties for steel, cast iron and rubber are reported. In this last case, rubber specifically consists in a *Nitrile Butadiene.*

Table 4. Properties of materials used in antivibration dampers

Property	Unit	Steel	Cast iron	Rubber
Density	*g/cm³*	7.86	7.1	1.32
Young Modulus	-	200	169	1.1
Poisson Coefficient	*GPa*	0.30	0.275	0.5

The objective of this simulation was to evaluate the damping effect offered to the machine tool by the use of various vibration dampers. It was realized comparing the results of modal simulations.
The machine tool geometry was simplified using the concept of *concentrated masses*. A total concentrated mass of 1960kg was distributed over eight application points. Their positioning was carefully defined with the aim at correctly representing the dynamic beaviour of the machine. The modal analysis allowed to determine the vibration characteristics in terms of natural frequencies and modes for the whole frame and in the case of relevant functional components of the machine tool. The initial natural frequencies, from first to fourth, are associated with a mode of flexural vibration, from the fifth to the eighth, they are related with torsional vibrations, while, from the ninth, they return to represent flexural vibrations (Figure 7). Comparing the effects of dampers in terms on the lower natural frequencies (Figure 8), it is evident that the combination of steel and rubber represents an optimal solution as antivibration effect: all the initial twenty frequencies are lower than *50Hz* and, consequently, lower than the typical frequency of excitation of machine tools during woodworking. Adding, there are no practical difference between the use of steel or cast iron and choice has to be related to different considerations (as costs, availability, maintenability, functionality).

6. Fluids

An novel and interesting application of uncommon materials in design of machine is offered by magneto-rheological fluids. The growing interest for magneto-rheological fluids mainly derives from their ability to provide a rapid and simple interface between the electronic and the mechanical control system. Potentially, these materials have the ability to radically change the electromechanical design of the machines in which it is possible their use. For instance, in (Koo, 2003), the use of magneto-rheological dampers in Semiactive tuned vibration Absorbers to control structural vibrations is described. However, the utilization of this advanced materials is feasible only if the devices containing magnetorheological fluids demonstrate to be capable of ensuring implementation of precise and rapid movement. Part of this research investigated the behavior of a commercial magneto-rheological clutch, a device able to provide a resistive torque against a rotating shaft by changing the viscosity of fluid materials by a modification in the magnetic field (Figure 9). This clutch was able to provide a specific resistive torque, proportionally related to the current passing by the electric winding inside the device (Figure 10). In this way, it was possible to control a mechanical propriety (the torque) by modulating an electrical current. This solution can be considered very interesting where an high accuracy in torque control is requested. At the same time, it was recognized that magneto-rheological devices can affected by a significant delay between the instants of activation of signal and the application of torque. As a consequence, the demand of verify the behavior of the clutch by a direct evaluation.

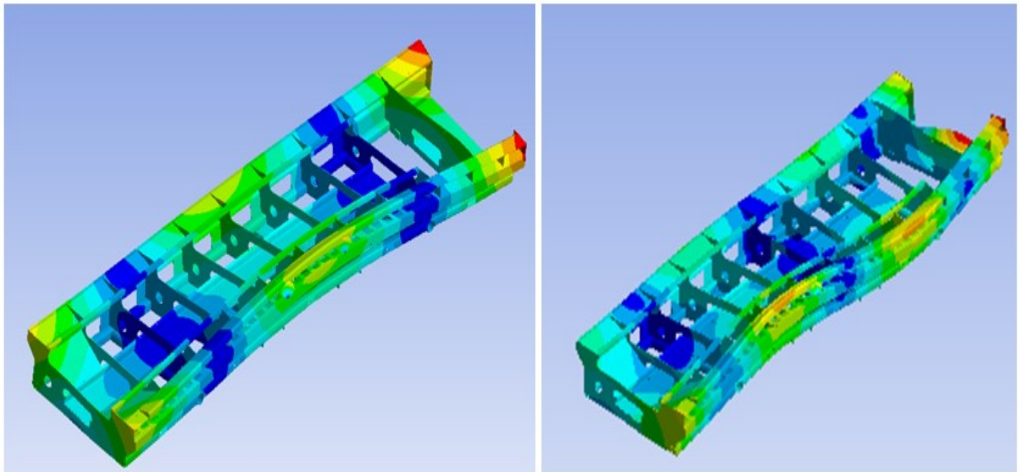

Figure 7. Deformation of frame related to flexural or torsional vibrations

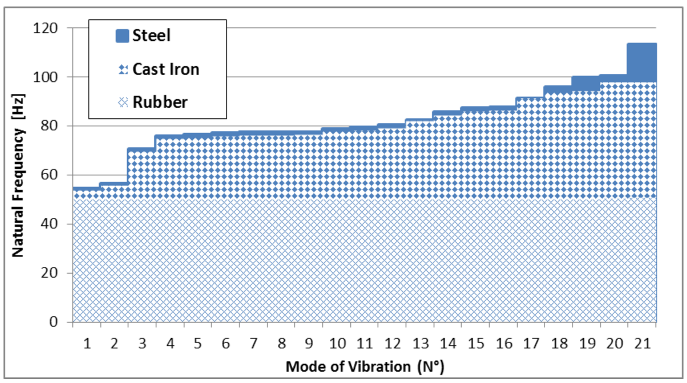

Figure 8. Natural frequencies in the case of dumpers realized with different materials

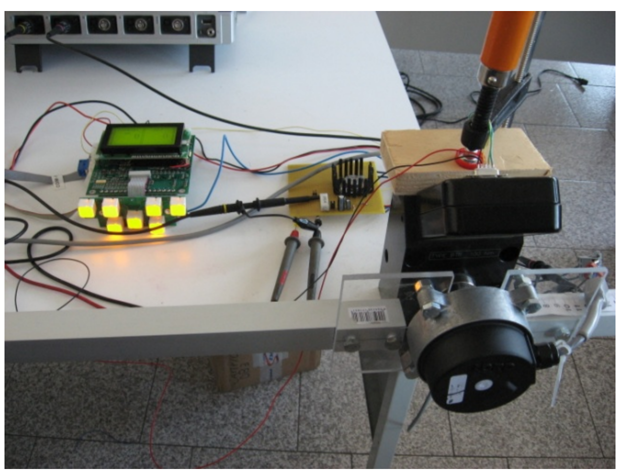

Figure 9. Experimental equipment for validating the functionality of a magneto-rheological clutch

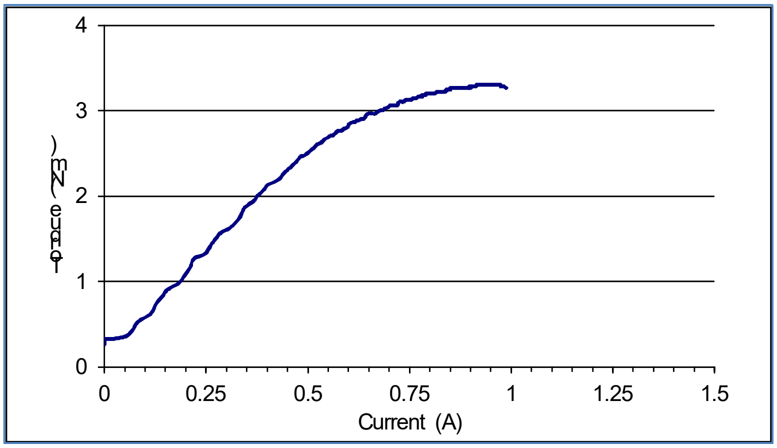

Figure 10. Curve of calibration of magneto-rheological clutch

Several tests were performed increasing the current and experimentally evaluating torque, trend and hysteresis. The experiment demonstrated the need to use software algorithms to fill the time gap between expected and measured trends, and to overcome the difficulty related to the hysteresis before using the clutch for high accuracy applications.

7. Conclusions

Historically, machine tools were purely mechanical and considerably simple. That has clearly changed. Nowadays, customer demands for greater performances and customization are also forcing manufacturers to use a wide variety of solutions to fulfill these more complex requirements. The need for intricate, multi-functional machines puts further pressure on manufacturers and their efforts to improve overall productivity and flexibility. With the aim at boost the rapid innovation, it is necessary to modify the traditional design procedures, more effectively defining and managing the complexity and interrelated requirements earlier in the conceptual design phase. Between the others aspects, changes in materials used for the realization of machine tools can represent a valid design solution for highest precision and productivity in woodworking. In fact, in this sector it is not rare that relevant advances in technology depend entirely on material changes, permitting to realize systems with new or improved functionalities. When choosing the materials for the fix structures and particularly for the motion-related components of a machine part or a piece of its assembly equipment, the physical properties of those materials are fundamental for the final performance of the plant. This paper described an overview of technical results and practical expedients, recently investigated by authors, in design of machine tools and their final effects on manufacturing. These design actions are related to the rational use of materials, sometimes very uncommon, permitting to improve the quality and precision in wood machining.

Acknowledgment: This investigation was supported by the European Union, IPA Adriatic CBC Program, inside the Adria-HUB project. More details regarding this transnational collaborative action are available in *Savoia et al.*.

References:

Angus, H.T. (2013). *Cast iron: physical and engineering properties*. Elsevier.

Ashby, M.F. (2004). *Materials Selection in Mechanical Design*. 2. ed. Oxford, UK: Elsevier.

ASM (1996). *Speciality handbook: cast irons*. United States: ASM International, 33-267.

Baicchi, P., Collini, L., & Riva, E. (2007). A methodology for the fatigue design of notched castings in grey cast iron. *Engineering Fracture Mechanics*, *74*(4), 539-548.

Blaszczyk, C., & Melon, M. *The Crucial Role of Material Selection In Machine Design*. Retrieved from: http://us.misumi-ec.com/maker/misumi/mech/tech/materialselection/

Campbell, F.C. (2008). *Elements of Metallurgy and Engineering Alloys*. Materials Park, Ohio, ASM International, 453.

Choi, J.K., & Lee, D.G. (1997). Manufacture of a carbon fibre-epoxy composite spindle-bearing system for a machine tool. *Composite Structures*, *37*(2), 241-251.

Dawson, S., & Schroeder, T. (2000). *Compacted Graphite Iron – A Viable Alternative. Engineered Casting Solutions*, in *AFS Translation*, Spring.

Dawson, S., & Schroeder, T. (2004). Practical applications for compacted graphite iron. *AFS Transactions*, *47*(5), 1-9.

Dimic, M., & Pavlovic, A. (2016). Actuality and the perspectives of the wood industry development in the countries of the Adriatic region. *International Journal of Quality Research*, *10*(1), 131-142.

Djapic, M., Lukic, Lj., & Pavlovic, A. (2016). Technical Product Risk Assessment: Standards, Integration in the ERM Model and Uncertainty Modeling. *International Journal of Quality Research*, *10*(1), 159-176.

Elliott, R. (1988). *Cast iron technology*. Butterworth-Heinemann.

Fragassa, C. (2016). Material selection in machine design: the change of cast iron for improving the high-quality in woodworking. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science. 230*(14); pp: 2499-2509.

Fragassa, C., & Pavlovic, A. (2016). Compacted and Spheroidal graphite irons:experimental evaluation of Poisson's ratio. *FME Translations*, *44*(3), 246-252.

Fragassa, C., Minak, G., & Pavlovic, A. (2016). Tribological aspects of cast iron investigated via fracture toughness. *Tribology in Industry*, *38*(1), 1-10.

Fragassa, C., Pavlovic, A., & Massimo, S. (2014). Using a Total Quality Strategy in a new Practical Approach for Improving the Product Reliability in Automotive Industry. *International Journal for Quality Research*, *8*(3), 297–310.

Fragassa, C., Radovic, N., Pavlovic, A., & Minak, G. (2016). Comparison of mechanical properties in compacted and spheroidal graphite irons. *Tribology in Industry*, *38*(1), 49-59.

Fragassa, C., Zigulic, R., & Pavlovic, A. (2016). Push-pull fatigue test on ductile and vermicular cast irons. *Engineering Review*, *36*(3), 317-322.

Hwang, H.Y., Lee, H.G., & Lee, D.G. (2004). Clamping effects on the dynamic characteristics of composite machine tool structures. *Composite Structures*, *66*(1-4), 399-407.

Koo, J.H. (2002-2003). *Using Magneto-Rheological Dampers in Semiactive Tuned Vibration Absorbers to Control Structural Vibrations*. Ahmadian, M. Tesi datt. Blacksburg, Virginia: Virginia Polytechnic Institute and State University, Lampman, S. (1996). *Fatigue and fracture properties of cast irons.* ASM International, Member/Customer Service Center, Materials Park, USA, 665-679.

Lee, D., Lee, C., Lee, H., Hwang, H., & Kim, J. (2004). Novel applications of composite structures to robots, machine tools and automobiles. *Composite Structures*, *66*(1-4), 17-39. http://dx.doi.org/10.1016/j.compstruct.2004.04.044

Lee, D., Sin, H., & Suh, N. (1985). Manufacturing of a Graphite Epoxy Composite Spindle for a Machine Tool. *CIRP Annals - Manufacturing Technology*, *34*(1), 365-369. http://dx.doi.org/10.1016/s0007-8506(07)61791-0

Minak, G., Soskic, Z., Ciric Kostic, S., & Fragassa, C. (2011) Analysis of an Automatic Wrapping Machine: Numerical Models and Experimental Results. In: Proceeding of *7th International Conference Research and Development of Mechanical Elements and Systems* (IRMES). Zlatibor, Serbia. 27-28 April 2011.

Möhring, H., Brecher, C., Abele, E., Fleischer, J., & Bleicher, F. (2015). Materials in machine tool structures. *CIRP Annals - Manufacturing Technology*, *64*(2), 725-748. http://dx.doi.org/10.1016/j.cirp.2015.05.005

Monno, M, & Mussi, V (2007). *Analysis of the problems use of materials. Traditional and innovative in sector of the machines tools: the use of innovative materials in design of machine tools*. MUSP. Retrieved from: http://www.musp.it/sites/default/files/Report%20 MUSP%206_1.pdf

Oswald, P., Friessnig, M., Reischl, P, & Rabitsch, C. (2015). Production Technology Requirements with Respect to Agile Manufacturing - A survey on how the metal forming industry can adapt to volatile times. *TEM Journal*, *4*(4), 346-350.

Pavlovic, A., & Fragassa, C. (2016). Analysis of flexible barriers used as safety protection in woodworking. *International Journal of Quality Research*, *10*(1), 71-88.

Ribeiro, I., Peças, P., Silva, A., & Henriques, E. (2008). Life cycle engineering methodology applied to material selection, a fender case study. *Journal Of Cleaner Production*, *16*(17), 1887-1899. http://dx.doi.org/10.1016/j.jclepro.2008.01.002

Rossi, M., & Mandelli, M. (2002). *Il manuale delle macchine utensili. Milano*: Tecniche Nuove.

Schmersal. *Wood: Safe solutions for your industry.* Retrieved from: http://www.schmersal.com/en/industry/wood/

SIEMENS. Advanced Machine Engineering for Industrial Machinery. Retrieved from: https://www.plm.automation.siemens.com/en_us/machinery/advanced-machine-engineering/index.cfm

Simões, C., Costa Pinto, L., Simoes, R., & Bernardo, C. (2013). Integrating environmental and economic life cycle analysis in product development: a material selection case study. *Int J Life Cycle Assess*, *18*(9), 1734-1746. http://dx.doi.org/10.1007/s11367-013-0561-9

Slocum, A. (2006). *Precision Machine Design*. Cambridge (USA): Massachusetts Institute of Technology.

Suh, J., Chang, S., Lee, D., Choi, J., & Park, B. (2001). Damping characteristics of composite hybrid spindle covers for high speed machine tools. *Journal Of Materials Processing Technology*, *113*(1-3), 178-183. http://dx.doi.org/10.1016/s0924-0136(01)00699-9

Suh, S.D., Kim, H.S, & Kim, J.M. (2004). Design and manufacture of composite high speed machine tool structures. *Composites Science and Technology*, *64*(10), 1523-1530.

Tiedje, N. (2010). Solidification, processing and properties of ductile cast iron. *Materials Science And Technology*, *26*(5), 505-514. http://dx.doi.org/10.1179/026708310x12668415533649

Tobias, S.A. (1965). *Machine tool vibration*. New York: Wiley.

Weck, M. (1980). *Handbook of machine tools vol.2 – Construction and mathematical analysis.* Chichester: John Wiley & Sons.

Giuseppe Lucisano
Consorzio Studi e Ricerche,
SCM Group
Italy
glucisano@scmgroup.com

Miladin Stefanovic
University of Kragujevac,
Faculty of Engineering
Serbia
miladin@kg.ac.rs

Cristiano Fragassa
University of Bologna,
Interdepartmental Centre for Applied Research on Advanced Applications in Mechanical Engineering and Materials
Italy
cristiano.fragassa@unibo.it