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# Suppressing tool chatter with novel multi-layered nanostructures of carbon based composite coatings

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ABSTRACT

Multi-layered nanostructured Cu and Cu–$CN_x$ composites synthesized by plasma-enhanced chemical vapour deposition were applied in the clamping area of a milling tool to suppress regenerative tool chatter. Scanning electron microscopy analysis showed a multi-layered nanostructure with excellent conformality, i.e. coating is not only uniform on planar surfaces but also around corners of the substrate. Cu:Cu$CN_x$ nanostructured multilayers with thicknesses of approximately 0.5:1.6 μm were obtained. With a diameter of 20 mm, the milling tool performed slotting processes at an overhang length of 120 mm. Modal analysis showed that a coating, with a thickness of approximately 300 μm, can add sufficient damping without losing stiffness of the tool, to increase the critical stability limit by 50% or 100% depending on cutting direction.



## 1. Introduction

Already in 1638, Galilei (1914) documented his observation on the vibration and simultaneously emitted whistling sound of a brass plate being swept with an iron chisel. As he described, a periodic pattern caused by the blade was left on the brass plate, with a distance between the lines dependent on the scraping speed. A very similar phenomenon is observed today in machining processes and is referred to as 'chatter' described by Taylor (1907). The theory of 'regenerative tool chatter' proposed by Tobias and Fishwick (1958) was a pioneer of explaining the chatter phenomenon by regenerative chatter theory.

The work of Tobias and Fishwick (1958) defined regenerative tool chatter as a self-excited phenomenon caused by the relative motion between a cutting tool and a work piece, and vibration mode. Since then, a number of studies were dealing with the theory of regenerative tool chatter, which is to be minimized or eliminated to improve the overall performance (e.g. processing speed, tool life time) of a machining tool. Such machining systems can be described by a block diagram as shown in Fig. 1.

Nomenclatures of the parameters in Fig. 1 are summarized in Table 1.

Attempts have been made to suppress the tool regenerative chatter using either passive or active methods. According to the thesis work of Daghini (2012), active methods utilize feedback monitoring of the cutting process and adjust the cutting parameters or machining system accordingly, whereas the passive approaches typically use passive control with adjusted machining parameters or improved mechanical structure properties.

Patents were filed by Smith (1966) and Andreassen et al. (1974) while providing tuned mass dampers embedded in tool holders. The concept was later applied on workpieces by Rashid and Nicolescu (2007). A further work by Yang et al. (2015) documented two degrees of freedom tuned mass dampers and increased the critical depth of cut by at least two folds.

Smith and Tlusty (1992) suggested a method to automatically regulate spindle speed and perform the process under optimized spindle speed to suppress chatter. Mei et al. (1994) found that it is possible to suppress chatter actively by online variation of cutting edge's rake and clearance angle. The rake angle's effect on cutting

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**Table 1**
Nomenclatures used in the block diagram representation of a machining system.

| $m$ | Modal mass | $\mu$ | Overlapping factor (Nigm, 1981) | $C_i$ | Velocity dependent cutting force coefficient (Altintas et al., 2008) |
|---|---|---|---|---|---|
| $V$ | Cutting speed | $\eta$ | Modal lossfactor | $\alpha_i$ | Acceleration dependent cutting force coefficient (Altintas et al., 2008) |
| $a_p$ | Depth of cut | $k$ | Modal stiffness | $x(0)$ | Initial displacement |
| $n$ | Spindle speed | $\dot{X}(0)$ | Initial velocity | $K_f$ | Specific cutting resistance (Kosaraju et al., 2011) |

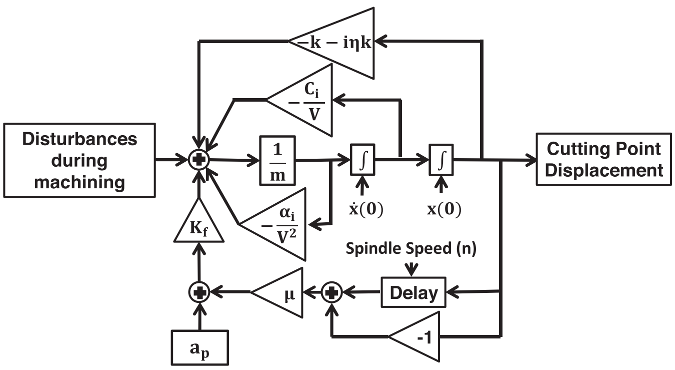


**Fig. 1.** Block diagram of a machining system and its dynamic properties concerning vibration.

force was illustrated by Kosaraju et al. (2011). Using smaller radius inserts by Ozlu and Budak (2007) and increasing feed rate by Lin (2008) were observed to suppress tool chatter by reducing overlapping factor. Shorter tools can as well eliminate tool chatter as suggested by Rama Kotaiah et al. (2010).

A piezo-electric actuator was integrated into the tool holding structure to exert a counteracting force against tooling vibration by Harms et al. (2004). Such a counteracting force was demonstrated to suppress tool chatter while attracted more practical implementation with the low cost trend of electronic devices.

The research work by Altintas et al. (2008) highlighted process damping's effect and made efforts to identify process damping's cutting force coefficients. It was proposed that reducing cutting speed could incorporate more process damping to stabilize machining processes. A time model of predicting process damping caused by various cross edge radius and flank profiles was later proposed by Ko (2015).

High damping materials can be applied in critical joint interfaces (node regions where vibrational strain energy concentrates) to improve damping properties of the structure as documented by Boden et al. (2003). Increased damping could lead to increased dynamic stiffness even at the price of decreased static stiffness. Designed-in damping in tooling structure by applying high damping viscoelastic materials (3M, 2012) was studied by Daghini (2012). Although the static stiffness of the tooling structure is reduced, the approach was shown to extend the stability limit due to the higher damping property. Adjusting normal pressure of machine tool structure's critical joint interface was also shown to increase dynamic stiffness to suppress tool chatter by FU et al. (2013b). However, these methods were at the price of reduced static stiffness.

Tuned mass dampers and high damping material in joint interfaces have been successfully applied on fixed tools, e.g. turning and grooving. However, rotating tools are still lacking feasible solutions. Moreover, a high damping material with high static stiffness applied in the critical joint area can further increase the structure's dynamic stiffness. This increase of dynamic stiffness can lift the stability limit curve even higher than that achieved by using low stiffness viscoelastic materials.

Schaller (2003) claimed metal matrix composites (MMCs) as smart choices for building up mechanical structures. Their high elastic moduli are provided by the metal matrix, while their excellent damping behaviour is a consequence of the internal friction caused by the boundary interfaces between the metal matrix and the impregnated materials. The mass density of MMCs can be kept low by applying compositions based on graphite, carbon fibre, or alike. Sahrim et al. (2011) pointed out that it is important to avoid agglomeration in order to maintain damping properties. Grain size is requested to be smaller than 20 nm to breach Hall–Petch strengthening effect and to excite grain boundary sliding suggested by Blanter et al. (2007) to improve material's internal friction for vibration damping purpose.

Composites with layered phases in the structure can eliminate the problem of nano particle agglomeration. Thus, thin film deposition methods such as plasma enhanced chemical vapour deposition (PECVD) patented earlier by Kouznetsov et al. (2013) for synthesizing MMCs are particularly attractive owing to the low process temperatures and to the bottom-up approach. With the thin film approach of the PECVD method, it is possible to obtain composites with a grain size less than 20 nm which facilitates grain boundary sliding to enhance the damping property. Moreover, the competing growth mechanism of energetic particles facilitates formulating a globular nano-crystalline structure as explained by Alami et al. (2009) and Lundin and Kostas (2012). This leads to nano-sized grains and high damping coatings.

The focus of this paper is to provide a viable solution for suppressing regenerative chatter in rotating milling tools by applying a novel carbon based composite coating with multi-layered nanostructure. The coating is used as a damping material at the clamping area of the tool. Such an approach is expected to sufficiently reduce vibrations, since most of the vibrational strain energy is concentrated in the clamping area (node regions) of the bending modes (or torsion modes) as suggested by Beranek and Vér (1992). The novelty of this study lies in the fact that, it provides a viable solution for damping vibrations in rotating tools with an extended critical stability limit of up to 100% higher compared to that of a conventional milling tool.

## 2. Experimental

### 2.1. Synthesis of the advanced MMC with PECVD method

The PECVD setup is described in detail elsewhere by Fu et al. (2013a). In brief, the reactor is evacuated first (background pressure of $\sim 10^{-3}$ Pa) followed by the introduction of process gases such as Ar (0.7–1 Pa, 50–70 sccm), $N_2$ (0.5–1 Pa, 25–50 sccm), $C_2H_2$ (0.5–1 Pa, sccm) and $O_2$ (0.1 Pa, 5 sccm). The plasma ignited in the chamber (with the typical current–voltage profiles shown in Fig. 2) served two purposes: to sputter Cu (target plate) from the cathode and to decompose the precursor gases (i.e. $C_2H_2$ and $N_2$) thus depositing Cu–$CN_x$ on the substrate. By periodic alternation of the gas composition the deposits have a periodic structure, each period corresponding to one plasma cycle. During the discharge, the plateau discharge was avoided by short pulse lengths and the utilization of only the plasma portion with high power.