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Processing and Damping Properties of Sputtered NiTi Thin Films for Tools in Machining Processes

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Nowadays, many manufacturing processes require the machining of complex forms with a high aspect ratio or cavities. Tools with a long overhang length are a common method to meet these requirements. Typical examples for this are boring bars for bore-turning and the milling with very long cutters. These tools tend to vibrate strongly due to their slender shape. The stress-induced transformation of austenite to martensite and the distinctive hysteresis loop allow the NiTi shape memory alloys (SMA) to absorb vibration energy. This article describes the innovative approach to dampen process vibrations by coating the tool shafts of cutting tools with long overhang with NiTi thin films. It explores how these thin films can be applied on polished tungsten carbide shafts and how their modal parameters are modified by these coatings. In a further step, this knowledge is used to calculate stability charts of corresponding machining processes. The study reported in this article identified the stabilizing effects of coatings with a thickness of 2-4 µm on milling processes. The minimum stability limit was increased by up to 200%.

Keywords damping, machining, NiTi, shape memory alloys, simulation, thin film

1. Introduction

Many machining processes today suffer from vibrations which reduce the possible machining parameters of modern machine tools considerably or otherwise, cause an increase of tool wear and a poor surface quality. Especially, the long and slender tools, which are used in internal longitudinal turning or in milling operations of cavities, are susceptible to vibrations due to their small axial section modulus (Ref 1). Earlier researches have shown that SMA has a high potential to dampen vibrations, especially at low oscillation frequencies (Ref 2, 3). Further investigations showed that the NiTi-alloys also have a certain damping capability when they are exposed to high-frequency vibrations over hundred cycles per second (Ref 4). Consequently, the SMA elements can reduce process vibrations when they are implemented into the tool bushing. This way, they enhance the usable parameter range of modern production processes (Ref 5, 6). Nevertheless, it is necessary to apply NiTi elements as close as possible to the tool tip to achieve the maximum damping effects, since damping is dependent on a structure's velocity. The application of NiTi thin films on tool shafts is an innovative approach to improve their damping properties. The article concentrates on the aspects of the application of the thin films as well as on the determination of their material properties. Furthermore, the study reported in this article describes the influence of the coating on the modal parameters of such tool shafts. Simulation software is used to transfer the results of the modal analysis to a modeled machining process. The resulting stability charts show the relevance of the NiTi thin films concerning stable machining processes related to the cutting depth and the revolution speed of the spindle. This allows drawing conclusions for real machining processes and offers a possible approach to optimize the NiTi coatings for tools with long overhang for ideal process stability.

2. Experimental

2.1 Magnetron Sputter Device and Characterization of NiTi Thin Films

An Alcatel 450 (DC) magnetron sputtering device was used to produce NiTi thin films. The films were sputtered in a clean room facility. NiTi 46.8 at.% targets were manufactured by cast melting (Ref 7). The base pressure of the vacuum chamber was approximately 1×10^{-7} mbar. Thin films were sputtered on 5 mm diameter cemented carbide shafts (K10, tolerance class H5, polished) by employing a specific device which allows an in situ rotation of the substrate during the sputtering process (Fig. 1) (Ref 8). NiTi films were then amorphous deposited without a shutter and with a 1.5 mm shutter width.

Thin films of NiTi were deposited on unheated substrates which results in an amorphous microstructure of the film. Subsequently, the samples were crystallized in a high vacuum chamber to avoid oxidation during the annealing process. The heat treatment was carried out ex situ by means of a rapid

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thermal annealing (RTA) system. The halogen-lamp heating chamber enables typical heating ramps of 50 K/s in a vacuum environment of about 10^{-6} to 10^{-7} mbar. The annealing temperature was held constant for 30 min at the maximum temperature of 650 °C, which turned out to be sufficient for crystallization of amorphous NiTi. In a second step, films were annealed for further 30 min at 450 °C, which is a common procedure for Ni-rich samples to induce the formation of Ti_3Ni_4 precipitates to adjust the conversion temperatures of the martensite to austenite phase transformation. The composition of the as-deposited amorphous films was determined by energy dispersive x-ray microanalysis (EDX: Oxford Instruments INCA 4.11) within a scanning electron microscope (SEM FEI—Helius). The film thickness was determined by a surface profiler (Ambios technology—XP-2). For x-ray diffraction (XRD) a Seiffert 3000 with Cu-Kα (λ = 1.54056 Å) x-ray source was used to identify the film structure as a function of annealing temperature.

2.2 Setup for Modal Testing

Modal analysis was performed to collect data about the effectiveness of the system's damping properties. The coated cemented carbide shafts (d = 5 mm) were fit into a hydrochuck tool holder. This tooling system was mounted on a massive steel base plate to minimize interfering frequencies that a real machine tool structure would show. The chosen overhang length of the cemented carbide shaft was 80 mm. This represents a very chatter-susceptible machining setup. Figure 2 shows the experimental setup.

The excitation of the tool system was performed with a shaker. The structural response was recorded with a single axis accelerometer. For controlling the measurement a Brüel & Kjaer frontend, model 7539A, was used in combination with a PC. The analysis of the frequency response takes place in a bandwidth from 0 to 600 Hz which was enough to cover the first-order vibration of the used beams. Since these beams have a large L/D ratio, the first order dominates their dynamic behavior in the later analyzed milling process. Accordingly, the excitation signal is implemented via a swept sinus from 0 to 600 Hz.

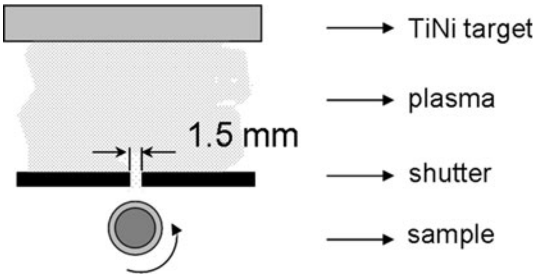

Fig. 1 Schematic of the rotational device principle

2.3 Simulation of Milling Tool Vibrations

Since the results of the modal testing of the coated beams are only the modal parameters mass m, natural angular velocity ω and damping constant γ of a single degree of freedom oscillator, they are not very meaningful to predict the behavior of real milling tools in the milling process. In order to get a preliminary guess of the influence of the tool coating, the simulation software NCChip (Ref 1) was used to obtain stability charts resulting from the modal parameters of differently coated beams which were assumed being two fluted milling tools. The simulation system used here constructs the chip shape, i.e., the shape of the material stock to be removed while the tool moves forward one tooth feed, at a position within an arbitrary NC-program as a CSG-Model (Constructive Solid Geometry) (Fig. 3). This makes it possible to compute the chip thickness at a particular rotation angle and also to assimilate the tool deflections into the chip shape in a simple and a very efficient way (Ref 1), to model the regenerative uncut chip thickness for the NC-milling process. From the chip shape, the uncut chip thickness distribution, used for determining the cutting forces, can be obtained easily by computing the difference between the entry and the exit point of a ray, like in ray tracing.

The chattering tool, or even the manufacturing system, is represented by an oscillator model which allows the prediction of the tool displacement after each step in the process using the cutting forces of the preceding step. After computing the current tool displacement the tool center point can be saved for further analysis of the vibration to generate stability diagrams by calculating the diameter of the Poincaré-section, i.e., the chatter strength.

3. Results and Discussions

3.1 Properties of the Sputtered NiTi Thin Films

The NiTi thin films were sputtered on eight cemented carbide (K10DIA, tolerance class H5, polished) samples. The thickness, the film structure, and the use of the shutter were varied, as shown in the Table 1, to understand their influence on the modal parameters of cemented carbide shafts and on the stability of corresponding machining processes.

To ensure that all samples are comparable, the stoichiometry of each sample was measured. Figure 4 shows the stoichiometric

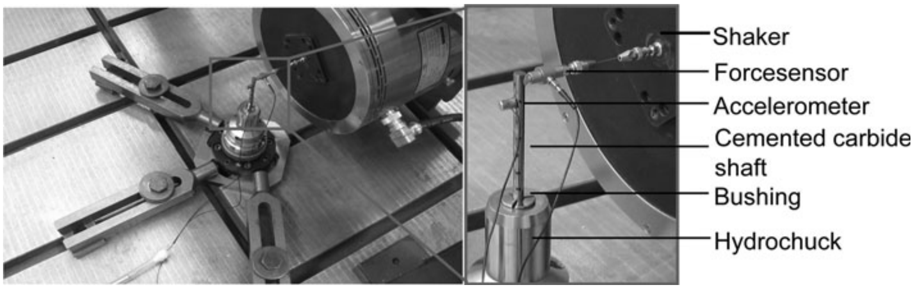

Fig. 2 Setup for the modal testing of a cemented carbide shaft in a hydrochuck tool holder

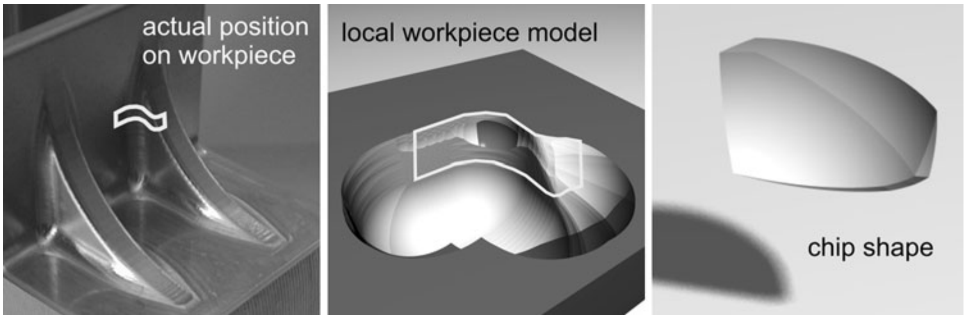

Fig. 3 Chip shape at an arbitrary position within an NC-program modeled as a CSG-object by intersecting a locally modeled workpiece with the milling tool model

Table 1 Deposited samples strategy

NiTi film thickness	Crystalline	Amorphous
2 μm		
With 1.5 mm shutter width	Sample 1	Sample 2
Without shutter	Sample 3	Sample 4
4 μm		
With 1.5 mm shutter width	Sample 5	Sample 6
Without shutter	Sample 7	Sample 8

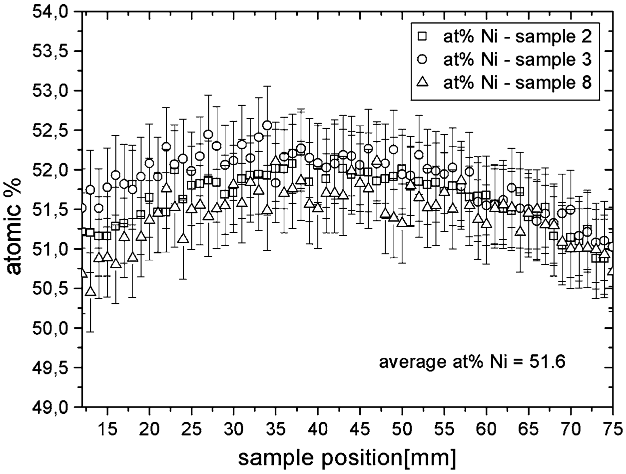

Fig. 4 Stoichiometry of the samples 2, 3, and 8. Each sample showed a very homogenous stoichiometry distribution along the sample of 51.6 at.% Ni average

results of the samples 2, 3, and 8. Each sample showed the same stoichiometry average of 51.6 at.% Ni along the sample. Before the realization of the modal tests, x-ray diffraction (XRD) was used to identify the crystallographic structure of each deposited film as a function of the annealing temperature. Figure 5 shows XRD spectra of substrate, NiTi as deposited film (amorphous), and NiTi thin film ex situ crystallized. The NiTi thin film after crystallization shows an austenite peak (110) at room temperature.

3.2 Modal Properties of Coated and Uncoated Cemented Carbide Shafts

The modal experiments concentrate on identifying the influence of the coating structure, its thickness and the way of its application. As Fig. 6 shows, the damping coefficients depend on the coatings structure as well as on the way of its application.

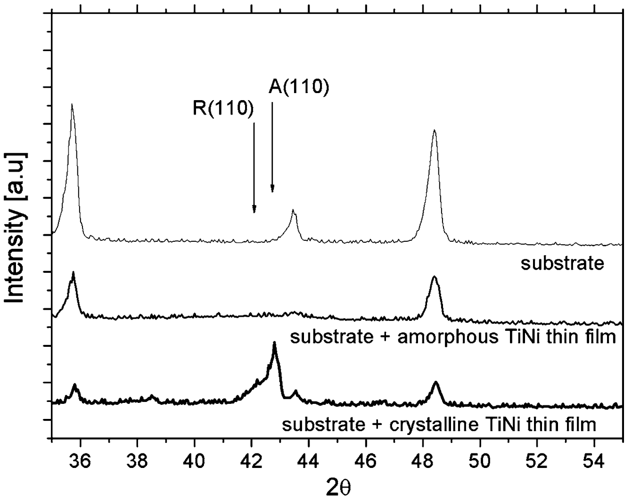

Fig. 5 NiTi film crystallographic structure as deposited (amorphous) and after annealing. The NiTi thin film after annealing shows an austenite peak (110) at room temperature

The damping coefficient γ of an amorphous structure of the NiTi coating is 14-24% higher when compared to a crystalline structured type. This result is unexpected, since amorphous NiTi does not possess the characteristic material properties of crystalline NiTi, such as super elasticity or shape memory. Especially, the distinctive hysteresis loop of the stress-strain behavior, which is supposed to be the dominating effect of the damping properties of NiTi, does not exist at amorphous material. Nevertheless, Yagi et al. (Ref 9) identified some metallic glasses to have high damping capabilities. Here, further research will be necessary to identify the damping effect of amorphous NiTi.

The use of a shutter blind in the sputter process is beneficial to the damping coefficients of the coated cemented carbide shafts. The increase of the damping coefficients ranges from 20 to 30%. The microstructure of the thin films sputtered without the shutter blind shows a nonhomogeneous growth, which can be explained by the different deposition angles during the film growth. To minimize the influence of the deposition angle, a shutter of 1.5 mm width was inserted in between the magnetron cathode and the cemented carbide substrate. The shutter was placed as close as possible to the substrate. This results in a

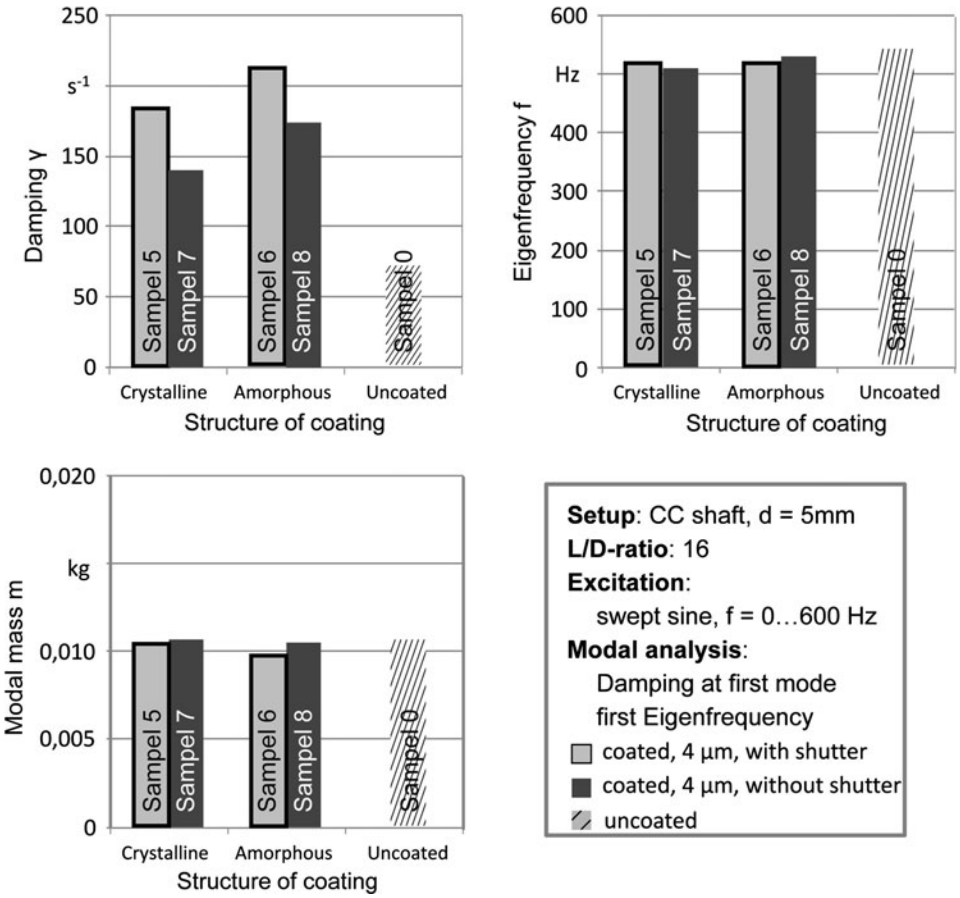

Fig. 6 Influence of the coating structure and the application technique on the modal parameters

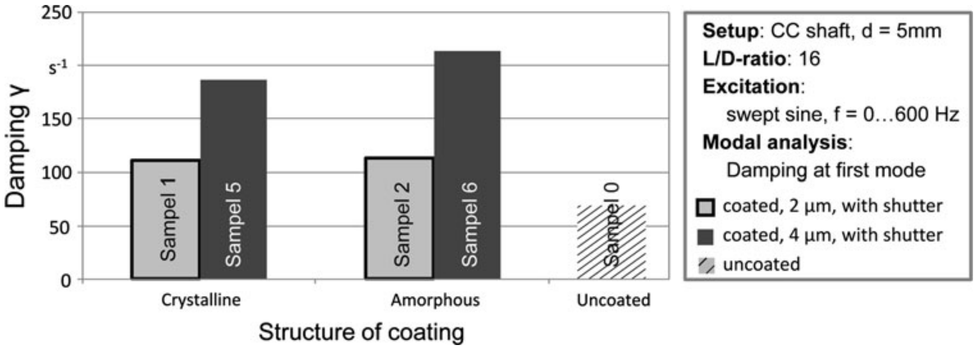

Fig. 7 Influence of the coating thickness on the modal parameters

deposition condition with an almost homogeneous particle flow normal to the rotating surface. This homogeneous particle flow causes a dense film growth without defects or local separations. Thus, the properties of NiTi alloys are more distinct and result in higher damping coefficients. Nevertheless, the NiTi thin films have always a beneficial impact on the modal damping compared to an uncoated shaft of cemented carbide, as the values of sample 0 in Fig. 8 show. The influence of the coating's thickness is obvious and more pronounced than that of the material's structure, as shown in Fig. 7. The more coating material is deposited on the cemented carbide shaft, the more chatter energy it can dissipate. The uncoated shaft shows a damping coefficient of $\gamma = 70\ \mathrm{s}^{-1}$. This value is more than tripled ($\gamma = 214\ \mathrm{s}^{-1}$) when a 4 µm coating of amorphous NiTi is applied. However, all kinds of NiTi coatings increase the damping coefficient of the substrate significantly.

3.3 Stability Charts

The simulation software described in section 2.3 is used to simulate stability charts of machining processes based on the modal parameters gathered in the modal tests. The design of the tool model indicates a chatter susceptible process with a small achievable cutting depth at stable process conditions. The machined material is Al7075—a high strength aluminum alloy. The analyzed rotational speeds of the tool range from

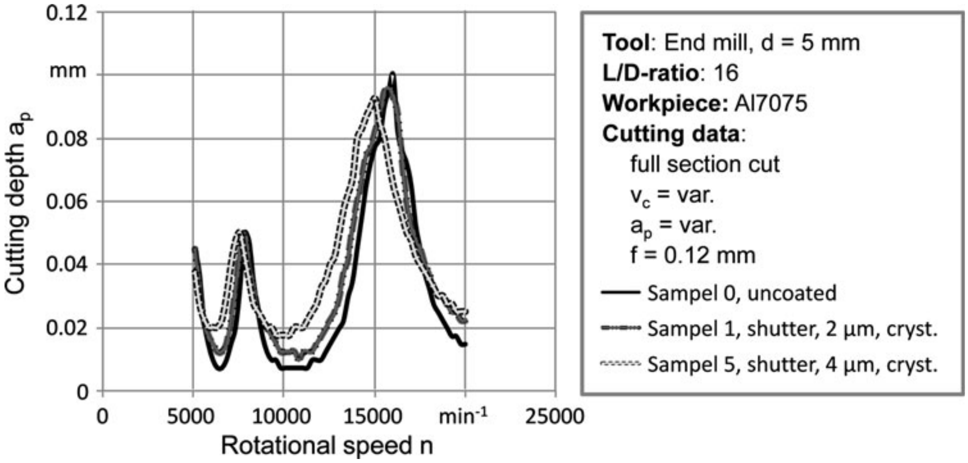

Fig. 8 Effects of the thickness of NiTi coatings on a tool shaft on stability limits in a chatter susceptible machining setup

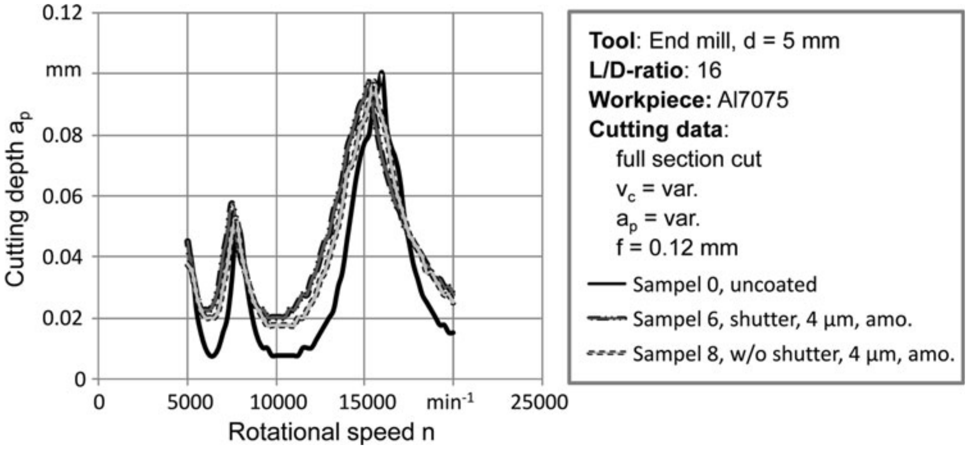

Fig. 9 Influence of the coating strategy on the machining stability

$n = 5{,}000\ \text{min}^{-1}$ to $n = 20{,}000\ \text{min}^{-1}$. Figure 8 shows the typical stability limits of milling processes depending on cutting depth and rotational speed. The stability limit of an uncoated tool shaft is compared to the stability limit of the cemented carbide shafts with 2 and 4 µm thick coatings of NiTi.

Only a small cutting depth a_p can be achieved regarding the chosen machining setup. Nevertheless, especially the minimum stability limits can be increased by a factor of ca. 2.7, rising from $a_p = 0.0075$ mm to $a_p = 0.020$ mm. A coating with a thickness of 2 µm enables a cutting depth of $a_p = 0.0125$ mm. Thus, the minimum stability limit increases proportionally with the coating thickness. These results accord with the measured values of the modal damping. The values of the maximum stability limit slightly decrease as well as the spindle frequency at these stability peaks does. This is of no relevance for real machining processes which cannot be configured in such way to work within the limits of a stability peak. This would drastically reduce the process reliability.

The influence of the coating strategy on the machining stability limits accords with the measured modal parameters of the tool shafts, too. Figure 9 depicts the stability limit of the uncoated cemented carbide shaft and the one with a coating of 4 µm. Here, the coating strategy is varied and sputtering with and without shutter blind is compared, respectively.

The difference in the resulting stability limit between the coating strategies is discernable. But the influence is not as pronounced as the modal parameters in Fig. 6 indicate. The stability limit of the coating sputtered without shutter blind lies at $a_p = 0.0175$ mm. The minimum stability limit can be increased up to $a_p = 0.02$ mm if a shutter blind is used. For an economical estimation, it has to be considered that the coating process with a shutter blind takes approximately twice the time than it does without it.

4. Conclusions

NiTi-SMAs are supposed to have a high damping potential. This has been proven especially for low-frequency excitation and thus is applied today, for example, in earthquake damping systems of skyscrapers (Ref 10). In special experimental setups, it could also be observed that compared to other materials like steel or aluminum, NiTi provides also a better damping at frequencies above 100 Hz (Ref 4). This article describes how the special properties of different NiTi SMA thin films can be used for the damping of chatter susceptible machining processes. It explains system properties regarding the damping characteristics and abilities of the used alloys.

The coating process itself proofed to be repeatable and reliable. The coating's structure can be adjusted by heat treatment after the sputter process. The use of a shutter blind allows the variation of the homogeneity of the coating's microstructure, thus influencing its mechanical properties. It could be observed that the modal damping γ was the only modal parameter to show the influence of the coating. The simulation of a chatter susceptible milling process showed that the areas of stable machining conditions could be increased significantly.

Acknowledgments

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