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Investigation of the interfacial damping characteristics of passively damped components in ultrasonic frequency range

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Abstract

Machining components made of brittle materials with the highest requirements in terms of form and surface tolerances represents a technological challenge in industrial environment. Ultrasonic vibration-assistance in milling processes is one of the most promising approaches. According to the current state of the art, vibrations are transmitted to the machine system, which reduces the service life of the applied spindle bearings. To reduce the expansion of these high-frequency vibrations in the machine system, numerous solutions were developed, which can only be integrated into rotating machine components to a limited extent. This study shows an innovative approach to vibration damping based on the integration of inserts into the base material of the machine component. For this purpose, cylindrical damping inserts made of EN-GJL-250 were installed into test specimens. Based on their frequency responses, the damping properties were determined. Furthermore, the effects of the surface pressure of the inserts on the overall damping behaviour were investigated by varying the geometric interference. As a result, it was shown that the damping ratio can be significantly increased by targeted use of interface damping.

Keywords: high-precision machining, ultrasonic vibration-assisted machining, structural damping, material damping

1. Motivation

The machining of high- and ultra-precision components, whether for direct use or for replication using injection moulding processes, results in high demands on the machining setup. Undesired vibrations of the tool or machining system are one of the most significant factors affecting machining results in high- and ultra-precision machining. For this purpose, the aim of this work is to investigate a passive vibration damping method that optimises structural damping by integrating cylindrical inserts into components of the machine structure. The basic dependencies of the surface pressure p_s and the surface roughness Ra with the damping characteristics are analysed below.

2. Material and structural damping

The damping of solid-state vibrations is fundamentally caused by the dissipation of energy from the vibrating system. Damping effects can be divided into external and internal damping. In external damping, the energy is dissipated into the surrounding atmosphere, e.g. in the form of sound waves. The inner energy dissipation ΔE leads to an increase in the vibrating systems temperature ϑ_{vib} due to internal friction effects [1]. However, the effects of internal damping are only effective if a relative movement takes place between two or more surfaces. These displacements can occur at dislocations and defects in the crystallographic structure or at micro-cracks within the material structure (material damping). It should be noted that material damping should not be considered as a material constant due to its strong dependence on ageing effects [2]. In addition, relative movements can also be present at interfaces of component assemblies (structural damping). Figure 1 illustrates these key damping mechanisms schematically.

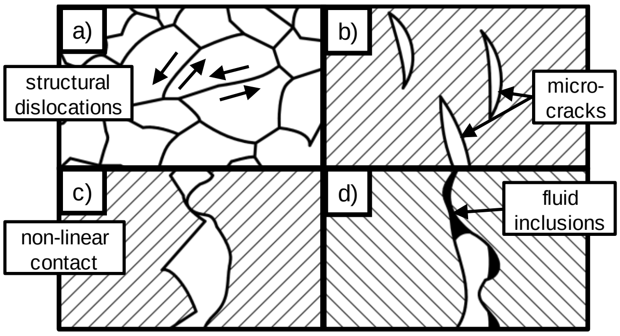

Figure 1. Main damping causes a) dislocations in crystal structure; b) micro-cracks; c) irregular interface conditions; d) fluid inclusions at the interface

In 1957, Löwenfeld [3] demonstrated that the connections between machine components exert a more significant impact on an assemblies overall damping than the material damping of individual components. For this reason, the damping effects occurring at bolted, riveted or welded joints were investigated in numerous scientific studies. Petuelli [4] examined the influence of joint surface pressures p_s on damping characteristics and found that an increase in surface pressure p_s substantially hinders relative movements, resulting in a reduced damping behaviour. The investigations by Brendel [5] showed that the damping significantly increased by filling the joints with liquid. Consequently, the use of interface damping through the targeted introduction of precisely defined separation and joining points represents a promising approach to the damping of high frequency vibrations on machine components.

The main factors influencing the damping properties are the surface pressure p_s and the surface roughness Ra, which are analysed in more detail [3, 4, 6].

3. Specimen Design

In order to record the interface damping independently of the material damping, test specimens were produced using same materials and same base geometries. Therefore, the variations of the specimens only affected the design of the interfaces in terms of surface roughness Ra and surface pressure p_s. The main bodies of the test specimens were made of C45 steel blocks, each with five holes drilled with a diameter of D = 10 mm. As damping inserts, cylindrical pins from grey cast iron type EN-GJL-250 with a length of l = 30 mm and a diameter of D = 10 mm were manufactured. In order to realise different surface pressures p_s between the main body and the cylindrical inserts, the holes in the main body are manufactured slightly smaller with defined diameter undersizes D_{uz}. To investigate the influence of the surface roughness Ra, the bores in half of the specimens were additionally reamed, which resulted in an improvement in surface roughness of Ra = 12 µm (drilled) to Ra = 2 µm (reamed). The damping inserts were integrated in advance by heating the main bodies to $\vartheta = 600\,°C$, which resulted in a widening of the holes due to thermal expansion. Based on this, the resulting surface pressure p_s at the interface was determined by calculation, which is also shown in Table 1 [6].

Table 1. Overview of the specimens' interface conditions

No.	Surface roughness Ra in µm	Diameter undersize D_{uz} in µm	Surface pressure p_s in N/mm^2
1	12	40	306
2	12	70	608
3	2	40	342
4	2	70	645
5	Reference - no damping inserts		

4. Modal- and Frequency Response Analysis

The vibration characteristics of the specimens were analysed using modal analysis and frequency response analysis. The modal analysis provides information on the natural vibration behaviour of the specimens, while the frequency response analysis shows the specimens behaviour under forced vibration excitation. The modal analysis was carried out using an impulse hammer excitation type 9722A of the company Kistler AG, Winterthur, Switzerland. The vibration response of the specimens caused by the impulse excitation was measured using a triaxial accelerometer type HT356A44 of the company PCB Piezotronics, Depew, USA. The resulting damping ratio D was determined using the half-power bandwidth method, analogue to [7]. As part of the frequency response analysis an ultrasonic transducer with an excitation frequency of $f_{ex} = 40$ kHz was used. It was bolted to one side of the test specimen. The amplitude a_{in} of the input vibration was measured using a laser-doppler-vibrometer type OFV-503 of the company Polytec GmbH, Waldbronn, Germany. The resulting vibration amplitude a_{out} was measured at the opposite side of the ultrasonic transducer. The degree of damping was represented by the amplitude reduction Δa, calculated as $\Delta a = a_{out} - a_{in}$. Consequently, the damping ratio D and the amplitude reduction Δa can be considered as comparable measures of the damping properties of the specimens, each for a natural and a forced vibration.

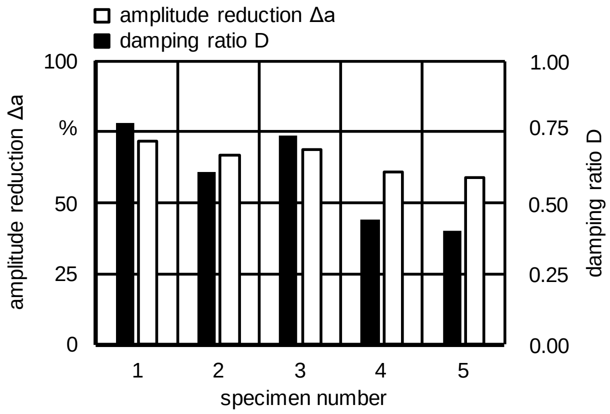

Figure 2. Results of the modal analysis (damping ratio D) and the response analysis (amplitude reduction Δa)

5. Experimental Results

Figure 2 summarises the experimental results, which could be obtained. The amplitude reduction Δa and the damping ratio D could be increased in all cases by installing damping inserts. Specimen No. 1 showed the largest amplitude reduction of Δa = 78 % and the highest damping ratio of D = 0.78. The smallest increase in amplitude reduction Δa and damping ratio D was observed for specimen No. 4. The improvements in damping found are significantly more pronounced in the natural frequency range than for forced vibrations with $f_{ex} = 40$ kHz. On average, the damping ratio D could be increased by 60 % for all samples compared to the reference specimen No. 5 (natural vibration), but the amplitude reduction only by Δa = 8 % (forced vibration) with $f_{ex} = 40$ kHz (Figure 2).

6. Conclusion

The described correlations between surface pressure p_s, surface roughness Ra and damping properties are consistent with established theoretical models. They are describing a reduction in the possible relative displacements at the interface and consequently a reduction in the damping properties. It could be shown that the ability of the specimens to dampen vibrations decreases with increasing surface pressure p_s. Furthermore, it could be determined that a lower surface roughness Ra shows a negative effect on the damping properties. Using this approach, vibrations in the machine structure can be specifically damped without adding an external energy. This work is supported by the funding program Zentrales Innovationsprogramm Mittelstand (ZIM) by the Federal Ministry for Economic Affairs and Climate Action (BMWK), Berlin, Germany.

References

[1] Frank, M.; Jaeger, M.; Groschup, B.; Hameyer, K.: Strukturdynamische Werkstoffdämpfung von Blechpaketen elektrischer Maschinen. Elektro- und Informationstechnik 193 (2022), S. 167 - 175.

[2] Bangsong, Y.; Xuanpu, D.; Rong, M.; Shuqun, C.; Zhang, P.; Hongjiang L.: Effects of heat treatment on microstructure, mechanical properties and damping capacity of Mg–Zn–Y–Zr alloy. Mat. Science and Engineering 594 (2014), S. 168 – 177.

[3] Löwenfeld, K.: Die Dämpfung bei Werkzeugmaschinen. Der Maschinenmarkt 63, 1957.

[4] Petuelli, G.: Theoretische und experimentelle Bestimmung der Steifigkeits- und Dämpfungseigenschaften normalbelasteter Fügestellen. Aachen, RWTH Aachen, Diss., 1983.

[5] Brendel, H.: Zur Schwingungsdämpfung von Fugenverbindungen. München, TU München, Diss., 1990.

[6] DIN 7190-1, Teil 1, (02.2017), Berechnungsgrundlagen und Gestaltungsregeln für Pressverbände. Berlin: Beuth.

[7] Beards, C. F.: Structural Vibration: Analysis and Damping. Oxford: Butterworth-Heinemann, 1996.