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Review

Bridging surface engineering and vibration attenuation: A tribo-dynamic perspective for manufactured mechanical systems

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Abstract: The attenuation of vibration is one of the most important requirements in the manufacture of mechanical systems which are required to meet high speed, high load, light weight and precision control requirements. A traditional approach to vibration control is to redesign the structure, use passive damping or isolation systems, or use active control; the dynamic properties of the surface and interfaces are considered secondary. The aim of the present review is to adopt a surface-centered point of view by discussing how surface engineering can be used to achieve vibration attenuation by regulating the stiffness in contact, stabilizing the friction, damping at the interface, suppressing wear and enhancing the integrity of the surface. Functional coatings, solid lubricant films, viscoelastic layers, surface texturing, micro/nanopatterning, mechanical surface treatments, architectures for additive manufacturing (AM), and smart adaptive surfaces are critically discussed with regard to their vibration-control mechanisms and limitations. The focus is on tribo-dynamic coupling, i.e., coupling between friction, wear, lubrication and vibration, which can either dampen or amplify the dynamic response, depending on the feedback mechanisms between the components. The review also examines experimental characterization, multi-scale modelling, and applications in bearings, gears, machine tools, rotating machinery, automotive systems, aerospace components, robotics and biomedical devices. An integration of tribology, material science, manufacturing and structural dynamics is emphasized for effective vibration attenuation at surfaces. Standardized testing, predictive modeling, durability assessment, and system-level design frameworks are key to future progress. The surfaces of engineered systems should therefore be considered as more than just a physical barrier, but as a functional dynamic interface that can act as a quieter, more efficient, and more reliable mechanical system.

Keywords: surface engineering; vibration attenuation; tribo-dynamics; functional coatings; manufactured mechanical systems

1. Introduction

In manufactured mechanical systems, vibration is a phenomenon that cannot be avoided, and it will occur under the influence of rotating imbalance, reciprocating motion, gear meshing, defects in the bearings, contact between frictional components, fluid–structure interaction, machining processes and external excitation [1]. For instance, in many engineering systems, over vibration is not just a nuisance to the operator, but it has a significant impact on dimensional accuracy, energy efficiency, structural integrity, acoustic performance, service life and safety. Vibration can cause degradation of bearings and shafts for high speed rotating machinery [2]. Regenerative chatter is considered one of the biggest challenges in machine tools since it reduces productivity and compromises surface quality. Unwanted vibration has a significant impact on comfort and control accuracy, fatigue resistance and reliability in vehicles, aircraft, precision instruments and robotic systems. With the growing development of modern manufacturing to lightweight structures, miniaturized components, high-speed operation and multifunctional mechanical assemblies, the requirement for vibration attenuation has become an integral part of the design and operation of advanced mechanical systems [3].

Traditional approaches to vibration control, structural redesign, passive damping, active control, and isolation mounting, have proven effective in large-scale systems where space, mass, and design flexibility are abundant [4]. However, modern mechanical systems are trending towards lightweight construction, higher power density, miniaturisation, and multifunctional integration. These trends reduce inherent structural damping, increase the surface-to-volume ratio, and make interfaces the dominant factor in system dynamics. Consequently, conventional methods often become impractical, overweight, or insufficient for compact, high-performance assemblies [5]. This limitation creates a pressing need for alternative strategies that operate at the very locations where vibration energy is generated and transmitted – namely, the surfaces and interfaces of contacting components.

In this review, the term "surface-centred point of view" refers to a design methodology wherein surface properties (roughness, coating architecture, residual stress, texture, etc.) are treated as active design variables for vibration control, rather than passive by-products of manufacturing. Likewise, "attenuation" is used consistently to denote three interrelated effects: (i) reduction of vibration amplitude at specific frequencies, (ii) flattening of resonance peaks, and (iii) increase in energy dissipation per cycle. The relative importance of each mechanism depends on the operating regime [6, 7].

Surface engineering is the intentional modification of the surface of a component to enhance its mechanical, tribological, chemical, thermal or functional properties [8]. Common techniques include coating deposition, surface texturing, laser treatment, shot peening, burnishing, nitriding, carburizing, polishing, surface alloying, severe plastic deformation, and the design and manufacturing of surfaces using additive manufacturing methods. The common techniques used are in order of use to improve wear resistance, corrosion resistance, fatigue strength, lubrication performance, and thermal stability [9]. However, their function in vibration attenuation has been approached in a more indirect and/or secondary manner. A coating, for instance, can be formulated to decrease friction and wear in a bearing, but it can also change the contact stiffness, damping, friction-induced instability, and noise generation. A textured surface can also help retain lubricant, and alter the dynamic interaction between the sliding/rolling interfaces. The peened surface can have compressive residual stress and refinement of the grain structure, and in addition can modify the fatigue response under vibratory stress. The examples presented here indicate that engineered surfaces can serve as protective layers and be functional dynamic interfaces.

The fundamental science that links surface engineering and vibration attenuation is that in real mechanical systems, typically, forces are not transmitted through ideal (smooth and perfectly bonded) interfaces [10]. Rather, vibration energy is frequently transmitted through rough, coated, lubricated, worn or treated surfaces. In these interfaces the energy dissipation process is dominated by the local contact phenomena involving frictional damping, micro-slip, viscoelastic deformation, asperity interaction, plastic deformation, phase transformation and interfacial hysteresis. The topology, hardness, internal stresses, architecture of the coating, adhesion with the substrate, roughness distribution, topology geometry and lubrication condition have all been found to affect how the vibration is generated, transmitted, attenuated and amplified [11]. Thus, surface properties should be viewed as active design variables for vibration control instead of by-products of manufacturing and finishing operations.

In spite of these good physical ties, the research interests of surface engineering and vibration attenuation have often been pursued separately. The main focus of surface engineering studies are tribological performance, wear mechanism, corrosion characteristics, fatigue life and surface integrity [12]. Vibration studies, however, typically are directed toward modal characteristics, damping ratios, transmissibility, dynamic stiffness, nonlinear response, and control strategies [13]. Therefore, the coupling of surface conditions and dynamics of the systems has not been fully incorporated into a single framework. This separation results in a knowledge gap: the surface modifications, which are extensively employed in manufactured mechanical systems, do not have a full characterization of their contribution to vibration attenuation, optimization and standardization.

The novelty of this review is that it tries to merge both research areas, traditionally separated by the materials used, by introducing the engineered surface as an active component of a manufactured mechanical system that can attenuate vibrations. This paper will not consider surface engineering from the viewpoint of only wear protection or review vibration control from the viewpoint of only structural dynamics; instead, the interface between surface engineering and vibration control will be discussed. It addresses the influence of coatings, textures, mechanical surface treatments, additive-manufactured surface architectures, and smart surface layers on the dynamic behavior as it impacts the contact mechanics, frictional stability, damping mechanisms, and surface–interface energy dissipation [14]. It is especially important for contemporary mechanical systems, in which the ratio of surface to volume grows, interfaces become a major factor in the performance of the system, and traditional methods of vibration control can be inadequate or impractical.

Another novelty of this review is that it is not a review of materials or idealized laboratory specimens but a review of manufactured mechanical systems. The vibration performance of a real component not only relies on the intrinsic properties of the material, but also on the manufacturing history, surface integrity, assembly state, operating circumstances and degradation over time [15]. For example, the same coating could have different damping properties when subjected to dry sliding, lubricated rolling, fretting, high temperature oxidation or impact loading. Likewise, a friction-reducing surface texture could excite or create instability in another condition of operation. This review has been put in place to put surface engineering techniques into perspective for bearings, gears, joints, machine tools, rotating machinery, aerospace components, automotive systems, robotics and precision devices so that the practical circumstances in which surface-based vibration attenuation can be effective can be highlighted [16].

Another unique aspect of the review is the inclusion of tribology, materials science, manufacturing and structural dynamics. Inherent multidisciplinarity is a feature of the vibration attenuation at engineered surfaces. It is related to the changes in surface topography, coefficient of friction, wear debris, lubrication film, adhesion between coating and substrate, residual stress, microstructure and dynamic contact stiffness [17]. These factors act on various length and time scales, ranging from the atomic scale dissipation of energy in thin films, to the modal response of components, to system level noise, vibration and harshness. Multiscale experimental methods and modeling tools such as surface profilometry, microscopy, nanoindentation, tribological testing, modal analysis, finite element simulation, contact mechanics, molecular dynamics and data-driven modeling are necessary, however, to attain a comprehensive understanding. The review will tie these methods together to offer a more comprehensive scheme for designing, testing and tuning surface treatments for vibration reduction.

The review also covers the new advanced and intelligent surface technologies. The recent advancement of laser surface texturing, multilayer and gradient coating, nanocomposite films, surface patterns inspired by nature, architected lattice surfaces and smart materials has led to new possibilities of tunable vibration attenuation [18]. Adaptive control of stiffness, damping, or friction behavior can be achieved using piezoelectric, magnetorheological, electrorheological and shape-memory surface layers. Another benefit of additive manufacturing is the possibility of designing the surface and subsurface architectures simultaneously, allowing the production of components with optimized surface and damping properties, lightweight design and functional surface response [19]. The results indicate that the vibration control solutions will in the future be integrated directly into the surfaces and interfaces of manufactured components, which will diminish the need for external vibration controlling devices.

But there are major hurdles to be overcome before surface engineering is a routinely adopted first line of defense against vibrations. The mechanisms of energy dissipation of vibration energy by engineered surfaces are often nonlinear, load dependent, frequency dependent, temperature dependent, and are influenced by wear evolution [20]. There are still very few standardized testing methods that correlate surface characteristics with vibration performance. Most experimental studies are based on short-term tribological or modal behavior, whereas industrial systems need to withstand the action of coupled mechanical, thermal, chemical and dynamic loading over a long period of time. Also, vibration attenuation optimization might not be compatible with the requirements for low friction, high hardness, corrosion resistance, manufacturability, cost, and environmental sustainability. These difficulties suggest a more comprehensive design approach to be combined with surface engineering and vibration dynamics.

The aim of this review is therefore to give an overview of the progress at the interface of surface engineering and vibration attenuation in a systematic manner. First it covers the basic mechanisms by which the surface and interface properties affect the generation, transmission and dissipation of vibrations [10]. It then provides a summary of the key surface engineering methods, namely, coatings, surface texturing, mechanical treatment, surfaces fabricated through additive manufacturing technology, and smart adaptive layers [9]. Experimental characterization techniques, modeling techniques and representative examples of manufactured mechanical systems are also reviewed [21]. Lastly, it provides an overview of the existing challenges and emerging research avenues, especially in the fields of multiscale modeling, standardized evaluation, intelligent surface design, and industrial implementation [22].

This article proposes a novel way to consider the vibration attenuation of advanced mechanical systems as dynamic functional interfaces of surfaces. This surface-centred approach is summarized in a schematic way in **Figure 1**, where the shift from classic vibration control techniques to engineered surfaces as functional dynamic interfaces is pointed out. The main idea is that vibration control is not only applicable to bulk structures, external dampers, or active control algorithms, but can also be accomplished by carefully designing the surfaces through which forces are transmitted, dissipated and transformed [4]. Thus, a surface engineering–vibration attenuation interface promises to be a viable route towards quieter, lighter, more reliable, and more efficient manufactured mechanical systems.

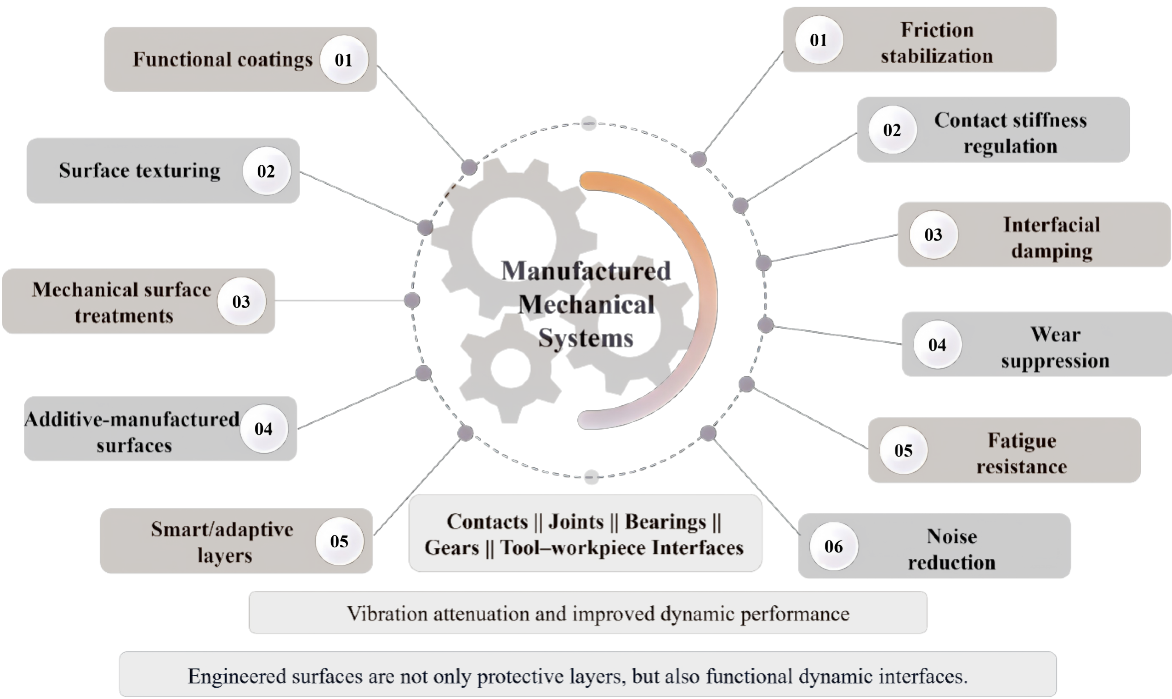

Figure 1. Conceptual framework showing how surface engineering strategies influence vibration attenuation in manufactured mechanical systems through friction regulation, contact stiffness control, interfacial damping, wear suppression, and surface-integrity enhancement.

2. Fundamentals of surface-dependent vibration attenuation

2.1. Surface and interface effects in mechanical vibration

The vibration analysis of manufactured mechanical systems is usually performed in terms of mass, stiffness, damping and external excitation. Although this framework is necessary, it frequently considers surfaces and interfaces as next to nothing but a set of secondary conditions. Vibration, however, is often produced, transmitted, modified, or absorbed by contact between components in real mechanical assemblies. Surface mediated force transfer is key to the operation of bearings, gears, bolted joints, guideways, seals, shafts, cutting tools, and sliding or rolling interfaces. Both bulk material characteristics and surface morphology, roughness, hardness, coating architecture, residual stress, lubrication state and wear evolution are important characteristics affecting the mechanical response of these interfaces [11].

The surface dependence of vibration is of particular significance in manufactured systems where most components are subjected to repeated contact, cyclic loading and varying environmental conditions [23]. Engineering surfaces have asperities, micro-defects, oxide layers, coatings, machining marks and subsurface deformation zones, which are not idealized smooth surfaces. The local variations in contact stiffness and damping change the overall dynamic response of a system. Modification of any surface condition can alter natural frequencies, change mode shapes, cause more friction induced instability or damp vibrations by adding more energy dissipation. Hence, the surface should be considered as a dynamic interface and not a fixed geometrical boundary.

An important point is that vibration attenuation by surface engineering does not just rely on increased damping. In most cases, the surface has to have five properties at once: not stick, not wear, be stiff, not fatigue and not heat up. A coating that is very compliant can help to dissipate energy but suffer from lower dimensional accuracy or load carrying capacity. Adding a hard coating can increase the wear resistance but it can also make the contact stiffer and allow the vibration to pass through more easily. A rough surface can provide stability in one operating regime, but can also create extra excitations in another. Therefore, vibration attenuation on the surface is a multi-objective problem that must take into account not only dynamics but other functional characteristics of the surface [24].

2.2. Vibration generation and transmission at contact interfaces

Mechanical vibration can be caused by various mechanisms such as imbalance, impact, gear meshing, bearing problems, reciprocating motion, flow vibration and machining instability etc. Many of these sources are affected by and dependent on conditions at the surface [25]. For instance, in rolling bearings, periodic or random excitations can be caused by microscopic roughness, defects, waviness, and lubrication breakdown. Tooth surface finish and the condition of the coating material affect the meshing stiffness, the transmission error, and noise in gear systems. The tool–workpiece interface is one of the critical factors for chatter formation, cutting stability and surface quality in machine tools. The following examples illustrate that vibration may not just be transmitted through surfaces, but that at least part of the vibration is generated by the surface itself.

The physical area of contact, asperity deformation, normal and tangential stiffness and interfacial damping are all factors which regulate the transmission of vibration through contact interfaces [26]. Since the real contact area is significantly smaller than the apparent contact area, there are microcontacts through which the force is transferred. These microcontacts deform, slip, separate or reform under dynamic loading leading to nonlinear stiffness and energy dissipation. This behavior is responsible for the fact that joints and interfaces can be major contributors to the damping of assembled mechanical systems. The interfacial damping, which is typically large in bulk material with frictional sliding, micro-slip and hysteresis, can be significant, whereas bulk material damping tends to be small in metals and ceramics.

One of the key points is the nonlinearity of the contact transmission. The stiffness between the contact surfaces can be increased with increasing preload, decreased with wear or be amplitude dependent [27]. Depending on the excitation, an interface can act almost elastically, and under higher excitation, it is possible to have partial slip and local separation. This amplitude-dependent behavior poses prediction and design problems. It also opens opportunities for surface engineering, since the contact response can be modified by means of coatings, textures, and treatments in a specific range of loads and frequencies. Therefore, in order to effectively reduce vibration, it is important to identify the vibration source as well as understand the filtering, amplifying, and dissipating effects of the surface contacts [28].

2.3. Surface-related energy dissipation mechanisms

There are a number of mechanisms by which surface-dependent vibration attenuation takes place. The most direct is frictional damping, which is the loss of mechanical vibration energy at an interface due to the relative motion of the parts [29]. This can happen via gross sliding, partial slip or microscopic asperity movement. Frictional damping has a substantial effect on vibration amplitude in layered structures, bearings, and sliding contacts (bolt joints). But it is not always desirable that frictional damping be present. Too much or too little in a fluctuation can result in stick–slip, squeal, chatter, or fretting damage. The goal is not to maximize the friction but to ensure stability and control of the frictional energy dissipation.

For example, frictional damping typically becomes significant when contact pressures range between 0.1 and 10 MPa and excitation frequencies lie below 1 kHz; above this range, wave-propagation effects and coating stiffness often dominate. Viscoelastic polymer coatings exhibit peak loss factors near their glass-transition temperature, with useful damping typically observed over a frequency band of 10 Hz to 5 kHz, depending on thickness and bonding conditions. These frequency- and load-dependent behaviours must be understood quantitatively to select the appropriate surface strategy [30–32].

Another significant mechanism is viscoelastic damping for polymer coatings, elastomeric layers and constrained layer systems [33]. These materials exhibit a lag in stress and strain with cyclic deformation, allowing for dissipation of energy during the repeated vibration cycles of the material. The coatings are desirable because they can be applied to existing structures without significant structural redesign. They are limited by temperature sensitivity, deterioration with aging, load dependence and tribological harshness. If the system is intended for high temperature or high load, the use of purely viscoelastic solutions might not be sufficient, unless they are paired with metallic, ceramic, or hybrid coating architectures.

Vibration energy could also be lost due to plastic deformation or microstructural changes in the vicinity of the surface. Residual compressive stress, work hardening and grain refinement are induced by surface treatments like shot peening, laser shock peening, ultrasonic nanocrystal surface modification, burnishing, etc [34]. These changes may improve resistance to fatigue and/or change the absorption or distribution of vibratory stress. However, if not controlled properly, damage accumulation is typically associated with plastic energy dissipation. If a surface dissipates energy by repeated plastic deformation, it can eventually crack, wear or become out-of-shape. This reinforces the importance of differentiating between “damping” (as in being beneficial) and “damaging” (as in being energy loss).

In coated systems, further dissipation can also take place at the coating-substrate interfaces, in multilayer structures or be caused by internal defects and phase boundaries [35]. Multilayer and gradient coatings can scatter elastic waves, lower stress concentration and present interfacial hysteresis. However, if the adhesion is not strong enough, or the mismatch between moduli is too high, then delamination can occur under cyclic loading. The effectiveness of such systems relies on the interfaces adding no energy to the system that can be a failure initiation site. This is one of the main challenges in surface engineered vibration attenuation.

2.4. Influence of surface morphology, roughness, and texture

The influence on the surface morphology is important for the vibration behaviour since it determines the contact formation, lubrication, local stiffness and frictional stability [36]. While many people consider it an undesirable imperfection in manufacturing, the phenomenon of roughness in vibration attenuation is more complicated. Moderate roughness can enhance frictional damping through asperity interaction and micro-slip, while too high a degree of roughness can, of course, cause excitation, wear and noise. When the surface is very smooth, the friction and wear can be reduced, but the interfacial damping can be reduced, and adhesion or stick–slip may occur under certain conditions. Hence, there is not a rigorous monotonic connection between roughness and vibration and it is greatly influenced by operating conditions.

These dynamic effects can also be added by introducing a surface waviness and periodic texture [37]. A geometric excitation source that can generate periodic vibration is the waviness of rolling elements, gear teeth or guideways. However, carefully engineered surface roughness, like dimples, grooves, or hierarchical patterns, can enhance lubricant retention, mitigate fluctuations in friction, and ensure more consistent contact dynamics. It can have a negative or positive effect on the body, depending on the type of geometric pattern and its use on the body. This difference is of significance in manufacturing since surface characteristics cannot be judged by only using average roughness indicators. Dynamic response parameters such as parameters of the texture directionality, spatial distribution, skewness, kurtosis and functional bearing area are sometimes more relevant.

New opportunities for vibration attenuation have been opened up by laser surface texturing and micro/nano-patterning. The shape, density and direction of surface features can be controlled to create the potential to manipulate hydrodynamic pressure, debris trapping, stiffness of contact and friction damping [38]. But the design space is large and challenging to generalize. A material that works well in a lubricated sliding application may not work as well in a dry contact or rolling application. Friction can also be reduced by making textures frictionless, as can frictional damping. The question is then not about whether or not texture is beneficial, but rather whether or not the texture is appropriate to the vibration mechanism, contact regime and service environment. Importantly, moderate roughness ($Ra \approx 0.2–1.0\ \mu m$) can enhance interfacial damping via asperity micro-slip under dry or boundary-lubricated conditions, while excessive roughness ($Ra > 2\ \mu m$) often generates additional harmonic excitation. Very smooth surfaces ($Ra < 0.05\ \mu m$) reduce damping and may promote stick-slip instability. Thus, the relationship is non-monotonic and regime-dependent [39].

2.5. Contact stiffness, damping, and tribo-dynamic coupling

Contact stiffness and damping play an important role in the dynamic behavior of manufactured mechanical systems. The contact stiffness represents how forces are transferred through an interface and the contact damping represents how much energy is lost due to vibration [40]. The surface topography, material properties, preload, lubrication, temperature and wear influence both properties. Unlike the bulk stiffness, the contact stiffness is nonlinear and can change during operation. The dynamic response of the system may vary over time as surfaces become worn, polished, oxidized or gather debris. This renders surface dependent vibration attenuation a process that is time dependent, and not a material performance characteristic.

The relationship between tribological processes and dynamic motion is known as tribo-dynamic coupling. Vibration can alter friction and wear due to changes in contact pressure, speed of sliding, film thickness of the lubricant and temperature. On the other hand, vibration can be altered by friction and wear, which alters the excitation force, damping, clearance and surface geometry. This feedback loop is the source of such problems as brake squeal, gear noise, bearing vibration, fretting fatigue and machining chatter. This loop can be broken or deflected by surface engineering, either to stabilize friction, decrease wear, or increase controlled damping [41]. However, if the surface is not designed properly, the loop can be intensified and self-excited vibration can occur.

An important problem is that the tribo-dynamic behavior can be frequency and regime dependent. Interfacial slip and frictional dissipation may be predominant at low frequencies. Wave propagation, coating stiffness and local resonance could also be more important at higher frequencies. The film thickness, pressure distribution and squeeze film effect can cause the lubricant film to either damp the vibration or cause instability under lubricated conditions. Thus, surface engineering techniques should be considered only on the basis of dynamic rather than static friction or wear experiments [16]. The traditional tribological parameters are not enough to describe vibration attenuation.

2.6. Surface integrity and manufacturing-induced dynamic behavior

The term “surface integrity” is used to describe the synergistic effect of surface topography, residual stress, surface microstructure, hardness, defects and subsurface deformation resulting from the manufacturing process [42]. It plays an important role in the connection between manufacturing processes and vibration performance. Any surface modification including machining, grinding, polishing, heat treatment, additive manufacturing, peening and coating deposition, will result in different surface signatures. These signatures impact not just fatigue and wear, but also dynamic stiffness, damping, and contact stability.

Residual stress is of special significance when vibrating loading. Peening and burnishing are effective methods for creating compressive residual stress, which can have a positive effect on the fatigue life of components subjected to cyclic vibration, thereby delaying the onset of cracks [17]. However, there is also the possibility that a residual stress gradient will affect local stiffness and distortion. Surface hardening may decrease the vibration induced by wear, but can also increase the risk of brittleness or contact noise if the surface properties are not appropriately matched to the substrate. In addition to this, the surfaces created in Additive Manufacturing may have a high roughness, presence of partially melted particles, pores and anisotropic microstructures. These features can cause increased damping in some cases, but can also act as sources of excitation or as fatigue initiation sites.

This suggests that there may be no distinction between surface engineering for vibration attenuation and manufacturing quality control. The surface treatment which can be seen as beneficial in the laboratory samples can behave differently on the complex industrial geometries. Dynamic performance is influenced by process repeatability, the uniformity of the coating thickness, adhesion, surface cleanliness and post-treatment finishing [43]. Thus, surface integrity should not just be seen as a quality inspection result, but rather as a design parameter.

2.7. Design implications for manufactured mechanical systems

The basics outlined above indicate that surface engineering is a strong but complicated route towards vibration attenuation. Its biggest advantage is that it can be applied to the specific areas where vibration occurs or is transmitted, such as contacts, joints, sliding interfaces, rolling elements, and functional surfaces [22]. This renders surface-based methods particularly appealing for small or lightweight systems where traditional dampers cannot be used. It can be applied to just the outer layer making this a relatively low mass change while still changing the overall dynamic stability.

But the design of surface engineering to achieve the desired vibration attenuation is not trivial, and must be carefully designed to combine material science, tribology, dynamics and manufacturing. Not necessarily the hardest, smoothest, roughest or most heavily damped surfaces are optimal. Rather, it’s the surface that determines the combination of stable friction, appropriate contact stiffness, controlled energy dissipation, wear resistance, fatigue strength and environmental durability. The balance is different for different applications [9]. A gear system might need to have low transmission error and high surface durability, whereas a bolted joint may need to have controlled micro-slip. The friction stability of a machine tool may be required to prevent chatter, while a precision instrument may have a very low requirement for disturbance transmission.

In general, the basic function of surfaces in vibration damping is the role of energy transfer mediation at interfaces [29]. A good engineered surface not only can cause vibrational energy to be dissipated, scattered, stabilized or redirected, but can also generate noise, instability and degradation if it is poorly engineered. The central question, then, is how to change the characteristics of these surfaces from wear-resistant walls to designed dynamic interfaces. This outlook lays the groundwork for the surface engineering approaches to be presented in the next section. The main surface and interface factors that affect vibration attenuation are summarized along with the advantages, disadvantages, and common applications in **Table 1**.

Table 1. Surface-dependent mechanisms of vibration attenuation.

Surface/interface factor	Main vibration related mechanism	Positive effect on vibration attenuation	Possible limitation or risk	Typical mechanical systems	Quantitative boundary conditions
Residual stress	Crack suppression and fatigue resistance under cyclic vibration	Delays vibration-induced fatigue failure	Excessive stress gradients (>500 MPa) may cause distortion or cracking	Turbine blades, springs, gears	Compressive residual stress >200 MPa beneficial
Lubrication film	Squeeze-film damping and friction stabilisation	Reduces contact fluctuation and dynamic instability	Film breakdown ($\lambda < 1$) may amplify vibration and wear	Bearings, piston systems, seals	Damping coefficient $\propto$ viscosity × (film thickness)$^{-3}$
Surface texture	Lubricant retention, debris trapping, contact regulation	Improves friction stability and reduces dynamic excitation	Poor texture design may introduce periodic force fluctuation	Bearings, seals, sliding pairs	Texture depth 1–10 µm, density 5–20% area
Coating-substrate interface	Interfacial hysteresis and wave scattering	Adds energy dissipation in multilayer systems	Weak adhesion causes delamination under vibration	Coated gears, tools, aerospace parts	Adhesion strength >50 MPa to avoid dynamic failure
Residual stress	Crack suppression and fatigue resistance under cyclic vibration	Delays vibration-induced fatigue failure	Excessive stress gradients (>500 MPa) may cause distortion or cracking	Turbine blades, springs, gears	Compressive residual stress >200 MPa beneficial

In summary, the mechanisms discussed above demonstrate that surfaces are not passive boundaries but active dynamic interfaces. Their influence on natural frequencies, damping ratios, and transmissibility is governed by contact stiffness, micro-slip, and local energy dissipation, all of which are controllable through deliberate surface engineering. This fundamental understanding underpins the specific strategies presented in the next section.

3. Surface engineering strategies for vibration attenuation

3.1. Functional coatings and thin films

Functional coatings are one of the most studied surface engineering approaches to enhance the mechanical, tribological, and dynamic behavior of the mechanical entities that are manufactured [17]. Coatings are useful in vibration attenuation applications because they can modify the interaction of contacting surfaces without any significant modification of the bulk geometry or structural design. The effects of their influence on vibration are primarily manifested as changes in the contact stiffness, frictional stability, wear resistance, interfacial damping, and acoustic emission. Coatings can either dampen vibrations by suppressing vibrations generated by friction, or by enhancing energy dissipation, preventing surface degradation, or changing the way waves propagate at the surface.

Hard coatings like diamond-like carbon, titanium nitride, chromium nitride, alumina, carbides, and other ceramic/oxide/nitride based films are used to enhance hardness, wear resistance and dimensional stability. They can provide benefits that are often indirect and substantial in the field of vibration. Hard coatings are capable of eliminating surface damage, adhesive wear and roughness evolution, thereby eliminating sources of vibration during long-term service. Maintaining stable surface geometry is important to control dynamic excitation in gears, bearings, cutting tools and sliding components. If the hard coating is too stiff or not sufficiently matched to the substrate, it can, however, increase the contact stiffness at the location and decrease the frictional damping, which can increase the transmission of vibrations. Hence, the dynamic functionality of hard coatings is not only determined by its hardness but also by its elastic modulus, thickness, strength of adhesion, residual stresses and compatibility in the contact regime [44].

Alternatively, coatings that use soft materials and solid lubrication, such as molybdenum disulfide, graphite, polytetrafluoroethylene, and polymer-based films, offer another way to achieve vibration attenuation [45]. Such coatings minimize friction fluctuation and quench stick–slip vibrations and noise that are the primary cause of self-excited vibration and noise in sliding contacts. They can create stable transfer films, which can enhance dynamic smoothness and decrease high frequency excitation. However, if the coefficient of friction is low, that does not necessarily mean that the coefficient of damping is high. Vibration attenuation is sometimes required in certain systems due to frictional energy dissipation and too low friction can lead to low interfacial damping. Further, soft coatings can also experience creep, wear, thermal degradation or failure under loads. For this reason, their most useful application is in cases where a high load-bearing capacity is not needed and friction stability is more significant.

Viscoelastic and elastomeric coatings are more likely to be directly related to vibration attenuation, since they absorb mechanical energy by inducing molecular relaxation within the coating [46]. As free layers or constrained layers, these coatings add a phase lag between the stress and the strain which will decrease the amplitude of vibrations and acoustic radiation. They are especially appealing for precision devices, panels, exposed components, and panel housings that are subjected to moderate dynamic loads. Their performance, however, is highly temperature, frequency, thickness and bonding dependent. An optimized coating for one frequency range may be ineffective at a different frequency range. This frequency-dependence constrains the application to be universal, but also provides possibilities for custom damping design.

One more sophisticated approach is the use of multilayer, gradient, and composite coatings, which combine different mechanical and damping characteristics within a single surface system [47]. Gradient structure can help to reduce stress concentration and enhance adhesion, and interfaces between layers can introduce energy dissipation at interfaces, which can scatter elastic waves. These coatings are promising for high performance systems which cannot meet all requirements in a single material. The key is ensuring that added interfaces don't become delamination weak planes, but energy dissipating features. However, the coating design should not only cover the conventional tribological optimization, but also incorporate the dynamic properties including loss factor, contact damping, acoustic response, and cyclic adhesion durability for vibration attenuation.

3.2. Surface texturing and micro/nano-patterning

Surface texturing is the process of creating controlled micro or nanoscale features on the surface of a part that alter the topography of the surface, e.g., dimples, grooves, pits, channels, ridges or hierarchical features [38]. In contrast to random roughness resulting from manufacturing flaws, engineered texture is engineered to affect contact mechanics, lubrication, debris retention and frictional behavior. Surface texture is an important characteristic of many vibration problems, and the possibility of controlling vibrations at the source is attractive.

For lubricated contacts, surface textures can be used to provide micro-reservoirs of lubricants, improve the hydrodynamic pressure, decrease the variation of friction, and retain wear debris [48]. The effects can be stabilizing to sliding or rolling motion and minimize vibration from impact (debris) or from lubricant starvation or intermittent adhesion. Textures can enhance tribological and dynamic characteristics in manufactured components such as bearings, seals, guideways and piston–cylinder systems, if they are well-designed. But it is important that the texture design must be compatible with speed, load, lubricant viscosity and contact geometry. A lubricating texture may not be film-forming under other conditions, resulting in further excitation or wear.

In dry or boundary lubricated contacts, textures affect the real area of contact and local pressure distribution. They can minimize adhesive contact or cause a controlled micro-slip, thus preventing stick–slip motion and friction-induced vibration. Some textures can also give rise to extra hysteresis due to deformation of asperities which leads to more energy dissipation. However, undue texture depth or density can decrease load-bearing area, increase stress concentration and create periodic fluctuations and forces. This is especially a problem when texture spacing and sliding speed or rotational frequency are combined, which triggers the excitation at characteristic frequencies. So the value of texture does not necessarily lie in the fact that it stabilizes the dynamics; it is when it is more stabilizing than it is exciting that it has a value [49].

It has captured great attention as one of the most interesting techniques due to its high precision, flexibility in pattern control and ability to process metals, ceramics, polymers and coatings. There are other techniques like lithography, chemical etching, micro-machining, abrasive jet process and patterning via additive manufacturing which also offer interesting ways for certain materials and scales. There's also been interest in bio-inspired patterns, like those found in shark skin, lotus leaves, and the scales of reptiles, which are often able to control both friction and fluid management, as well as resist damage. To engineer bio-inspired concepts into mechanical vibration control, however, more than just geometric replicas are needed. The texture should be assessed under realistic loading, speed, temperature and degradation conditions [37].

The main scientific challenge in surface texturing for vibration attenuation is the lack of universal design rules. Texture geometry affects multiple coupled variables, including friction coefficient, pressure distribution, lubricant film thickness, contact stiffness, thermal behavior, and wear evolution [50]. As a result, optimization must consider not only steady-state friction reduction but also transient dynamic response, noise generation, and long-term stability. Future texture design will likely rely on combined tribological testing, modal analysis, numerical simulation, and data-driven optimization to identify patterns that are dynamically robust rather than merely tribologically efficient.

3.3. Surface mechanical treatments

Surface mechanical treatments modify the near-surface region through plastic deformation, residual stress generation, work hardening, and microstructural refinement [42]. Techniques such as shot peening, laser shock peening, ultrasonic nanocrystal surface modification, deep rolling, burnishing, and severe plastic deformation are widely used to improve fatigue life, wear resistance, and surface integrity. Their relevance to vibration attenuation lies in their ability to change how surfaces respond to cyclic loading, contact stress, and vibration-induced damage.

Shot peening and laser shock peening introduce compressive residual stresses that delay crack initiation and growth under repeated loading [34]. In components exposed to vibration, such as turbine blades, springs, shafts, gears, and aerospace structures, fatigue resistance is closely linked to vibration durability. By strengthening the surface and reducing crack sensitivity, these treatments do not necessarily reduce vibration amplitude directly, but they reduce the damage caused by vibration. This distinction is important. Some surface treatments attenuate vibration energy, while others improve resistance to vibration-induced failure. Both functions are valuable, but they should not be confused.

Ultrasonic nanocrystal surface modification and related severe plastic deformation methods refine surface grains and increase hardness while often improving residual stress distribution [51]. These microstructural changes can influence damping through dislocation activity, grain boundary motion, and localized plasticity. However, the relationship between grain refinement and vibration damping is complex. Higher hardness may reduce wear and stabilize dynamic response, but excessive hardening may reduce intrinsic material damping or increase brittleness. Similarly, residual compressive stress improves fatigue performance but may introduce distortion or alter contact stiffness. Effective use of these treatments, therefore, requires a balance between strength, stability, and damping.

Burnishing and deep rolling are especially relevant for precision mechanical systems because they improve surface finish while introducing beneficial compressive stress [34]. Smoother and harder surfaces can reduce vibration sources associated with roughness, waviness, and wear. At the same time, reduced roughness may decrease frictional damping at interfaces. This illustrates a recurring trade-off in surface engineering: a surface optimized for low wear and low friction may not always provide maximum vibration attenuation. For assembled systems, controlled micro-slip may be beneficial, whereas for precision sliding systems, friction stability and low excitation may be more important.

Mechanical surface treatments are attractive because they are scalable and compatible with many industrial components [52]. However, their dynamic effects are often evaluated indirectly through fatigue or wear tests rather than direct vibration measurements. To fully exploit these treatments for vibration attenuation, future studies should connect surface integrity parameters with modal damping, contact stiffness, transmissibility, and noise response. Without this connection, the vibration benefits of surface mechanical treatments will remain largely empirical.

3.4. Additive manufacturing-enabled surface design

The possibilities of surface and subsurface design that additive manufacturing has opened up include complex geometries, lattice structures, graded materials, and controlled porosity, which would be difficult or impossible to manufacture using traditional manufacturing methods. In the field of vibration attenuation, additive manufacturing has a two-fold significance. First, high roughness, partially melted particles, stair steps, pores and anisotropic microstructures are often present in as built surfaces and these features can significantly affect the vibration behavior. Secondly, additive manufacturing can be used purposefully to create surfaces and near-surface architecture to increase damping or wave attenuation [9].

Surface roughness and defects are considered disadvantages when using additive manufacturing methods because these can lead to shorter components' fatigue life and wear [53]. These may also cause vibrations due to irregular contact, stress concentration and unstable friction. If there is uncontrolled surface roughness in rotating or sliding parts, it may be a significant source of noise and dynamic excitations. Hence, post-processing techniques like machining, polishing, chemical finishing, heat treatment, peening and coating are frequently necessary. These processes not only enhance the appearance of the component but also alter the dynamic boundary conditions of the component.

Coordinately, additive manufacturing can produce a surface architecture that can dissipate or direct vibration energy [9]. Porous skins, lattice layers, cellular structures, and graded surface zones can decrease the effective stiffness, scatter elastic waves, and can increase internal friction. Architected surfaces can be engineered either as local damping layers or phononic structures which can dampen specific frequency bands. This is especially useful for lightweight applications such as aerospace, automotive, robotics and precision systems where the addition of mass is not desirable. The damping function can be built into a produced component rather than adding an external damper.

But there are key challenges to the use of additive manufacturing to achieve vibration attenuation. Process-induced defects, anisotropy, residual stress and material variability can influence the correlation between designed architecture and actual dynamic behavior. The geometry and porosity of the lattice can vary slightly, affecting the frequencies to be absorbed and/or mechanical reliability. In addition, architected surfaces have to be capable of satisfying the following requirements: wear resistance, cleanability, dimensional accuracy, fatigue life, and manufacturability. Therefore, additive manufacturing is not a “one size fits all” strategy, but rather a tool for combining surface function, structural design and dynamic control [14].

The most potential path is the union of AM and post-processing/coating technologies. A vibrating lattice or a graded surface can be printed on a component, which is then treated or coated for better wear resistance and contact stability. These combined methods can be helpful in dealing with the drawbacks of any single method. They also need design tools that are integrated to predict the surface performance and the system dynamics [52].

3.5. Smart and adaptive surfaces

Smart and adaptive surfaces are new strategies in surface engineering that involve changes in the surface properties when the external conditions or stimuli change [54]. Adaptive surfaces are to be tuned in real-time or semi-actively, in order to adjust the friction, stiffness, damping, shape, or interfacial behavior. This is very useful for mechanical systems with variable vibration properties due to varying speed, load, temperature, wear or environmental conditions.

Piezoelectric surface layers can transform mechanical deformation into electrical energy, and can also be used for active or semi-active vibration control [55]. They can be integrated on structural surfaces or contact surfaces to perform sensing, actuating, and/or energy harvesting. They have speedy response and can be compatible with control systems. But piezoelectric layers tend to be brittle and sensitive to bonding quality, temperature and fatigue. Their implementation on complex contact surfaces, especially with the presence of wear and impact, is still challenging.

Magnetorheological (MR) and electrorheological (ER) surface layers can be made softer or stiffer depending on the magnetic or electric field. These materials exhibit a fast change in mechanical response which can be applied to adaptive vibration isolation, clutches, mounts and interface control [56]. They have the possibility of changing the interface damping depending on operating conditions, which is the key to their potential in surface engineering. However, they have to be generated on the field, sealed, and made durable, as well as securely attached to mechanical parts. They are more usable in a controlled assembly than in a high wear exposure contact at the moment.

Another approach to adaptive surfaces is to use shape-memory alloys or shape-memory polymers to alter the shape, stiffness or recovery stress of the surface at a specific temperature or other stimulus [57]. These can be employed to adjust contact pressure, change surface geometry and change structural damping. Self-lubricating and self-healing coatings also add to adaptive vibration control by ensuring consistent friction and avoiding wear-induced excitations. These surfaces do not necessarily act to actively suppress vibrations in the traditional control sense, but they do ensure dynamic stability for extended service lives.

The important takeaway is the concept of moving vibration attenuation from the "design" to the "condition. This is critical because many vibration issues are not static—changing over time due to wear, temperature, speed, and load. Smart surfaces, however, add complexity, cost, and reliability issues [57]. They will be successful if they can deliver adaptive functionality while maintaining durability, manufacturability, and safety.

3.6. Integrated design considerations

The surface engineering approaches mentioned above are not standalone but should be viewed as complementary. In the real world, a mechanical system may incorporate coatings, textures, surface treatments, additive manufacturing, and smart materials [58]. A textured surface could be coated, a peened component could be polished, an additively manufactured lattice could be given a damping layer, and a smart surface could be protected with films. These hybrid methods are generally superior to any single method, as they must simultaneously control vibrations, friction, stiffness, damping, wear, fatigue, and environmental stability.

The general design concept is to optimize the surface strategy in accordance with the dominant vibration mechanism. Frictional instability may be the most effective type of vibration to stabilize with friction; coatings and/or textures might be the most effective solution [59]. Then, if the vibrations are transmitted through joints, there may be a need for controlled damping between them. Direct damping may not be as vital as residual stress engineering when vibration-induced fatigue is the primary concern. Architected additive surfaces might be useful for situations where weight reduction and broadband attenuation are needed. Thus, selecting a treatment should be the last step in the surface engineering process, and a dynamic diagnosis of the surface system should follow.

Finally, there is a need to shift from "trial and error" surface modification to "mechanism-based" surface engineering to control vibrations. The most successful surfaces will be those that combine tribological durability and predictable dynamic function. Close coupling to surface characterization, vibration testing, numerical modeling and manufacturing control are required. The design of mechanical systems as engineered dynamic interfaces can also reduce vibrations from external systems or even by redesigning the contact and boundary layers that are responsible for creating, transferring, and dissipating vibrational energy [60]. The comparative assessment of the main surface engineering strategies, their dominant functions in vibration control, advantages, and limitations is presented in **Table 2**.

Table 2. Comparison of surface engineering strategies for vibration attenuation.

Surface engineering strategy	Representative techniques/materials	Dominant vibration-control function	Major advantages	Key challenges
Hard functional coatings	Diamond-like carbon (DLC), TiN, CrN, Al_2O_3, carbide/nitride coatings	Wear suppression, contact stability, stiffness regulation	High durability, reduced surface degradation, improved service life	May increase contact stiffness; risk of cracking or delamination
Solid-lubricant and soft coatings	MoS_2, graphite, polytetrafluoroethylene (PTFE), polymer-based films	Friction stabilization and stick–slip suppression	Reduces friction fluctuation and noise generation	Limited load capacity, thermal sensitivity, and wear degradation

Table 2. *Cont.*

Surface engineering strategy	Representative techniques/materials	Dominant vibration-control function	Major advantages	Key challenges
Viscoelastic damping coatings	Polymer layers, elastomeric coatings, constrained-layer coatings	Direct energy dissipation through internal damping	Effective vibration amplitude reduction, easy surface integration	Frequency- and temperature-dependent behavior
Surface texturing	Laser dimples, grooves, hierarchical micro/nano-patterns	Lubrication control, debris trapping, contact stiffness tuning	Can reduce friction instability and improve tribological performance	Requires careful design; may introduce geometric excitation
Surface mechanical treatments	Shot peening, laser shock peening, burnishing, and ultrasonic surface treatment	Fatigue resistance, residual stress engineering, surface strengthening	Improves vibration durability and crack resistance	Direct damping effect may be limited or difficult to quantify
Additive manufacturing-enabled surfaces	Lattice skins, porous layers, and graded surface structures	Wave scattering, lightweight damping, local stiffness tailoring	Enables integrated structural and surface design	Process variability, roughness, defects, and post-processing needs
Smart and adaptive surfaces	Piezoelectric layers, magnetorheological films, shape-memory surfaces	Tunable damping, stiffness, friction, or sensing response	Adaptive response to changing operating conditions	High complexity, cost, integration, and durability issues

3.7. Selection guidelines for surface engineering strategies

Choosing the most appropriate surface treatment for a given vibration problem requires matching the dominant excitation mechanism to the surface function. **Table 3** provides a decision-oriented summary:

Table 3. Selection guidelines for surface engineering strategies.

Vibration problem	Recommended surface strategy	Key dynamic metric to target	Avoid if…
Friction-induced squeal/chatter	Solid-lubricant or low-friction coatings; surface texturing to stabilise μ	Coefficient of friction variation ($\Delta\mu < 0.05$)	High contact pressure (>50 MPa) without support
Resonance amplification (high Q-factor)	Viscoelastic or constrained-layer coatings	Loss factor >0.1 in target frequency band	Temperature >80 °C or high cyclic stress
Vibration-induced fatigue (crack initiation)	Shot peening, laser shock peening, or burnishing	Compressive residual stress >200 MPa	Thin sections (<1 mm) prone to distortion
High-frequency noise (>5 kHz)	Hard coatings with high acoustic impedance; micro-texturing for wave scattering	Surface acoustic impedance mismatch	Coating delamination risk under impact
Broadband vibration (multiple modes)	Additive-manufactured lattice skins; graded or multi-layer coatings	Broadband loss factor, no sharp peaks	Process variability and post-processing costs
Precision positioning/low-amplitude vibration	Smooth (Ra <0.1 μm) with controlled microtexture; compliant polymer layers	Contact stiffness linearity and low hysteresis	Creep or aging of polymer layers

This decision framework is not exhaustive but illustrates the principle that the dynamic function not just tribological performance must guide the choice of surface engineering.

4. Characterization, modeling, and applications in manufactured mechanical systems

4.1. Bridging scales and methods

A central challenge in surface-engineered vibration attenuation is the mismatch between the microscopic length scale of surface features (nanometres to micrometres) and the macroscopic scale of system vibration (millimetres to metres). To bridge this gap, experimental characterisation, modelling, and application studies must be connected through well-defined transfer relations. For example, surface roughness and coating stiffness (measured via profilometry and nanoindentation) serve as inputs to contact-mechanics models that calculate contact stiffness and damping. These contact parameters then feed into finite-element or multibody dynamic models that predict natural frequencies, transmissibility, or force response at the system level. The following subsections elaborate on each of these interconnected levels, with explicit cross-references showing how data from one method informs another [61–64].

4.2. Experimental characterization methods

The effectiveness of surface engineering for vibration attenuation cannot be evaluated solely through surface inspection or conventional tribological testing. Because engineered surfaces influence vibration through coupled mechanical, tribological, and dynamic mechanisms, characterization must link surface conditions to system-level responses. This requires a combination of surface analysis, contact testing, modal characterization, and operational vibration measurement. A major challenge is that surface properties are often measured at the micro- or nanoscale, while vibration attenuation is usually assessed at the component or system scale [65]. Bridging this scale gap is essential for reliable interpretation.

Surface morphology is commonly examined using optical profilometry, stylus profilometry, atomic force microscopy, scanning electron microscopy, and three-dimensional surface reconstruction [66]. These techniques provide information on roughness, waviness, texture geometry, asperity distribution, coating defects, wear scars, and surface degradation. However, average roughness parameters alone are insufficient for predicting vibration behavior. Parameters related to spatial distribution, skewness, kurtosis, bearing area, texture directionality, and wavelength content are often more relevant because they influence contact stiffness, lubrication, and excitation frequency. Therefore, surface characterization for vibration attenuation should move beyond simple roughness reporting and toward functional topography analysis.

Material and microstructural characterization are equally important. X-ray diffraction can evaluate residual stress and phase composition. At the same time, Raman spectroscopy, transmission electron microscopy, nanoindentation, and microhardness testing can reveal coating structure, hardness, elastic modulus, and local mechanical response [67]. These properties determine whether the engineered surface behaves as a stiff protective layer, a compliant damping layer, or a graded interface. Adhesion and cohesion tests are particularly important for coated systems because vibration and cyclic contact can accelerate delamination. A coating that performs well in static wear tests may fail under dynamic loading if its interface cannot sustain repeated shear and normal stress.

Tribological testing provides insight into friction coefficient, wear rate, lubrication behavior, stick–slip tendency, fretting response, and surface durability [68]. Pin-on-disk, ball-on-disk, reciprocating sliding, rolling contact, fretting, and high-temperature tribometers are commonly used. Nevertheless, many tribological tests are conducted under steady or simplified conditions, whereas real mechanical systems experience variable loads, vibrations, impacts, temperatures, and lubrication conditions. For vibration-related studies, tribometers should ideally be combined with force sensors, acoustic emission monitoring, and vibration measurements to analyze friction fluctuations and dynamic response simultaneously.

Dynamic characterization methods include impact hammer testing, shaker excitation, modal analysis, transmissibility measurement, operational vibration monitoring, laser Doppler vibrometry, and acoustic emission analysis [69]. These methods quantify natural frequency, damping ratio, mode shape, vibration amplitude, noise radiation, and frequency response. Their integration with surface analysis allows researchers to identify how coatings, textures, treatments, or wear evolution alter dynamic performance. The critical issue is repeatability. Small differences in preload, mounting condition, surface cleanliness, humidity, or lubrication can strongly affect contact damping. Therefore, standardized test protocols are necessary if surface-engineered vibration attenuation is to progress from laboratory demonstration to industrial design.

4.3. Multiscale modeling approaches

Modeling is a crucial tool for understanding surface-dependent vibration attenuation because many mechanisms are difficult to isolate experimentally. The dynamic behavior of an engineered surface can span scales ranging from atomic friction and microstructural deformations to asperity contact, component vibration, and system-level noise. All of these effects cannot be described with only one model. Rather, multiscale and multiphysics modeling techniques are needed to bridge the gap between surface characteristics and vibration response [70].

At the contact level, a rough-surface contact model is used to describe the real contact area, asperity deformation, contact stiffness, and contact damping [40]. Classical statistical models offer a convenient starting point but often rely on idealized assumptions about asperity shape, elastic deformation, and independent contacting locations. Advanced numerical contact models can incorporate measured 3D surface topography, elastic-plastic deformation, adhesion, lubrication, and thermal effects. The significance of these models is that they relate directly to contact stiffness and damping, which in turn affect vibration transmission. The predictive power, however, is sensitive to the quality of surface data and to realistic boundary conditions.

Coated, textured, treated, and assembled parts are extensively analyzed using finite element modeling. Surface textures and coatings can be modeled as thin layers with different elastic, viscoelastic, or plastic properties, and the influence of these models on local stress concentration, lubricant pressure, and dynamic contact response can be analyzed [48]. Residual stress fields and hardened layers can be applied to fatigue and vibration simulations for surface mechanical treatments. The drawback is the high computational cost, particularly when the details of surface features are incorporated into large structural models. However, it is often necessary to have simplified equivalent models; such models may lose local mechanisms.

The tribo-dynamic models are especially useful because they can account for friction, wear, lubrication, and vibration. These models can be used to explain phenomena such as brake squeal, gear whine, bearing vibration, fretting fatigue, and machining chatter. They demonstrate that vibration can not only be a consequence of dynamic excitation but also a force that initiates the evolution of the surface. During vibration, the friction coefficient, contact stiffness, wear depth, and film thickness of the lubricant can vary, which may lead to vibration feedback that can cause instability or attenuation. In these models, the effect of surface engineering can be tested by adjusting friction laws, damping parameters, texture geometry, or wear coefficients. However, calibration is not that easy, given a load- and history-dependent tribological parameter and the speed and temperature dependencies [37].

Molecular dynamics and microstructural simulations are used to give insight into atomic friction, coating deformation, interfacial sliding, phase transformation, and energy dissipation in nanostructured surfaces at smaller scales [71]. These techniques can be applied to investigate thin films, solid lubricants, and nano-textured interfaces. One weakness is that they typically use length and time scales that are much smaller than those of actual mechanical systems. Hence, they are most useful for elucidating mechanisms rather than for directly predicting vibrations at the component level.

Recently, data-driven and machine-learning models have been investigated to correlate surface descriptors with dynamic performance. These models can detect hidden correlations and optimize surface design by combining surface images, roughness parameters, coating properties, operating conditions, and vibration signals. They are, however, a function of good data quality, physical interpretation, and testing in other operating conditions. Predictions based on data alone may not generalize well when applied outside the training environment. The most promising is physics-informed modeling, where machine learning is used to augment, not supplant, contact mechanics, tribology, and structural dynamics [72]. The feedback relationship among surface evolution, tribological behavior, and system-level vibration response is represented in **Figure 2**, emphasizing why surface engineering must be evaluated under coupled dynamic operating conditions.

4.4. Applications in bearings, gears, and rotating machinery

Applications of surface engineering for vibration attenuation are among the most important, including bearings, gears, shafts, seals, and more [59]. This is achieved through repeated contact and is highly susceptible to surface defects, surface roughness, surface waviness, lubrication instability, and wear-induced degradation. Periodic excitation, broadband noise, or progressive damage can result from even minor surface irregularities. So, surface condition control plays a key role in reducing vibration and improving reliability.

Engineered coatings and surface finishes in rolling bearings can help minimize adhesive wear, micropitting, smearing, and lubricant degradation [73]. Stable surfaces keep surfaces rolling smoothly and limit vibration signatures caused by defects or roughening. Conventional lubrication cannot be applied in vacuum, dry, or high-temperature environments; in such cases, solid lubricant coatings may be of assistance. However, coatings should not crack or delaminate under repeated Hertzian contact stress. A reduced-friction coating may introduce new failure modes if it does not resist rolling contact fatigue.

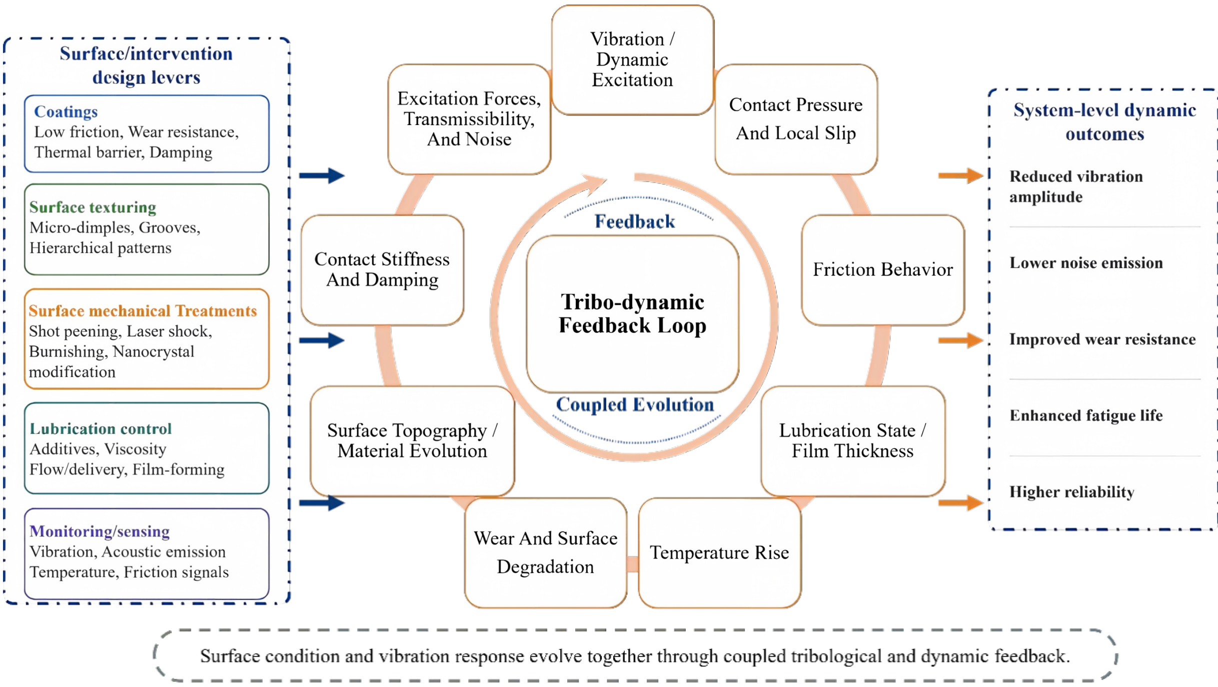

Figure 2. Tribo-dynamic coupling loop showing the feedback relationship among vibration, contact mechanics, friction, lubrication, wear, surface degradation, and system-level dynamic response.

Surface engineering influences gear contact stiffness, friction, wear, transmission error and acoustic radiation [74]. Stabilizing the meshing interface by hard coatings, superfinishing, shot peening, or laser texturing can increase durability and decrease noise. But the dependence of gear vibration on tooth geometry and load distribution makes it impossible to compensate for poor macro geometry and misalignment through surface engineering. It works best in combination with gear design, lubrication monitoring, and high-precision manufacturing.

Surface treatments for reduction of imbalance due to wear, fretting at joints, and fatigue due to cyclic vibration are also useful for the rotation of machinery, including turbines, compressors, motors, and spindles. Vibration can quickly become amplified by surface degradation, particularly in high-speed systems, where it is not solely a function of damping. What is important to realize is that the ability of surface engineering to reduce vibration is usually indirect in rotating machinery, in that the vibration is reduced over time because the growth of the vibration source is prevented [75].

4.5. Applications in machine tools, joints, and precision systems

Another relevant field in which surface-dependent vibration is crucial is machine tools and manufacturing equipment. In machining processes, chatter is caused by the dynamic interaction between the tool, workpiece, machine structure, and process [76]. Friction, adhesion, temperature, coating condition, and surface wear govern the tool–chip and tool–workpiece interfaces. Reducing friction fluctuations, delaying wear, and enhancing cutting stability are all achievable with tool coatings. Too high or too low friction or a coating that is too stiff, can, however, change how chips are formed, sometimes in an undesirable manner that leads to chatter. Hence, the selection of coatings for machining should take into account not only tool life but also dynamic cutting behavior.

Contact stiffness and damping also play an important role in guideways, slides, spindle interfaces, and clamping systems of machine tools [77]. The influence of stick–slip and positioning accuracy can be engineered by surface scraping, texturing, coating, and lubrication designs. In precision manufacturing, small vibration amplitudes can cause significant problems with surface finish and dimensional accuracy. Surface engineering is an appealing option here because bulky damping devices are not required to enhance damping and friction stability.

Structural damping losses are frequently observed at bolted joints, press fits, and assembled interfaces. Micro-slip at the contact surfaces dissipates energy, and this micro-slip is controlled by roughness, coatings, preload, and surface treatments. Coatings or textures may be applied to adjust friction and prevent loosening, fretting or excessive slip [58]. However, micro-slip maximization may conflict with the integrity and fatigue resistance of the joints. The design intent is to manage energy dissipation at the interface without causing damage to the system.

Optical instruments, robotics, micro-positioning stages, and medical devices are applications that require low vibration transmission and stable dynamic behavior. For such applications, there is a demand for smooth motion, low wear and particle generation, and predictable damping of the surfaces. There may be value in polymer coatings and solid lubricants, micro-textures and compliant surface layers, but these will need to be carefully assessed with respect to creep, aging, contamination, and environmental sensitivity [78].

4.6. Applications in automotive, aerospace, robotics, and biomedical systems

There are solid demands for noise, vibration, and harshness control across the automotive and railway sectors [79]. Surface engineering's applications include brake components, engine parts, gears, bearings, suspension joints, and wheel–rail contacts. For instance, the issue of brake squeal relates closely to the vibration caused by friction, and hence, surface coatings, friction films and texture control are of great relevance. Surface condition influences the rolling noise, wear and vibration transmission in wheel–rail systems. But harsh, ever-changing operating conditions mean that long-term durability and consistency are as critical as the initial vibration reduction.

Aerospace systems demand lightweight structures that are highly reliable under vibration, fatigue, temperature changes, and in harsh environments. Vibration durability and damage tolerance can be enhanced through surface treatments (such as shot peening, laser shock peening, thermal barrier coating, erosion-resistant coating and architected surfaces produced using additive manufacturing). The primary value of turbine blades and aircraft structures is to limit vibration-induced fatigue, rather than to achieve a significant increase in damping. Surface-engineered vibration solutions need to be repeatable, stable over time, and fail-safe because of the strict certification requirements for components used in the aerospace industry [80].

Lightweight components, high-speed motion and precise control are getting more and more in demand for robotic systems [81]. Vibration leads to reduced positioning accuracy, higher control effort and shorter service life. Or surface coatings/textures can provide better joint stability, gear performance, actuator smoothness, and contact reliability. Compliant/adaptive surface layers that incorporate damping and flexibility can also complement soft and wearable robotic systems. The challenge is to keep the performance predictable in repeated motion and contact conditions.

Surface-mediated vibration and wear are also relevant for biomedical mechanical systems, like implants, prosthetic joints, dental devices and surgical equipment [82]. In implants, micro-motion and vibrations can affect wear debris formation, implant stability and comfort. Two of the most important areas of surface coatings and textures are biocompatibility and osseointegration, as well as wear resistance, although the dynamic effects have not received sufficient attention. In biomedical applications, any vibration attenuating surface must also meet specific biological safety, corrosion and long-term durability specifications. **Table 4** catalogs the representative applications of surfaces providing vibration attenuation across manufactured mechanical systems, relating major vibration issues, surface strategies and evaluation needs.

Table 4. Application matrix for surface-engineered vibration attenuation in manufactured systems.

Application area	Major vibration problem	Relevant surface engineering approach	Expected performance benefit	Critical evaluation requirement
Rolling bearings	Defect-induced vibration, roughness excitation, lubricant instability	Superfinishing, DLC coatings, solid-lubricant films, micro-texturing	Reduced vibration signatures, smoother rolling, improved wear resistance	Rolling contact fatigue, coating adhesion, long-term lubrication stability
Gear systems	Gear whine, transmission error, tooth wear, meshing impact	Hard coatings, shot peening, polishing, laser texturing	Lower noise, improved tooth durability, stabilized contact stiffness	Load distribution, tooth geometry, coating fatigue resistance
Machine tools	Chatter, cutting vibration, stick–slip motion	Tool coatings, guideway texturing, low-friction coatings, damping layers	Improved cutting stability, surface finish, and machining accuracy	Dynamic cutting tests, tool wear, thermal stability
Bolted and assembled joints	Joint slip, fretting, nonlinear contact vibration	Controlled roughness, anti-fretting coatings, surface treatments	Increased interfacial damping and reduced loosening	Preload sensitivity, fretting fatigue, repeatability
Automotive brake systems	Brake squeal and friction-induced vibration	Friction films, surface texturing, thermal-resistant coatings	Reduced squeal, improved friction stability	Temperature cycling, wear debris, noise testing
Aerospace components	High-cycle fatigue, blade vibration, lightweight structural vibration	Laser shock peening, thermal barrier coatings, architected AM surfaces	Improved fatigue resistance and vibration durability	Certification, thermal loading, reliability under service conditions
Robotics and precision systems	Positioning vibration, joint instability, backlash-related vibration	Solid-lubricant coatings, compliant layers, adaptive surfaces	Higher motion smoothness and control accuracy	Creep, aging, repeatability, low-amplitude vibration testing
Biomedical devices and implants	Micro-motion, wear debris, patient discomfort	Biocompatible coatings, porous surfaces, polished articulating surfaces	Improved fixation stability, reduced wear-induced vibration	Biocompatibility, corrosion resistance, long-term wear behavior

4.7. Comparative assessment and reliability considerations

Different surface engineering strategies offer different advantages and limitations. Hard coatings provide wear resistance and geometric stability, but may transmit vibration if too stiff. Soft coatings and solid lubricants stabilize friction but may lack durability under high loads. Viscoelastic coatings dissipate energy effectively but are temperature- and frequency-dependent. Textured surfaces can improve lubrication and friction stability, but may introduce geometric excitation if poorly designed. Mechanical treatments improve fatigue resistance but may not directly increase damping. Additive manufacturing enables architected attenuation but faces variability and surface quality challenges. Smart surfaces provide adaptability but introduce complexity and reliability concerns [53].

The central reliability issue is that engineered surfaces evolve during service. Wear, oxidation, fatigue, contamination, coating degradation, lubricant aging, and thermal cycling can change contact stiffness, damping, and friction [78]. A surface that attenuates vibration initially may lose effectiveness or become a new excitation source after degradation. Therefore, long-term testing under realistic coupled conditions is essential. Evaluation should include not only initial damping performance but also durability, repeatability, maintenance requirements, and failure modes.

From an industrial perspective, cost, scalability, process control, environmental impact, and compatibility with existing manufacturing lines are decisive. Surface engineering strategies must be both practical and scientifically effective. The most promising approaches are likely to be those that provide multiple benefits simultaneously, such as wear resistance, fatigue improvement, friction stability, and vibration reduction. This multifunctional value can justify implementation more readily than vibration attenuation alone [83].

4.8. Toward standardized evaluation and system-level integration

One obstacle to progress is the lack of a standardized method to measure how well vibration attenuation is achieved on the surfaces. It is difficult to compare the results of studies because they use different geometries, methods of excitation, surface parameters and vibration indicators. Measuring procedures for surface condition, contact parameters, damping, transmissibility, noise and degradation should be specified in standard procedures for the various operating conditions [40]. These standards would help to enhance reproducibility and promote industrial adoption.

This is as important as system-level integration. Surface engineering must be used in an early stage of the design process, as a variable control rather than used after the structural engineering design. Digital twins, multiphysics simulation, and condition monitoring can help with this integration by linking surface state to vibration response throughout the service life. Surface degradation monitoring using sensors, acoustic emission monitoring, and vibration diagnostics can also be used to detect degradation before failure [70].

In general, the characterization and modeling results and application studies reveal that numerous manufactured mechanical systems can benefit from surface engineering for vibration attenuation. It requires integrating micro-scale surface design with macro-scale dynamic performance. There is a need for additional predictive models, standardized testing, realistic durability testing, and integrated design models in the field. Such a combination is the only way that engineered surfaces can be used as effective vibration control components, and not just for wear or corrosion protection [20].

5. Industrial implementation and practical considerations

For surface-engineered vibration attenuation to transition from laboratory research to industrial practice, several practical factors must be addressed. Cost is a primary concern: hard coatings such as DLC or TiN typically add 10–30% to component cost, while laser texturing and peening may add 5–15%, and these additional expenses must be weighed against the savings from reduced warranty claims, extended maintenance intervals, and improved performance [84–86]. Scalability also varies widely—technologies such as shot peening, burnishing, and polymer coating are readily scalable to high-volume production, whereas laser texturing and additive manufacturing are currently limited by throughput and capital investment, though they are rapidly improving. Process repeatability is equally critical, as surface treatments are sensitive to substrate condition, cleaning, and process parameters; statistical process control and in-line surface monitoring are essential to ensure consistent dynamic performance across batches. Environmental impact is another growing consideration, since many coatings involve hazardous chemicals or high energy consumption; water-based coatings, dry-coating processes like physical vapor deposition (PVD), and recyclable materials are gaining traction to meet tightening regulations. Integration with existing manufacturing lines is a key success factor—treatments that can be applied at the final finishing stage, such as micro-texturing or burnishing, are more readily adopted than those requiring dedicated production steps. Finally, maintenance and repairability must be considered, as engineered surfaces degrade over time; strategies that allow in-situ re-treatment, such as burnishing or lubrication replenishment, or easy recoating will be preferred in long-life applications. A pragmatic implementation pathway is to adopt surface engineering in stages: first, cost-effective treatments like shot peening and polymer coatings can provide moderate improvements, while advanced techniques like texturing and multi-layer coatings can be introduced where vibration problems are critical and the performance gains justify the higher cost. In all cases, close collaboration between surface engineers, dynamicists, and manufacturing engineers is indispensable for successful industrial deployment, ensuring that dynamic performance is treated as a design parameter from the outset rather than an afterthought [7, 87–89].

6. Conclusion

This review has established that surfaces and interfaces in manufactured mechanical systems are not mere protective boundaries but active, dynamic domains that govern vibration generation, transmission, and dissipation. The evidence from functional coatings, surface texturing, mechanical treatments, additive-manufactured architectures, and smart adaptive layers demonstrates that deliberate surface engineering can achieve significant vibration attenuation, provided that design decisions are based on a mechanistic understanding of tribo-dynamic coupling rather than empirical trial-and-error.

Several key insights emerge from this synthesis. First, vibration attenuation is multi-mechanistic: it may arise from frictional damping, viscoelastic loss, wave scattering, fatigue resistance, or friction-stabilisation, and the dominant mechanism depends critically on the frequency, load, temperature, and lubrication regime. Second, surface properties are non-monotonically related to vibration performance: increasing roughness, hardness, or coating thickness can either damp or amplify vibrations depending on the operating window, so optimisation must be regime-specific. Third, tribo-dynamic coupling is a two-way feedback loop, vibration alters friction, wear, and lubrication, which in turn modify contact stiffness and damping, feeding back into the vibration response, so effective surface engineering must account for this evolution over time. Fourth, cross-scale integration is essential: characterisation at micro/nano scales must be linked to component-level dynamic models through validated contact-mechanics and equivalent-damping formulations, and this integration remains the weakest link in current practice.

Despite the promising evidence, major gaps persist. Standardised testing protocols are lacking for measuring surface-dependent damping, transmissibility, and noise under realistic combined loading. Predictive models that incorporate surface degradation (wear, oxidation, fatigue) into dynamic simulations are still immature. Industrial implementation faces hurdles of cost, scalability, process repeatability, and environmental compatibility, which are rarely addressed in academic studies. Future research should therefore prioritise the development of physics-informed machine learning models that correlate surface descriptors with dynamic performance, digital twin frameworks that update surface state in real time for adaptive control, multi-objective design approaches that balance attenuation with wear, fatigue, thermal stability, and manufacturability, and life-cycle assessment to quantify long-term reliability and environmental footprint.

In conclusion, the emerging paradigm of designing surfaces as functional dynamic interfaces offers a viable path towards lighter, quieter, more durable, and energy-efficient mechanical systems. By moving beyond the traditional separation of tribology, materials science, and structural dynamics, the engineering community can unlock the full potential of surface engineering for vibration control, not as an afterthought, but as a foundational element of mechanical design.

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