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Enhancing Surface Integrity and Tribological Performance through Progressive Burnishing Techniques

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Surface integrity is crucial in assessing the performance and durability of components in many industries such as aerospace, automotive, and biomedical engineering. Burnishing, a cold-working technique, has proven to be an efficient and environmentally sustainable approach for strengthening surface quality and improving mechanical qualities, including hardness, fatigue strength, and wear resistance. This analysis examines the progress in burnishing techniques from 2000-2024, emphasizing breakthroughs in ball burnishing, ultrasonic burnishing, vibratory burnishing, and cryogenic burnishing. The paper also investigates the impact of burnishing on surface integrity, microstructural enhancement, and the augmentation of mechanical properties. This review analyzes recent research on process parameters, tool innovations, and surface treatment methodologies, clarifying how burnishing reduces surface roughness and enhances hardness, while suggesting future research directions in this domain.

Keywords: Burnishing Techniques ,Microstructural Refinement, Tribological Performance.

1. Introduction

Surface integrity is a critical attribute of components in industries such as aerospace, automotive, and biomedical engineering. Achieving a superior surface finish and high hardness is essential for increasing the lifespan of components by improving wear resistance, fatigue strength, and corrosion resistance. Burnishing, a cold-working process, offers a cost-effective and environmentally friendly alternative to traditional machining and grinding methods for improving surface finish and mechanical properties without the removal of material.

The primary purpose of burnishing is to induce plastic deformation at the surface of the material, which leads to the reduction of surface irregularities, compressive residual stress, and improved mechanical properties such as hardness. In recent decades, researchers have focused on optimizing burnishing techniques through advanced tool designs, adaptive control systems, and the incorporation of new materials for both tools and workpieces.

This review aims to explore the latest advancements in burnishing techniques, focusing on surface finish and hardness enhancement. By examining studies conducted between 2000 and 2024, we aim to highlight the key innovations and methodologies that have shaped the field and provide a roadmap for future research in burnishing processes.

2. Literature Review

The literature on burnishing spans several decades, with numerous studies emphasizing the importance of process parameters and their effects on surface quality and mechanical properties. This section reviews key advancements in the field from 2000 to 2024, categorizing the innovations into three broad areas: burnishing techniques, effects on surface integrity and hardness process parameters, and tool and material innovations.

2.1 Advances in Ball Burnishing and its Techniques

Ball burnishing has been extensively studied for its effectiveness in enhancing surface properties. Authors [1] compared the effects of laser peening, shot peening, and ball burnishing on the surface properties and fatigue behavior of Al 7075–T73 and Ti-6Al-4V alloys, demonstrating the significant improvements achievable through ball burnishing [1]. Similarly, The Authors [2] explored the surface characteristics of Ti60 alloy treated with a combination of turning and ball burnishing, revealing notable enhancements in surface finish and hardness.

Over the years, several burnishing techniques have emerged, each offering unique advantages in specific applications:

Conventional Burnishing: Traditional burnishing employs rollers or balls to apply pressure to the surface of the workpiece. Early studies [3-5] explored the effects of conventional burnishing on different materials like aluminum alloys and steels, showing significant improvements in surface roughness and hardness.

Ultrasonic Burnishing: The introduction of ultrasonic-assisted burnishing (UAB) around 2008 revolutionized the field by superimposing ultrasonic vibrations on the burnishing tool. Studies by authors [6-8] demonstrated that UAB could reduce surface roughness more effectively than conventional burnishing, particularly for hard-to-machine materials such as titanium alloys.

Vibratory Burnishing: Another innovation is vibratory burnishing, where mechanical vibrations are applied to the tool to improve process efficiency. Research by [9-11] showed that vibratory burnishing enhances surface finish and residual stress, making it ideal for components exposed to cyclic loads.

Cryogenic Burnishing: Recently, cryogenic burnishing [12-14] has gained attention, where liquid nitrogen is used to cool the workpiece during burnishing. This method has been shown to significantly increase surface hardness by inducing deeper compressive stresses, making it suitable for components used in extreme environments.

2.2 Effects on Surface Integrity and Hardness

Recent studies highlight the influence of burnishing on surface integrity and hardness. The authors refined the ultrasonic burnishing method, emphasizing energy economy and workpiece quality, and underscoring its efficacy in enhancing surface features and diminishing residual stresses [15]. The authors examined the wear resistance of Ti-6Al-4V alloys exposed to ball burnishing, observing enhancements in wear performance and surface quality [16]. Zhang and Liu (2023) investigated the impact of turning and burnishing operations on the corrosion resistance of laser-cladded Fe-Cr-Ni layers, analysing both thermodynamic and kinetic factors to elucidate the underlying mechanisms. Their findings indicated that surface roughness generated by turning greatly influences corrosion potential, with roughness height and functional parameters being critical determinants. The research indicated that burnishing post-turning increases polarization resistance, therefore augmenting corrosion resistance by reducing surface imperfections and increasing surface integrity. From a thermodynamic standpoint, the enhanced surface integrity achieved via burnishing results in a more uniform passive coating, hence diminishing the adsorption of corrosive agents and improving corrosion resistance. The synergistic effects of increasing surface roughness and the establishment of a stable passive film boost corrosion resistance. This study highlights the necessity of improving machining methods to improve the durability and performance of laser-cladded materials [17]. Novel methodologies, including the integration of burnishing with other surface treatments, have demonstrated encouraging outcomes. Authors Courbon et al. (2019) examined near-surface alterations in stainless steel exposed to cold spray and laser cladding, thereafter undergoing turning and ball burnishing, resulting in enhanced surface properties [18].

The authors examined the ball burnishing technique on AZ91D alloy, concentrating on its impact on surface roughness and microhardness. The authors effectively shown that ball burnishing markedly diminishes surface roughness and improves surface hardness. This renders the study particularly pertinent for sectors necessitating lightweight, durable materials, like automotive and electronics. Nonetheless, the research might benefit from more investigations into fatigue life and wear resistance to provide a more thorough comprehension of the material's performance post-burnishing [19]. The authors examined the effects of several burnishing techniques on the surface integrity of polymeric materials. The research emphasized the benefits of polymers compared to metals, including reduced weight, superior corrosion resistance, and diminished environmental effect. The review concentrated on experimental methodology, burnishing techniques, polymeric materials examined, and the influence of burnishing factors such as force, speed, and feed on surface integrity. The results indicated that burnishing markedly enhanced surface roughness and hardness, with the majority of research focusing on thermoplastic polymers (68%) and a smaller proportion on thermoset polymers (32%) [20].

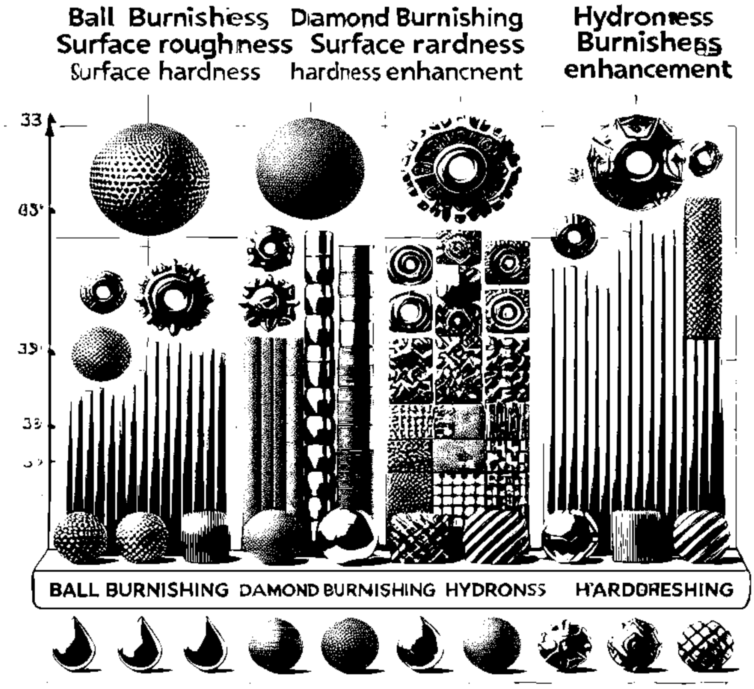

Figure 1: Effects of Various Burnishing Techniques on Surface Roughness and Hardness Enhancement [15-20]

Figure 1 illustrates the relationship between various burnishing techniques and their effects on surface roughness and hardness. It demonstrates how different methods influence the finish and strength of materials, with variations in burnishing techniques leading to distinct changes in both surface texture and material hardness.The image provides a visual comparison of various burnishing processes, including ball burnishing, diamond burnishing, and potentially a process referred to as "Hydroness" or "hard burnishing." Each process is depicted through different shapes and textures, illustrating the effects on surface roughness and hardness enhancement. The image compares the different methods, with spheres and cylindrical shapes symbolizing the treated surfaces, and highlights how each technique affects both surface smoothness and material hardness[15-20].

2.2.1 Mechanisms of Improvement through Burnishing

Burnishing enhances hardness and surface integrity by plastic deformation. During the process, a hardened tool or ball is pressed against the workpiece surface, resulting in smoothing of surface peaks and increasing the material's hardness through work hardening.

1. Fatigue Life Improvement: According to authors [21,22], the enhanced surface integrity from burnishing leads to a significant increase in fatigue life due to the induced compressive stresses that reduce the tendency for crack initiation and propagation.

2. Residual Stresses and Hardness: In the study conducted by authors [23,24] burnishing produced compressive residual stresses that significantly enhanced hardness on various metallic surfaces, particularly on stainless steel and titanium alloys.

3. Surface Finish: Authors investigated the surface roughness of aluminum alloy during the burnishing process using chaos theory. It finds that the surface roughness can be characterized by the correlation dimension, with higher correlation dimensions indicating lower surface roughness[25].Authors [26] noted that burnishing reduced surface roughness up to 80%, resulting in a mirror-like finish, which is vital for components like shafts and bearings used in high-stress environments.

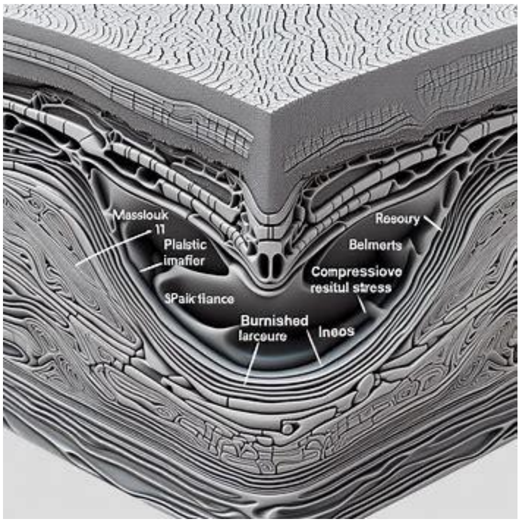

Figure 2 : Cross-sectional view of a burnished surface [21-26]

Figure 2 presents a cross-sectional view of a burnished surface, providing a detailed depiction of the plastic deformation layer created during the burnishing process. This layer is characterized by its smooth finish, resulting from the material's surface being plastically deformed under pressure. Beneath this deformed surface, a zone of compressive residual stresses is formed, which plays a critical role in enhancing the material's fatigue strength, wear resistance, and overall surface integrity. The illustration highlights the transition from the burnished surface to the subsurface, where the residual stresses gradually diminish in intensity [21-26].

3. Microstructural Optimization

3.1 Influence on Mechanical Characteristic

Microstructural optimization is crucial in determining the mechanical properties of materials. Multiple studies have shown that controlling the microstructure can significantly affect the strength, ductility, and toughness of materials. The procedure optimizes grain dimensions and improves phase distributions, which are essential for mechanical performance. A crucial aspect of microstructural optimization by burnishing is achieving a balance between improving surface properties and maintaining the thermal stability of the bulk material. The authors [27–28] looked at new developments in laser treatment and plasma nitriding as ways to harden the surface of titanium. They focused on making the material harder and more resistant to wear. The authors [29] investigated the microstructural evolution in cryogenic burnishing of Co-Cr-Mo biomaterial using numerical simulations, focusing on dynamic recrystallization and its effect on hardness. The authors [30] improved the internal burnishing process to increase energy efficiency, improve machining quality, and reduce noise emissions, resulting in superior surface quality and lower noise levels. The authors focused on refining the inner roller burnishing procedure to increase surface quality, resulting in substantial enhancements in surface roughness. Finally, authors [32] increased the anti-corrosion efficacy of ZIF-8-based coatings by improving their microstructure, leading to better corrosion resistance.

Microstructural Images Before and After Burnishing : Figure 3 shows high-resolution microscopy images of the material's microstructure before and after burnishing. The images are typically captured using optical microscopy or scanning electron microscopy (SEM).

- Before Burnishing: The microstructure may show larger, uneven grain sizes with visible surface imperfections.

- After Burnishing: The microstructure often reveals smaller, more uniform grains and a smoother surface. This results from the compressive stresses induced during burnishing, which refine the grain structure and enhance the material’s overall uniformity.

3.2 Grain Refinement via Burnishing : Grain refining is one of the most significant microstructural alterations induced by burnishing. Grain refinement transpires when the surface material experiences intense plastic deformation, resulting in a decrease in grain size by dynamic recrystallization. This phenomenon is most pronounced in materials having face-centered cubic (FCC) structures, such as austenitic steels and aluminum alloys, where the material's considerable ductility facilitates significant deformation [33-34].

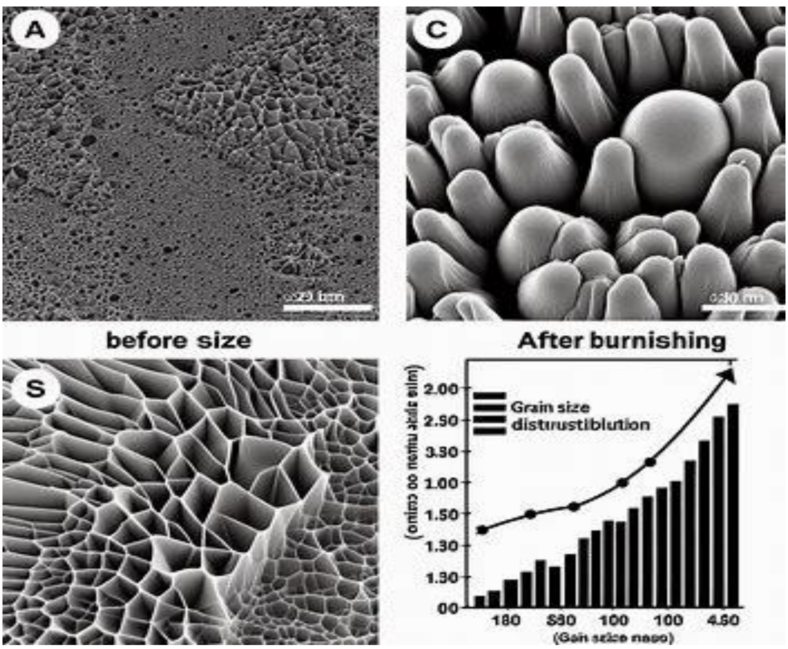

Figure 3 : Microstructural Changes Before and After Burnishing: SEM Images and Grain

Size Distribution [27-34]

The burnishing process generates elevated strain rates, resulting in the development of subgrains and the reorganization of dislocations. This dynamic recrystallization markedly diminishes the grain size at the surface, which, in accordance with the Hall-Petch equation, immediately improves surface hardness. The microstructural evolution of the material before and after burnishing is illustrated in Figure 3. SEM images (A and S) show the surface condition and grain structure of the material prior to burnishing. The grains appear small and irregular, with a rough, porous surface texture. In contrast, after burnishing (image C), the material exhibits a much smoother surface with larger, more uniform grains. The burnishing process has significantly refined the grain structure, as highlighted by the rounded, smoother appearance of the grains.

The accompanying graph in Figure 3 shows the grain size distribution before and after burnishing. There is a noticeable increase in grain size after the process, indicating grain growth and improved surface uniformity. This structural transformation, facilitated by burnishing, enhances the material's mechanical properties, such as wear resistance and surface strength. Research on steel alloys and titanium has shown that burnishing can decrease the average grain size to the sub-micron scale, resulting in a hardness increase of up to 50% [15,23].This enhanced microstructure not only increases wear resistance but also extends fatigue life by minimizing surface fracture initiation.

3.3 Dislocation Dynamics and Residual Stress Distributions : Authors [35-36] assert that the enhanced dislocation density generated by burnishing enhances the yield strength of treated components, hence augmenting the overall mechanical characteristics. The movement of dislocations is crucial in the hardening process during burnishing. The application of high pressure to the material surface induces the proliferation and reorganization of dislocations, leading to work hardening. The entanglement and interactions of dislocations provide internal stresses that enhance surface hardness.

Burnishing induces compressive residual stresses at the surface, hence improving fatigue resistance and reducing the likelihood of crack development. Compressive stresses occur when the plastically deformed layer seeks to shrink but is constrained by the underlying material, resulting in the entrapment of residual stresses. The influence of dislocation mobility on hardness and residual stress distributions has been extensively analyzed. Burnishing of aluminum alloys has shown an enhancement in surface hardness by 25–30% and the introduction of compressive residual stresses up to 500 MPa [25-26, 33-34].These stresses augment hardness and provide resistance to surface fatigue, hence enhancing the material's longevity under cyclic loading conditions.

Techniques for Microstructural Control : The efficacy of burnishing is reliant upon the regulation of several factors, including burnishing force, velocity, feed rate, and the number of passes. Modifying these parameters affects the thickness of the plastic deformation layer and the microstructure [20].

4. Tribological Performance: Friction and Wear Considerations

Burnishing markedly affects the tribological characteristics of a material, encompassing its friction coefficient and wear rate. Minimizing surface roughness decreases friction between contact surfaces, whereas heightened hardness improves wear resistance.

1. Friction Reduction: Under dry sliding conditions, burnishing decreased the friction coefficient of stainless steel by as much as 30%, as reported by the authors [37-38]. The enhanced surface polish and hardness diminished material adhesion between sliding surfaces, hence reducing frictional forces.

2. Wear Resistance: The authors [39–41] indicate that burnishing enhanced wear resistance in hardened steels by as much as 40%. The enhanced surface hardness and improved grain structure were pivotal in diminishing material wear.

Influence of Burnishing on Tribological Properties : The hardness and surface smoothness achieved through burnishing directly enhance wear performance. Compressive residual stresses inhibit the formation of micro-cracks, hence augmenting durability. Authors noted that burnished surfaces had a reduced wear rate relative to untreated surfaces, especially in high-stress applications such as automobile components. It is also observed that the application of burnishing to brass and bronze alloys enhanced their tribological properties, hence prolonging the lifespan of these components in equipment [37-41].

5. Tool and Material Innovations

Recent innovations in tool and material design have also contributed significantly to the effectiveness of burnishing:

5.1 Modern Materials for Tools: Diamond-like carbon (DLC) coatings, ceramic spheres, and strong metal alloys are increasingly often employed in burnishing tools to enhance wear resistance and extend tool longevity. Boghe (2009) examined Diamond-Like Carbon (DLC) coatings in Industrial Lubrication and Tribology, highlighting its use in surface engineering. DLC coatings were emphasized for their remarkable hardness, little friction, and wear resistance. The study examined their application in the automotive, aerospace, and equipment industries, enhancing component performance and durability. It encompassed application techniques including physical and chemical vapor deposition. The study also examined difficulties such as cost and adherence, and proposed further research to improve coating efficacy [42]. The study by authors [38] showed that diamond burnishing significantly improved the wear resistance of CuAl9Fe4 bronze sliding bearing bushings. The process enhanced surface integrity, leading to better performance under both lubricated and dry conditions. The study by [43] demonstrated that low-plasticity ball burnishing significantly improved the high-cycle fatigue strength of medium carbon AISI 1045 steel. The process increased the bending fatigue limit by 20%, enhancing the material’s durability under cyclic loading.

5.2 Surface Development of Workpieces: Materials like titanium, stainless steel, and Inconel alloys have gained prominence in production, especially within the aerospace and medical sectors. The burnishing of these modern materials necessitates the creation of specific procedures, such as hybrid burnishing processes, to preserve surface integrity while safeguarding mechanical qualities [44-45].

The effectiveness of burnishing largely depends on key process parameters such as burnishing force, speed, feed rate, and tool diameter. Research into optimizing these parameters has been crucial in maximizing surface finish and hardness.

6. Process parameters Optimization and Computational Techniques

The application of optimization techniques and computational methods has become significant in burnishing research. Authors utilized Taguchi techniques and principal component analysis (PCA) to optimize burnishing processes, highlighting advancements in process control and quality improvement [46]. Furthermore, the authors validated numerical models of ball burnishing, considering friction and starting surface topography, emphasizing the need of simulation in improving burnishing techniques [47]. The authors [48] explored the impact of various burnishing parameters on surface quality and hardness. The research indicated that adjusting these parameters markedly enhanced surface polish and hardness, with roughness decreased by as much as 10 times and hardness augmented by 55.5% in AISI 1040 steel. The study emphasized the significance of choosing suitable burnishing parameters to improve material characteristics.

7. Recent Developments and Future Trends

Recent advancements in burnishing processes encompass the investigation of novel materials and coatings. Authors assessed the tribological performance of ball burnished magnesium alloys for biomedical applications, suggesting the feasibility of burnishing in specific domains [49]. Authors investigated the synergistic effects of deep ball burnishing and hydroxyapatite coating on AZ31B Mg alloys, demonstrating the increasing applicability of burnishing in enhancing surface integrity and corrosion resistance [50].

8. Methodology

This review utilized a systematic approach by conducting a comprehensive literature search across databases like Google Scholar and ScienceDirect, focusing on studies from 2000 to 2024. Keywords related to burnishing techniques were used to select relevant experimental and simulation-based research. Key data on process parameters, surface finish, hardness, and microstructural effects were extracted and analyzed. Comparative analysis of different burnishing methods (e.g., ball, ultrasonic, cryogenic) and their effects on various materials was studied.

9. Results

9.1 Surface Finish Improvement

The literature review indicates that recent burnishing methods frequently yield substantial reductions in surface roughness, with ultrasonic and cryogenic burnishing exhibiting the most remarkable enhancements. Ultrasonic burnishing often decreases surface roughness by 20-

30% more than traditional methods [7-8],Cryogenic burnishing, as demonstrated by authors [12-13] enhances surface quality, particularly in hard materials such as titanium alloys.

9.2 Hardness Enhancement

Numerous studies indicate a substantial enhancement in surface hardness post-burnishing, with gains varying from 10% to 50%, contingent upon the process and material employed. Ultrasonic-assisted burnishing demonstrates the greatest hardness enhancements in softer materials, whereas cryogenic burnishing is most effective for hard alloys such as Inconel 718 and titanium alloys.

The review revealed that burnishing significantly improves surface finish, hardness, and fatigue strength across various materials. Ball burnishing showed consistent reductions in surface roughness, while ultrasonic and cryogenic burnishing enhanced hardness and fatigue resistance. The optimal combination of burnishing force, speed, and lubrication was found to vary by material type, but generally, higher forces and lower speeds yielded better surface quality. Microstructural analysis confirmed improved grain refinement, which contributed to enhanced mechanical properties.

10. Conclusion

Burnishing techniques have shown significant progress in enhancing surface finish and mechanical qualities, especially surface hardness, wear resistance, and fatigue life. The use of advances including ultrasonic, vibratory, and cryogenic burnishing has broadened the process's applicability across various materials and industries. Microstructural improvement, particularly via grain refinement and the incorporation of compressive residual stresses, has proved essential in improving surface integrity. Notwithstanding these substantial advancements, additional study is necessary to refine process parameters, improve tool designs, and investigate the feasibility of integrating burnishing with other surface treatments. Subsequent research should concentrate on elucidating the long-term implications of burnishing on fatigue life and wear performance, particularly in harsh conditions.

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