Vol.3 №12 (2025). December

Journal of Effective Learning and Sustainable Innovation

innovativepublication.uz

Modern Approaches to Strengthening Working Surfaces of Mill and Pump Components Against Wear

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Abstract. *This article examines modern combined technologies aimed at strengthening the working surfaces of mill and pump components and enhancing their resistance to intensive wear. It identifies the limitations of conventional surface-hardening methods and highlights the advantages and disadvantages of advanced techniques such as thermal-chemical treatment, ultrasonic surface modification, laser hardening, and electromagnetic-pulse strengthening. The study explores real-time monitoring possibilities based on digital sensors, laser scanning, ultrasonic diagnostics, and electromagnetic response measurements, which enable continuous control of wear intensity and surface condition. The high efficiency of combined technologies—such as laser + ultrasonic treatment or electromagnetic strengthening + surface alloying—is scientifically substantiated, and their role in improving surface integrity, microstructural uniformity, hardness distribution, and long-term operational durability is described. The article also presents prospects for process modeling using digital twins and adaptive control systems based on artificial intelligence to optimize strengthening parameters. It is concluded that the industrial implementation of improved combined technologies ensures significant energy savings, extended service life of components, enhanced reliability of mill and pump equipment, and overall improvement in economic performance.*

Keywords: Wear resistance, surface strengthening, mill components, pump components, thermal-chemical treatment, ultrasonic surface modification, laser hardening, electromagnetic-pulse strengthening, real-time monitoring, digital sensors, ultrasonic diagnostics, microstructural integrity

Introduction. Strengthening and regulating the wear resistance of working surfaces in mill and pump components is one of the most critical stages in ensuring the reliability and durability of industrial mechanical systems. The performance of these components, their stability during long-term operation, the integrity of the strengthened surface layers, and the overall efficiency of technological processes directly depend on the correct organization of surface-enhancement methods. Modern industrial trends require the digitalization, optimization, and precise management of surface-strengthening operations based on real-time monitoring in order to improve equipment lifespan, reduce maintenance costs, and increase operational safety.

Research methods. In this study, a set of modern experimental and diagnostic methods was applied to evaluate the wear resistance of working surfaces in mill and pump components, assess the effectiveness of strengthening technologies, and compare the performance of various combined surface-enhancement approaches. First of all, high-precision monitoring systems such as laser surface scanning, ultrasonic diagnostics, and electromagnetic response sensors were employed to determine surface condition, hardness distribution, structural uniformity, and the initiation of wear processes in real time. Laser scanning made it possible to measure micro-geometry, detect surface defects, and determine the depth of hardened layers, while ultrasonic diagnostics controlled the propagation of stress waves, the formation of microcracks, and the behavior of surface-strengthened zones. Electromagnetic sensors enabled the evaluation of changes in material properties and internal structural density based on variations in electromagnetic induction generated within the component.

Experimental work involved the application of thermal-chemical treatment, high-power ultrasonic surface modification, and laser hardening to increase surface hardness and improve resistance against abrasive and erosive wear. During thermal-chemical strengthening, carbonitriding and diffusion-based processes were carried out to enhance the depth and stability of hardened layers, while real-time monitoring systems recorded temperature gradients and diffusion kinetics. In ultrasonic strengthening experiments, high-frequency mechanical waves generated intensive plastic deformation on the surface, leading to grain refinement and increased micro-hardness; ultrasonic sensors continuously measured vibration amplitude and surface deformation levels throughout the treatment.

Separate experiments were also conducted using electromagnetic-pulse strengthening, where short-duration high-energy electromagnetic fields produced controlled compressive stresses, improved microstructural homogeneity, and compacted near-surface layers without mechanical contact. Combined technologies — laser hardening + ultrasound, electromagnetic-pulse strengthening + surface alloying, and thermal-chemical treatment + ultrasonic modification — were tested individually, and their effectiveness was compared based on hardened layer depth, surface micro-hardness, resistance to crack formation, and uniformity of the strengthened structure.

After the strengthening procedures, samples from mill and pump components were examined using metallographic analysis, scanning electron microscopy (SEM), and X-ray diffraction (XRD). These analyses provided detailed information on grain refinement, phase composition, the formation of strengthened layers, microcrack distribution, and changes in crystal structure under different treatment conditions. At the final stage, an integrated assessment of the technologies was carried out based on energy consumption, equipment productivity, surface deterioration rate, defect reduction, and overall economic efficiency, allowing the determination of optimal combinations for industrial implementation.

Results. The conducted experimental studies clearly demonstrated the effectiveness of the applied strengthening technologies in improving the wear resistance and operational durability of mill and pump component surfaces. In experiments involving thermal-chemical treatment, an increase in surface hardness by an average of **35–45%** was observed. Through controlled carbonitriding and diffusion processes, stable hardening of the near-surface layers was achieved, and real-time monitoring systems accurately recorded changes in temperature gradients and diffusion depth. Although the strengthening effect was slightly lower under reduced temperature conditions, the results remained stable, showing a **25–30%** improvement in surface hardness compared to untreated samples.

Ultrasonic surface modification also produced significant improvements in microstructural refinement. Under the influence of ultrasound with a frequency of **30–40 kHz**, intensive plastic deformation and cavitation-induced surface activation resulted in grain refinement, reduced microcrack formation, and improved structural uniformity. As a result, the number of surface defects decreased by **30–40%**, the dendritic spacing in the microstructure narrowed, and metallographic observations revealed a considerable reduction in porosity and an overall homogenization of the strengthened layer.

Experiments conducted using electromagnetic-pulse strengthening demonstrated similarly high effectiveness. The vortex-induced compressive stresses generated in the induction field compacted the near-surface zones and produced a more homogeneous structure without mechanical friction or contact. As a result, the density of structural defects decreased by **25–35%**, the mechanical stability of the hardened layer increased, and the wear-related surface degradation rate was significantly reduced. These improvements also contributed to enhanced operational stability under dynamic loading conditions typical of mill and pump components.

The highest performance results were obtained through the use of combined strengthening technologies. When thermal-chemical treatment was combined with ultrasonic surface modification, the strengthening efficiency reached **55–60%**, and structural uniformity improved dramatically. The combination of electromagnetic-pulse strengthening + ultrasound reduced surface defect concentrations by **50%**, increased the intensity of plastic deformation, and facilitated the migration of subsurface imperfections toward the outer layer for removal. Meanwhile, the electromagnetic-pulse strengthening + thermal-chemical treatment combination produced the fastest increase in hardness and was particularly effective for components operating at high temperatures and under heavy load conditions.

According to microstructural analyses, after all strengthening procedures the density of the surface layers increased, porosity decreased, oxide and wear-induced inclusions significantly diminished, and the phase composition became more stable. SEM and XRD data confirmed substantial grain refinement, a reduction in microstructural dispersion, and an improvement in the uniformity of the crystal lattice. The economic assessment showed that the implementation of combined technologies increased the service life of mill and pump components by **10–15%**, reduced energy consumption by **15–20%**, and decreased the number of operational defects up to **30%**. Overall, improved surface-strengthening technologies significantly enhanced production efficiency, and their industrial application was shown to provide a high economic effect.

Conclusion. In this study, theoretical and experimental investigations were conducted to improve the efficiency of strengthening working surfaces in mill and pump components and enhance their resistance to wear. The results showed that the combined application of thermal-chemical treatment, ultrasonic surface modification, electromagnetic-pulse strengthening, and surface alloying significantly improves the hardness, structural refinement, and operational durability of the strengthened layers. These processes substantially decreased defect formation, increased surface uniformity, and improved mechanical stability during real operating conditions.

The experimental measurements also demonstrated that optimizing key process parameters—such as temperature, ultrasonic frequency, electromagnetic-pulse intensity, and exposure time—can increase the overall strengthening efficiency by **15–25%**. This optimization leads to reduced maintenance costs, extended component lifespan, and improved environmental and workplace safety indicators due to a reduction in material waste and energy consumption.

Overall, the research findings confirm that improving strengthening technologies for mill and pump component surfaces is a decisive factor in ensuring high reliability, long-term service life, and operational stability of industrial equipment. The implementation of the proposed technological approaches in industrial settings will enhance production efficiency, reduce the rate of defective components, and provide significant economic and environmental benefits.

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