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Impact of Cryogenic Cooling on Burnishing of Ti-6Al-4V: An Optimization Approach

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Abstract

The present study investigates the influence of cryogenic cooling on the burnishing process of Ti-6Al-4V, a widely utilized titanium alloy in aerospace and biomedical applications. While conventional burnishing enhances surface integrity by inducing compressive residual stresses and improving hardness, excessive heat generation limits its effectiveness. Cryogenic-assisted burnishing, incorporating liquid nitrogen as a cooling medium, presents a promising alternative to mitigate thermal softening and enhance mechanical properties. This study systematically optimizes the burnishing process using the Taguchi method, evaluating the effects of key parameters like speed, feed rate, depth of cut, and number of passes on surface roughness and microhardness. Results indicate that cryogenic process significantly enhances hardness, with improvements of up to 31.5% compared to normal counterpart. However, cryogenic conditions also led to elevated surface roughness, with the maximum Ra increasing from 0.347 µm (normal) to 1.17 µm under extreme cooling (-196 °C) due to embrittlement and lower plastic deformation at ultra-low temperatures. These results highlight the critical need for process optimization to balance mechanical enhancement with surface finish degradation. The study provides actionable insights into the cryogenic burnishing of Ti-6Al-4V and demonstrates its potential as a superior surface modification strategy for high-performance engineering applications.

Major Findings: *Cryogenic burnishing of Ti-6Al-4V enhanced microhardness by 31.5% through suppressed thermal softening and improved strain hardening but increased surface roughness due to embrittlement and limited plastic deformation at ultra-low temperatures. Taguchi optimization helps balance these effects, enhancing applicability in aerospace and biomedical fields.*

Keywords: *Burnishing, Cryogenic, Cooling, Microhardness, Surface Roughness, Taguchi Optimization, Ti-6Al-4V*

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1.0 Introduction

1.1 Background and Importance of Ti-6Al-4V

The aerospace and biomedical industries extensively utilize titanium alloys including Ti-6Al-4V because of their exceptional mechanical properties. Ti-6Al-4V demonstrates an ultimate tensile strength of about 950 MPa which exceeds both aluminium alloys (400-500 MPa) and stainless steels (600-700 MPa)[1]. The low density of this material approaches half of steel making it suitable for applications that require weight optimization in aircraft structures and biomedical implants[2]. The combination of properties in Ti-6Al-4V makes it suitable for creating essential components which serve as aircraft components and turbine blades and orthopaedic implants and biomedical devices[3]. Due to its low thermal conductivity titanium alloys produce significant processing complications since heat generation becomes excessive during manufacturing operations. Varying heat levels during manufacturing cause titanium to soften thermally and create both defective surfaces and intensified tool deterioration that shortens component life and performance[4].

1.2 Limitations of Conventional Surface Finishing Techniques

Ti-6Al-4V components show their durability and mechanical performance based on surface integrity because surface defects reduce fatigue life and wear resistance in aerospace and biomedical applications[5]. The most common surface finishing techniques used to enhance surface quality are grinding and polishing[6]. The stress-inducing methods commonly used in surface finishing create tensile residual stresses which reduce material fatigue strength and wear resistance. The material removal process of grinding and polishing makes these methods unsuitable for applications needing exact dimensional stability[7]. An alternative approach to surface enhancement is burnishing, a chip-less cold working process that improves surface roughness, induces beneficial compressive residual stresses, and enhances microhardness[8]. Surface deformation using controlled pressure leads to grain refinement while improving mechanical properties according to burnishing. The surface characteristics enhancement capabilities of conventional burnishing remain effective, but the heat produced in the process impairs its overall effectiveness[9]. The work hardening effect becomes inconsistent because heat responsible for thermal softening diminishes this effect which produces an irregular surface finish. The implementation of an effective cooling system in burnishing operations will help address these process restrictions[10].

1.3 Potential of Cryogenic-Assisted Burnishing

The effectiveness of cryogenic assisted machining in tool wear reduction with improved sustainability has led researchers to pay substantial attention in recent years as demonstrated by Marakini *et al*[11]. The research by Maximov and Duncheva[12] demonstrated cryogenic assisted burnishing as a remarkable approach because it improves both surface integrity and fatigue resistance for machining titanium alloys. The process delivers three benefits by preventing thermal softening together with oxidation and tool wear which results in enhanced mechanical strength. The processing technique of cryogenic burnishing requires liquid nitrogen which acts as an ultra-cold cooling agent throughout the treatment. Material response stability and enhanced surface integrity result from the heat management effect during the process[13].

The cryogenic-assisted burnishing process provides three main advantages which include improved microhardness together with decreased surface defects and elevated resistance to wear and fatigue[14]. The suppression of thermal softening by cryogenic cooling comes with a potential side effect that causes material embrittlement and surface roughening depending on the conditions. The optimization of the process requires a deep understanding of how cooling intensity affects material response and burnishing parameters to achieve maximum effectiveness.

1.4 Literature Review and Research Gaps

Research on burnishing techniques has investigated parameter optimization alongside surface integrity enhancement and hybrid burnishing approaches. Zhang *et al.,*[15] conducted research to optimize Laser-Assisted Burnishing (LAB) parameters for improving Ti-6Al-4Vsurface integrity. The study demonstrated that LAB treatment produced a surface finish of Ra = 0.364 μm

while simultaneously raising microhardness values from 324.4 HV to 464.8 HV and generating a compressive stress of -392.7 MPa at 300°C. The authors established that LAB achieved these enhancements through deep plastic deformation together with temporary material softening. Varpe *et al.*,[16] reviewed the burnishing process parameters like force, speed, feed, and passes highlighting their impact on surface roughness and microhardness of aluminium, steel, and titanium alloys. It was reported that fatigue strength, wear resistance, and compressive residual stresses were improved. Swirad *et al.*,[17] investigated the effect of ball burnishing on Ti-6Al-4V under fretting at 100-300°C and reported that, compared to turned samples, wear decreased, though wear rates and friction rose at 300°C. The enhancements were linked to surface hardening and roughness reduction and finally it was concluded that burnishing is a cost-effective alternative to abrasive machining. Maximov and Duncheva[12] reviewed Cryogenic-Assisted (CrA) and Cool-Assisted (CoA) burnishing processes, emphasizing their benefits in reducing roughness, increasing microhardness, and enhancing residual stresses and the results showcased improved wear, corrosion resistance, and fatigue life. Liquid nitrogen and dry ice were used as cooling media and the study analysed the influence of process parameters on surface integrity and performance. Raza and Kumar[18] reviewed burnishing tool designs and categorized them into ball, roller, Low Plasticity Burnishing (LPB), and diamond burnishing. Process parameters affecting surface integrity like tool material and geometry were analysed. It was reported that Cemented carbide and TiN-coated tools showed superior performance, while LPB provided deep compressive stresses. It was finally concluded that roller burnishing achieves finer finishes and ball burnishing enhances hardness.

Sivarupan *et al.*,[19] reviewed cryogenic coolants in titanium machining, highlighting their benefits in reducing cutting temperatures, friction, and tool wear while enhancing sustainability. Liquid nitrogen and carbon dioxide were analysed for machinability improvements. Cryogenic cooling outperformed conventional coolants in cost-effectiveness and environmental impact. Hybrid methods like cryogenic MQL were explored for enhanced performance. Challenges in coolant delivery and embrittlement were noted, with future research focusing on optimizing cryogenic systems for industrial use. Hou *et al.*,[20] investigated the effects of combined surface burnishing and Deep Cryogenic Treatment (DCT-SBP) on Ti–6Al–4V alloy, reporting reduced surface roughness, increased microhardness, and refined grain structure. XRD confirmed no phase change but indicated higher strain. Electrochemical tests in Hank's solution revealed improved corrosion resistance, while wear tests showed lower friction and narrower scars. Overall, DCT-SBP enhanced the alloy's surface integrity and durability, supporting its biomedical potential. Korkmaz *et al.*,[21] reviewed the role of cryogenic cooling in machining difficult-to-machine alloys like titanium and Inconel, highlighting its superiority over conventional coolants in reducing tool wear, enhancing surface finish, and controlling heat. They emphasized the benefits of liquid nitrogen and explored hybrid approaches with MQL and nanoparticles, which further improved lubrication and efficiency. The study concluded that cryogenic and hybrid systems significantly enhance machining performance and sustainability.

Somatkar *et al.*,[22] reviewed the effects of roller burnishing on surface integrity, emphasizing how parameters like speed, feed, and depth influence roughness, hardness, and residual stress. They found optimized conditions enhance finish and induce compressive stresses. Cooling methods (cryogenic, MQL, hybrid) and modelling techniques (RSM, ANN, ANFIS) were shown to improve process outcomes. While surface quality improved, out-of-roundness needs further study. Overall, roller burnishing was affirmed as an effective method for enhancing component performance in critical industries. Skoczylas *et al.*,[23] studied slide burnishing effects on X6CrNiTi18 stainless steel, highlighting improvements in surface roughness, microhardness, and residual stress. Optimal results were achieved at a 0.06 mm/rev feed and 230 N force, with microhardness increasing by 42.7% and hardened layer thickness reaching 100 μm. FEM simulations showed deeper compressive stresses up to 1.1 mm. Positron lifetime analysis revealed a rise in τ_{mean} with increasing force, indicating higher defect concentration. While feed influenced roughness, it had minimal effect on τ_{mean}. The study emphasized the interplay between deformation and defect evolution in enhancing surface integrity. Mebarek *et al.*,[24] investigated ball burnishing on S235JR steel and optimized parameters using Box-Behnken design. They found that burnishing force and ball diameter greatly reduced surface roughness (Ra >96%). XRD showed grain refinement without phase

change, and microhardness increased by 22% to 40 µm depth. Corrosion tests revealed improved potentials and lower current densities, while EIS (Electrochemical Impedance Spectroscopy) confirmed enhanced resistance. SEM (Scanning Electron Microscopy) and EDS (Energy Dispersive X-ray Spectroscopy) showed fewer corrosion spots. The study concluded that ball burnishing effectively improves surface finish and corrosion resistance in structural steels.

Arun Prasad and Stalin John[25] optimized internal roller burnishing of MgSiC composites using Taguchi multi-objective method. They identified optimal parameters—500 rpm, 0.5 mm/rev feed, and 0.03 mm stock—achieving 0.1555 µm roughness, 66.9 HV hardness, and 0.0595 mm out-of-roundness. The process improved surface finish by 67.15%, hardness by 37.52%, and reduced out-of-roundness by 46.68% over boring. FESEM and AFM confirmed enhanced surface quality, and validation tests showed <5% error, confirming the method's effectiveness for automotive use. Nguyen *et al.*,[26] optimized diamond burnishing of AISI 4140 using a hybrid Kriging–CRITIC–Crow Search–TOPSIS model, targeting energy efficiency (EF), friction (COF), and wear rate (SWR). Using vortex tube–assisted MQL, they identified optimal parameters (V = 160 m/min, D = 0.10 mm, f = 0.05 mm/rev, DT = 7 mm, IR = 2.00 µm), achieving a 34.1% EF gain, 33.2% COF reduction, and 8.1% SWR decrease. Model predictions closely matched experiments, with feed rate and speed being the most influential factors. Improved surface hardness, reduced roughness, and 16.8% cost savings validated the approach's industrial potential. Bourebia *et al.*,[27] examined how ball burnishing affects the mechanical and impact properties of S355JR steel, focusing on burnishing force and number of passes. Using factorial design and RSM, they found that optimal parameters (10 kgf, 3 passes) improved surface hardness by 30.46% and impact toughness by 26.28%, with a hardened depth of 319.52 µm. Higher force (20 kgf) further increased rupture strength by 30.8% without reducing ductility. SEM revealed distinct fracture patterns tied to processing conditions. While quenching and tempering showed greater improvements, burnishing offered effective surface-specific enhancement via plastic deformation.

Zhou *et al.*,[28] performed a bibliometric analysis of 1257 SBP-related publications (1990–2020) using Web of Science data. They identified China, the USA, and Germany as key contributors with increasing global collaboration. Major research themes included surface integrity, residual stress, and nanostructure evolution. Six research clusters were mapped, covering parameter optimization, modelling, and fatigue performance. Tools like CiteSpace, VOSviewer, and HistCite revealed influential works by Hassan, Altenberger, and Lu. The study concluded that SBP has evolved into a mature field with strong prospects in smart manufacturing and advanced surface engineering. Sayadi *et al.*,[29] studied the effects of shot peening and burnishing on SLM-fabricated 316L stainless steel. Burnishing notably reduced surface roughness (Ra to 1.32 µm), eliminated most near-surface pores, and increased microhardness to 290 HV. Fatigue life rose from 135,000 (as-SLMed) to 353,000 (SP) and 3,030,000 cycles (burnished). Fractography showed crack initiation shifted from surface to subsurface after treatment. Overall, burnishing was more effective than SP in improving surface quality and fatigue performance.

Despite the growing adoption of cryogenic techniques, their isolated impact on burnishing Ti-6Al-4V remains inadequately understood. A systematic optimization of cryogenic-assisted burnishing parameters is critically lacking in correlating microhardness gains with surface integrity trade-offs. Most existing studies focus on conventional burnishing or other hybrid machining techniques, leaving a research gap in optimizing cryogenic burnishing parameters for improved hardness and surface roughness. Additionally, while cryogenic cooling is known to enhance hardness, its influence on surface finish has been less explored, necessitating further investigation.

1.5 Research Objectives and Scope

Cryogenic burnishing will improve microhardness but may adversely affect surface roughness due to embrittlement. This study aims to investigate the impact of cryogenic cooling on the burnishing process of Ti-6Al-4V and optimize process parameters using the Taguchi method. The key parameters considered include burnishing speed, feed rate, depth of cut, and the number of passes, with their effects analysed on both surface roughness and microhardness. The study seeks to provide insights into the complex interaction between cryogenic cooling and burnishing mechanics, determining the optimal balance between enhanced hardness and surface finish integrity. The findings of this research will contribute to

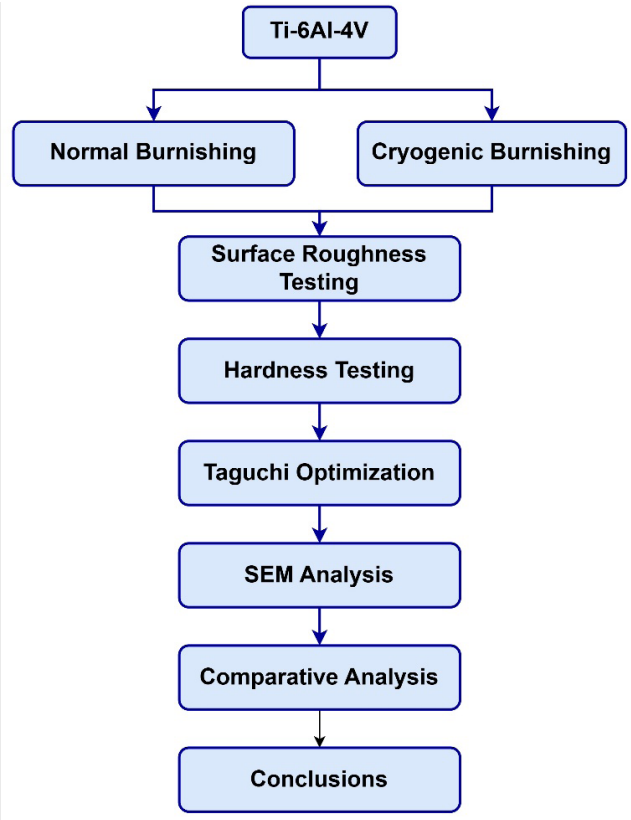


Figure 1. Flowchart of the work.

the advancement of surface enhancement techniques for Ti-6Al-4V components, particularly in high-performance applications such as aerospace and biomedical industries. The study will also serve as a foundation for future work on hybrid cooling techniques and process refinements to maximize the benefits of cryogenic-assisted burnishing. The methodology adopted in this study is illustrated in the research flowchart presented in Figure 1.

2.0 Materials and Methods

2.1 Material

Ti-6Al-4V was chosen for this study due to its high strength, excellent wear resistance, and widespread applications in aerospace and biomedical industries. The chemical composition of Ti-6Al-4V is mentioned in Table 1.

2.2 Experimental Setup

The burnishing experiments were conducted on an HMT NH22 lathe using a tungsten carbide ball burnishing tool.

Table 1. Chemical composition of Ti-6Al-4V (wt.%)

Element Name	Weight (%)
Al	6.300
V	4.180
Fe	0.025
C	0.007
N	0.001
H	0.002
O	0.140
Ti	89.345

Table 2. Mechanical properties of Ti-6Al-4V

Property (units)	Value
Hardness (Brinell)	334
Hardness (Vickers)	349
Ultimate Tensile Strength (MPa)	950
Tensile Yield Strength (MPa)	880
Elongation at Break (%)	14
Poisson's Ratio	0.342
Charpy Impact (J)	17
Fatigue Strength (MPa)	510
Fracture Toughness (MPa)	75
Shear Modulus (GPa)	44
Shear Strength (MPa)	550

The tool was mounted on a rigid tool holder to ensure stability during operation. The experiments were conducted under two burnishing conditions:

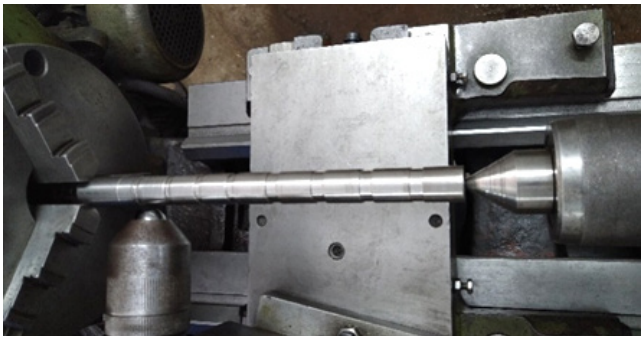
1. Normal Burnishing - Performed at ambient temperature without coolant.
2. Cryogenic Burnishing - Liquid nitrogen was supplied through a controlled delivery system to maintain low temperatures during burnishing.

2.3 Specimen Details

The specimens were prepared in cylindrical form with dimensions of 20 mm in diameter and 18 mm in length on a single rod of 250 mm length. The specimens were prepared as eight sections on the single rod for convenience enabling each experimental run to be carried out on a length of 18 mm. The specimens fabricated on the rod are presented in Figure 4.



(a) HMT NH22 lathe.



(b) Burnishing process.

Figure 2. Lathe machine.



Figure 3. Burnishing tool.



Figure 4. Specimens in sections on a single rod.

2.4 Taguchi Experimental Design

Taguchi technique was employed through L_9 orthogonal array for optimization purpose, considering the factors and levels mentioned in Table 3. In this study, the L9 orthogonal array Table 4 was selected to efficiently analyse the influence of four key parameters such as burnishing speed, feed rate, depth of cut, and number of passes, each at three levels. The L9 design significantly reduces the number of experiments making it cost- and time-effective. While Taguchi designs primarily focus on main effects rather than interactions, the selected control factors were assumed to have minimal interaction based on prior studies.

The Taguchi analysis was conducted separately for normal and cryogenic burnishing to determine optimal conditions for achieving minimal surface roughness and maximum microhardness.

2.5 Measurement Techniques

The surface roughness (Ra) of the samples was measured using a Taylor Hobson Surtronic S-300 surface roughness tester represented in Figure 5. Vickers microhardness tester Figure 6 was used to evaluate hardness. The Vickers hardness test involves pressing a diamond indenter. The applied load ranges from 1 to 100 kgf and it is typically maintained for 10 to 15 seconds.

Table 3. Factors and their levels

Code	Control Factor	Units	Level		
			1	2	3
X1	Speed	m/min	100	130	155
X2	Depth of Cut	mm	0.5	0.7	0.9
X3	Feed	mm/rev	0.05	0.1	0.15
X4	Number of Passes	count	1	2	3

Table 4. Taguchi L_9 array

Run	X1	X2	X3	X4
1	100	0.5	0.05	1
2	100	0.7	0.1	2
3	100	0.9	0.15	3
4	130	0.5	0.1	3
5	130	0.7	0.15	1
6	130	0.9	0.05	2
7	155	0.5	0.15	2
8	155	0.7	0.05	3
9	155	0.9	0.1	1

2.6 Cryogenic Burnishing Setup

The dispensing mechanism ensures that liquid nitrogen reaches the cutting zone at a consistent temperature of -196°C, optimizing cooling efficiency. The cryogenic burnishing setup is shown in the Figure 7.



Figure 5. Surface roughness tester.



Figure 6. Microhardness tester.

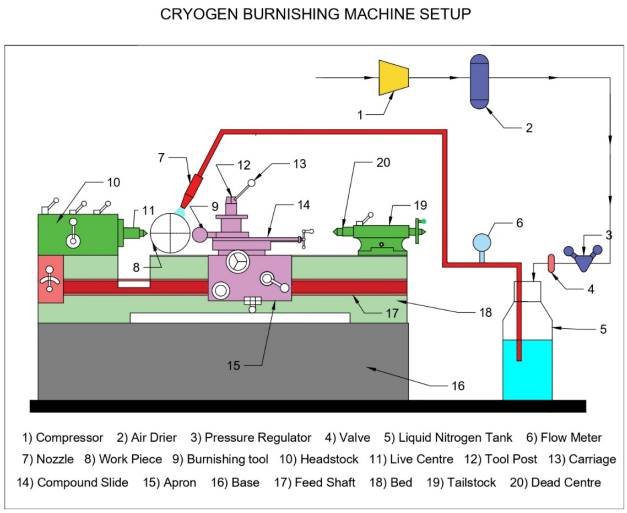


Figure 7. Cryogenic burnishing setup.

2.7 Scanning Electron Microscope

Hitachi High-Technologies Corporation's S-3700N model SEM machine was used to capture high-resolution images of the surfaces and to observe the microstructural characteristics of the specimens. A focused electron beam interacts with the sample, generating secondary electrons to reveal the topography of the material.

3.0 Results and Discussion

3.1 Effect of Burnishing Parameters on Hardness and Surface Roughness

Table 5 presents the hardness values obtained for Ti-6Al-4V under both normal and cryogenic burnishing conditions across different process parameters. The data clearly illustrates that cryogenic burnishing consistently enhances hardness compared to normal burnishing, with improvements ranging from moderate to substantial depending on parameter variations. The most significant increase is observed in Run 8, where cryogenic burnishing achieves a hardness of 468.2 HV, compared to 356.3 HV in normal burnishing, demonstrating a remarkable enhancement due to cryogenic cooling. Similarly, Run 6 exhibits a notable jump from 387.9 HV in normal conditions to 453.9 HV under cryogenic conditions, indicating the effectiveness of low-temperature burnishing in strengthening the material. The improved hardness can be attributed to the reduced thermal softening and enhanced work hardening effects facilitated by liquid nitrogen cooling, which minimizes grain deformation and promotes a more refined microstructure[3-30]. This enhancement in hardness is particularly beneficial for applications demanding superior wear resistance and fatigue strength in Ti-6Al-4V components, reinforcing the viability of cryogenic burnishing as a superior alternative to conventional methods[31].

Table 5 also presents the surface roughness (Ra) values obtained for Ti-6Al-4V under normal and cryogenic burnishing conditions, revealing an unexpected trend where cryogenic burnishing generally increases surface roughness compared to normal burnishing[32]. This outcome contrasts with the anticipated benefits of cryogenic cooling, suggesting that excessive cooling may have led to increased brittleness, reduced plastic deformation, and inadequate material flow, resulting in a rougher surface texture[33]. Notably, Run 8 exhibits

Table 5. Hardness and surface roughness results after burnishing

Run	Hardness (HV)		Surface Roughness (Ra)	
	Normal Burnishing	Cryogenic Burnishing	Normal Burnishing	Cryogenic Burnishing
1	405.6	407.7	0.243	0.552
2	352.7	371.1	0.320	0.574
3	409.5	425.9	0.268	0.378
4	387.9	438.3	0.377	0.801
5	391.1	410.3	0.633	1.000
6	387.9	453.9	0.357	0.352
7	354.6	397.8	0.434	0.797
8	356.3	468.2	0.347	1.170
9	385.7	391.6	0.318	1.130

the highest increase, with Ra rising from 0.347 µm in normal burnishing to 1.17 µm under cryogenic conditions, indicating a significant deterioration in surface finish. The extreme cooling process in Run 9 led to surface roughness rising from 0.318 µm to 1.13 µm which validates the negative impact of intensified cooling. Identification of a special parameter set may counterbalance the roughening effects since Run 6 showed no significant change in surface roughness. These findings highlight the complex interplay between cooling, material response, and burnishing mechanics that emphasize the need for optimized process conditions to balance hardness improvements with surface integrity in cryogenic burnishing applications.

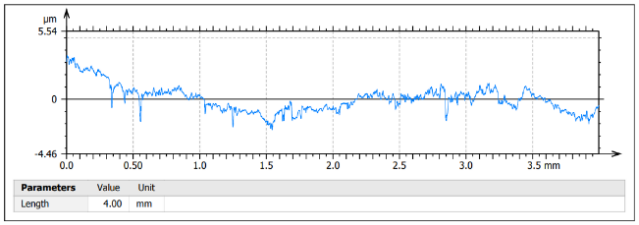
The increased surface roughness observed in cryogenic burnishing of Ti-6Al-4V can be attributed to several key factors related to material behaviour and process mechanics under extreme cooling conditions:

1. Reduced Plastic Deformation: Cryogenic temperatures significantly lower the ductility of Ti-6Al-4V that make it less responsive to the compressive stresses applied during burnishing. Unlike normal burnishing, where material plastically deforms and smoothens out surface irregularities, cryogenic cooling limits the material's ability to flow that lead to a rougher surface.
2. Increased Brittleness and Microfractures: The extreme cold from liquid nitrogen can induce localized embrittlement that causes microcracks or surface fractures instead of the intended smooth finishing. This embrittlement effect prevents the surface from achieving the desired compressive smoothness that led to a rougher finish.
3. Higher Work Hardening Rate: Cryogenic cooling increases the work hardening rate of Ti-6Al-4V, making the material more resistant to further deformation. As a result, instead of the burnishing tool flattening the asperities, it may cause more surface irregularities due to insufficient material compliance.
4. Inadequate Lubrication and Adhesion Issues: At cryogenic temperatures, lubricant effectiveness decreases due to freezing or increased viscosity that led to higher friction and inconsistent material flow. This can result in tearing, uneven surface features, or micro-gouging effects that degrade the surface finish.
5. Thermal Contraction-Induced Roughness: Rapid cooling induces thermal contraction and differential shrinkage in the material that potentially led to residual stress buildup and surface irregularities. These contractions can cause minor distortions that worsen surface roughness instead of improving it.
6. Burnishing Tool Interaction at Low Temperatures: The burnishing tool's interaction with the hardened surface may differ at cryogenic temperatures, where increased contact stiffness could lead to more pronounced surface asperities rather than a smooth, polished outcome.

These factors collectively explain why cryogenic burnishing increased surface roughness in most cases instead of improving it as typically expected. To counteract these effects, process optimization like adjusting burnishing force, feed rate, and cooling intensity may be necessary to balance the benefits of hardness enhancement with improved surface finish. Surface roughness (Ra) results of Run 1 (lowest in normal burnishing) and Run 8 (highest in cryogenic burnishing) in the cases of normal and cryogenic burnishing are presented in Figure 8 and Figure 9 respectively for a sample purpose.

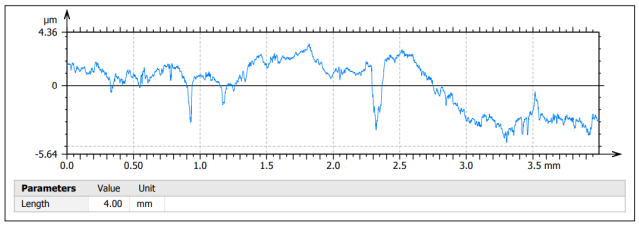
3.2 Optimization of Burnishing Process Parameters using Taguchi Technique

Figure 10 presents the ANOM plot for hardness after normal burnishing, illustrating the influence of key process parameters on the hardness of Ti-6Al-4V. The plot highlights that an optimal combination of parameters significantly enhances hardness due to strain hardening and improved surface integrity. A moderate burnishing



ISO 4287		
Amplitude parameters - Roughness profile		
Rp	0.823 µm	Gaussian filter, 0.8 mm
Rv	1.59 µm	Gaussian filter, 0.8 mm
Rz	2.41 µm	Gaussian filter, 0.8 mm
Rc	1.76 µm	Gaussian filter, 0.8 mm
Rt	3.45 µm	Gaussian filter, 0.8 mm
Ra	0.243 µm	Gaussian filter, 0.8 mm
Rq	0.348 µm	Gaussian filter, 0.8 mm
Rsk	-1.33	Gaussian filter, 0.8 mm
Rku	8.14	Gaussian filter, 0.8 mm
Material Ratio parameters - Roughness profile		
Rmr	46.9 %	c = 1 µm under the highest peak, Gaussian filte..
Rdc	0.534 µm	p = 20%, q = 80%, Gaussian filter, 0.8 mm

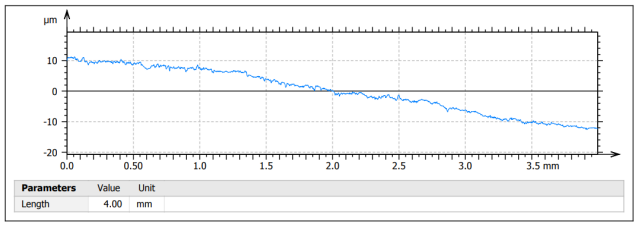
(a)



ISO 4287		
Amplitude parameters - Roughness profile		
Rp	1.26 µm	Gaussian filter, 0.8 mm
Rv	3.11 µm	Gaussian filter, 0.8 mm
Rz	4.37 µm	Gaussian filter, 0.8 mm
Rc	2.78 µm	Gaussian filter, 0.8 mm
Rt	6.83 µm	Gaussian filter, 0.8 mm
Ra	0.552 µm	Gaussian filter, 0.8 mm
Rq	0.793 µm	Gaussian filter, 0.8 mm
Rsk	-1.24	Gaussian filter, 0.8 mm
Rku	6.30	Gaussian filter, 0.8 mm
Material Ratio parameters - Roughness profile		
Rmr	2.05 %	c = 1 µm under the highest peak, Gaussian filte..
Rdc	0.971 µm	p = 20%, q = 80%, Gaussian filter, 0.8 mm

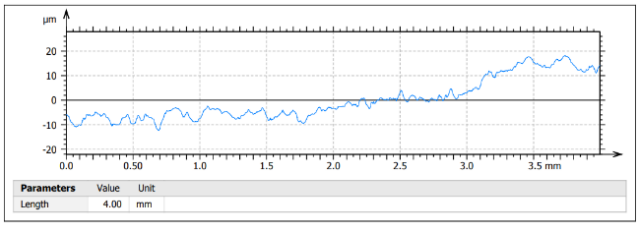
(b)

Figure 8. Surface roughness results of run 1.



ISO 4287		
Amplitude parameters - Roughness profile		
Rp	1.27 µm	Gaussian filter, 0.8 mm
Rv	1.37 µm	Gaussian filter, 0.8 mm
Rz	2.64 µm	Gaussian filter, 0.8 mm
Rc	1.91 µm	Gaussian filter, 0.8 mm
Rt	2.90 µm	Gaussian filter, 0.8 mm
Ra	0.347 µm	Gaussian filter, 0.8 mm
Rq	0.448 µm	Gaussian filter, 0.8 mm
Rsk	0.0757	Gaussian filter, 0.8 mm
Rku	3.26	Gaussian filter, 0.8 mm
Material Ratio parameters - Roughness profile		
Rmr	21.5 %	c = 1 µm under the highest peak, Gaussian filt..
Rdc	0.681 µm	p = 20%, q = 80%, Gaussian filter, 0.8 mm

(a)



ISO 4287		
Amplitude parameters - Roughness profile		
Rp	3.08 µm	Gaussian filter, 0.8 mm
Rv	3.95 µm	Gaussian filter, 0.8 mm
Rz	7.03 µm	Gaussian filter, 0.8 mm
Rc	4.90 µm	Gaussian filter, 0.8 mm
Rt	8.70 µm	Gaussian filter, 0.8 mm
Ra	1.17 µm	Gaussian filter, 0.8 mm
Rq	1.47 µm	Gaussian filter, 0.8 mm
Rsk	-0.337	Gaussian filter, 0.8 mm
Rku	3.15	Gaussian filter, 0.8 mm
Material Ratio parameters - Roughness profile		
Rmr	5.18 %	c = 1 µm under the highest peak, Gaussian filt..
Rdc	2.60 µm	p = 20%, q = 80%, Gaussian filter, 0.8 mm

(b)

Figure 9. Surface roughness results of run 8.

speed appears to facilitate effective plastic deformation without excessive heat generation, while an increased depth of cut contributes to localized work hardening[34]. The feed rate plays a crucial role in determining material flow and hardness uniformity, with an optimal range ensuring consistent compression without surface defects[35]. In addition to that, the number of burnishing passes directly correlates with hardness improvement as multiple passes refine the grain structure and induce compressive residual stresses[36]. Excessive passes may lead to stress relaxation that reduce overall benefit.

Figure11 presents the ANOM plot for hardness after cryogenic burnishing that demonstrate the impact of process parameters on the hardness of Ti-6Al-4V under cryogenic

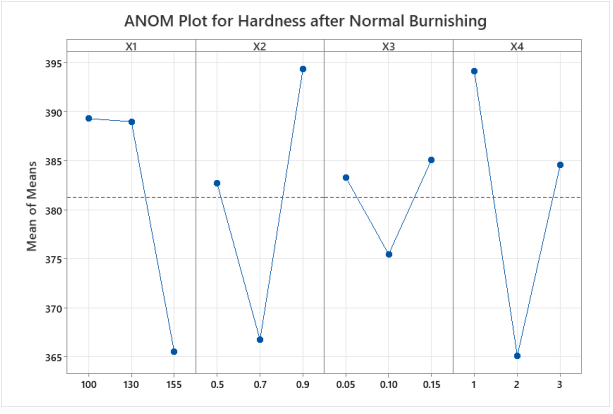


Figure 10. ANOM plot for hardness after normal burnishing.

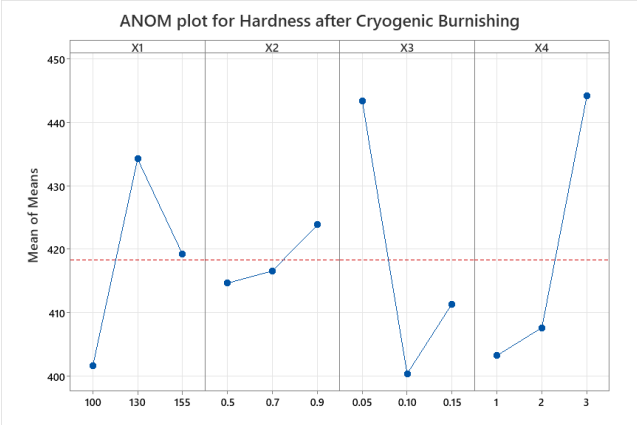


Figure 11. ANOM plot for hardness after cryogenic burnishing.

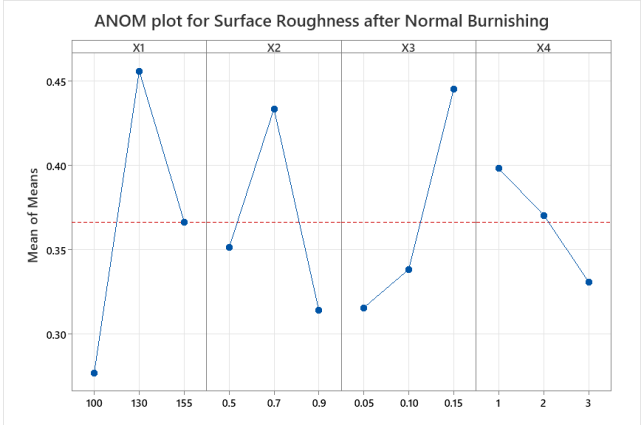


Figure 12. ANOM plot for surface roughness after normal burnishing.

conditions. The plot shows substantial hardness improvement above normal burnishing because the combination of thermal softening suppression along with strain hardening enhancement occurs through liquid nitrogen cooling. Hardness reaches its maximum when an appropriate cutting speed and depth are selected because, excessive cooling gives the material a brittle texture and decreases plastic deformation potential[37]. The feed rate controls uniformity in compressive stress distributes throughout the material which reaches optimal range criteria for producing hardness while preventing microscopic fractures. Similarly, the number of burnishing passes contributes to increased hardness, as multiple passes refine the grain structure and introduce beneficial compressive residual stresses[38]. However, excessive passes may lead to embrittlement or surface damage due to extreme cooling effects.

The surface finish of Ti-6Al-4V results from process parameters are shown in Figure 12 for ANOM plot of surface roughness after normal burnishing. The plot indicates that optimal parameter selection leads to a reduction in surface roughness as burnishing promotes plastic deformation that smooth out surface irregularities. The burnishing effect seems to be limited by the tool-material interaction time, so a moderate speed may be beneficial, as high speed may reduce this time. Similarly, an optimal depth of cut ensures sufficient material flow and surface refinement without causing excessive strain or defects. The feed rate is critical with a controlled feed that minimize the formation of surface asperities to maintain uniformity. The number of passes also plays a key role, as multiple passes enhance surface finish by eliminating micro-peaks and valleys. Furthermore, excessive passes may introduce work hardening effects that could prevent further smoothing. The ANOM analysis underscores the importance of process optimization in achieving a superior surface finish through normal burnishing that is essential to improve fatigue life and reduce friction in Ti-6Al-4V components.

Figure 13 presents the ANOM plot for surface roughness after cryogenic burnishing, illustrating the impact of process parameters on the surface finish of Ti-6Al-4V under cryogenic conditions. Unlike normal burnishing, the plot suggests an overall increase in surface roughness, likely due to the embrittlement effect caused by extreme cooling with liquid nitrogen. Reduced plastic deformation at cryogenic temperatures limits the ability of the material to flow and fill surface asperities, leading to higher roughness values. While an optimal speed and feed rate can help control material displacement and improve smoothness, excessive cooling may reduce ductility, causing microfractures or tearing instead of a polished finish. Additionally, deeper cuts and multiple passes, which typically enhance surface quality in normal burnishing, might contribute to increased roughness due to the stiffened material's resistance to deformation. The findings highlight the need for careful process optimization in cryogenic burnishing to balance hardness improvements with surface integrity, ensuring the best performance for Ti-6Al-4V applications.

3.3 SEM Analysis

Microscopic analysis was conducted on Run 8 specimen where maximum hardness was exhibited with cryogenic burnishing. The SEM images in Figure 14 reveal distinct

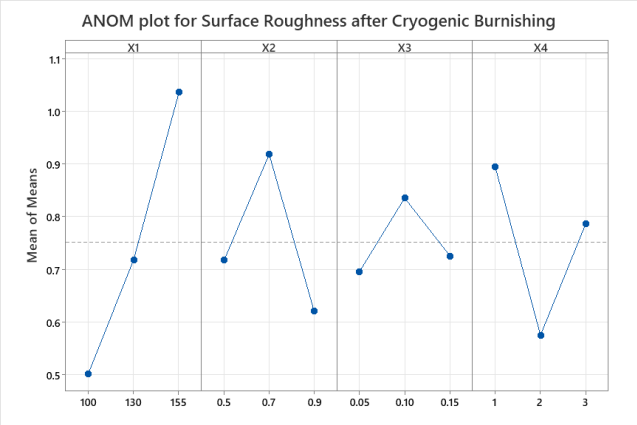
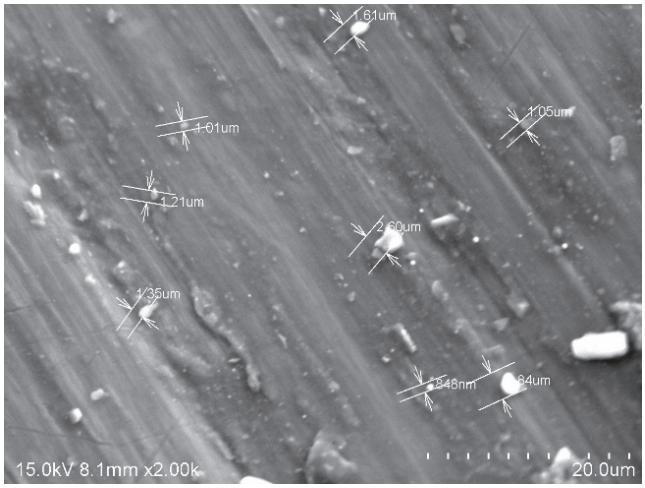


Figure 13. ANOM plot for surface roughness after cryogenic burnishing.

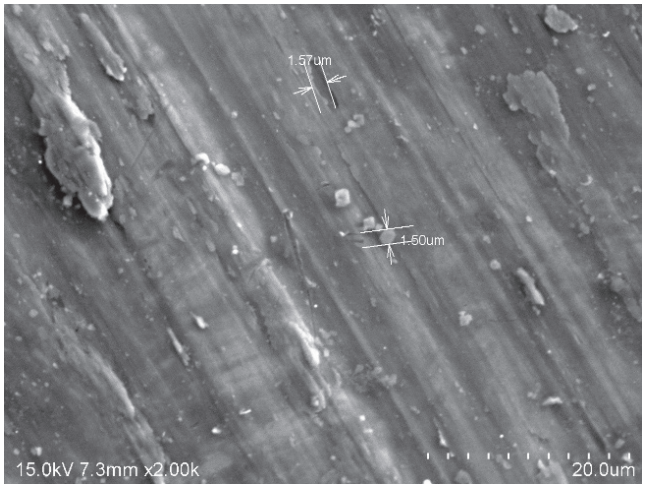
differences in surface morphology between normal and cryogenic burnishing of Ti-6Al-4V. Under normal burnishing (Figure 14(a)), the surface exhibits smooth, plastically deformed features with well-aligned shear bands and flattened asperities, indicating effective material flow and ductile behaviour[39]. The absence of cracks or surface tearing reflects uniform compressive deformation, contributing to improved surface finish and moderate hardness. Conversely, the cryogenically burnished surface (Figure 14(b)) appears significantly rougher, with visible microcracks, fragmented zones, and abrasive tracks. These features point to embrittlement caused by ultra-low temperatures, which restrict dislocation mobility and reduce ductility[40]. Instead of plastic smearing, the hardened surface fractures under compressive stress, producing surface irregularities. This aligns with the observed increase in hardness (468.2 HV) and surface roughness (Ra = 1.17 µm) for Run 8 under cryogenic conditions. While cryogenic burnishing enhances hardness through strain hardening, it compromises surface integrity[41]. These SEM observations underscore the need to carefully optimize process parameters to balance the benefits of hardness improvement with acceptable surface finish in cryogenic burnishing applications.

3.4 Contribution to the Engineering Community

This research makes a significant contribution to the engineering community by advancing the understanding of cryogenic-assisted burnishing for Ti-6Al-4V alloy,



(a) Normal Burnishing



(b) Cryogenic Burnishing

Figure 14. SEM images of run 8.

a material of critical importance in aerospace and biomedical engineering. By systematically optimizing key process parameters through the Taguchi method, this study bridges the gap between enhanced surface hardness and deteriorated surface finish under extreme cooling conditions. The findings provide engineers with actionable insights for tailoring surface enhancement techniques in components where fatigue strength, wear resistance, and dimensional accuracy are paramount. Furthermore, this work lays the groundwork for future development of hybrid cooling strategies and adaptive burnishing systems, thereby contributing to the evolution of sustainable and precision-based surface engineering practices for high-performance materials.

4.0 Conclusions

This study systematically evaluated the impact of cryogenic cooling on the burnishing process of Ti-6Al-4V using the Taguchi optimization approach.

- The key findings reveal that cryogenic burnishing enhances microhardness due to the suppression of thermal softening and increased strain hardening. Compared to conventional burnishing, cryogenic-assisted burnishing achieved up to a 31.5% improvement in hardness that make a promising method for applications requiring superior wear resistance and fatigue strength.
- An unexpected increase in surface roughness was observed in most cryogenic burnishing conditions. The results suggest that the embrittlement effect at ultra-low temperatures reduces the material's ability to plastically deform that lead to increased asperities and microfractures. This contradicts the typical benefits of burnishing, where improved surface integrity is expected. The analysis of process parameters further highlighted that excessive cooling intensity, coupled with higher burnishing forces, may contribute to rougher surfaces rather than smoother finishes.
- The optimization analysis using the Taguchi method demonstrated that selecting appropriate burnishing parameters is crucial in mitigating the trade-off between enhanced hardness and deteriorated surface roughness. Adjusting the feed rate, depth of cut, and number of passes can help optimize the process to achieve a balance between mechanical strengthening and surface quality.

Overall, the findings provide valuable insights into the complex interaction between cryogenic cooling and burnishing mechanics. While cryogenic-assisted burnishing is a viable technique for improving hardness, its application for surface finishing requires further refinements to control embrittlement effects. Future studies should explore hybrid approaches, such as controlled intermittent cryogenic cooling or post-burnishing surface treatments, to enhance both hardness and surface smoothness. This research paves the way for optimizing cryogenic burnishing as a next-generation surface enhancement technique for high-performance Ti-6Al-4V components in aerospace and biomedical industries. These insights warrant further exploration into adaptive cryogenic burnishing techniques with real-time feedback control.

5.0 References

1. Radnia A, Ketabchi M, He A, Li D. Effects of ECAP and subsequent recovery on microstructure, mechanical, tribological and corrosion properties of Ti-6Al-4V alloy. J Mater Res Technol. 2025; 35. PMCid:PMC11522389. https://doi.org/10.1016/j.jmrt.2025.02.111
2. Freitas BJ, Vidilli AL, Guerra BA, Ferreira DC, Kasama AH, Paes MT, Koga GY, Bolfarini C. Ti-6Al-4V and Ti-6Al-4V-0.1 Ru alloys in oil and gas Exploration: A review of performance and hydrogen embrittlement. J Alloys Compd. 2025: 179258. https://doi.org/10.1016/j.jallcom.2025.179258
3. Ni C, Zhu J, Zhang B, An K, Wang Y, Liu D, Lu W, Zhu L, Liu C. Recent advance in laser powder bed fusion of Ti-6Al-4V alloys: microstructure, mechanical properties and machinability. Virtual and Physical Prototyping. 2025; 20(1): e2446952. https://doi.org/10.1080/17452759.2024.2446952
4. Pop AB, Nagy RS, Titu AM, Medan N, Filip AC. Recent contributions to the development of barrel end-mill machining technologies for titanium alloys in the aerospace context. aerospace. 2025; 12(1). https://doi.org/10.3390/aerospace12010055
5. Čolić K, Kostić SM, Sedmak S, Gubeljak N, Grbović A. Structural integrity and life assessment of Ti-6Al-4V orthopaedic implants. Metals. 2025; 15(3):333. https://doi.org/10.3390/met15030333
6. Li X, Shao W, Tang J, Chen J, Zhao J. Towards understanding the influencing mechanism of barrel finishing on tooth surface integrity and contact performance. Wear. 2025: 206020. https://doi.org/10.1016/j.wear.2025.206020
7. Guo L, Yang S. Precision Grinding. Precision machining process and technology, Singapore: Springer nature. 2025: 1-35. https://doi.org/10.1007/978-981-16-4003-2_6-1 https://doi.org/10.1007/978-981-16-4003-2_6-1
8. Kebede FT, Felho C. Transforming burnishing techniques: A novel method to enhance efficiency and surface quality through tool feed variation. J Manuf Mater Process. 2025; 9(3):71. https://doi.org/10.3390/jmmp9030071
9. Ojeda ACO, Becerra BELesso VA, Arredondo RJF, Robles SA. Effect of burnishing methods on surface integrity of polymeric materials: A review. J Braz Soc Mech Sci Eng. 2024; 46(3):137. https://doi.org/10.1007/s40430-024-04718-z
10. Mishra SK, Ghosh S, Aravindan S. State-of-the-art research and corresponding industrial perspective for the use of textured surfaces in machining applications.

J Micro Manuf. 2025: 25165984241301537. https://doi.org/10.1177/25165984241301537
11. Marakini V, Charudat P, Achar BP, Sahoo B, Bhat U. Cryogenic machining induced corrosion resistance of magnesium alloy AZ91. Next Materials. 2025; 8: 100600. https://doi.org/10.1016/j.nxmate.2025.100600
12. Maximov J, Duncheva G. Effects of cryogenic-and cool-assisted burnishing on the surface integrity and operating behavior of metal components: a review and perspectives. Machines. 2024; 12(5): 312. https://doi.org/10.3390/machines12050312
13. Sachin B, Narendranath S, Chakradhar D. Enhancement of surface integrity by cryogenic diamond burnishing toward the improved functional performance of the components. J Braz Soc Mech Sci Eng. 2019; 41:396. https://doi.org/10.1007/s40430-019-1918-1
14. Uddin M, Santifoller R, Hall C, Schlaefer T. Effect of combined grinding-burnishing process on surface integrity, tribological, and corrosion performance of laser-clad stellite 21 alloys. Advanced Engineering Materials. 2023; 25(8):2201332. https://doi.org/10.1002/adem.202201332
15. Zhang H, Feng B, Lin D, Guo W, Cai Y, Xue J, Aslam J, Song Q, Wang B, Liu Z. Enhanced mechanical properties of Ti-6Al-4V titanium alloy through laser-assisted burnishing. Int J Adv Manuf Technol. 2025; 137:2635-2648. https://doi.org/10.1007/s00170-025-15288-2
16. Varpe NJ, Tajane R. Overview of burnishing process as a surface improvement technique. manufacturing strategies and systems. 2025:234-66. https://doi.org/10.1201/9781032725086-16
17. Swirad S, Pawlus P. Effect of ball burnishing on fretting at elevated temperatures. materials. 2024; 17(23):5960. https://doi.org/10.3390/ma17235960 PMid:39685396 PMCid:PMC11643990.
18. Raza A, Kumar S. A critical review of tool design in burnishing process. Tribology international. 2022; 174: 107717. https://doi.org/10.1016/j.triboint.2022.107717
19. Sivarupan T, Bermingham M, Ng CH, Sun S, Dargusch M. A review of the use of cryogenic coolant during machining titanium alloys. Sustainable Materials and Technologies. 2024: e00946. https://doi.org/10.1016/j.susmat.2024.e00946
20. Wen-tao H, Ning L, Hai-dou W, Zhi-hai C, Zhi-guo X, Zhong-yu P. Research on the microstructure and corrosion-wear resistance mechanism of Ti-6Al-4V alloy under cryogenic burnishing. J. Mater. Res. Technol 2025; 35:5854-5871. https://doi.org/10.1016/j.jmrt.2025.02.189
21. Korkmaz ME, Gupta MK. A state of the art on cryogenic cooling and its applications in the machining of difficult-to-machine alloys. Materials. 2024; 17(9):2057. https://doi.org/10.3390/ma17092057 PMid:38730865 PMCid:PMC11084919.
22. Avinash AS, Rashmi D, Satish S. Ch. enhancing surface integrity and quality through roller burnishing: A comprehensive review of parameters optimization, and applications. communications on applied nonlinear analysis. 2024; 20(1):151-169. https://doi.org/10.52783/cana.v31.563
23. Skoczylas A, Zaleski K, Matuszak J, Ciecieląg K, Zaleski R, Gorgol M. Influence of slide burnishing parameters on the surface layer properties of stainless steel and mean positron lifetime. materials, 2022; 15(22):8131. https://doi.org/10.3390/ma15228131 PMid:36431616 PMCid:PMC9694956.
24. Mebarek AM, Bourebia M, Laouar L, Nassim B. Effect of ball burnishing process on surface roughness and corrosion behavior of S235JR steel. Int J Adv Manuf Technol. 2024; 130:3431-3444. https://doi.org/10.1007/s00170-023-12906-9
25. Prasad A, John MR. An optimisation of the internal roller burnishing process for magnesium composites using Taguchi Multi objective optimization method. Materials science and technology. 2024; 40(17). https://doi.org/10.1177/02670836241273485
26. Nguyen TT, Nguyen TA, Dang XB, Van AL. Multi-performance optimization of the diamond burnishing process in terms of energy saving and tribological factors. Proceedings of the institution of mechanical engineers, Part E. 2023; 238(6):2714-2727. https://doi.org/10.1177/09544089231163407
27. Slawomir S, Pawel P. Effect of ball burnishing on fretting at elevated temperatures. materials (Basel). 2024; 17(23): 5960. https://doi.org/10.3390/ma17235960 https://doi.org/10.3390/ma17235960 PMid:39685396 PMCid:PMC11643990.
28. Zhen-Yu, Z, Qiu-Yang Z, Cong D, Ju-Yu Y, Zhong-Yu P. A review of the development of surface burnishing process technique based on bibliometric analysis and visualization. Int J Adv Manuf Technol. 2024; 115. https://doi.org/10.1007/s00170-021-06967-x
29. Sayadi D, Rangrizian H, Khodabandeh A, *et al*. Using shot peening and burnishing to improve fatigue performance of additively manufactured 316L stainless steel. Proceedings of the institution of mechanical engineers, Part L. 2023; 238(4):707-722. https://doi.org/10.1177/14644207231196266
30. Cagan SC, Leksycki K. Analysis of surface roughness after ball burnishing of pure titanium under environmentally friendly conditions. Applied sciences. 2025; 15(4):1746. https://doi.org/10.3390/app15041746

31. Karthikeyan S, Kathiresan S, Suja T. Effect of deep cryogenic treatment on machinability and corrosion resistance of titanium grade 2 alloy using electrical discharge machining process. J Mater Eng Perform. 2024; 34. https://doi.org/10.1007/s11665-024-10084-7
32. Ganesh M, Arunkumar N. A sustainable approach in deep hole drilling of Ti6Al4V: Effect of cryogenic cooling on hole parameters and its evaluation. J Manuf Process. 2024; 121:343-360. https://doi.org/10.1016/j.jmapro.2024.05.048
33. Zheng K, Zhao X, Pan L, Ren Z. Ultrasonic rolling strengthening of TC11 titanium alloy surface: corrosion and wear properties under extreme conditions. Wear. 2024; 550:205415. https://doi.org/10.1016/j.wear.2024.205415
34. Shen X, Ma S, Wang Z, Yu Z, Zhang J, Ma X, Zhu J, Yin Y, Pan S, Wei F. Multiscale mechanical performance evaluation of L-DED Ti6Al4V by novel Ultrasonic Burnishing (UB). J Manuf Process. 2024; 124:708-719. https://doi.org/10.1016/j.jmapro.2024.06.023
35. Shukla OA, Rawat R, Vidya S. Transforming machining technology with cryogenics: Advancements and innovations. Advances in manufacturing and materials, lecture notes in mechanical engineering. 2024: 273. https://doi.org/10.1007/978-981-97-3173-2_19.
36. Liu J, Feng P, Wang Z, Zhang J, Feng F, Zhang X. Collaborative improvement of structure shape and surface integrity in titanium alloy hole burnishing. Chin J Mech Eng. 2025; 38(1):14. https://doi.org/10.1186/s10033-024-01164-9
37. Tabatabaeian A, Ghasemi AR, Shokrieh MM, Marzbanrad B, Baraheni M, Fotouhi M. Residual stress in engineering materials: A review. Advanced engineering materials. 2022; 24(3):2100786. https://doi.org/10.1002/adem.202100786
38. Oliveira DA, Martins AM, Santos AJ, de MagalhŃes CF, AbrŃo AM. Influence of the hydrostatic ball burnishing on surface quality and ultra-microhardness. J Braz Soc Mech Sci Eng 2024; 46(2):74. https://doi.org/10.1007/s40430-023-04639-3
39. Toboła D, Morgiel J, Maj Ł. TEM analysis of surface layer of Ti-6Al-4V ELI alloy after slide burnishing and low-temperature gas nitriding. Applied surface science. 2020; 515:145942. https://doi.org/10.1016/j.apsusc.2020.145942
40. Tang J, Luo H, Qi Y, Xu P, Ma S, Zhang Z, Ma Y. The effect of cryogenic burnishing on the formation mechanism of corrosion product film of Ti-6Al-4V titanium alloy in 0.9% NaCl solution. Surface and Coatings Technology. 2018; 345:123-1231. https://doi.org/10.1016/j.surfcoat.2018.03.102
41. Li Y, Wang X, Yang S, Hou L, Wei Y, Zhang Z, Yang X. Investigation on wear behavior of cryogenically treated Ti-6Al-4V titanium alloy under dry and wet conditions. Materials. 2019; 12(18):2850. https://doi.org/10.3390/ma12182850PMid:31487877 PMCid:PMC6766037.