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Enhancement of Dry Reciprocating Wear Resistance of Aluminium 6061 and Polyamide 66 through Burnishing

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***Abstract* — This study investigates the wear behaviour of burnished Aluminium 6061 (Al6061) and Polyamide 66 (PA66) surfaces subjected to dry linear reciprocating motion. Ball and roller burnishing were applied under varying speeds, feed rates, and burnishing depths. Surface roughness and hardness were measured, followed by tribological testing under dry reciprocating conditions, and surface morphology was analyzed using a metallurgical microscope. Results indicate that optimal surface enhancement for both materials occurs at a burnishing speed of 300 rpm, a feed rate of 0.16 mm/rev, and a burnishing depth of 1 mm. Under these conditions, ball burnishing achieved the greatest reduction in average roughness, with improvements of 90.5% for Al6061 and 35.3% for PA66, while roller burnishing produced modest hardness gains of 3.1% for Al6061 and 1.6% for PA66. Ball burnishing also yielded the most substantial decrease in specific wear rate, with reductions of 90.6% for Al6061 and 87% for PA66. These findings demonstrate that optimized burnishing parameters can markedly enhance the tribological performance of both metallic and polymeric components under dry reciprocating conditions, offering practical insights for improving component durability.**

Keywords—Burnishing, Average roughness, Specific wear rate, Hardness formatting.

I. INTRODUCTION

Wear is a pervasive challenge in components subjected to dry linear reciprocating motion, such as pistons, rollers, and sliding mechanisms. Continuous reciprocation progressively degrades material surfaces, widening clearances between mating parts and increasing the risk of vibration, fretting, and eventual component failure. Surface engineering has emerged as a pivotal strategy to mitigate wear; however, the effectiveness of any treatment hinges on selecting a technique suited to the specific material and operating conditions.

Burnishing is a chipless surface treatment method that plastically deforms surface asperities through controlled contact and redistribute the material to fill surface valleys (Fig. 1) [1]. This mechanism can dramatically enhance surface roughness, hardness, wear resistance, and corrosion resistance [2–5]. Beyond performance gains, burnishing offers practical advantages. It is cost-effective, simple to implement, and requires minimal operator expertise. Mechanically, the process can increase yield strength and induce compressive residual stresses in the surface layer, delaying or suppressing fatigue crack initiation that typically originates at the surface [5–7]. Realizing these benefits, however, demands precise control over critical parameters, including force, feed rate, speed, depth of penetration, and number of passes [8–11].

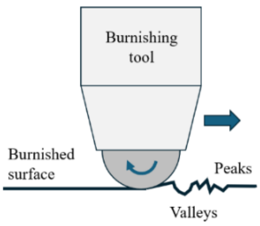

Fig. 1. Burnishing mechanism.

Although burnishing has been extensively studied for metals, its potential for polymers remains underexplored, particularly under dry linear reciprocating wear conditions. Previous studies by the

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authors have investigated the influence of burnishing on surface quality and tribological behaviour of individual materials, particularly polymers under dry sliding conditions [9, 12]. However, those studies were primarily limited to a single-material system under a conventional sliding wear configuration and did not address the comparative behaviour between fundamentally different material classes. The present study conducts a comparative investigation of both metallic (Al6061) and polymeric (PA66) materials under identical burnishing and dry reciprocating wear conditions. The combined evaluation of surface roughness, hardness, and specific wear rate enables a unified understanding of how burnishing parameters influence surface integrity and wear mechanisms. Furthermore, the inclusion of both ball and roller burnishing tools provides insight into the role of contact geometry in governing deformation behaviour and surface modification. This integrated approach offers new understanding of the mechanistic relationship between burnishing parameters and tribological performance across different material classes.

II. EXPERIMENTAL DETAILS

A. Ball and Roller Burnishing Tools

The design of the burnishing tools (Fig. 2) plays a critical role in determining the effectiveness of the process [13]. The ball burnishing tool employed in this study features a carbon steel alloy shaft and a 10 mm carbon-chromium steel burnishing ball that rolls freely on three 5 mm supporting carbon-chromium steel balls. A lubrication valve ensures consistent kerosene application, as dry burnishing can compromise surface quality. A removable cap, secured with set screws, allows for ball replacement and cleaning, preventing debris accumulation and maintaining process reliability. The supporting balls enable free rotation, preventing sticking and ensuring uniform burnishing across the surface. The roller burnishing tool consists of a carbon steel shaft and a hardened carbon-chromium steel roller. The roller's surface is treated to enhance hardness and durability, minimizing the risk of cracking under vibrational loads. It is rigidly affixed to the shaft using bolts and spacers, allowing only vertical rolling motion, with a contact width of 1 mm.

Fig. 2. Ball burnishing tool (left) and roller burnishing tool (right).

B. Materials and Burnishing Operation

This study focuses on Aluminium 6061 and Polyamide 66, both widely used engineering materials. Specimens were initially turned on a CNC lathe at a spindle speed of 330 rpm, feed rate of 0.196 mm/rev, and cutting depth of 0.5 mm. Ball and roller burnishing operations (Fig. 3) were subsequently performed on the same lathe to preserve concentricity. Coolant was applied throughout the process to prevent heat-induced surface degradation. A summary of burnishing conditions is given in Table I. The selected ranges of burnishing parameters were determined based on previously reported burnishing studies and preliminary trials. The parameter limits were chosen to ensure that sufficient plastic deformation could be induced while avoiding excessive penetration that could damage the polymer surface. In particular, the burnishing depth range was limited to 2 mm to prevent severe deformation or surface tearing of PA66, which possesses significantly lower yield strength and higher elastic recovery than metallic materials.

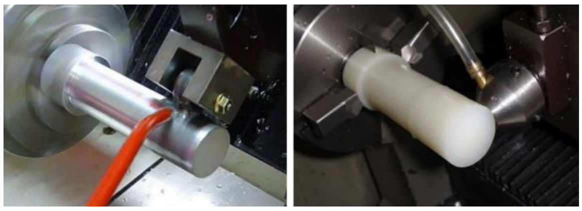

Fig. 3. Ball burnishing (left) and roller burnishing (right).

Table I. Summary of burnishing conditions.

Parameters	**Range**
Burnishing speed, *n* (rpm)	150 to 600
Burnishing feed rate, *f* (mm/rev)	0.08 to 0.32
Burnishing depth, *d* (mm)	0.5 to 2

C. Surface Roughness and Hardness Test

Surface roughness was evaluated using a Perthometer S2 profilometer for both burnished and unburnished specimens. Surface hardness was assessed with a Vickers Hardness Tester for Al6061 and a Shore D Hardness Tester (TH210) for PA66. To ensure the reliability of the results, each experimental condition was repeated three times, and the average value was reported. The variation between repeated measurements remained within ±5% for surface roughness and ±3% for hardness measurements, indicating good experimental repeatability.

D. Tribo Tests

Wear resistance of the surface was assessed under dry conditions using a linear reciprocating tribometer (Fig. 4). The setup consisted of a specimen holder, a 40 N dead weight, and a counterface material corresponding to the specimen, i.e., Al6061 for Al6061 samples and PA66 for PA66 samples. Tests were conducted for 600 seconds at 40 rpm, corresponding to a sliding velocity of 0.224 $m \cdot s^{-1}$ and a total sliding distance of 400 m. Specific wear rates were determined from weight loss measurements taken before and after testing using an analytical balance with 0.1 mg resolution (Shimadzu AW220). Post-burnishing surface morphology was examined with a metallurgical microscope at 40× magnification to assess wear patterns and surface damage. The specific wear rate, W_r, is calculated as Eq. (1):

$$W_r = \frac{dv}{F_n dx} \tag{1}$$

, where dv is the volume loss, F_n the normal load, and dx the sliding distance [6]. Post-burnishing surfaces were examined using a metallurgical microscope at 40× magnification.

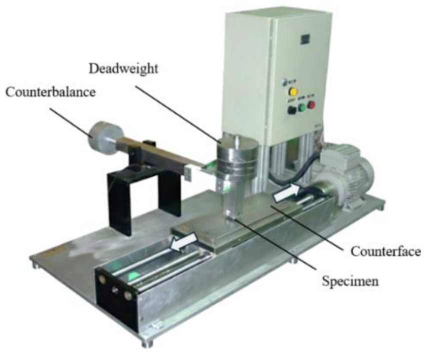

Fig. 4. Linear reciprocating tribo machine.

III. RESULTS AND DISCUSSIONS

A. *Results of Surface Roughness*

The present study investigated the effect of varying burnishing speeds on the surfaces of previously turned Al6061 and PA66 specimens. Figure 5(a) illustrates the relationship between burnishing speed and average surface roughness, revealing a pronounced parabolic trend. Initially, increasing burnishing speed led to a substantial reduction in average roughness, demonstrating the effectiveness of plastic deformation in flattening the asperities left by the turning operation. This reduction reached a maximum at an optimal speed of 300 rpm, corresponding to improvements of 90.5% and 65.9% for Al6061 via ball and roller burnishing, respectively. For PA66, the improvements were more modest, with gains of 32.4% and 22.6% for ball and roller burnishing, respectively. The reduction in surface roughness with increasing burnishing speed up to 300 rpm can be attributed to enhanced plastic flow of surface asperities under higher strain-rate deformation [14]. At moderate speeds, the burnishing tool repeatedly compresses the peaks generated during the turning operation, causing plastic flow into adjacent valleys and producing a smoother surface profile. This effect is particularly effective in ductile metallic materials such as Al6061, where dislocation motion facilitates stable plastic deformation. However, when the burnishing speed becomes excessively high, the contact time between the burnishing tool and the surface decreases, reducing the effectiveness of controlled plastic deformation. Simultaneously, frictional heat generation increases at the tool–workpiece interface. For metallic materials, this may locally reduce yield strength and promote unstable surface flow. In polymers such as PA66, the viscoelastic response of the material makes it more sensitive to temperature rise, leading to localized softening and partial elastic recovery after deformation [15]. In addition, dynamic instabilities such as tool chatter and elevated interfacial heating caused by insufficient lubricant interposition disrupt the controlled deformation process, generating irregular surface features [16]. Overall, ball and roller burnishing effectively enhanced surface quality for both materials. Notably, all burnished surfaces exhibited average roughness values substantially lower than those of the turned surfaces, except for the PA66 roller burnished at the highest speed, which showed an 8.6% deterioration. This anomaly suggests that at elevated speeds, the material's ability to withstand dynamic and thermal loads is exceeded, resulting in localized surface degradation.

These quantitative results are corroborated by optical microscopy observations (Fig. 5(b)). The turned surfaces exhibited deep, parallel feed marks, whereas burnished surfaces appeared markedly smoother and more uniform. Original feed marks were smeared and flattened, demonstrating successful micro-reconstruction of the surface layer. From a tribological perspective, the significant reduction in average roughness is particularly important, as it is closely associated with the induction of beneficial compressive residual stresses and increased surface hardness, both of which contribute to enhanced resistance to wear and fatigue [17].

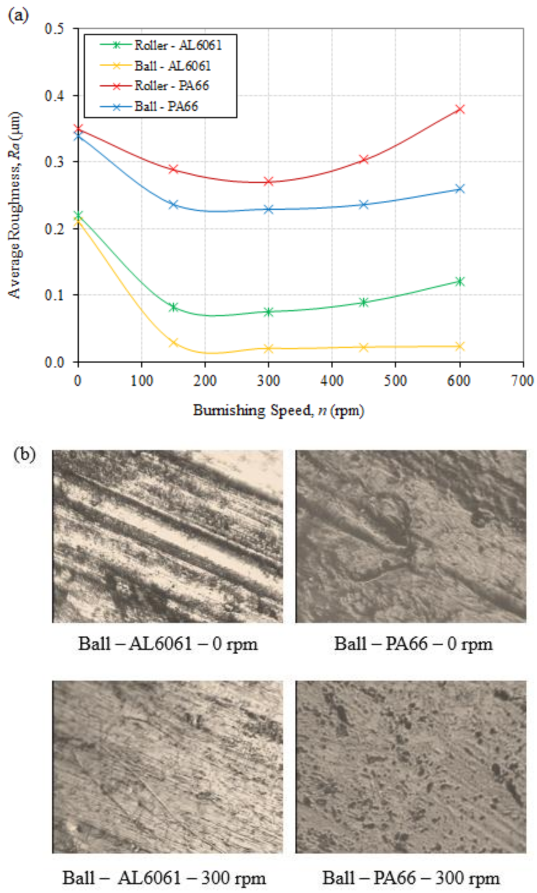

Fig. 5. (a) The effect of burnishing speed on average roughness and (b) Optical microscopy images of turned and ball burnished surfaces.

Figure 6 illustrates the effect of burnishing feed rate on surface roughness. The burnishing feed rate, representing the axial distance the burnishing tool advances along the workpiece per revolution, is a critical parameter influencing surface quality. Its effect on roughness is governed by the volume of material deformed per unit time, the degree of overlap between successive passes, and the uniformity of plastic flow. At a very low feed of 0.08 mm/rev, the overlap between consecutive passes is high, ensuring the surface is worked multiple times and effectively closing the original turning grooves, thereby reducing average roughness. However, excessively small feed rates may produce redundant deformation of already flattened regions, which does not significantly improve surface finish and may even promote localized surface smearing, particularly in polymeric materials [18, 19]. Conversely, when the feed rate becomes too large, the spacing between successive burnishing tracks increases, reducing the overlap of deformation zones. As a result, some asperities remain only partially deformed, leading to an increase in average surface roughness. Similar to burnishing speed, burnishing feed rate exhibits a parabolic relationship with surface roughness, with an optimal value around 0.16 mm/rev for all materials and tool types. At this feed, tool geometry and contact pressure achieve an ideal balance, providing sufficient overlap to flatten asperities effectively without inducing detrimental effects. This optimal feed rate yields the best surface finish and is typically associated with the favorable compressive residual stress profile [20]. Increasing the burnishing feed beyond this optimum reduces surface quality, as the burnishing ball or roller begins to skip over material, leaving undeformed peaks or partially flattened grooves, which raises the average roughness [21].

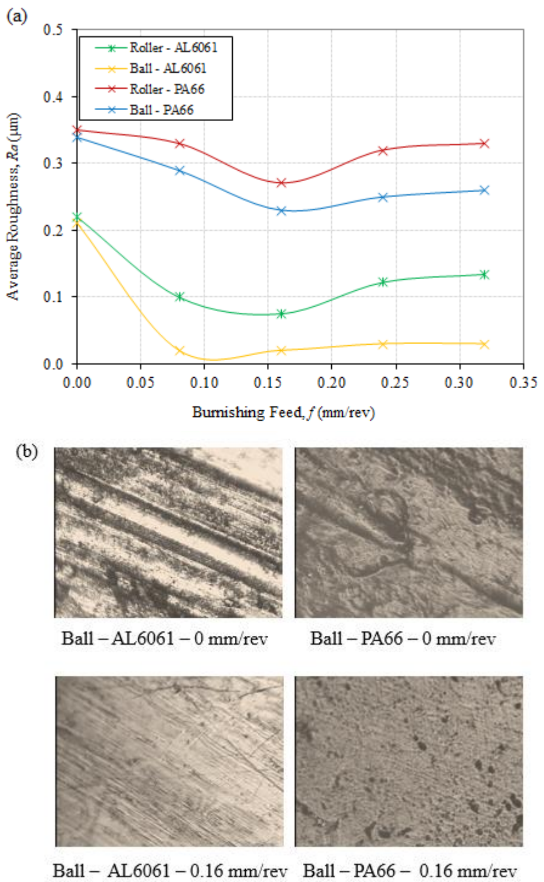

Fig. 6. (a) The effect of burnishing feed on average roughness and (b) Optical microscopy images of turned and ball burnished surfaces.

Ball burnishing consistently outperformed roller burnishing in achieving lower average roughness for both materials. For the ductile Al6061 alloy, ball burnishing produced significantly lower roughness values than the roller, reaching a minimum of 0.02 µm at 300 rpm. Similarly, for PA66, ball burnishing yielded a minimum roughness of 0.23 µm at the same speed. This superior performance is attributed to the point contact geometry of the burnishing ball tool, which generates higher localized contact pressure compared to the line contact of the roller, promoting more effective plastic deformation and flattening of surface asperities. A pronounced difference was also observed between the metallic alloy and the polymeric material. Across all burnishing conditions, Al6061 achieved average roughness values approximately an order of magnitude lower than PA66. For Al6061, roughness fell below 0.1 µm with both tools, whereas PA66 remained above 0.2 µm. This disparity arises from the materials' mechanical properties. The high ductility and low yield strength of Al6061 enable smooth, predictable plastic flow under burnishing, resulting in highly effective surface flattening. In contrast, the viscoelastic nature of PA66, including elastic recovery and potentially lower thermal conductivity, leads to localized heating, smearing, and partial elastic rebound, which limit the attainment of very low roughness values. Microscopy of the turned PA66 surface revealed less distinct grooves than Al6061, further highlighting the differences in material response to machining and subsequent plastic deformation.

Burnishing depth is intrinsically linked to burnishing force, as both parameters directly govern the contact pressure and the extent of subsurface plastic deformation generated during the process [12]. The applied force and resulting depth must be sufficient to exceed the material's yield strength while avoiding excessive penetration that could degrade the surface. Figure 7(a) illustrates the effects of ball and roller burnishing depth on the average roughness of Al6061 and PA66. At very small burnishing depths, the imposed pressure may not exceed the yield strength of the material, resulting primarily in elastic deformation of surface asperities. Under these conditions, only limited flattening of the turning marks occurs, and the improvement in surface roughness remains modest. As the burnishing depth increases, the contact pressure rises sufficiently to progressively deform the asperities and produce a smoother and more uniform surface profile. This mechanism explains the sharp reduction in roughness observed as burnishing depth increases from 0.5 mm toward the optimal value. An optimal depth exists at which average roughness reaches a minimum, often correlated with the maximum peak-to-valley height of the initial turned surface [22]. For Al6061, this optimal depth is 1 mm for both ball and roller burnishing. For PA66, roller burnishing achieves the same optimal depth of 1 mm, while ball burnishing requires 1.5 mm. The difference in optimal depth between Al6061 and PA66 can be attributed to their distinct mechanical responses. The ductile metallic structure of Al6061 facilitates stable plastic flow under compressive loading, allowing efficient smoothing at moderate penetration depths. In contrast, PA66 exhibits viscoelastic–plastic behaviour and elastic recovery after deformation, which reduces the permanent smoothing effect of the burnishing tool. Consequently, slightly greater penetration depths are required in some cases to compensate for this elastic recovery and achieve comparable surface improvement. Exceeding this depth increases average roughness, as excessive penetration induces uncontrolled lateral material flow, leading to surface tearing, micro-cracking, spalling, or the formation of piled-up ridges that act as new asperities. Deeper penetration typically results in more extensive subsurface compressive stresses, which are critical for enhancing fatigue life [23]. Ball burnishing consistently produces lower average roughness than roller burnishing across the entire depth range due to the point-contact mechanics of the ball, which generate higher localized stresses that more effectively plastically deform the material into surface valleys.

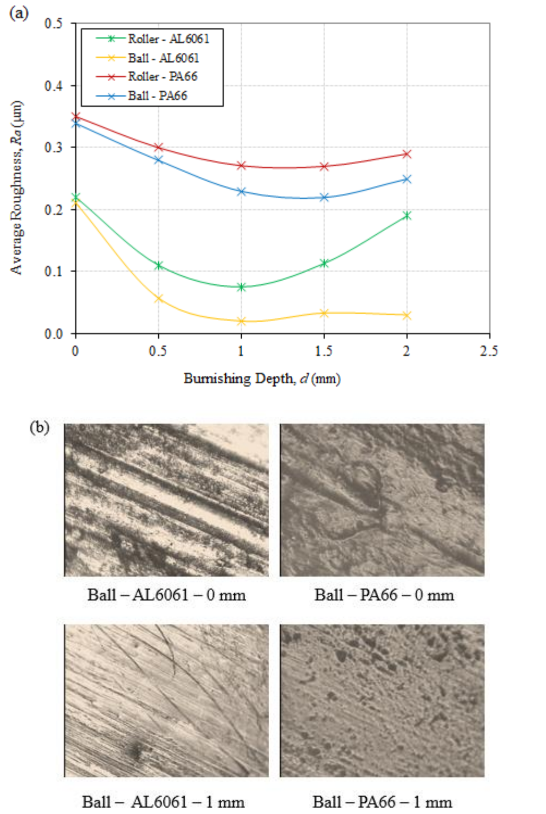

Fig. 7. (a) The effect of burnishing depth on average roughness and (b) Optical microscopy images of turned and ball burnished surfaces.

Optical microscopy images (Fig. 7(b)) confirm the effectiveness of burnishing at the optimal depth of 1 mm. The initially turned Al6061 surface exhibits pronounced, parallel feed marks, which are smeared, flattened, and reduced in depth after ball burnishing, demonstrating successful surface reconstruction via plastic flow. The PA66 surface also becomes smoother, although its initial grooves are less distinct. Achieving this optimal depth is crucial for tribological performance, as it not only minimizes average roughness but also maximizes the introduction of beneficial compressive residual stresses in the subsurface layer, thereby enhancing resistance to wear and delaying fatigue crack initiation.

B. Results of Hardness and Specific Wear Rate

Figure 8 shows the effect of burnishing speed on the hardness and specific wear rate of Al6061 and PA66. Surface hardness was measured using the Vickers HV10 scale for Al6061 and the Shore D scale for PA66. A clear correlation is observed between surface hardness, average roughness, and specific wear rate, highlighting the fundamental tribological interplay established by the burnishing process. In Al6061, plastic deformation induced by burnishing leads to work hardening, with maximum hardness generally achieved around 300 rpm. This is the same speed at which minimum average roughness is observed. This correlation indicates that the parameters producing the smoothest surface also promote the most effective subsurface strain hardening. Increased hardness directly corresponds to reduced specific wear, consistent with Archard's wear equation, which predicts that wear is inversely proportional to hardness. In this study, Al6061 hardness increased from approximately 105 HV10 (turned surfaces) to over 108 HV10 at 300 rpm, contributing to a substantial reduction in specific wear rate for both ball and roller burnishing. In contrast, PA66 exhibited a smaller gain in hardness due to its viscoelastic nature.

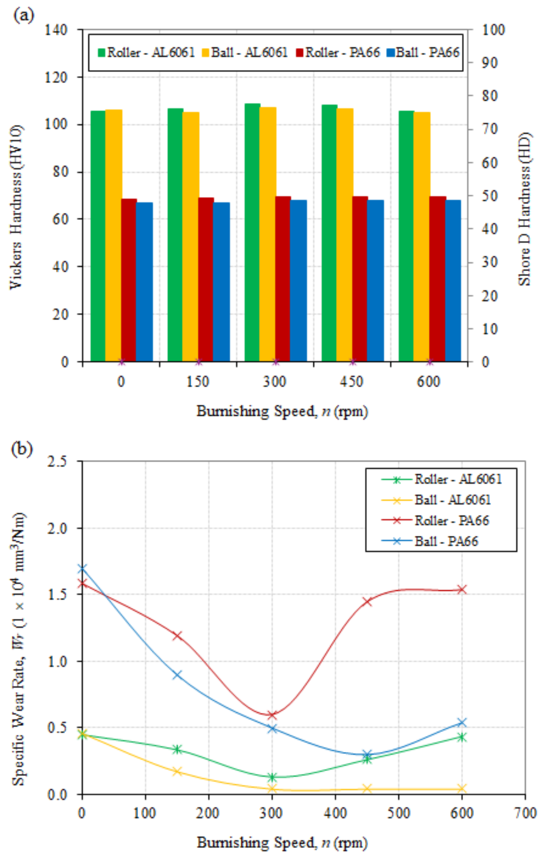

Fig. 8. The effect of burnishing speed on (a) Hardness (b) Specific wear rate.

The parabolic trends observed in specific wear rate as a function of burnishing speed can be explained by the competing effects of beneficial surface modification and surface degradation mechanisms. The specific wear rate of Al6061 decreased by approximately 90.6% relative to the turned surface at the optimal burnishing speed of 300 rpm, while PA66 experienced a reduction of 82.4%. This improvement results from the combined effect of reduced surface roughness and increased hardness, which together mitigate ploughing, adhesion, and abrasive wear during sliding. Beyond the optimal speed, the specific wear rate for roller-burnished Al6061 and PA66 increases sharply, reflecting degradation of surface integrity at high speeds. This rise is primarily driven by increased average roughness caused by tool chatter and localized thermal softening, along with potential reductions in beneficial compressive residual stresses, making the surface more prone to fatigue wear. Notably, Al6061 achieves a considerably lower specific wear rate than PA66 due to its ability to work harden, whereas the polymer's lower hardness and viscoelastic behaviour result in a higher baseline wear rate.

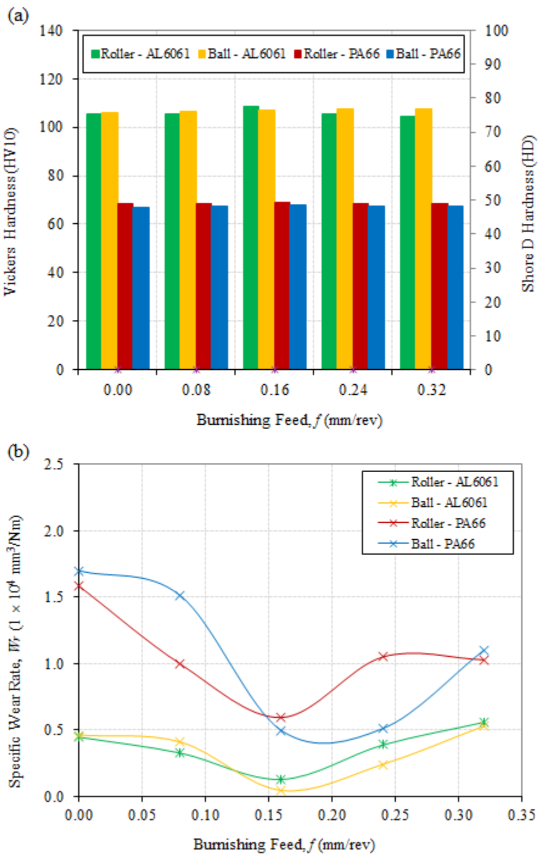

Fig. 9. The effect of burnishing feed on (a) Hardness and (b) Specific wear rate.

Figure 9 shows the effect of burnishing feed rate on hardness and specific wear rate. The HV10 hardness of Al6061 remains nearly constant across the range of feed rates, peaking slightly at the optimal feed of 0.16 mm/rev. This stability indicates maximum work hardening in Al6061 occurs early in the burnishing process and remains unaffected by track overlap. The ball burnishing tool consistently produces marginally higher hardness values for both Al6061 and PA66 compared to the roller tool, reflecting the more effective strain hardening achieved when tool–workpiece contact is stable. The optimal feed of 0.16 mm/rev also corresponds to the lowest specific wear rate for all burnishing tool–material combinations. The pronounced work hardening of Al6061 results in a substantially lower specific wear rate compared to the softer PA66 polymer.

The specific wear rate exhibits a clear correlation with burnishing feed, closely mirroring the trend observed for average roughness. As the feed approaches 0.16 mm/rev, the specific wear rate decreases to a minimum. Beyond this optimal feed, specific wear rate increases for all materials and tool types. This increase is primarily due to the reduced overlap between burnishing tracks at higher feeds, which leads to higher average roughness and more aggressive inter-surface contact. Elevated roughness induces localized stress concentrations and micro-pitting, accelerating abrasive wear. Consequently, excessive feed rates compromise the surface integrity, highlighting the critical importance of optimizing burnishing feed to achieve minimal wear.

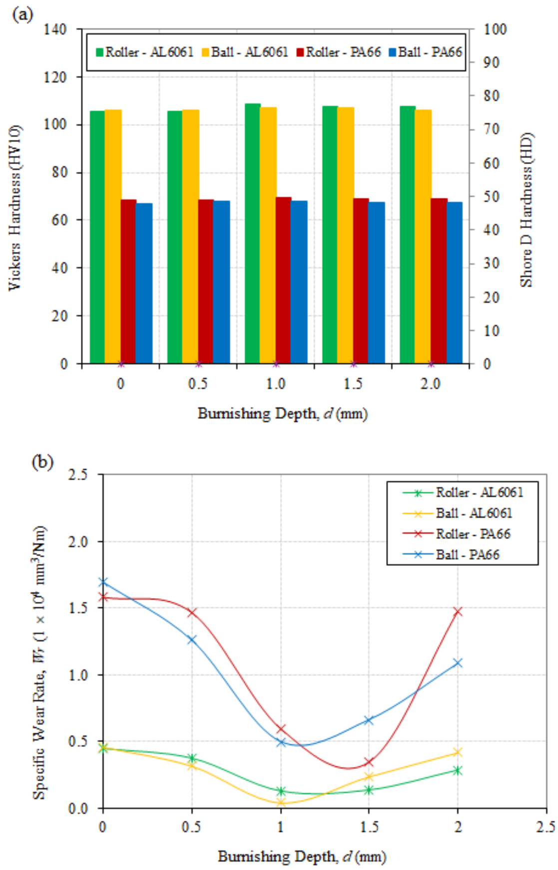

Fig. 10. The effect of burnishing depth on (a) Hardness and (b) Specific wear rate.

Figure 10 shows the effect of burnishing depth on hardness and specific wear rate for both materials. The hardness data show that surface hardness rapidly plateaus after an initial penetration depth of approximately 0.5 mm, remaining stable despite further increases in burnishing depth. This behaviour indicates that maximal strain hardening achievable through cold working is reached early, with additional depth primarily increasing the thickness of the hardened layer rather than the magnitude of surface hardness. Notably, this peak hardness coincides with the depth at which average roughness is minimized, confirming that the optimal depth for maximum cold work aligns with the most effective surface flattening and reconstruction.

The specific wear rate exhibits a parabolic relationship with burnishing depth, closely mirroring the trend observed for average roughness. At relatively low burnishing intensities, the applied contact pressure is insufficient to induce significant plastic deformation throughout the surface asperities. As a result, only partial smoothing of the surface is achieved. Consequently, the material exhibits a relatively lower hardness and higher wear rate. As the contact pressure becomes sufficient to exceed the yield strength of the surface layer, plastic deformation allows the asperities to be effectively flattened while simultaneously inducing strain hardening in the near-surface region [17]. The combined effect of reduced roughness and increased hardness improves the load-bearing capacity of the surface and reduces the real area of contact during sliding. Under these conditions, both abrasive and adhesive wear mechanisms are suppressed, leading to the observed minimum in specific wear rate, achieving around a 90.6% improvement for ball-burnished Al6061. When the burnishing depth exceeds the optimal range, excessive plastic deformation may result in surface pile-up, micro-crack initiation, or localized tearing [24, 25]. In addition, increased frictional heating at higher burnishing intensities can reduce the effectiveness of strain hardening, particularly in the case of PA66, where viscoelastic softening becomes significant. These effects increase surface roughness and introduce stress concentrations that accelerate material removal during sliding contact, thereby increasing the specific wear rate. The difference in behaviour between Al6061 and PA66 further highlights the role of material properties in burnishing performance. Al6061 exhibits pronounced strain hardening due to dislocation accumulation, resulting in a strong correlation between reduced roughness, increased hardness, and reduced wear. In contrast, PA66 shows limited hardening capability and significant elastic recovery, leading to smaller improvements in hardness and a greater sensitivity to thermal and deformation-induced softening. As a result, although both materials exhibit similar trends, the magnitude of improvement is significantly greater for Al6061. This emphasizes the importance of selecting an appropriate burnishing depth to optimize both the surface finish and the tribological performance of the materials.

The observed relationship between burnishing parameters, surface integrity, and wear performance can be interpreted within the framework of classical contact mechanics and Archard's wear law. According to Archard's model, the wear volume is proportional to the applied load and sliding distance and inversely proportional to the hardness of the softer contacting surface [26]. However, in practical tribological systems, the real area of contact is governed not only by hardness but also by surface roughness and asperity geometry. Burnishing modifies both factors simultaneously by plastically deforming surface asperities and inducing strain hardening in the near-surface layer. From a contact mechanics perspective, smoother surfaces reduce asperity interaction and lower the real contact area under a given load, thereby decreasing local contact stresses and mitigating adhesive and abrasive wear mechanisms. At optimal burnishing conditions, the combined effect of reduced roughness and increased hardness minimizes wear, consistent with Archard-type behaviour. In contrast, excessive burnishing parameters can degrade surface integrity through unstable plastic flow and defect formation, increasing the effective contact area and stress concentrations, which in turn accelerates wear. This framework explains the parabolic trends observed in the experimental results and highlights the critical balance between surface smoothing and deformation-induced damage in determining tribological performance.

IV. CONCLUSION

The present study demonstrates that both roller and ball burnishing substantially enhance the surface properties of Al6061 and PA66, including average roughness and specific wear rate, thereby improving overall wear resistance compared to unburnished surfaces. In contrast, improvements in surface hardness were incremental. These enhancements generally increase with burnishing speed, feed rate, and depth up to optimal thresholds, beyond which excessive parameters lead to performance degradation. Optimal burnishing parameters in this study, 300 rpm speed, 0.16 mm/rev feed, and 1 mm depth, produced the lowest surface roughness and wear rates while achieving maximum hardness for both materials. These results underscore that carefully controlled burnishing is a highly effective strategy for enhancing the tribological performance of both Al6061 and PA66, with ball burnishing providing the most significant improvements in surface finish and wear resistance, and roller burnishing offering moderate hardness enhancement.

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AUTHOR CONTRIBUTIONS

Kean Ong Low: Conceptualization, Formal Analysis, Investigation, Paper Writing, Supervision.
Sindhu Jagjeet Singh: Formal Analysis, Investigation, Methodology.

CONFLICT OF INTERESTS

No conflict of interests was disclosed.

ETHICS STATEMENTS

Our publication ethics follow The Committee of Publication Ethics (COPE) guideline. https://publicationethics.org/

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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