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RESEARCH ARTICLE

TOOL WEAR ANALYSIS OF 22MNB5 BORON STEEL CUTTING TOOLS IN ALUMINIUM ALLOY MACHINING UNDER LUBRICATED AND UNLUBRICATED CONDITIONS

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Abstract. This study explores the potential of 22MnB5 boron steel as a cutting tool material for machining AA6061 aluminium alloy under lubricated and unlubricated conditions. Conventional high-speed steel (HSS) tools often face rapid wear and limited hot hardness at high cutting speeds, while carbides and ceramics, though effective, are costly or brittle. To address this gap, four 22MnB5 samples with different hardness levels (45.5–70 HRC) were prepared through hot stamping and heat treatment. Hardness tests, ball-on-disc wear experiments, and machining trials were conducted at cutting speeds ranging from 100 to 450 m/min with a constant feed of 0.1 mm/rev and depth of cut of 0.5 mm. The heat-treated sample (70 HRC) showed the best tribological performance, achieving the lowest coefficient of friction (0.2114) and superior wear resistance. Machining trials revealed that lubrication reduced tool wear by an average of 15.8 %, while the most stable performance occurred at cutting speeds of 200-350 m/min. Wear mechanisms varied with speed and condition, shifting from built-up edge formation at lower speeds to tribolayer effects at higher speeds. Overall, the findings suggest that 22MnB5 boron steel, particularly in its heat-treated form, provides a durable and cost-effective alternative to HSS, with promising potential for sustainable machining applications.

Keywords: 22MnB5, machining, tool wear, tool life, built-up edge, flank wear.

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1. INTRODUCTION

Machining is a fundamental process in manufacturing, involving the removal of material to achieve the desired shape and dimensions of a workpiece. The efficiency of this process is largely determined by the cutting tool, which plays a crucial role in productivity, surface finish quality, and cost-effectiveness. However, as cutting tools are used repeatedly, they undergo wear, leading to reduced performance, increased tool replacement costs, and potential disruptions in production [1,2].

Steel, especially high-speed steel (HSS), has long been established for use in cutting tools. The main reasons are its strength, affordability, and availability. This material also performs well in general machining tasks and offers moderate wear resistance, making it suitable for mass production in industry. However, with industries moving towards higher-speed and more demanding operations, especially in fields like aerospace and automotive, HSS offers limitation to fall short in performance during prolonged high-speed machining. The level of hot hardness and wear resistance provided by HSS is not sufficient, leading to shorter tool lifespan, higher replacement rates, and increased production costs. Because of this, researchers have started exploring new materials that offer better resistance to wear, greater thermal stability, and stronger cutting capabilities [3,4].

So far, several alternatives to HSS have been studied. Carbide tools, for example, are already well known. These tools are harder, more heat resistant, and usually last longer than HSS. Research by Gupta et al. [5] and Shioda et al. [6] confirmed that carbide tools offer better surface finish and extended tool life when used on aluminium. The downside is the cost, carbide tools are expensive and not always feasible for small to medium-sized workshops. Ceramic tools also show promise. They offer excellent wear resistance and perform well at high temperatures, as demonstrated in Hadzley et al. [7]. But the brittle nature of ceramics makes them prone to chipping, which is a problem in tougher machining tasks or when shock loads are involved. Another group of alternatives includes coated tools. Tools coated with materials like TiAlN or CVD diamond have been developed to extend tool life and improve cutting performance. Ali et al. [8] found that TiAlN coatings significantly improved wear resistance in HSS tools, while Fox-Rabinovich et al. [9] informed that CVD diamond coatings helped reduce built-up edge during aluminium machining. Even so, coated tools can still face challenges under harsh machining conditions.

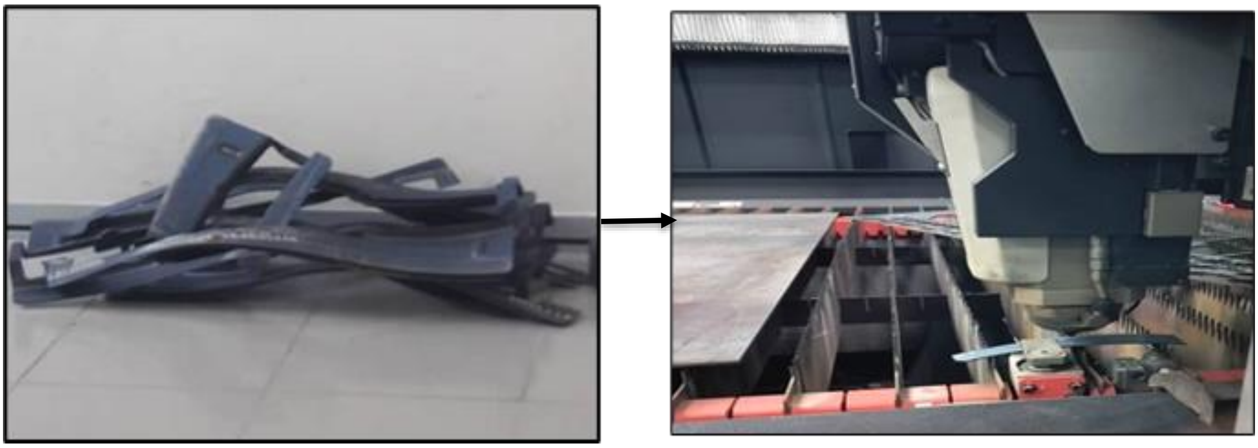
HSS is still widely used for aluminium cutting, but at higher speeds it wears quickly, reducing surface quality and raising costs. Aluminium alloys like AA6061 also adhere to the tool, forming built-up edges, increasing friction, and accelerating wear. A promising alternative is 22MnB5 boron steel, whose high strength and hardness may provide longer, more consistent performance, though its behaviour under various conditions is not yet well understood. In automotive manufacturing, hot stamping heating steel sheets, forming them, and rapidly cooling can quadruple strength, reduce weight, and maintain accuracy [10]. This makes it essential for lightweight, crash-resistant components. 22MnB5, known for its hardness and toughness, transforms from ferrite to austenite and then martensite during heat treatment, enhancing wear resistance [11]. While ideal for structural parts, its potential as a cutting tool, especially for aluminium, remains underexplored. An investigation into the wear characteristics of 22MnB5 under real machining conditions is essential for assessing its capability to combine strength, wear resistance, and cost efficiency, thereby contributing to the development of durable and economically viable tooling solutions for sustainable manufacturing practice.

2. MATERIALS AND METHODS

Manufacturing of 22MnB5 boron steel cutting tools began with recycled material from the hot stamping process. Samples were laser-cut and evaluated for hardness and coefficient of friction, as shown in Figure 1. Four sample types were prepared according to criteria commonly available in industry, as presented in Table 1. Sample A consisted of an untreated blank. Sample B was prepared by industrial hot stamping and achieved 52 HRC, while Sample C was industrial hot-stamped to 60 HRC.

Sample D was a blank heat-treated in a conventional furnace at 950 °C for 2 hours, followed by water quenching.

All samples underwent hardness and friction testing. The hardness test was conducted using a Rockwell hardness tester. During the assessment, the indenter applied a major load of 150 kgf, penetrating further into the specimen. The load was maintained for the dwell time before being released to record the hardness value. The scratch test was conducted using a ball-on-disc wear tester. A 6 HRC stainless steel ball was reciprocated against the sample under a 10 N load for 1800 s, producing a 3 mm wear track. Wear behavior was assessed under controlled pressure and sliding speed. The best-performing material selected for further tool wear and machining trials.



(a) (b)

Figure 1: (a) Raw material of 22MnB5 and (b) 22MnB5 Boron steel sample cutting by laser machine

Table 1: The designated condition of each sample

Sample	Condition
Sample A	Blank sample
Sample B	Hot stamped sample obtained from industry with 52HRC hardness
Sample C	Hot stamped sample obtained from industry with 60HRC hardness
Sample D	Blank sample that heats treated by conventional furnace

Machining tests were carried out on AA6061 aluminium alloy under lubricated and unlubricated conditions with machining parameter performed according to Table 2. The workpiece material was prepared with a diameter of 80 mm and a length of 260 mm. Tool life was measured until average flank wear (Vb) reached 0.3 mm, following ISO 3685 guidelines and wear mechanisms were examined using an optical microscope. The RNGN 120300 insert was securely attached to the CRDN252543 tool holder. The experiment consisted of performing machining tests on a CNC turning machine. The machining experiments were carried out in controlled conditions with a set machining duration of 4 minutes. The cutting speeds ranged from 100 to 450 m/min, with a constant feed rate of 0.1 mm/rev. A constant cutting depth of 0.5 mm was consistently maintained during the experiments. After finishing the machining operations, tool wear was assessed using a tool maker microscope. The wear mechanism was investigated using a scanning electron microscope.

Table 2: Machining parameters

Cutting Speed	Feed Rate	Depth of cut
100 m/min	0.1 mm/rev	0.5 mm
150 m/min	0.1 mm/rev	0.5 mm
200 m/min	0.1 mm/rev	0.5 mm
250 m/min	0.1 mm/rev	0.5 mm
300 m/min	0.1 mm/rev	0.5 mm
350 m/min	0.1 mm/rev	0.5 mm
400 m/min	0.1 mm/rev	0.5 mm
450 m/min	0.1 mm/rev	0.5 mm

3. RESULTS AND DISCUSSION

Figure 2 shows the hardness of Samples A-D. Sample A, untreated 22MnB5 boron steel, with measured hardness of 45.5 HRC. Industrial hot-stamped Samples B and C recorded hardness of 52 HRC and 60 HRC respectively. Sample D, heat-treated in a conventional furnace and water-quenched, underwent a ferrite-to-austenite transformation followed by martensitic cooling, achieving the highest hardness of 70 HRC, surpassing Sample C.

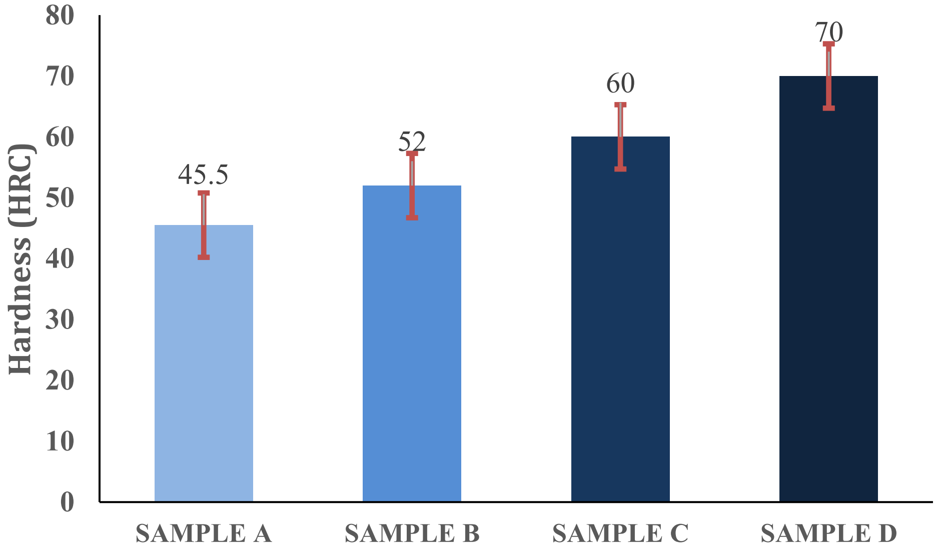


Figure 2: Comparison of hardness across samples

The mechanical response of 22MnB5 boron steel is shown in Figure 3. The untreated sample (Sample A) recorded hardness of 45.5 HRC, reflecting its ferritic–pearlitic structure. Industrial hot stamping improved hardness, with Sample B at 52 HRC and Sample C at 60 HRC. The increase is due to martensite formation during rapid cooling. Sample D reached 70 HRC. This exceeds the normal range for industrial hot stamping.

Sample C and D were taken from the same component, but their hardness values are different. Several possible factors may explain this difference. During hot stamping, parts expand, creating different regions suitable for cutting tool production. Uneven heating and cooling can cause incomplete quenching and affect hardness. As shown in Figure 3, two such regions are identified: Area D (flat, top panel) and Area C (side panel). Area D benefits from direct pressure from the upper stamp press, resulting in efficient lateral compression and higher hardness. In contrast, Area C shows lower hardness (60 HRC) as it conforms to sidewall contours. This may result from incomplete stretching in corner regions, causing residual stresses, or from inefficient quenching due to poor cooling channel contact, which limits heat transfer and prevents full microstructural hardening.

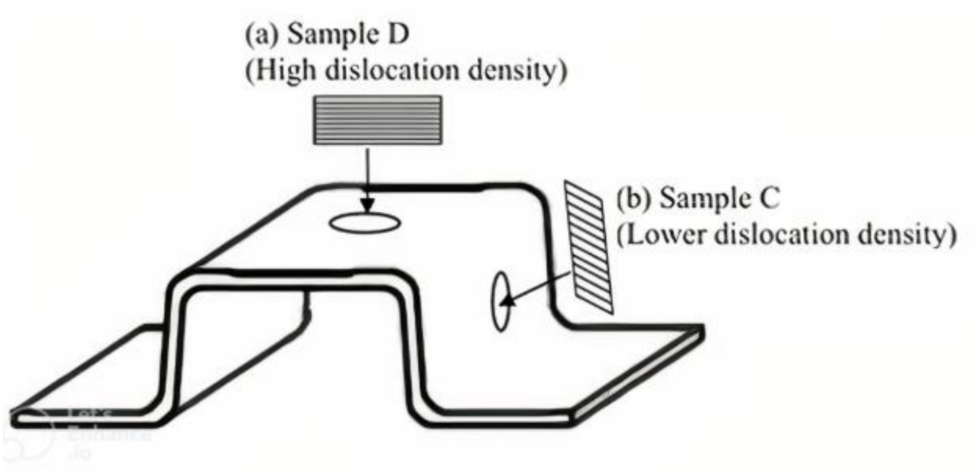


Figure 3: Illustration of dislocation density for Sample C and D

The hardness value of 70 HRC recorded for Sample D is exceptionally high for 22MnB5 boron steel. Reported literature generally places the hardness of hot-stamped 22MnB5 in the range of 50–62 HRC after martensitic transformation [10,11]. The measured hardness of 70 HRC confirms that the thermal cycle employed furnace heating followed by water quenching was sufficient to achieve full austenitization and accelerate martensitic phase formation upon cooling. This outcome signifies the maximum attainable hardenability; however, it should be acknowledged that excessive hardness is frequently correlated with reduced toughness and heightened susceptibility to brittle failure [12,13]. The result may reflect localized surface conditions or measurement sensitivity, as microstructural heterogeneity can influence Rockwell readings. In addition, since all 22MnB5 samples were obtained from industry, this sample might have already undergone another treatment during industrial processing. An additional heat treatment was later applied to this sample. Further validation through repeated hardness tests and complementary microstructural analysis is recommended to confirm the reliability of this result.

Figure 4 shows the coefficient of friction (CoF) profiles for four samples: untreated blank (A), industrial hot-stamped 52 HRC (B), industrial hot-stamped 60 HRC (C), and furnace heat-treated (D). Increasing hardness produced minimal changes in CoF, which remained stable around 0.3 for Samples A (0.3071 µm) and B (0.2999 µm). Sample C had a slightly lower CoF of 0.2446 µm, while Sample D recorded the lowest at 0.2114 µm. These reductions in C and D are likely due to microstructural changes from heat treatment, though the overall effect on friction behaviour was minimal.

Figure 5 shows the effect of different wear traces of boron steel. The figure given shows the sliding direction, which covers a distance of 3 mm. This study investigates the width of the wear tracks on boron steel surfaces. The surface of the blank sample is shown in Figure 5(a). Obviously, there is a significant surface penetration with highest coefficient of friction (COF) at 0.3071. The estimated length of the scratch is about 2800 µm, with a width of about 1600 µm. Scratch marks are easy to identify because of their consistent white color, resulting from the delamination of flaked surfaces that cover the entire scratched area. Based on Figure 5(b), the scratch area appears smaller, with a length of approximately 2400 µm and a height of about 1000 µm. The white scratch region is confined to a specific localized area, with a coefficient of friction (COF) of 0.2999. The specimen shows a remarkable ability to resist indentation when subjected to external stress. On the other hand, the results shown in Figure 5(c) show that in the sample C, there is no visible white scratch effect on the worn area. The width of the scratch area is noticeably smaller, measuring around 800 µm in height, while the length remains consistent at around 2400 µm. The pin-on-disc mechanism caused shear deformation of the sample and the surface exhibited significant resistance during the process, with a COF of 0.2446. Figure 5(d) presents a scanning electron microscopy (SEM) image of Sample D, revealing minor surface scratches. The observed scratch region exhibits a relatively small spatial extent, measuring approximately 600 µm in height, with an average length of 2400 µm. Additionally, Sample D possesses a substrate hardness of 70 HRC, which may contribute to its superior wear resistance. The presence of these surface scratches suggests localized material deformation, likely influenced by the hardness and microstructural characteristics of the material. The relatively lower coefficient of friction (0.2114) observed for Sample D may be attributed to its high hardness, which reduces surface adhesion and deformation during sliding contact [14,15].

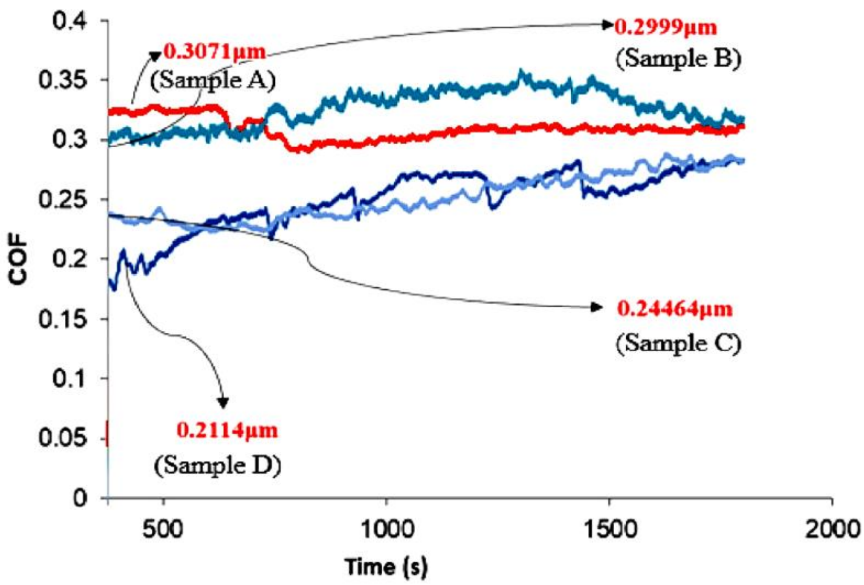


Figure 4: Coefficients of friction of samples Vs Time

Figure 6 shows the effect of cutting speed on tool wear when machining 22MnB5 boron steel with AA6061 under unlubricated and lubricated conditions. In unlubricated machining, wear increased with speed from 100 to 350 m/min but dropped significantly at 450 m/min, indicating an unstable wear pattern. In lubricated machining, wear consistently decreased as speed increased, reaching 0.081 mm at 450 m/min. These results highlight the importance of selecting appropriate parameters for achieving optimal mass production [16].

In unlubricated machining, tool wear ranged from 0.15 to 0.27 mm, while in lubricated machining it ranged from 0.08 to 0.18 mm, a 15.8% average reduction with coolant. Wear appeared most stable at cutting speeds of 200-350 m/min. The circular cutting tool large nose radius (12 mm vs. the typical 1.2-1.6 mm) increased contact area, requiring more energy for shear deformation and generating higher interface temperatures [17]. Coolant helped lower temperatures, reduce friction, and remove debris from the cutting zone. Higher cutting speeds reduced tool wear in both unlubricated and lubricated conditions. With its moderate strength, AA6061 engages quickly with the tool nose radius at high speeds, increasing deformation, friction, and cutting temperatures. Elevated temperatures soften the alloy, lowering flow stress [18]. As machining lasted 4 minutes, heat effects on tool wear were significant, allowing efficient cutting and improved material removal.

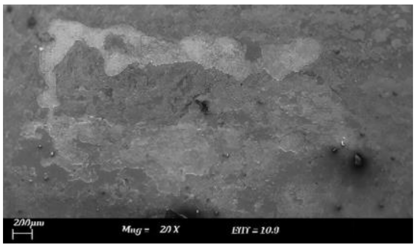
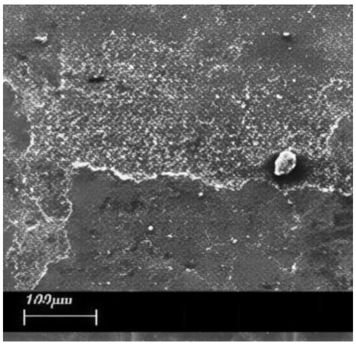
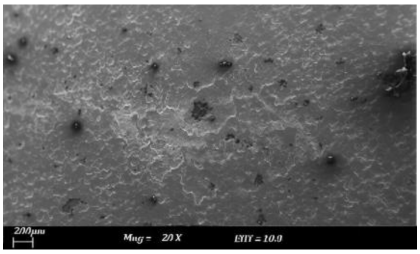
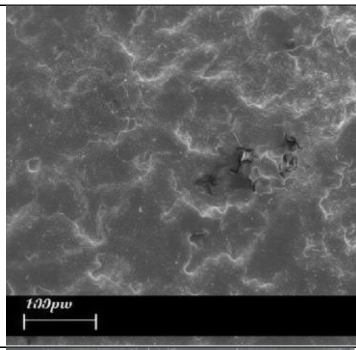
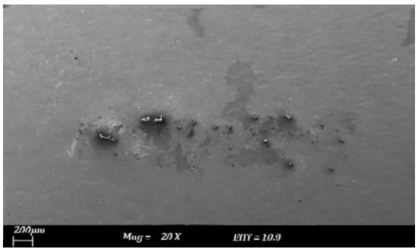
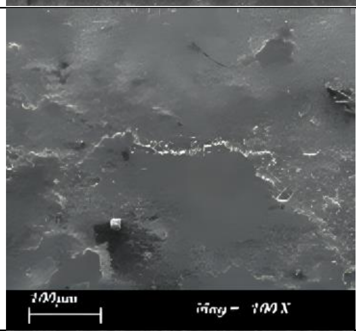
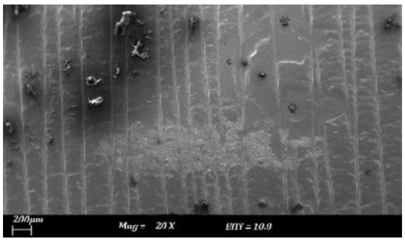
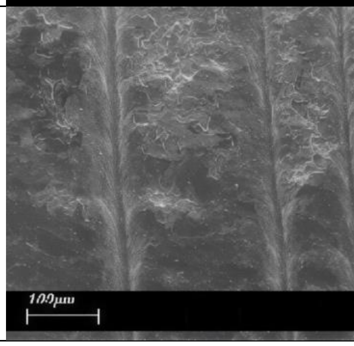
Sample Types	Full view of scratch SEM images	Detailed view of the highlighted region
Sample A Estimated Wear Area (Length x Height): 2800 µm x 1600 µm Coefficient of Friction: 0.3071		
Sample B Estimated Wear Area (Length x Height): 2400 µm x 1000 µm Coefficient of Friction: 0.2999		
Sample C Estimated Wear Area (Length x Height): 2400 µm x 800 µm Coefficient of Friction: 0.2446		
Sample D Estimated Wear Area (Length x Height): 2400 µm x 600 µm Coefficient of Friction: 0.2114		

Figure 5: Wear traces on 22MnB5 boron steel

Figure 7 shows wear characteristics when machining 22MnB5 under unlubricated conditions condition at 100 m/min. Laser marking produced distinct ridge formations, and SEM revealed prominent built-up edges at the tool nose. High cutting temperatures and pressures caused molten metal to adhere, altering tool shape and contact area, which increased cutting force, friction, and temperature. Prolonged machining under these conditions would likely accelerate tool wear and degrade surface finish [17,18].

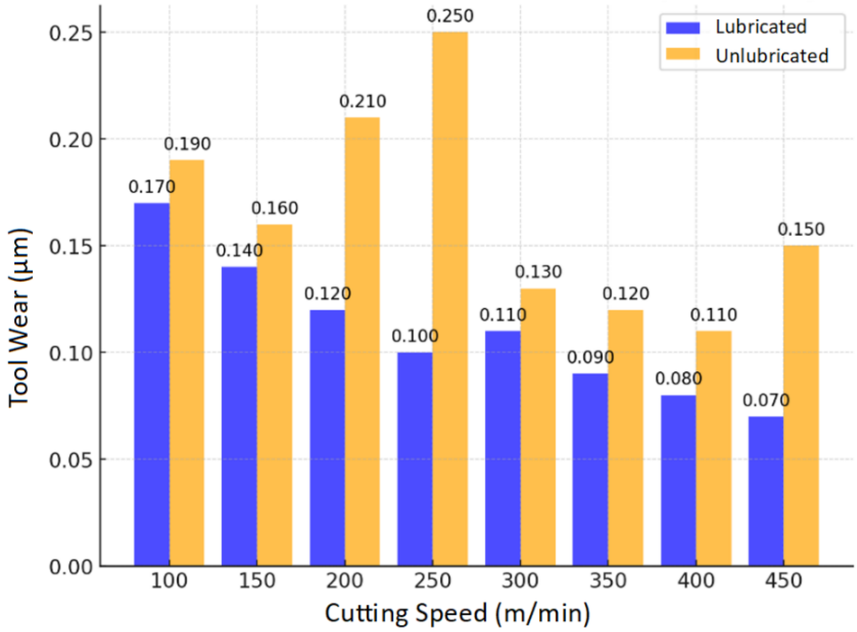


Figure 6: Effect of cutting speed on tool wear for both machining 22MnB5 boron steel with Al 6061 under unlubricated and lubricated conditions

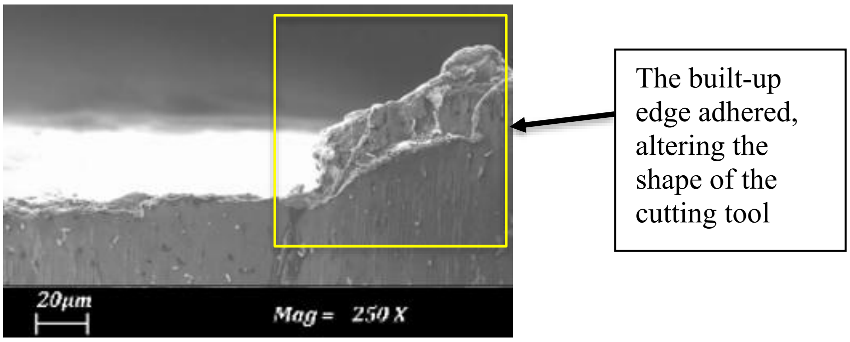


Figure 7: Wear characteristics when machining 22MnB5 boron steel at the lower cutting speed of 100 m/min in unlubricated condition

Coolant reduced tool wear by creating a cleaner cutting area and limiting built-up edge formation, as shown in Figure 8. The flank region displayed mainly scratch marks and minor ridges. Worn surfaces revealed free debris, indicating particle detachment from adhesion between alloys during friction. This detachment, likely driven by high rotational impact, was sometimes aided by tribolayer oxidation, which encouraged loose particle buildup. During shearing, such debris acted as an abrasive, causing ploughing and groove formation on the alloy surface [19,20].

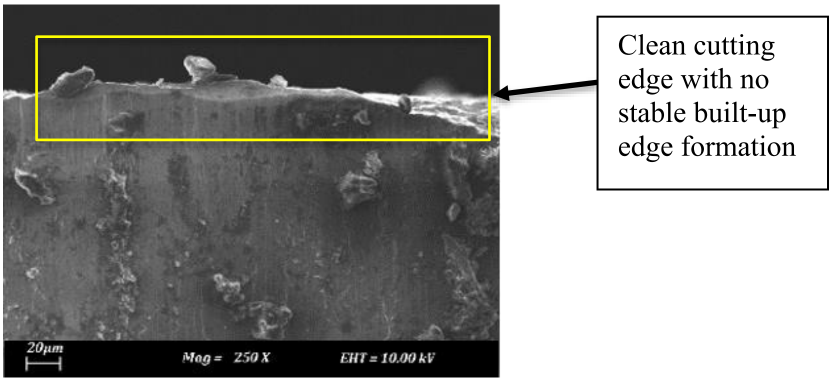


Figure 8: Wear characteristics when machining 22MnB5 boron steel at the lower cutting speed of 100 m/min in lubricated condition

Figure 9 depicts the wear patterns seen during unlubricated machining, focusing on the machining of 22MnB5 boron steel with AA6061 as the cutting tool, operating at a speed of 450 m/min. The illustration depicts a significant layer of aluminium alloy firmly attached to the edge of 22MnB5 boron steel. Based on the observation, it appears that adhesive wear was the main mechanism in the wear area during the short cutting period. Adhesive wear occurs when a portion of AA6061 detaches from the workpiece and gets stuck at the cutting interface. The content enclosed within the provided space started to melt due to the increased temperature and pressure. The research conducted by Shetter et al. [21] noted that scratching the surfaces in opposite directions caused the molten portion of aluminium alloy to slide on the cutting tool surface. The behavior described led to the creation of a tribolayer, which helped decrease the wear rate as a solid lubricant. Moreover, the layer helps improve thermal conductivity, making it easier for heat to be absorbed from the cutting zones and ultimately decreasing wear [22].

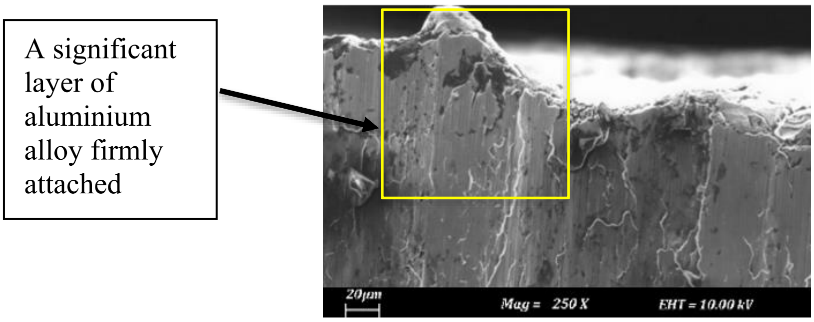


Figure 9: Wear characteristics of unlubricated cutting when machining 22MnB5 boron steel with Al 6061 at the higher cutting speed of 450 m/min

Figure 10 depicts the wear characteristics seen during lubricated cutting of 22MnB5 boron steel with AA6061 as the cutting tool, particularly at a notably high cutting speed of 450 m/min. Similar to Figure 9, the wear characteristics seen in both cutting conditions showed a neat look with little adhesion layer formation. The mentioned observation suggests that a higher cutting speed helps reduce the formation of a tribolayer or built-up edge, especially when working in lubricated conditions [23]. The decrease in size of the built-up edge was more noticeable with cutting speed than with feed rate or depth of cut. When the cutting speeds were reduced, it was noted that the molten layer of AA6061 tended to stick to the tool edge. Throughout the machining process, the gradual buildup of the edge layer helped bond a section of the workpiece with the tool through atomic diffusion. The impact of heat treatment at the cutting zone resulted in a shift in microstructure, leading to the partial hardening of specific built-up edges [23,24]. When the cutting speed was raised, the increased rotational force caused the accumulated edge to break while also creating successive depositions of molten material. The mentioned occurrence has the potential to contribute to the fatigue failure of the cutting tool [25].

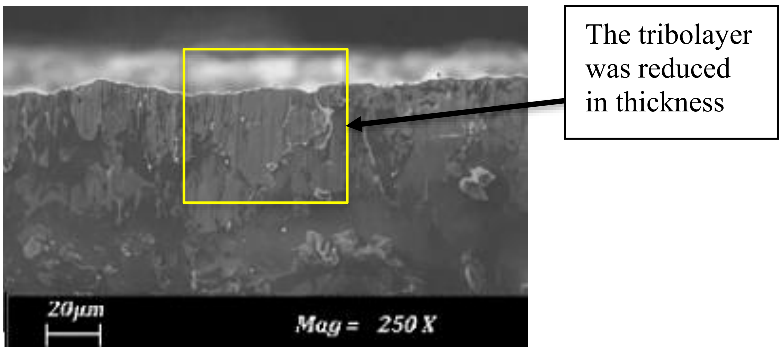


Figure 10: Wear characteristics of lubricated cutting when machining 22MnB5 boron steel with AA 6061 at the higher cutting speed of 450 m/min

4. CONCLUSIONS

This study investigated the effects of hardness and the coefficient of friction on the tool wear of 22MnB5 boron steel cutting tools when machining AA6061 aluminium alloy under unlubricated and lubricated conditions. The findings indicate that hardness significantly influences wear resistance, with Sample D (heat-treated at 70 HRC) demonstrating superior performance in terms of reduced wear and lower coefficient of friction (CoF). The wear mechanism analysis revealed that built-up edge formation occurs at lower speeds, while tribolayer effects dominate at higher speeds, particularly under unlubricated and lubricated conditions. This study also highlighted the importance of heat treatment in enhancing the mechanical properties of 22MnB5. Samples that underwent hot stamping exhibited improved hardness, but inconsistencies in quenching affected hardness distribution, potentially influencing tool performance. The coefficient of friction remained stable across all samples, but lower CoF values in Sample D suggest improved tribological performance due to heat treatment.

Based on the tool wear analysis, lubricated machining clearly helped reduce wear around 15.8% lower compared to unlubricated machining. When the cutting speed was increased, the formation of built-up edge minimized. The use of coolant also helped a lot in dispersing heat, which reduced adhesive wear and lessened surface damage. In addition, the study also highlighted how important cutting speed is in controlling wear. The most stable results came from moderate speeds, in the range of 200 to 350 m/min. Overall, the results support the idea that 22MnB5 boron steel can work well as a cutting tool material, especially for machining aluminium alloys. With high hardness, good wear resistance, and stable friction performance, this material shows strong potential to replace conventional high-speed steel.

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Author Contributions

All authors contributed toward data analysis, drafting and critically revising the paper and agree to be accountable for all aspects of the work.

Disclosure of Conflict of Interest

The authors have no disclosures to declare.

Compliance with Ethical Standards

The work is compliant with ethical standards.

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