COMPARISON OF MACHINING AND WEAR PERFORMANCE OF 22MnB5 BORON STEEL AND HIGH-SPEED STEEL CUTTING TOOLS ON 6061 ALUMINIUM ALLOY

**M.R. Fairuz[1,2], A.B. Hadzley[1*], A.W. Norfariza[1], M.M. Fauzi[1],
P.H. Lailatul[1], R.N. Ana[1] and S.G. Herawan[3]**

[1] Fakulti Teknologi dan Kejuruteraan Industri dan Pembuatan,
Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian
Tunggal, Melaka, Malaysia.

[2]Petroleum Safety Division,
Department of Safety and Health Malaysia, Wilayah Persekutuan Putrajaya,
62530 Putrajaya, Malaysia

[3]Industrial Engineering Department, Faculty of Engineering
Bina Nusantara University, Jakarta, 11480, Indonesia

*Corresponding Author's Email: hadzley@utem.edu.my

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ABSTRACT: In an effort to utilize a robust material for friction-resistant applications, high-strength and high-hardness 22MnB5 boron steel is widely employed. Its unique properties make it thinner and lighter while retaining high strength, making it suitable for demanding tasks. This study evaluates the performance of 22MnB5 boron steel as a cutting tool for machining aluminum alloy Al 6061 and compares it with high-speed steel (HSS). A round piece of 22MnB5 boron steel, specified as RNGN 120300, was laser-cut and tested in CNC turning with cutting speeds of 200 to 300 m/min, a feed rate of 0.1 mm/rev, and a depth of cut of 0.5 mm. Results indicate that 22MnB5 boron steel outperforms HSS in machining Al 6061, offering tool life improvements of 5% to 11%. The wear mechanism for 22MnB5 boron steel was primarily abrasive at lower cutting speeds, while built-up edges at increased cutting speeds led to adhesive wear in the form of a tribolayer.

KEYWORDS: *22MnB5 Boron Steel; Tool Wear; Tool Life; Machining; Cutting Tool*

1.0 INTRODUCTION

Machining is a critical aspect and often the dominant factor in most manufacturing industries. Several factors influence machining production efficiency, with the type of cutting tool being a key one. The quality of a cutting tool depends on its design, intended shape, material composition, and the cutting environment. The use of cutting tools with appropriate materials, combined with suitable cutting parameters, can enhance tool life, produce better surface finishes, and increase the efficiency of machining components. This, in turn, can lead to improved product quality and reduced production time and costs [1-2].

High-speed steel (HSS) cutting tools are a preferred choice across industries due to their ability to cut hard materials and maintain durability over extended periods. Renowned for their superior hardness and enhanced toughness, HSS tools are particularly well-suited for machining medium-strength materials such as aluminium alloys and plastics. Their efficiency reduces energy consumption during cutting operations, thereby extending tool life and lowering operational costs. A key advantage of HSS tools is their widespread availability and versatility, enabling them to machine most low-hardness steels while delivering excellent surface finishes and efficient production outcomes. Furthermore, advancements in cutting tool manufacturing have expanded the range of HSS options, making them adaptable to diverse industrial applications. These tools are commonly employed for tasks such as turning, grinding, drilling, and boring. Beyond machining, HSS is also utilised in high-wear applications, including agricultural cutters and mining equipment. Despite their benefits, HSS cutting tools face challenges, particularly their limited hot hardness, which can compromise performance in high-temperature operations. This limitation can lead to issues such as wear and edge melting, especially in applications involving severe friction or elevated thermal conditions. Addressing these challenges remains a focal point for improving the durability and reliability of HSS tools in demanding environments [3-5].

In the progress of developing hard and refractory materials in industry, 22MnB5 Boron Steel has been introduced as a specialized material designed for high-strength applications, particularly in metal stamping processes where exceptional durability and resistance to wear are critical. Initially, 22MnB5 Boron Steel is prepared with a fine, homogeneous grain structure predominantly composed of ferrite, with minor pearlite and cementite phases. Ferrite has a fundamental body-centered cubic (BCC) crystal structure. Heating the 22MnB5 Boron Steel to 800°C transforms the ferrite microstructure into austenite, changing the crystal structure to face-centered cubic (FCC) . Following stamping and heat treatment in a quenching environment, the microstructure of 22MnB5 transitions into the martensite phase. During this process, the crystal structure changes to body-centered tetragonal (BCT) and undergoes high strain due to the applied pressure. This results in a highly strained martensitic microstructure, increasing the hardness of the boron steel to 15 GPa, with a potential hardness reaching up to 80 HRC. This enhanced hardness provides a significant advantage when operating under high friction and temperature conditions.

Since boron steel is capable of being operated at high temperatures while possessing high hardness, it is likely that this material can perform well in wear-resistant applications. Its ability to maintain structural integrity and resist deformation under extreme conditions makes it an ideal candidate for environments that involve significant friction and heat. The high hardness of boron steel contributes to its resistance to abrasive wear, while its thermal stability ensures that it does not lose its mechanical properties even at elevated temperatures. This combination of attributes suggests that boron steel can significantly enhance the durability and lifespan of components used in demanding applications, such as automotive parts, cutting tools, and heavy machinery [9-10].

Previously, Hernandez et al. [11] analyzed the wear characteristics of boron steel by conducting a dry sand wheel test to study how temperature impacts its wear properties. At temperatures between 20 and 100°C, the wear rate of boron steel decreased due to the formation of a tribolayer on the plastically deformed surface. However, at higher temperatures, the wear rate increased due to the recrystallization of the ferrite grains in the samples. The study identified a mix of microcutting and microplowing as the major wear mechanisms.

In another study, Elena et al. [12] examined the friction and wear characteristics of 22MnB5 using specialized pin-on-disc testing. When testing uncoated 22MnB5 samples, whether toughened or not, the study found that the predominant wear mechanisms were abrasive wear and oxidative wear [13]. Translation movement during the friction test may lead to the continual separation of the oxide coating between the surfaces in contact. Some of these films may conform to the 22MnB5 disc, and increased friction can enhance three-body abrasive wear between the pin and disc samples.

In a separate study, Muro et al. [13] tested three types of tool steels against boron steel under varying temperature and lubrication conditions. The aim of the study was to understand the interactions between the tool steel and the boron steel blank during the forging process. The results showed that a protective layer formed on the contact surface during interaction, serving as a barrier to reduce heat. However, some parts of the oxide layer were hard and abrasive, contributing to three-body wear. The carbide content in the tool steels was identified as a major factor responsible for the wear damage observed in the boron steel.

Recently, Costa et al. [14] used boron steel as protective masks for hot forging operations. The boron steel was applied as flat and axial masks with large cycles strategically positioned at critical areas during the hot forging process. It was found that boron steel effectively performed as masks for surface protection due to its high hardness. The protective masks were able to operate without failure under large cyclic loads, with plastic deformation identified as the dominant wear mechanism.

From the studies mentioned above, it has been found that boron steel possesses a microstructure with high hardness and durability, allowing it to withstand aggressive conditions. Most previous investigations focused on surface wear caused by forming processes such as stamping and drawing. This study examines the wear characteristics of 22MnB5 Boron Steel under varying machining conditions in depth. Several samples of boron steel were cut from the blank part, heat-treated, and then formed into round-shaped samples. These were mounted on a tool holder, and the samples were subsequently tested while machining Al 6061 aluminum alloy under wet conditions. Comparisons were made with HSS cutting tools in terms of wear performance. The outcomes of this research will provide valuable insights into optimizing the use of boron steel as an alternative cutting tool, thereby contributing to the development of more efficient and durable materials for industrial use.

2.0 METHODOLOGY

2.1 Sample Preparation

Figures 1 to 4 show the process of fabricating the cutting tool. The cutting tool was prepared from a metal sheet blank part, directly supplied by the industry from the hot stamping process. The cutting tool was then cut into a round shape using a laser cutter, as shown in Figure 1. It was subsequently heat-treated using a furnace to convert its microstructure into the martensitic condition, including heating the sample to the austenitic temperature, as shown in Figure 2, and quenching, as shown in Figure 3. Once ready, the tool was inserted into the tool holder to perform machining. The final sample of the 22MnB5 boron steel cutting tool is shown in Figure 4, created after the heat treatment process was completed.

Figure 1: The procedure of cutting a 22MnB5 boron steel sample by a laser cutting machine

Figure 2: Heat treatment process by furnace

Figure 3: 22MnB5 boron steel sample undergo a rapid water soak for the quenching process

Figure 4: Final sample of 22MnB5 boron steel cutting tool

2.2 Machining Trials

The machining trials will involve testing samples of 22MnB5 boron steel and high-speed steel (HSS) cutting tools to cut Al 6061 aluminum alloy under wet conditions. Only two cutting speeds were selected, 200 m/min and 300 m/min, while maintaining a constant feed rate of 0.1 mm/rev and a depth of cut of 0.5 mm. These details are presented in Table 1. The CNC turning machine used in this examination is shown in Figure 5. Every machining experiment adheres to the standards set by ISO 3685, which assesses tool life by measuring the average wear of the cutting tool up to Vb at a distance of 0.3 mm. The wear mechanism can be visualized using an optical microscope.

Table 1: Machining Parameters

Cutting Tool	Tool Holder	Cutting Speed	Feed rate	Depth of Cut

22MnB5 Boron Steel	CRDN25243	200 & 300 m/min	0.1 mm/rev	0.5 mm
High-Speed Steel	CRDN25243	200 & 300 m/min	0.1 mm/rev	0.5 mm

Figure 5: CNC machine for machining trial

3.0 RESULTS AND DISCUSSION

3.1 Machining Performance

Figure 6 shows the comparison of machining performance between 22MnB5 boron steel and HSS. Both cutting tools were tested at a lower cutting speed of 200 m/min and a higher cutting speed of 300 m/min. At 200 m/min, the boron cutting tool outperformed HSS, recording 861 seconds compared to 820 seconds, which is a 5% improvement. At the higher cutting speed of 300 m/min, the 22MnB5 boron steel performed better at 630 seconds compared to 595 seconds for HSS, which is a 15% improvement.

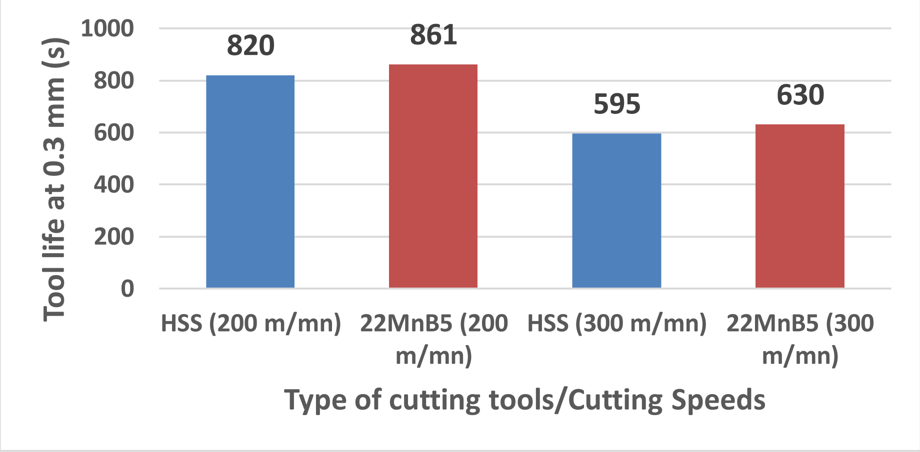

Figure 6: Graph comparison of machining performance time vs Tool Life at cutting speed 200 and 300 m/min for 22MnB5 Boron steel and HSS cutting tool

When analyzing these findings, it is essential to consider the mechanical properties of the materials used. HSS is well-known for its exceptional hardness and resistance to wear, which is why it is often the top choice for cutting tools. 22MNB5 boron steel demonstrates exceptional hardness and impressive tensile strength, proving to be a valuable resource for challenging cutting scenarios, especially when operating at elevated cutting speeds. Moreover, its outstanding thermal properties aid in maintaining stability even at elevated temperatures, hence enhancing its efficiency in extended machining processes. The wear patterns and tool life observed closely correspond to the mechanical characteristics of boron steel 22MnB5, suggesting improved durability and the potential for longer tool life compared to HSS cutting tools [15-16].

In the study conducted by Korotkov et al. [17], it was found that HSS may experience several disadvantages, including overheating and inadequate alloying elements. Overheating of HSS can result in a non-uniform microstructure due to uneven austenite distribution throughout the material. Additionally, while high-speed steel achieves high strength due to the inclusion of certain alloying elements, there is a possibility that crucial elements such as tungsten and molybdenum are not mixed properly in the composition. This can result in inconsistencies in the material, leading to variations in hardness.

On the other hand, the current study's results align with the findings of Ersoy et al. [18] and Long et al. [19] regarding the enhanced strength of boron steel. Boron steel was prepared using two methods: hot stamping and hot rolling. In the hot stamping process, the blank is heated to a high temperature and then rapidly stamped with integrated cooling capabilities. Similarly, in the hot rolling process, the boron steel is heated and then passed through a cooling reservoir, facilitating the recrystallization of the microstructure from the pearlite-bainite phase to martensite. This results in a more uniform microstructure throughout the heated blank, leading to a uniform increase in the strength of the boron steel. When used in machining operations, boron steel can potentially offer better wear resistance compared to high-speed steel.

Overall, the experimental results demonstrate the superior performance of the 22MnB5 boron steel cutting tool over the HSS cutting tool in machining aluminium alloy 6061. This difference is especially evident when operating at lower cutting speeds, as illustrated in Table 2. An impressive 5-15% performance boost highlights the effectiveness of boron steel 22MNB5 as a valuable alternative in metal machining applications. It is crucial to take into account other factors like production costs and equipment maintenance, as they play a significant role in the overall efficiency of the machining process.

Table 2: Machining results

Cutting Tool	Cutting Speed: 200 m/min	Cutting Speed: 300 m/min
	Time (s)	Time (s)
HSS Cutting Tool	820	325
22MnB5 Boron Steel Cutting Tool	861	360

3.2 Wear Observation

Figure 7 shows the wear development of 22MnB5 Boron steel cutting tool at the lower cutting speed of 200 m/min. Observation of wear at early stage of 69s demonstrated the uniform formation of flank wear with minimal sign of material lost. As the machining progressed into 641s, the flank wear steadily increased until it reached 0.223 mm as shown in Figure 8. Starting from the 861s of machining time, ridge foramtion started to appear at the specific location of worn region as the flank wear increase, as the machining prolonged until the tool wear reached 0.312 mm, the ridges continuous to spread at the same region which reflected the abrasive wear form strongly at that region as shown in Figure 9. Such ridge formation reflected that abrasive wear was dominant, resulting from the continuous contact and friction between the cutting tool and the harder particles in the material being machined. This persistent interaction causes the tool's surface to be gradually worn down, forming grooves and ridges that signify the abrasive action. Consequently, the tool's efficiency and durability are compromised over time due to the progressive material loss [20-21].

Figure 7: Minor formation of flank wear at 69 seconds for 22MnB5 Boron steel cutting tool

Figure 8: Flank wear increased at 641 seconds for 22MnB5 Boron steel cutting tool

Figure 9: Ridge formation occurs in the specific area where the cutting tool contact with the chip for 22MnB5 Boron steel cutting tool

Figure 10 shows the wear development of HSS cutting tool at the lower cutting speed of 200 m/min. Observation of wear at early stage of 65 seconds which demonstrated the uniform formation of flank wear with minimal sign of material lost. As the machining progressed into 473 seconds, the flank wear steadily increased until it reached 0.210 mm as shown in Figure 11. Starting from the 473 seconds of machining time, chipping started to appear at the specific location of worn region. There are evidence of very small BUE at the localized region where the chip at the cutting tool engaged. Figure 12 show that the formation of wear to be gradually increased as the machining prolonged from 473 to 820 seconds with consistent wear rate without catastrophic chipping. On the same time, the BUE continuous to spread at the same region which seems the adhesive wear form strongly at that region.

Figure 10: Formation of flank wear at 65 seconds for HSS cutting tool

Figure 11: Small BUE appears at 473 seconds machining time for HSS cutting tool

Figure 12: Flank wear increase with small BUE appears for HSS cutting tool

Figure 13 illustrates the wear development of a 22MnB5 boron steel cutting tool at a high cutting speed of 300 m/min. In the initial assessment, after 40 seconds of machining, the wear marks on the cutting tool were barely visible. The machining was conducted over a short duration using aluminum alloy. After 363 seconds of machining, Figure 14 shows a clearer image of the wear area, where a tribolayer has formed. Minor built-up edges (BUE) were observed along the cutting tool's edge, indicating excessive heat generation [22-23].

Figure 12: Minor formation of notch and flank wear at 40 seconds machining time for 22MnB5 Boron steel cutting tool

Figure 13: Wear started to develop at the middle of flank area at 363 seconds machining time for 22MnB5 Boron steel cutting tool

As machining continued for up to 595 seconds, the wear area became more pronounced, as shown in Figure 15. The tribolayer appeared firmly attached to the edge of the cutting tool, indicating that the high pressure and temperature experienced at the cutting face resulted in a strong bonding of the tribolayer to the tool. This created a robust interface, akin to welding, which intensified with prolonged machining. The strong adhesion led to material transfer from the workpiece to the cutting tool, causing material loss and contributing to wear at the cutting edge. This material degradation at the cutting edge can be attributed to particle loss as the chip slides aggressively [22-23].

Figure 14: The tribolayer appeared firmly attached to the edge of the cutting tool for 22MnB5 Boron steel cutting tool

Figure 15 shows the wear development of HSS cutting tool at the higher cutting speed of 300 m/mm. Early observations after 70 seconds of machining showed minimal wear on the cutting tool. However, after 420 seconds of machining, evidence of built-up edge (BUE) formation was observed, along with noticeable flank wear. The BUE appeared along the boundary of the wear area, reflecting significant metal-to-metal contact. This contact likely resulted in the transfer of molten metal, which led to sliding, welding, and solidification at the cutting tool's edge [23-24].

Figure 15: Flank wear occurs on the cutting edge at 70 seconds machining time for HSS cutting tool

Figure 16: Wear steadily growth on flank area at 420 seconds machining time for HSS cutting tool

Machining at 525 seconds revealed significant surface scratches on the cutting tool, as shown in the Figure 17. A distinct molten aluminum layer was observed on the wear area, with solidified aluminum visibly adhering to the surface. This solidified layer indicates an adhesive wear mechanism, where the molten material contributes to material transfer and increased wear on the cutting tool [23-24].

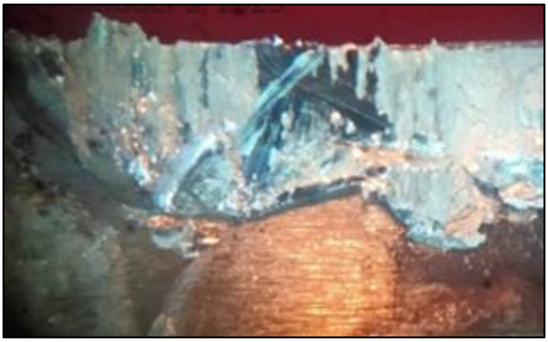

Figure 17: A distinct molten aluminum layer was observed on the wear area at 595 seconds machining, with solidified aluminum visibly adhering to the surface.

According to research by Hua et al. [25], there are two possible ways the tribolayer affects wear mechanisms. At lower cutting speeds, the wear mechanism is expected to be dominated by the mechanical action at the contact interfaces. In such conditions, hard materials interacting with softer materials cause wear through direct scratching. This phenomenon is likely to be observed at low speeds, such as in this case, where the machining of boron steel at a lower cutting speed of 200 m/min represents the mechanical action of sliding between the cutting tool and workpiece material, resulting in dominant abrasive wear.

However, if machining is performed at higher speeds, such as 300 m/min, the increased friction and pressure will cause partial melting of the aluminum and the cutting tool surface, leading to the formation of a tribolayer. Additionally, an oxidation layer may form, which could change the surface characteristics, making it either ductile or brittle. Further machining will alter the way the workpiece material is removed, causing greater defects to the tool edge. This phenomenon, observed with boron steel at high speeds, may also occur with high-speed steel (HSS) at both low and high speeds [25-26].

4.0 CONCLUSION

The study explores the capability of boron steel to be applied as a cutting tool. A blank part of the boron steel is cut, heated, and heat-treated into a specific round shape in the form of a tool insert. Machining performance is assessed by comparing it with high-speed steel (HSS) cutting tools through observations of wear under varied parameters. Based on the experimental practice, several conclusions are deduced:

1. A decrease in cutting speed leads to an increase in the lifespan of the boron steel cutting tool. For instance, at a cutting speed of 200 m/min, the tool lasts 861 seconds, up to 5% longer compared to HSS. At 300 m/min, it lasts 630 seconds, up to 11% longer compared to HSS.
2. The dominant failure mode of boron steel is flank wear. This wear results from the flank side of the cutting tool being in contact with the material, leading to the formation of grooves, which is evidence of abrasive wear.
3. The dominant failure mode of HSS is adhesive wear. The formation of built-up edge (BUE) occurs predominantly due to high temperatures, which disturb the machining process. This is evidenced by the flow of molten metal sticking to and plugging the tool, resulting in cumulative material loss.

These findings indicate that boron steel performs effectively as a cutting tool, particularly in applications requiring high wear resistance and the ability to withstand high temperatures.

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AUTHOR CONTRIBUTIONS

M.R. Fairuz: Conceptualization, Methodology, Writing- Original Draft Preparation; A.B. Hadzley: Supervision; A.B. Norfariza, M. Mohd Fauzi, P. Lailatul Harina, S.G. Herawan: Validation, Writing-Reviewing and Editing.

CONFLICTS OF INTEREST

The manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agree with its submission and declare no conflict of interest on the manuscript.

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