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Influence of oil-based and water-based lubrication on tool wear of DLC/TiAlN-coated punches in blanking of stainless steel

Muhammad Shuhaimi Ibrahim, Mohd Hafis Sulaiman*, Mohd Idris Shah Ismail

Department of Mechanical and Manufacturing, Faculty of Engineering, Universiti Putra Malaysia, MALAYSIA.
*Corresponding author: hafissulaiman@upm.edu.my

KEYWORDS

Water fluid
Sheared edge
Blanking
Double coating
Wear

ABSTRACT

This study aims to eliminate the use of oil-based lubricants in the metal forming process by integrating a new tribological system of double-layered Carbon/Titanium Aluminum Nitride (DLC/TiAlN) with water-based lubrication. The research compared the performance of traditional oil-based lubricant (cutting fluids) against water-based lubricants containing Magnesium Oxide (MgO) and Silicon Carbide (SiC) nanoparticles. This water-based lubricant, prepared through a two-step method, is applied to the surface of 1 mm thick SUS304 stainless steel during the blanking process. A mixture of MgO and SiC reduces the coefficient of friction more effectively than when using a single additive. The combined effect of using DLC/TiAlN-coated tools with water-based lubricants with MgO/SiC additives increases resistance to galling, leading to a 14% reduction in draining force compared to dry friction and a 3% reduction compared to cutting fluids. Moreover, the combination of MgO/SiC minimizes the formation of burrs at the edge of the product during the blanking process. The water-based lubricants with MgO/SiC are a competitive alternative to oil-based lubricants in the metal forming industry.

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1.0 INTRODUCTION

Blanking and punching are common processes in the metal forming of sheet metal. These techniques are often integrated with various other metalworking operations as both are intermediate and final production steps and they are also utilized to fabricate components of vehicles (Moghadam et al., 2020). During the blanking process, the wear mechanism of the tool progresses through three distinct phases: initially, abrasive wear is dominant, followed by adhesive wear, and finally, the growth of friction junctions. Surface damage occurs due to friction as the tool moves and touches the surface of the product, leading to issues such as pitting, plastic deformation, chipping and cracking. In the sheet metal forming process, the coating on the tool serves as a protective barrier against wear, thereby extending the life of the tool (Trzepieciński, 2023). These improvements not only protect equipment but also ensure consistent quality of products in metal forming operations (Abraham et al., 2020).

Diamond-like carbon (DLC) coatings are widely recognized across multiple sectors, including automotive, biomedical, and tooling components, due to their impressive qualities. These include a low coefficient of friction, exceptional hardness, superior wear resistance, and the ability to shield the die surface. The properties of DLC coatings make them very suitable for a variety of tribological uses in mechanical systems. It plays an important role in increasing the durability and reliability of components such as valve train tappets, gears and piston pins, thereby extending the service life of these systems. In addition, coatings based on nitride and carbide materials offer substantial protection against wear. These advanced coatings are engineered to enhance the durability of various tools and components, ensuring their longevity even under extreme conditions. This coating is commonly used in the manufacture of sheet metal components due to its durability and protective qualities. Among these, titanium aluminum nitride (TiAlN) coating has gained popularity as a protective layer for cutting and forming operations. Its application extends beyond these uses, providing enhanced durability and performance in various industrial processes. TiAlN stands as a highly preferred hard coating material, offering superior hardness and better resistance to fatigue fracture when contrasted with Titanium Nitride (TiN) coatings (Q. He et al., 2021). Meanwhile, multilayer coatings are often preferred over single-layer coatings due to their superior performance enhancement capabilities (Liu et al., 2022). In studies of Li et al., (2021) found that multilayer coating TiAlN/WS had a low coefficient leading to reducing flank wear around 45.9 % compared to single layer TiAlN and increased the cutting length up to 200 % at the same flank wear of 0.3.

Furthermore, water-based lubricants (WBLs) garnered attention from researchers who developed them to enhance performance due to their eco-friendly nature and significant potential in engineering applications, including electric vehicles, machining, and metal forming (Morshed et al., 2021). Besides, WBLs offer a range of advantages, including affordability, superior thermal conductivity, and cooling properties, along with high fluidity and eco-friendliness (Wang et al., 2021). These attributes make them an attractive choice for various applications where environmental concerns and efficiency are paramount. However, WBLs exhibit suboptimal tribological properties, characterized by inadequate friction reduction, low viscosity, and a propensity for corrosion when subjected to high contact loads and rapid sliding speeds (Rahman et al., 2021). To overcome these limitations, further research and development are needed to enhance the performance of WBLs in demanding mechanical environments. One promising approach is the integration of nanoparticles into lubricants as it can enhance lubricants to overcome these issues, improving their properties and performance. This synergy combines the superior lubricity of nano additives with the high cooling capacity of water, resulting in a more efficient and effective lubrication solution (Morshed et al., 2021). By integrating nanoparticles, the lubricant benefits from the unique characteristics of these tiny structures, leading to advancements in mechanical operations. Several nanoparticles have been used in lubricants such as Magnesium oxide (MgO) and Silicon carbide (SiC). The study by Ahamed et al., (2020), investigates the impact of MgO and SiC nanoparticles in lubricants, finding that an optimal concentration of 0.3 wt% of nanoparticles can reduce the coefficient of friction (COF) by 66% for MgO and 25% for SiC. These findings were derived from tests conducted using the pin-on-disk method. Other studies have shown that nanoparticle combinations, including SiO2 and graphene, enhance the tribological properties of water-based lubricants, leading to significant reductions in friction and wear (Xie et al., 2019). Moreover, the unique chemical activity of MgO presents distinct advantages in certain applications, especially under high-load conditions (Liang et al., 2024). The incorporation of minor quantities (0.10 wt%) of MgO into a lithium bis(trifluoromethanesulfonyl)imide (LiTFSI) solution markedly decreases the coefficient of friction (COF) to around 0.004. This modification not only reduces friction but also notably improves the load-bearing capacity (Liang et al., 2024). SiC has the potential to achieve a friction coefficient as low as 0.014 and a wear rate of approximately 10^{-6} mm^3/Nm under optimal conditions (Su et al., 2024).

Stainless steel stands out as a notable category of alloys, known for their exceptional properties including exceptional resistance to corrosion and oxidation, non-magnetic properties, and compatibility with biological systems (Lo et al., 2009). The 304 stainless steel variants are widely used in manufacturing various components in electronic devices and medical equipment due to these beneficial properties. As a result, advances in fine blanking techniques were set in motion, leading to the innovation of fine blanks made from stainless steel, increasing the applicability of the technique across a wide range of applications. Seo et al., (2004) used fine blanking techniques compared to traditional methods such as wire electric discharge machining or hobbing to produce sprockets from stainless steel sheets.

In punching and blanking processes, separating the tool from the workpiece surface is challenging due to the generation of active material that impedes lubrication at the tool-workpiece interface. This often leads to material adhering to the punch, a problem known as galling. Applying hard coatings combined with lubricant can effectively address these issues. This is especially beneficial when comparing environmentally friendly water-based lubricants to traditional oil-based lubricants (Wang et al., 2017). In this paper, the blanking process was used to investigate the effect of magnesium oxide (MgO) mixed with silicon carbide (SiC) nanoparticles as additives in water lubricant. A double-layer DLC/TiAlN coating was used as the punch tool, and 1 mm stainless steel SUS304 was used as the blanking sample/workpiece. Additionally, a commercial cutting fluid and MgO/SiC water lubricant were employed to evaluate their performance.

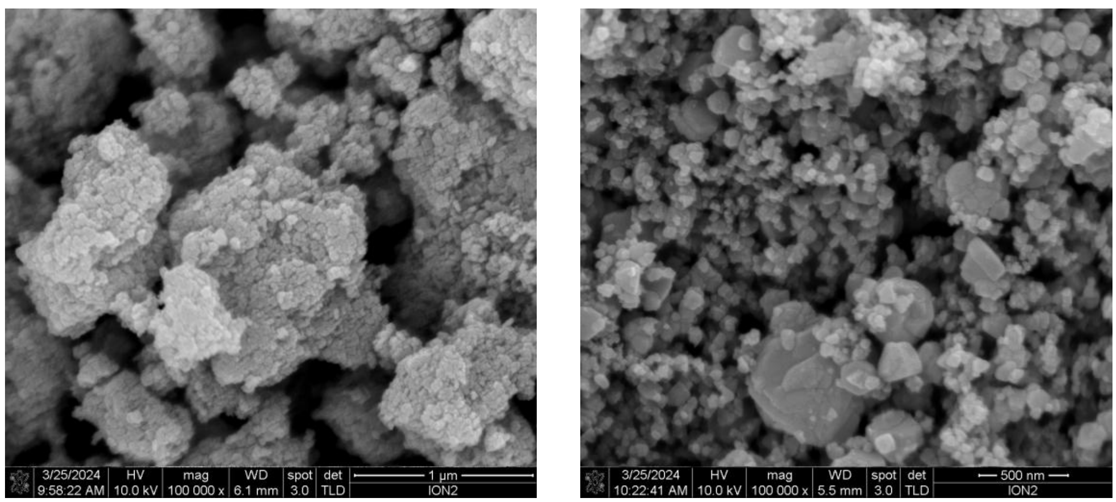
2.0 EXPERIMENTAL PROCEDURE

100 ml Water lubricant was prepared using two-step methods. Distilled water (DI water) was mixed with 2.0 wt% of glycerol using a magnetic stirrer for 10 minutes at 1200 rpm. While stirring, 0.05 wt% of Polyvinylpyrrolidone (PVP) was added into the solution. Then, the nanoparticle 0.2 wt% of MgO and 0.1 wt% SiC was added into the solution and continuously mixed with an overhead stirrer for 30 minutes with a speed of 1200 rpm, power input 800W and 50/60 Hz frequency. The solution was homogenized using ultrasonication for 30 minutes, power input

of 120 W and a frequency of 40 kHz as detailed in our previous work (Rui et al., 2023). Table 1 shows the summary of water lubricant content.

Table 1: Information of lubricant.

Lubricant	Information
(WBL with additive) MgO/Sic	0.2 wt% MgO nanoparticles + 0.1 wt% SiC nanoparticles + 2.0 wt% glycerol + 0.05 wt% PVP + DI water
(oil-based lubricant) Cutting fluid	Commercial lubricant (Relton, heavy duty cutting fluid)



(a) (b)

Figure 1: Field Emission Scanning Electron Microscopy (FESEM) image of (a) MgO and (b) SiC nanoparticles at 100k magnifications.

The Field Emission Scanning Electron Microscopy (FESEM) images of MgO and SiC nanoparticles are depicted in Figure 1(a) and Figure 1(b), respectively. These images were captured at a magnification of 4 µm. Examination of the figures reveals that the MgO and SiC nanoparticles predominantly exhibit irregular shapes. The MgO particles appear to be aggregates of smaller nanoparticle structures, and the SiC particles display a nearly small spherical form with a smooth surface, the latter having more pronounced angular features. The size of most of these nanoparticles ranges between 20 for SiC nanoparticles and 40 nm for MgO nanoparticles.

The tribological performance of the water-based lubricants (WBLs) was evaluated using a block-on-ring test apparatus, as depicted in Figure 2, following the ASTM G77-98 standard, following methodologies like those used in previous work (Sharuddin et al., 2023). Both the cylindrical block and the ring were fabricated from AISI 52100 bearing steel. The testing was conducted over a 2600 m distance with parameters as in Table 1.

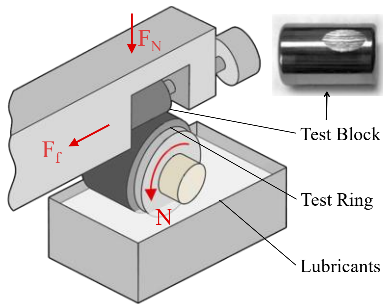


Figure 2: The schematic diagram of the block-on-ring test,

Table 1: the test parameters (Rui et al., 2023)

Parameters	Details
Block	d: 14 mm l: 14mm Ra: 0.0363 µm Rq: 0.0455 µm
Ring	d: 40 mm w: 12mm Ra: 0.6453 µm Rq: 0.8317 µm
Normal load F_N	490.5 N
Speed N	490 rev/min
Room Temperature T	31 °C
Note: d is diameter, l is length, w is width	

Stainless steel SUS304 was used as a blanking sample/workpiece. The summary of its properties is shown in Table 3. SUS304 has its percentage of element content show the percentage in Table 4.

Table 3: The properties of the workpiece stainless steel SUS304.

Properties	Value
Tensile Strength, Ultimate	505 MPa
Tensile Strength, Yield	215 MPa
Modulus of Elasticity	193 GPa
Shear Modulus	77 GPa
Poisson’s Ratio	0.29

Table 4: The component of the element for stainless steel SUS304.

Material	Component Element (%)							
	C	Cr	Fe	Mn	Ni	P	Si	S
SUS304	≤0.08	18~20	66.345~74	≤2	8~10.5	≤0.045	≤1	≤0.03

High-Carbon High-Chromium alloy steel (SKD11) with surface harness 60 HRC was coated with double-layer coating (DLC/TiAlN) using High power impulse magnetron sputtering (HiPIMS) was used as punch tool in this experiment that was provided by CemeCON Scandinavia. The coating film and the setup diagram are described in Figure 3 and its properties are shown in Table 5. The blanking process was undergone 50 times in lubricant condition using cutting fluid and MgO/SiC water lubricant by using double layer coating tool DLC/TiAlN.

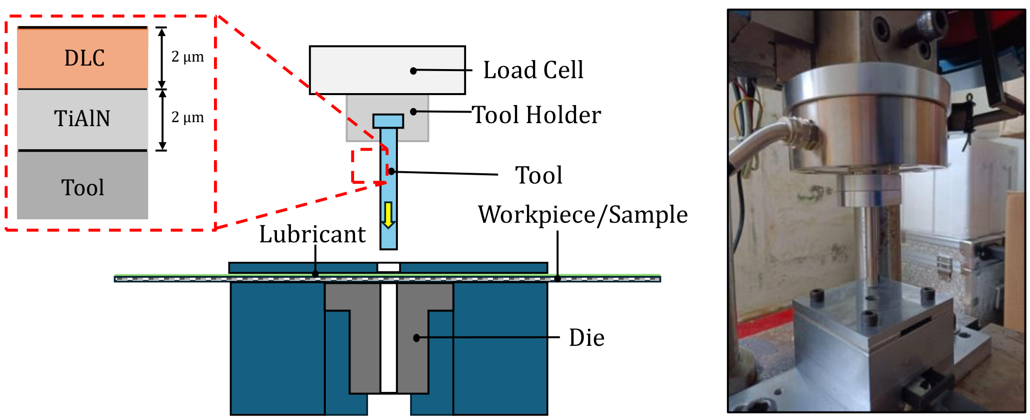


Figure 3: Blanking setup process diagram and coating film of the DLC/TiAlN.

Table 5: Mechanical properties of punch tool.

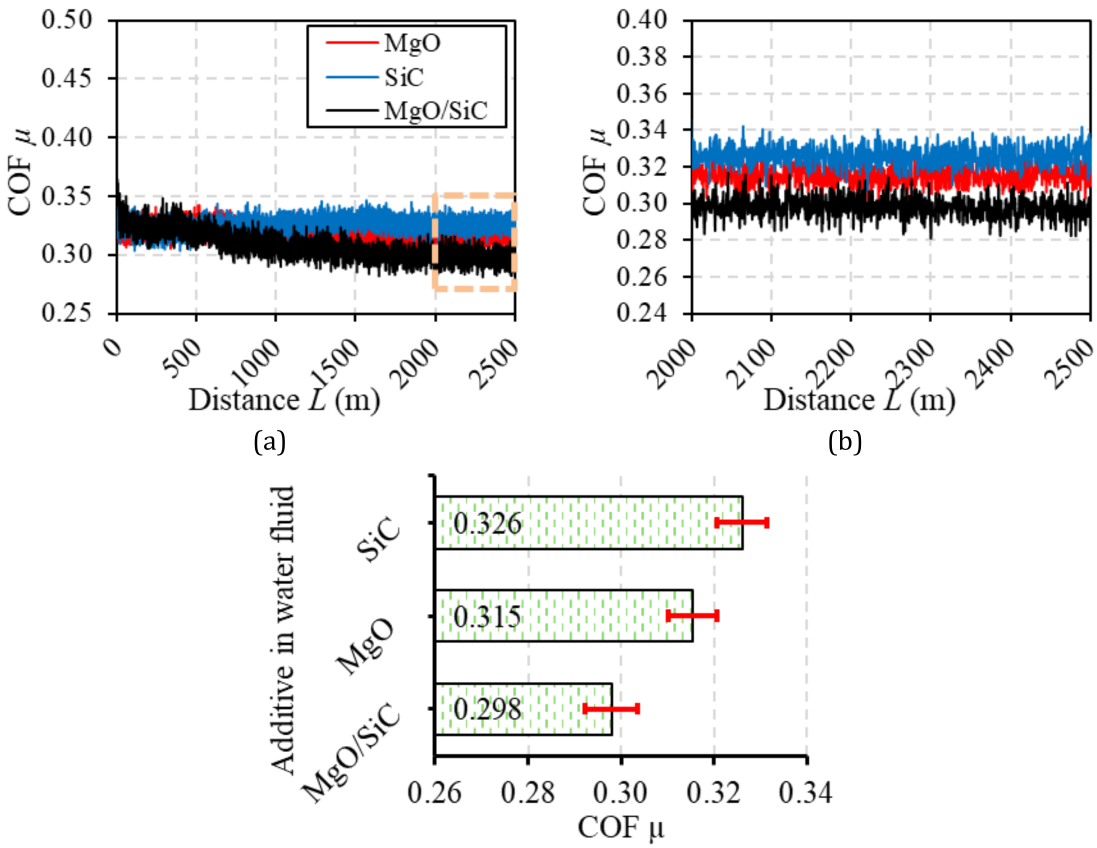
Tool Coatings	Thickness (μm)	Hardness (HV)
DLC/TiAlN	4 ±0.4	~3000

3.0 RESULTS AND DISCUSSION

3.1 Friction Analysis

Analysis of Figure 4(a) reveals that the coefficient of friction (COF) for the MgO/SiC water-based fluid starts at a relatively high value of about 0.35 and decreases to a minimum of about 0.28 when the distance reaches 2500 meters. This pattern shows a trend towards stabilization of the COF along the sliding distance. The average COF, as determined upon reaching a steady state depicted in Figure 4(b), is shown to be 0.298. This value indicates a consistently stable friction performance with minimal deviation from the mean. In contrast, Figure 4(c) illustrates that the SiC additive alone has the highest COF, with an average of 0.326, while the MgO additive alone shows a slightly lower COF of 0.315. The combined MgO/SiC additive mixture produced the most significant COF reduction around 8% and 5% compared with single additive SiC and MgO respectively, with an average of 0.298. These data show that the synergistic effect of the MgO/SiC combination significantly improves performance by reducing COF more effectively than either additive alone, with SiC alone being associated with the highest COF among the additives tested. As reported by Ahamed et al., (2020), they found that 66% and 25% reduction of COF for SiC additive and MgO additive in their study of comparison of thermo-physical and tribological characteristics of nanolubricant.

MgO nanoparticles are recognized for their soft structure, which allows them to deform and form thin films under significant loads. This feature is important to maintain an effective lubrication layer that ensures continuous protection while maintaining surface integrity (Wang et al., 2017). SiC nanoparticles, which are almost spherical shape, can function as ball bearings during tribological processes, contributing to the polishing effect (He et al., 2021; Wang et al., 2017; Yao et al., 2021)



(a) (b) (c)

Figure 4: (a) Coefficient of friction each additive in water fluid; (b) Coefficient of friction at steady state;(c) average coefficient of friction of difference additive in water fluid.

3.2 Effects of Blanking Force

The average blanking force on the punch tool required during the blanking process of Stainless Steel SUS304 is shown in Figure 5, it is compared with MgO/SiC water fluid cutting fluid and dry friction. Based on the result

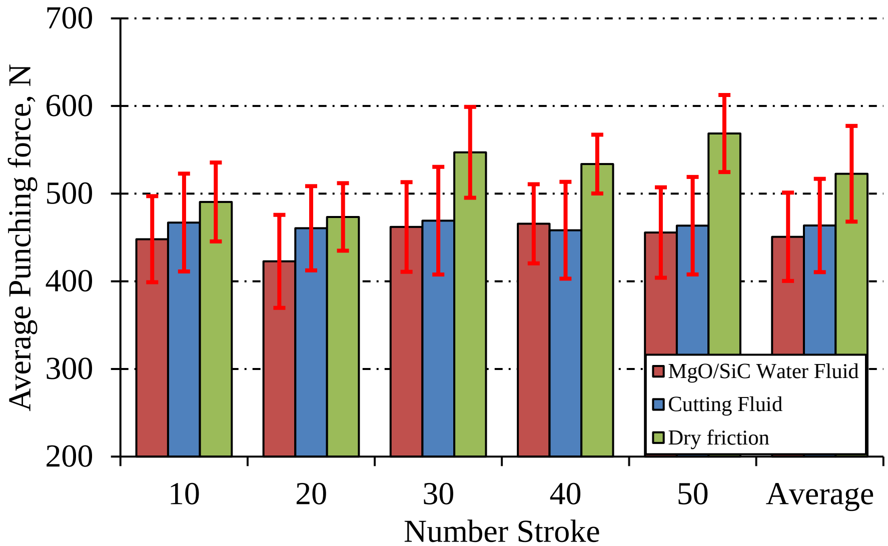


Figure 5: The average of blanking force for every 10 strokes until 50 strokes on each condition.

Based on the result, the combination of water fluid and surface coating could reduce the blanking force, it obtained the lowest blanking force compared with the process using cutting fluid. Using dry friction conditions shows the highest force needed compared to using a combination DLC/TiAlN coated punch tool and lubricant. It needed more than 500 N after the tool 30 number stroke. For the process using water fluid, the average reduction of blanking force was around 3% compared with using cutting fluid and around 14% reducing for using dry friction condition surface applied after average taken after 50 strokes, it reduces from 463.69 N and 522.70 N to 450.82 N, respectively. By applied lubrication, it can reduce the blanking force. It is due to the changing of lubrication from boundary lubrication to mixed lubrication (Shisode et al., 2020). A mixed lubrication regime is influenced by friction force by two factors, first is direct contact between solid-solid asperity surface and second is shear stress generated by lubrication pressure between the tool punch and workpiece (Shisode et al., 2021). During the blanking process, the lubricant prevents the surface of the tool and workpiece from direct contact and reduces friction (Ouyang et al., 2022).

3.3 Tool Wear of DLC/TiAlN-Coated Punches

The wear mechanism after the blanking process has been identified and analyzed, and a detailed examination of the punch cutting edges after 50 strokes were conducted. Images in Figure 6 illustrate the wear process. Using a DLC/TiAlN coated punch, the tool exhibited an abrasive wear area near the edge after 50 strokes. The material loss occurred due to contact pressure on the tool surface, leading to abrasive wear. The coating peels off at the most area at the end of the tool (figure 6(a)). Little chipping was observed on the edge of the punch (Figure 6(b)) (Budinski, 1999). In comparison, the dry friction tool (Figure 6(c)) showed adhesive wear, where the workpiece material adhered to the tool.

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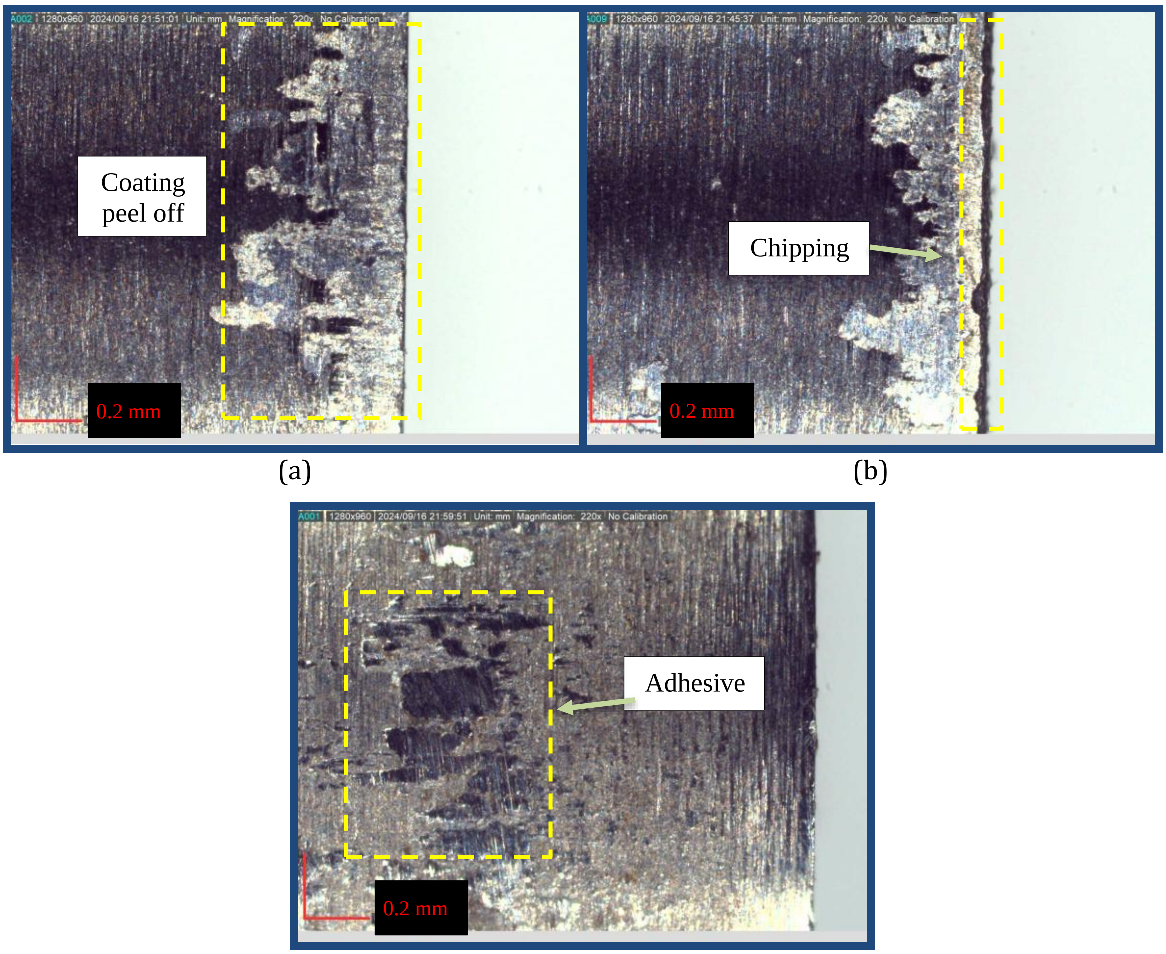


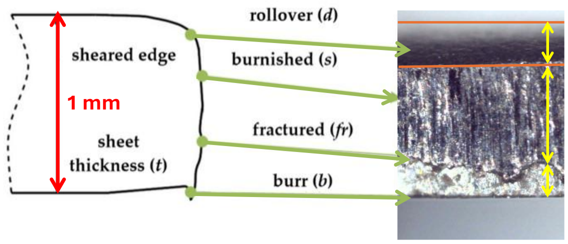
(a) (b)

(c)

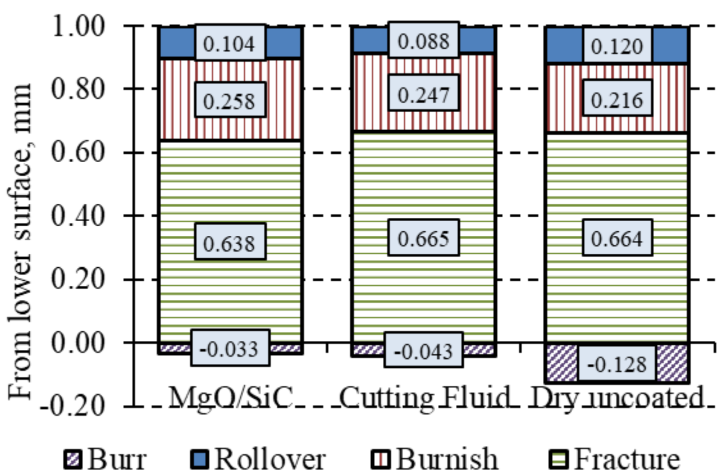
Figure 6: Edge and face wear of the punch after 50 strokes at 220x magnification: (a) DLC/TiAlN coated punch combine MgO/SiC water fluid; (b) DLC/TiAlN coated punch combine cutting fluid; and (c) dry friction.

3.4 Surface Integrity of Workpiece

The surface quality of the product in blanking is determined by the characteristics of the sheared edge, as shown in Figure 7(a). Microscope images of the cut edge were used in this study to evaluate part geometry by examining the rollover, burnish, fracture, and burr under different conditions. The results were averaged for each zone and are shown in Figure 7(b). Here, rollover, burnish, and fracture are measured in relation to the sheet thickness of 1 mm, and burr height formation is noted. Burr formation is a common issue in mechanical cutting and metal forming. The height of burrs can be minimized by selecting appropriate technological parameters, particularly cutting clearance, which depends on material thickness and type (Bohdal et al., 2021). This study showed the influence of the tool on burr height, with a coated punch reducing burr heights by approximately 74% and 67% compared to dry friction (0.128 mm) when using MgO/SiC water fluid and cutting fluid, respectively, combined with DLC/TiAlN coated punch. The burnish value after 50 strokes was higher with DLC/TiAlN coated punch and lubricant compared with dry friction, showing a 12% increase with MgO/SiC water fluid and a 0.4% increase with cutting fluid. For fracture, using DLC/TiAlN coated punch and MgO/SiC water fluid reduced it compared to dry friction and cutting fluid conditions by around 4%. The difference in fracture between dry friction and cutting fluid conditions was less than 0.2%. The rollover width primarily depends on the cutting clearance value and increases as the clearance becomes larger (Kubik et al., 2021).



(a)



(b)

Figure 7: (a) cross-sectional scheme and the one obtained experimentally (front view); (b) depth rollover, burnished, fracture and burr at sheared edge by using DLC/TiAlN coated punch and lubricant.

CONCLUSIONS

This study assessed the wear performance of DLC/TiAlN coated punch on tool surfaces during the blanking and punching of stainless steel sheets under oil-based (cutting fluid) and water-based lubrication and dry friction conditions. The following conclusions have been drawn from the findings:

a) The combined use of MgO and SiC additives results in a reduction of the coefficient of friction (COF) by approximately 5%, compared to a single additive of MgO and around 8% for SiC
b) Applying lubricant on the tool during the punching operation reduced the maximum force load. A 14% reduction was observed using MgO/SiC water lubricant compared to the dry friction condition, and a 3% reduction was observed using cutting fluid.
c) The height of the burr decreased significantly when using lubricant at room temperature. There was a 74% reduction when using the combination of DLC/TiAlN coated punch and MgO/SiC water fluid and 67% for using cutting fluid compared to the dry friction tool with different 0.01 mm between using water-based lubricant and cutting fluid.
d) Water-based lubricants are an alternative that can compete effectively with conventional cutting fluids.

The specific combination of DLC/TiAlN coated punch with MgO/SiC water fluid proved to be particularly advantageous for achieving optimal results in terms of burr height.

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