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Enhancing wear resistance in blanking and punching of stainless-steel sheets under dry friction and solid lubrication conditions using single-layer ceramic- and carbon-based hard coatings

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KEYWORDS

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ABSTRACT

Punching and blanking encounter challenges in separating tool and workpiece surfaces due to the formation of highly active virgin material, negatively impacting tool surfaces and product quality. To prevent this issue, hard coatings are applied to the tool surfaces. In this study, the wear severity of ceramic-based (TiN and TiAlN) and carbon-based (DLC) coatings deposited on punches during blanking and punching under dry friction and solid-form graphite lubrication were evaluated and compared with uncoated punches. The experiments were performed on 1-mm AISI304 stainless steel sheet thickness at room temperature. The findings indicate that there were no significant differences in force and wear measurements when using all test coatings in dry friction conditions. However, when applying a thin layer of TiN ceramic coating on the tool surface and using solid graphite lubrication, it effectively protected the tool and reduced punching force by 7%. This combination also improved wear resistance in the shearing zone, resulting in an extended tool service life and enhanced surface finish.

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1.0 INTRODUCTION

In sheet metal forming like fabricate a part of the car, e.g., in the seat adjustment or the powertrain of a car, the most use process are blanking and punching that combination with several metal forming process as an intermediate or finishing production step (Moghadam et al., 2020). The quality of the product that is produced from the blanking and punching operation will influence many factors, for example the tool material properties, tool design, tool wear and the condition when stamping. In a blanking process, the mechanism of wear occurring that characterized by three distinct phases where abrasive wear, adhesive wear and growth of friction junctions are respectively dominant. Surface damages are caused of the friction during the movement of the tool that contact to the surface of the product, the damage such as galling, plastic deformation, chipping, and cracking (Choi et al., 2013). The hard PVD and CVD coatings successfully compete with the traditional thermo-chemical treatments, in resistance from abrasive wear (Escher & Henke, 2006). The coating can increase the tool life, it also acts as a protection from wear, specifically adhesions and abrasions (Atiqah Badaluddin et al., 2018). (Horiuchi et al., 2012) found that DLC coating one of solution to reduce the friction during the deep drawing at room temperature. Additionally, the friction coefficient at room temperature can be reduced up to 73 % compared to non-coating and up to 90% different between DLC coating and non-coating at 200°C.

The coating serves a dual purpose in sheet-metal forming: it extends the lifetime of the tools, in which promotes protection against wear, particularly abrasion and adhesion. Since the last few years, the use of different material combinations enables the production of layers with diverse shapes and structures (Khadem et al., 2017). The coating can be single layer coating, multiple layer coating and various other type (Vereschaka et al., 2017). Traditional PVD layers like TiN, Ti-C-N, CrN, and Ti-Al-N are structured as single-coating architectures. These architectures exhibit distinct characteristics, including variations in morphology, structure, defects, grain size, composition, and gradient, which are influenced by parameters during processing. The processing parameters play a crucial role in determining the specific properties of the coating (Atiqah Badaluddin et al., 2018). Multilayered coatings consist of a regularly repeated structure of lamellae comprising multiple materials. Employing multilayer coatings offers advantages in stress modification, enhanced resistance to crack propagation, and improved substrate adhesion. Furthermore, this design allows for creating multifunctional coatings by alternating different coating systems. To meet specific cutting application needs, adjustments in thickness and layer composition are required. Combining different alloyed systems enables each layer to fulfill distinct tasks, such as controlled lubrication, increased oxidation resistance, and strengthening, resulting in a comprehensive and tailored solution (Schleinkofer et al., 2014).

Lubricants are generally used to reduce friction and serve as anti-friction properties, giving more benefit in terms of reducing the energy lost due to friction and reducing the required punching force. One of the common types of lubricants used is solid lubricant because of its low friction (Grüner & Merklein, 2014). The purpose of the solid lubricant is to reduce the value of the coefficient friction by creating the chemical and physical on the worn surface that form through the physical and chemical reactions (Gong et al., 2020; Kumar et al., 2022). The most widely used solid lubricant is graphite due to its good lubricant performance in terms of the easy sliding behavior associated with weak Van der Waals bonds between layers and the stable structure because of the strong covalent bond within the layer, as well as its self-lubricating and dry lubricating properties (Scharf & Prasad, 2013). The formation of burrs is a common occurrence when producing sheet metal using a punch and die. Unwanted burrs are formed at the edges of the blank during blanking (Barik et al., 2018). Burrs are typically unwanted material that extends beyond the edges of the product or blank, resulting from plastic deformation during machining or metal forming. Manufacturers always target to produce blank with a minimum amount of burr.

In punching and blanking, separating the tool from the workpiece surface becomes challenging because the creation of active workpiece material makes it hard for the lubricant to reach the tool-workpiece interface. This results in the workpiece material sticking to the punch and causing a problem called galling. Using hard coatings can solve these emerging issues. Therefore, this study aimed to evaluate the wear performance of ceramics and carbon hard coatings on tool surfaces during blanking and punching of stainless-steel sheets under dry friction and solid graphite lubrication conditions. The experiments were performed on 1-mm AISI304 stainless steel sheet thickness at room temperature, and the wear resistance of different test coatings was evaluated and compared with uncoated punches using microscopic images, which focused on measurements of rollover, burnish, fracture, and burr zones.

2.0 MATERIALS AND METHODOLOGY

The workpiece material was used Stainless Steel SUS304 that properties as shown in Table 1. The thickness of the workpiece was 1 mm. All the tools had substrate SKD11 with hardness 255 under Brinell. Table 2 and Table 3 show the component element of the SUS304 material and SKD11 substrate.

Table 1: 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 2: The component of the element for Stainless Steel SUS304 (MatWeb).

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

Table 3: The component of element for SKD11 (Hadi et al., 2022).

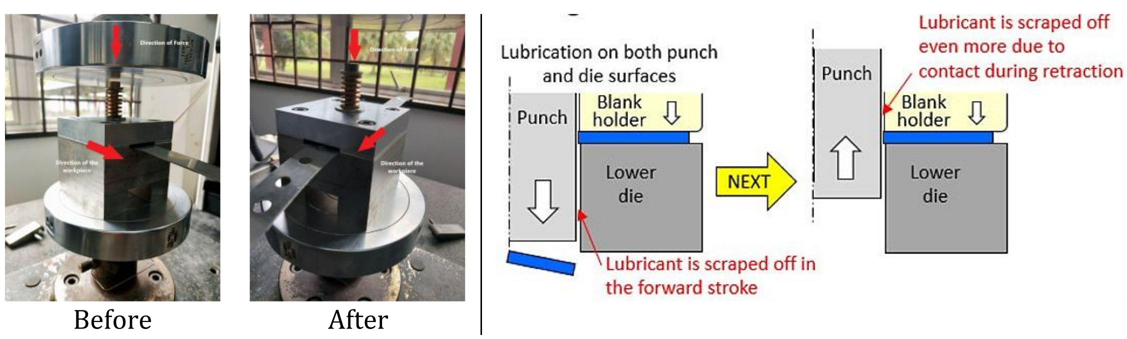
JIS	Component Element (%)										
	C	Cr	Cu	Fe	Mn	Mo	Ni	P	Si	S	V
SKD11	1.4 ~ 1.6	11 ~ 13	≤ 0.25	81.9 ~ 86.6	≤ 0.6	0.8 ~ 1.2	≤ 0.5	≤ 0.03	≤ 0.4	≤ 0.03	0.2 ~ 0.5

The experiment tested four different coatings including non-coating. The coatings are Titanium nitride (TiN), Titanium Aluminium Nitride (TiAlN), and Diamond-like Carbon (DLC). Mechanical properties of the test hard coatings deposited on tool surfaces. The hardness of the tool surfaces before the coating procedure was 62 HRC. The measurements of mechanical properties of the hard coatings after the coating procedure were listed in Table 4.

Table 4: Mechanical properties of TiN, TiAlN, and DLC hard coatings.

Test Coatings		**Thickness (μm)**	**Hardness (HV)**
Ceramic-type	TiN	5 ±0.3	~2240
	TiAlN	6 ±0.2	~3250
Carbon-type	DLC	5 ±0.4	~2500

Figure 1(a) illustrated the setup of the workpiece holder during the punching process on the INSTRON 3382 machine. As depicted in Figure 1(a), both before and after the blanking procedure, the presence of active workpiece material presented a challenge in allowing the lubricant to adequately reach the tool-workpiece interface when the punch was retracted to its original position after the punching procedure. The schematic presented in Figure 1(b) revealed that the additional contact caused by the workpiece during punch retraction removed the lubricant (Moghadam et al., 2020), resulting in severe wear on the tool surface (Sulaiman et al., 2019). To mitigate this galling phenomenon and address the high contact pressures during the experiment, hard coatings were applied to the tool surfaces for additional protection (Sulaiman et al., 2018), alongside the incorporation of effective boundary lubrication properties (Hafis et al., 2013). All test coatings were compared with the uncoated ones.



(a) (b)

Figure 1: The setup during punching process.

3.0 RESULTS AND DISCUSSION

The maximum force load on the punch for Stainless Steel was shown in Figure 2. Based on the result, different surface coating is not very different for the maximum force load, but by adding solid- form graphite lubricant during the punching process, it can reduce the maximum force load. For surface coating TiN, the experimental force obvious difference result that reduce approximately 7% in lubricated condition from 1.71 GPa to 1.59 GPa. Uncoated and TiAlN coating has reducing of maximum force around 2% for both of tool punch from 1.70 GPa but for DLC coating, it much different between dry and lubricant condition which is 0.003 GPa. The punching force is reduced when applied to the lubricant. This is because the lubricant regime has been changing to mixed lubrication from boundary lubrication (Shisode et al., 2020). In the mixed lubrication regime, the overall frictional force is influenced by two factors: the friction resulting from direct contact between surface asperities and the shear stress generated by the lubricant under pressure at the interface between the tool and the workpiece (Hol et al., 2015). Graphite possesses a remarkable capability to create a solid film lubricant due to the presence of two distinct types of chemical bonds. The weak Van der Waals forces that govern the bonding between its individual layers allow these layers to easily slide over each other, rendering graphite an excellent lubricant. Its lamellar structure further enhances its friction-reducing properties. During the friction process, the solid graphite lubricant can be transferred onto the counterpart's surface, effectively preventing direct contact between the metals, and thereby preventing adhesion and scuffing (Wang, 2013).

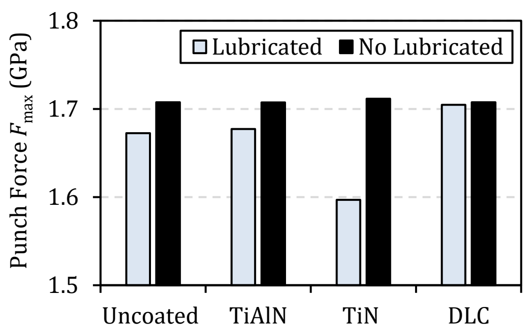


Figure 2: The maximum force load on the punch for Stainless Steel workpiece.

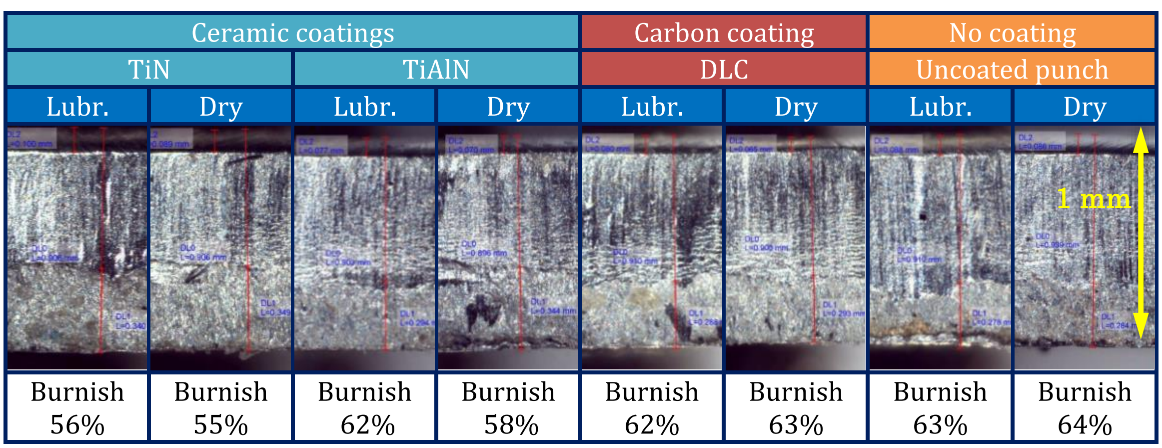


Figure 3: The image Shear Affected Zone (SAZ) the Stainless Steel on the slug; (a) TiN Lubricated; (b) TiN No Lubricated; (c) DLC Lubricated; (d) DLC No Lubricated; (e) Uncoated Lubricated; (f) Uncoated No Lubricated; (g) TiAlN Lubricated; and (h) TiAlN No Lubricated.

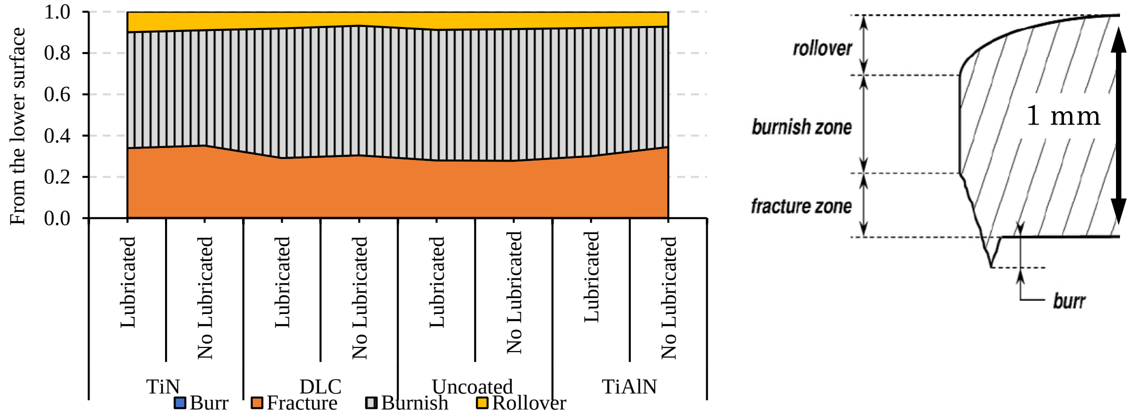
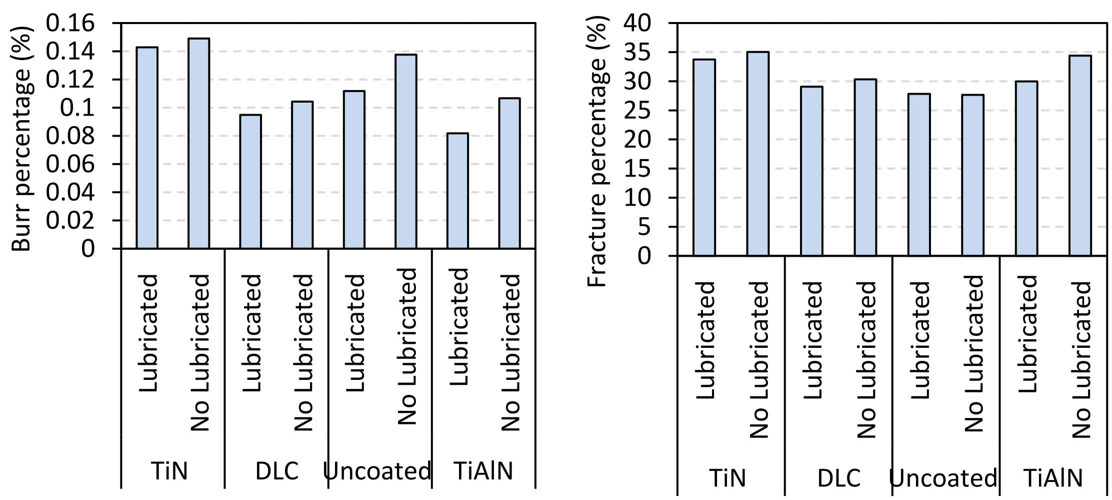


Figure 4: The Shear Affected Zone for the Stainless Steel on the slug in dry and lubricant condition and edge profile scheme on slug (Falconnet et al., 2015).

Figure 3 and Figure 4 show the microscope image and overall effect for slug workpiece under shear affected zone.



(a) (b)

Figure 5: The percentage of heigh from overall; (a) Burr percentage; (b) Fracture percentage.

Based on the experiment, the Burr from the workpiece reduced when the solid-form lubricant was applied during the punching process as shown in Figure 5(a). By applied the solid-form lubricant also reduce the Fracture on the workpiece as shown in Figure 5(b). According to (Bohdal et al., 2020) the formation of the burr on the surface is one of the problems facing in shaping product that involves with mechanical cutting techniques. Based on experimental and numerical studies of tool wear processes in the nibbling process from (Bohdal et al., 2022) found that the burr height can be reduce by using the layer of coating surface on the tool punch. In Figure 5(a), By using coating DLC, the height of burr is mostly the lower between all the tool which around 1.04 μm in dry condition. In lubricant condition, reducing happen to all surface coating. TiAlN is the lower value which is around 0.8 μm and reducing up 23 %. According to (Kindsmüller et al., 2021) state that lubricant can influence on the adhesive force that can affect to burr clamping force or burr. They found that the burr clamping force reduces when applied the lubricant, since friction that reduce between burr and surface of punch.

The fracture zone is not much effected when applied the lubricant, according to (Fazily et al., 2019), the fracture zone been affected due to temperature when the punching process. From their experiment, the fracture zone decreases when the temperature increases. This phenomenon occurs due to the activation of non-basal deformation, which leads to a notable enhancement in material ductility. Based on the result, the difference value of fracture between dry and lubricant for TiAlN is 0.04 mm which is the bigger difference among all coating that from 0.34 mm in dry condition. Factures for DLC and TiN in dry condition are 0.3 mm and 0.35 mm, respectively and decrease 0.012 mm for both tools but not much difference for uncoated tool.

CONCLUSIONS

This study assessed the wear performance of single-layer ceramics and carbon hard coatings on tool surfaces during the blanking and punching of stainless-steel sheets under dry friction and solid graphite lubrication conditions. The following conclusions have been drawn from the findings:

a) Applying lubricant on the tool during the punching operation reduced the maximum force load.
b) The height of the burr and the fracture decreased significantly when using lubricant at room temperature.
c) The combination of TiAlN coating with solid lubricant exhibited the largest difference in burnish height between both conditions, while TiN coating demonstrated the lowest burnish height among all tools.

These findings highlight the effectiveness of lubricant application in reducing force load and improving surface quality during punching operations. Additionally, the specific combination of TiAlN coating with solid lubricant proves to be particularly advantageous for achieving optimal results in terms of burr height.

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