Mathematical Modelingof Mechanical Properties of PVD Coated Steel Blanking Punch

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Abstract

To improve tool life of blanking punches four types of PVD coatings were used, TiN coating, TiCN coating, TiAlN coating and CrN coating. In this work, the mechanical properties such as hardness, wear and fatigue were studied. All types of coating are deposited on blanking punches which were hardened to reach core hardness 60-62 HRC and grinding to get surface roughnessRa = 0.4 µm.The hardness test, wear test and fatigue test were used to characterize the punches properties especially durability and life time. An A10 washer stamp was used to try out the punches and a high number of strokes were done for every punch. It was found that the TiAlN coated punch has the best properties. It had highest hardness value, lowest wear rate value, had maximum number of cycles to failure, and most ultimate stress. Also the TiAlN coated punch suffered from less wear and had most smother performance.Finally, a mathematical modeling correlating between hardness, wear and fatigue of blanking punch with the chemical composition of PVD coating type were developed.

Keywords:*Blanking Punch – Hardness – Wear – Fatigue*

1. Introduction

Blanking is a common technique in high volume production. In general application of the blanking sheet steels, such as in the automotive industry, a blanking tool should produce several million parts during the life time of tool material. During the blanking process, the wear of punched occurs due to the cyclic contact f the opposite surface. Therefore, the punch material must have high resistance against wear during the process **[1, 2]**.

Blanking tool, the wear of punch and die directly affects the quality of parts. The errors in the produced parts by blanking are classified as dimensional, position, form and surface error **[3].**

The wear of tooling considerably alters the cutting conditions, raising the demand for press force and reduces the life of tools, also it's changing the clearance between the punchanddie which causes damage to the surface of the parts**[4]**.

Increase the shearing angle of punch tool concurrently reduces the stress and increasing the cutting tool life[5].To reduce the wear of tooling and improve the life of tools, a layer of hard-coating canbe used. The use of thin coatings enables abrasion, adhesion and diffusion wear, and friction to be reduced and heat resistance to be enhanced.

The coating is deposited on tools by physical vapor deposition(PVD) process, in this process the substrate surface and the growing film are subjected to a continuous or periodic flux of energetic massive bombarding particles sufficient to cause changes in the film formation process and the properties of the deposited film.Bombardment can take place in a plasma or vacuum environment[6].

For cutting tools, there is a need to go from semiconductor to metal. So, it will be needed a means to deposit metals. PVDis based on the concept that there exists afinite “vapor pressure” above any material. Thematerial either sublimes (direct solid to vaportransition) or evaporates (liquid to vapor transition). Using PVD coating technique gives highest tool purity due to low pressures [7]. The PVD coating of the punch with a surface layer of improved hardness and low friction may reduce wear.

Thin hard of TiCN, nACRo, and nACo PVD coating effect on wear performance of fine-blanking punches[8]. Coatings nACRo and nACo have better average wear resistance in fine-blanking compared with TiCN.

The blanking performances of the AlCrN-coated produced by PVD and uncoated punches were evaluated under the actual operating conditions for sheet-steel blanking [9]. The wear resistance of AlCrN coatings was investigated and compared with the wear resistance of uncoated punching tools. The degrees of wear at the cutting edge and on the flank of the punch proved to be reduced by the AlCrN coatings obtained by PVD.

PVD coating of punch TiAIN and AlCrN in real work conditions for sheet steel blanking[10]. Evaluation was based on the wear resistance of PVD coatings in the conditions of blanking of sheet steel. For the wear mechanisms investigated using scanning electron microscope, it was revealed that abrasion and adhesion are the main responsible mechanisms and result in the plastic deformation on the punch cutting edge and the coating flaking on flank surface. It shown that AlCrN coatings showed better blanking performance than TiAlN coatings

In the present work a steel punch has coated with four different types of coating materialTiN, TiCN, TiAlN and CrNas will show in section 2 to increase the time life, hardness, number of cycles to failure, and decrease wear rate. The microstructure examinations and hardness, wear, fatigue tests were used for inspecting durability and lifetime of the punches after coating will explain in section 3.A mathematical model implementedas a new approach in punch material studying to compare the testes results of the experimentally work with the theoretical calculations it.Changing in punch characteristics after coating with different types of materials will appeared in details at section 4.

2. ExperimentalWork

2.1. Materials

The cold work tool steel "X155CrMoV12" was used as punch material, where low carbon steel "St37-2" was used as work piece.

2.2. PVD Coating

Before do the coating process all blanking punches was hardened and tempered to get core hardness 60-62 HRC, after that the substrate surface was precision ground finished to get surface roughness Ra = 0.4.

The coating layers were deposited using ion plating process as shown in **Figure 1**, where the substrate material is vaporized and bombarded by high-energy gas ions which sputter off the material present on the surface which results in a constant cleaning of the substrate.

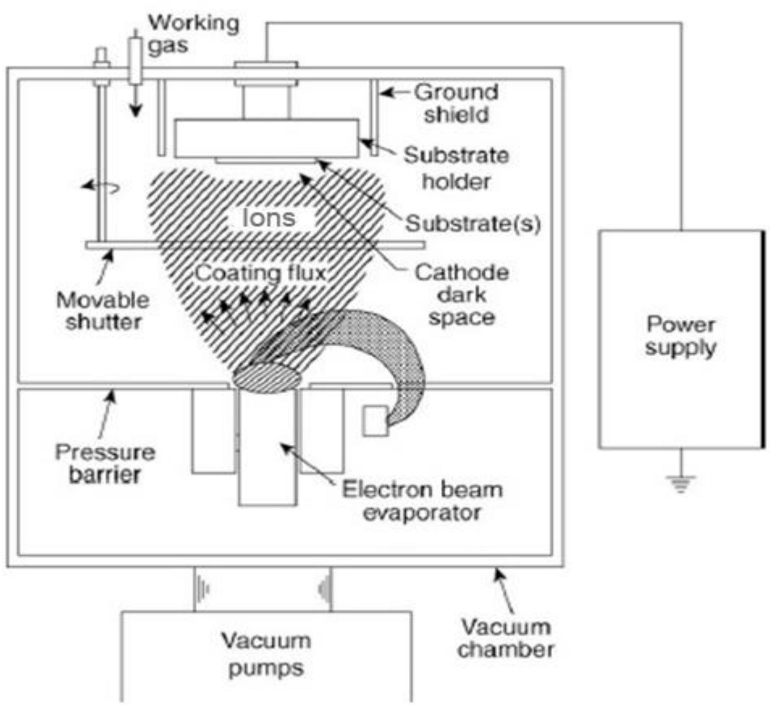


Figure 1: Ion Plating Process

In this work, effecting of materials coating changing were study by using TiN (Titanium Nitride), TiCN (Titanium Carbon Nitride), TiAlN (Titanium Aluminum Nitride) and CrN (chromium Nitride)materials deposited through LD-600A PVD coating machine. The coating materials characteristics [11] shown in **Table 1**.

Table 1: Coatings Materials Characteristics

Coating	TiN	TiCN	TiAlN	CrN
Thickness (µm)	3	3	3	3
Color	Gold	Silver-Gray	Black	Silver
Temperature (ºC)	500	400	700	500

2.3. Punches Inspections

The microstructure examinations and hardness, wear, fatigue and tensile tests were used for inspecting durability and lifetime of the punches. These tests were performed related to ASTM- A892 [12]. The specimen had prepared to get mirror surface by enchanting with chemical etchant 3%NTAL + 97% Alcohol.

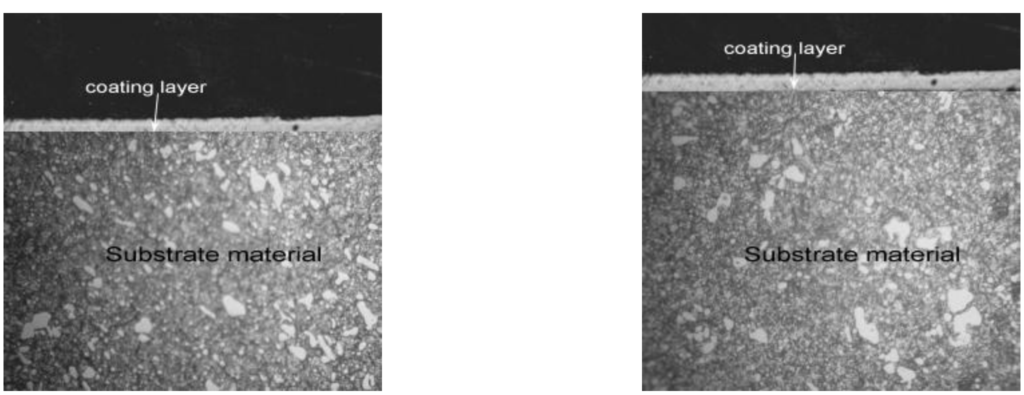
To measure the hardness of coated surface the micro hardness test was performed according to ASTM-E384 [13]with (91 kg) applied force.The pin-on-disk method according to ASTM-G99 [14]was used to get wear rate for each punch. The coated specimen with (7.8 mm) diameter was used as pin. The tester was adjusted to (200N) load and(200r.p.m) speed for (15 min).The fatigue test was performed according to ASTM-E466 [15], with (500N)applied load which performed till specimen failure.

An A10 washer stamp was used to try out the punches using a 20T gantry type hydraulic press and 10000 blanking process was done for every punch.

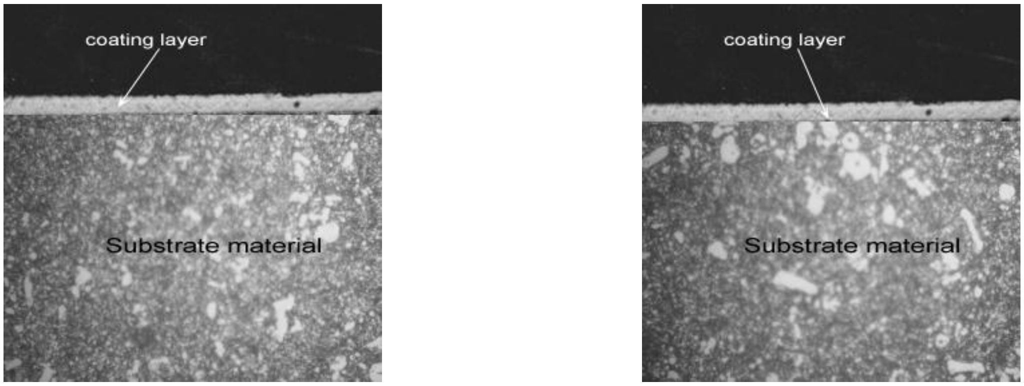
3. Results

3.1. Microstructure Examinations

The microstructures of the punches coating layer and substrate material are showing in **Figure 2.**



(a) (b)



(c) (d)

Figure 2: Punches microstructure (X1000),**(a)**TiNCoated Punch,**(b)**TiCN Coated Punch, **(c)**TiAlN Coated Punch, and **(d)**CrN Coated Punch

It is noticed that coating layer thickness is equal for all punches and coating layer is homogeneous and it is cohesive with substrate material.

3.2. Hardness Test

The Vickers hardness profile of all punches versus distance from edge of punch is shown in **Figure 3.** The TiAlN coated punch has the highest hardness value which reaches to (3044 HV). While the uncoated punch has the less hardness value which reaches to (764 HV).

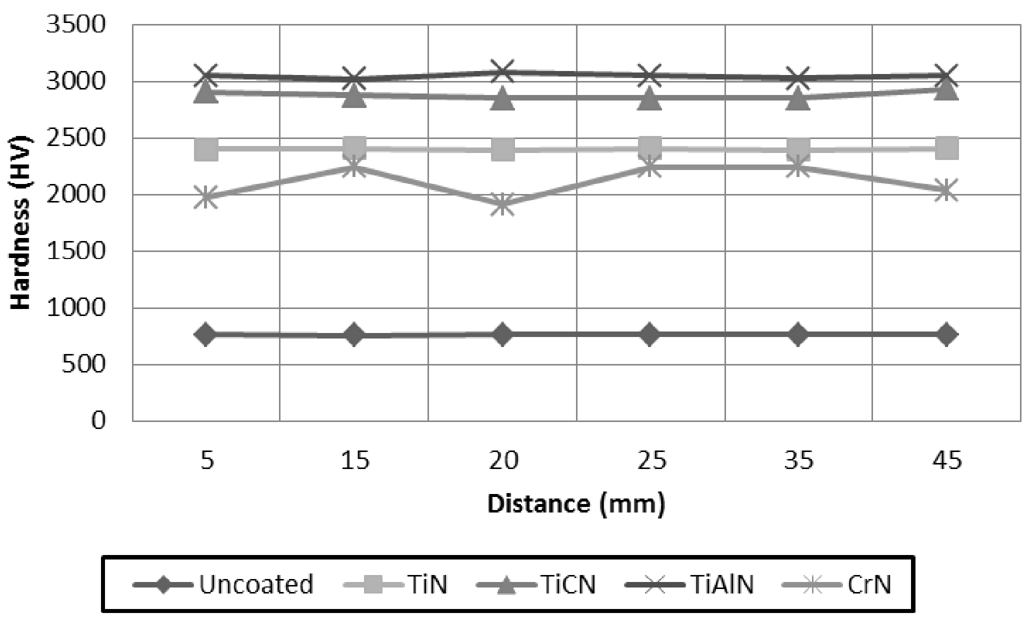


Figure 3: Vickers Hardness Profile Plot

This occurs because the high proportion of iron carbide, iron nitride, molybdenum carbide and titanium aluminum nitride in TiAlN coated punch.

3.3. Wear Test

The values of weight losses and wear rate for five types of punches are shown in **Figure 4**.The effect of coating punch with TiN, TiCN, TiAlN and CrN materials on the wear rates of five punchesappeared

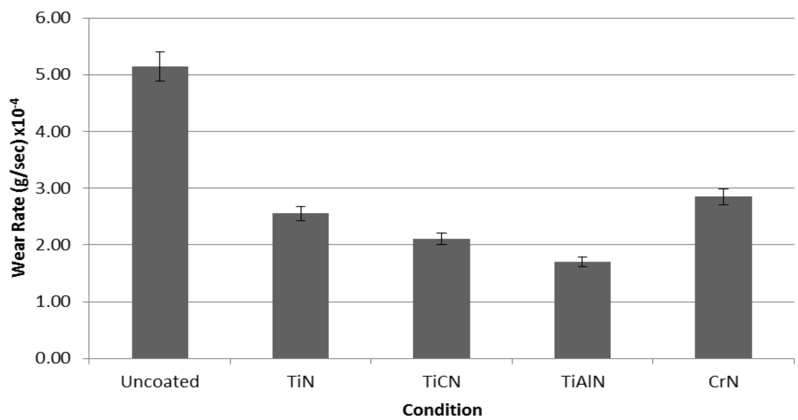


Figure 4: Punches Wear Rate

that,the TiAlN coated punch has the less wear rate value which reaches to ($1.70x10^{-4}$ g/sec) while the uncoated punch has the highest wear rate value which reaches to ($5.15x10^{-4}$ g/sec).

3.4. Fatigue Test

The alternating stress amplitude versus number of cycles to failure (S-N curve) for the five punches is shown in **Figure 5, t**he TiAlN coated punch has the highest number of cycles to failure which reaches to (1500000) cycles while the uncoated punch has the less number of cycles to failure which reaches to (500000) cycles.

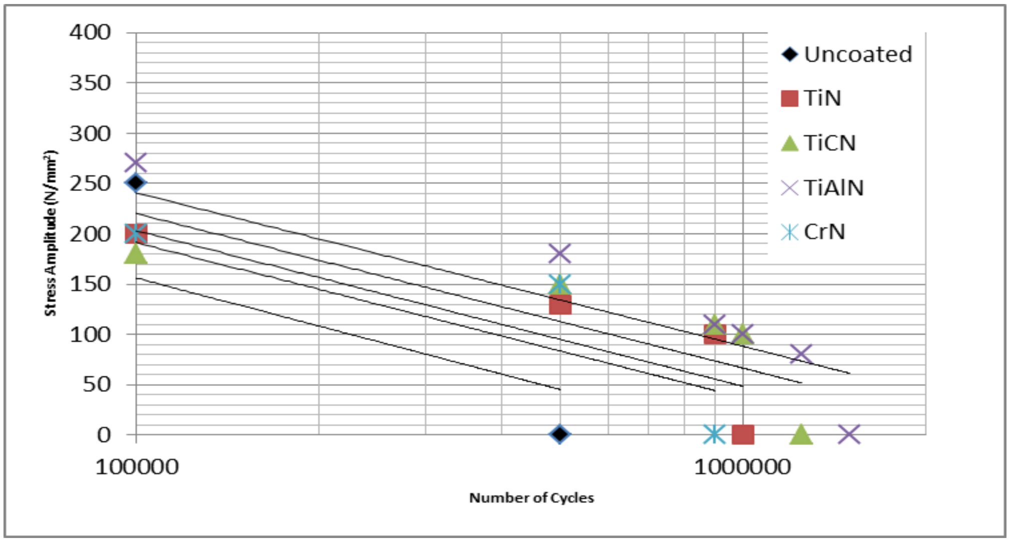


Figure 5:S-N Curve for Punches

3.5. Blanking Process

The weights of five punches before and after blanking process and weight loss are shown in **Table 2.**

Table 2: Punches Weight Loss after Blanking Process

Condition	Weight (g)		Weight Loss(g)
	Before	After	
Uncoated	115.50	114.00	1.50
TiN	115.50	114.80	0.70
TiCN	115.60	115.00	0.60
TiAlN	115.70	115.20	0.50
CrN	115.60	114.80	0.80

The weight losses related to the wear of five coated punches shown in **Figure 6**.It's clear that the TiAlN coated punch suffered less wear where is loss only (0.50g),while the uncoated punch suffered most wear where it loss (1.50g). Also a change in performance of punches during blanking process was noticed.

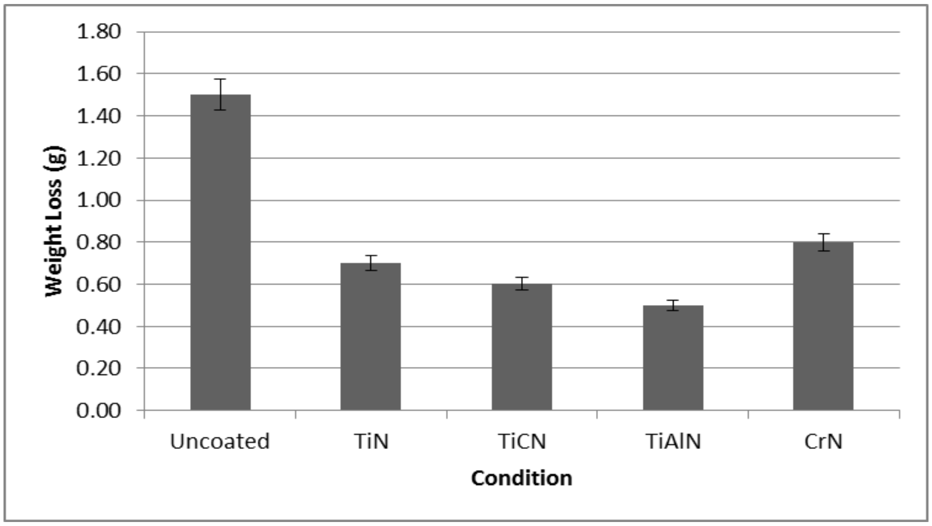


Figure 6: Punches Weight Loss after Blanking

The coated punches were smoother during the process than uncoated one, and the TiAlN coated punch was smoother one.

4. Discussions

The results of punch hardness test, wear rate test, and fatigue test, for coated and uncoated punches are shown in **Table 3.**The tests were done for the punch before and after coating. As appeared in the table, the hardness of TiAIN is higher than the hardness of the other punch coating materials because the high proportion of titanium compound and molybdenum carbide in the TiAlN coated punch. Increasing proportion of titanium compound and molybdenum carbide in TiAIN coated punch caused decrease the punch wear rate than the others coating materials.

Table 3: Tests Values for Coated and Uncoated Punches

Punch Condition	Tests		
	Hardness (HV)	Wear Rate (gm/s)	Fatigue (N^{O}. of cycles to failure)
Uncoated	764	$5.11x10^{-4}$	500000
TiN	2401	$2.78x10^{-4}$	1000000
TiCN	2879	$2.22x10^{-4}$	1250000
TiAIN	3044	$1.89x10^{-4}$	1500000
CrN	2112	$2.89x10^{-4}$	900000

As a result of increasing hardness and decrease wear rate of TiAIN punch coated material, the TiAIN coated punch has the highest number of cycles to failure than any punch conditions. Also the ultimate stress of the TiAIN coated punch as explain in thetable results' has greatest value because the high proportion of iron carbide in TiAlN.

The concentration of chemical compounds in coated and uncoated punches was determined by using XRD (X-Ray Diffraction). The percentages of the punches compounds are shown in **Table4.**Increasing percentages of Fe_3C (Iron Carbide), and Mo_2C (Molybdenum Carbide) in punch material have a good effect in improving thepunch hardens **[16], [17].**

As shown in the table, the coating materials changing the punch material chemical compounds percentages, also the Fe_2N (Iron Nitrate) was appeared in the punch material chemical compound after the punches that coated with TiN, TiCN, TiAlN, and CrN.

Table 4: X-Ray Diffraction Analysis of Coated and Uncoated Punches

Compound name	Uncoated Punch	TiN Punch Coated (37% Titanium Nitride)	TiCN Punch Coated (30% Titanium Carbon Nitride)	TiAlN Punch Coated (25%Titanium Aluminum Nitride)	CrN Punch Coated (37% Chromium Nitride)
Fe_3C (Iron Carbide)	49%	13%	18%	29%	28%
Mo_2C (Molybdenum Carbide)	6%	9%	13%	16%	8%
□-Fe (Ferrite)	45%	7%	12%	8%	22%
Fe_2N (Iron Nitrate)	--------	34%	27%	22%	5%

The analysis of XRD for the punch material after coating as show in the table has maximum values of Fe_3C, and Mo_2C when the punch coated with TiAIN. Increasing the iron nitrate Fe_2N percentage in punch material compound after coating with TiAIN improved the hardness, punches life and also gave a good effect on the number cycle's number of failure. Decreasing the quantity of ferrite-Fe in the punch after coating with TiAIN gave a required tool specification of hardness, wear rate, and fatigue stress value. Comparing the table values conformed that, using TiAIN as a coating material for punch tool improved punch mechanical properties than the others coating materials.

3.7. MathematicalModeling

The Minitab 17 package (Statistical software for analysis in statistics and econometrics)[18] used for mathematical modeling to correlate between mechanical properties such as hardness, wear and fatigue with chemical composition of PVD coating type was developed as follows:

$$\text{Hardness} = 2495 - 40.63\ Fe_3C + 146.8\ Mo_2C - 13.79\ \alpha\text{-}Fe - 23.25\ Fe_2N$$

$$\text{Wear} = 0.000136 + 0.000005\ Fe_3C - 0.000016\ Mo_2C + 0.000005\ \alpha\text{-}Fe + 0.000005\ Fe_2N$$

$$\text{Fatigue} = 673625 - 2365\ Fe_3C + 68804\ Mo_2C - 10457\ \alpha\text{-}Fe - 5556\ Fe_2N$$

Through applied the upper Minitab 17 mechanical properties equations, the values of the hardness, wear rate, and fatigue cycle's number shown in **Table 5.**

Table 5: Minitab 17 Software Analysis Data

Mechanical Properties	Uncoated Punch	TiN Punch Coated (37% Titanium Nitride)	TiCN Punch Coated (30% Titanium Carbon Nitride)	TiAlN Punch Coated (25%Titanium Aluminum Nitride)	CrN Punch Coated (37% Chromium Nitride)
Hardness	2477.638	2494.0598	2498.8383	2500.4871	2491.4471
Wear Rate	1.3974×10^{-4}	1.3386×10^{-4}	1.3407×10^{-4}	1.3419×10^{-4}	1.3697×10^{-4}
No. of Cycles (Fatigue)	671888.74	676888.88	679388.86	681888.91	675888.78

The values of the mechanical properties for different types of punch coated materials showed a match with the experimentally results. As appeared in **Table 5** thehardness, wear rate, and fatigue for punch coated with TiAIN have best values compared with the other types of coated punch materials.

4. Conclusions

In this work an improvement of punch tool life is tried to reach by deposited a Nano-coating layer on blanking punch.

- The TiAlN coated punch has the highest hardness value which reaches to (3044 HV). While the uncoated punch has the less hardness value which reaches to (764 HV).
- The TiAlN coated punch has the less wear rate value which reaches to ($1.70x10^{-4}$ g/sec). While the uncoated punch has the highest wear rate value which reaches to ($5.15x10^{-4}$ g/sec).
- The TiAlN coated punch has the highest number of cycles to failure which reaches to (1500000) cycles. While the uncoated punch has the less number of cycles to failure which reaches to (500000) cycles.
- The TiAlN coated punch has the highest ultimate stress value which reaches to (168267 N/mm^2). While the uncoated punch has the less ultimate stress value which reaches to (46400 N/mm^2).
- After high number of blanking process the TiAlN coated punch suffered less wear, while the uncoated punch suffered most wear; also it was had most smoother performance during blanking process.

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