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ANALYSIS OF THE AISI D2 STEEL STAMPING TOOLS LIFE THROUGH THE APPLICATION OF PVD COATINGS

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Abstract. *The use of titanium nitride coatings (**TiN**), applied by Physical Vapor Deposition (**PVD**) has shown a significant increase in the several areas of the industry where there is friction. The following study analyzed how this type of coating influences the process of tool tip wear down, with the intention of investigating how the punch tools life, used for making holes in thick sheet of metals can be increased. Therefore to make some tests, two groups of punch tools and dies were manufactured in **AISI D2** steel. Two of them were thermally treated (hardened and annealed) and the other two, besides the thermal treatment, were **PVD** coated with **TiN**. The tests were made by punching holes in laminated sheets of **LNE600 (NBR 6656)** steel **7** thick using an automatic hydraulic press. The obtained results showed the great benefit of using this type coating and the life of the tools increased **60**% in relation to the punch tools without the coating.*

Keywords: *PUNCHING, TOOL STEEL, PVD COATING, WEAR*

1. INTRODUCTION

The use of the stamping tool process to make holes has recently been encouraged because of its high productivity and low cost. The stamping tool set used is composed of punch and die, and the punch tool is always responsible for determining its life (Brito, 2004).

The life of the punch tool is shortened mainly due to its wearing downcaused by the friction against the punched material. According to the standard **DIN 50320**, the progressive loss or wearing down of the solid surface of a solid body is caused by mechanical action, contact and relative movement against a solid, liquid or gas body. Tribologic action is the name given to the action on the surface of a solid body for contact and relative movement against a solid, liquid or gas body (DIN 50320, 1979).

For the systematic analysis of the wearing process, the components and the substances that participate directly of the process should be physically separated from the considered equipment. The components and the substances that participate directly of the wearing process are called elements of the tribological system. These elements along with the tribologically relevant properties and their mutual interactions form the structure of the tribological system. For the tribological system the punch tool is the body, the die is in the adjacent environment, the air is in the interfacial environment and the metal sheet is the workpiece, according to the Figure 1.

According to the **DIN 50320** standard (DIN 50320, 1979), four essential mechanisms of wearing exists: adhesion, abrasion, contact fatigue and tribochemical reaction. The adhesion depends on the physical and chemical properties of the materials in contact, magnitude of the applied force, besides surface roughness and contamination (Frisch, 1981). The material surfaces are not perfectly flat and, therefore, it contains reentries so that the contact between them only happens in a few points. Therefore, the real area of contact is a fraction of the apparent total area, turning the developed stresses in these areas very high, is able to even cross the limit of the yield stress of the material (Kalpakjian, 1995). The abrasion of tools is caused by the mechanical interaction of rough saliencies or even by metallic particles against the work surfaces, which results in a microcutting mechanism (Kalpakjian, 1995). The tool wear due to contact fatigue is characterized by the formation of cracks caused by cyclical loads applied to the surface. The tribochemical wear is characterized by friction between two solid surfaces, which causes the formation and continuous removal of the reaction layer in the contact surface (Kalpakjian, 1995).

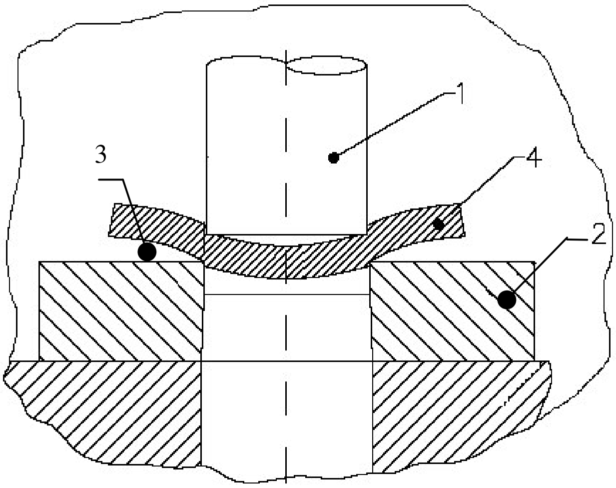


Figure 1 – Tribological System of the Stamping Set: (1) body, (2) counterbody, (3) interface and (4) workpiece. (DIN 50320, 1979)

A demand for more wear resistant components has been increasing interests in developing alternative processes of improvement tribological and tribochemical surface properties (Pinedo, 2004). In order to reduce the effects caused by tool wear, coatings are used broadly in processes with the presence of severe friction forces. Nowadays, the process of Physical Vapor Deposition (**PVD**) is more used for coating due to better thickness control, to propitiate the deposit of layers of different materials and even with different concentration levels along the deposited thickness (Brink, 1998). In this study the results of the application of titanium nitride (**TiN**) coatings are presented for punch tools of steel **AISI D2** used in punching holes in steel **LNE600** sheets with the objective of identifying the benefits of this protection for the tool's lifespan.

2. EXPERIMENT

Two sets of punch tools and dies were manufactured in **AISI D2** steel by machining process and subsequent polishing to the value of **0.19µm** average roughness **Ra**. Roughness was analyzed through a bench Perthen - I Model **S8P** roughness equipment, mechanical contact with tip radius of **10µm** without skate (**FRW 7So model**). This measurement happened before and after the application of TiN coatings, only on the tool's tip. Soon afterwards the tools went to the thermal treatment. For thermal treatment a controlled atmosphere furnace was used. The pieces were positioned in the furnace at room temperature; the heating rate was of **250°C/h**. The homogeneity was reached at **600°C** and the time of permanence used to guarantee the temperature in the whole microstructure was **1 hour**. Then the austenitizing was done at **1150ºC** with **15 min** flooding time in order to guarantee the complete modification of the steel structure. The cooling of the pieces was done through the air, until they reach **60ºC**. The tempering temperature was **550ºC** for **45min**, followed by air cooling. With the tools, a circular sample of **40mm** in diameter, made with the same material, followed the same heat treatment.

The hardness of the punch tools and dies was performed in a Rockwell C tester**,** using a hardness test equipment Officine *Galileo* on the external surface of the punch tools. Three hardness measurements were made for each one of the punch tools analyzed. These measurements happened before the application of the **TiN** coating and the average value was **59 ± 2 HRC**.

After the hardness measurement, the punch tool and die set and the specimens used for tests were taken to **PVD TiN** coating at BRASIMET INDÚSTRIA E COMÉRCIO LTDA, located in the city of São Paulo-SP. Vapor generated by electron beam was used. Punch tool, die and a sample plate were covered at the same time. First, they were cleaned for ultrasound process, mounted in the camera and received one more cleaning with inert gas (argon).

The parameters used were:
- Substrate temperature = 450°C
- Deposition time = 1.8 hours
- Pressure inside the camera = 18 x 10^{-4} mbar
- Mixes gaseous = 50 % C_2H_2 + 50 % N_2
- Entrance flow = 200 cm^3/min
- Current = 180 A.

The stamping tests were performed at DANA INDÚSTRIAS LTDA, located in the city of Osasco-SP. The manufactured pieces were truck side rails made with **LNE600** steel **7mm** thick. In this side rails the punch tools were tested in real conditions of production. The equipment used for punching was a Computerized Numeric Control (**CNC)** *Beauty* punch machine, with capacity of **50 tons**. Tests parameters used were the same as the normal ones of production which are: punching speed of 25 **mm.s^{-1}**, punching force of **30** tons and without lubrication.

The punch tools have a diameter of **15.9mm** and in relation to the die, a clearance of **12%** was left to produce the best superficial finish of the holes and longest life (Faria and Beltrão, 2004). Tool tips have convex forms. Figure 2 shows the two punch tools with convex tips, being P1 punch tool with **TiN** coating and **P2** punch tool without coating. The average lifespan for this punch tool type is **15,000** holes. The criteria of lifespan used in the test were: the minimum diameter of the punched hole smaller than **15.7mm**, the deformation of the hole larger than **0.3mm** and finally, the circularity of the hole larger than **0.3mm**. If none of the above criteria are seen, the noise level generated in the working area will be used as a criterion to end of the punch tool life for safety reasons.

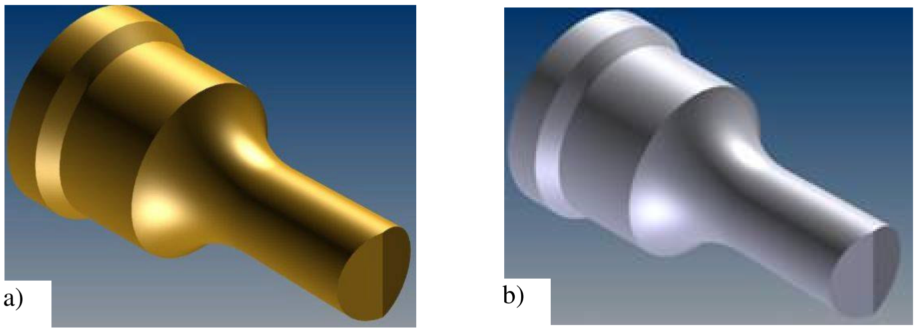


Figure 2 – a) Punch Tool **P2** (with **TiN** coating) and b) Punch Tool **P4** (without **TiN** coating)

Punched specimens of **LNE600** were analyzed after **1,000** holes. An example of the steel strip obtained during process is presented in Figure 3.

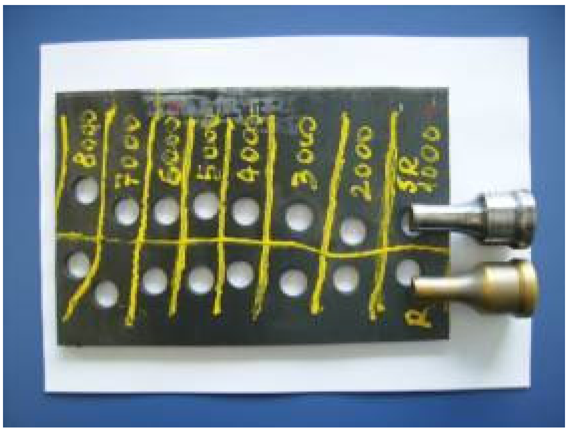


Figure 3 – Example of a Punched specimens

Indentation tests were made on the surface, with the objective of evaluating the **TiN** layer adhesion to the **AISI D2** steel substrate, according to the **VDI 3198 standard** (Vidakis et al, 2003). A Rockwell C indenter with a diamond tip radius of **0.2mm** and load of **150Kg** was used. The images of tested surfaces were obtained by an optical microscope model **84342 - Neomet** Union. The same microscope was used to evaluate **TiN** coating thickness, measured in a cross-section of the specimens. For these measurements, **Onimet** software was used.

The circularity (difference of maximum and minimum diameters) and the minimum diameter were measured by a portable Romer model **ARM100 serie 712** three-dimensional machine, to evaluate the quality generated in the holes.

The specimens with punched holes were cut obliquely for the verification of the hardness variation, imposed by the punch tool penetration in the raw material (work-hardening). Before the measurements were taken a 3mm deep cut was made. The measurements were made starting from the border of punch tool penetration towards the sheet material, presented in Figure 4. The measurement of the Vickers micro-hardness (**HV**) was performed in a **MVK-G2** Mitutoyo tester using a load of **1Kg.**

In punching operations, the first step of the cutting process is the punch tool compression of the work piece to produce part of the surface deformation. If the deformation is high, the quality of the hole is not acceptable. The plastic deformation was measured through the deformed area of the holes produced by punching (round area in the punched border). The measurement was made with a Mitutoyo manual vernier caliper after the traverse cut of the specimen, with the aid of a magnifying glass to facilitate the visualization of the beginning and the end of the deformed area.

After punching tests, images of the worn surfaces were obtained in a Zeiss **SEM 725 DSM 940** Scanning Electron Microscope (**SEM**). Thus, the wear mechanisms of punch tools and the fracture analysis were performed, which could occur during the tests of long duration for the convex punch tools.

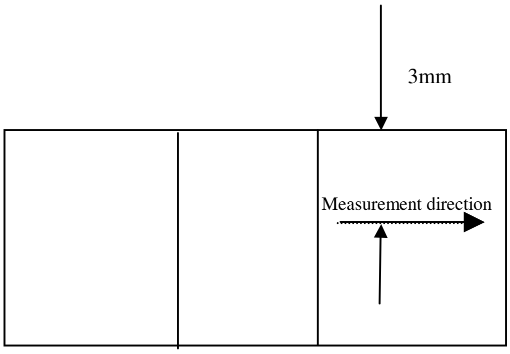
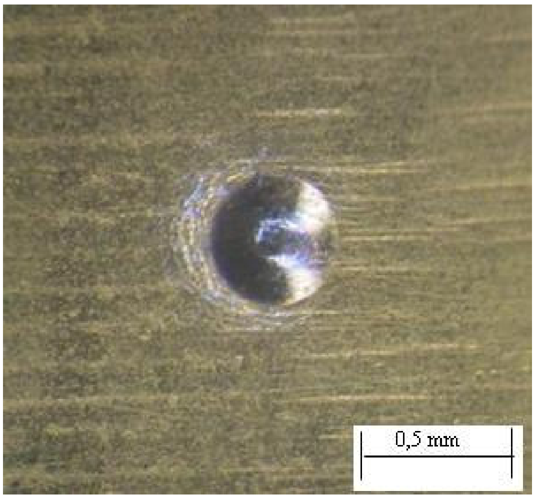


Figure 4 – Measurement positions for Vickers micro-hardeness tests

3. RESULTS AND DISCUSSION

3.1. Characterization of the TiN Coating Adhesion to AISI D2 Substrate

The objective of this test was to observe the **TiN** film adhesion to the substrate of **AISI D2** steel. Thus, the related subsequent studies of the **TiN** layer can be validated. The Rockwell C indentation marks magnified **50** times in a coated specimen are shown in Figure 5. The accumulation of coating on the impression side can be observed, and that caused layer detachment. Following the **VDI 3198** standard, this result can be considered as **HF4** level, an acceptable level for industrial applications. Figure 6 shows a cross-section of the specimen for **TiN** coating thickness visualization, and this value was about **1μm**.



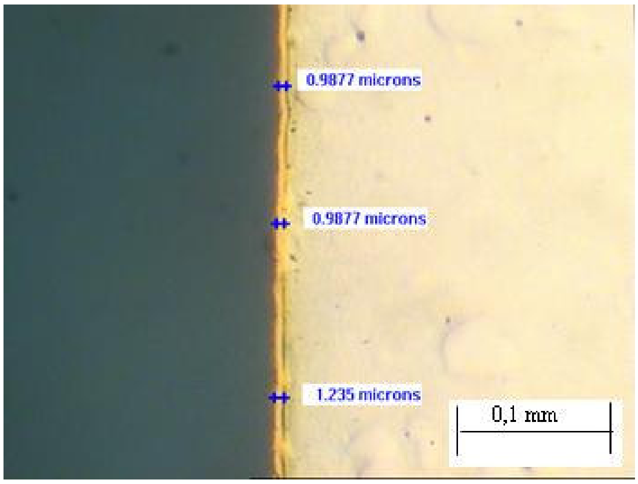


Figure 5 - ***Rockwell*** C Indentation mark onto **TiN** coating**.**

Figure 6 – Cross-section of **TiN** Coating, showing its thickness.

3.2. Tool life

The average punch tool life used in this type of operation (punching holes of **15.9mm** of diameter **7mm** thick in sheets of **LN600**) is about **15,000** holes (data obtained from Dana Indústrias Ltda). The convex punch tools with and without **TiN** coating (**P2** and **P4**) were:

- Punch Tool **P2**: 22,000 holes
- Punch Tool **P4**: 12,000 holes

The punch tool **P2** which reached **22,000** holes, had a considerable increase in life when compared with punch tool **P4**, which reached **12,000** holes. The punch tool's end was not driven by any of the three criteria (the minimum diameter of the printed hole smaller than **15.9mm** in more than **0.2mm**, the deformation of the hole larger than **0.3mm** and finally, the circularity larger than **0.3mm**). Usually, what causes the punch tool end of life is the lateral wear generated by the minimum diameter of the hole. The punch tool **P4** became useless, after 12,000 holes, due to the fracture that happened on its cutting edge. Probably, a micro-fracture, generated by fatigue, caused a catastrophic crack and that caused tool tip fracture. The punch tool **P2** was treated again due to the high noise, probably caused by the increase of the hole's border deformation and the metal chips in the scrap.

3.3. Minimum Diameter and Circularity

The diameter of punched holes tends to decrease with the increase of tool wear. For the control of this reduction, punched holes were measured. The minimum diameter condition for punched holes with increase of the holes number is shown in Figure 7. It can be observed that after **12,000** holes the decrease in diameter for punch tools **P2** and **P4** is just **0.03mm**. This shows that **TiN** coating does not influence the wear rate. Tool **P4** worked up to the **12,000th** hole and then broke.

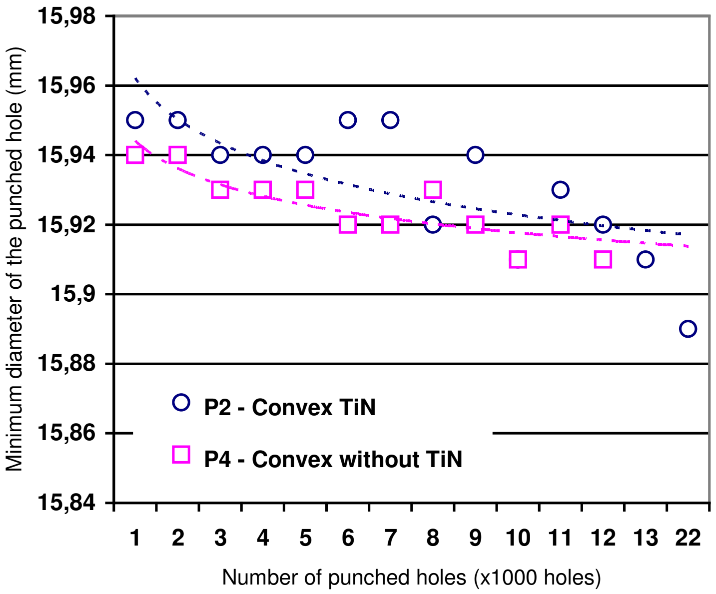


Figure 7 – Diameter variation of the punched holes in relation to the number of them

Tool deformation and wear**,** misalignments during assembly, machine instability among other factors could cause differences between minimum and maximum punched hole diameter and also affect the dies. This variation compared with number of holes can be seen in Figure 8.

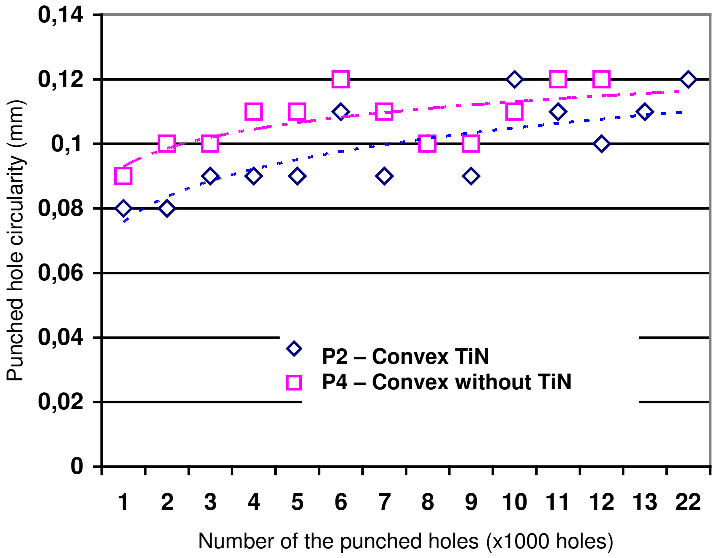


Figure 8 – Punched hole circularity in relation to the number of holes

3.4. Work-hardening analyzes

Punching holes is a process accompanied by plastic deformation in the work piece. A result of this plastic deformation is the work-hardening of the punched hole's borders as well as the scraps. The variation of the punched holes Vickers micro-hardness made by punch tools **P2** and **P4** and their distribution, starting from the cut border, in relation to the number of punched holes is shown Figure 9 and Figure 10, for convex tool with or without **TiN** coating, respectively.

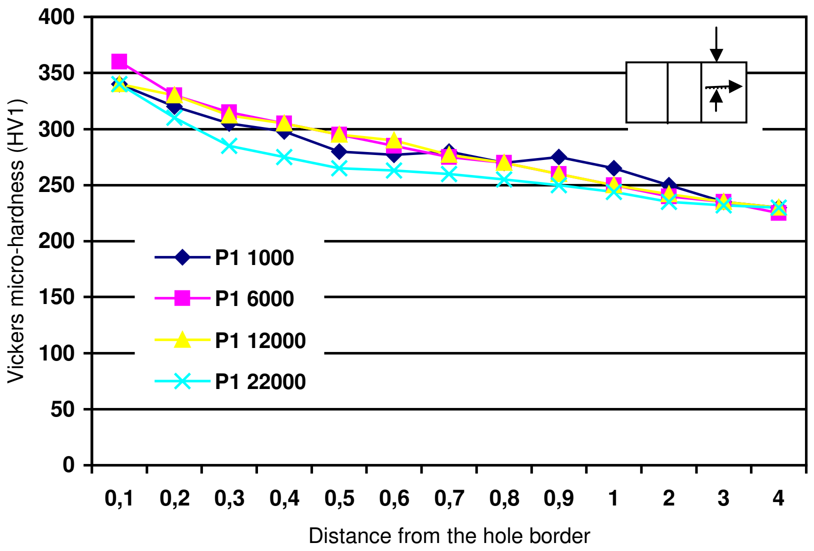


Figure 9 – Micro-hardness variation as a function of the hole border depth, for convex punch tool with **TiN** coating (**P2**).

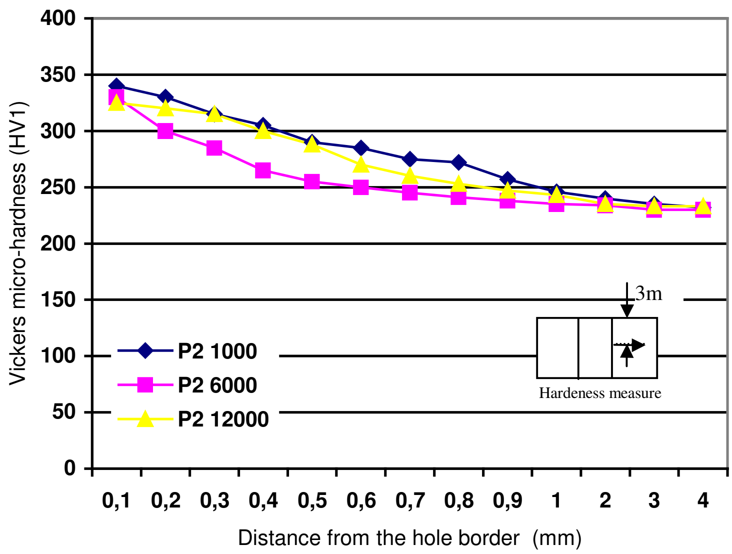


Figure 10– Micro-hardness variation as a function of the hole border depth, for convex tool without **TiN** coating (**P4**).

One can be observe micro-hardness values for convex punch tool with **TiN** coating (**P2**) has no significance larger than those obtained for convex punch tool without coating (**P4**). The micro-hardness next to the hole border presented higher values, dropping to raw material values (close to the **4mm**). This is justified, mainly, by the comparison from the **22,000th** punched hole **P2** curve to the **P4** tool curve. These values are similar due to the fact that **TiN** coating of the punch tool tip **P2** got worn down completely when it reached **22,000th** hole.

3.5. Deformation of the Punched Hole's Borders

In punching, the first step in the cutting process is tool compression against the work piece to produce surface deformation. If the deformation is high, ex. **1 mm**, the quality of the hole is not acceptable. The variations in the border deformations of the holes when using convex tools with and without **TiN** coatings are shown in Figure 11.

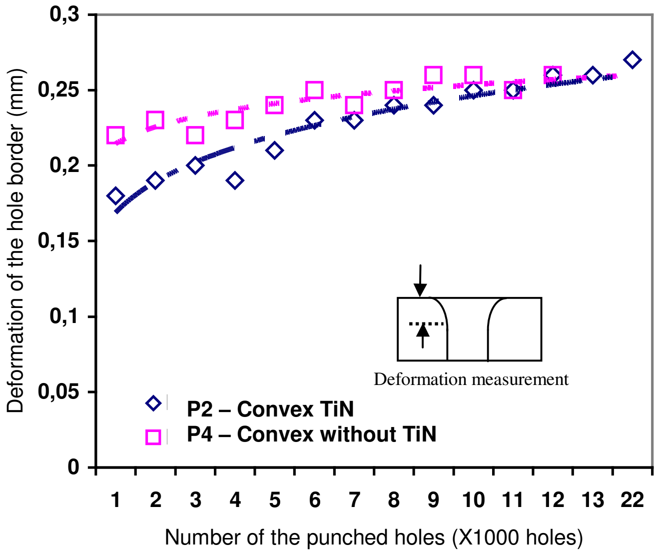


Figure 11 – Punched hole border deformation for tools **P2** e **P4**.

3.6. Side Wear

Usually the axial cutting force is high in punching processes. This makes tool side wear down during punching. In Figure 12 it is possible to see a convex tool side without **TiN** coating (**tool P4**) and in Figure 13 convex tool side with **TiN** coating (**tool P2**). Tool **P4** presented lateral wear due to mechanical adhesion mechanism or to the welding of cut material's layers in punch sides. This mechanism will progressively increase the friction force and that can cause micro-fractures in tool sides. This is the typical tool wear due to adhesion, and the sequence of this mechanism can lead to the abrasive wear. In that case once the material's layer adhered to the tool it can be detached. For tool **P2**, only lateral wear of the coating can be observed due to abrasion (micro-ploughing), without adhesion or material welding, this confirms the benefit of **TiN** coating, although there was a wearing down of the cutting edges. Therefore, the combination of cyclical loads and abrasion wear are the causes of tool lateral wear**,** which reduces the nominal hole diameter and increases the clearance between punch and die.

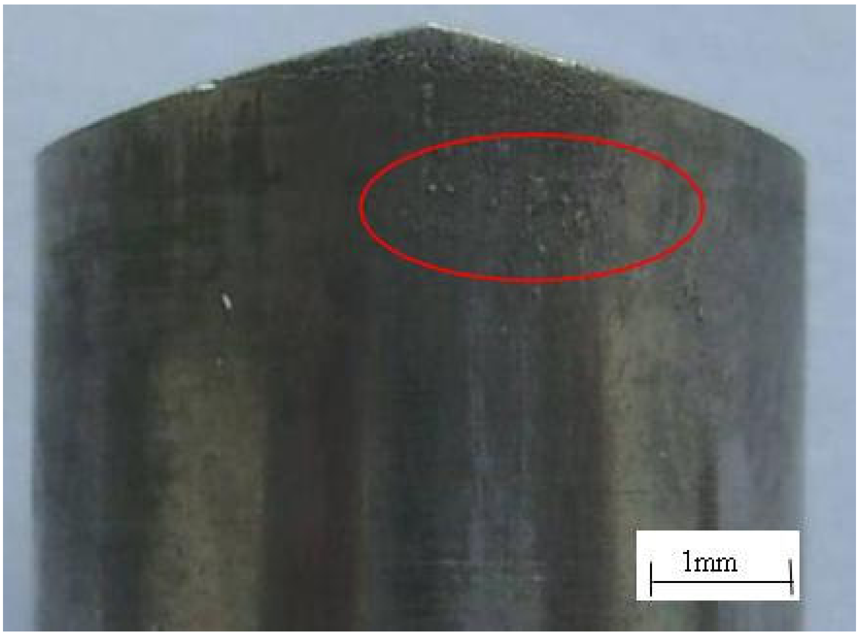


Figure 12 – Lateral Wear of the Punch Tool **P4**.

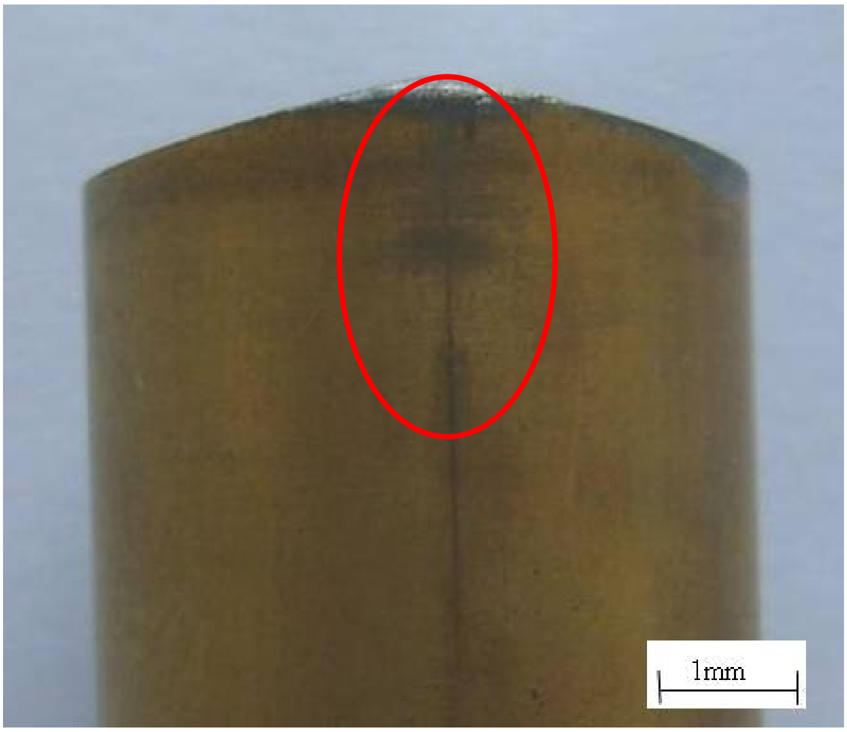


Figure 13 – Lateral Wear of the Punch Tool **P2**.

3.7. Tool Flank Wear

The main consequence of this type of wear is the rounding of the tool cutting edge. The failure mechanism shows how small crushed fragments could fracture and break the tool's cutting edge, producing micro-fracture and abrasion as shown in Figure 14. The main causes of this fact are loading cycle during punching operation and also large thermal variations of the tool. The consequence is the deformation of large areas of the hole. Machining marks, originated from production process, can facilitate failure by cracking. The two punch tools analyzed presented this failure.

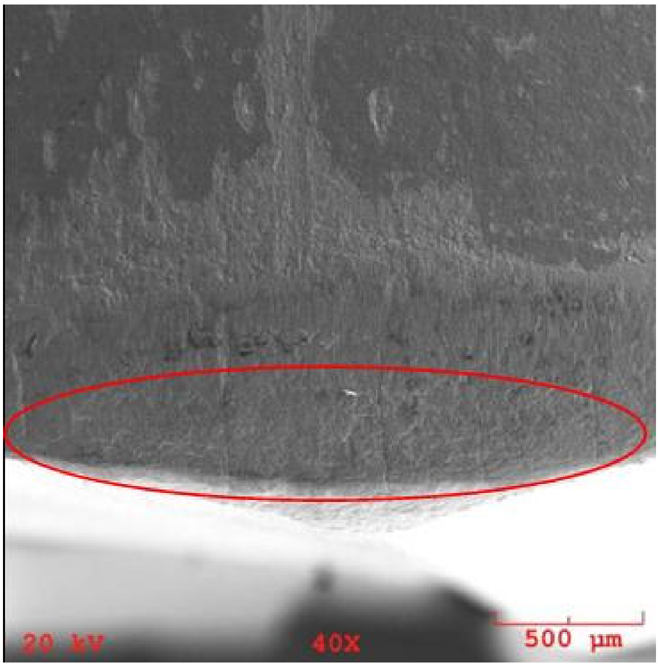


Figure 14 – Cutting Edge Micro-cracking (abrasion). Punch **P2**.

Another failure observed was fracture caused by fatigue mechanisms. This happened only for convex tools without **TiN** coating (**P4**), and it was probably caused by friction forces. Figure 15 shows fracture in punch **P4**. Such edge morphology directly affects cutting forces, changing punching conditions. The fracture was begun with cracks, which were currently generated by mechanical and thermal fatigue inherent to the punch process. When these cracks spread, fracture flaws could appear leading to a tool segment fracture.

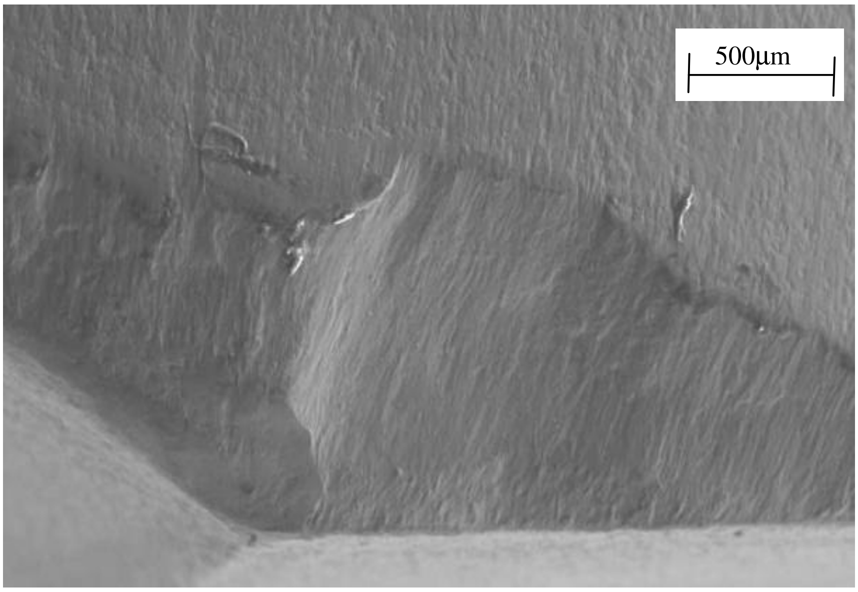


Figure 15 – Cutting Edge Fracture in tool **P4**

4. CONCLUSIONS

The deposition of **TiN** layers for **PVD** was successful for the steel **AISI D2** substrate, quenched and tempered and with average roughness of **0.19µm Ra**. It was about **1µm. TiN** coatings did not show significant influence on the decrease of the punched hole´s diameters or in the difference among the largest and the smallest diameter of these holes with the increase of holes punched. The Vickers micro-hardness of the punched hole borders was no larger for the convex tools with **TiN** coatings than tool without that. The deformation of the hole's border became larger for the convex tools without coating. However, the convex punch with **TiN** coating had a larger increase, due to the **TiN** wear.

There was adherent material in convex tools without **TiN** coating. For the convex tool with **TiN**, only the **TiN** layer wear down was noticed, making the benefit of this type of coating evident. Micro-cracks were observed in both of punch tools studied in the final tests. Only the convex tool without **TiN** coating presented fractures on the cutting edge. The convex tool without **TiN** coating had a lifespan of **12,000** holes, limited by edge fracture. The convex tool with **TiN** coating had a lifespan of **22,000** holes limited by the noise generated during its use. There was proof of the **TiN** coating benefits when applied to **AISI D2** steel punch tools.

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