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LIGHT CARDBOARD PRODUCTION PROCESS AND CUTTING TOOL LIFE IMPROVEMENT

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Abstract:
This paper carries out results from our research in order to improve the performances of the cutting tools intended for cardboard blanking for the production of light cardboard packing products. For this purpose, in our research, it is develop a methodology for prolonging the cutting tool life by two methods: coating (sputtering of thin film or physical vapor deposition) and ionic implantation. In the same time, it is realized an analysis of the significance of the influencing factors on the durability of the cutting tools because this influences directly their performance in the manufacturing process.

Key Words: Cutting Tool Life, Coating, PVD, Ionic Implantation, Cardboard Blanking

1. INTRODUCTION

In production conditions, the material and the geometrical-stereo metrical configuration of the cutting edge are the biggest influencing factors regarding its resistance to wearing out and consequently tool life durability. The materials for the production of the cutting tools are continually improved [3,10,11]. A part from sintered carbide as the most widely used material, other technologies such as coating, ceramic materials, sialon, industrial diamond and cubic bore nitride, are also coming into use.

The cutting tools, applicable on modern CNC machines for folding carton and cardboard product industry, are based on the following constructive solution: a set of cutting tools is mounted on a basic steel plate, according to previously designed contour with a CAD model.

- Basic plate in sheet steel with an intermediate epoxy resin layer and plastic type - creasing plate die board,
- Cutting tools for orthogonal cutting with geometric and stereo metric characteristics.

The technological features of CNC machines for this production process determine conditions in which the production is performed by orthogonal cutting that is significantly less appropriate than the oblique cutting with regard to the intensity of wearing out of the cutting edge [1,6,8].

This paper represents research for cutting tools life prolonging, from two aspects:

- Processing the cutting edges by two methods: coating (sputtering of thin film or physical vapor deposition) and ionic implantation, that are improved the surface hardness as well as its resistance to wearing out resulting in prolongation of tool life.
- Determination of the optimal operating conditions and machining parameters (cutting force, cutting pressure, cutting speed) for exploitation of the cutting edges, as significant parts from the cutting tool, with using of optimization methodology for selection of machining parameters.

2. SPECIFICATION OF THE ANALYSED CUTTING TOOLS

Working position of one set of the cutting tools for blanking cardboard for one product-RODEO blanket, around the contour, is shown in the Figure 1. The cutting tools and the product are from production line in the Macedonian printing company “Bato & Divajn”.

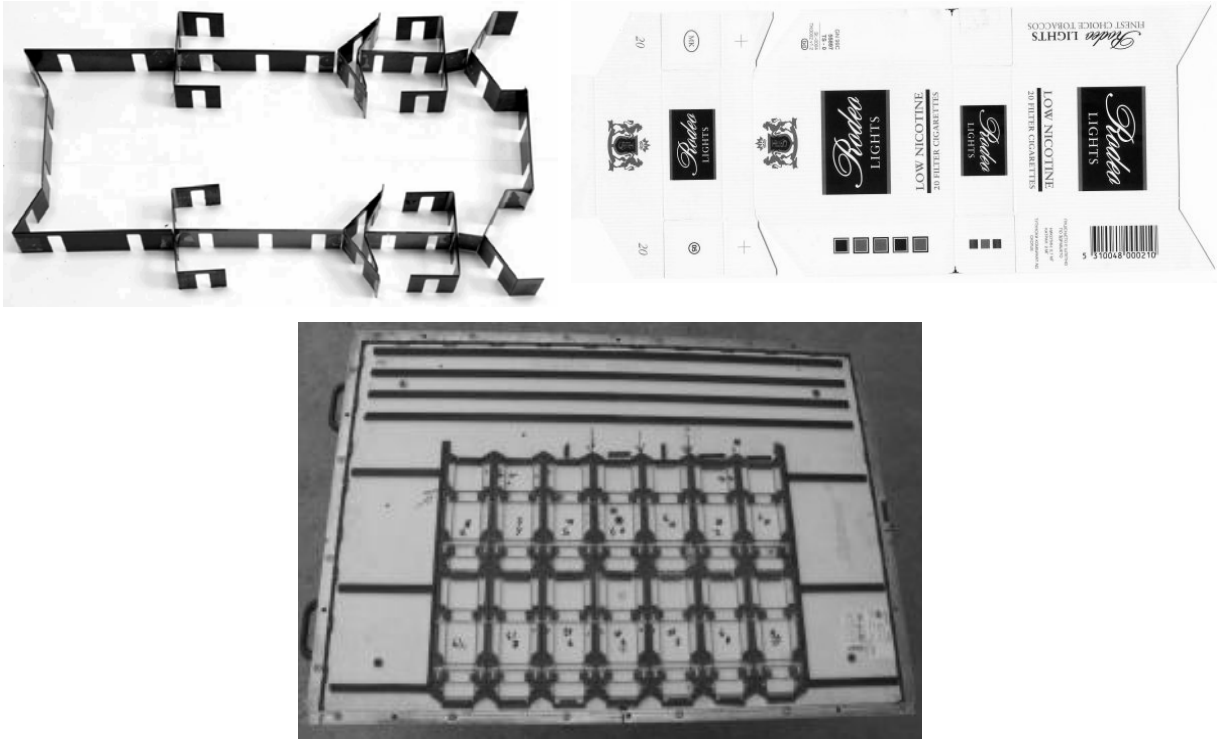
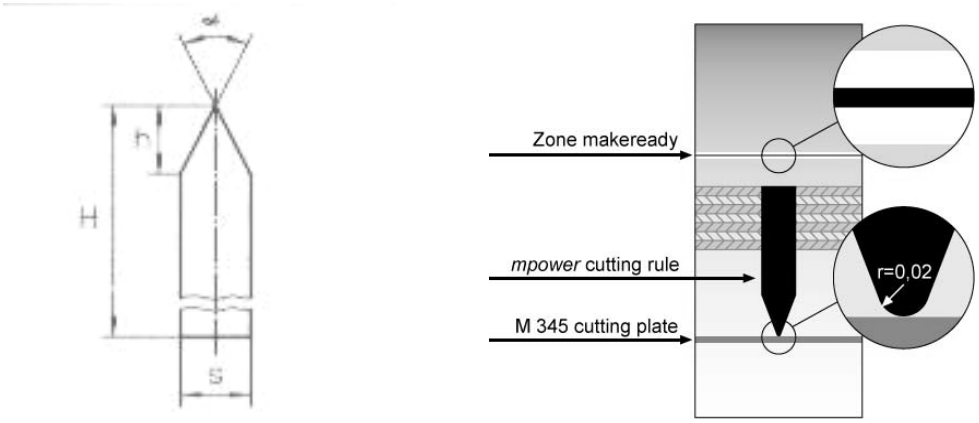


Figure 1: One set of the cutting tool and complete of the cutting plate with tools.

3. ANALYSING OF CUTTING TOOLS CARACTERISTICS USED IN CARBOARD PRODUCTION

Cutting tools use in the process for cutting the paper have the standard form shown in Figure 2, with basically geometric characteristics: angle $a=52^o$ and width $s=0.71$ *[mm]*.



a) Elementary cutting tool b) Cutting tool on the cutting plate

Figure 2: Geometrical form of the cutting tool.

For detected the chemical and mechanical characteristics of the cutting material and recognized the microstructure, it is made these analyses in the Institute for Technical Control in Skopje.

I. Chemical analysis done the follows parameters:

- Material of the cutting tool is tool steel Ck45 (DIN) or C1531 (JUS),
- Chemical structure is done in the Table I.

Table I: Chemical structure of the tool's material.

Chemical structure									
C%	Si%	Mn%	P%	S%	Cu%	Al%	N%	Cr%	Ni%
0.45	0.23	0.82	0.009	0.005	0.03	0.034		0.15	0.03

II. Microstructure test report done the microstructure/morphology results detected by electronic microscope. In the report, it is done the scanning electron micrographs showing the material structure (Fig. 3).

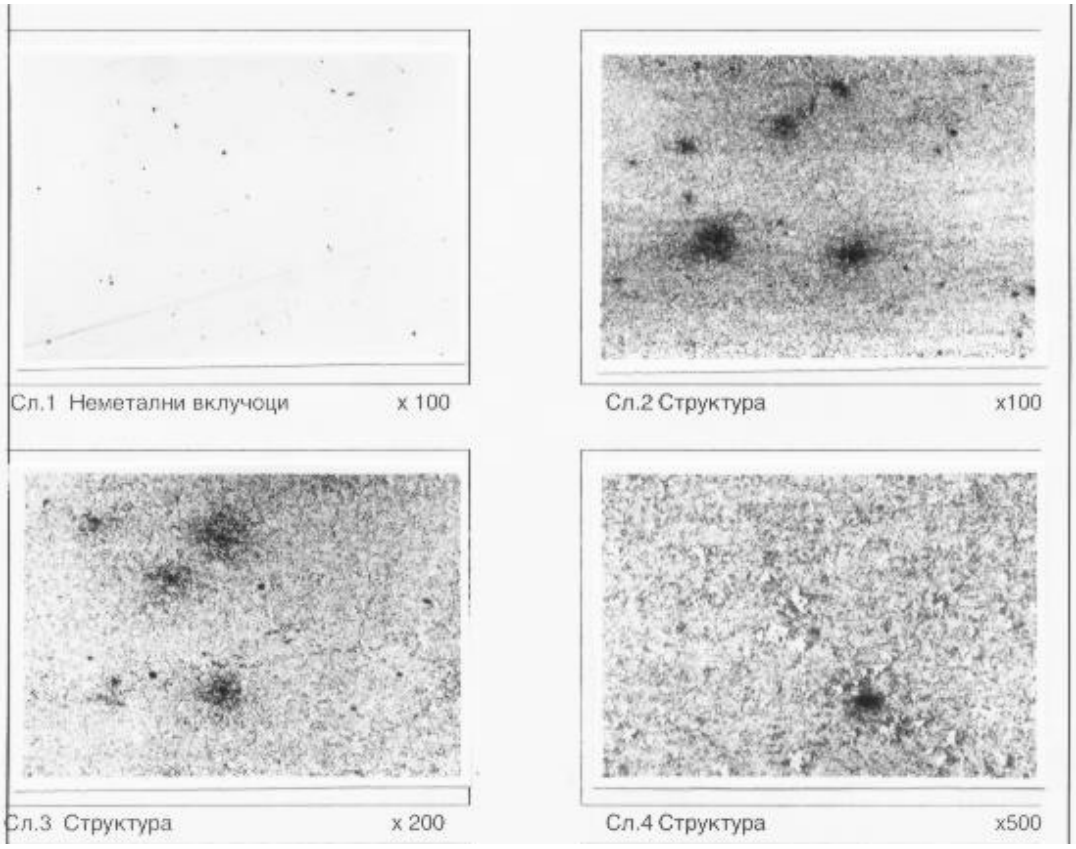


Figure 3: Microstructure test report.

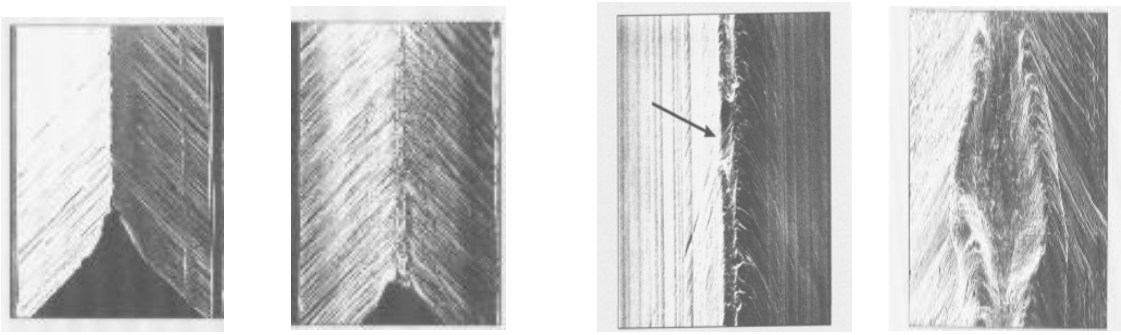
III. Mechanical test report done the hardness of the cutting material (with using of diamond sphere hardness measurement), Table II.

Table II: Mechanical test for cutting material.

	Rockwell	Brinell	Vickers
Hardness	109 HRB	311 HB	316 HV

4. CUTTING TOOL WEAR

In the cutting process, the cutting tip penetrates into the material in order to separate it. There is intensive contact between the metal surface of the cutting tip and the material being cut. Here the geometry, structure and surface material of the cutting tip play a major role as wear factors. Similarly, the material, type of carton, cardboard, the composition of the material, carton density and quantity of fillers also determine the wear. The cutting tip of the unused tool shows a very uniform cutting tip contour with minor irregularities on the surface (Fig. 4.a). After the use, wear as a significant factor is destroyed the cutting tool (Fig. 4.b).On the Figure 4.b), it is showed the microscope view of the main types of cutting tip wear.



(Magnified 100:1) (Magnified 100:1) (Magnified 500:1) (Magnified 1000:1)
a) Cutting tool edges before use b) Cutting tool edges after use

Figure 4: Cutting tool edges before and after use.

The process “wear” is an extraordinarily complex issue. In the die cutting sector have the “wear” complex as an abrasion phenomenon, adhesion phenomenon, tribo-chemical reaction, surface destruction etc. Fig.5 shows the main mechanisms, according to which abrasion phenomenon is dominated in the die cutting sector.

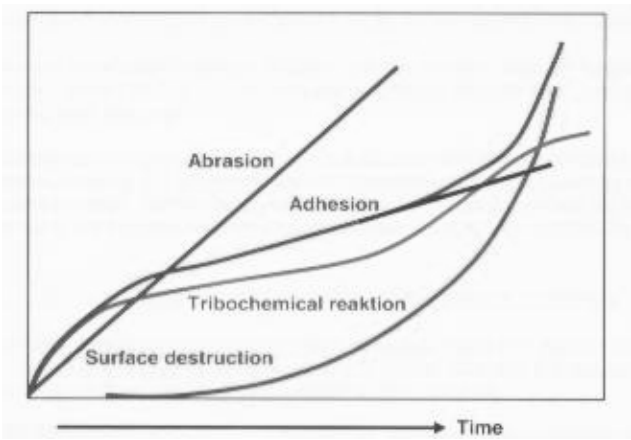


Figure 5: Linear extent of wear as a function of operating time for the main wear mechanisms.

5. APLYED METHODOLOGY FOR CUTTING TOOLS COATING

In order to improve the cutting tool for cardboard blanking, the increasing has been made according to two methodologies for cutting tools hard thin coating layers:

- PVD-physical vapor deposition and
- Ionic implantation.

The demand for cost efficiency in production and the development of new products ranging widely in complexity, material composition, size and surface finish have required industry to develop new cutting materials and to adopt new machining strategies for optimization of the production process. The cutting tools are the key of every industrial production [4,5,6]. The tool price usually presents a sizeable share in the product end-price; therefore it is important to enhance the tool lifetime and productivity. The first way is the proper tool material choice. Generally this includes various tool steels and hard metals, whereas in the last year the ceramic and composite materials have been implemented. In the cardboard blanking process, cutting tools usually are made from tool steels.

Together with the development of the tool materials, the protective coatings have been developed as well. Their common feature is the protection of the tool by their high hardness and chemical inertness; however, they are relatively brittle and expensive so they are not appropriate for bulk tool material. The combination of bulk material and the coating ensures optimal tool properties. Due to their unique physical, chemical, thermo physical and mechanical properties, coatings, as a hard thin layers or ionic implantation layers, are already interpolated in the category of the advanced technology materials.

5.1. Advantages of the Various Hard Thin Layers Coating Techniques

The development of new cutting tool materials during the last few years is based mainly on sub micron hard metal substrates as well as new coatings techniques [3,9,10,11]. The development of sub micron and nano-powders with higher strength and higher fracture toughness solves problems in machining high-temp alloys, hard materials and in dry cutting. The development and industrial implementation of the hard protective coatings technologies for cutting materials, it is done with the CVD-Chemical Vapor Deposition and PVD-Physical Vapor Deposition techniques.

When using CVD process, temperature is about 1000°C and the pressure is relatively high. In this CVD process a relatively thick layer is produced (2 to 20 μm) made of various thickness and material combinations of carbides, nitrides and oxides. Each one of these layers provides good properties with respect to hardness, heat conductivity, toughness or adherence to the substrate. The coating sequence depends on the various properties of each material.

There are many PVD variants in use today (magnetron sputtering, evaporation by laser, cathode arc, electron beam etc.) [11]. Their common feature is the vacuum environment and the substrate temperature is relatively low, from 200°C up to about 500°C. This physical vapor deposition process can produce thin nitride layers with a coating thickness between 3 - 6 μm.

The most common hard coatings are based on transition metal nitrides (TiN, CrN), but in the last decade there has been a vast increase in multi-component coating (TiAlN), multilayer coatings (TiN/TiAlN) as well as carbon-based coatings (DLC). The newest generation is represented by nano-composite (TiN+DLC) and lubricating coating (WC+C).

The most important feature of the hard protective coatings is to reduce wear and in this way to increase the tool lifetime. So it is important to know which mechanism has the highest contribution to the wear (abrasion, adhesion, corrosion, high temperature, material sticking etc.) in order to find the most suitable coating for the desired process. A combination of certain coating properties opens possibilities for new technological procedures. Aside from the price reduction such a procedure of coating is superior from the ecological standpoint. The hardness of the various coating-layer compositions is improved then the basically cutting tools. The hardness of TiC is the highest, TiAlN and TiCN are very high, reaching between 2500 to 3000 HV. The TiC layer with the highest hardness improves resistance to mechanical wear. The disadvantage of TiC layer is the lower chemical stability and the higher friction coefficient.

5.2. PVD - Deposition for Cutting Tools Coating

During the solving the problem with cutting tools in production process in Bato&Divajn Corporation, there have been realized experimental protective coating to apply as a solution for improvement of cutting tool life. Therefore, it has realized mechanical properties analysis for the basic cutting tool material (as a substrate) applied during the blanking cardboard with influence of various parameters (coating thickness, substrate hardness, proceeding treatment etc.) on micro-hardness, adhesion and internal stress. Of special interest was the crack appearance and the coating failure linked to it.

In all kinds of thin films the diffusion processes play a major role, especially at the boundary film-air (oxidation, corrosion) and substrate-film (diffusion of substrate elements into the film and reverse). These processes are made at different temperatures, where it is done the changes of the concentration profile and crack appearance.

After preliminary analysis, we have decided that optimal type of coating for analyzed cutting tool material is thin film of metal nitride TiN, with follows characteristics:

TiN characteristics: • Material: titanium nitride • Color: gold • Thickness: 1-4 μm • Micro-hardness: 2300 $HV_{0.05}$ • Deposition temperature: 200-450^{0}C	
The coating is suitable for the protection of: • Cutting tools for machining of non-alloyed steels • Tools for cold forming of metals • Tools for extrusion of plastics • Die-casting tools	

The hard coating process for the cutting tool analyzed in this project, has been made with PVD technique using device for deposition in Jozef Stefan Institute, Laboratory for coating techniques, Ljubljana, Slovenia (Sputtering apparatus Ceme-Con CC800/7, produced in Germany, showed on Figure 6). The principle of the device operating is sputtering with four unbalanced magnetrons. The vacuum system has two stages (rotary and turbo molecular pump), which enables the base pressure of $2 \cdot 10^{-6}$ mbar. The working pressure during deposition is $1\text{-}2 \cdot 10^{-3}$ mbar. The technological procedure has three stages: heating by infra-heaters, ion etching (cleaning) and deposition of the coating. The procedure is entirely computer-controlled for every deposition.

Figure 6: Sputtering apparatus Ceme Con CC800/, Jozef Stefan Institute, Slovenia (maximum dimension of tools: 400mm x 400mm x 300mm).

The deposition of thin film, over the substrate as a cutting tools analyzed in experiment, was made on the deposition temperature 200°C, in accordance with material characteristics of the substrate. Figure 7 shows one cutting tool for cardboard blanking with coating thin film from TiN. On the Figure 8, it is presented cutting plate with assembled TiN coating cutting tools.

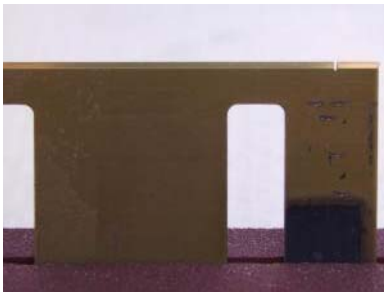


Figure 7: Coating cutting tool with TiN.

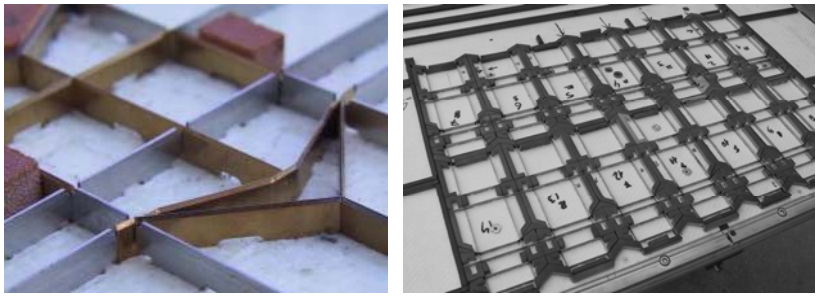


Figure 8: Assembled coating cutting tools.

5.3. Ionic Implantation for Cutting tools Coating

Ionic implantation is a relatively new methodology for cutting tools processing, using the atoms of nitrogen and their implanting in crystal structure-grate of the tool material, with out of deposition of hard thin layer. Implantation is a methodology for improvement of the mechanical characteristics of the basic material.

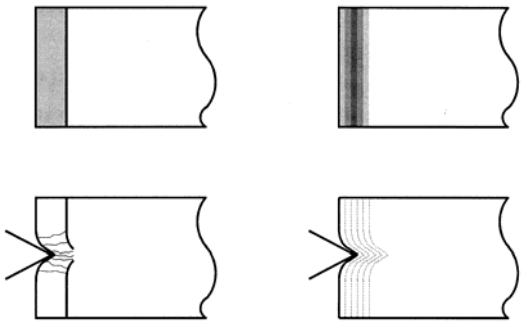
During the ion implantation process the surface is bombarded with ions at very high speeds. The ions penetrate into the surface and stay in the outermost layer of the surface (Fig. 9). In this way a re-alloyed surface layer with outstanding properties is created.

Ion implantation can solve some of the most common durability and maintenance problems of tools and machine parts arising from: abrasive wear, adhesive wear, corrosion and fatigue. This process is a unique surface treatment for reducing wear, friction and corrosion. It can make tools and machine parts a few times longer.

With ion implantation, there is:

- No risk of heat induced distortion or softening
- No cracking or flaking of the surface layer
- No change of surface dimensions (Fig. 10) and surface finish.

Figure 9: Ions penetration into the surface.



a) Coating ting layer b) Ion implantation surf.

Figure 10: Change of surface dimensions.

Because of these unique features the ion implantation treatment can be performed on finished high precision tools and components even if extreme dimensional tolerances are specified.

Ionic implantation, as a process is realize in implanter, show on the Figure 11. The implanter equipment is an accelerator, witch have the following characteristics in order to address most of the industrial applications: gaseous and metal ions (*N, B, C, O, Ti, Cr* ..), energy range 100-200 keV, doses 2 to 5.10^{17} atoms/cm^2, beam currents 5 to 10 mA for a few hours processing time.

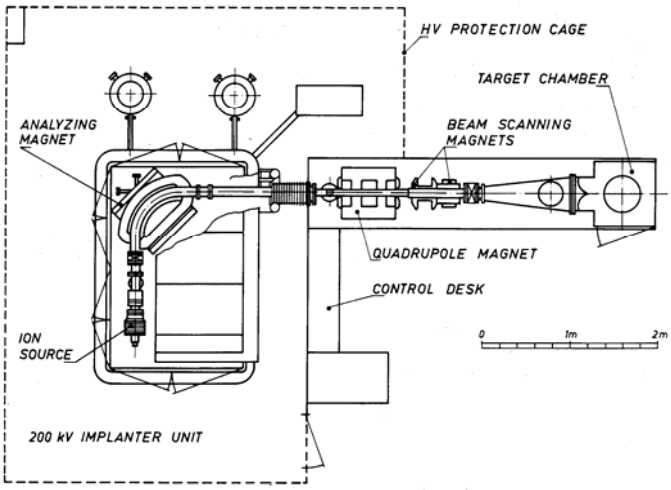


Figure 11: Layout of HIGH CURRENT IMPLANTER in the standard configuration.

The essential difference between ion implantation and other surface treatment is that it is not an “add-on” process, but the ions are embedded inside the surface layer without any dimensional change. The ion implantation process, over the cutting tools surface in our research, has made in the implanter equipment for industrial application. The process was made with nitrogen ions, energy range 200 keV, beam current 5 mA and doses 5.10^{17} [atoms/cm^2].

Ion implanted cutting tools for cardboard blanking have the same metal-gray color. Figure 12 shows one cutting tool for cardboard blanking with ion implanted surface. On the Figure 13, it is presented cutting plate with assembled ion implantation processed cutting tools.

Figure 12: Ion implanted cutting tool.

Figure 13: Assembled ion implanted cutting tools.

6. EXPERIMENTS WITH TiN-COATING CUTTING TOOLS AND IONIC IMPLANTED CUTTING TOOLS

In our research, the experiments had made as a testing of coating cutting tools in real production conditions, during the cardboard sheets blanking process.

Paper cutting process is checked during the production of one product in Bato&Divajn plant. The product was one type of blanket with 240.000 cardboard parts for cutting. It has

expected good quality of cutting blankets. Previously, in production process short tool life had done inferior quality of cutting blankets after a few cutting cardboard sheets (Fig.14).

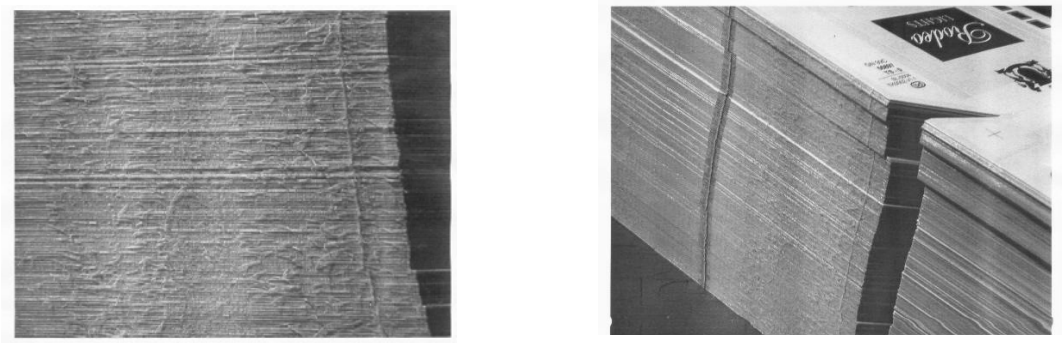


Figure 14: Dissatisfactory quality of cutting blankets.

Realisation of the experiments had made in the production process with the coating cutting tools (TiN coating tools with PVD-Physical Vapour Deposition and implanted tools with II-Ionic Implantation). Experiments are realised on the CNC machine JAGENBERG WPM 304, in the Bato&Divajn Corporation (Fig. 15).

Figure 15: CNC machine JAGENBERG WPM 304.

Figure 16: Results-cutting cardboard blankets.

Results, from this activity (Fig. 16):

- Increasing of the production process efficiency by lengthening the period of use until the replacement of the old tool with a new set.
- Increasing of the productivity as a result of the improvement of the tool performance i.e. the total number of cardboard sheets blanked with a single tool is increased.

7. DETERMINATION OF OPTIMAL OPERATING CONDITIONS

In the research [8], it is proposed the new technological solution with developing of the methodology for determination of the optimal operating conditions and machining parameters for exploitation of the cutting edges, as significant parts from the cutting tool. The methodology is developed with Mat LAB solver.

Determination of the optimal machining parameters is subordinate to many significant factors of the operating condition [1,2,4,7]. Machining parameters are direct depended by the many factors, as a:

- Type of carton or cardboard,
- Type and quantity of fillers,
- Condition in the working area (temperature, moisture, dust),
- Geometrical composition of the cutting tool plate with cutting edges.

Cartons are produced in two or three levels in accordance with application. When used fir surface finishing and for good printing characteristics, cartons are coated regardless of their composition. The coating has an ach content of up to 70%. In carton grades with high levels of waste paper, such as duplex or triplex cartons, the filler consisting of waste paper can also have ash levels of up to 16%. Considerably higher wear rates must therefore be expected in coated cartons. But pure cellulose cartons, for example in the weight class for cigarette boxes, also have a filler content of a good 10%, primarily carbonates.

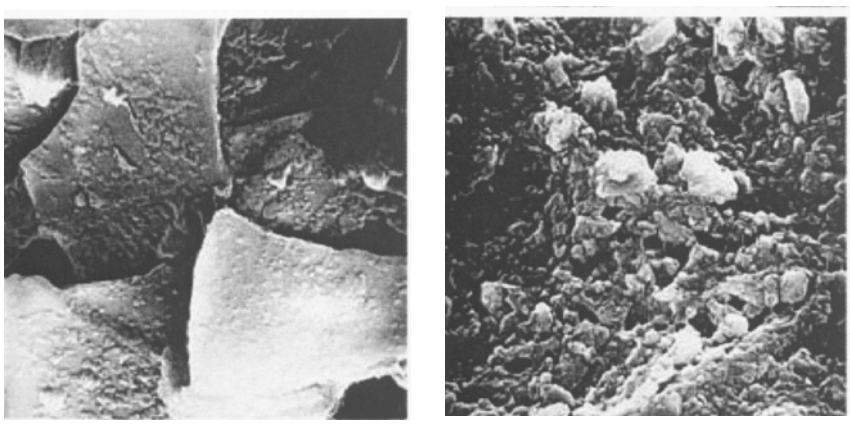
In the production processes in Bato & Divajn Corporation, for their products, usually it is used various coated cartons, as a follow types done in the Table III. The table summarizes the main data for describing the materials.

Table III: Characteristics of several types of used cartons.

Grate	1 GC2	2 ZS cast-coated	3 ZS in nass	4 ZS
weight [gr/m2]	240	232	240	230
thickness [mm]	0.35	0.27	0.30	0.29
density [gr/mm3]	0.66	0.88	0.80	0.80
Ash [%]	14.1	13.5	8.2	6.9

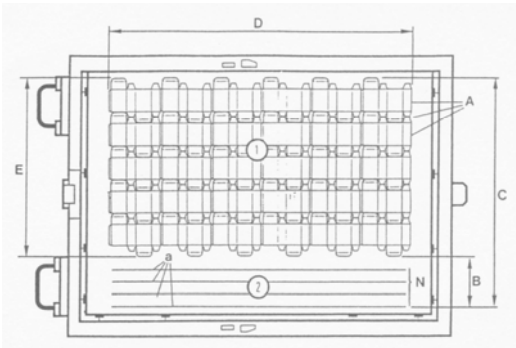
The experiments are made for one type of product (RODEO cigarette box), which is produced from cardboard 4-ZS done in the table. This type of cardboard is named EXEL-230 with weight 230 [gr/m^2], thickness 0.29 [mm], density 0.8 [gr/mm^3] and ash 6.9%. The results are usable for many types of cartons for cardboard products.

Fillers used in modern carton board in particular make a great contribution to wear. Fillers are mineral dust. They act as small abrasive particles. Their size, shape and hardness make up a crucial share of the wear rate. This increases with size, angularity and hardness of the grains. The following fillers are widely used: kaolin, a silicon/aluminum-oxide compound and calcium carbonate. At the lower end of Mohs' hardness scale, kaolin is relatively soft. By contrast, calcium carbonate is a sharp edged polyedric crystalline structure with hardness in the middle of the hardness scale, so that it is correspondingly harder with a more intensive effect on wear. Figure 17 shows the microstructure of kaolin and calcium carbonate types of fillers.

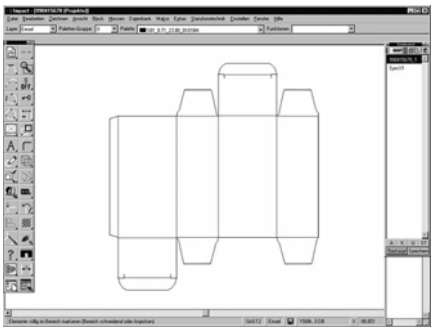


a) Kaolin b) Calcium carbonate

Figure 17: Type of fillers in cartons.



a) Cutting tool plate



b) Form of one blanket

Figure 18: Geometrical composition of the cutting tool plate with cutting edges.

During the realization of this research, it is developed method for determination of the optimal machining parameters for exploitation of the cutting tools in blanking process of cardboard products (Fig.18). Geometrical composition of the cutting tool plate is preparing by the computer solving of the cutting edges optimal order, following the blanket contour. Determination of cutting force in dependence of geometrical parameters of the cutting tool plate, as a significant factor for process making (Fig. 19), is solving with (1):

$$F = \frac{m \cdot B \cdot A}{E} [N] \tag{1}$$

Parameters	
F [N]	Cutting - blanking force
m	Coefficient depended of cardboard type
A [cm]	Sum of length of cutting rules (die-cutting)
B [cm]	Tool length of kerning
E [cm]	Tool length of blanking
D [cm]	Tool width of blanking
Z	Number of blankets on the cutting plate
N	Number of steaks for kerning *N=F/Z*

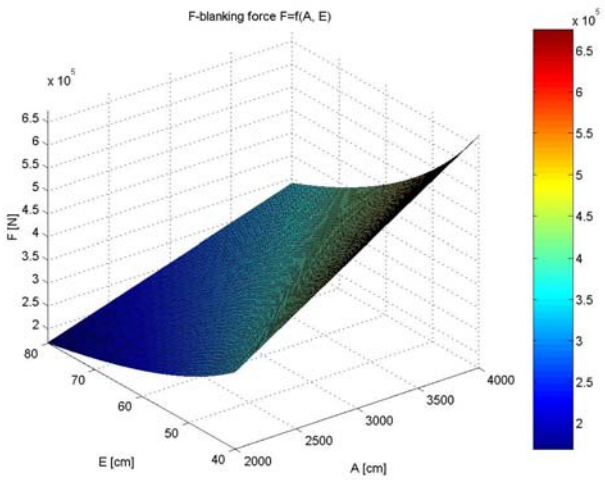


Figure 19: Diagram of cutting force dependence on geometrical parameters of tool plate.

For machining process made on the machine Jagenberg WPM 304, it is solved optimal machining parameters with developed method. For cutting force, it is solve next value, show on the Figure 20. Developed method for determination of optimal machining parameters is applicable for each machining process made on the analyzed machine in various conditions (type of paper or cardboard, configuration of blanket etc).

$$F = \frac{k \cdot B \cdot A}{E} = \frac{445 \cdot 14 \cdot 3456}{76.5} = 280000[N] = 280[kN] \tag{2}$$

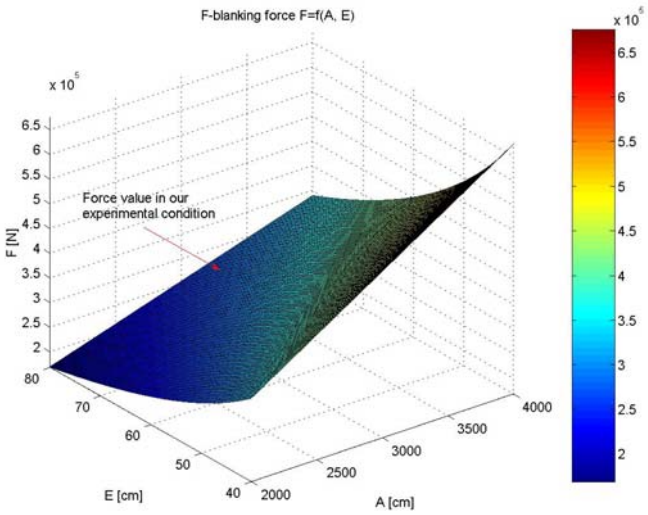


Figure 20: Diagram of cutting force in machining process with improved cutting tool plate.

8. COST-BENEFIT ANALYSIS

In this final report, it is done the complete:

By prolonging the tool life of the cutting tools, It is expected to have a direct influence on the improvement of productivity and the economy of the production process. The effective production (measured per number of items) was significantly enlarged, 2 to 6 times. This is become obvious by carrying out a cost-benefit analysis i.e. a cost estimate of the conditions incorporated in the real production process, where were made the experiments. Results from cost-benefit analysis in measurement value are done in follow:

- ***Extending of tool life*** of the cutting edges of the tool, by coating 2 times and by ionic implantation 6 times,

Tool life extension of the cutting tools	TiN coating cutting tools	Ionic implantation cutting tools
	2 times	6 times

- ***Increase of productivity*** as a result of the improvement of the tool performance i.e. the total number of sheets blanked with a one set of tool was increased. In measurement value, it is done the processed sheets with existing cutting tool compared by coating cutting tool and ionic implanted cutting tool.

Number of processed sheets with one set of cutting tool		
Existing cutting tools	TiN coating cutting tools	Ionic implantation cutting tools
40.000	80.000	240.000

- ***Increase in efficiency*** of the production process by lengthening the period of use until the replacement of the old set of tool with a new set. In measurement value: price of cutting tool (die plate with one set of cutting edges) is 12.000 €. Successively, max of four sets of cutting edges may be mounted on the basic die plate.
    - The price of one set of standard cutting edges is 800 €.
    - The price of coating of one set of cutting edges is 200 €.
    - The price of ionic implantation of one set of cutting edges is 350 €.

Total price of cutting tool	
Total price of standard cutting tools	$12.000 + 4 \cdot 800 = 15.200$ €
Total price of TiN coating cutting tools	$(12.000 + 200) + 4 \cdot (800 + 200) = 16.200$ €
Total price of ionic implantation cutting tools	$(12.000 + 350) + 4 \cdot (800 + 350) = 16.950$ €

- Efficiency of the production process, explicated by ***total number of sheets*** produced with one type of cutting tool (the basic die plate with four replaceable sets of cutting edges):

Total number of processed cardboard sheets with one type of cutting tool	
Existing cutting tools	40.000 (basic cutting tool) + 4 x 40.000 (new sets)=200.000 sheets
TiN coating cutting tools	80.000 (basic cutting tool) + 4 x 80.000 (new sets)=400.000 sheets
Ionic implantation cutting tools	240.000 (basic cutting tool) + 4 x 240.000 (new sets)=1.200.000 sheets

- ***Cost-benefit analysis*** done by direct impact of cutting tool cost in designation of cost for final product - one blanket as a produced item. During the cost-benefit analysis, it is solved cutting tool price participation-C_t, in the total price-C of each item (blanket), as a final product, and it is done:

Cutting tool price participates in the price per sheet (14 blankets)		
Existing cutting tools	PVD coating cutting tools (TiN)	Ionic implantation cutting tools
$C_t = \frac{15.200}{200.000} = 0.076$ €	$C_{tPVD} = \frac{16.200}{400.000} = 0.041$ €	$C_{tII} = \frac{16.950}{1.200.000} = 0.014$ €

- As a result, it is obtained ***ratio for decreasing of product price***, defined as:
  Ratio by PVD technology - k_{PVD}

$$K_{PVD} = \frac{C_t}{C_{tCVD}} = \frac{0.076}{0.041} \approx 2 \qquad K_{PVD} = 2$$

  Ratio by II technology - k_{II}

$$K_{II} = \frac{C_t}{C_{tII}} = \frac{0.076}{0.014} \approx 5.5 \qquad K_{II} = 5.5$$

9. CONCLUSION

Implementation of results from this research for the cardboard blanking manufacturing process, as well as an improvement of existing technology, by means of surface treatment and optimisation of condition, was enabled in one Macedonian company.

Expectation of direct influence of new solution, proposed in this research, into the improvement of productivity and efficiency of the production process is demonstrated as a justification. Implementation of II technology is superior compared by standard tool and tool coated by PVD technology. Therefore, k_{II} - ratio for decreasing of product price, by implementation of ionic implantation, has the maximum value.

For solving the total price of the product-blanket, it is calculated the influence of many parameters of the production process, as a prices of the paper or cardboard, printing, pre-press designing etc. In this research, it is done the result from economic aspect, as a reduction of product price by reduce the cutting tool participation in total price.

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