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Optimization of the ASPN Process to Bright Nitriding of Woodworking Tools Using the Taguchi Approach

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The subject of the research is optimization of the parameters of the Active Screen Plasma Nitriding (ASPN) process of high speed steel planing knives used in woodworking. The Taguchi approach was applied for development of the plan of experiments and elaboration of obtained experimental results. The optimized ASPN parameters were: process duration, composition and pressure of the gaseous atmosphere, the substrate BIAS voltage and the substrate temperature. The results of the optimization procedure were verified by the tools' behavior in the sharpening operation performed in normal industrial conditions. The ASPN technology proved to be extremely suitable for nitriding the woodworking planing tools, which because of their specific geometry, in particular extremely sharp wedge angles, could not be successfully nitrided using conventional direct current plasma nitriding method. The carried out research proved that the values of fracture toughness coefficient K_{Ic} are in correlation with maximum spalling depths of the cutting edge measured after sharpening, and therefore may be used as a measure of the nitrided planing knives quality. Based on this criterion the optimum parameters of the ASPN process for nitriding high speed planing knives were determined.

Keywords Active Screen Plasma Nitriding, high speed steel, process parameters optimization, Taguchi method, woodworking tools

1. Introduction

1.1 The Specificity of Wood Machining Tools and the Choice of Nitriding Technology

The specificity of machining conditions of wood and wood-derivative materials consists of simultaneous occurrence of several factors that contribute to intensive wear of woodworking tools. These are (Ref 1-3):

- application of very high rate of feed,
- extremely sharp cutting edges of the tools,
- intensive abrasive wear and high working temperature,
- low thermal conductivity and high anisotropy of mechanical properties of the machined material.

Low alloy and high speed steels are common materials used for planing and shaping knives fabrication. Because of the advantageous features of these steel grades, i.e., relatively low price and easy manufacturing of special knifes, e.g., very long, with extremely low wedge angles or with special complex shapes, they cannot be replaced in many applications by any other harder and more abrasion resistant material like stellites, carbides, or PCD (Ref 3, 4).

Research described in the paper concerns development of the nitriding technology of planing knives made of high speed steel (HSS) AISI M2. Most nitriding systems operate with the substrates maintained at cathodic potential. This technique is referred to as direct current plasma nitriding (DCPN). However, it is also possible to produce a nitriding effect while the substrates are separated from direct plasma, where active nitriding species are produced. Such a method is utilized in post-discharge nitriding and in the newest plasma nitriding technique—Active Screen Plasma Nitriding (ASPN) (Ref 5-9).

In the ASPN technology, developed by Georges (Ref 10), the high potential is applied to a mesh screen (cathodic cage) surrounding the parts to be treated. The ASPN technique is based on the general principle of post-discharge nitriding—plasma species are generated at the active screen and flow through it towards the nitrided substrates (Ref 5, 11, 12). Substrates are placed on the central worktable, which is insulated from the screen (cathode) and from earthed chamber walls (anode). Radiation from the surrounding screen heats the substrates to the nitriding temperature. Working gaseous mixture enters between the chamber walls and the screen and is ionized in the discharge operated on the screen. The produced plasma contains a mixture of highly energetic ions, electrons and excited neutral gaseous particles. The gas flow has been intentionally directed to induce the motion of active particles through the mesh screen and the center of the chamber towards the center of the worktable, from where it is pumped out. An additional power supply can be used to bias the worktable and treated substrates relative to the screen.

The main technological consequence of different discharge configurations in DCPN and ASPN systems is that in DCPN technique nitrogen mass transfer depends on the discharge current density which is the highest at the blades of cutting

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tools (the so-called edge effect), which leads to creation of deeper and more brittle nitrided layers in these regions, and in consequence to reduced service life of nitrided and duplex treated cutting tools. In contrast to the DCPN, in ASPN technique the edge effect does not occur—there is no local overheating and overnitriding of tool blades, therefore this technique is more suitable for nitriding cutting tools with very sharp wedge angles, such as woodworking tools and was used in the research described in the paper.

1.2 The Aim and the Scope of the Research

The aim of the research was to develop technological parameters for bright nitriding of woodworking planing knives made of HSS AISI M2 in the newly built ASPN device. In order to speed up the process of the nitriding parameters optimization the design of experiments using the Taguchi approach was applied for development of the plan of experiments and elaboration of obtained experimental results. Taguchi method was developed for experimental optimization of multiparameter technological processes and allows to reduce significantly the number of experiments necessary to study the effect of particular process parameters on the final product of the process (Ref 13). The method proved to be very effective in optimization of surface engineering processes (Ref 14-17). The Taguchi method uses the summary statistic η called signal-to-noise (S/N) ratio, which allows to evaluate the influence of process parameters on the obtained properties of the product. The statistical analysis of S/N ratio and analysis of the experimental data using the analysis of variance (ANOVA) provide information about statistically significant factors of the process and allow to find optimum levels of process parameters (Ref 16). The value of η (S/N) is calculated from the formula that expresses the criterion for the quality characteristic to be optimized. When it is appropriate to maximize certain desirable characteristics of the product the criterion 'the larger-the-better' is used and the signal-to-noise ratio η is given by the formula:

$$\eta = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right).$$

In the case when it is appropriate to minimize certain undesirable characteristics of the product the criterion 'the smaller-the-better' is applied and the formula for η calculation is:

$$\eta = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}y_i^2\right).$$

In both formulas y is the quality characteristic. Note that the summary statistics η are formulated in such a way that independently of the type of the problem the aim of the optimization procedure is maximization of η (signal-to-noise ratio S/N).

For planning experiments within the Taguchi's procedure orthogonal arrays are used—the system of experimental plans (tables) that allow the calculation of the maximum number of independent (orthogonal) main characteristic of the product with a minimum number of experiments. Within described research the computer programme STATISTICA developed by StatSoft® was used for generation of the experimental plan, statistical analysis of the results and calculation of the optimal parameters of the ASPN process.

2. Experimental

2.1 The ASPN Device and Nitrided Tools

Nitriding processes were carried out in an own construction ASPN device, developed and manufactured in the Institute of Mechatronics, Nanotechnology and Vacuum Technique of the Koszalin University of Technology. The view and the schematic diagram of the device are presented in Fig. 1(a) and (b), respectively. The vacuum chamber of the device has a diameter of 800 mm and a height of 1000 mm. The main elements of the technological equipment installed inside the vacuum chamber are:

- system of gaseous atmosphere supply and evacuation containing gas inlet located axially under the upper cover of the chamber, gas deflector of a diameter of 660 mm and gas outlet located axially in the center of the worktable,


(a)

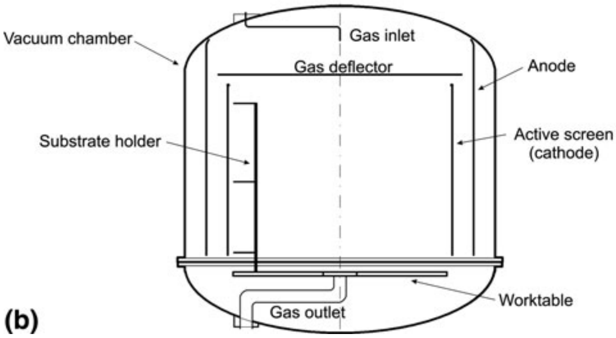
(b)

Fig. 1 The ASPN device used in the research: (a) the general view, (b) the schematic diagram

- system of discharge electrodes containing mesh active screen (cathode) 620 mm in diameter and 490 mm high and the anode of a diameter of 720 mm,
- worktable of a diameter of 600 mm,
- substrate holder.

Planing knives made of HSS AISI M2 were used as substrates in all the experiments. The knives, selected from normal production batch, were 100 mm long, 30 mm wide, 3 mm thick and had the wedge angle of 41°. They were quenched and tempered to the hardness of 62 ± 1 HRC and pre-sharpened by the producer. No surface finish of the knives was applied before nitriding—the knives were only cleaned using standard PVD cleaning procedure and then installed in the substrate holder.

2.2 Development and Optimization of the ASPN Process Parameters

The optimization of the ASPN process parameters has been done in two series of experiments planned and carried out according to the Taguchi approach. The first series contained nine experiments planned using the orthogonal table L9 (3^4)—four process parameters at three value levels. The parameters optimized in the first experimental series were: process duration, composition of the gaseous atmosphere, the substrate BIAS voltage and the substrate temperature (Table 1). The mixtures of nitrogen and hydrogen were used as nitriding atmospheres, but for safety reasons the maximum percentage content of hydrogen was limited to 50%, therefore in the processes carried out at the lowest nitrogen content argon was added to the nitriding atmosphere. The pressure of the gaseous atmosphere during nitriding and the conditions of heating and cooling phases were set constant (Table 2). The plan of nine experiments prepared according to the Taguchi's orthogonal table L9 (3^4) is presented in detail in Table 3.

As measures of the nitrided layers quality the total layer thickness, compound layer thickness and the fracture toughness coefficient were used. The aim of the first stage of the process optimization was to achieve the nitrided layer without the compound zone, but with maximum possible thickness and maximum fracture toughness coefficient. Based on the results obtained in the first series of experiments, in the second series the substrate BIAS voltage, the substrate temperature and atmosphere total flow during nitriding phase were fixed at the values: BIAS = −100 V, T = 500 °C, Q_Σ = 1400 mL/min. The optimized parameters were: process duration, composition of the gaseous atmosphere, and the pressure of the gaseous atmosphere (Table 4). The parameters of heating and cooling phases were kept at the same levels as in the first series. According to the Taguchi approach for three parameters at two value levels the orthogonal table L4 (2^3) was applied and the sequence of four experiments was performed (Table 5). In the second part of the optimization procedure the total layer thickness, surface hardness, and the fracture toughness coefficient were used as measures of the nitrided layers quality. After execution of both experimental series final experiments were carried, which allowed fine adjustment of the ASPN process parameters.

2.3 Investigation of the Nitrided Layers Properties

Besides the properties used in both experimental series as measures of the layers quality, i.e., total layer thickness, compound layer thickness, fracture toughness coefficient and surface hardness, the phase composition of the layers, their hardness profiles and metallographic structure were investigated. Total thickness of the layers and the thickness of the compound zones were determined optically on the etched microsection of the layers using metallographic microscope Nikon MA 200. Fracture toughness coefficient was determined according to the procedure given in Ref 18 from the formula:

$$K_{\mathrm{Ic}} = 0.0319\left(\frac{P}{al^{1/2}}\right)$$

where P is the indentation load, a the mean diagonal half length, and l the mean crack length.

Surface hardness of the nitrided substrates was measured with Future-Tech Vickers hardness tester FV-700 at the applied load of 100 N (HV10), whereas hardness profiles of the layers were determined on the microsections of the layers using nanohardness tester Fischerscope HM 2000 XYp at the applied load of 500 mN (HV0.05). The phase composition of the layers was determined by XRD technique with diffractometer DRON 2.0 using Co Kα radiation.

The results of the optimization procedure were verified by the tools' behavior in the sharpening operation performed according to normal industrial practice after fitting the knives in the 8 knife hydro head. Sharpening was performed using Weinig Rondamat 980 Automatic Grinder working according to standard procedure of planing knives sharpening. After sharpening operation the

Table 2 Fixed process parameters in the first experimental series

Phase of the process	Parameter	Value
Heating	Atmosphere pressure	2 hPa
	Atmosphere composition	80% Ar/20% H_2
	Atmosphere total flow	1000 mL/min
Nitriding	Atmosphere pressure	2 hPa
	Atmosphere total flow	1600 mL/min
Cooling	Atmosphere pressure	2 hPa
	Atmosphere composition	100% Ar
	Atmosphere total flow	800 mL/min

Table 1 The parameters optimized in the first experimental series and their value levels applied in the experiments

	Parameter			
Parameter value level	Nitriding phase duration, h	Atmosphere composition, %	BIAS voltage, V	Substrate temperature, °C
Level 1	4	25% N_2/50% H_2/25% Ar	−100	500
Level 2	5	50% N_2/50% H_2/0% Ar	−150	525
Level 3	6	75% N_2/25% H_2/0% Ar	−200	550

Table 3 Plan of experiments of the first series prepared according to the Taguchi's orthogonal table L9 (3^4)

Process number	Nitriding phase duration, h	Atmosphere composition, %	BIAS voltage, V	Substrate temperature, °C
Process 1	4	25% N_2/50% H_2/25% Ar	−100	500
Process 2	4	50% N_2/50% H_2/0% Ar	−150	525
Process 3	4	75% N_2/25% H_2/0% Ar	−200	550
Process 4	5	25% N_2/50% H_2/25% Ar	−150	550
Process 5	5	50% N_2/50% H_2/0% Ar	−200	500
Process 6	5	75% N_2/25% H_2/0% Ar	−100	525
Process 7	6	25% N_2/50% H_2/25% Ar	−200	525
Process 8	6	50% N_2/50% H_2/0% Ar	−100	550
Process 9	6	75% N_2/25% H_2/0% Ar	−150	500

Table 4 The parameters optimized in the second experimental series and their value levels applied in the experiments

Parameter value level	Nitriding phase duration, h	Atmosphere composition, %	Atmosphere pressure, hPa
Level 1	4	20% N_2/30% H_2/50% Ar	2
Level 2	5.5	25% N_2/25% H_2/50% Ar	3.5

Table 5 Plan of experiments of the second series prepared according to the Taguchi's orthogonal table L4 (2^3)

Process number	Nitriding phase duration, h	Atmosphere composition, %	Atmosphere pressure, hPa
Process 1	4	20% N_2/30% H_2/50% Ar	2
Process 2	4	25% N_2/25% H_2/50% Ar	3.5
Process 3	5.5	20% N_2/30% H_2/50% Ar	3.5
Process 4	5.5	25% N_2/25% H_2/50% Ar	2

cutting edges of the knives were analyzed using metallographic microscope Nikon MA 200. The spalling depth of the cutting edge caused by sharpening operation was accepted as the measure of the nitrided knives quality.

3. Results and Discussion

3.1 Results of the First Series of Experiments Executed According to Taguchi's Orthogonal Table L9 (3^4)

The transverse cross-section of the planing knife after nitriding is presented in Fig. 2(a). During sharpening the nitrided layer is removed from the clearance face of the knife and only the rake face remains hardened (Fig. 2b). The exemplary microsection of the nitrided layer after measurement of the microhardness distribution is shown in Fig. 2(c). The properties of the nitrided layers created in the processes performed within the first series of experiments are summarized in Fig. 3. The phase composition and structure of the layers are given in Fig. 3(a) and (b). X-ray diffraction patterns presented in Fig. 3(a) indicate that the created layers consist of diffusion zone of nitrogen solution α-Fe(N) and the compound zone of iron nitride γ′-Fe_4N, but no iron nitride ε-$Fe_{2\text{-}3}N$ of higher nitrogen content was found. Besides the peaks from α-Fe(N) and γ′-Fe_4N phases of the nitride layer, in the recorded XRD spectra the peaks from Me_6C carbides are visible. These peaks occur in the x-ray diffraction patterns of non-nitrided M2 steel. In alloy steels various types of carbides are formed depending on the contents of strong carbide forming elements. In the investigated M2 (HS6-5-2) steel carbides of MC, M_2C, and M_6C type occur in the form of: $(Fe_{0,06}W_{0,1}Mo_{0,15}V_{0,65}Cr_{0,07})C_{0,89}$, $(Fe_{0,27}W_{0,44}Mo_{0,55}V_{0,43}Cr_{0,29})C$, and $(Fe_{2,52}W_{0,76}Mo_{0,79}V_{0,26}Cr_{0,29})C$, respectively (Ref 19). The thickness of the diffusion zone in the layers ranged from 50.7 μm (process 1) to 102.5 μm (process 8), while the compound zone thickness varied from 0 (processes 1 and 4) to 5.9 μm (process 3). As it is seen from Fig. 3(b) the thickness of the compound zone does not correlate with the thickness of the diffusion zone—the thickest compound zone of 5.9 μm was obtained in the layer with the diffusion zone 87.7 μm thick, while in the layer with the thickest diffusion zone (102.5 μm) the compound zone of the thickness of only 2.6 μm was obtained. This observation can be explained based on the ANOVA analysis, which shows that the nitride layer thickness is determined first of all by the substrate temperature, while the thickness of the compound layer depends mainly on the composition of the gaseous atmosphere (Fig. 4a, b). Also the mechanical properties of the

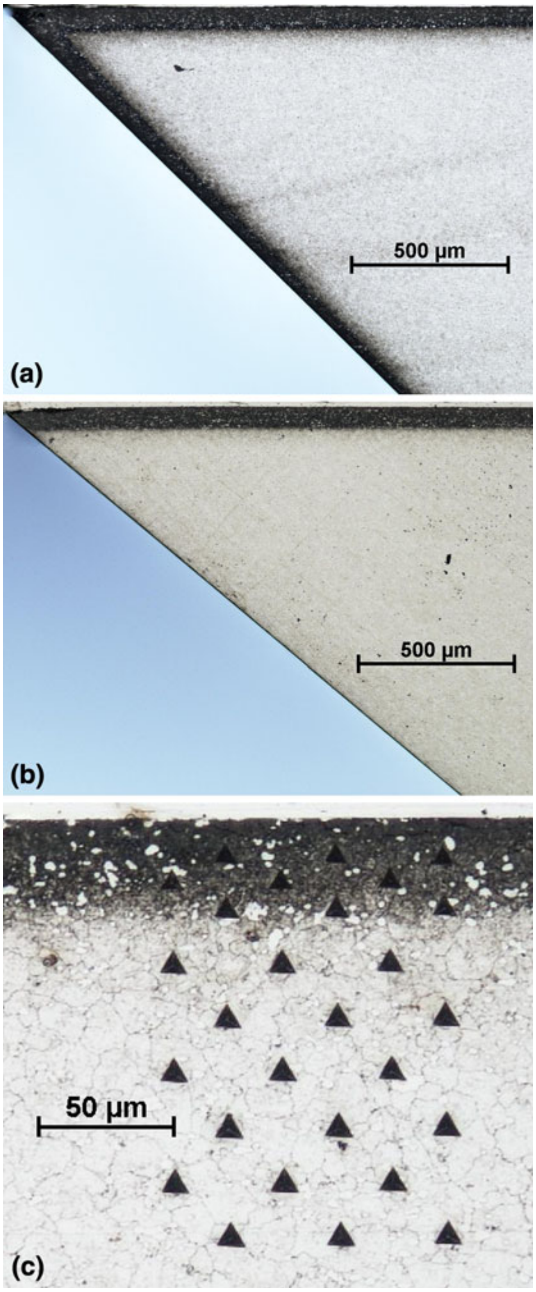

Fig. 2 Nitrided layer created on the planing knife: (a) cross-section of the planing knife after nitriding, (b) cross-section of the nitrided planing knife after sharpening, (c) microsection of the nitrided layer after measurement of the microhardness distribution

obtained layers, i.e., surface hardness, maximum microhardness, microhardness profiles, and the values of the fracture toughness coefficient (K_{Ic}) are highly diversified (Fig. 3c, d). The maximum microhardness does not follow exactly the changes of the surface hardness, because the first one depends mainly on the thickness of the γ'-Fe_4N compound layer, while the second one depends on the α-Fe(N) solution zone thickness. The comparison of the fracture toughness coefficient values with the thickness and the hardness of the layers (Fig. 3d) indicate a correlation existing between K_{Ic} values and the total thickness of the layers. The highest value of K_{Ic} was obtained for the nitrided layer with the lowest thickness of 50.7 µm. This observation is consistent with that formulated in (Ref 20) that a decrease in the wear resistance of high speed tool steels could occur with nitrided depths higher than 50 µm due to increasing embrittlement. Moreover the occurrence of such a correlation in the layers nitrided using ASPN technology indicate that the increase in brittleness with increasing thickness of the layers is not caused by the edge effect, which does not occur in this nitriding method. The increase in brittleness should be rather ascribed to the stress level in thicker layers. Although the highest value of K_{Ic} was shown by the layer of bright nitriding, it would be difficult to indicate the correlation between the fracture toughness coefficient and the thickness of the compound layer—layers obtained in the processes 4 and 5 contradict the existence of such correlation. And similarly, hardly one can show the correlation between K_{Ic} and the surface hardness or maximum hardness of the layers.

The influence of the individual process parameters on the total thickness, the compound zone thickness, and the fracture toughness of created nitrided layers were determined by the Taguchi approach using computer programme STATISTICA (StatSoft®) and is shown in Fig. 4. The aim of the first series of experiments was to achieve the nitrided layer without the compound zone, with maximum thickness, and with maximum fracture toughness. Accordingly, the criterion 'the larger-the-better' was applied to evaluate the influence of process parameters on the layer thickness and its fracture toughness, while the dependence of the compound zone thickness on the nitriding conditions was estimated using the criterion 'the smaller-the-better'. As it follows from the diagram in Fig. 4(a), in order to obtain maximum thickness of the nitrided layer the ASPN process should be performed at following process parameter values: duration of 4 h (level 3), atmosphere containing 75% N_2 and 25% H_2 (level 3), substrate BIAS of −150 V (level 2), and the substrate temperature of 550 °C (level 3). Moreover, the analysis showed insignificant effect of the substrate BIAS on the layer thickness. The diagram shown in Fig. 4(b) indicates that the thickness of the compound layer is determined first of all by the composition of the gaseous atmosphere. The lowest thickness of the compound layer can be obtained in the process carried out for 5 h (level 2 of the process duration), in the atmosphere containing 25% N_2, 50% H_2, and 25% Ar (level 1), at the substrate BIAS of −100 V (level 1) and at the substrate temperature of 500 °C (level 1). The same set of the value levels of the atmosphere composition, the substrate BIAS, and the substrate temperature lead to the maximalization of the fracture toughness of the created nitrided layer (Fig. 4c). Process duration has negligible influence on the layer fracture toughness.

The presented results of the first series of experiments allowed to define the ASPN process parameters that determine analyzed properties of the nitrided layer, i.e., its total thickness, compound zone thickness, and the fracture toughness of the layer. They also show that in order to reach the planned aim of the experiments, i.e., to achieve the nitrided layer without the compound zone, with maximum thickness and with maximum fracture toughness, the compromise combination of ASPN process parameters must be selected from among those indicated by the Taguchi procedure as optimal for individual properties of the layers. Before selection of such an optimal set of process parameter values the second series of experiments was performed in order to get additional information on the variation of the nitrided layer properties at lower nitrogen content and higher pressure of the process atmosphere.

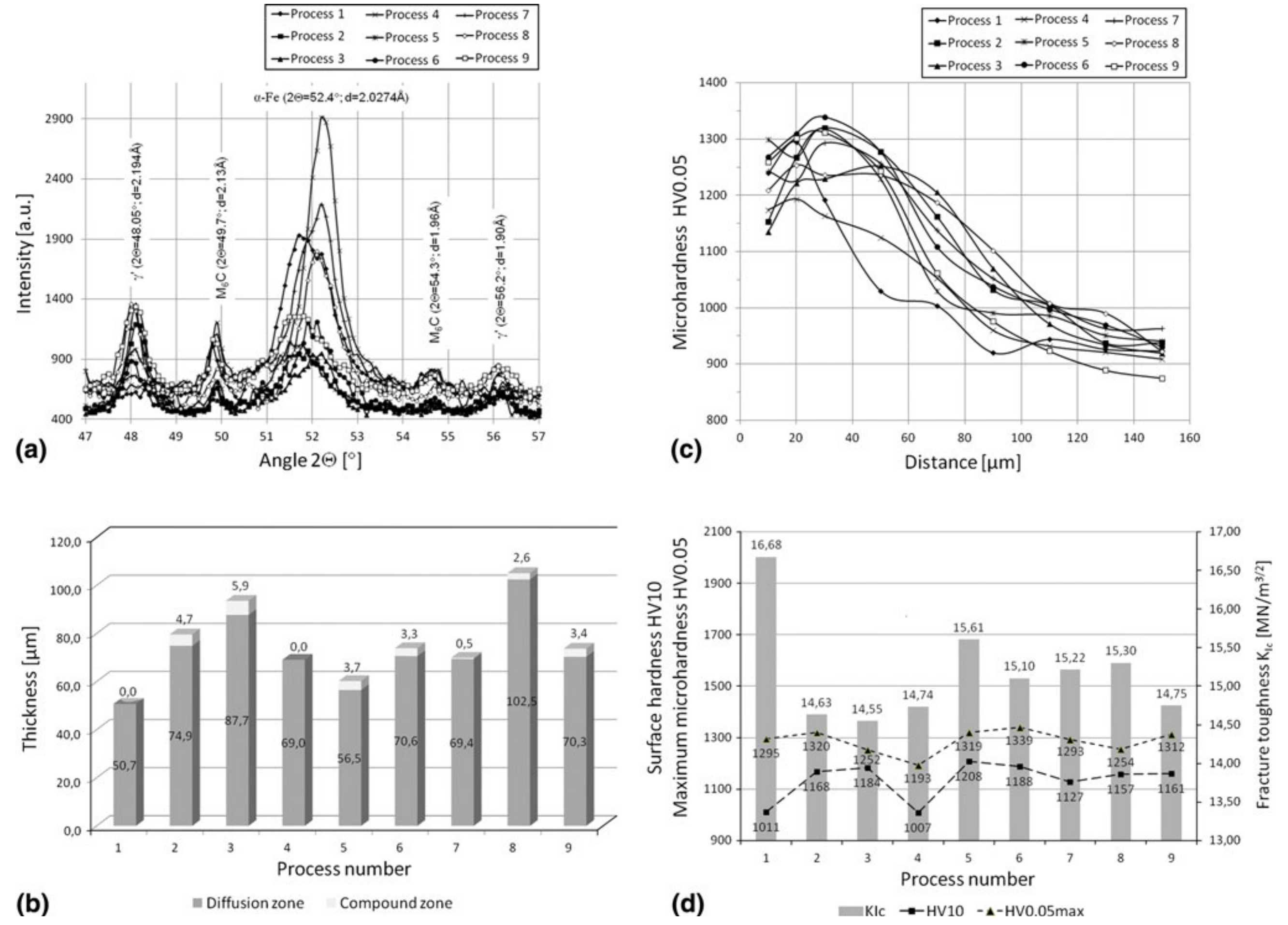

Fig. 3 The properties of the nitrided layers created in the processes performed within the first series of experiments: (a) phase composition, (b) structure of the layers, (c) microhardness profiles, (d) hardness and fracture toughness

3.2 Results of the Second Series of Experiments Executed According to Taguchi's Orthogonal Table L4 (2^3)

The properties of the nitrided layers created within the second series of experiments are presented in Table 6. All created layers were bright nitriding layers, i.e., did not contain the compound zone of iron nitrides, but their thickness and mechanical properties differed significantly. Wide ranges of the values of the obtained layers properties, selected as the measures of the layers quality in the second series of experiments, i.e., the total layer thickness (11.0-48.3 μm), surface hardness (832-996 HV10) and the fracture toughness coefficient (15.50-38.78 MN/m$^{3/2}$), indicate that the ASPN process is very sensitive to analyzed parameters, particularly to the pressure of gaseous atmosphere. The results of the analysis performed with the Taguchi procedure using computer programme STATISTICA are shown in Fig. 5. From the presented diagrams it follows that in the conditions of the experiments executed within the second series the fracture toughness of the nitrided layer, which is critical for the performance of the planing knives because of their specific geometry, is almost completely determined by one process parameter—atmosphere pressure (Fig. 5c). At low process pressure (2 hPa) the fracture toughness of the layer drops dramatically. This result confirms the observation formulated in (Ref 21) about higher fracture of the nitrided layers created in low pressure (2 hPa) DCPN processes and means that this tendency occurs also in ASPN despite the lack of energetic ion bombardment of the nitrided substrates in this technology. On the other hand, at higher pressure of the ASPN process the thickness and surface hardness of the nitrided layer drop significantly (Fig. 5a, b). It means that in the ASPN processes optimized for planing knives, higher pressure should be applied in order to achieve high fracture toughness of the tools. The thickness and surface hardness of the nitrided layer should be improved by increasing process duration rather, which has positive influence on the layer thickness and hardness without significant detrimental effect on the phase structure, than by increasing nitrogen content in the gaseous atmosphere, which leads to the formation of the compound zone of iron nitrides (Fig. 4b).

3.3 Final Adjustment of the ASPN Process Parameters for Planing Knives Made from High Speed Steel

The aim of the final stage of process optimization was to adjust the technological parameters of ASPN process so as to achieve the main goal of the research, i.e., to create on the surfaces of the planing knives made of HSS the nitrided layers of high fracture toughness and maximum possible thickness and hardness, which would pass the standard industrial operation of sharpening and could be subjected to the field test on highly effective planing machine.

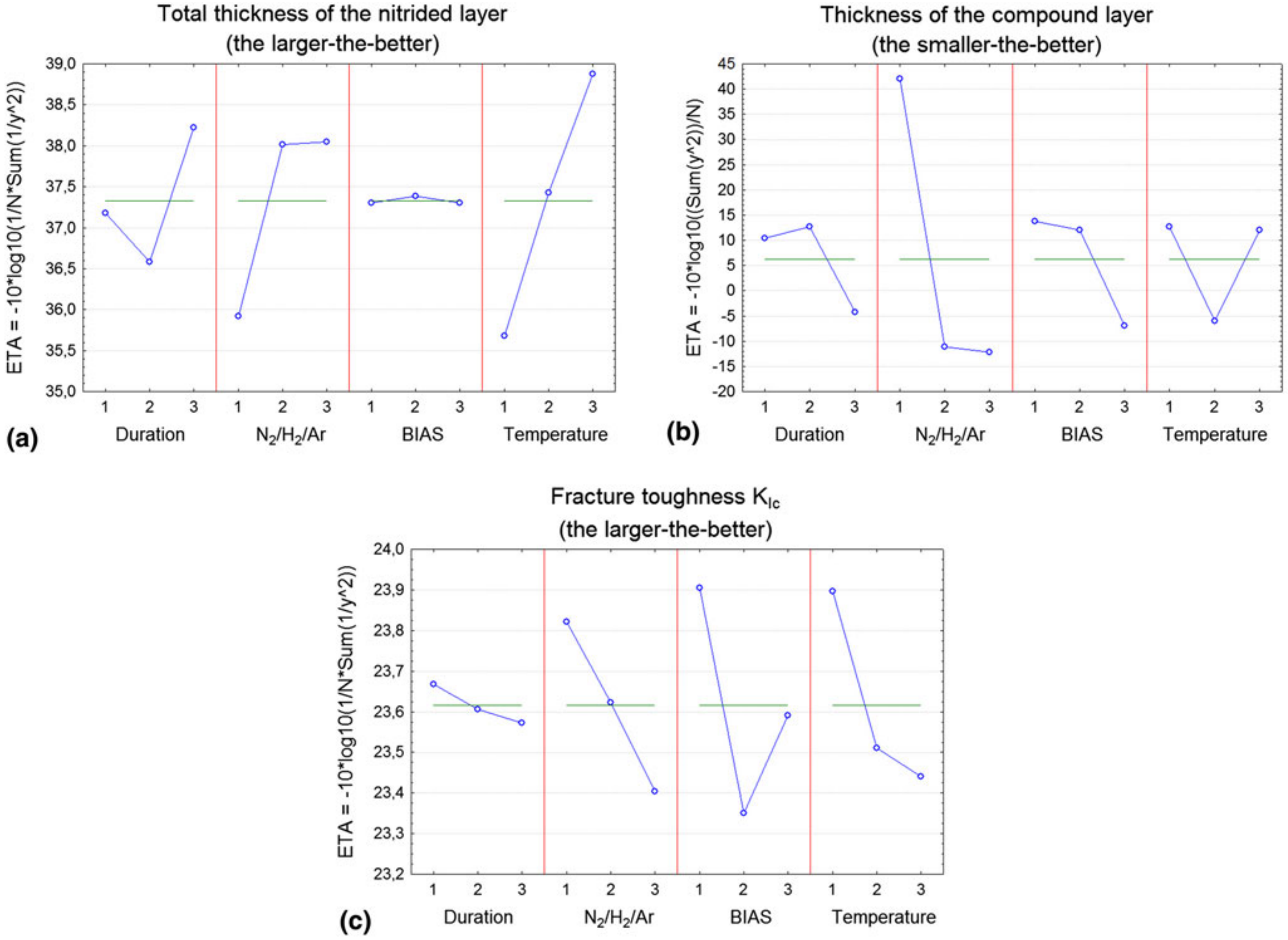

Fig. 4 The influence of the individual process parameters used in the first series of experiments on the properties of nitrided layers: (a) the effect of each parameter on total thickness of the layer, (b) the effect of each parameter on the compound layer thickness, (c) the effect of each parameter on the fracture toughness coefficient

Table 6 The properties of the nitrided layers created within the second series of experiments

Process number	Layer thickness, μm	Surface hardness HV10	Maximum hardness HV0.05max	Fracture toughness (K_{Ic}), MN/m$^{3/2}$
Process 1	31.0	888	1185	18.33
Process 2	11.0	832	941	38.78
Process 3	16.4	849	992	38.72
Process 4	48.3	996	1318	16.50

Based on the results of two series of experiments, which were planned, executed and elaborated using the Taguchi approach, a final series of six experiments was planned for final verification. In the final series of processes the substrate BIAS voltage, the substrate temperature and atmosphere total flow were kept at the levels set for the second series of experiments, i.e., BIAS = −100 V, T = 500 °C, Q_Σ = 1400 mL/min. The process duration, as well as composition and pressure of the gaseous atmosphere were used as variable parameters for precise tuning of the nitrided layers properties (Table 7). These parameters varied only slightly around the values indicated as a result of analysis done using the Taguchi procedure.

The values of the fracture toughness coefficient and the main properties of the nitrided layers created in the final series of experiments are presented in Fig. 6. Despite narrow intervals of variation of the process parameters, the properties of the nitrided layers produced in individual processes differ significantly. The thickness and the fracture toughness coefficient are in the ranges of 25.0-42.5 μm and 17.82-28.78 MN/m$^{3/2}$, respectively. The presented results confirm the trends, indicated as a result of the analysis made using the Taguchi approach, that the atmosphere pressure is the most important parameter of the ASPN process in adjusting the fracture toughness of the layers. Even as small as 0.2 hPa, variation of the pressure is significant for the fracture toughness coefficient. Its value is higher in the layers created at the atmosphere pressure of 2.5 hPa in comparison with these nitrided at 2.3 hPa, even for the layers similar in thickness and hardness, e.g., obtained in the processes V2 and V6. The layers obtained in these two processes confirm also the above mentioned indication, that

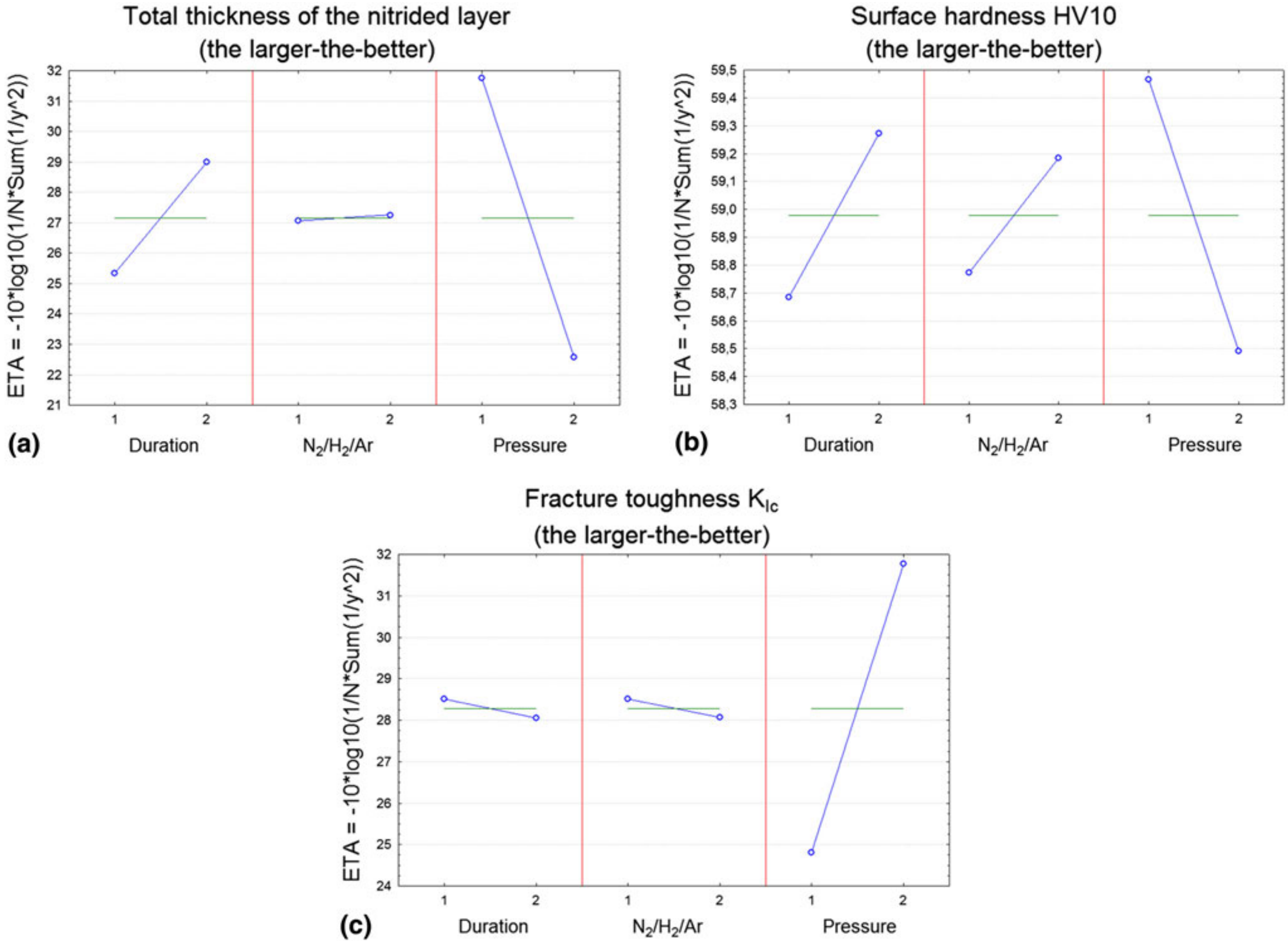

Fig. 5 The influence of the individual process parameters used in the second series of experiments on the properties of nitrided layers: (a) the effect of each parameter on total thickness of the layer, (b) the effect of each parameter on surface hardness of the layer, (c) the effect of each parameter on the fracture toughness coefficient

Table 7 The parameters of the verification processes

	Parameter values		
Process number	**Nitriding phase duration, h**	**Atmosphere composition, %**	**Atmosphere pressure, hPa**
Process V1	6	25% N_2/25% H_2/50% Ar	2.5
Process V2	6.5	25% N_2/25% H_2/50% Ar	2.3
Process V3	7	25% N_2/25% H_2/50% Ar	2.3
Process V4	6	20% N_2/30% H_2/50% Ar	2.5
Process V5	6.5	20% N_2/30% H_2/50% Ar	2.5
Process V6	7	20% N_2/30% H_2/50% Ar	2.5

when increasing the pressure, to compensate the layer thickness drop, instead of increasing the nitrogen content it is better to enlarge duration of the process.

3.4 Verification of the Created Nitrided Layers in the Sharpening Operation

The planing knives nitrided in the processes V1-V6 were installed in the 8 knife hydro head (Fig. 7) and subjected to the test of sharpening performed according to standard industrial procedure applied for such types of woodworking tools. In the two remaining seats of the head the standard, non-nitrided knives were installed for comparison. As a measure of the nitrided knives quality the spalling depth of the cutting edge was applied. The results of the sharpening test are presented in Table 8 and Fig. 8. The cutting edge of non-nitrided knife after sharpening is shown in Fig. 8(a). The susceptibility of the nitrided knives' cutting edges to spalling shown in the sharpening test correlate with the measured values of fracture toughness coefficient. The deepest cavities, up to 25 µm, were identified on cutting edges of the knives nitrided in the processes V2 and V3 carried out at the pressure of 2.3 hPa

(Fig. 8c), i.e., these which also showed the lowest values of the fracture toughness coefficient. Moreover, the spalling on these knives have continuous character, whereas on the cutting edge of the knife nitrided at the pressure of 2.5 hPa (process V5), which showed the highest value of K_{Ic}, the spalling occur only locally and maximum non-uniformities of the cutting edge were limited to 15 µm (Fig. 8b). Also the comparison of the behavior of knives nitrided in the processes V2 and V6, which show similar thickness and hardness of the layers, confirms higher fracture toughness of the knives nitrided at higher pressure (Table 8).

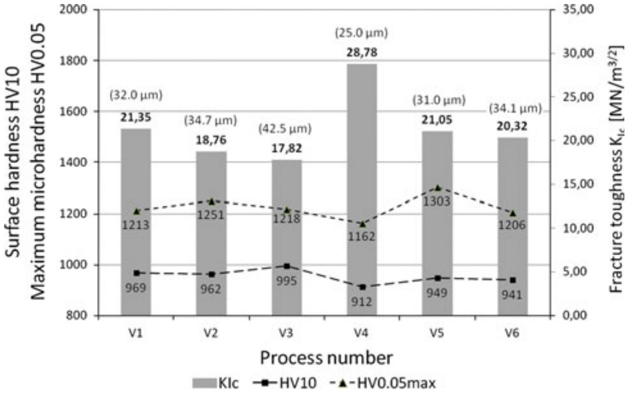

Fig. 6 The values of the fracture toughness coefficient, surface hardness, and maximum microhardness of the nitrided layers created in the final series of experiments (the thickness of the layers is given additionally in brackets)

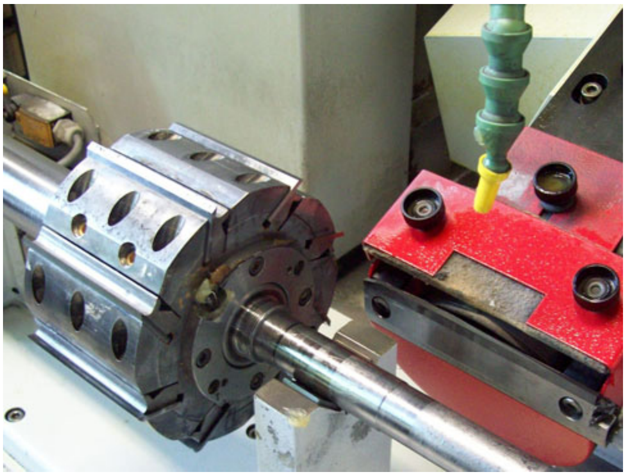

Fig. 7 Nitrided planing knives installed in the 8 knife hydro head during sharpening test performed on the automatic grinder Weinig Rondamat 980

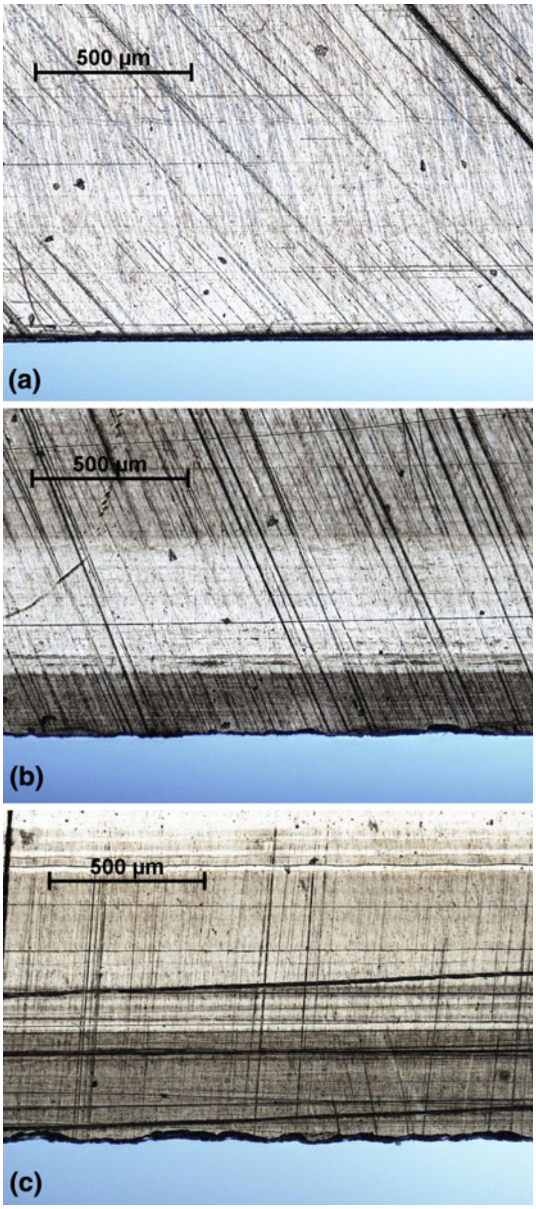

Fig. 8 Cutting edges of planing knives after the sharpening test: (a) non-nitrided, (b) nitrided at the pressure of 2.5 hPa, (c) nitrided at the pressure of 2.3 hPa

Table 8 The results of the sharpening tests

Process number	Fracture toughness coefficient K_{Ic}, MN/m$^{3/2}$	Maximum spalling depth, µm	Type of spalling
Process V1	21.35	17.7	Continuous
Process V2	18.76	25.1	Continuous
Process V3	17.82	18.0	Continuous
Process V4	28.78	15.0	Local
Process V5	21.05	17.0	Continuous
Process V6	20.32	16.1	Continuous

4. Conclusions

The studies described in the article related to the development of the technological parameters of the ASPN process in the prototype, the newly built device and their optimization for nitriding planing knives for woodworking made of HSS AISI M2. The main challenge in the carried out research was to develop, in the possible shortest time, the industrial technology for nitriding the tools used in woodworking production in the newly constructed device, which characteristics were completely unknown. To speed up the process of the technology development the Taguchi approach of planning experiments was used, moreover from the very beginning of the research the nitriding processes and investigations of the nitrided layers properties were carried out using real tools as the substrates. Also the verification of the suitability of the obtained nitrided layers on planing knives for woodworking was done in the sharpening operation performed in industrial conditions according to standard sharpening procedure. The results of the presented research indicate that:

1. The Taguchi method of design of experiments proved to be very effective for processing the experimental results and optimization the technological parameters of the ASPN process. Thanks to the Taguchi approach it was enough to carry out two series of experiments containing thirteen experiments in total to determine individual influence of each investigated process parameter on the properties of created nitrided layers. Without using the Taguchi scheme as much as 89 ($3^4 + 2^3$) experiments would have been necessary to get such a set of information.
2. The results of the carried out research confirmed suitability of the ASPN technology for nitriding cutting tools made of HSS with extremely sharp wedge angles, like woodworking planing tools.
3. The critical parameter of the nitrided woodworking planing knives is the fracture toughness of their cutting edges. The carried out research proved that the values of fracture toughness coefficient K_{Ic} are in correlation with maximum spalling depths of the cutting edge measured after sharpening, and therefore may be used as a measure of the nitrided planing knives quality.
4. The main technological indications for nitriding HSS planing knives are:

- the total thickness of the nitrided layer is determined mainly by the substrate temperature and the pressure of the gaseous atmosphere, process duration and atmosphere composition have moderate effect, while the effect of the substrate BIAS is insignificant;
- the thickness of the compound layer is determined first of all by the composition of the gaseous atmosphere;
- the fracture toughness of the nitrided layer, which is critical for the performance of the planing knives, is almost completely determined by one process parameter—atmosphere pressure;
- in the ASPN processes optimized for planing knives, higher pressure and low nitrogen content should be applied in order to achieve high fracture toughness of the tools, whereas the thickness and surface hardness of the nitrided layer should be improved by increasing process duration.

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