K.-D. BOUZAKIS, G. SKORDARIS,
S. HADJIYIANNIS, I. MIRISIDIS, N. MICHAILIDIS

RESEARCH

Wear Behaviour of Pvd Coated Tools With Respect to Annealing Treatments

Strength properties alterations may occur in the already deposited film material during the physical vapour deposition (PVD), induced by annealing, at the process temperature. Similar annealing mechanisms occur in PVD films during heat treatments, at a temperature corresponding to the temperature of the deposition. In the described investigations, cemented carbide inserts were coated through high ionisation sputtering PVD processes with a $(Ti_{46}Al_{54})N$ film, keeping all process parameters constant, except the deposition time, which was set according to the desired film thicknesses. The coated specimens were isothermally annealed at deposition temperature for various time periods. The occurred coating superficial stress-strain laws were determined versus the film thickness, through nanoindentations and a FEM-based evaluation method of the corresponding results. The detected film strength properties were correlated to the performance of the corresponding coated cutting inserts. In this way, annealing durations dependent on the coating thickness were predicted, enhancing the tool wear resistance in milling. Finally, the obtained results were theoretically explained by means of a FEM simulation of the cutting process.

Keyword: *PVD coatings, isothermal strength properties gradation, annealing duration, deposition temperature, cutting performance.*

1. INTRODUCTION

The high potential of increasing the wear resistance of coated tools through appropriate heat treatments, has been gaining wide industrial interest. Relevant investigations were carried out, aiming to document the annealing effect on the superficial mechanical properties of PVD films and on their cutting performance [1-8]. In this context, a few minutes annealing, close to the deposition temperature, is reported to increase the cutting performance in the case of a 4 µm thick $(Ti_{46}Al_{54})N$ film [8].

Figure 1 indicates potential magnitudes influencing the cutting performance of coated tools. The effects of some of these parameters, i.e. the cutting wedge radius, the coating material properties, the coating annealing etc, on the wear behavior are described in [9,10,11].

K.-D. BOUZAKIS, G. SKORDARIS,
S. HADJIYIANNIS, I. MIRISIDIS, N. MICHAILIDIS
Laboratory for Machine Tools and Manufacturing Engineering, Mechanical Engineering Department, Aristoteles University of Thessaloniki,
54124, Greece
G. Erkens, I. Wirth
CemeCon AG, Adenauerstr. 20B1, D-52146 Würselen, Germany

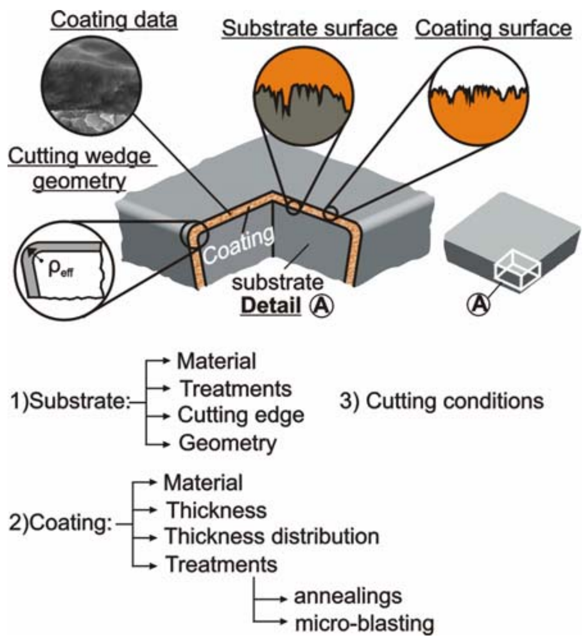

Figure 1. Parameters affecting the coated tool cutting performance.

In figure 2 the superficial coating grain size occurring at various coating thicknesses is illustrated, it is assumed that the power law during the PVD process remain constant. The cone-shaped column growth [12,13,14] leads to increased superficial grains size in comparison to those on an intermediate plane parallel to the substrate surface. This phenomenon can be related to the mobility of the adatoms during the film growth due to the fact that the deposited coating acts as an isolator to the magnetic plasma flux and thus the energetic particle bombardment and the flux as well as energy distribution are affected [15,16]. Due to the coarser superficial microstructure it is expected that a diminishing of the film mechanical strength properties occurs.

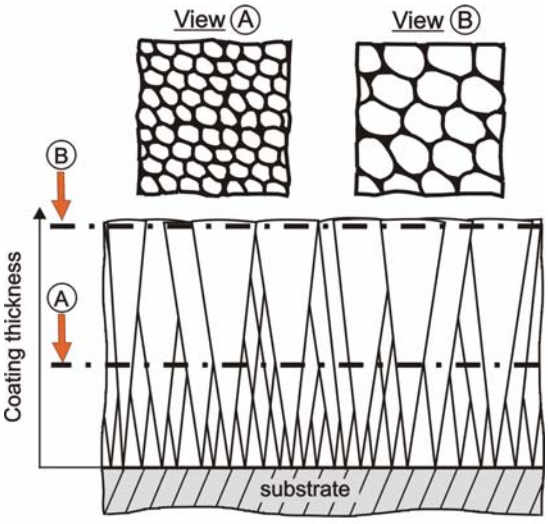

Figure 2. Coating columnar microstructure and occurring grain sizes at various coating thickness.

Considering these results, PVD coated cemented carbide inserts, with various film thicknesses, were annealed for various durations at a temperature of 450°C, corresponding to their deposition's one. At this temperature, in accordance to the non-equilibrium phase diagram of the system TiN-AlN [17,18] (see figure 3) and to the chemical composition of the investigated $(Ti_{46}Al_{54})N$ coatings, no phase transformation or separation occurs during the isothermal annealing. On the other hand film hardness modifications may occur, induced byatom migrations and dislocation displacements [1,2,19].

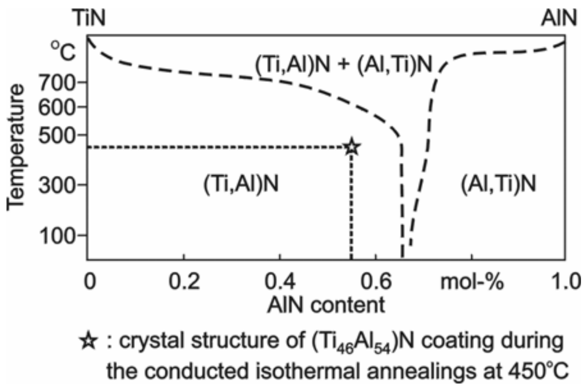

Figure 3. Phase diagram of the metastable system TiN-AlN.

In the frame of the described investigations, the film mechanical strength properties, resulting after the coating deposition as well as after the film isothermal annealing at deposition temperature, were detected versus the film thickness through nanoindentations and a FEM supported evaluation method of the related results [20,21,22]. Moreover, the cutting performance of the coated inserts was thoroughly investigated and the wear evolution was explained with the aid of a FEM-simulation of the cutting process, considering the determined film strength properties.

2. DETERMINATION OF THE SUPERFICIAL COATING STRENGTH PROPERTIES AFTER VARIOUS LONG ISOTHERMAL ANNEALINGS

During heat treatments of coated inserts in normal atmosphere, film oxidation may occur. The oxidation mechanisms at various temperatures were assiduously analysed for $(Ti_{1-X}Al_X)N$ films in [6,23,24]. The superficial oxidation sensitivity is restricted at temperatures less than 500°C and thus its contribution to superficial composition and mechanical properties modifications is negligible. In order to avoid a potential oxidation of the film surfaces, the annealings were conducted in an Ar-atmosphere.

The maximum indentation depth and hardness [25], occurring after isothermal annealings of various durations at deposition temperature (450°C), are exhibited in figure 4, where the maximum nanoindentation depth is displayed versus the annealing duration for various coating thickness cases. The indicated surface roughnesses remained practically invariant in all film annealing cases. In the film thickness cases of 2 and 4 μm the superficial hardness is maximized and stabilized after five minutes and over 15 minutes annealing time respectively. Similar investigations in thicker coating thickness cases of 8 and 10 μm demonstrated a similar behaviour, however a longer annealing duration, of ca. 60 minutes, was necessary to reach the maximum hardness. Furthermore, up to 120 minutes, a decrease and subsequently a stabilization of the hardness were observed,approximately at the corresponding initial value of the untreated as deposited film.

These trends can be explained, considering the effect on the film hardness of atom migrations and dislocation displacements up to the grain boundaries [1,2,19]. Taking into account that at the conducted annealing temperature and film mechanical composition no phase transformation or separation occurs (see figure 3), two competing mechanisms can be responsible for the hardness modifications. An improvement of the coating crystal microstructure and thus a hardness decrease take place, versus the annealing time, due to dislocation removals in the film grains. On the other hand, the grain boundaries are reinforced, when diffused atoms and dislocations reach them and stop there, thus enhancing the grains embedment and the film hardness.

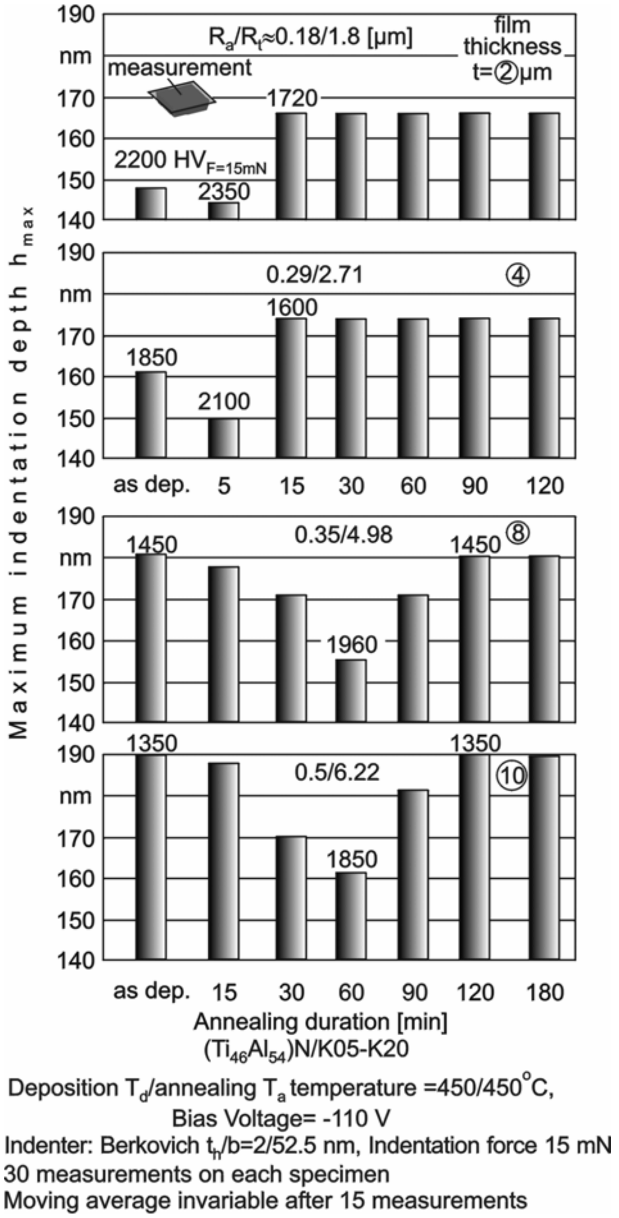

Figure 4. Maximum indentation depth on different thick coatings, after various annealing durations

The latter mechanism is more intense at the annealing begin, according to the illustrated results in figure 4, since the increase of film hardness is visible. On the other hand, the atom and dislocation movements within the film grains are dominant during the subsequent annealing time, causing a hardness deterioration (see figure 4). In the case of thicker 8 and 10 μm coatings, due to their coarser superficial micro-structure [9,10,19], the atom and dislocation displacements up to the grain boundaries are larger. In this way longer annealing times are required to obtain the maximum hardness, as shown in the diagrams at the bottom part of figure 4. In all the investigated coating cases, the film hardness is stabilized, after a certain annealing time, dependent on the film thickness, since no further atom migrations and dislocation displacements take place.

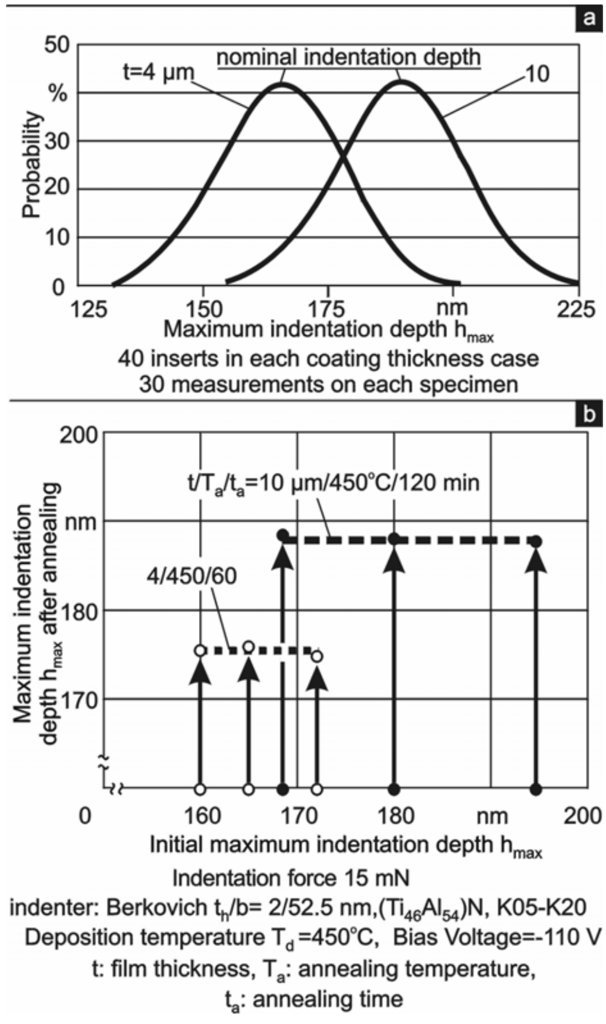

Figure 5. Maximum indentation depth distribution probability in different coating thickness cases (2a) and initial hardness alteration after various annealing durations (2b).

Figure 5a illustrates characteristic probability distributions of indentation depth of PVD-films with various thickness levels [9,10]. A reduction of the maximum (nominal) indentation depth results in the 10 μm thick coating, compared to the 4 μm one, among others, due to the coarser superficial coating microstructure [9,10,19]. In order to investigate the effect of the pristine superficial hardness on the stabilized one, PVD coatings of the same thickness and different hardness were isothermally heat-treated. Figure 5b shows the modification of maximum indentation depth of different hard, 4 and 10 μm thick coatings, after 60 and 120 min annealing time respectively. The stabilized maximum indentation depth after annealing is practically not affected by the pristine coating superficial hardness.

The superficial stress-strain curves for various thick coatings and annealing durations are presented in figure 6, as obtained of the methods introduced in [20,21,22]. In addition the elasticity modulus remains practically stable, as also found in [26]. On the other hand, the yield (S_Y) and the maximum (S_M) strength depend on the annealing duration. The yield strengths of the 8 and 10 μm thick coatings are maximized after approximately one hour annealing time, whereas in the investigated thinner film cases, only after few minutes. The mechanical properties are stabilized over a certain annealing duration, depending on the coating thickness.

3. COATING STRENGTH PROPERTIES GRADATION, INDUCED BY ANNEALING DURING THE FILM DEPOSITION AND BY ISOTHERMAL HEAT TREATMENT AT THE DEPOSITION TEMPERATURE

A coating structure may be considered consisting of individual layers, with their own mechanical properties. Every layer is exposed to an annealing after its deposition at the PVD process temperature. The annealing duration corresponds to the rest time, up to the deposition of the overall coating thickness. The resulting coating hardness gradation during the film deposition is explained in figure 7. As the coating thickness grows up (see figure 7a), the nominal superficial film hardness decreases [9,10,25]. In this way hardness and mechanical properties stratification result, as displayed in figure 7b. On the other hand, the coating properties are affected through annealing mechanisms during the film deposition. Hereupon according to the outcomes of the previous section, the superficial hardness depends on the annealing duration and on the coating thickness, as illustrated in figure 7c. Hence, the film hardness gradation versus the film thickness, shown in figure 7b, is modified as demonstrated in figure 7d. A further annealing at deposition temperature, after the formation of the overall film thickness, does not affect the hardness of layers, which is already stabilized, according to the related annealing time and layer location within the coating thickness (see figure 7e).

The alterations of the maximum indentation depth and of the yield strength in individual film structure "layers" are demonstrated in figure 8a at various times during the deposition of a 4 μm thick film..

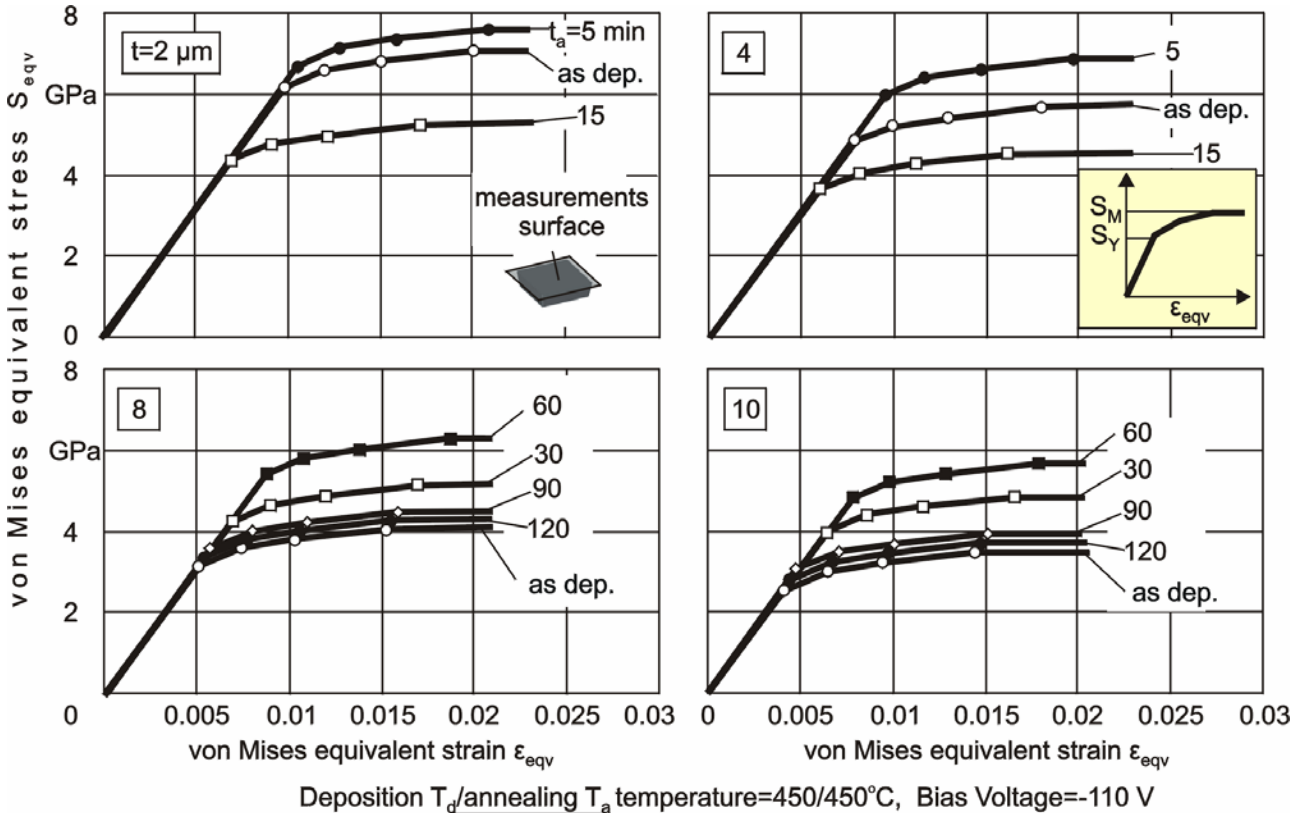

Figure 6. Superficial stress strain characteristics of different thick coatings after various annealing durations.

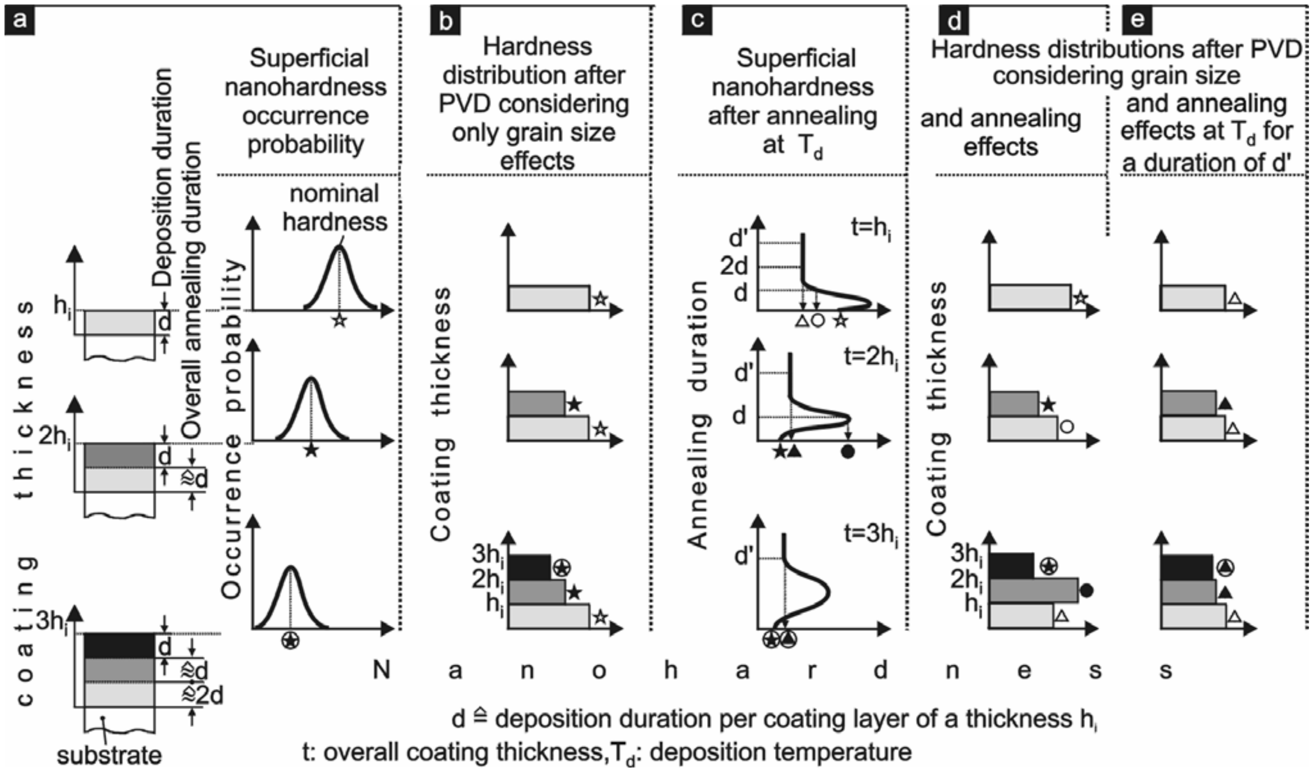

Figure 7. Resulting hardness gradation in thin films, after their deposition and after an annealing at deposition temperature, due to grain size as well as annealing effects.

The superficial maximum indentation depth and the related yield strength amount to 148 nm and 6.1 GPa correspondingly, after the deposition of the first 2 μm thick layer. Hereupon the maximum indentation depth is equal to that one, of an as deposited 2 μm thick coating, shown in figure 3. The development of the first film layer lasted approximately 120 min. The mechanical properties of this first layer are affected, due to annealing activation, during the deposition of the next 1 μm thick layer, at an overall deposition time of ca. 180 minutes. The maximum indentation depth of the first layer corresponds to that one of a 2 μm thick coating, annealed for 60 (=180-120) minutes, as exhibited in figure 3. On the other hand, the indentation depth of the second deposited layer is equal to the nominal one of a 3 μm thick film, since up to 180 minutes the deposition of a coating with an overall thickness of 3 μm was accomplished [9,10]. In similarly, the indentation depth modifications can be determined in the further deposited film layers, shown in figure 8a, up to the overall deposition time of 240 minutes. A further isothermal annealing of the deposited coating, affects the "layer" strength properties, as displayed in figure 8b. A 5 minutes annealing reduces the maximum indentation depth only in the upper thin "layer", from 161 to 150 nm,whereas a longer than 15 min annealing period increases the maximum indentation depth, in accordance to the results presented in figure 2.

The strength properties of a 10 μm coating were also determined versus the thickness by means of the previously described methodology (see figure 9a). The mechanical properties of the already existing "layers" are modified after the deposition of a new one, according to their location within the coating structure and to the annealing duration after their deposition. These properties are further affected, in the case of subsequent isothermal annealings of various durations, as displayed in figure 9b. Furthermore, the overall annealing time during the film deposition was longer than 120 minutes for all film layers, up to an overall film thickness of 8 μm. Hence, in accordance to the results shown in figures 4 and 6, the corresponding mechanical strength properties were stabilized, whereas the strength properties of the three upper "layers" depend on the annealing durations. A 60 minutes annealing maximizes the mechanical properties of the top layer. Through a further heat treatment of the same duration, i.e. for an overall annealing time of 120 min, all layer properties are stabilized, as demonstrated in the related graph at the bottom of figure 9b.

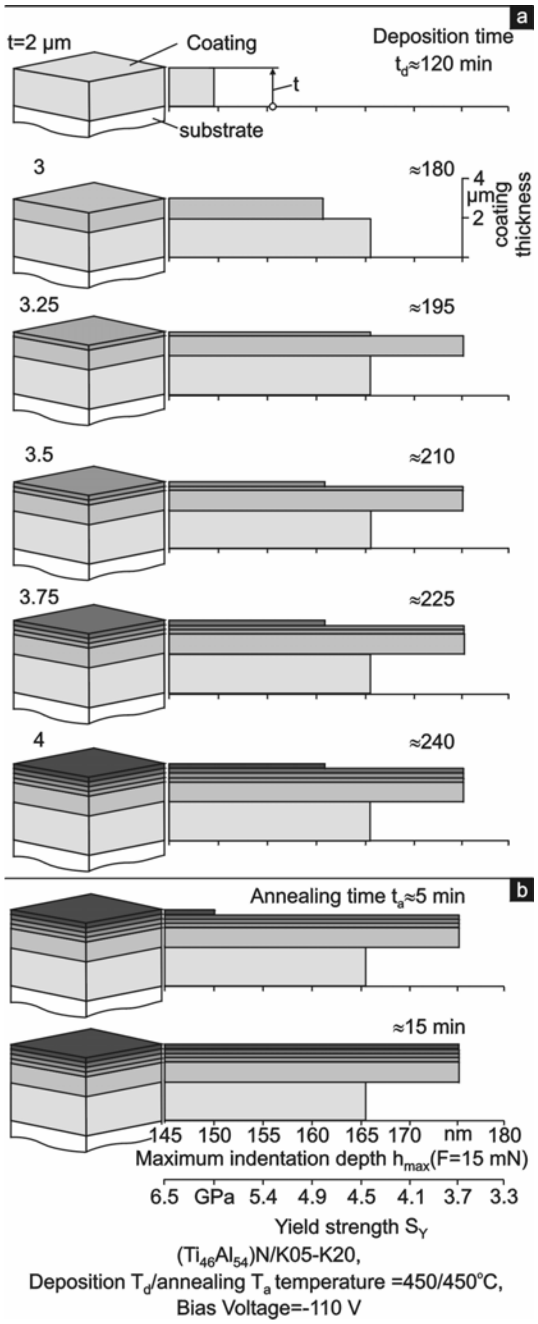

Figure 8. Occurring mechanical properties versus the coating thickness during the film deposition of a 4 µm thick film and their modifications due to a further annealing.

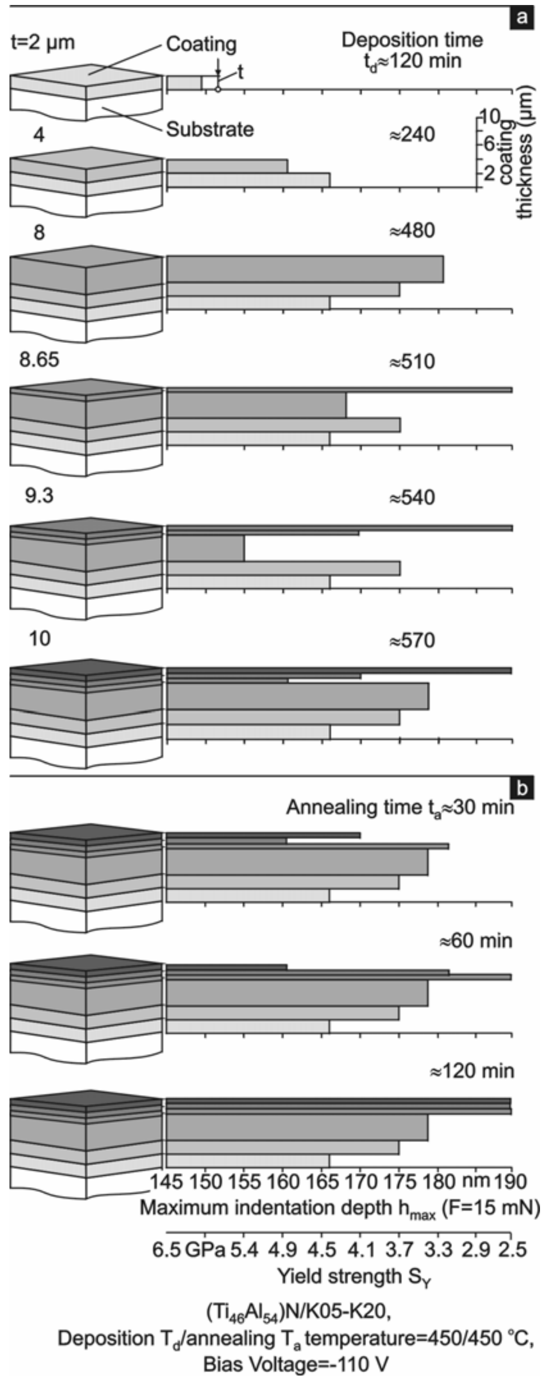

Figure 9. Resulting mechanical properties versus the coating thickness during the film deposition of a 10 µm thick film and their modifications owing to a further annealing.

4. VERIFICATION OF THE DETERMINED FILM MECHANICAL PROPERTIES GRADATION BY MEANS OF NANOINDENTATIONS

In order to check the validity of the predicted film mechanical properties stratification, occurring after the physical vapour deposition and isothermal annealings, nanoindentations were conducted. The stress field at an indentation force of 110 mN is exhibited in figure 10 in three cases concerning the film mechanical properties gradation. The calculations were conducted by means of the FEM supported simulation of the nanoindentation [20,21,22] and revealed that the occurring stress fields depend on the coating strength properties stratification. The stress distribution, in the third case, is associated to material properties, occurring after the film deposition, considering grain size and annealing effects during the PVD-process, as shown in figure 9. The measured course of the indentation depth versus the indentation force, displayed in figure 11a, was compared to the corresponding calculated ones, employing the FEM-based simulation of the nanoindentation. In the conducted calculations, film mechanical properties gradations were considered, as presented in figure 10.

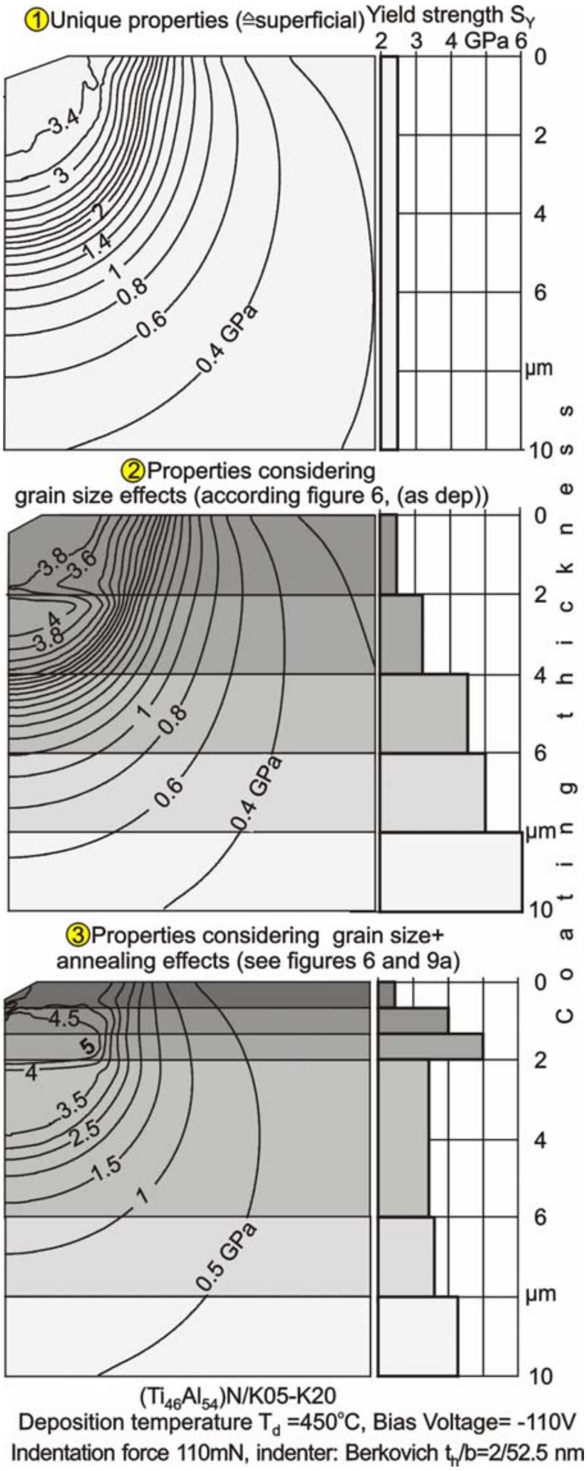

Figure 10. Occurring stress fields during nanoindentation, considering various assumptions, concerning the coating strength properties gradation.

The resulting force deviations dF_i/F_i between measured and calculated indentation forces versus the indentation depth, are illustrated in figure 11b. The force deviations due to the various stress fields, occurring during the indenter penetration (see figure 10), are lower than ±5%, only in the case that both grain size and annealing effects on the film strength properties were taken into account.

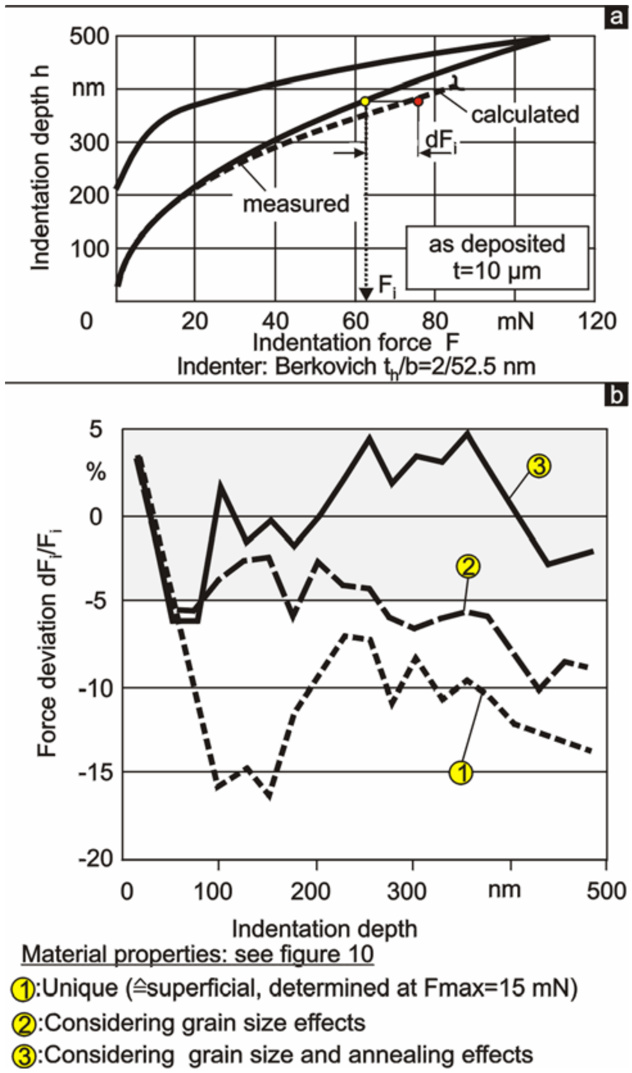

Figure 11. Deviations between measured and calculated nanoindentation forces versus the penetration depth, in the case of an as deposited coating, considering various assumptions concerning the film strength properties stratification.

Similar results were obtained in the case of the same 10 μm thick coating, annealed for one hour at 450°C. The measured indentation depth versus the indentation force is shown in figure12a. A slightly increased indentation force is required, from 110 mN up to 120 mN, in order to reach the same maximum indentation depth of ca. 0.5 μm, as in the case of deposited coating, shown in the previous figure. This behaviour can be explained considering the hardness growth in the top film layer due to annealing activation, as presented in figure 8. The force deviations dF_i/F_i are plotted versus the indentation depth in two cases, concerning the coating properties stratification (see figure 12b). In the first case the coating strength is assumed as unique versus the film thickness and in the second one graded, due to grain size and annealing effects. Only in the second case, the force deviations are lower than ±5%.

The described results show that only through the consideration of the predicted film mechanical properties gradations after the film deposition and isothermal annealings at deposition temperature as illustrated in figure 8 and 9, a precise description of the related experimental results can be achieved in the FEM based simulation of nanoindentation. In this way the found graded coating mechanical properties are verified.

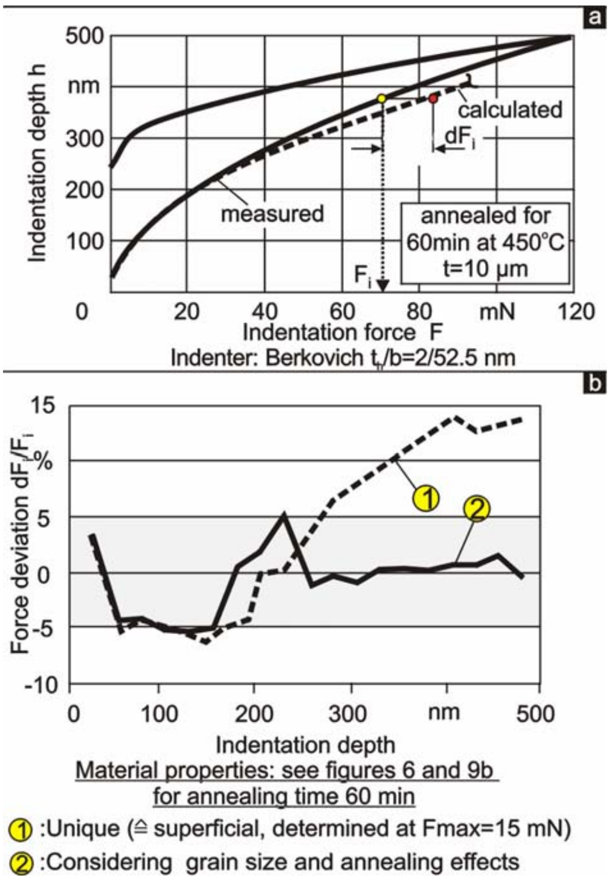

Figure 12. Deviations between measured and calculated nanoindentation forces versus the penetration depth, in the case of a coating, annealed for 1h at deposition temperature, considering various assumptions concerning the film strength properties gradation.

5. EFFECT OF THE ANNEALING DURATION ON THE WEAR BEHAVIOUR OF COATED CEMENTED CARBIDE INSERTS IN MILLING

In order to evaluate the influence of the annealing duration on the wear behaviour of coated cemented carbide inserts of various film thickness, various milling investigations were carried out. The experiments were performed using a 3-axis numerically controlled milling centre (see figure 13). A prescribed number of successive cuts was set, before every inspection of the cutting insert wear status and the flank wear was plotted versus the accumulated number of cuts. In the conducted investigations PVD coated carbides inserts with 4 and 10 µm film thicknesses were applied, annealed for different durations.

The inserts coated with a 10 µm thick PVD film show a superior wear behaviour in comparison to these ones with 4 µm thick films, as explained in [9,10]. In the case of a 10 µm thick coating, the wear resistance is maximized after 30 min annealing time. Herein a tool life of $145x10^3$ cuts was obtained, at a flank wear width of approximately 0.2 mm. A slight diminishing of the tool life occurs after 120 minutes annealing time, in comparison to the as deposited coating case. On the other hand, in the case of a 4 µm thick coating, the cutting performance is enhanced already after five minutes annealing, since the maximum tool life corresponding to 65 $x10^3$ cuts was reached, at the flank wear width of ca. 0.2 mm.

The achieved numbers of cuts are displayed versus the isothermal annealing duration, in figure 14a, in three coating thickness cases, up to the flank wear of 0.2 mm. The cutting performance has a maximum in both 8 and 10 µm film thickness cases, associated to an annealing duration of approximately 30 minutes, although the superficial hardness is maximized after a longer annealing time, of about 60 minutes (see figure 14b). On the other hand, the wear resistance of cemented carbide inserts, coated with a 4 µm thick film, is improved after only a 5 minutes annealing in accordance with the results presented in figure 13. In this case, the wear resistance and the superficial film hardness are maximized practically after the same annealing duration, as illustrated in figures 14a and 14b correspondingly. This behaviour will be theoretically explained in the next section.

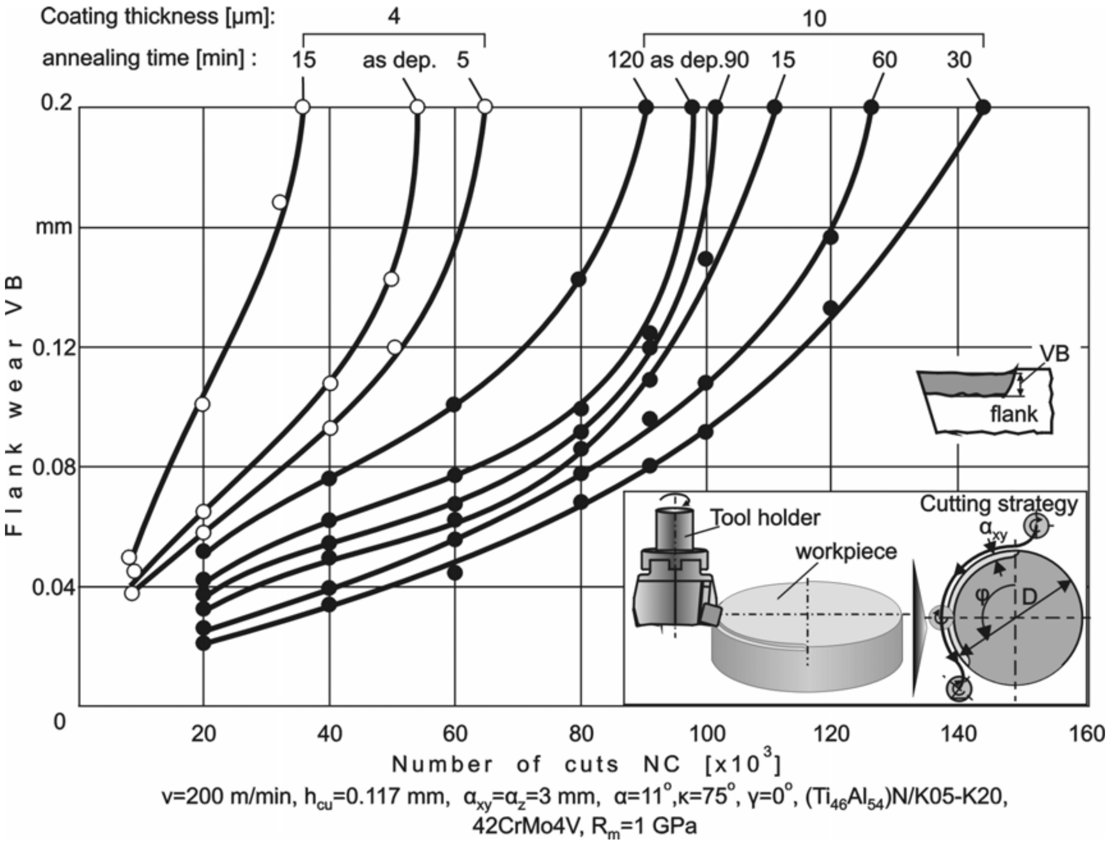

Figure 13. Flank wear development versus the number of cuts of coated cemented carbide inserts of various film thickness and annealing durations.

6. WEAR BEHAVIOUR INTERPRETATION, CONSIDERING THE COATED INSERTS CUTTING EDGE LOADS, BY MEANS OF A FEM SIMULATION OF THE CUTTING PROCESS

In order to explain the introduced experimental results in the previous sections, various calculations were performed, by means of the FEM-based model illustrated in figure 15a. This model simulates the cutting edge loads during the material removal [27,28]. The coated cutting edge is reasonably described by a plane strain model, as shown in figure 15b. The resulting cutting loads, triangularly distributed on the tool rake, are transformed in individual superficial normal (P_n) and tangential (P_t) pressures, acting on each finite element, within approximately the chip contact length ccl. The stress strain law of the cemented carbide substrate is displayed in figure 15c, whereas the coating "layers" strength properties are exhibited in figures 6, 8 and 9. These data are further considered in the cutting process FEM- simulation, to capture the effect of the annealing duration at deposition temperature, on the wear resistance of coated tools.

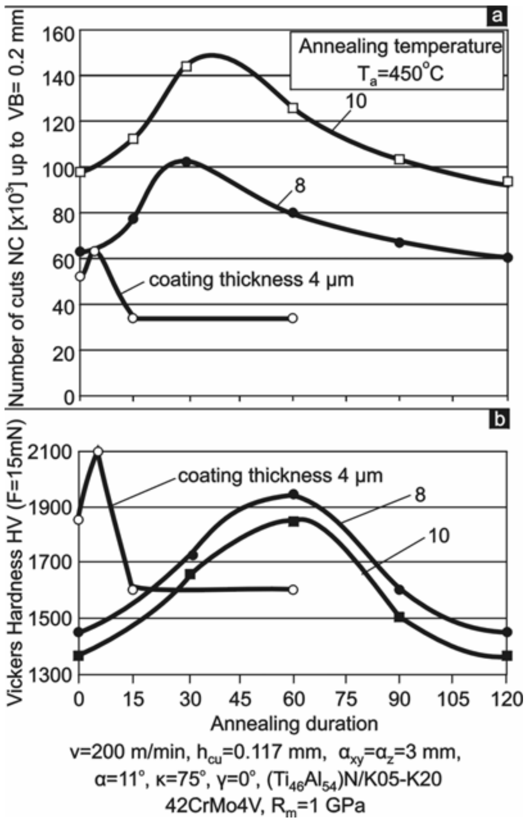

Figure 14. Achieved number of cuts up to a flank wear width of 0.2 mm, in different coating thickness and annealing cases.

The resulting stress distributions in milling are exhibited in figures 16a, 16b and 16c, when untreated coated inserts as well as annealed ones, for 5 and 15 minutes correspondingly are applied. The 4 μm film structure was simulated with two internal layers of 2 and 1 μm thickness respectively and 4 further ones, each one with a 0.25 μm thickness. The strength properties are modified due to annealing activation only in the superficial layer, since during the film deposition, in all internal "layers", the annealing lasted more than 15 minutes and thus according to the results introduced in figure 4, the area of the cutting edge, between flank and rake [6,8,30]. However, the improved mechanical mechanical properties are stabilized. Substrate micro-blasting is performed before the film deposition to enhance the coating adhesion and hence the cutting performance [29]. The coating fracture initiation in all investigated cases is caused mainly by film fatigue in the transient properties in the case of a 5 min annealed coating, compared to the related ones of an as deposited film, contributed to a fatigue strength increasing and to a wear resistance enhancement [8]. Furthermore, in the case of the film, annealed for 15 minutes, the coating is stressed over the yield strength in the transient cutting wedge region (see figure 16c). Stresses over the yield strength correspond to restricted number of cuts, until the coating failure initiation [8,9,10,30], thus accelerating the tool wear evolution.

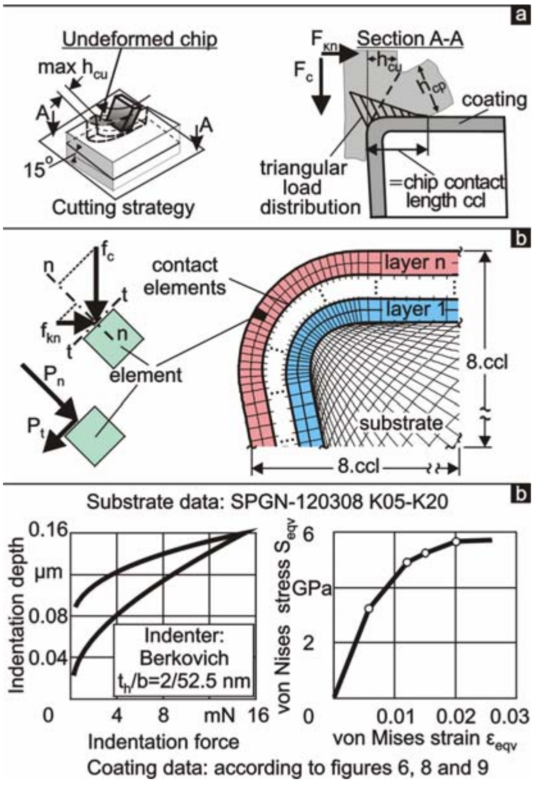

Figure 15. Milling process kinematics and FEM simulation of the coated tool loads.

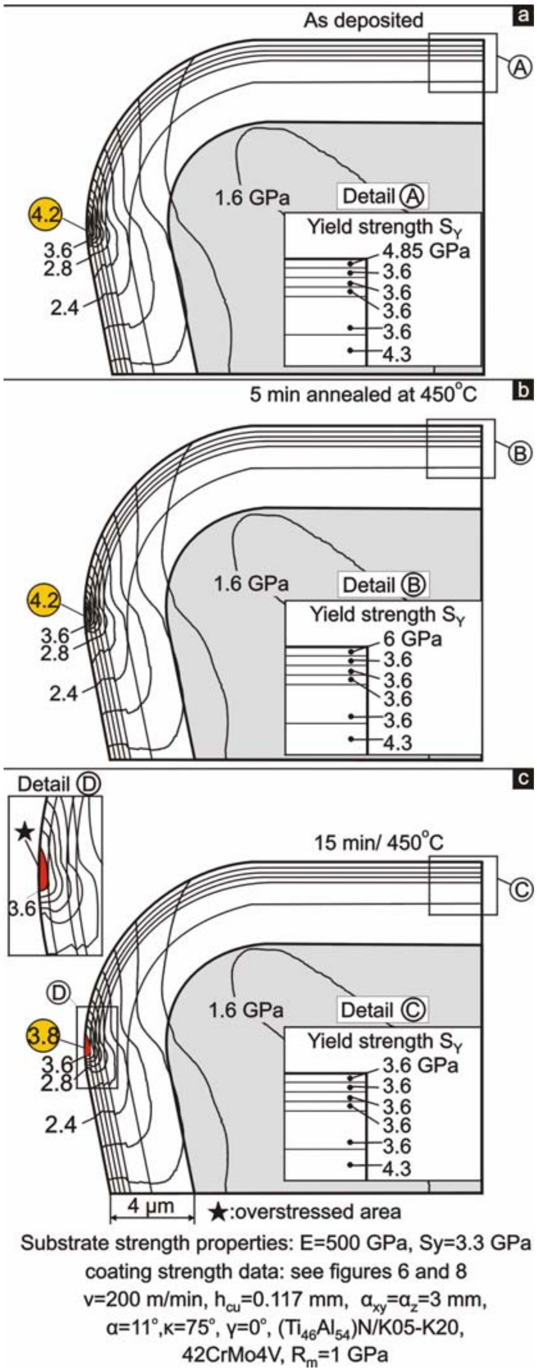

Figure 16. Stress distributions during milling within a 4 μm thick coating, annealed for various durations and considering the corresponding film strength properties gradations.

Taking into account the found coating strength properties stratifications, the stress distributions during milling, in a 10 μm thick coating, annealed for various durations, were determined (see figure 17). The thick coating was simulated with the aid of three internal layers, with a film thickness of 2, 2 and 4 μm respectively, and three upper ones, each one with a thickness of ca. 0.65 μm. The maximum von Mises equivalent stress, as expected, appears in all examined cases at the cutting edge roundness close to the flank. In the untreated coating case, the maximum equivalent stress amounts to 3 GPa, i.e. it is larger than the corresponding yield strength of the superficial coating layer (see figure 17a), thus, leading to a failure initiation in this layer, modifying the effective cutting edge roundness [9,10]. On the other hand, although an increase of the maximum equivalent stress from 3.1 to 3.7 GPa occurs, after an annealing duration of 30 minutes (see figure 17b), the improved strength properties of the two superficial layers prevent an early coating damage.

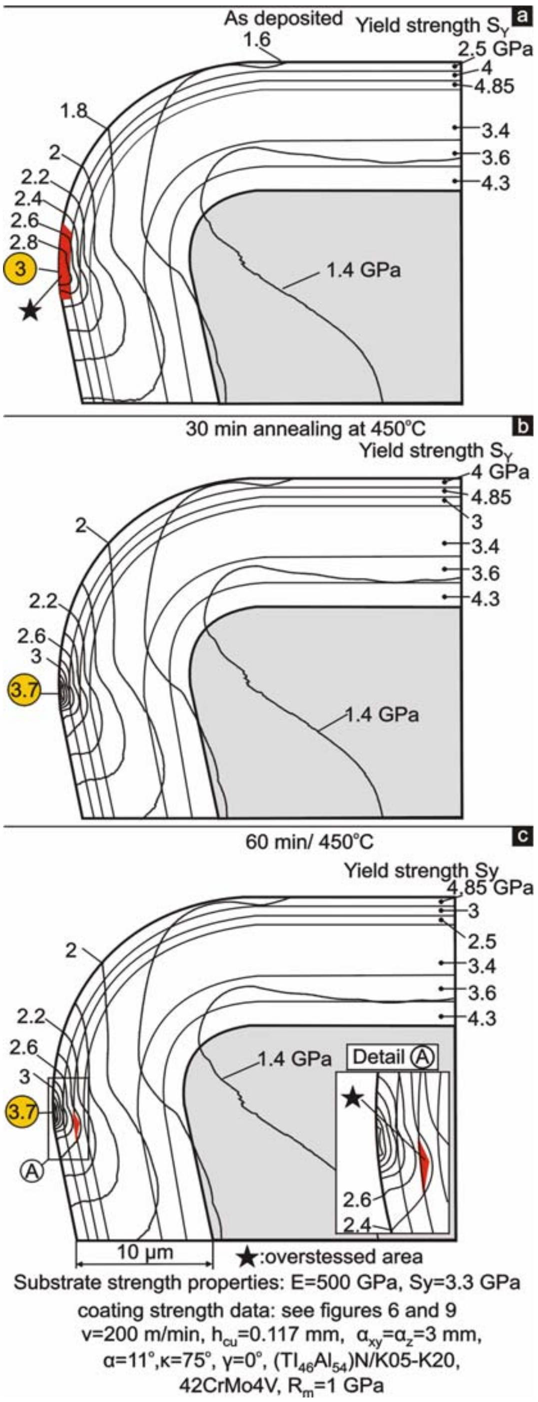

Figure 17. Stress distributions during milling within a 10 µm thick coating, annealed for various durations and considering the occuring film strength properties stratifications.

A further annealing up to 60 min, although the superficial hardness has reached its maximum, results to the development of an internal overstressed coating area, exhibited in figure 17c, hence, to a initiation of film failure due to the restricted number of cuts without coating fatigue damage [8,9,10,30] and to an accelerated progress of wear.

7. CONCLUSIONS

The potential of increasing the cutting performance of PVD TiAlN coated inserts with different film thicknesses, through isothermal annealing at deposition temperature was investigated. The graded coating strength properties were determined through nanoindentations and a FEM supported evaluation of the related results, after the deposition and annealings of various durations. The annealed coated cutting inserts were further examined in milling, revealing an enhanced cutting performance in the case of a 10µm coating, after an annealing for 30 minutes at 450°C, although the maximum superficial hardness was reached after a 60 minutes annealing time. On the other hand, the maximum superficial hardness and the wear resistance increase in the case of a 4 µm thick coating, were attained after a shorter (5 minutes) annealing duration. Finally, the obtained results were sufficiently explained through the developed FEM simulation of the cutting process.

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