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J.A. SMOLIK*

HYBRID SURFACE TREATMENT TECHNOLOGY FOR INCREASE OF HOT FORGING DIES

HYBRYDOWA TECHNOLOGIA OBRÓBKI POWIERZCHNIOWEJ DO ZWIĘKSZANIA TRWAŁOŚCI MATRYC KUŹNICZYCH

Hot working dies are influenced by three main factors causing their destruction: the cyclically changeable mechanical loads, intensive thermal shocks, as well as intensive friction, and erosion. Modification of surface properties with the use of hybrid plasma methods seems to be an effective way of improving its durability. The best known and widely used surface treatment hybrid technology is a combination of the nitriding process with the deposition of hard antiwear coatings by means of PVD methods. The designed composite layer "nitrided layer / Cr-CrN" was obtained with the use of the hybrid technology, which consist of ion nitriding followed by arc-evaporation coating deposition. The maintenance testing was performed on the forging dies employed for production of various parts in the automotive industry. The best durability was obtained for the dies used for the forging of rolling bearing tracks. In comparison with the durability of the dies subjected solely to the gas nitriding, nearly an increase of 600% in the durability was noticed.

Keywords: hybrid surface treatment technology; forging dies; multilayer coatings

W procesie obróbki plastycznej na gorąco matryce kuźnicze narażone są na działanie trzech głównych czynników niszczących: cyklicznie zmiennych obciążeń mechanicznych, intensywnych szoków cieplnych oraz intensywnego tarcia i erozji. Jednym z najbardziej efektywnych sposobów zwiększania trwałości matryc kuźniczych jest modyfikowanie właściwości warstwy wierzchniej matryc hybrydowymi technologiami obróbki powierzchniowej. Najbardziej znaną i jednocześnie najbardziej rozpowszechnioną technologią hybrydową jest połączenie procesu azotowania z osadzaniem twardych powłok o charakterze przeciwzużyciowym metodami PVD. Wybrana do badań warstwa hybrydowa typu „warstwa azotowana/powłoka Cr-CrN" została otrzymana z wykorzystaniem technologii hybrydowej będącej połączeniem procesu azotowania jarzeniowego oraz nakładania powłok metodą odparowania łukowego. Testy eksploatacyjne zostały przeprowadzone z wykorzystaniem matryc kuźniczych wykorzystywanych w produkcji różnych elementów dla przemysłu samochodowego. Najlepszą trwałość uzyskano dla matryc wykorzystywanych w procesie kucia bieżni łożysk tocznych. Opracowana hybrydowa technologia obróbki powierzchniowej umożliwiła uzyskanie blisko 6 krotnego wzrostu trwałości matryc kuźniczych, w porównaniu z trwałością matryc standardowych poddawanych jedynie procesowi azotowania.

1. Introduction

In the process of hot working, dies undergo an impact of three main factors causing their destruction: the cyclically changeable mechanical loading, intensive thermal loads, as well as intensive friction and erosion. In order to lower the yield point of the forged material, one needs to heat it to the temperature of 1000 to 1200°C. The cyclically changeable loading, resulting from the specificity of the forging process, makes the forging die heat up by the forged material and then cool down, also in a cyclic way. It is assessed that the temperature of the forging die surface may reach 600°C to 900°C [1]. Due to intensive, cyclic temperature changes in the surface of the forging die, which lead to thermal and structural stresses, very convenient conditions to produce a grid of cracks appear. This form of destruction of the forging die is called the thermal fatigue. All forms of structural disorder in the material of the forging die [2], e.g. carbide precipitations, point defects, dents, scratches, are locations of stress concentrations. A cyclic, changeable character of external mechanical loading, acting on the forging die during the process of production, results in fatigue phenomena known as the mechanical fatigue of the material. The intensity of the mechanical fatigue is accelerated by the cracks arisen due to the thermal fatigue, which cause an increase in the stress concentration in the zones of the cracks. The interdependence between the mechanisms of thermal and mechanical fa-

* INSTITUTE FOR SUSTAINABLE TECHNOLOGIES NATIONAL RESEARCH INSTITUTE, DEPARTMENT OF SURFACE ENGINEERING, 26-600 RADOM, 6/10 PULASKIEGO STR., POLAND

tigues make the researchers consider them simultaneously as one process of a thermo-mechanical nature. The effective way to improve the durability of forging dies is a modification of the surface properties by the constitution of layers or coatings having appropriate properties. This approach is justified by the fact that all the processes of the forging die destruction, i.e. the thermo-mechanical fatigue, plastic deformation, abrasive wear, and erosion, are located just in the surface layer of the die.

One of the most perspective directions of the development of surface engineering is related to hybrid technologies [3-4], which best fulfil the expectation of the industry concerning obtaining proper properties of the surface of tools and machine components. Hybrid technologies of surface treatment, being a combination of single processes in one multi-stage, continuous technological process, belong to the most advanced technologies in materials and surface engineering. This combination makes it possible to modify the surface properties to a considerable extent. As a result, hybrid technologies make it possible to modify the substrate surface properties and the properties of the deposited coatings. A proper selection of the properties of particular constituents of hybrid layers, i.e. the structure, chemical composition, morphology of the substrate and coating materials, gives a synergic effect.

The mostly known and widely used surface treatment hybrid technology is a combination of gas or glow-discharge nitriding process with the process of deposition of hard antiwear coatings by means of PVD methods. The effect of the hybrid technology with such a configuration is a hybrid layer consisting of a nitrided layer and a PVD coating deposited directly on it. The effectiveness of the "behaviour" of hybrid layers ("nitrided layer/PVD coating") in the process of increasing the durability of dies has been widely discussed in the literature [5-6]. One points out that their effectiveness differs depending on the properties of the nitrided layer and the deposited PVD coating. The best results in this scope were obtained for a hybrid layer "nitrided layer/CrN coating" [7]. A simultaneous occurrence of the two presented structure elements, i.e. the nitrided layer and CrN coating results in their synergic interaction. The nitrided layer increases the surface hardness and substrate resistance to plastic deformation, protecting in this way the CrN coating from a loss of internal cohesion and adhesion. The CrN coating plays an important role in an improvement of the hybrid layer properties – it constitutes a barrier isolating the substrate, and limiting the influence of external impacts on its destruction process.

2. Analysis of wear mechanism of forging dies covered by composite layer "nitrided layer/CrN coating"

The analysis of dies with a hybrid layer of the type – "nitrided layer/CrN coating", differing in the coating thickness [8], revealed a very important role of the CrN coating in mitigating the wear intensity of dies. An analysis of the hardness change of forging dies at various maintenance stages (Fig. 1) proved that in the initial maintenance period a factor decisive for limiting the wear intensity is, first of all, the thickness of the CrN coating. Thicker CrN coatings reduce more effectively an influence of the temperature of the forged material on the process of tempering of the die material. Owing to this, thicker CrN coatings prevent better the decrease in the hardness of the die during the forging process, and in the effect counteract the plastic deformation of the die more effectively.

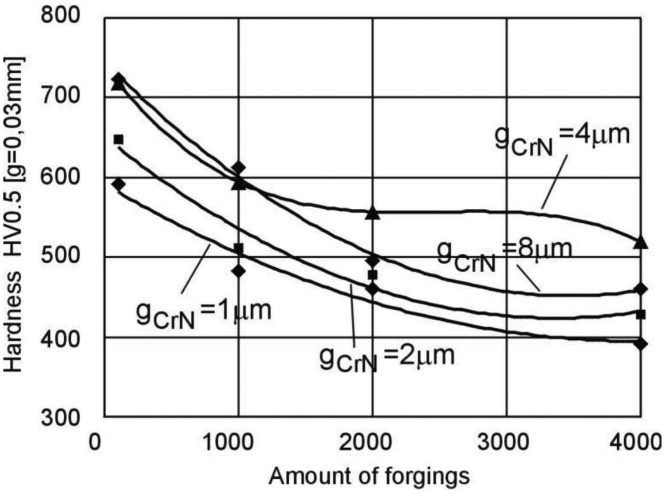

Fig. 1. Change of hardness at the depth of g=0.03 mm versus the number of produced forgings, for dies covered with CrN coatings having different thickness

A cyclic character of the forging process causes the coating resistance to thermo-mechanical fatigue to become more vital. As a result of the fatigue phenomena, in the material of the CrN coating a dense grid of cracks occurs, and this in the effect leads to the creation of spallings, which locally decrease the coating thickness, or even cause a complete substrate uncovery. A comparative analyses of the failure intensity of forging dies with nitrided layer/CrN coating hybrid layers after their various maintenance time (Fig. 2), as well as own stresses in CrN coatings versus their thickness (Fig. 3), revealed that CrN coatings having higher compressive stresses improve the fatigue durability in the forging process.

Based on the above, it seems to be well founded to conclude that the main role of a PVD coating as an component of a hybrid layer „nitrided layer/CrN coating"

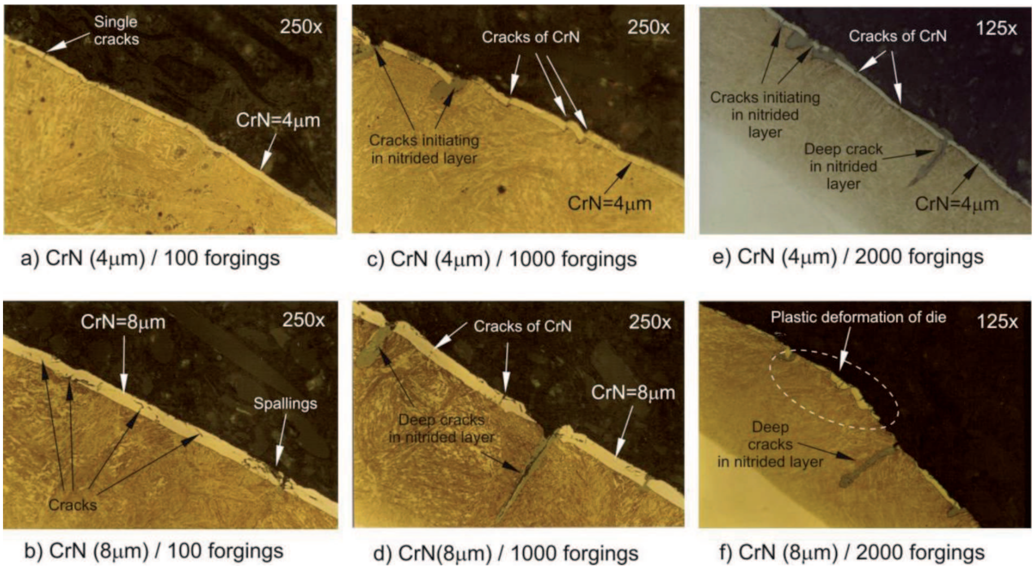

Fig. 2. Comparison of the intensity of destructions in 4 μm and 8 μm thick CrN coatings on forging dies after the execution of 100, 1000, and 2000 forgings

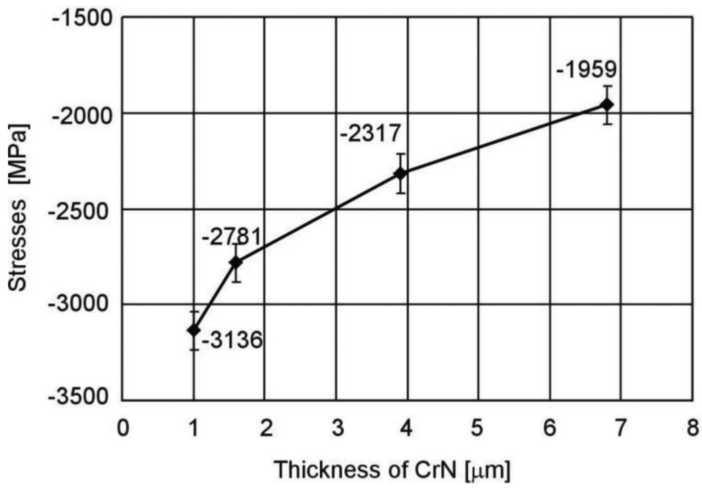

Fig. 3. Results of measurement of own stresses in CrN coatings of various thickness, deposited in the arc-vacuum process on the EN X38CrMoV5.3 steel substrate having the nitrided layer

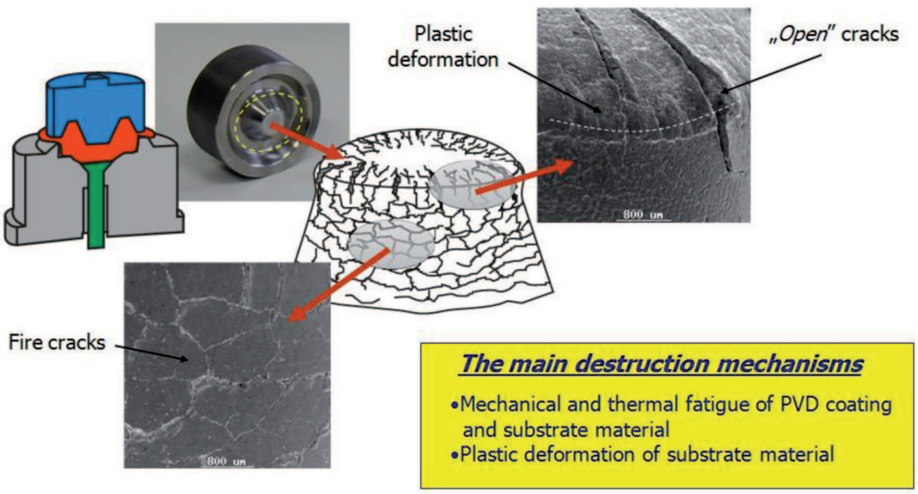

Fig. 4. Main mechanisms of destruction of forging dies having the hybrid layer "nitrided layer/CrN coating"

is to prevent from the influence of the high temperature, whose source is the forged material, and to resist the fatigue processes resulting from a cyclic character of the forging process (Fig. 4).

3. Optimisation of the composite layer "nitrided layer/PVD coating" for improving durability of forging dies

Based on the main destruction mechanisms of forging dies having the hybrid layer "nitrided layer/CrN coating" (figure 4), as the most effective optimisation direction of the hybrid layer „nitrided layer/PVD coating" leading to the increase of forging dies durability, an expansion of a single-layer PVD coating into the direction of a multi-layer coating on the basis of CrN and metallic Cr has been recognized. According to a multi-stage mechanism of multi-layer coatings destruction [9-10] described in literature, they are characterised by the increased crack resistance. Borders between subsequent constituent layers of a multi-layer coating are places, in which microcracks change their propagation directions or fade. This phenomenon decreases the possibility of microcracks propagation deep into the coating by prolonging the way of a single crack and reducing at the same time, its energy. According to numerous literature data [11-15], the multi-layer Cr-CrN coatings are characterised by a very good crystallographic matching of the subsequent constituent Cr and CrN [11] layers and the creation of several dozen nanometer thick crystal transient layer [12]. It ensures good coating's cohesion and in the end good maintenance properties: great adhesion [13], abrasive wear resistance [14] and better stress pattern [15]. Constituent layers of metallic chromium in multi-layer Cr-CrN coating compensate tensile stress triggered by the differences in the linear thermal expansion of steel (α_{Stal} =10-13x10^{-6} K^{-1}) and CrN (α_{CrN} =0.7x10^{-6} K^{-1}). The thermal expansion coefficient of chromium has an intermediate value $\alpha_{Stal}>\alpha_{Cr}>\alpha_{CrN}$ and amounts to α_{Cr} =4.5x10^{-6} K^{-1}. In the paper [14] it was proved that the occurrence of constituent layers with higher plasticity considerably increases the resistance of multi-layer coating to abrasive wear. The results of experimental studies show in this case a significant role of metallic chromium constituent layers which, through plastic deformation possibility, limit the operation of hard particles in the friction zone. The results of simulation studies presented in papers [16-17] proved that both the value of stresses initiated in the Cr-CrN coating, as well as its susceptibility to plastic deformations, indeed depend on its structure, i.e. order of deposited Cr and CrN layers towards substrate and mutual relation of their thickness. In case when the first constituent layer of Cr-CrN multi-layer coating directly connecting to substrate is a layer of metallic chromium, a stress relaxation occurs at the boarder of substrate and coating, and, as a result, a significant improvement of coating's adhesion with substrate can be observed. At the same time the most external constituent layer of Cr-CrN multi-layer should be CrN layer, which is the result ensures greater resistance to plastic deformation. In the paper [18] it was proved that in case of steel containing from 3% of Cr to 5.2% of Cr the thickness ratio Cr/CrN≈1/3 in Cr-CrN multi-layer coating ensures the most uniform distribution of stresses in two mutually perpendicular directions, in the plane parallel to surface. As a result of an analysis conducted in order to increase the durability of forging dies, a hybrid layer "nitrided layer/CrN coating" was selected as demonstrated in Fig. 5.

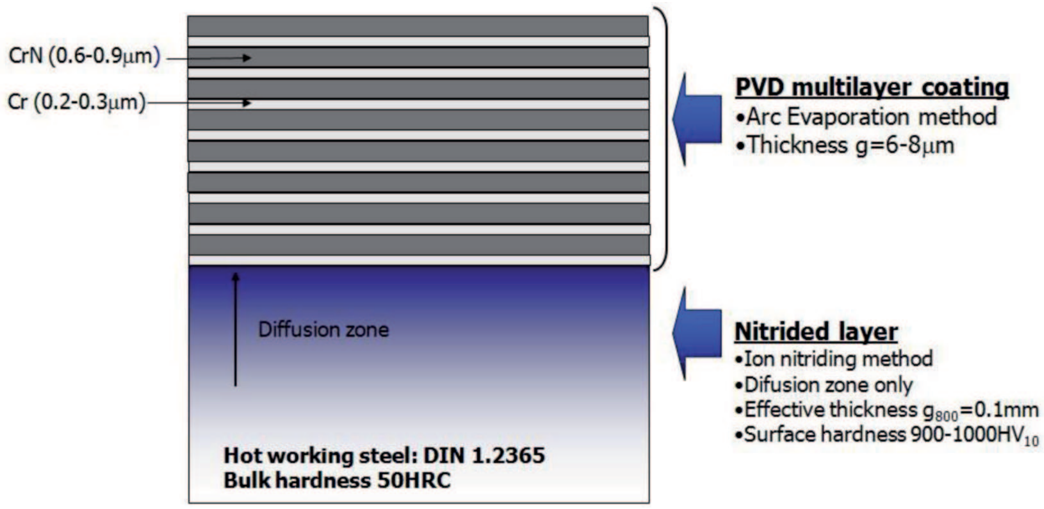

Fig. 5. Design of the hybrid layer „nitrided layer/multilayer Cr-CrN coating" intended for improving the durability of forging dies

4. Technological realization

A designed hybrid layer "nitrided layer/(Cr/CrN)x8" was obtained with the use of hybrid method which is a combination of ion nitriding process and coatings deposition by means of arc-evaporation on dies made of steel grade EN X32CrMoV3.3 intended for forging of rolling bearing track. To do so, *Standard* arc-vacuum device developed at ITeE-PIB in Radom was applied. Parameters of the hybrid technology developed are shown in Table 1. The structure and properties of the created hybrid layer are shown in Fig. 6.

5. Maintenance testing

In order to verify the effectiveness of the deposited hybrid layer for improving the durability of forging dies, maintenance testing of various types of dies under industrial conditions was carried out (Fig. 7).

TABLE 1

Hybrid technology stages of developing hybrid layer "nitrided layer/(Cr/CrN)x8" on steel EN X32CrMoV3.3

Stage	Temperature T [°C]	Arc current I_{ARC} [A]	U_{bias} [V]	Deposition time t [min]	Pressure p [mbar]	Atmosphere
Heating	to 520	–	–	–	2.5	25%Ar+75%H_2
Nitriding	520	–	–	120	4.3	8%N_2+92%H_2
Nitriding	520	–	–	120	4.3	6%N_2+92%H_2
Cooling	–	–	–	60	–	–
Ion etching	to 420	5 x 80	−950	1	$<10^{-4}$	–
Deposition Cr	380-420	5 x 80	−50	10	5.0 x 10^{-3}	100% Ar
Deposition CrN	380-420	5 x 80	−200	15	3.5 x 10^{-2}	100% N_2
Cooling	<200	–		120	$<10^{-4}$	–

Phase structure of nitrided layer	Diffusion layer only
Surface hardness	HV10=950-1050
Effective thickness g800	g800=0.15mm
Thickness of (Cr/CrN)x8 coating	g=8μm
Thickness of Cr interlayers	gCr=0.1-0.2μm
Thickness of CrN interlayers	gCrN=0.8-0.9μm
Hardness of (Cr/CrN)x8 coating	HV=1700-2100
Young modulus of (Cr/CrN)x8	E=280-340GPa
Friction coeficient: (Cr/CrN)x8-steel	μ=0.24-0.26
Roughness: Ra/Rz/Rt	0.27 / 1.49 / 2.65
Adhesion (*scratch-test*)	Fcohesive =15N Fadhesive = 80N Ftotal removing = 115N

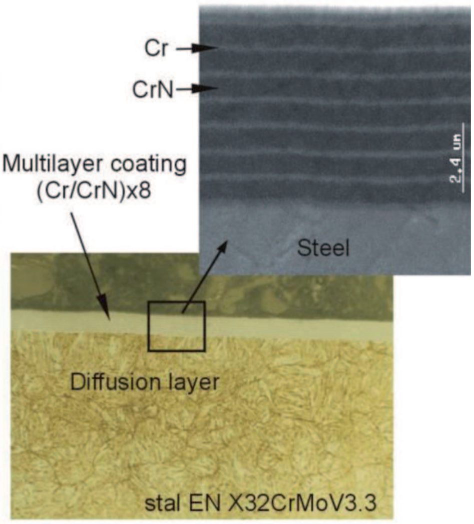

Fig. 6. Properties and structure of composite layer "nitrated layer/(Cr/CrN)x8

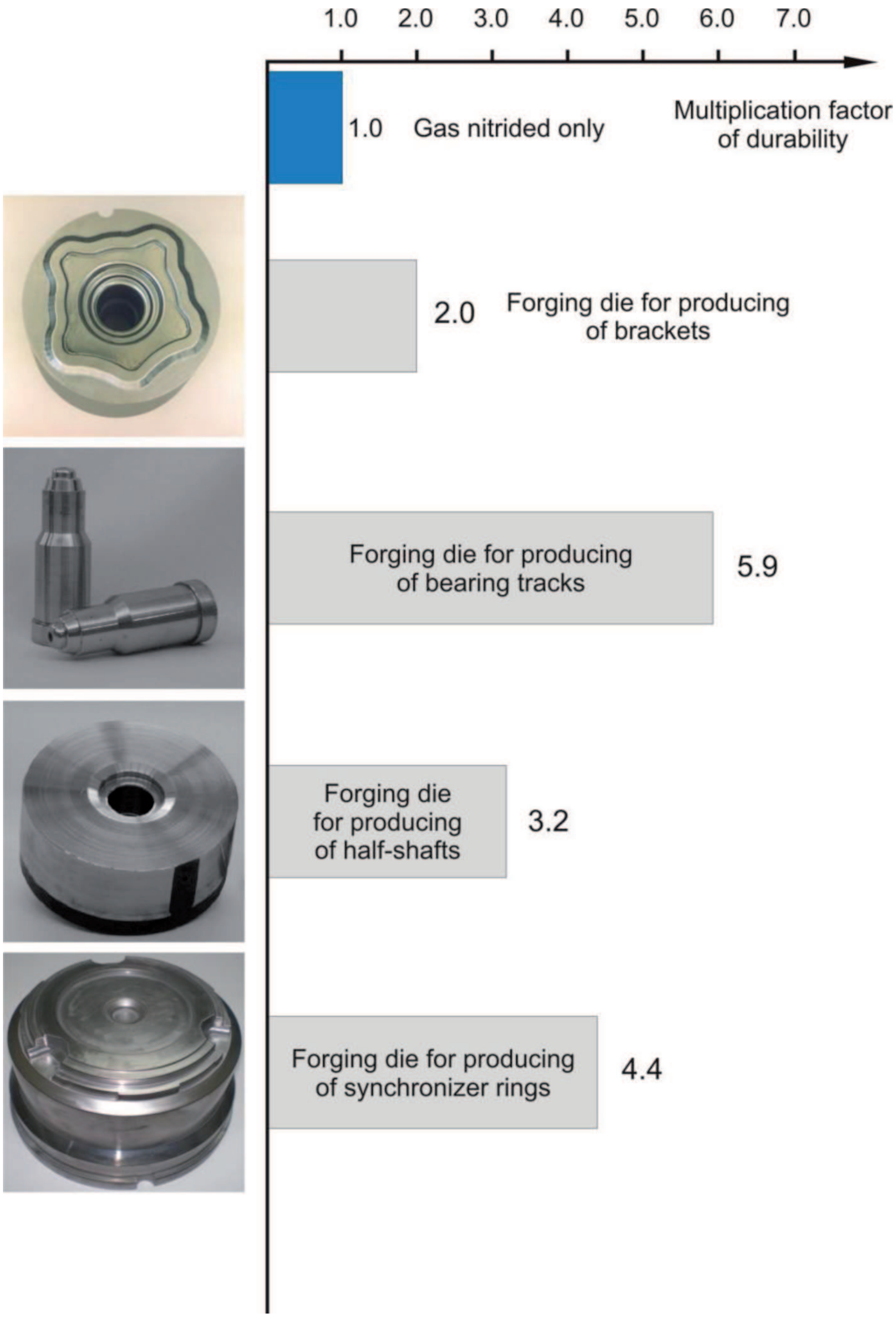

Fig. 7. Results of the maintenance testing for various types of forging dies covered with the hybrid layer "nitrided layer/Cr-CrN" according to the technology developed at ITeE-PIB in Radom

The maintenance tests were performed on forging dies made of DIN 1.2344 steel, employed for production of various parts in the automotive industry, i.e. brackets (EN 25CrMo4 steel), half-shafts (EN C45 steel), rolling bearing tracks (EN 100Cr6 steel), and synchronizer rings (EN 16MnCr5 steel). The forging process was realized in an automatic cycle using Hatebur-70 press. The forged material's temperature was 1150°C, and the die's temperature 250 to 300°C. In all forging processes emulsion lubricants based on the water-graphite solution were used. The assessment of the wear of the dies was carried out according to the quality procedures implemented in the forging shop, taking into account the surface parameters and tolerances of the forgings. The maintenance test results show that all the forming dies having the hybrid layer "nitrided layer/Cr-CrN" give better durability than the dies that had undergone only gas nitriding. The best durability was obtained for the dies used for the forging of rolling bearing tracks (59000 forgings produced). In comparison with the durability of the dies subjected solely to the gas nitriding (≈10000 forgings), near 6-tuple increase in the durability has been noticed (Fig. 7).

6. Summary and conclusions

The hardness change analysis of forging dies, with composite layers nitrided layer/CrN coating, at their various maintenance stages (Fig. 1), proved that in dies' initial maintenance period a key factor deciding for limiting the intensity of their wear is the thickness of CrN coating. Greater CrN coating thickness reduces the forging temperature's influence on the tempering of the die's material more effectively. Because of it, the thicker CrN coating prevents the decrease of the die's hardness in the forging process much better, and in the effect counteracts the die's plastic deformation more effectively. In further maintenance process, a cyclic character of forging process results in the situation where the die's material resistance to thermal and mechanical fatigue becomes more vital. As a result of fatigue processes in the material of CrN coating a dense grid of cracks occurs and this, in the effect, leads to the creation of spallings, which locally decrease the coating's thickness or even cause a complete substrate uncovery. A comparative analysis of the failure intensity of forging dies with nitrided layer/CrN composite layers after their different maintenance time (Fig. 2) and the state of own stresses in CrN coatings with various thickness, revealed that CrN coating with greater own compressive stresses (Fig. 3) are characterised by greater fatigue durability in the cyclic forging process. Based on the above, a conclusion that the main role of PVD coating as an element of composite layer „nitrided layer/CrN coating" is to counteract the influence of high temperature on the die material, seems to be justified. In order to realise this aim effectively PVD coating should fulfil two basic conditions: to be characterised with a considerably lower, thermal conductivity coefficient, compared to steel, and to possess appropriately high fatigue resistance so that it can effectively resist fatigue processes in the forging process.

The obtained results of maintenance testing revealed that composite layer „nitrided layer/(Cr/CrN)x8" ensures a multiple durability increase of forging dies applied in the process of forging rolling bearing tracks. According to the authors of this article, the above allows to state that the identification of destruction factors operating in the maintenance process and the identification of dominating surface destruction mechanisms is necessary to design hybrid layers for anti-wear purposes effectively.

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