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The wear mechanism of hybrid layer "PN+CrN" during the hot forging process

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Properties

ABSTRACT

Purpose: One of the most perspective development directions of surface engineering is related to hybrid technologies, which best fulfil the expectations of the industry concerning the obtainment of adequate properties of the surface of tools and machine components. The best known and widely employed hybrid technology of surface treatment using the diffusion phenomenon is the combination of gas nitriding or plasma nitriding (PN+CrN) followed by the deposition of hard, wear resistant coatings by the PVD methods. In this paper the wear mechanisms of forging dies, covered with the PN+CrN hybrid layer were analysed.

Design/methodology/approach: The hybrid layers PN+CrN selected for testing were obtained by means of a multi-stage technology of surface treatment encompassing plasma nitriding (PN) and arc-evaporation process. Maintenance tests were conducted at Institut für Umformtechnik und Umformmaschinen in Hannover, according to different forging time.

Findings: It was demonstrated that the dominating mechanisms of the wear process of forging dies covered with the PN+CrN hybrid layer are: thermo-mechanical fatigue of the CrN coating and thermo-mechanical fatigue and plastic deformation of steel substrate.

Research limitations/implications: The CrN coating is of great importance in the wear process of forging dies covered with the PN+CrN hybrid layer. Very important in the die wear process is the resistance of the CrN coating to brittle cracking. CrN coating reduces, and as a result significantly limits, stresses initiated in the substrate in the forging process by the operation of external impacts. According to the results of simulation tests, 3 μm-thick CrN coating limits stresses initiated in material and hence reduces the possibility of plastic deformation occurrence in substrate.

Practical implications: The obtained results of the tests have been practically applied in the surface engineering laboratory to develop modern surface engineering solutions aimed at increasing the effectiveness of different hybrid layers PN+CrN.

Originality/value: In order to ensure the required level of effectiveness of the use of layered composites of the PN+PVD type to increase the durability of forging dies, it is necessary to properly select the composites on the basis of the analysis of the intensity of forging dies wear mechanisms.

Keywords: Hybrid surface treatment technology; Thin coatings; Composite layers; Forging dies

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1. Introduction

One of the most perspective directions in the development of surface engineering is related to hybrid technologies [1-4], which best fulfil the expectations of the industry concerning the obtainment of 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 material and surface engineering. This combination makes it possible to modify surface properties to a considerable extent. In the effect, hybrid technologies enable the modification of 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, causes a synergic effect. This approach gives many possibilities of a modification of the surface properties that, using standard surface treatment techniques, would be impossible. The current development of hybrid technologies for coatings and layers focuses on the two main research directions: hybrid technologies using various surface treatment methods step by step [5-6] and multi-source hybrid technologies employing various surface treatment methods simultaneously in the same time of technological process [7-8].

The best known and widely employed hybrid technology of surface treatment using the diffusion phenomenon is the combination of gas nitriding or ion nitriding followed by the deposition of hard, wear resistant coatings by means of PVD methods [9-10]. The effect of the hybrid technology with such configuration is a hybrid layer consisting of a nitrided layer and a PVD coating deposited directly on it. A simultaneous occurrence of the two presented structure elements, i.e. the nitrided layer and PVD coating, results in their synergic interaction. The nitrided layer increases the surface hardness and substrate resistance to plastic deformation in the near-surface zone. This gives the higher stiffness of the substrate-coating system, protecting in this way the PVD coating from a loss of internal cohesion and adhesion to the substrate. The consistent PVD coating constitutes a barrier isolating the substrate nitrided surface and limiting the influence of external impacts on its destruction process. An appropriate modification of the PVD coating properties enables to achieve reduction in the friction coefficient, increase in resistance to abrasive wear, and improvement in thermal resistance.

Due to special properties of the hybrid layer of the nitrided layer /PVD coating type hybrid layers are more widely applied in industry, especially in respect of increasing the durability of tools, including dies for aluminium pressure casting [11-12], tools for cold plastic treatment [13] and hot forging dies [14-15]. Examples of the practical employment of hybrid layers of the nitrided layer /PVD coating type confirm their effectiveness in increasing the durability of tools utilised in very difficult working conditions. They clearly indicate the great importance of the correct maintenance conditions-adjusted selection of hybrid layer components, including the particularly thin PVD coating. At the same time, based on the results of research works concerning the effectiveness of the practical use of hybrid layers of “the nitrided layer /PVD coating type” [16-18], one has to conclude that the effectiveness of the hybrid layers of the nitrided layer /PVD coating type may differ, depending on the sort of the substrate material and the sort of the treated material. Therefore, very important seems to be the question: *How should the properties selection process of a hybrid layer of the nitrated layer /PVD coating type be best carried-out in order to increase the durability of tools in a specific industrial application?* In this case it is crucial to accurately recognise the destruction mechanisms and their triggers with reference to specific types of tools. Maintenance tests of dies working till a complete wear provide information enabling only a comparison of different hybrid layers in respect of their effectiveness in the process of increasing the durability of covered tools or machine elements. They also create a basis for an appropriate selection of materials and a type of surface treatment. They do not, however, provide sufficient data on an efficient optimization way of a given hybrid layer, so that its effectiveness in increasing the durability would be as high as possible. An intentionally led optimisation of a hybrid layer requires an analysis of its wear mechanisms in a specific application during the whole maintenance process.

The paper presents the results of a scientific experiment which was aimed at recognising the wear mechanisms of the hybrid layer „nitrated layer /CrN coating” during the execution of the hot plastic treatment process.

2. Experimental

2.1. Parameters of maintenance tests

Maintenance tests of dies working till their complete wear provide information enabling only the comparison of different hybrid layers in respect of their effectiveness in the process of increasing the durability of covered tools or machine elements. They also create a basis for the selection of materials and the type of surface treatment. They do not, however, provide sufficient information on an efficient optimization way of a given hybrid layer, so that its effectiveness at increasing the durability would be as high as possible. An intentionally led optimisation of a hybrid layer requires an analysis of its wear mechanisms in a specific application during the whole maintenance process.

The examination of tool wear mechanisms requires in each case a very thorough selection of parameters of conducted maintenance tests. It is necessary to select specific test parameters so that their lasting time could be shortened to the maximum and, at the same time, the obtained results would enable to formulate as detailed as possible conclusions on wear mechanisms of the examined tools. In order to properly select the post parameters of the maintenance tests for forging dies with the generated hybrid layer of the nitrided layer /PVD coating type the results of maintenance tests conducted in industrial conditions [19-21] presented in Fig. 1 were analysed. The conducted analysis allowed to assess the impact of various factors on the durability of dies for hot plastic treatment, including: automation degree of the forging process (automatic or non-automatic), temperature parameters of forging process, types of die material, type of material treated and type of PVD coating and its thickness in the hybrid layer of the nitrided layer /PVD coating type.

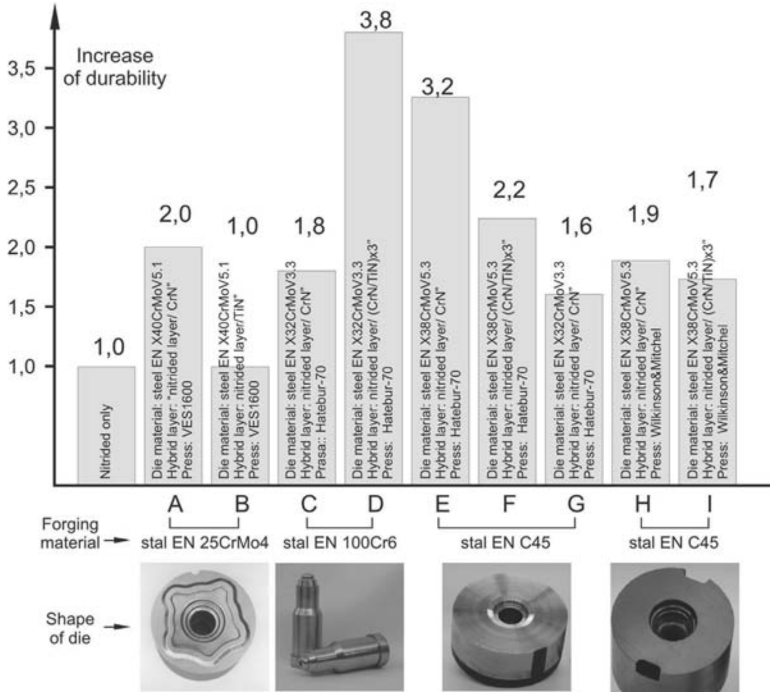

Fig. 1. Results of maintenance tests in industrial conditions for forging dies with various hybrid layers of the nitrated layer /PVD coating type [19-21]

Automation of the forging process

The comparison of forging results presented in Fig. 1, obtained in the automatic cycle (Hatebur press) and the non-automatic cycle (Wilkonson&Mitchel press), achieved for the same tool material, the same forged material and the same hybrid layer (E-H and F-I) demonstrated from 30% to 70% higher durability growth in case of the automatic process. The automatic forging process ensures greater stability and repeatability of technological parameters, i.e. die temperature, forged material temperature, cooling and lubricating intensity as well as forging frequency.

Forged material

The assessment of impact of the forged material on the durability of forging dies is very difficult. Generally, it has to be stated that the occurrence of Mo, Ni and Ti in the chemical composition of forged material reduces its plasticity, which – according to the author – reduces the die lifetime. Based on the above it can be stated that out of three sorts of steel:

- EN 25CrMo4 – 0.25%C; 0.75%Mn; 0.4%Si; 1%Cr; 0.2%Mo;
- EN 100Cr6 – 1%C; 0.3%Mn; 0.25%Si;, 1.5%Cr;
- EN C45 – 0.45%C; 0.65%Mn; 0.4%Si; 0.4%Cr; 0.1%Mo; 0.4%Ni;

of which forgings were made, EN 100Cr6 steel was characterized by the best plasticity while EN C45 by the worst. The results of the maintenance tests conducted for the C and G dies (Fig. 1), that can be applied with different forged steels, demonstrated after all their very similar durability, despite significant differences in the content of Mo and Ni. The reason for such a small difference in the durability of the above dies may be both differences in their shapes and the parameters of the nitrided layer and the PVD coating. In this case a special attention must be paid to differences in the thickness of the CrN coating for both dies. In case of the die marked with the G symbol the thickness of the chromium nitride coating amounted to $g_{G\text{-}CrN}$=6 μm and was by 30% higher than for the C ($g_{C\text{-}CrN}$=4.5 μm) die. In the work [22] it was demonstrated that in case when $\lambda_{of\ coating} < \lambda_{of\ substrate}$ the thermal flux flowing into the substrate decreases in direct proportion to the coating thickness. Taking into account the conclusion formulated by the author, stating that limiting the thermal flux to the die matters greatly to increasing the die durability, it can be adopted that in case of the G die it was the increased thickness of the CrN coating, which might have significantly risen its durability. As a result, despite harder maintenance conditions, its durability is not much worse than of the die marked with the C symbol, for which the forged material was EN 100Cr6 steel.

Die material

The subject of testing and assessment were forging dies made of three sorts of steel, intended for hot working:

- EN X40CrMoV5.1 – 0.39%C; 1.1%Si; 0.4%Mn; 5.2%Cr; 1.4%Mo; 0.95%V;
- EN X32CrMoV3.3 – 0.31%C; 0.3%Si; 0.35%Mn; 2.9%Cr; 2.8%Mo; 0.5%V;
- EN X38CrMoV5.3 – 0.35%C; 0.3%Si; 0.4%Mn; 4.7%Cr; 2.5%Mo; 0.2%Ni; 0.7%V.

The absolutely best results were achieved for EN X38CrMoV5.3 steel containing nickel additive. Nickel reduces the critical quenching rate and as a result the internal stresses decrease after thermal treatment. This parameter is especially important in the forging process of materials with lower plasticity as for example EN C45 steel. From among three sorts of steel for hot working that were analysed, the EN X38CrMoV5.3 steel is also characterised by the lowest value of martensite start temperature $t_{Ms} \approx 240^{o}$C. According to the author, exactly this sort of steel will be characterised by a lower than others value of structural tensions initiated in the maintenance process.

Shape of test die

Another very important stage of maintenance test selection is the choice of die shape. The analysis of dies of different shapes and the assessment of damage intensity of dies employed in industrial forging processes (Fig. 1 and Fig. 2) demonstrated that the die edges and the places with the smallest cross-section with intensified thermal impacts and stress concentration are subject to the most intensive wear.

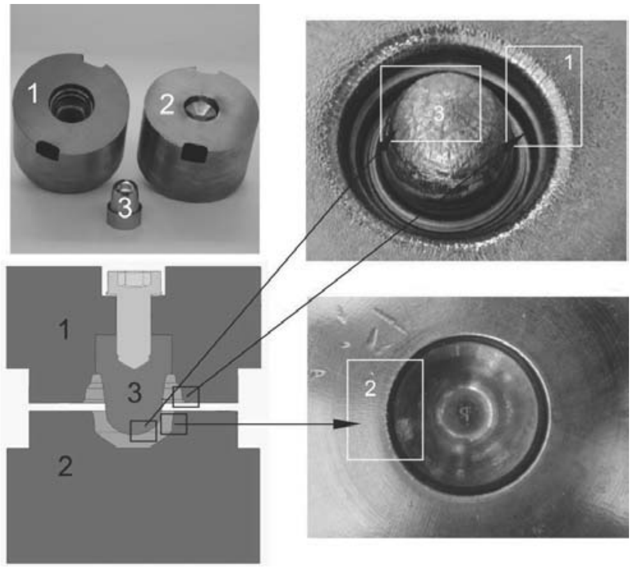

Fig. 2. Comparison of wear intensity in different places of forging dies

Based on the conducted analysis, it has been adopted that the shape of the die which will successfully enable to determine the wear mechanisms of tools for hot forging with the generated hybrid layer of the nitrided layer / CrN type, will be cylindrical shape with centrally placed pivot in form of a chamfered cone (Fig. 3).

Temperature parameters of forging process

Simulation tests were carried out for the die selected for tests, of shape shown in Fig. 3, in order to evaluate how temperature parameters of forging process, i.e. temperature of forged material – t_K and die temperature – t_M, impact the value of mechanical loads having an effect on the die. The simulation tests were carried out with the use of Forge3 f-my Transvalor software [23-24] for three different temperature parameters of forging process, adopting EN X38CrMoV5.3 steel as die material and EN C45 steel as forged material (Fig. 4).

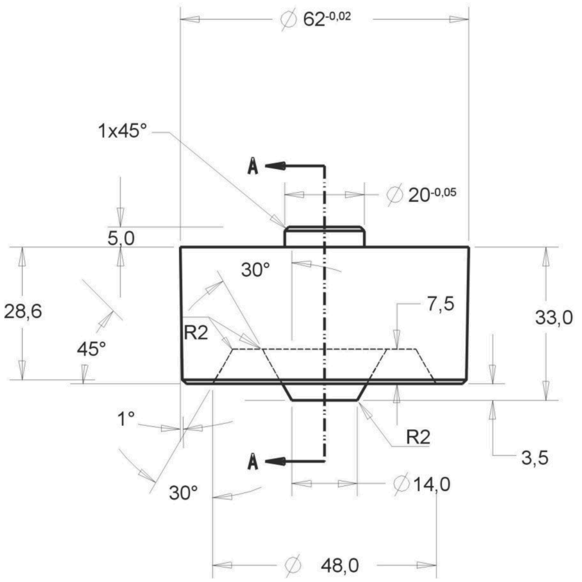

Fig. 3. Shape of forging die selected for maintenance tests

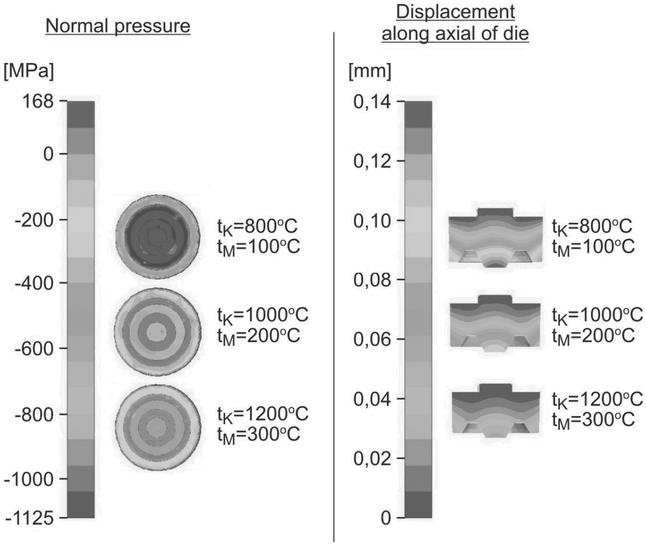

Fig. 4. Results of the simulation tests carried out for forging dies selected for maintenance tests, by means of the Forge3 software

The simulation tests enabled first of all (Fig. 4) the evaluation of normal pressures on the front surface of the pivot, which for the three analyzed temperatures of the forged material 800^{o}C, 1000^{o}C and 1200^{o}C amount to respectively: P_{800}=1100 MPa, P_{1000}=800 MPa, P_{1200}=500 MPa. Next, based on these results, it has been demonstrated that the places mostly exposed to plastic deformation are the surface of the centrally placed pivot, and above all the R_2 edge between the lateral and front surface of the cone. It was also demonstrated that the intensity of these damages decreases along with the temperature increase of forged material. The appropriate selection of maintenance parameters should ensure comparable values of plastic limit of the die material and pressures occurring during maintenance. This will protect the die against failure-inducing wear and will simultaneously ensure great destruction intensity of the die. Taking account of the fact, that the surface layer of die may warm up to the temperature >600°C [25], it must be stated that the plastic limit value for the analysed steel after hot working (≈500 MPa) is comparable with the occurring pressures only in case when forged material temperature t_K=1200°C.

PVD coating material

Analysis of impact of different PVD coatings in hybrid layer of the nitrided layer /PVD coating type on maintenance durability of forging dies (Fig. 1) demonstrated that for the same forged materials, the same die materials, as well as the same character of forging process (automatic or non-automatic process) the dies with CrN coating were characterised by higher maintenance durability than dies with TiN coating or (CrN/TiN) x3 multi-layer coating. Among the PVD coatings under investigation CrN coating has by far the lowest thermal conductivity and at the same time the highest resistance to oxidation ($t_{O2(CrN)}$=720°C, λ_{CrN}=0.183 $Wcm^{-1}K^{-1}$) [26-27]. This was proved by the testing of wear intensity of E and F dies after maintenance process, out of which the former (E) covered with CrN coating forged 33400 shapes, while the latter (F) covered with (CrN/TiN)x3 multi-layer coating forged 21200 shapes. In the case of the die with CrN coating much lower friction wear, as well as much lower intensity of damage as a result of thermo-mechanical fatigue was observed. The effect was even more obvious for dies collaborating with forged material of lower plasticity, i.e. with EN C45 steel containing Mo and Ni.

In order to evaluate the distribution of stresses initiated in die through external forces impact in the forging process a computer simulation was carried out using ELASTICA 3.0 software by ASMEC [28-29]. The simulation was carried out for steel substrate covered with 50 μm-thick CrN coating. Material data, necessary for the simulation, provided in Table 1, were adopted from the library provided together with ELASTICA 3.0. The analysis was carried out up to depth of 3 μm assuming pressure with spherical indenter of 10 μm radius with force of 10 mN.

Results of simulations presented in Fig. 5 demonstrated that value of stresses generated in the forging process as a result of external forces does not exceed tension resistance for chrome nitride (Rm_{CrN}=9GPa). Maximum stresses occur on the depth of ca. 0.3 μm and amount to ca. 6.5 GPa. Stress distribution makes it possible to indicate minimum thickness of CrN coating ensuring that value of stress in the substrate would not exceed its plasticity limit. Assuming the plasticity limit for EN X38CrMoV5.3 steel substrate (Table 1) $Re_{Substrate}$=1.6 GPa, in order to ensure lower-than-the-above value of stress in the substrate, the minimum thickness of CrN coating should amount to ca. 1.6 μm. However, as a result of heating the near-surface zone of a die to the temperature of >600°C, the plasticity limit of different sorts of steel intended for hot working decreases to the value of ca. 500 MPa. The simulation carried out (Fig. 5) demonstrated that stress below this level occur only in the distance of >3 μm from the surface.

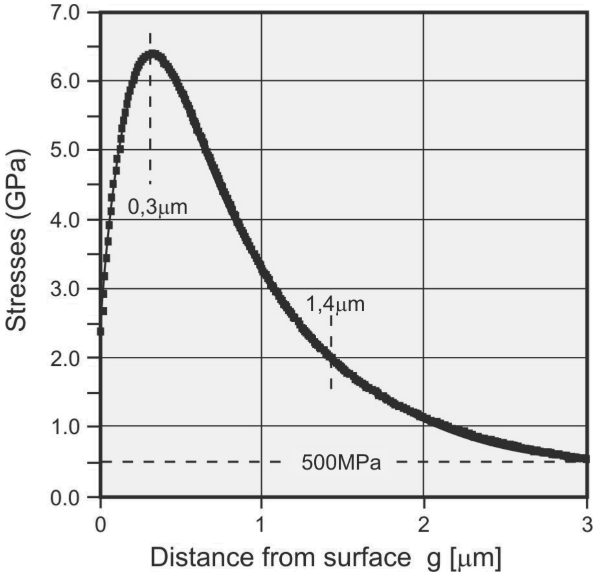

Fig. 5. Simulation of stress distribution versus distance from the surface for steel substrate covered with 50μm –thick CrN coating, carried out using ELASTICA 3.0 software

Taking into account the possibility to decrease plasticity limit of die material to the level of ca. 500 MPa as a result of contact of a tool with forged material one needs to assume that the minimum thickness of CrN coating that would effectively withstand mechanical loads affecting die will be coating of thickness of >3 μm.

On the basis of analyses carried out, in order to evaluate mechanisms of destruction of hybrid layer of the nitrated layer /PVD coating type, the following maintenance parameters were adopted:

- die material: hot working steel EN X38CrMoV5.3 – hardness after thermal treatment 48-50 HRC;
- effective thickness of nitrated layer: g_{800}=0.1 mm;
- PVD coating: chrome nitride – CrN;
- forged material: carbon steel EN C45;
- automatic forming process: Eumuco press, Maxima SP30a;
- die temperature: t_M=300°C;
- forged material temperature: t_K=1200°C.

Table 1.
Material data adopted for simulation of stress distribution, using ELASTICA 3.0 software

	Material	Young's modulus E, GPa	Poisson constant ν	Density g, g/cm^3	Strength parameters
Indenter	Diamond	1100	0.10	3.51	Rm=50 GPa
Substrate	Steel	200	0.30	7.80	Re=2 GPa
Coating	CrN	300	0.25	2.80	Rm=9 GPa

Table 2.
Stages of production technology of layered composites on dies for the production of gears pre-forging and steel synchronizer rings

Stage	Name of the stage	Temperature T, °C	Voltage U_{bias}, V	Arc current I, A	Time t, min	Pressure p, mbar	Atmosphere
1	Heating	to 520	-	-	-	2.5	25%Ar+75%H_2
2	Nitriding	520	-	-	420	4.3	15%N_2+85%H_2
3	Soaking	520	-	-	360	4.3	100%H_2
4	Cooling	-	-	-	60	-	-
5	¹⁾ Ion etching	to 420	–950	5x80	1	< 10^{-4}	-
6	¹⁾ Break	-	-	-	1	< 10^{-4}	-
7	CrN Coating	²⁾ 380-420	–200	5x80	120	3.5 x 10^{-2}	100%N_2
8	Cooling	<200	-	-	120	< 10^{-4}	-

Remarks:
1) Stages (5) and (6) are to be realised consecutively until the temperature of the substrate T=420ºC is reached
2) In stage (7) temperature in the range of 380-420ºC

Table 3.
Parameters of forging process

Device	Forging load, T	T_{die}, °C	$T_{material}$, °C	Cooling
Eccentric press	3150	300	1200	Graphite + water

2.2. Hybrid layer deposition parameters

The hybrid layers PN+CrN selected for testing were obtained with the use of a multi-stage technology of surface treatment encompassing plasma nitriding (PN) and arc-evaporation processes realised with the use of a hybrid technological device produced at ITeE-PIB in Radom. The technological parameters of the production of selected hybrid layers are presented in Table 2.

2.3. Maintenance tests and materials investigations

Maintenance tests were conducted in Institut für Umformtechnik und Umformmaschinen in Hannover, according to the parameters presented in Table 3. At the same time, in order to carry out the analysis of destruction mechanisms of forging dies versus their maintenance time, individual parts of tools forged respectively: 100, 1000, 2000 and 4000 shapes.

The following material properties were determined for all obtained hybrid layers:

- the hardness and Young's modulus of the PVD coating (*Nano Hardness Tester*);
- the distribution of hardness and morphology of nitrided layer (*Neophot 32, Future TECH*);
- the cracking intensity in the nitrided layer and CrN coating (Neophot 32, SEM) and the morphology of the surface (SEM).

3. Results and discussion

3.1. Metallographic investigations

The results of metallographic investigations for forging dies coated with PN+CrN hybrid layer, after forging different number of shapes, were shown in Fig. 6. Detailed analysis of near-surface

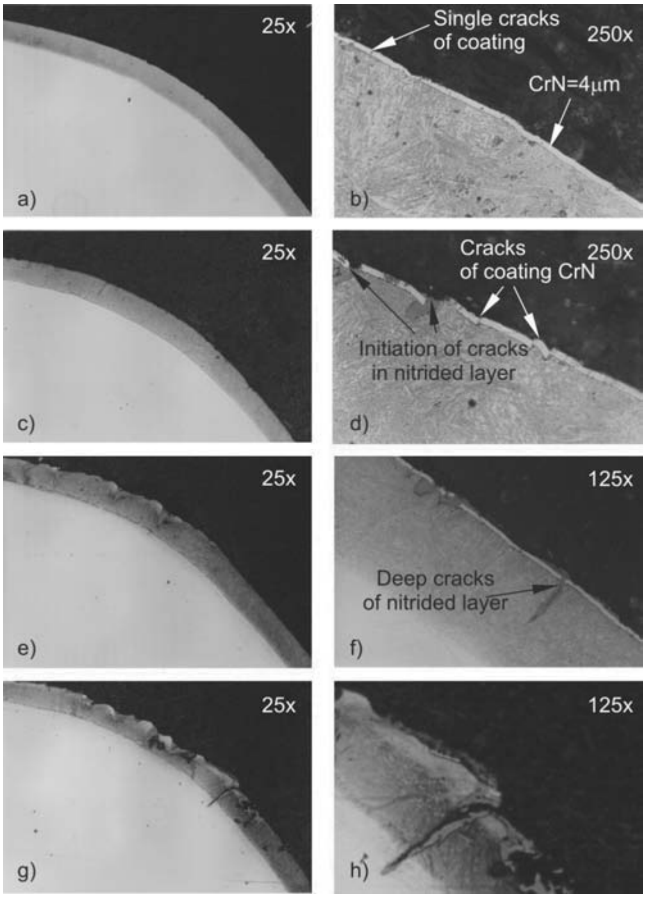

Fig. 6. Results of metallographic investigations of R2 edge of dies after forging different numbers of shapes: a, b) 100pcs., c, d) 1000pcs., e, f) 2000pcs., g, h) 4000pcs

zones of the tested dies demonstrated that after forging 100 shapes (Figs. 6a,b) no damage is seen either in CrN coating or in nitrided layer. After forging 1000 shapes (Figs. 6c,d) damages visible in the coating are primarily its cracks perpendicular to the surface. Areas where cracks in substrate material originate occur very rarely. The results of metallographic investigations after forging 2000 shapes (Figs. 6e,f) demonstrated that CrN coating keeps covering significant area of the die. Inclination of cracks and surface rippling (Fig. 6e) visible in this case indicates the occurrence of plastic deformation of substrate material.

After forging 4000 shapes (Figs. 6g,h) CrN coating is only locally noticeable. Numerous deep cracks, as well as numerous losses and chippings were observed in the nitrided layer. In addition much larger plastic deformation of the substrate material was observed.

3.2. Analysis of hardness changes

Figure 7 presents distributions of hardness versus distance from surface for dies covered with PN+CrN hybrid layer, after forging different numbers of shapes, i.e. 100pcs., 1000pcs., 2000pcs. and 4000pcs. The resulting hardness distributions were related to the distribution of hardness carried out after surface treatment, but prior to the commencement of forging. The results of measurements demonstrated that hardness of substrate material in the near-surface zone decreases during die maintenance. Hardness reduction is the effect of tempering of die material as a result of its contact with a shape of temperature of t_K=1200°C.

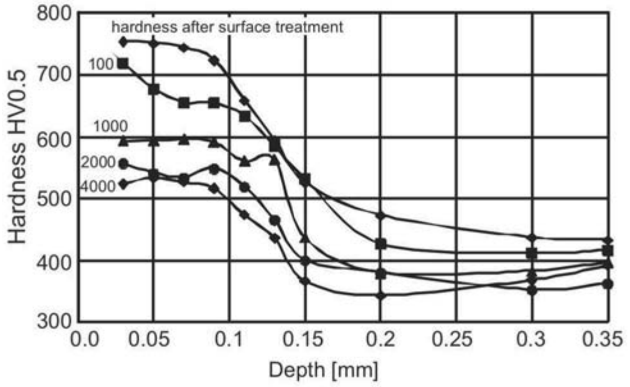

Fig. 7. The results of hardness measurements versus distance from the surface, for dies with PN+CrN hybrid layer after forging different numbers of shapes

Comparative analysis of the hardness distributions (Fig. 7) and the results of metallurgic investigations (Fig. 6) demonstrated that minor plastic deformation of dies was noticed only when substrate hardness amounted to ca.550 HV.

3.3. Analysis of crack intensity

All dies covered with PN+CrN hybrid layer and subject to maintenance tests have been made subject to observations using Hitachi 2660 scanning probe microscope. On the basis of the observations and taking into account the results of metallographic investigations and the results of hardness investigations, a mechanism of destroying PN+CrN hybrid layer in the course of hot plastic treatment was proposed.

Figures 8 a-d demonstrate subsequent stages of wear of a centrally located pivot of the forging die under maintenance tests in accordance with parameters shown in Table 3. After forging 100 shapes (Fig. 8a) as a result of cyclic impact of mechanical loads and heat shocks, individual cracks originate in CrN coating. Radial cracks are located chiefly on R2 edge, while circumferential cracks are located on lateral surface of a pivot. In the initial stage of forging dies maintenance cracks propagating mainly perpendicularly to the surface of the coating (Fig. 6b) are initiated in CrN coating. The cracks propagating in the whole depth of the coating are effectively suppressed at the boundary between the coating and nitrided layer.

After forging 1000 shapes (Fig. 8b), the already initiated process of cracking intensifies. In parallel impact of high temperature of a shape entails tempering of substrate, followed by gradual decrease of its plasticity limit (Fig. 7). On the next stage of destruction (Fig. 8) intensification of cracking process leads to forming of a thick net of cracks, what may entail local chipping of CrN coating. As a result thermal protection becomes weaker and substrate tempering intensity increases. In parallel, places of CrN coating losses become places of stress concentration what results in cracks in substrate being initiated in these places. Decrease of plasticity limit is at this moment great enough for plastic deformation of die material to occur along axis perpendicular to die front. Plastic deformation of die front surface causes radial deformation of die and forming of distinctive open cracks on R2 edge (Fig. 8c).

Alteration of a tool shape entails the increase of forging resistances. In parallel, thick net of cracks on die lateral surface and forming net of cracks on its front surface, as well as deep open cracks on R2 edge and significant decrease of substrate plasticity limit the result in very large decrease of temporary durability of a die. This in turn causes local chippings and losses of die material (Fig. 8d). Further maintenance increase forging resistance even further and lead to failure-inducing wear of the die.

4. Summary and conclusions

The article presents analysis of the course of the process of wear of forging dies covered with PN+CrN hybrid layer.

In the initial stage of the maintenance process cyclic effect of mechanical loads and heat shocks result in the initiation cracks in the CrN coating, perpendicular and parallel to surface. During further maintenance the process intensifies, leading to the creation of local chipping of CrN coating and exposure of steel substrate. These places, in line with the notch principle, become spots of stress concentration. As a result of lack of cover of CrN coating, substrate material in these spots is also more exposed to influence of heat shocks, resulting from cyclic character of forging process. As a result the areas of exposed substrate material become areas where thermo-mechanical fatigue initiates cracks in the nitride layer. Apart from the above the process of steel substrate tempering intensifies, and as a result its plasticity limit decreases.

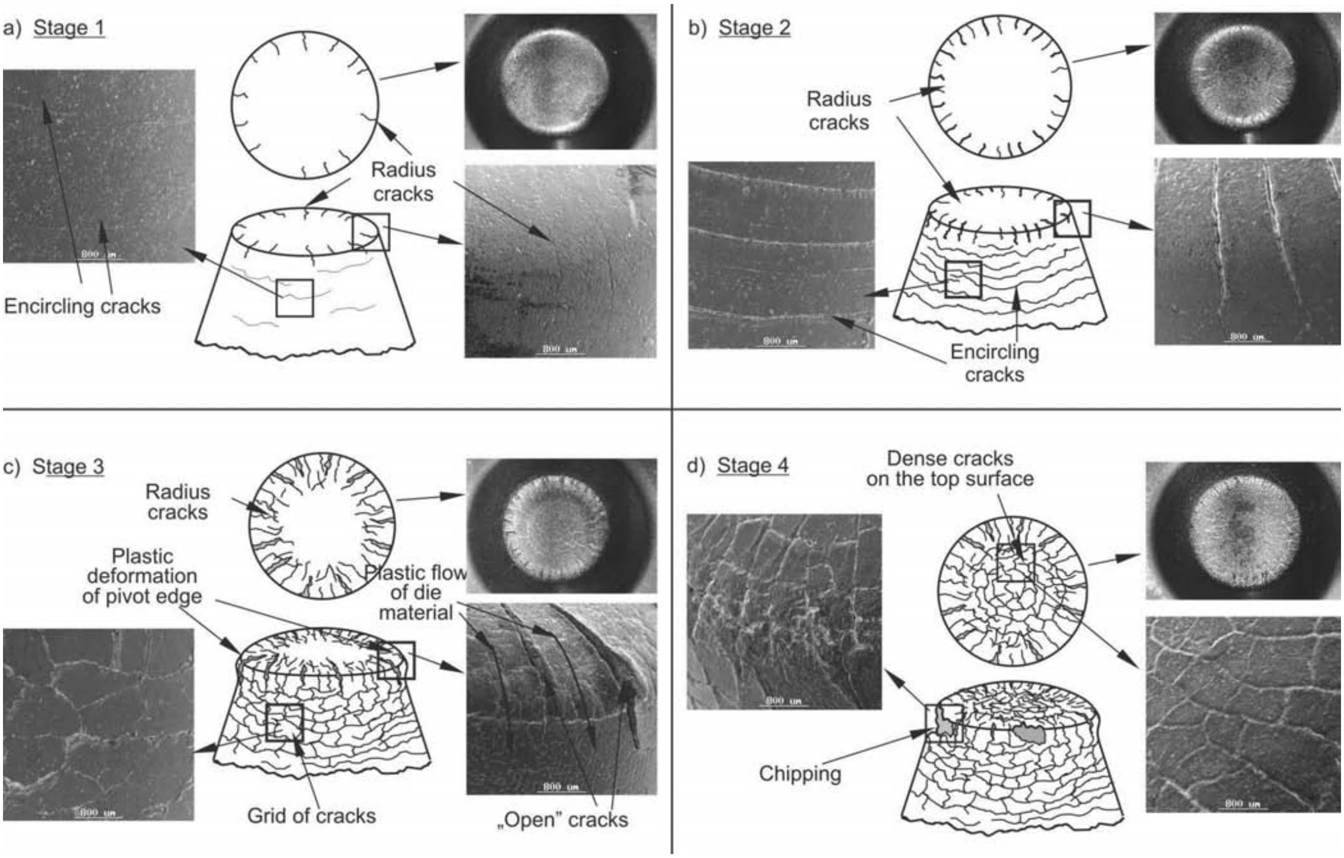

Fig. 8. Next stages of destruction of forging dies with the PN+CrN hybrid layer in the hot plastic treatment process

Steel substrate is no longer able to sustain stresses resulting from external forces and becomes subject to plastic deformation. This induces significant increase of forging resistances. Coating and substrate cracks originated in thermo-mechanical fatigue and decrease of substrate plasticity limit result in a great decrease of its temporary endurance and as a consequence local die chipping. Further maintenance increase forging resistance even further and soon lead to failure-inducing wear of the tool.

On the basis of results obtained the following conclusions have been reached:

- The main mechanisms of the process of wear of forging dies coated with PN+CrN hybrid layer are: thermo-mechanical fatigue of CrN coating as well as thermo-mechanical fatigue and plastic deformations of steel substrate.
- CrN coating plays particularly significant role in the process of wear of forging dies covered with PN+CrN hybrid layer. Since one of the main mechanisms of wear of the dies under investigation is thermo-mechanical fatigue of CrN coating, very important role in the process of dies wear is played by the resistance of CrN coating to brittle cracking. Another positive effect of CrN coating is decreasing of stresses initiated in the substrate in the process of forging by external forces. Simulations indicate that CrN coating of 3 μm reduces stresses initiated in substrate material during maintenance up to value of ca. 500 MPa. The possibility of plastic deformation occurrence in steel substrate is hence reduced, even in case of its plasticity limit decreased as a result of thermal impacts.

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