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INVESTIGATION OF THE INFLUENCE OF HYBRID LAYERS ON THE LIFE TIME OF HOT FORGING DIES

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The paper deals with the issues related in the process of drop forging with special attention paid to the durability of forging tools. It presents the results of industrial investigation of the influence of hybrid layers on hot forging dies. The effectiveness of hybrid layers type nitrided layer/PVD coating applied for extending the life of forging tools whose working surfaces are exposed to such complex exploitation conditions as, among others, cyclically varying high thermal and mechanical loads, as well as intensive abrasion at raised temperature. The examination has been performed on a set of forging tools made of Unimax steel and intended for forging steel rings of gear box synchronizer in the factory FAS in Swarzedz (Poland).

Key words: forging, tool life, forging dies, hybrid (nitrid) layers

INTRODUCTION

The hot metal forming tool life is influenced by a number of factors which can be divided into three basic groups. They are factors related to [1, 2]:

a) the forging: material, mass, shape and temperature of the forging, dimension tolerances, required surface roughness,

b) the die: material (kind, quality), hardness (kind of heat treatment), die design and dimensions, manufacturing technology, accuracy of manufacturing, number of die impressions, impression surface roughness, die temperature during work, number of die regenerations, the way of the die fixing in the press (hammer),

c) exploitation: shape of the initial material or blank, kind of machine (size, impact speed, technical condition), time of the forging stay in the die, forging temperature range, kind of heating device and the atmosphere in it, forging heating (even, uneven), the influence of scale, kind of die lubrication, the way of die heating prior to work, execution of the forging process (continuous, with intervals), the worker's qualifications and scrupulosity.

The factors related to the exploitation, as well as those related to the forging, usually do not vary significantly and, in most cases, they are predetermined. As far as the forging is concerned, the decisive parameter is its destination. The manufacturer has a limited field of action due to the number of requirements he must meet which are imposed by the orderer (the material of the forging, its shape, dimensions etc). In the case of exploitation, superior parameters are the technological and technical parameters of the forging shop, i.e. the available machines. For that reason, the factors related to the die, especially its material and execution technology, are the ones which contribute most to the die life. Both the high tooling cost and the severe working conditions make it advisable to use high-alloy hot working steels for the forging tools [2,3]. Such steels should have high hardness, good mechanical properties and good abrasion resistance at working temperatures which are defined within the range of 250 – 700 °C [1]. It is also important that they should be adequately forged and free of surface and internal defects.

All the processes of forging die destruction (plastic strain, abrasive wear, thermal and mechanical fatigue, erosion) take place in the top layer of the tool impression. Therefore, the next step to extend the life of forging tools is to determine the properties and structure of the die top layer. This is affected by making layers or coatings with adequate properties a result of which is a barrier limiting the influence of destructing factors and acquisition of the desired utilization properties. Surface engineering has been rapidly developing recently, especially in the field of hybrid technologies of the top layer modification [4,5,6,7], and creates possibilities of the most effective extension of the forging tool life.

Market requirements, as well as the desire of the elasticity an effectiveness of production and the continuous search of savings have made enterprise FAS look for new solutions including the extension of die life. The combination of knowledge concerning the creation of surface layers and the question of obtaining longer forging tool life has resulted in attention drawn to the possibility of covering dies with special hybrid layers type nitrided layer/PVD coating.

INVESTIGATION METHODOLOGY

Hybrid layer type nitrided layer/PVD coating has been obtained on substrates of hot working alloy steel

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commercially known as Unimax with the following chemical composition: 0,5 % C, 0,2 % Si, 0,5 % Mn, 5 % Cr, 2,3 % Mo and 0,5 % V. The samples on which the duplex type coatings have been made had the shape of disks with the diameter of 30 mm and the thickness of 10 mm. The design of the hybrid layers and execution of them on forging tools has been performed in the Department of Surface Engineering of the Institute for Sustainable Technologies in Radom (Poland).

The hybrid layers type nitrided layer/PVD coating made on Unimax steel substrate have been obtained with the use of the following devices: CDS-Standard made by IforST Radom and MZ383 made by MetaplasIonon Garmisch-Partenkirchen. The processes of making duplex type layers have been affected in two stages in a separate cycle. The first stage comprised the execution of ionnitriding of the forging tools on the CDS-Standard device. The processes were effected with the use of an optical system of the ionnitriding intensity control, with the following parameters: temperature T= 500 °C; atmosphere – N2 + H2; pressure p = 4,3 mbar; spectral signal intensity ratio, $p(N^+/H^+)$ = 1,5; time, τ = 420 minutes.

On the substrate prepared as above, PVD coatings have been imposed. The chromium nitride coating (CrN) has been made in the CDS-Standard device while the coating of titanium-aluminium nitride (TiAlN) has been made in the MZ383 device. The parameters of PVD coating performed by the arch – vacuum evaporation method are presented in Table 1.

Table 1 **Parameters of imposition of CrN and TiAlN coatings**

Coating material	CrN	TiAlN
Pressure in the chamber p /mbar	3,5	4,0
Working gases	100 % N_2	100% N_2
Substrate voltage U_{bias} / V	-150	-150
Cathodes current I_k / A	4 x 70	6 x 55
Temperature t / °C	400	400
Time τ / min	90	90

INVESTIGATION RESULTS

Examination of hybrid layers

First, hardness measurement has been performed on the cross section of a Unimax steel sample (Φ 30 x 10) nitrided in a test process. This has enabled hardness distribution and the diffusion layer thickness to be determined (Figure 1). The next examination performed was the measurement of the die surface hardness after nitriding (Table 2), performed with the use of Rockwell indenter with the standard load of 150 g.

The thickness of the PVD coatings made has been determined by the method of crater abrasion. BERNEX AG Olsen calotester has been used for that purpose. The average coating thickness: CrN – 5,5 μm, TiAlN – 4,0 μm.

The measurements of hardness and Young's modulus of the PVD coatings have been performed on an NHT hardness tester made by CSEM. The hardness and the Young's modulus have been measured with the maximum indentation of the indenter, h_{max} = 200 - 400 nm. The indentation has not exceeded 10% of the examined coating thickness. The following results have been obtained: CrN coating – hardness 1 800 – 2 000 HV, Young's modulus, E = 280 – 300 GPa; TiAlN coating – hardness 2 600 – 2 700 HV, Young's modulus E = 350 - 380 GPa.

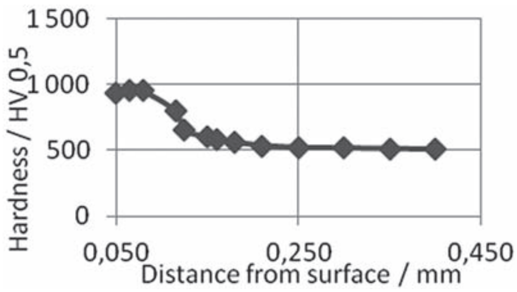


Figure 1 Hardness distribution of the nitrided layer on a Unimax steel substrate

The measurements of the adhesion force of the coatings made on the nitride Unimax steel substrate have been performed on the Scratch-Tester REVETEST device made by CSEM. The measurement results can be seen in Table 3.

Table 2 **Hardness distributions of the forging die material after ionnitriding**

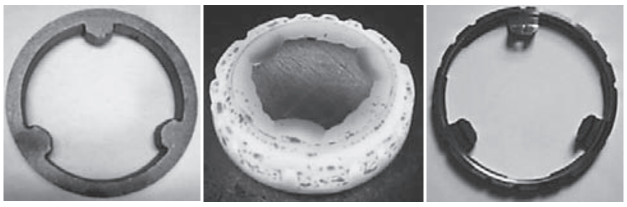
Depth / mm	Average hardness / HV 0,5	Average hardness / HRC
0,03	898	67
0,05	935	68
0,07	945	68
0,09	937	68
0,11	811	64
0,13	646	58
0,15	593	55
0,17	576	54
0,19	566	53
0,21	543	52
0,25	534	51
0,30	524	51
0,35	519	50
0,40	520	50
Surface hardness	1 071	70

Table 3 **Results of adhesion measurements of the coatings embedded on ionnitrided substrate**

Sample designation	Character of coating destruction and recorded force value / N		
	Outer cracking	Outer spalls	Total break
CrN	20	55	90
TiAlN	20	33	70

Investigation of the influence of the hybrid layers on the life time of hot metal forming tools

Industrial verification of the tools for hot forging of synchronizer ring no. 9 051 276 (Figure 2) provided with the hybrid layer type nitrided layer/PVD coating has been performed with the use of a batch of blanks intended for it (Figure 2a). A view of that ring just after the operation of drop forging can be found in Figure 2b, while Figure 2c shows a "ready made" synchronizer ring.



a) b) c)

Figure 2 Synchronizer ring 9 051 276: a) blank, b) forging, c) "ready made"

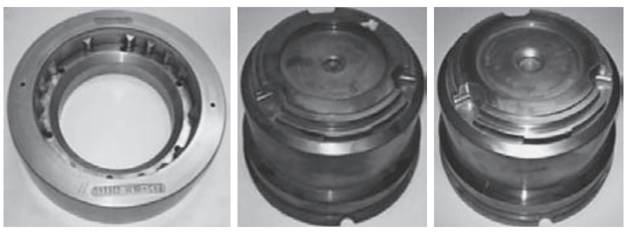
Life time investigation has been performed on a specially selected die and two punches intended for hot forging of gear box synchronizers.

Knowing the life times of dies for that product obtained so far, the investigators performed exploitation tests with the use of a set of forging tools (Figure 3) with a hybrid layer applied; the set consisted of:

- the die (Figure 3a)with a hybrid layer type nitrided layer/CrN coating,
- punch I (Figure 3b) with a hybrid layer type nitrided layer/TiAlN coating,
- punch II (Figure 3c) with a hybrid layer type nitrided layer/CrN coating.

The investigation has been performed on a stand including:

- a crank press of Czech production – Smeral LZK 1 000,
- induction heater.



a) b) c)

Figure 3 The set of forging tools used in the investigation: a) die, b) punch I, c) punch II

With a batch of 8 350 blanks at disposal, a decision has been made to perform a manual forging operation in a continuous mode, i.e. for 24 hours a day with no stops. Forging was kept on in a three-shift system, each shift of 8 hours (a man on breakfast break being replaced by an alternate). Due to the fact that the set of tools included two punches with various PVD coatings, in order to verify the durability and for accurate determination of the wear magnitude, the investigators decided to replace the punch after approximately half a batch with a new one whether the previous one was suitable for further work or not.Once the Quality Assurance Service has accepted the press settings and the forging dimension conformance with the drawing has been approved, the operator started forging the whole production series intended for the investigation (the parameters of exploitation examinations have been assembled in Table 4). In the first setting, the forging tools fixed in the press included a die covered with CrN coating and a punch covered with TiAlN coating which, in accordance with the assumptions, has been replaced after forging 4 040 rings. In the second setting, in addition to the die kept for further exploitation, the press has been provided with a punch covered with CrN coating. This set of tools has been used to forge further 4 310 rings. A simple mathematical calculation shows that the durability of the die itself has reached the level of 8 350 pieces of forgings.

Table 4 **Characteristics of operational investigation**

Die material	UNIMAX hot working steel
Heat treatment parameters	hardening – T_{hard} =1 020 °C tempering - T_{temp1} = 540 °C (120 min) tempering – T_{temp2} = 550 °C (120 min) hardness after heat treatment 56-68 HRC
Parameters of the nitrided layer	structure – diffusion zone thickness – 0,15 mm method - glow discharge nitriding (T = 500 °C, p = 4,3 mbar, τ = 420 min, atmosphere: $N_2 + H_2$, $p(N^+/H^+)$ = 1,5)
PVD coating (die)	material – chromium nitride CrN thickness – 5,5 µm method – arc – vacuum evaporation (T = 400 °C, p = 3,5 mbar, τ = 90 min, $U_{bia\ s}$= -150 V, I_{source}= 4 x 70 A, atmosphere: 100 % N_2)
PVD coating (punch I)	material - titanium-aluminium nitride, TiAlN thickness - 4 µm method – arc – vacuum evaporation (t = 400 °C, p = 4,0 mbar, τ = 90 min, U_{bias}= -150 V, I_{source}= 6 x 55A, atmosphere: 100% N_2)
PVD coating (punch II)	material – chromium nitride CrN thickness – 5,5 µm method – arc – vacuum evaporation (T = 400 °C, p = 3,5 mbar, τ = 90 min, U_{bias}= -150V, I_{source}= 4 x 70A, atmosphere: 100% N_2)
Forged material	Alloy steel 16MnCr5
Forging process	manual (continuous – 24 hours) Smeral LZK 1 000 press maximum capacity 1 000 MG cooling and lubricating agent – water + graphite
Die temperature	T_D= 200 °C
Punch temperature	T_P= 250 °C
Temperature of the forged material	T_{FM}= 1 100 °C

ANALYSIS OF THE RESULTS

The achievement of 8 350 gear box synchronizer ring forged by only one die with a hybrid layer type nitrided layer / PVD coating is a much promising result. This is almost 3 times the life of ion nitrided die made of Unimax steel and over 4 times the life of ion nitrided die made of WCLV steel (Figure 4).

In detailed consideration of the kind and degree of wear which the tools used in the investigation have undergone, it should be noted that a part of the 9 051 276 ring surface is "ready made" in the forging operation and is not subjected to further machining (Figure 5a).

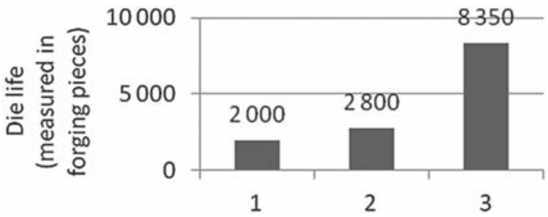


Figure 4 Synchronizer ring forging die life: 1) WCLV + ion nitriding, 2) UNIMAX +ion nitriding, 3) UNIMAX +hybrid layer type nitrided layer / PVD coating

This is important because inspection and measurement of those surfaces on the forging made allow for the determination of the die and punch condition (degree of destruction) and for the decision to regenerate the tools or discard them. In the case under investigation, the punch forms "ready made" the whole internal diameter between the protrusions distributed on the circumference at intervals of 120 ° (Figure 5a), as well as a fragment of the protrusion on both sides of it (Figure 5b). Similarly, the die forms all the dents distributed on the outer diameter of the ring (Figure 5c, d).

As the first one, the wear of the punch covered with the TiAlN coating has been analysed. For that purpose, selected fragments of the forgings have been inspected (numbers 1 – 8, every 500-th piece was put aside), where, firstly, disadvantageous increase of rounding can take place as a result of the forged material sticking to the punch and, secondly, due to abrasive wear, scratches on the ring inner diameter can appear. Both those causes eliminate the tool from further operation after they exceed certain admissible level. In order to prevent it, it is subjected to grinding, which however, deteriorates the protective layers made. Regeneration can be performed for a limited number of times, usually 2 – 3 ones. The punch I with TiAlN coating has been regenerated three times. First time, just after it had forged about 600 pieces - due to formation of scratches on the forgings, second time due to the increase of the value of the rounding at the protrusion after the punch had forged 2 600 pieces; third time also because of the increase of the rounding after about 3 800 pieces had been forged.

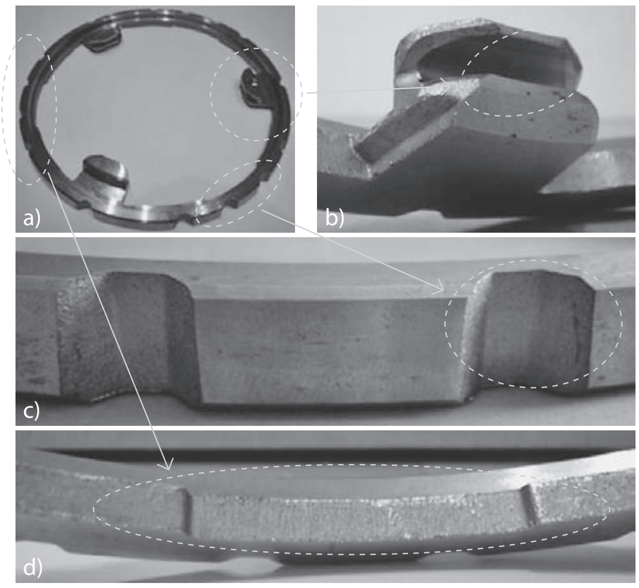


Figure 5 Ring with marked surface sections "ready made" in the process of drop forging: a) general view, b) fragment of a protrusion, c) fragment of the outer diameter with dents, d) fragment of the inner diameter between the protrusions

Similarly, the process of destruction of a punch covered with a CrN coating has been analysed. For that purpose, too, selected forging fragments have been inspected (numbers 9 – 16, every 500-th forging has been put aside).

Punch II, with a CrN coating, has been regenerated only once due to the increase of the radius of rounding at the protrusion after it had made about 3200 pieces.

As regards the die with CrN coating it has forged the whole batch of 8 350 pieces with no regeneration. The dimensions of the roundings on the dents on the outer diameter of the forging were so small after the execution of the whole production batch that there was no reason to grind the tool.

CONCLUSIONS

Basing on the results of the investigation performed, the following conclusions have been formulated**:**

1. The durability of forging tools with hybrid layer type nitrided layer / PVD coating used in a process of continuous manual forging is 3 – 4 times longer than that of dies subjected only to ion nitriding.

2. The dominating mechanism of die and punch destruction was abrasive wear.

3. The wear of the punch covered with CrN coating was found to be less that of the TiAlN coated one, which can be related to the better sliding properties of chromium nitride as well as its larger elasticity and adhesion to the substrate.

4. On the basis of the degree of destruction of forging tools, it is estimated that, if a punch with TiAlN coating were used, 500 more forgings could be made. With the use of a punch and die with the CrN layer, even as many as 1 000 forgings could be made.

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Note: Responsible translator: Natalia Trawinska, Poznan College of Modern Languages, Poznan, Poland