HYBRID SURFACE TREATMENT TECHNOLOGY FOR IMPROVING DURABILITY OF HOT FORGING TOOLS

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Abstract

This study focused on tools used in the hot forging process of lid type components manufactured for the automotive industry. The tools were coated with different PN+PVD hybrid layers in order to improve tool durability. The tool wear represented by material degradation was evaluated through 3D scans of periodically collected samples. The samples' microhardness and microstructure were also analyzed. The results demonstrated an extent of the hybrid layers efficiency in improving tool durability for industrial forging applications.

Keywords: Forging tools, forging

1. INTRODUCTION

The tools used in hot forging processes are exposed to the operation of many degradation mechanisms, which cause their rapid wear. They include: intensive thermal shocks, cyclically varying mechanical loads and intensive friction at high pressures. The working surface and the surface layer of the tools are especially exposed to the operation of these factors, and so, most of the occurring degradation mechanisms apply to this tool area [2]. At present, the most frequently used method of improving the durability of forging tools is nitriding. Despite the fact that this method is well-known and well-mastered, it does not always provide a clear effect of durability improvement. That is why new methods are being searched for, which will aim at improving the durability of the tools in forging processes. The most recently created methods undoubtedly include hybrid technologies consisting in applying two or more surface engineering techniques. Hybrid techniques can combine e.g. thermo-chemical treatment methods and one of the PVD techniques. This technology makes it possible to provide proper operation properties as well as create a barrier which will effectively limit the impact of the degradation mechanisms.

In the analysis of the durability of the tools used in industrial production processes, we can meet with its different definitions. From the production point of view, the most practical definition seems to be the one mentioning the number of the produced forgings which meet the quality requirements, manufactured with the use of the given tool. However, in practice, in many cases, the decision about removing the used tool is made by the technologist on the basis of a visual assessment of the quality of the manufactured element as well as measurements in selected control points by means of traditional measuring tools or simple curve gauges. This method does not, however, allow for a complex assessment of the quality and shape of the whole element. More and more often, especially during forging of responsible components at forging plants, based on the observations, the so-called mean durability of the used tools is determined, which is often lower than the actual durability. Next, on this basis, after the pre-established number of forgings has been produced, in the case of a multi-operation forging process, the operator replaces this tool, regardless of its state [1, 3-5].

In turn, from the scientific point of view, the tool durability is connected with its resistance to degradation factors present during its operation. In this case, it is very important to perform an objective assessment and analysis of the degradation mechanisms, which cause the wear. This is especially crucial during the testing of a new tool material, or a tool after a special treatment, as well as in the case of a different technology aiming at improving durability. The research included examination of the effect of the use of different hybrid layers of the nitrided layer + PVD coating type on the durability of punches used lid hot forging. For the determination of the degree of wear of the analyzed tools, during service tests, 3D scanning of cyclically sampled forgings was applied, on which the defect of the tool was represented. A detailed analysis of the mechanisms was performed based on the structural tests. The used analysis methods allow for an objective assessment of the effectiveness of hybrid layers in the durability improvement of tools used in industrial forging processes.

2. TEST SUBJECT

For the tests, the process of hot forging of a lid was selected (**Figure 1a**). The analyzed process was realized with the use of the P-1800T press in three forging operations: operation I - upsetting, operation II - blocking and operation II - finishing forging. The forged material was C45 steel, billet dimensions: diameter 55 cm, length 95 mm, weight 1.77 kg. The initial temperature of the charge material equaled 1150 °C.

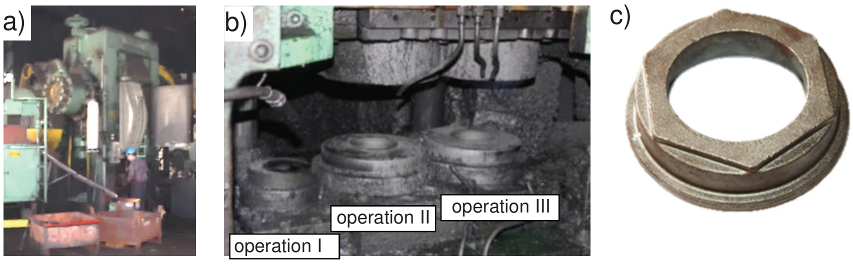

Figure 1 **a)** Massey 1800T press, b) lid forging tools mounted on the press, c) a ready lid forging

In the analyzed process, the tools are made of WCL steel. After thermal treatment, the tools for operation II and III undergo nitriding. The research focused on the second forging operation (blocking) (**Figure 1b**). A detailed geometrical analysis was performed on the punch of the upper die, whose durability is the lowest in the analyzed process (**Figure 2**).

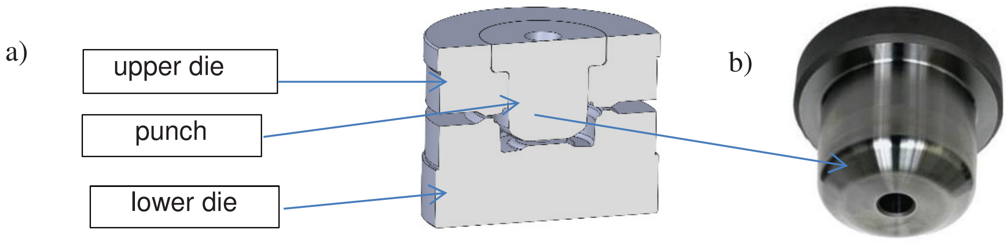

Figure 2 a) Scheme of the blocking operation for the produced element, b) analyzed punch

3. TEST METHODOLOGY

In order to improve tool durability, a hybrid layer coating of the nitrided layer/PVD coating type was applied. It was decided to apply two coating variants: CrN (chromium nitride) and TiCrAlN. The hybrid layers were designed and manufactured at the Surface Engineering Faculty, Institute for Sustainable Technologies of the National Research Institute in Radom. The process of multi-stage hybrid treatment of the analyzed tools was performed in three stages:

- stage I - vacuum thermal treatment of the steel substrate,
- stage II - forming a nitrided layer by the ion nitriding method,
- stage III - deposition of selected PVD coatings.

Tables 1 and **2** present the properties of the obtained nitrided layer being part of the hybrid layer and the properties of the used PVD coatings.

Table 1 Nitrided layer parameters

Phase structure	Diffusion zone
Surface hardness	1000 HV0.5
Thickness of the zone, hardness 800HV	g_{800} = 0.13 mm

Table 2 Properties of CrN and TiCrAlN coatings

	CrN coating	TiCrAlN coating
Thickness	g ≈ 5.28 µm	g ≈ 6.7 µm
Hardness	H = 24 ± 1.6 GPa	H = 30 ± 2.1 GPa
Young modulus	E = 279 ± 16 GPa	E = 337 ± 12 GPa
Coefficient of friction - steel	μ = 0.32	μ = 0.48
Coarseness	Ra/Rz/Rt=0.43/1.16/1.92	Ra/Rz/Rt=0.29/2.28/3.40
Adhesion	Fn_{C1}=46 N, Fn_{C2}=60 N, Fn_{C3}=103 N	Fn_{C1}=15 N, Fn_{C2}=83 N, Fn_{C3}=101 N

The tools prepared in this way underwent service tests under the industrial conditions of the Kuźnia Jawor S.A. (Jawor Forging Plant Ltd.), where 6000 forgings were produced with the use of each punch. For comparison, the same number of forgings was made with the use of the punch applied so far that is with the use of the same thermal treatment + nitriding.

In the measurements of the geometrical changes of the forgings, the measuring arm ROMER Absolute ARM 7520si was used together with the Polyworks software and the Real Time Quality Meshing technology. The arm makes it possible to perform classic measurements with the use of a measuring probe as well as non-contact measurements by means of the linear laser scanner RS3 integrated with the arm, which allows for collecting up to 460 000 points / s for 4600 points on the line, at the linear frequency of 100 Hz, with the declared accuracy at the level of 2 sigma 30 µm.

4. MACROSCOPIC ANALYSIS

First, an analysis was made of the punch with a nitrided layer (**Figure 4a**). Its wear can be observed mainly on the front surface, where irregularities resembling ‘dunes’ are formed.

a) b) c)

Figure 3 Macro-image of punches after producing 6000 forges: a) with a nitrided layer, b) with a PN + CrN layer, c) with a PN + AlCrTiN

In the radial area, grooves characteristic to abrasive wear are present. Similar grooves are visible directly at the hole of the knock-out (**Figure 3a**). On the punch with the PN + CrN layer, after producing the same number of forgings, the traces of wear are significantly smaller and more uniform. On the front surface, clear grooves characteristic to abrasive wear are visible, formed in the radial direction. As regards the conic surface, we can see a network of thermo-mechanical cracks. Additionally, on all the surfaces, it is possible to see a thick oxide layer (**Figure 3b**). On the punch with the PN + AlCrTiN layer, the highest wear is also in the case of the front surface. On the whole front surface, we can see clear deep grooves characteristic to abrasive wear, which are formed in the radial direction and which cross the radius onto the conic surface (**Figure 3c**).

5. DIMENSIONAL ANALYSIS

The result of the measurements by way of the 3D scanning technology is a cloud of points. Next, based on the obtained point cloud, with the use of the program, the polygonal surface was calculated, consisting of elementary triangles, which reflected the geometry of the measured object. In order to reproduce the course of the punch wear, selected series of forgings were scanned (every 500 items) from the total number of 6000 items, for each of the three punches.

Figure 4 shows scans of the internal part of the forgings (every 500 items) for the forgings made with the use of the punch with the PN + CrN layer. The results are presented in the form of a change in the shape of the selected surface in reference to the nominal CAD model. The scans for the increasing number of forgings point to a progressing wear of the tool (punch). The wear is localized in the central part, in the vicinity of the knock-out hole and it is irregular at the initial stage of the forging process. The following step of the investigations was collecting the measurement data obtained from the scanned forgings in the form of a diagram presenting the material degradation (volume change) calculated based on the volume changes between the surfaces of the consecutive forgings produced with the analyzed punches (**Figure 6a**). The dependence of the volume difference was described with the third degree polynomial function.

Based on the presented diagram (**Figure 5**) resembling a classic wear curve (Lorenz curve), as the tools were removed before their total wear, we can observe interesting relations and distinguish between a few ranges (periods) of wear. And so, the wear of the analyzed punches increases very rapidly at the beginning of the forging process up to about 1500 - 2000 items. This is connected with the adjustment of the whole system (forging-tools). We can, however, notice that, in the case of the punches with the PVD coatings, the values of the analyzed wear parameter, in this period of operation, is twice as low as in the case of the nitrided punch.

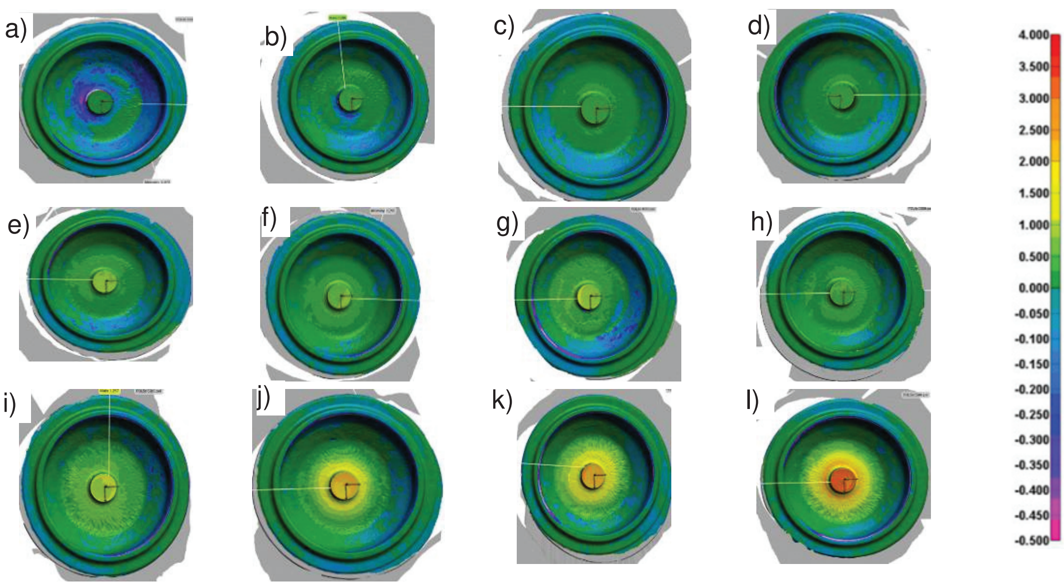

Figure 4 Comparison of the scans of the internal part of the forgings produced with the PN + CrN coated filler, in the form of a shape change in the selected surface, in reference to the nominal CAD forging model, after: a) 500, b) 1000, c) 1500, d) 2000, e) 2500, f) 3000, g) 3500, h) 4000, i) 4500, j) 5000, k) 5500, l) 6000 items

After reaching the matched (adjustment) state, that is above 1000 - 2000 forgings, the state of the so-called normal tool operation begins, characterizing in an approximately stabilized level of intensity of the above mentioned degradation phenomena, which, in the analyzed case, reaches about 4800 forgings for the PN+CrN coating and about 5500 and 5700 forgings for the punch with the nitrided layer and the PN+ AlCrTiN type PVD layers.

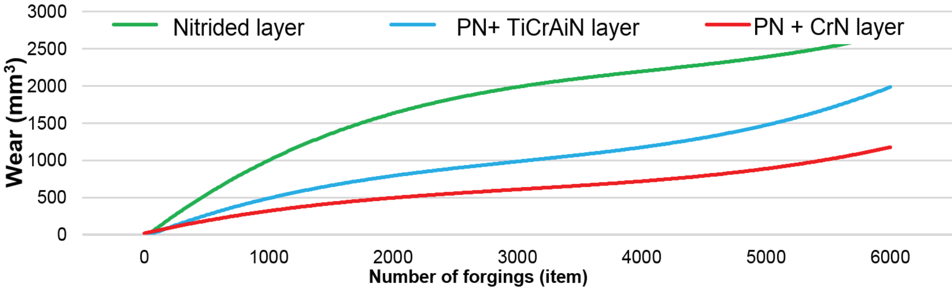

Figure 5 Comparison of the material degradation (volume change) based on the analysis of the volume changes between the surfaces of consecutive forgings of the analyzed punches

The classic Lorenz curve, at the end of the normal operation time, usually transfers to the state of accelerated wear, which can be observed in the case of all the analyzed fillers. It is worth noting that, in the case of the PN + CrN coating, the value of the analyzed wear parameter, throughout the whole operation time, is significantly low than in the case of the remaining fillers. In practice, this makes it possible to obtain the maximum number of forgings of the shape closest to the ideal one. This minimizes the costs of the future mechanical treatment by way of minimizing the amount of the material necessary for removal.

6. MICROSCOPIC ANALYSIS

A detailed analysis of the changes in the surface layer of the analyzed tools was performed with the use of the scanning microscope TESCAN VEGA 3. The paper presents exemplary results of the analysis for the area marked in **Figure 6a**, which included the conic part of the punch.

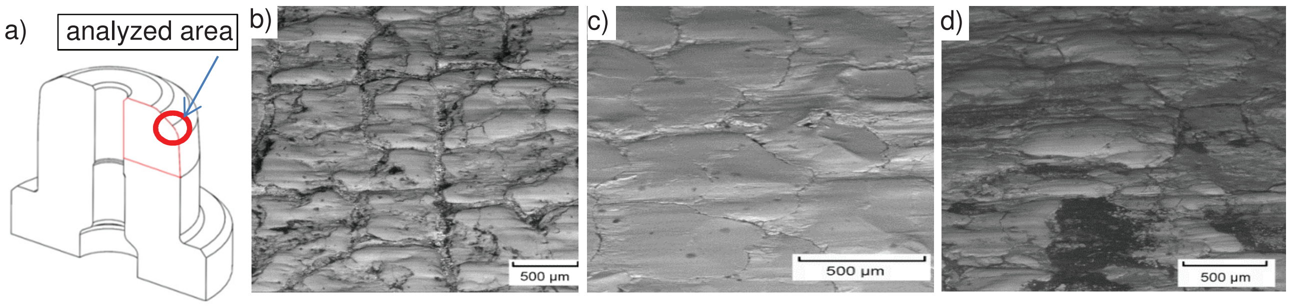

Figure 6 a) Punch section with marked area selected for analysis, view of the working surface of the analysed punch surface after producing 6000 forgings, b) with a Nitrided layer, c) with a PN + CrN layer, d) with a PN+ TiCrAiN layer

In this area, no geometrical loss was observed. According to the presented wear distributions in the remaining areas, the thin PVD is quickly removed, and so, a detailed analysis of the tool's surface in this area is especially important, as the differences in the character of wear can directly depend on the type of the applied coating. On the surface of all the analyzed punches, we can see an intensive network of thermo-mechanical cracks. However, the observed crack networks differ in appearance for the particular tools. In the case of the tool where only nitriding was applied, the cracks forming the network have an open character (**Figure 6b**), which causes the network to have a higher tendency for spalling. This can cause an increase of the oxidation rate of the internal crack surfaces and the formation of additional wedging forces. The surface of the punch with the TiCrAlN coating looks similar, whereas the crack network is slightly less intense (**Figure 6c**).There is, in turn, a significant difference in the appearance of the punch with the CrN coating. The cracks forming the network are narrow and the surface of this punch is undoubtedly the most even one (**Figure 6d**).

7. MICROHARDNESS TESTS

The hardness distributions were made with the load of 100g by the Vickers method, at the distance of 2.5 mm from the working surface of the tool. The paper presents only the results for the area marked in **Figure 7**.

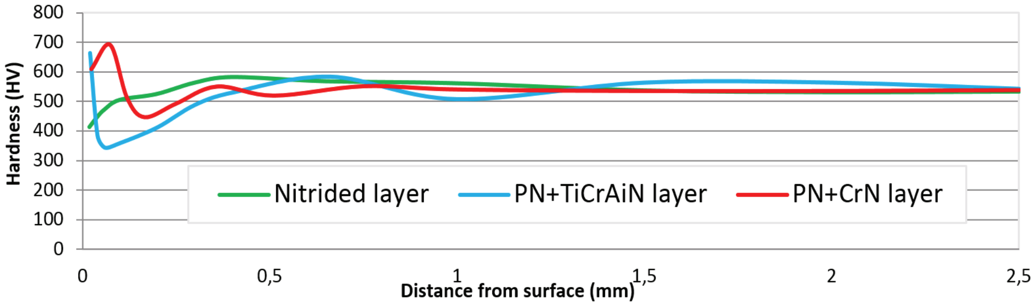

Figure 7 Microhardness distribution of punches

In the analyzed area, where no wear is observed, the drop of hardness is caused by material tempering in the surface area as a result of the contact with the hot material. This effect is especially visible for the nitrided punch, where the hardness drop is up to 400 HV, which also proves the loss of properties of the nitrided layer (**Figure 7**). In the case of the punches with hybrid layers, the hardness directly beneath the surface is higher than that of the core, which proves the presence of a nitrided layer. In turn, at the depth of about 0.2 mm from the surface, the hardness drops to about 400 HV (**Figure 7**), while for the punch with the TiCrAlN coating - to 300 HV (**Figure 7**), and next, it gradually increases to the hardness of the core. This can be explained by material tempering directly beneath the hybrid layer. As it can be inferred from the determined microhardness distributions, the applied hybrid layers protect, to some extent, the surface layer from the disadvantageous operation of high temperature.

8. CONCLUSIONS

The presented investigations showed that modifying the properties of the surface layer by way of applying hybrid techniques, such as hybrid layers of the nitrided layer + PVD coating type, makes it possible to effectively increase the durability of forging tools in the hot forging processes. The analysis proved that, in the case of the punch used in the examined process, the hybrid layer with the CrN coating exhibits better operation properties, which can be connected with better sliding properties as well as higher elasticity and adhesion to the substrate (**Table 2**).

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