APPLICATION OF ZEROFLOW NITRIDING TO IMPROVE THE LIFETIME OF FORGING TOOLS

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Abstract

This article describes problems related to the lifetime of tools used for hot forging. The results of industrial tests, involving the application of ZeroFlow nitriding for the purpose of improving tool lifetime, are presented. One of the bottom dies was subjected to detailed analysis on account of its short lifetime. Analysis of a standard die was also conducted for the purposes of comparison. Based on comprehensive tests of tools (surface scanning, microhardness measurements, observation under a microscope), after a specific number of manufactured forgings, it was demonstrated that the application of ZeroFlow gas nitriding can effectively increase the lifetime of tools used in hot die forging processes.

Keywords: Forging tools, forging, ZeroFlow method, nitriding

1. INTRODUCTION

The lifetime of tools used in industrial production processes is a problem to which much attention has been devoted for quite some time. The lifetime of tools has a significant impact on production costs, since tools costs make up even 30-40% of total production costs in certain cases, and the quality of manufactured products also depends on the quality and lifetime of tools [1-3]. Tools used in industrial forging processes are a special case, where extremely heavy operating conditions cause these tools to be characterized by a very low lifetime. This is particularly visible in hot die forging processes, where tools are subjected to the simultaneous action of the three main factors causing their destruction, i.e. intense thermal shocks, cyclically variable mechanical loads and intense friction, over the course of their work. These factors pertain, above all, to the near-surface layer of the tool, and in light of this, modification of the surface layer of forging tools is the most effective method of improving their lifetime [3].

Despite the development of many different surface engineering methods, nitriding remains the most popular method of improving forging tools' lifetime. Nitriding increases tools' resistance to abrasion, fatigue strength, and improves corrosion resistance. Observations of many industrial forging processes in which nitrided tools were applied have proven that this treatment makes it possible to increase tool lifetime several times over. Studies have shown that tools must have a specific, uniform structure for the nitrided layer to improve tool life effectively. Generally, over the course of nitriding, a diffusive zone of ferrite supersaturated with nitrogen with precipitations of carbonitrides and γ' nitrides forms first, and then, depending on process parameters, a continuous zone of ε+γ' nitrides and carbonitrides forms on the surface, with growing content of ε nitrides. As it turns out, nitrided layers with a surface zone of the ε phase are generally characterized by inferior functional properties, mainly because they exhibit low ductility simultaneously with high resistance to abrasion, which makes them suitable for work under conditions where there are lower dynamic loads. In turn, a layer made up of γ' nitrides and carbonitrides contributes to increased resistance to abrasion and scoring as well as to increased corrosion resistance. However nitrided layers without compound zones are characterized by very good fatigue strength and are less susceptible to cracking due to thermal fatigue, which makes them suitable for work under conditions of high thermal loads. Unfortunately, this technology has not yet been mastered despite many years of application. Errors in nitriding processes are caused by careless execution and a lack of precise control over process parameters, resulting in an inappropriate nitride layer [3-7].

2. ZEROFLOW METHOD

Nitriding methods currently applied make it possible to obtain nitrided layers of any specific structure thanks to precise regulation of the chemical composition of the nitriding atmosphere and nitrogen potential. One example is the ZeroFlow method, developed by SECO WARWICK, which is based on performing the nitriding process using a single-ingredient atmosphere consisting solely of ammonia (NH_3) dissociating inside the furnace retort, the concentration of which determines the degree of nitriding potential. In practice, this is realized by regulating the flow rate of ammonia through the retort and by periodically closing and opening ammonia supply to the retort. The fact that the flow rate of ammonia into the retort is periodically reduced to zero is of particular significance. This makes it possible to significantly reduce the consumption of process gases in comparison to conventional nitriding methods and also simplifies the nitriding station as well as the process itself while simultaneously preserving full control over layer growth kinetics [4-6].

3. RESEARCH METHODOLOGY

Tools used in the hot forging process were analysed. The selected process is performed in three operations: upset forging, preliminary die forging, and finish forging. The initial temperature of the billet material is 1150 - 1180°C (forging temperature). 20HG steel was used as the material of the forging. The tools are made from 1.2343 hot-work tool steel. Analysis of the effectiveness of applying ZeroFlow nitriding for the purpose of improving tool lifetime was conducted for the bottom die insert in the second operation, for which the lowest lifetime (approx. 8 000 forgings) was observed [3].

Tools with two variations of nitrided layers obtained using the ZeroFlow method were tested and studied, and for comparison, a tool with a nitrided layer obtained by traditional gas nitriding was also tested. Nitriding processes for the tools intended for testing were performed by SECO/WARWICK S.A. in Świebodzin. ZeroFlow nitriding processes had differing process parameters, so nitrided layers of varying structure were obtained. **Table 1** presents the parameters of applied nitriding processes. Special samples (pilots) made from the same material as the tools were also found inside the furnace retort during the execution of nitriding processes.

Table 1 Parameters of nitriding processes

No.	Nitriding method	Parameters of the nitriding process
1	Traditional nitriding	1st step 500 °C / 5 h / deg. of dissociation NH_3 15-20 % 2nd step 540 °C / 15 h / deg. of dissociation NH_3 30-60 %
2	ZeroFlow no. 1 (ε)	1st step 490 °C / + 1 h / N_p = 15 $atm^{-1/2}$ 2nd step 550 °C / + 10 h / N_p = 3.0 $atm^{-1/2}$
3	ZeroFlow no. 2 (γ')	1st step 490 °C / + 1 h / N_p = 15 $atm^{-1/2}$ 2nd step 550 °C / + 13 h / N_p = 0.6 $atm^{-1/2}$

Tools after the nitriding process were subjected to operational tests, in which each tool was used to forge 7500 forgings. Next, the tools used in this manner were subjected to thorough analysis. Conducted tests included: macroscopic observations, microscopic observations using a scanning electron microscope of the working surface in selected areas, microstructural analysis and microhardness measurements.

Moreover, in each of the performed nitriding processes, besides the tool, test samples, so-called pilots made from 1.2343 steel and prepared in the same manner as tools, were also treated. Analysis of these pilots will allow for, which were then tested in order to determine the properties of the near-surface layer of tools before their operation.

4. TESTING OF TEST SAMPLES

Test samples made from 1.2343 steel, were also treated by heat treatment and nitriding process to determine the properties of the surface layer of tools before their operation. Following thermochemical treatment, these pilots were cut, polished and etched, and then their microstructure was observed and microhardness of the surface layer measured. A view of the microstructure of selected samples is presented in **Figures 1-3**. In order to protect against chipping of the white layer, samples were nickel-plated.

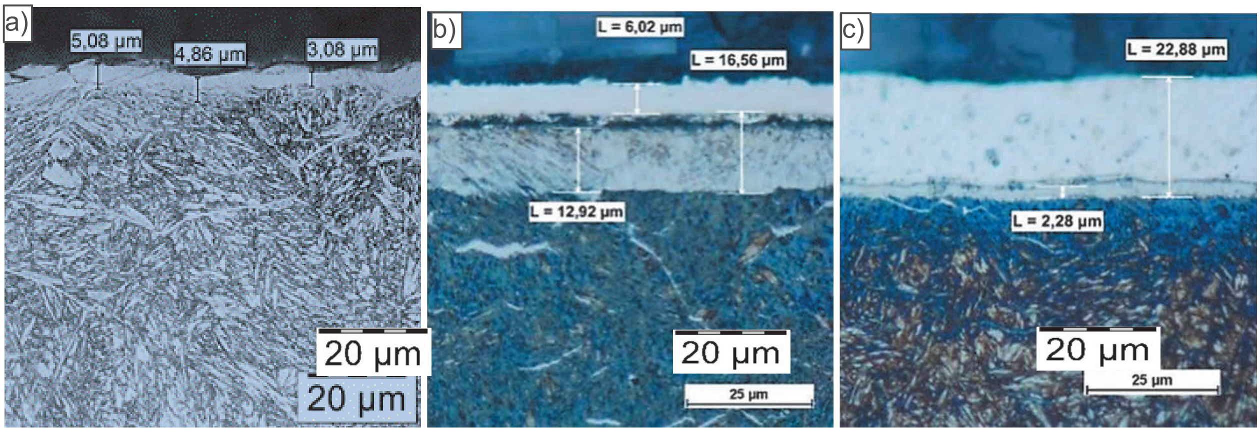

Figure 1 View of the microstructure of the nitrided layer: a) traditional nitriding, b) ZeroFlow nitriding variant no. 1 (ε), c) ZeroFlow nitriding variant no. 2 (γ')

When the traditional method was applied, a diffusive zone of α nitrides with γ' precipitates visible mainly on the surface (**Figure 1a**) was obtained. Nitrided layers obtained in the ZeroFlow nitriding process consisted of an α diffusive zone with γ' nitride precipitates on the surface and a non-continuous, thin zone of ε iron nitrides with a maximum thickness of approx. 3.5 μm in variant no. 1 (**Figure 1b**). However in variant no. 2, a nitrided layer with a γ'+ α structure was obtained (**Figure 1c**).

Next, microhardness distributions (**Figure 2**) were determined on the prepared samples, and these profiles provide information about changes in hardness at various depths in the near-surface layer. ZeroFlow nitriding makes it possible to obtain a clearly thicker layer with similar maximum hardness but a different hardness profile at a depth below 0.1 mm. Layers nitrided using the ZeroFlow method have a milder hardness reduction, which is favourable from the perspective of these layers' resistance to fatigue cracking and tempering.

5. MACROSCOPIC STUDIES OF DIES

Macroscopic observations showed traces of various wear mechanisms such as abrasive wear, fatigue cracking and oxidation, which occurred with varying intensity in individual areas. Abrasive wear mainly occurs on the edge of the bridge (**Figure 3, no. 3**) and in parallel with thermomechanical fatigue on the central face surface (**Figure 3, no. 1**). Oxidation is observable, particularly on the lower face surfaces (**Figure 3, no. 2**). Based on observations of the tool's surface and previous studies [1], 3 areas in which the aforementioned wear mechanisms are dominant were distinguished. The scheme of the division is presented in **Figure 3**. Further analysis of tool life was conducted in these areas from the perspective of the resistance of tools with the applied nitrided layers to the tool wear mechanisms dominant in these areas.

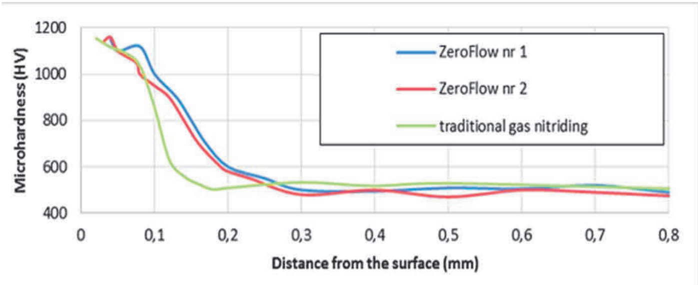

Figure 2 Microhardness distributions determined on studied samples after nitriding

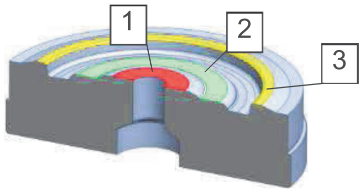

Figure 3 Areas of analysis on the tool surface

5.1. Thermomechanical fatigue resistance tests

In the area marked in **Figure 3**, the tool's surface is subjected to intense thermal shocks since it remains in contact with the hot material for the longest time and the stream of sprayed cooling and lubricating fluid is directed straight towards this area, causing intense thermal shocks to occur in this area [3].

Figure 4 presents selected results of SEM surface analysis in area 1 (**Figure 3**).

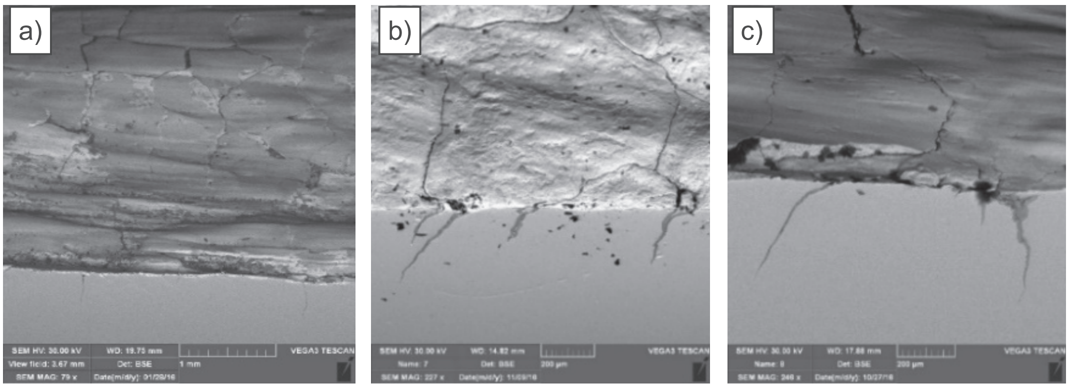

Figure 4 SEM view of the surface in area no. 1 on a tool nitrided a) traditionally, b) by ZeroFlow variant no. 1 (ε), c) by ZeroFlow variant no. 2 (γ')

A fatigue crack network was observed on the surface of the tested tools, and these cracks were deformed as a result of the material's tempering in the near-surface layer. In addition, abrasive wear occurs in this area, visible in the form of furrows oriented along the line of the material's flow over the die's surface. Microstructural analysis, was conducted in order to explain the method by which cracks form and propagate into the tool. Observation of cracks on the cross-section showed the presence of cracks of various lengths, reaching up to 400 µm, propagating into the tested tools perpendicularly to the surface or along γ' nitride precipitates inside the nitrided layer. Crack propagation is generally trans-crystalline, however a tendency to propagate along nitrides precipitating on the grain boundaries of what was formerly austenite is observed locally, particularly in tools with a larger amount of such precipitates. The total size of wear, expressed as material loss, is the greatest for the traditionally nitrided tool, while the tool nitrided by ZeroFlow no. 2 (γ') is characterized by the highest durability.

5.2. Oxidation resistance tests

In area 2, a significant part of the due surface is covered by a non-uniform, flaky layer of oxides. Wear often takes on the form of excess material instead of material loss. The structure of the oxide layer was studied by

SEM microscopy, because oxides are too brittle to polish effectively and observe by means of light microscopy. Selected results of studies are presented in **Figure 5**.

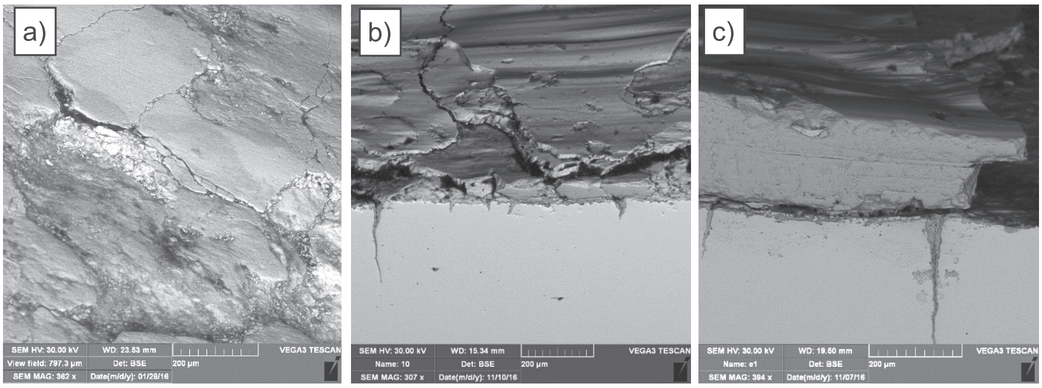

Figure 5 View of the oxide layer in area 3 on a tool nitrided a) traditionally, b) by ZeroFlow variant no. 1 (ε), c) by ZeroFlow variant no. 2 (γ')

The formations visible on the surface are built at the cost of the tool's material, and they then crack and detach from the surface as a result of interactions with the formed material. To confirm the contents of these precipitates as iron oxides, testing of chemical composition was performed using the EDX method. The results are presented in **Figure 5**.

Analysis of chemical composition showed significant iron content, which confirms the assumption and rules out the possibility that these precipitates may be stuck lubricant residue or other contaminants. Studies showed a high tendency for oxidation of the surfaces of tools nitrided by ZeroFlow no. 1 (ε).

5.3. Abrasive wear resistance tests

Abrasive wear of forging tools usually occurs at locations where pressures and the path of the formed material's movement over the tool's surface are the greatest/longest. Furthermore, this wear usually occurs as a consequence of fatigue cracking, where a crack network is present, the depressions of which give rise to abraded furrows (**Figure 6**). In the case of the analyzed tools, the most intensive abrasive wear occurs at the edge of the bridge where the flash forms - area 3 (**Figure 3**).

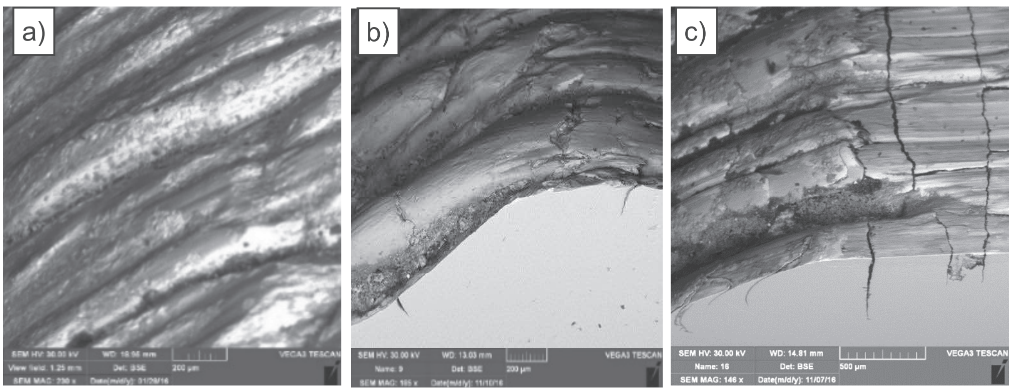

Figure 6 SEM view of tool nitrided a) traditionally, b) by ZeroFlow variant no. 1 (ε), c) by ZeroFlow variant no. 2 (γ') in area 3 of analysis

SEM and macroscopic observations showed varied resistance to abrasive wear of tools with different nitrided layers. The lowest resistance was observed for the traditionally nitrided tool (**Figure 6a**), moderate resistance for the tool nitrided by ZeroFlow variant no. 1 (ε) (**Figure 6b**) and the highest resistance for the tool nitrided by ZeroFlow variant no. 2 (γ') (**Figure 6c**).

5.4. Tempering resistance testing - microhardness analysis

In order to determine resistance to the action of elevated temperatures, a series of microhardness tests was performed on the cross-section, in the direction from the surface perpendicularly into the tool. The degree of the material's tempering in the surface layer was compared between the studied nitrided tools after their exploitation in the 2 of 3 studied areas. The results are presented in **Figure 7**.

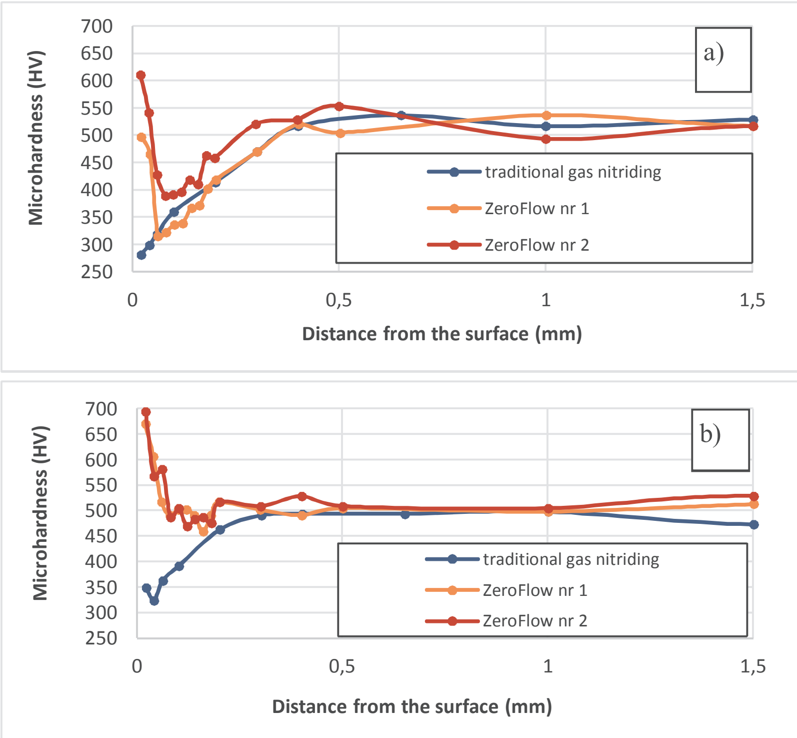

Figure 7 Comparison of microhardness in the surface layer of tools after exploitation; a) area 1, b) area 2

The comparison presented in **Figure 7** concerns 2 areas. In area 1 (**Figure 7a**), the tool's surface was in contact with the forging for the longest time, and normal forces were also the greatest [3], thus all tools were tempered in the near-surface layer, however tools nitrided by ZeroFlow, particularly variant no. 2, exhibited a certain resistance to tempering and maintained a partially elevated hardness. In area 2 (**Figure 7b**), where both pressures and contact time were lower, strong tempering of the traditionally nitrided layer took place, however other tools lost hardness only partially and a zone of reduced hardness did not form directly under the nitrided layer. In summary, tools nitrided by means of the ZeroFlow method exhibited greater resistance to the action of high temperatures in contact with the hot-forged material.

6. CONCLUSIONS

Conducted studies made it possible to comprehensively evaluate the applied nitrided layers from the perspective of improvement of forging tools' lifetime. The following conclusions were formulated on the basis of analysis:

1) Tool lifetime depends, above all, on the type of applied layer and the method of its creation.
2) Excessive precipitation of γ' nitrides forming on grain boundaries of former austenite intensify the

process of fatigue crack formation and propagation along grain boundaries in the material.

3) The nitrided layer obtained by means of the ZeroFlow method is characterized by a mild reduction in hardness and greater depth of the nitrided layer, which results in greater resistance to the action of high temperatures causing local tempering of the near-surface layer.
4) The tool nitrided by ZeroFlow variant no. 2 (γ') is characterized by the highest resistance to thermomechanical fatigue and abrasive wear, and this is due to the lower, controlled amount of nitride precipitates in the diffusive layer and on the surface.
5) The tool nitrided by ZeroFlow variant no. 1 (ε) is characterized by a longer lifetime than the traditionally nitrided tool, however it exhibits a greater tendency for formation of an oxide layer on the surface.

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