

Load-Adapted Surface Modifications to Increase Lifetime of Forging Dies

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Abstract. Diffusion treatments offer possibilities to enhance the performance and the service lifetime of hot forging tools. In combination with coating after nitriding, the surface layer hardness can be further increased. Within the scope of this study, a surface layer hardness above 2,000 HV_{0.005} was determined for borided or DLC (diamond-like carbon) coated surface layers. An increased surface layer hardness improves the abrasive wear resistance of forging dies. Furthermore, the plastic deformation of thermally softened forging die areas can be reduced. Beside these desirable effects, the ductility of diffusion treated or coated near surface layers is reduced and thermomechanical cracks are promoted. Therefore, additional approaches were developed to improve the thermomechanical crack behavior of forging dies. Patterned plasmanitriding by the use of coverages to prevent areas from nitrogen diffusion, new combination processes of plasmanitrocarburizing (PNC) followed by plasmanitriding (PN) and the innovative boriding were investigated on different abstraction levels. A system of several testing rigs was set up to enable the abstraction of the thermal shock conditions in different stages. The patterned nitriding, boriding and combination plasma process (PN + PNC) were evaluated in a series of industrial field tests to derive recommendations for suitable tool treatments.

Introduction

Forging dies are subjected to high mechanical and tribological loads, resulting in tool wear, which can be reduced by an increased surface layer hardness, achievable by diffusion treatments and coatings [1]. Cyclical processes with high rates in the temperature changes act during die forging simultaneously with high forces. They promote several wear mechanisms such as abrasive and/or adhesive wear, plastic deformation and tribochemical reactions [2]. In addition, crack formation and propagation are observed on the tool surface [3]. During the forming operation, the mechanical load and the tribological conditions under the thermal regime are responsible for most of the wear patterns, which can be investigated afterwards.

Thermal cycles at the beginning and the end of the forging process, combined with the application of cooling lubricants, cause thermal shock conditions and affect the microstructure of the tool steel [4]. This results in tempering effects of the surface zone whereby the material is changing the properties towards brittle behavior. The consequences are intensive crack formation and propagation [5].

Investigation Concept

Within the last decade, the authors worked cooperatively on this topic in order to enhance service life times and profitability of forging dies through a number of different concepts such as diffusion or coating treatments [6]. The results have shown that wear reduction strategies must be adapted to the

specific wear mechanisms in each forging process. For this purpose, the authors have developed a concept for the evaluation of wear reduction strategies using different testing methods. First, after the analysis of the load spectrum and wear mechanisms in industrial forging dies, treatment strategies tailored to the required forging processes are designed.

The abstraction of thermal shock conditions is the aim of the described work, which intended to investigate the corresponding effects with tools enabling different loading rates (Figure 1). Starting point is a simple oven tempering test which represents an abstract model of the cyclic thermal stress induced in the forging process without normal load. The next approach is the input of thermal energy through contact without loading, since the heat conduction between two solid contact partners is significantly higher.

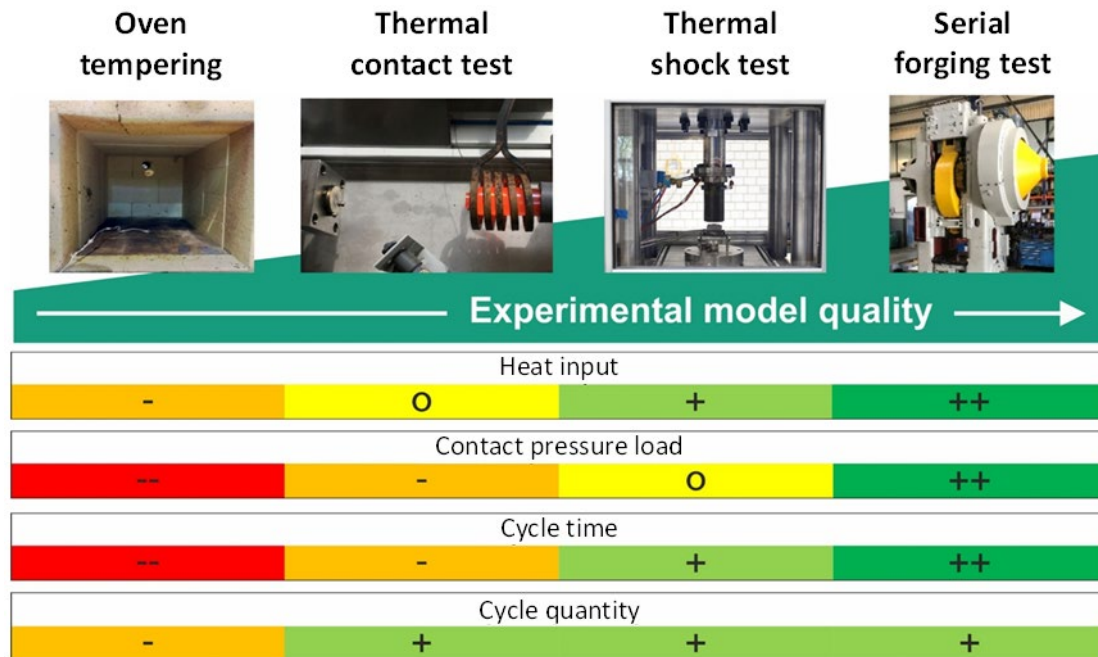


Figure 1: Modelling approaches of thermal shock conditions with varying degree of abstraction.

A rig for the thermal shock test with adaptable conditions related to industrial production and serial forging test conditions as well was a central aspect of the discussed work. Figure 2 (left) shows the construction consisting of an inductively heated stamp (upper part), the sample holder (lower part) and control units.

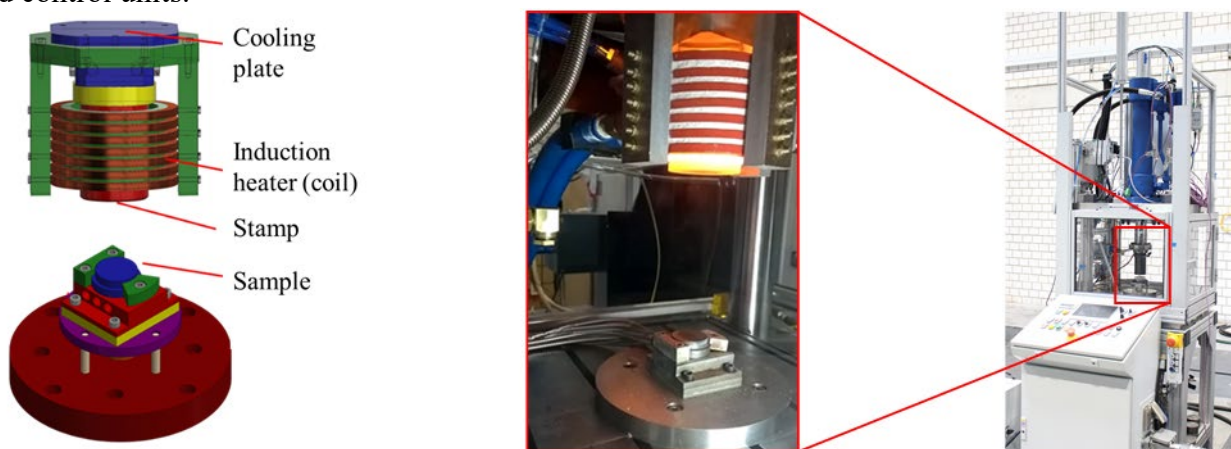


Figure 2: Developed thermal shock test rig.

The developed rig with a hydraulic actuator (force up to 150 kN) is shown in Figure 2 (mid and right). The stamp is pressed onto a fixed sample, resulting in heat conduction under forging conditions. Accordingly, samples are made of hot working tool steel to represent forging dies.

Between each load cycle, cooling lubricants can be applied to the sample's surface by a spray device. Heating and cooling rates, pressure contact times, temperatures as well as cycle times can be individually adapted to different forging processes.

After evaluating the wear behavior on an abstract level, the most promising approaches are applied and tested in serial forging tests on a laboratory scale. Different tool geometries were designed, emphasizing predominant load components as thermal load, abrasive wear caused by material flow and cracking in mechanically loaded dies that tend to crack in sharp geometrical transitions [7]. After these tests, the wear behavior of each tool is analyzed in order to determine the treatments suitable for industrial application. Finally, the most promising treatments are applied in industrial serial forging processes and analyzed afterwards.

Development of Adapted Plasma Diffusion and DLC Coating Treatments

Diffusion treatment aims at basic hardening mechanisms by altering the near-surface zone of steel materials with precipitations of nitrides/carbides/borides and generation of compressive stresses. Different process approaches are relevant for an effective thermal shock preservation of the tool surfaces and developed and analyzed in the presented work.

Diffusion treatment methods. The material used was the steel AISI H11, which was quenched and tempered to 48 ± 2 HRC. Specimen were prepared with glass-bead blasting operations to create a defined surface topography and support the cleaning procedure before diffusion treatment. Diffusion treatments were conducted in an industrial plasma diffusion chamber (co. Rübigen Anlagentechnik, type PN 100/150) under different conditions. The main treatment parameters were treatment duration (16 h and 64 h), temperature (520 °C and 560 °C) and nitrogen and methane content of the treatment atmosphere (N_2 10 % and 80 %; CH_4 15 %). The duty cycle values (ratio of pulse duration to pulse length) were adjusted between 0.17 and 0.25 at a voltage of 560 V. For boriding treatment a plasma diffusion equipment (co. PlaTeG, type PP20 80/140) was used with a temperature range of 650 °C to 740 °C and process time of 2 h to 8 h within boron containing atmosphere (BCl_3 2-30 %; H_2 0-80 % N_2 ; Ar 3-6 %) at 2 mbar to 3 mbar. Between 650 V to 700 V and duty cycles of 0.17 and 0.25 a plasma is not necessary.

Layer analysis. Hardness depth profiles were determined according to DIN EN ISO 6507 using a micro hardness tester (co. Qness, type Q10A+) on cross-section specimens with test loads of 0.5 N, to characterize different surface modification treatments and thermal softening of near surface layers. In order to analyze the microstructure, scanning electron microscopy investigations were carried out (co. Zeiss, type LEO 1530) and additional energy dispersive X-ray analysis (co. Oxford Instruments, type X-Max SDD 80mm²). Scratch tests are used to characterize the layer adhesion of DLC coatings and were carried out according DIN EN ISO 20502 (co. Rtec Instruments, type SMT-5000).

Combination process PNC + PN. The parameter choice for a diffusion treatment is important to define the hardness gradient from the surface to the unaffected base material. The main process parameters are temperature, duration of treatment, gas atmosphere and the plasma parameter (pulse-pause-ratio) depending on the specific steel material.

While high hardness and a steep gradient negatively influence the crack sensitivity of the tools, starting with low surface hardness (ductile zone of up to 30 µm) with a following hardness increase and then a shallow gradient to the unaffected base material is positive in the context of thermal shock loading [6]. A combination of plasmanitrocarburizing (PNC) with following plasmanitriding (PN) can reduce tool wear since the formation of carbonitrides may provide different mechanical properties in the surface layer.

Patterned nitriding. Earlier investigations [8] with locally nitrided tools motivate the innovative concept of structured surfaces with patterns. This should enhance the crack resistance using ductile surface areas to improve crack resistance between areas with a high abrasive resistance and thermal stability. Figure 3a shows the principle of transferred patterns of diffusion preventing pastes onto the forging die engraving with different methods. The polished and etched cross-section (Figure 3b) reveal the corresponding nitriding profiles in the subsurface of the material.

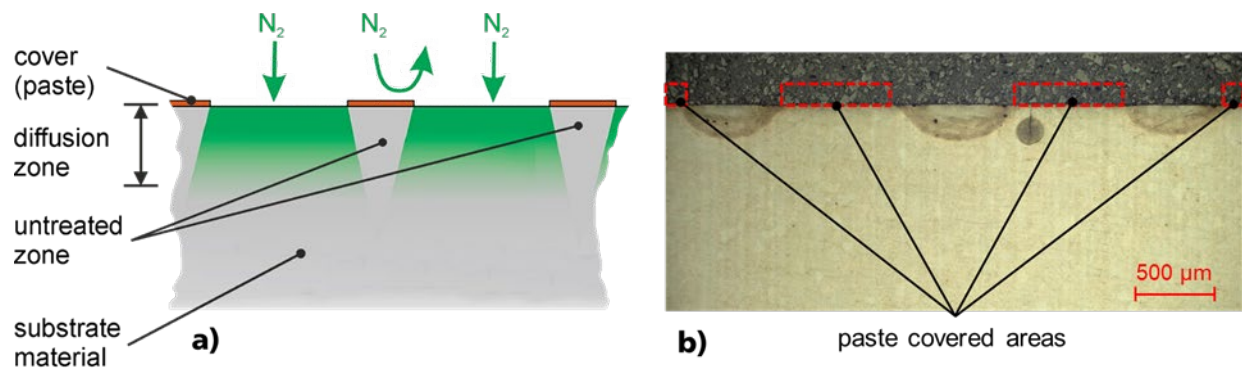


Figure 3: Patterned nitriding principle.

A variety of patterns adjusted to different geometry and load conditions are possible. Figure 4 (1-4) shows the concept of patterning with a plotted foil to transfer the paste structures via air brush technique on complex 3D geometries (Fig. 4, right). For the patterning a special paste, which prevents the nitrogen diffusion (co. Avion, type blue line) with structuring methods developed using a pattern cutting system via craftplotter (co. Silhouette, type Cameo 3) is used.

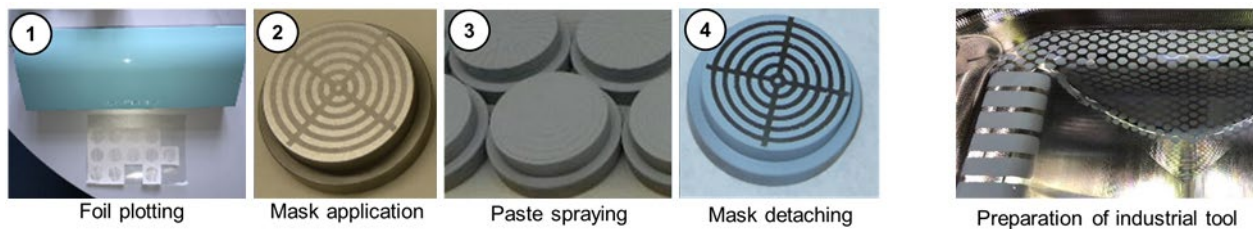


Figure 4: Structuring concept for the preparation of industrial tools to investigate the approach of structured diffusion treatment.

Boriding. The boriding treatment is a promising approach to increase the surface layer hardness of forging dies. Boriding treatments are industrially available with boron paste or powder pack techniques [9]. The innovative boriding procedure of the reported study is based on the diffusion of gaseous media with BCl_3 as source and additionally post-treatment (annealing) process. During boriding, boron penetrates the surface near material zone in different stages (Figure 5a, b, c) forming precipitations of borides with iron and different boron content. The result is a two-phase system consisting of FeB and Fe_2B (Figure 5d).

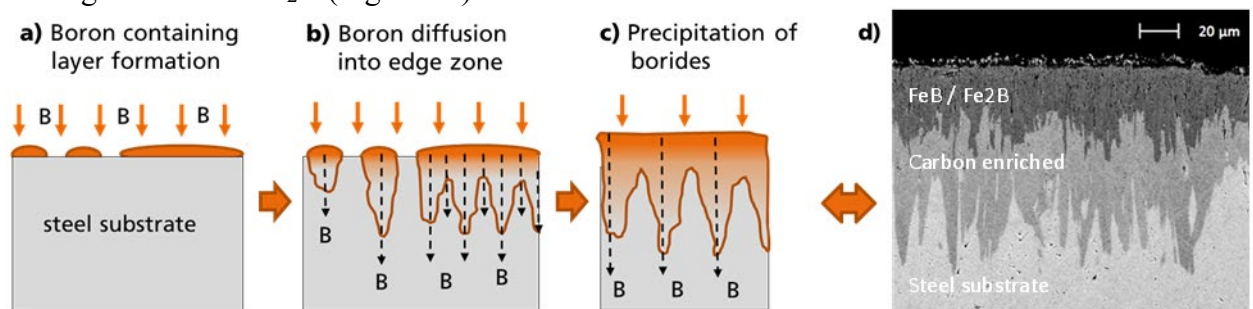


Figure 5: Boriding process mechanism steps and resulting microstructure.

Since the processes have to be conducted at a high temperature levels above $730^\circ C$, the base material softens since the annealing temperature is exceeded and requires thermal post-treatment. Figure 6 shows EDX analysis of the microstructures of borided steel AISI H11 before and after annealing.

The as-treated state shows the two phases FeB / Fe_2B . Below the boride phases, carbon enrichment can be observed. Additional chromium carbides are detectable in both phases as well. After thermal post-treatment the iron boride layers transform, the chromium carbides dissolve and Cr-B and Fe-Si rich phases segregate. Due to this transformation, a significant increase in hardness from $2,000\text{ HV}_{0.005}$ to $2,350\text{ HV}_{0.005}$ is measurable.

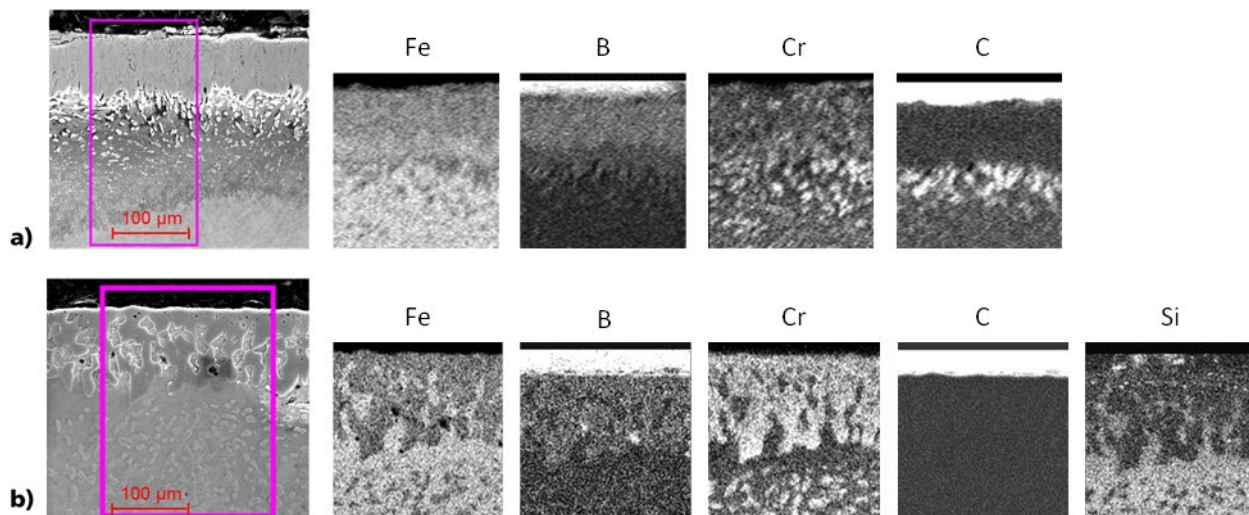


Figure 6: Microstructure and elementary composition in EDX line scan.

DLC coatings. All specimens made of AISI H11 tool steel were quenched/tempered and nitrided (520 °C, 16 h and 10 % N₂ atmosphere). Subsequently, carbon-based coatings were produced by magnetron sputtering Physical Vapor Deposition (PVD). They feature excellent friction conditions and high hardness. Due to the oxidation at higher temperatures, DLC coatings are mainly applied to cold forming tools. By doping DLC coatings with other elements, the temperature stability can be improved. In this study, DLC coatings were doped by 30 % tungsten and vanadium enriched atmospheres. Highest hardness value at room temperature of 2,030 HV_{0.005} was achieved with tungsten-DLC. In comparison, vanadium-DLC showed a hardness of 1,300 HV_{0.005}. By means of scratch tests according to DIN EN ISO 20502, it was found that tungsten-DLC also features an approximately three times higher coating adhesion at 600 °C.

Experimental Forging Tests

Serial Forging process. The serial forging tests on a laboratory scale were carried out on an eccentric press (co. Eumuco, type SP30d). Solid billets of AISI 4140 were inductively heated up to 1,150 °C. The tool geometry used is shown in the bottom right corner of figure 7. This geometry is used as the upper die and is subject to high thermal loads on the centric mandrel. The tools were heated constantly to 180 °C during the forging tests to reproduce the stationary conditions in long-running serial applications. Cyclic thermal loads occurred due to the contact to the billets and subsequent spray cooling in each forging cycle. By using automated handling systems, spray cooling and lubrication application, reproducible process conditions similar to industrial application were guaranteed. A process cycle time of 7 seconds for each forged part was reached [10].

Industrial forging tests. After the forging tests on laboratory scale, the most promising treatments were applied in a total of 5 different industrial forging processes. Due to confidentiality reasons, the process parameters and individual tool geometries provided by the industrial partners are not disclosed entirely and limited to sections in the presented results.

Analysis Methods. Tool wear was documented for all forging dies via stitched photographic images (co. Sony, type Alpha 7 Mark 3). For the serial forging tests on laboratory scale, the geometrical deviations were determined by 3D-profilometry (co. Keyence, type VR-3200). Due to the larger dimensions of the industrial dies, these geometrical deviations were analyzed using a 3D-Scanning system (co. GOM, type ATOS 2 400). All metallographic prepared specimens were etched by Nital (5 % HNO₃) to visualize the microstructure.

Results of Serial Forging Tests

Figure 7 shows a comparison of wear patterns and different wear values from non-destructive wear analysis. Due to the highest thermomechanical alternating stress, the focus of the investigations lies

on the mandrel of the tool engraving. There is a basic tendency for all examined tool variants that the dominant wear mechanism is not abrasive wear, but the thermo-mechanical crack formation. When comparing the geometry of the center mandrel of the reference state before use and after loading with 2,000 cycles with all modified tools, there is no significant wear in the mandrel area. All of the tools examined, show a positive geometry deviation on the face and the outer surface indicating a deposit on the tool surface. These can be residues of the graphite lubricant used or adhesions of the forged steel. The individual negative geometrical deviations seem to reveal deepened individual cracks, but no abrasive wear is visible.

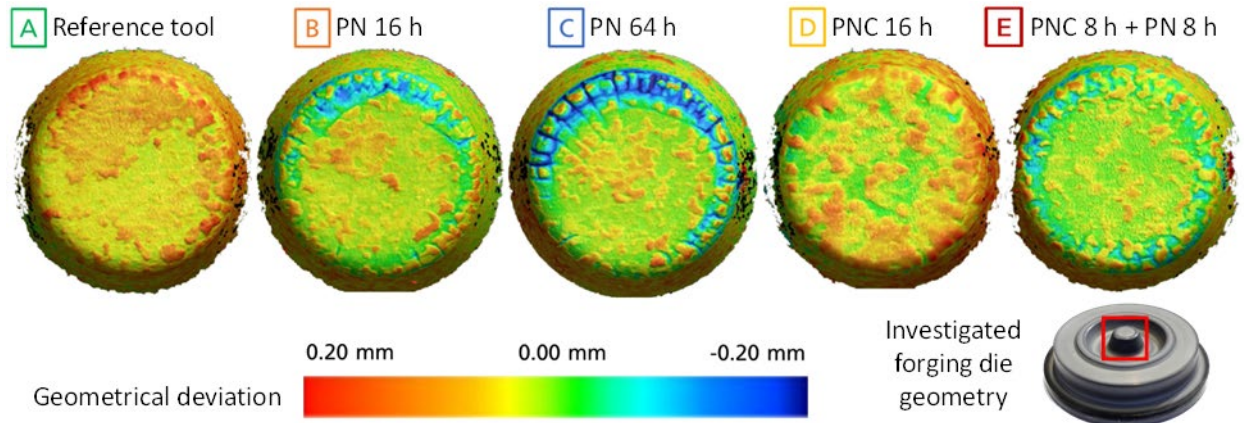


Figure 7: Geometric comparison of 3D scans of the model forging tools (material AISI H11) after 2,000 forging cycles; PN = plasmanitriding; PNC = plasmanitrocarburizing with following index for treatment time (16 h, 64 h).

The damage behavior at the mandrel radius after cyclic loading is shown in Figure 8 for all PN and PNC treatment variants. To characterize the wear behavior, hardening depth profiles were determined on cross sections and the microstructure was analyzed. It is obvious that the surface layer is softened to a depth of approx. 500 μm , largely independent of the treatment. Only the 64 h long-term plasma nitriding (tool C) prevents the softening because of a sufficient nitriding hardening depth. All of the samples show isolated cracks with exception of the combination treated (tool E) where no cracks appear in the examined cross section area.

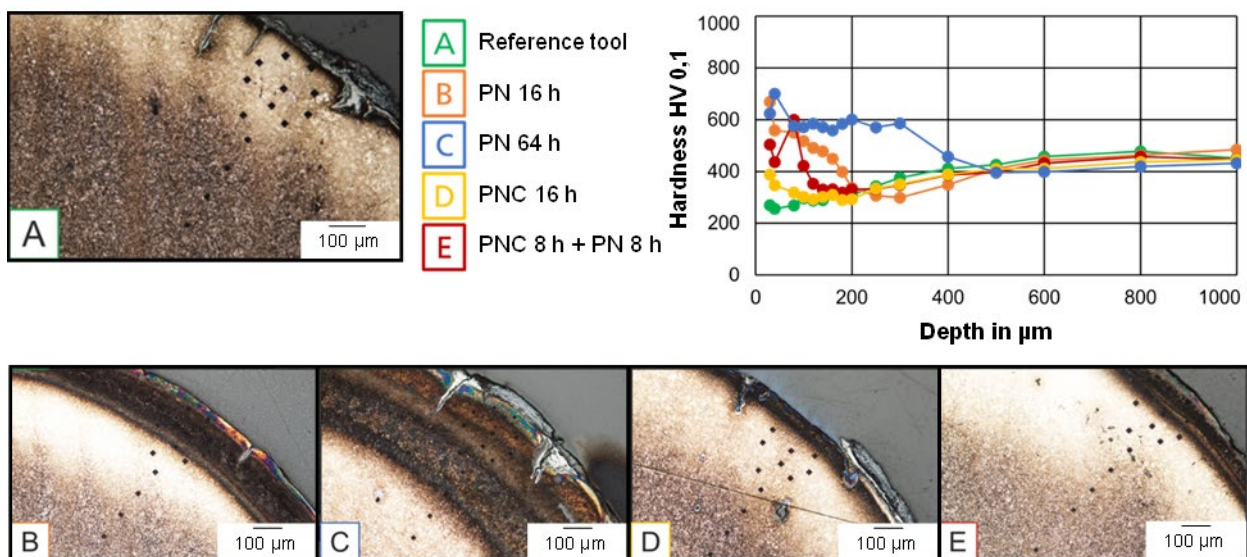


Figure 8: Wear analysis on cross sections of model tool surfaces for different diffusion treated tools after 2,000 forging cycles.

Compared to the top face, there are significantly fewer cracks on the mandrel radius and they do not differ significantly in depth. According to this, the treatments on the center mandrel do not seem to have any significant influence on the crack growth. As a result of thermal softening, the maximum hardness is reduced, especially in the case of treatments with a higher hardness gradient in the surface

layer at the tools B, D, E. Considering superimposition of tribological load, the damage will be pronounced with further loading cycles. A sufficiently high nitriding hardening depth through long-term plasma nitriding (tool E), however, can effectively prevent the softening effect.

Results of Industrial Forging Tests

Following the findings so far, the tool modifications of the industrial field test were prepared with the combination treatment PNC + PN and plasma boriding without structuring and the long-term plasma nitriding (64 h) in combination with the patterning approach, as well.

Combination treated forging dies show similar microstructure patterns at the inlet radius of a ridge path with high thermal loads, displayed in Figure 9. Exemplarily, Figure 9b shows a cross section of the modified zone at the radius. The nitrided zone has been removed and several cracks are visible running almost parallel to the edge zone. Furthermore, a white layer (martensite) has formed at the radius, due to geometry-related high cyclic thermomechanical loads. The austenite start temperature was exceeded on contact with the heated billet and was rapidly decreased by an application of cooling lubricants. Therefore, highest hardness values were measured in this rehardened surface layers (Figure 9a). A lightened microstructure area along the edge zone is typical for worn areas. Considering the hardness depth profiles, these surface layers were thermally softened. In individual spots, segments of the nitrided edge zone are still recognizable and seem to be intact in terms of thickness and geometry. However, they no longer follow the edge zone contour, but are moved and tilted.

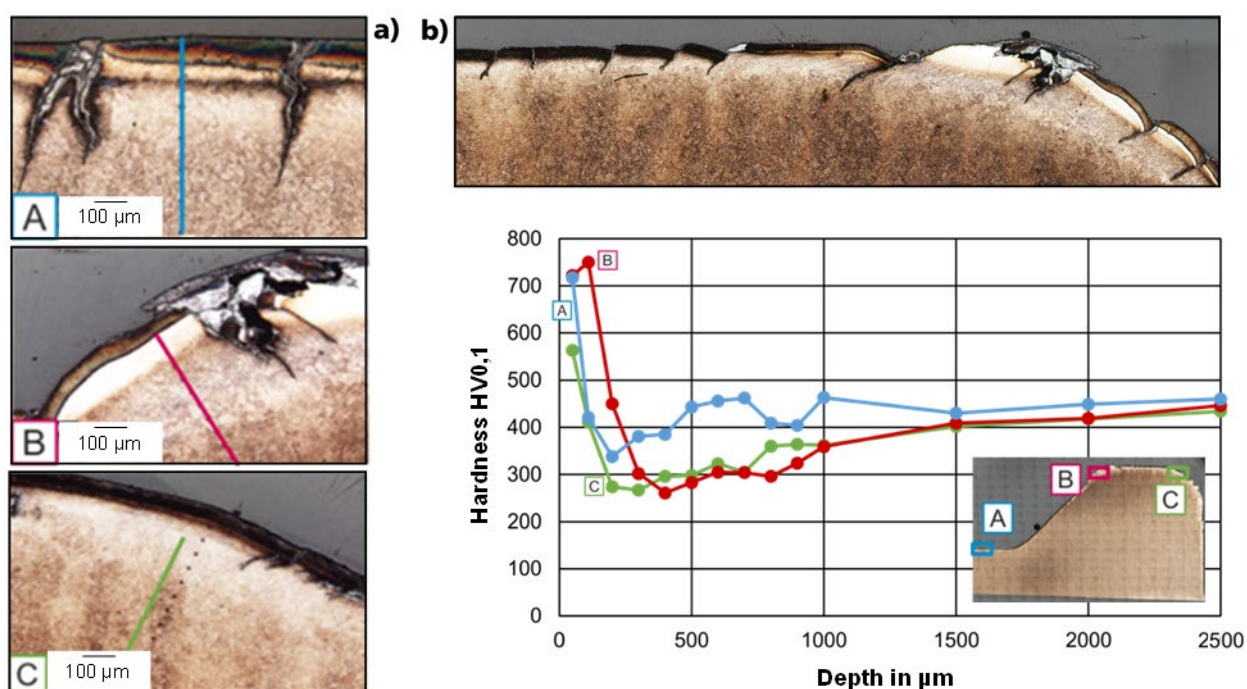


Figure 9: Micro hardness distribution at various points under the edge of a preform die tool (upper die) treated with a combination treatment PNC + PN at end of service lifetime.

The concept of load-adapted patterned diffusion treatments were applied to the complex industrial forging dies shown in Figure 4 on the right. In the center of Figure 10, this area is shown in the worn state after forging. Macroscopically, the highest abrasive wear is localized at convex inner radii. This is caused by increased thermal loads and surface layer softening. Furthermore, there is a plastic deformation between the radii and tool center, which appears as a linear gradation and is proven by metallographic analysis. 3D-Scans were performed, in order to determine the wear-related geometry changes of the tool based on CAD-models. Figure 10a shows the geometrical change at the burr path of a fully diffusion treated die area, while Figure 10b represents a patterned diffusion one. As a result, the abrasive wear is greater in the patterned diffusion treated area. A similar result can be observed

at convex radii, whereby Figure 10c shows the fully diffusion treated radius. This is caused by lower hardness in covered tool areas. However, the patterned diffusion treatment technique is expected to reduce thermomechanical cracks, with an improvement in high thermal and low mechanical loaded tool areas (e.g. behind the radius on burr path). In conclusion, patterned nitriding should be adapted to the tool loads.

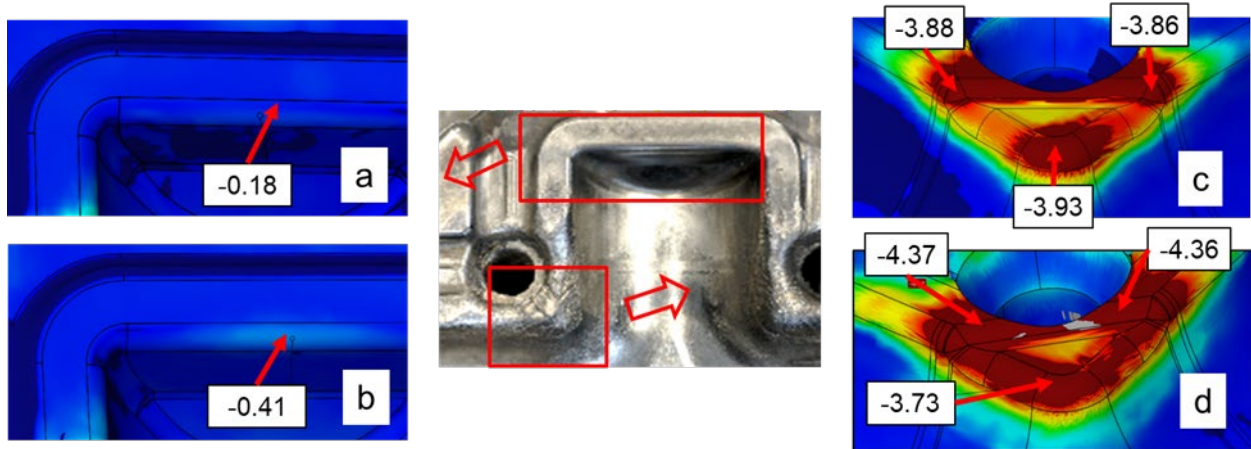


Figure 10: Industrial forging die after operation and end of life with completely (a, c) and structured nitriding (b, d) in differently loaded zone of the tool: inner flash path of the die (a, b) and convex radius (c, d).

Figure 11 (left) shows a nitrided forging die for which the geometrical changes in the worn state was determined by comparison to CAD models. In addition, Figure 11 (right) shows a borided tool. The maximum geometry deviation of the nitrided forging die is 2.01 mm. For the borided tool, a maximum geometry deviation of 0.99 mm can be observed. It is important to note that the nitrided forging die was subjected to an increased quantity of forging cycles of about 42.1 %. Considering the approximately 100 % reduced geometry deviation of the borided tool, an improvement of abrasive wear resistance can be assumed. It must be taken into account that wear progress is not linear, the lifetime of forging dies depends on many variables and this is a simplified assumption. Examining both metallographic cross sections, it can be seen that the nitrided variant featuring fewer but deeper cracks. The increased crack depth is related to the quantity of forging cycles as well as non-linear crack growth. In case of the nitrided forging die a partially intact nitriding zone is recognizable and the borided tool still features FeB / Fe₂B phases. Furthermore, the borided forging die shows material disruptions. These indicate a high surface layer hardness, which also correlates with the increased crack sensitivity and abrasive wear resistance.

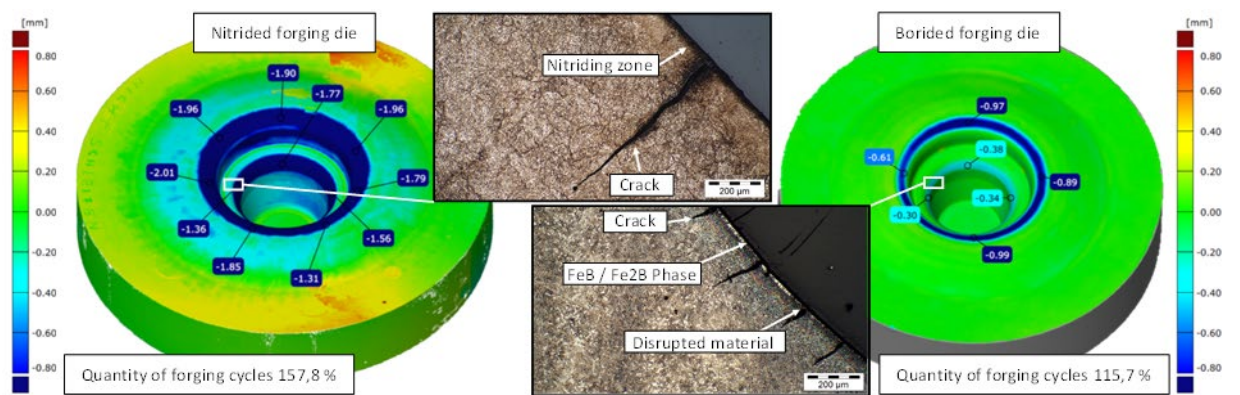


Figure 11: Nitrided (left) and borided (right) industrial forging die after operation and end of life.

Summary

The results of the presented work allow the recommendation of diffusion treatments for the enhancement of forging tool surfaces under load conditions of thermal shock with the following frame conditions.

- Structured diffusion profiles enable the possibility of graded hardness areas on the tool surface and adaptation to the local predominant load situation. Covered surface layer are prone to abrasive wear, but can reduce thermomechanical cracks. For the application of patterned diffusion treatments, it is recommended to analyze the wear behavior of the forging dies in the initial state, in order to protect high thermal and low mechanical loaded tool areas against thermomechanical cracks (e.g. burr path).
- Boriding and intensive nitriding offer possibilities to preserve the tool areas against thermal overloading and softening. Due to the increased hardness, borided forging dies show an increased thermomechanical crack sensitivity.
- A combination treatment of 8 h plasma nitrocarburizing followed by plasma nitriding of 8 h has shown positive effects regarding abrasive wear and thermomechanical crack resistance. This is due to increased hardness of carbonitrides and low duration of treatment.
- The hardness of tungsten-DLC coatings is similar to borided surface layers and features an increased thermal stability, compared to vanadium-DLC. However, DLC-coated forging dies need to be tested in forging experiments.

Acknowledgments

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