

Influence of the nitriding process on the durability of tools used in the production of automotive forgings in industrial hot die forging processes on hammers

Research Article

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Abstract: This work concerns the analysis of the application of the nitriding process to forging dies used for the production of automotive forgings on a hammer. The subject technological process concerns the production of forgings of a ring section made of AISI 304 stainless steel. The subject process is carried out on a LASCO HOU-160 forging hammer with a power of 16 kJ, in two operations, on the blocking impression and then on the finishing impression. In order to assess the influence of the nitriding process on the durability of tools, operational tests are carried out for three sets of tools after thermochemical treatment under real industrial conditions and then confronted with the results for standard tools (without a nitrided layer). The comprehensive studies carried out, including macroscopic analyses combined with scanning, numerical modeling, and microstructural tests for both standard tools and after nitriding, show a decrease in the durability of forging tools as a result of the use of nitriding in relation to the previous technology. It should also be considered that the process was carried out on hammers, for very thin forgings. Then, there are very high dynamic loads, which can lead to cracking of hard nitriding layers.

Keywords: Hot forging • Nitriding • Durability of forging tools • Ring forging

1. Introduction

The durability of forging tools is still a complex issue and requires detailed analysis in order to understand the mechanisms that destroy forging tools and affect their time of use and determine ways to limit their impact on the process. The durability of forging tools is most often defined as the number of forgings produced that are compliant with the technical and quality specifications and that can be produced using one tool or a set of forging tools without additional refining processes before their regeneration, repair, or reproduction [1,2]. Another term for service life is the total number of working hours spent producing correct forgings [3,4]. Therefore, the price of forgings is largely a result of the cost of tools, hence the

more controlled or high it is, the lower the price of the forging [5]. The current state of knowledge, a review of the available literature, and currently implemented hot die forging processes in Europe show that the costs associated with the production of forging tools account for approx. 25–40% of the total production costs in hot forging processes (data collected from Polish Forging Association and EUROFORGE in 2022 and 2023) [6]. Despite the continuous development of technology and attempts to increase the durability of tools by using new materials, heat treatment, and thermo-chemical treatments, the problem of low, not very repeatable durability has not been successfully solved [7–11]. As a consequence, this causes numerous additional costs related not only to the production of new tools and the preparation of a set of tooling but also to stopping production and the loss of time for additional tool replacement, as well as the costly process of reheating the tools to

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200–250°C. In view of the growing quality requirements for forging recipients and the need to implement precise forging, forges are obliged to maintain high quality of forging surfaces, which makes it necessary to maintain tools in very good condition throughout their operation. Also, these requirements force you to change tools frequently or increase their durability. For these reasons, the aspect of durability of forging tools used in industrial hot forging processes is very important.

Rising gas and energy prices as well as high inflation have a negative impact on the competitiveness of forges. Due to the above aspects, they are looking for solutions aimed at reducing their production costs. One of the key aspects in this regard is the durability of forging tools. From literature data, it is known that the cost of forging equipment is 25–40% of the unit cost of the forging (Figure 1). This shows how important the durability of forging tools is in the unit cost of the forging. Hence, the search for a solution determining the increase in the durability of forging tools and certain guidelines for obtaining higher durability than those obtained so far.

An individual approach consisting of changing the type of material used for tools in order to increase its durability, or the use of heat treatment to a higher hardness, or the nitriding process does not bring the desired effects due to the complexity of the issue and mechanisms that destroy forging tools. As a consequence, changes in individual parameters can lead to the opposite result in the form of even lower tooling durability.

The mechanisms of destruction of forging tools (Figure 2) are very complex, which means that it is necessary to analyze each case individually in order to select the optimal working parameters of forging tools. For this purpose, there is a need to have a single tool describing the mechanisms that destroy the forging dies and specifying the procedure to be followed during the forging process.

The durability of forging tools is still the subject of many scientific studies conducted in many research centers around

the world. Nevertheless, there is no single, comprehensive tool specifying how to avoid and/or minimize the impact of mechanisms of destruction of forging tools in industrial forging processes in order to reduce the cost of producing forgings. It should be clearly emphasized that in order to provide a correct and complete analysis, each die forging process should be considered individually, i.e., analyzed under specific industrial conditions because even a small difference in the geometry of the forging, a different aggregate, or slightly different temperatures will imply changes. This means that, for each forging process, there will be different dominant destructive mechanisms or their combinations. Therefore, appropriate solutions should be selected for them, allowing for increasing the operational durability of forging tools. Factors influencing the durability of forging equipment can be divided into several groups. The first one is related to the forging tool, the next one to the forgings produced on them, and the third one to the process parameters [12–16]. In the case of factors related to the tool, we can distinguish the type of material used for forging tools, the type of heat treatment, the quality of tool manufacturing, the shape of working cavities, and the design of forging tools in terms of the correct execution of their design [17–23]. Another group of factors is related to forging, i.e., the material it is made of (carbon steel, stainless steel, aluminum alloys, copper titanium, etc.), the complexity of the forging shape, the initial temperature of forging, the tolerances of forging, and the roughness of the surface of forging. Another area influencing the durability of forging tools is related to the process itself, i.e., the process parameters, the type of process, the type of forging unit used, or the forging technology [24–33]. The main changes that can be introduced to the process are related to the area of tools because the process or forging parameters are most often predetermined by the technology or the customer or impossible to change [11,12,34,35]. Therefore, within the scope of this work, it was decided to verify one parameter allowing for increasing the service life of forging tools, i.e., thermochemical

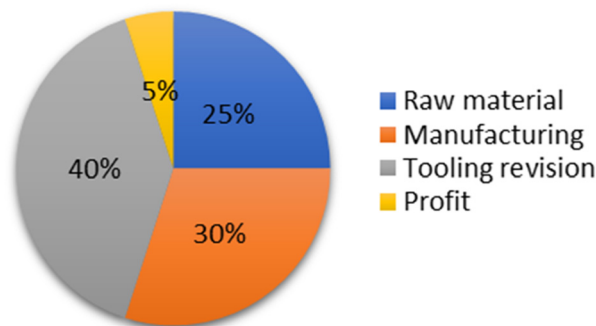


Figure 1. Cost of forging.

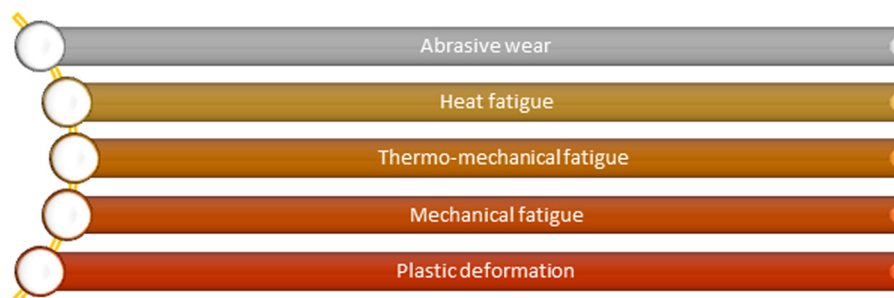


Figure 2. Mechanisms of wear of forging tools. The elaboration is based on Kannappan A.: Wear in Forging Dies – A Review of World Experience. *Met. Form.* Vol. 36 No. 12 (Dec 1969), s. 335; Vol. 37 No. 1 (Jan 1970), s. 6.

treatment, in our case, nitriding. Nevertheless, thermochemical treatment processes in some cases will provide positive results only for selected forging processes and are then economically justified. Others will not allow for obtaining satisfactory economic benefits or in extreme cases may have a negative impact on the durability of forging tools [36–39].

Forging of austenitic steels is carried out at temperatures, typically 900–1,300°C, in the range where the steel still has an austenitic structure. Austenitic steel 304, characterized by high corrosion resistance and good mechanical properties at high temperatures, also has high plasticity, which makes it relatively easy to forge compared to other types of steels. It fills the forging tool cavities relatively easily, but its disadvantage is also intensive crack penetration and acceleration of the decohesion processes of the surface layer of the forging tools. Therefore, forging of high-alloy austenitic steels is most often characterized by low durability of forging tools. Adhesive wear occurs when, as a result of high pressure and temperature during the forging process, micro-joints are formed between the tool surface and the processed material. In the case of high pressures during the forging process and too low stability of the nitrided layer, avalanche cracking, tacking, and formation of defects in the surface layer of forging tools may occur. Another factor accelerating the degradation process may be an improperly conducted nitriding process [42]. Additionally, as studies on the issue

of durability have shown, each forging process should be considered individually because a small change in technological parameters or in other aspects of technology may cause significant changes, e.g., in the frequency and periods of occurrence of various destructive mechanisms, which significantly affect the operational durability.

The aim of the work is to investigate and determine the effect of thermochemical treatment – nitriding – on the service life of forging tools for manufacturing AISI 304 stainless steel forgings in the hot die forging process on a hammer in a multiple system. The primary goal of nitriding is to obtain an increase in the durability of forging tools while ensuring a stable and high-performance technological process. The work verified why the nitriding process did not bring the expected results.

2. Research subject and methodology

The subject technological process concerns the production of forgings of a ring section made of AISI 304 stainless steel. The subject process is carried out on a LASCO HOU-160 forging hammer with a power of 16 kJ, in two

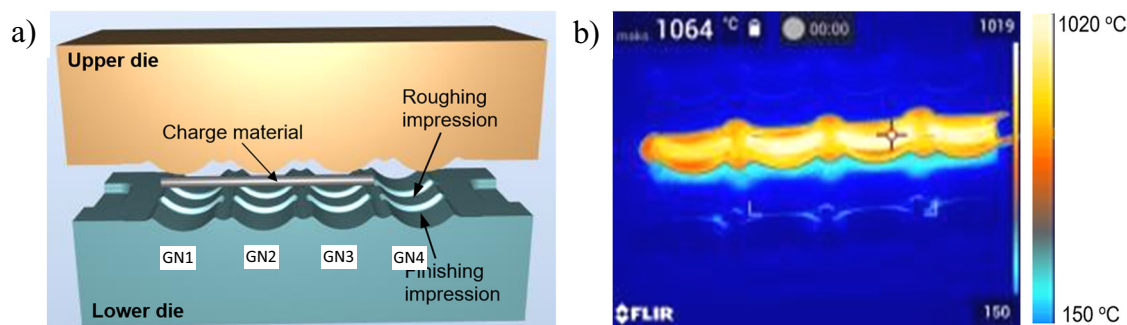


Figure 3. (a) CAD model of forging tools and (b) an example photo from a thermal imaging camera of the technological process.

operations, on the blocking impression, and then on the finishing impression. Every forging is divided into four parts, which are marked GN1, GN2, GN3, and GN4 in Figure 3. The temperature of the input material is 1,165°C. The forging tools are made of hot work tool steel 1.2344 and subsequently heat treated to a hardness of 48–50 HRC. The dimensions of a single forging tool are 150 mm × 150 mm × 400 mm, i.e., about 75 kg. In the process, two forging tools are used: upper and lower. Subsequently, roughing and finishing of the working impressions are carried out. The forging tools produced in this way using a high-precision machining center are subjected to quality control and subsequently transferred to production. Figure 3 shows photos of the CAD model of forging tools and thermography from the process.

Table 1 presents the average durability for tool sets manufactured using standard technology and thermochemical treatment (nitriding).

In Figure 4 is presented a comparison of wear forging dies for standard tools without nitriding (Figure 4a) and with a nitriding surface (Figure 4b) and faulty forgings (Figure 4c) obtained from tools after nitriding, in which defects are visible in the form of damage to their surface in the corners (in the area of a radius equal to 1 mm).

As can be seen in Table 1 and Figure 4, nitrided tools produce three times fewer forgings than tools without nitriding, despite the fact that the wear (geometric loss) of tools after nitriding is four times smaller and amounts to 0.05 mm compared to 0.2 mm for tools without nitriding. The reason for withdrawing nitrided tools despite the lower wear (shown in 3D scans) is visible defects in forgings, especially on radii, which is intriguing, because nitriding, as one of the main methods of increasing durability, should increase the service life of forging tools. In order to explain the decrease in the durability of the tools after nitriding, the following methods and techniques as well as measurement and research tools are used to carry out subsequent research and development works. The planned research is divided into several stages:

- Comprehensive analysis of forging technology through macroanalysis of the tool condition combined with the

analysis of geometric changes in the die surface using, among others, an ATOS 3D scanner.

- Measurements of the geometry of the forging tools are performed using a Mitutoyo STRATO Apex 776 automatic measuring machine, a Mahr XC 20 contour measuring machine, and an ATOS 3D scanner. Numerical modeling of the forging process for detailed analysis of the forging tools is done based on the current manufacturing technology and the necessary documentation, including 3D solids, models, and drawings based on the current technical documentation using CAD SolidWorks 2024 and CAM Mastercam 2024 software.
- Numerical analysis of the forging process is carried out using FORGE NxT 3.0 software.
- Study of the influence of thermochemical treatment, i.e., nitriding on forging tools in order to increase the service life based on metallographic analysis using a TESCAN VEGA3 optical microscope with an EDX detector.

3. Results and discussion

3.1 Comprehensive analysis of the currently implemented forging technology

The current technology of producing die forgings of a ring section made of AISI 304 material is implemented on a LASCO HO-U160 forging hammer with an impact force of 16 kJ. The input material is heated in an induction heater. The forging process is carried out in manual mode. The input material is heated to the forging temperature, and then the blacksmith operator takes it from the dropper and transfers it to the blocking impressions where hammer blow takes place, following which it is transferred to the finishing impression where one hammer blow takes place. Then, the blacksmith puts the forgings produced in this way on a belt

Tool durability	Tool durability (pcs)			Average (pcs)
	First set of tools	Second set of tools	Third set of tools	
Standard manufacturing process (forging tools without gas nitriding)	3,380	3,200	3,150	3,243
Forging tools with gas nitriding	1,200	1,070	1,370	1,213

Table 1. Comparison of the durability of forging tools.

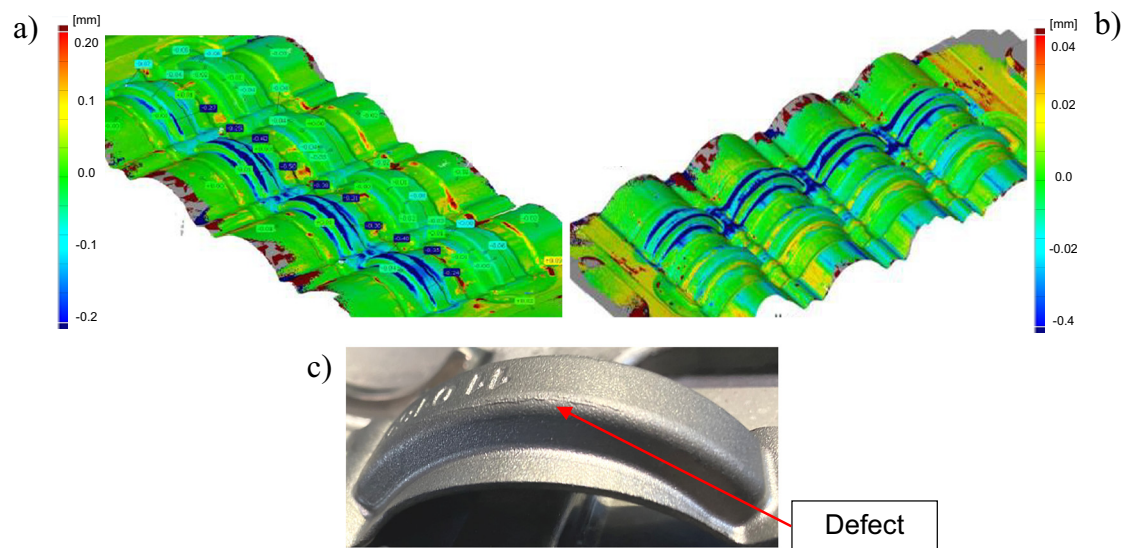


Figure 4. Comparison of forging dies for (a) standard tools after 1,370 pieces, (b) nitriding tools after 1,200 pieces, and (c) an example of faulty forgings in nitriding tools.

conveyor. Lubrication is performed manually by the blacksmith operator. The lubricant Graphitex 289 with water is used in a ratio of 1:10. The cycle time of this process is 11 s. The hot die forging process on a hammer is selected to test the durability of forging tools. Forging tools for the production of a ring section forging are manufactured using an advanced 3-axis center. In order to verify the correctness of the tool manufacture and its compliance with the technical documentation, measurements are performed using a Mitutoyo STRATO Apex 776 automatic measuring machine, and Figure 5 shows a view of the new forging tools along with selected measurement results for a representative set of forging tools.

They are then transferred to perform hot die forging operations on a hammer. These are standard tools without additional refining processes, including nitriding, which at the same time constitute a reference point for further research and the possibility of increasing the service life of the dies. After

a specified period of use, in accordance with the company's internal procedures, they are dismantled and transferred for further measurements. The tools are transferred for measurements after producing 3,380 forgings. In the first stage, a visual inspection of the forging tools is carried out, immediately after cleaning them, in order to determine the greatest loss of material. The critical places of the tools are shown in Figure 6.

As displayed in Figure 7, significant loss of material can be seen on the blocking impression, primarily for the upper forging tool and, to a lesser extent, for the lower forging tool. No significant loss of material is observed on the finishing impression for both the upper and lower dies. The entire forging tools are then scanned in order to observe them in relation to the reference (new) tools. In order to perform a more complete analysis and reconstruct the history of progressive tool wear, after the completion of subsequent stages of the production series of the forging process, they are removed, cleaned, and scanned.

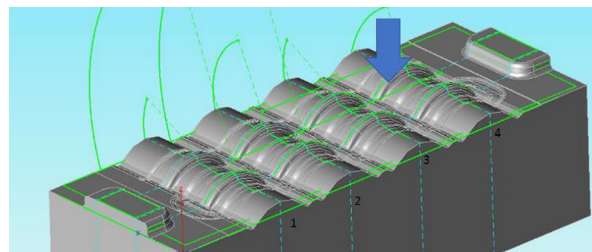


Figure 5. View of the upper forging die along with the results of scanning measurements of the upper forging tools on the Mitutoyo measuring machine (new forging tools).

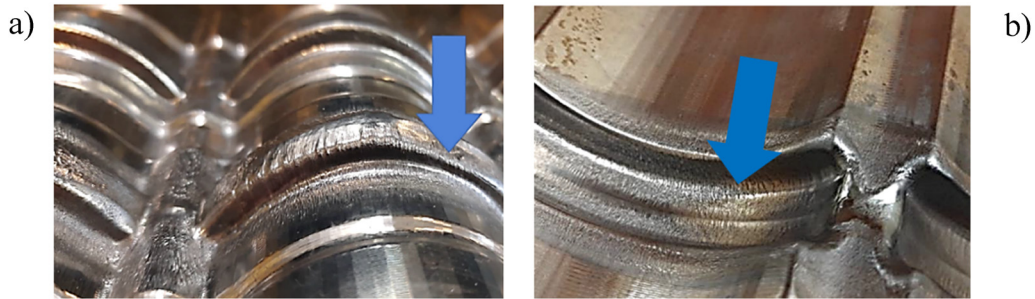


Figure 6. Visual evaluation of forging tools without nitriding after production of 3,380 forgings: (a) upper tool and (b) lower tool.

Therefore, in the case of the forging process for the next set of forging tools, it is decided to scan it after producing a specific number of forged elements (1,370, 2,240, and 3,380), where each such element has four individual forgings. Figure 6 shows scans of the upper forging tool after specific numbers of forged elements are produced. Analyzing the scanning results with the increasing number of forgings, the greatest wear can be observed on impressions 2GN and 3GN, then 4GN, and the least on impression

1GN. Due to the fact that the process is carried out in manual mode, it can be assumed that the amount of lubricant applied is the greatest for the two middle impressions. The Graphitex 289 lubricant with water is used in a ratio of 1:10. The lubricant is applied in increased amounts for the blocking and finishing impression for the upper forging tool and a smaller amount for the blocking and finishing impression for the lower forging tool. The operator starts applying the lubricant from

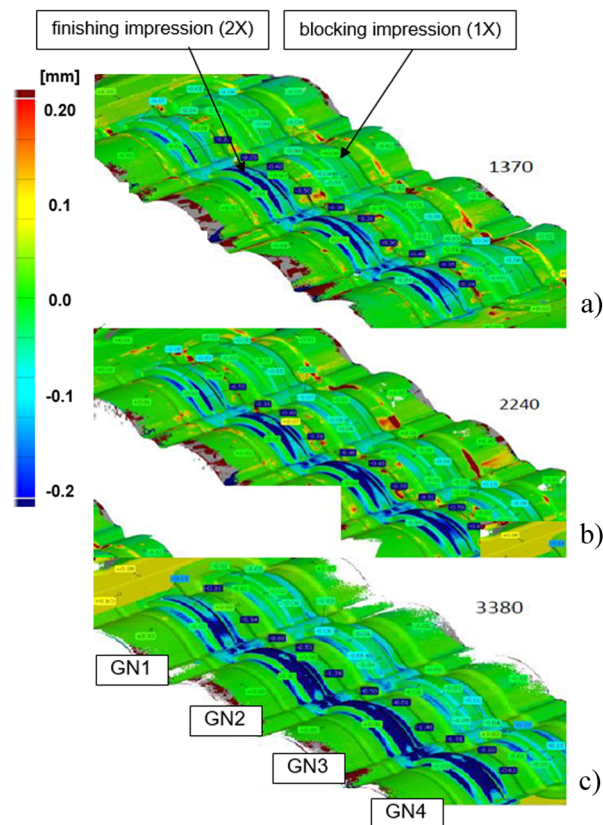


Figure 7. Scanning results of the upper forging tools after production of standard tools without nitriding: (a) 1,370 pcs of forgings, (b) 2,240 pcs of forgings, and (c) 3,380 pcs of forgings.

impression 1GN, switching on the spray by pressing the button on the lance, while switching off the valve in the middle of impression 4. It follows that the full opening of the lance valve occurs primarily for impressions 2GN and 3GN, so the lubricant is applied to these impressions in full. Moreover, based on the above tool scans, it can be seen that the trend described above for worn tools has been present since the beginning of their use, and after 1,370 pieces of forgings, the greatest wear of impression can be observed for 2GN, 3GN, then 4GN, and to the least extent 1GN.

The forging tool is withdrawn from production with the quantity of 3,380 pieces of forgings. The forging tool is withdrawn due to the dimensions of the forging not compliant with the technical specification. As can be seen, the intensive wear of the blocking impression causes faster wear of the finishing impression, which in consequence leads to the production of products not compliant with the technical specification, where the material loss is up to 0.6 mm. It should also be emphasized that the effect of premature wear from the blocking impression is transferred to the finishing impression, which leads to the production of forgings with defects.

3.2 Numerical analysis of forging tools and forging process

Numerical modeling is carried out for forging in the shape of a ring segment produced in a quadruple system. Numerical modeling of the forging process is carried out using FORGE NxT 3.0 software. Calculations are carried out in accordance with the adopted assumptions. The shaping

conditions related to the kinematics of tool movement are assumed in accordance with the characteristics of the Lasco hammer with a maximum impact energy of 16 kJ. The boundary conditions regarding the initial temperature of the input material, the temperature of the tools, and the times of individual processes are assumed based on the technological cards of similar forging processes and the technological assumptions provided by the manufacturer. Table 2 presents select initial boundary conditions that are assumed in the calculations of the forging process in four-impression dies.

Figure 8a shows the arrangement of tools for the forging process together with the arrangement of the input material and exemplary temperature field distributions just after the forging process in the finishing impression in the lower die (Figure 8b), as well as abrasive wear distributions according to the Archard model (Figure 8c).

During the process, there is a very short contact with the die impressions, which causes the tool temperature to increase to slightly over 320°C. Analysis of the results, in particular the distribution of the temperature field in the impressions indicates that the highest temperature values are found in the areas where individual forgings are joined together and amount to about 300°C, while in the impressions the temperatures are the highest on the bridges (260°C), and in the impressions themselves they amount to about 210°C. The temperature distributions obtained in finite element method (FEM) after the finish forging operation are correct because this was confirmed by temperature measurements in the industrial process using a thermal imaging camera (Figure 8b). In the case of abrasive wear, the highest values occur, similarly to the temperature fields, i.e., in the areas of joining and on the bridges (Figure 8c). Figure 9 shows the course of forging forces in the process for both cavities.

As can be seen, the maximum load in the blocking and finishing impression is similar and amounts to about 600 tons, which should not be a problem for the effort of the entire tools, but for the surface layer such forces can be a relatively large load, especially in the case of using hybrid layers or nitriding alone. Therefore, in order to more completely analyze the loads on the surface layer of the tools, finite elements of various sizes are applied to the tools; in the areas near the impressions the smallest possible elements are placed in order to better represent the states of deformation and temperature prevailing inside, and in particular stresses (pressures). During the simulation, the tools are loaded with momentary forces that depend on the degree of filling of the cut and the impact energy setting parameters used (Figure 10).

Input raw material	Ø12 mm × 276 mm
Number of strokes	1× (blocking impression): 12.5 kJ – 1 stroke; 2× (finishing impression): 5.5 kJ – 1 stroke
Temp. of the raw material	1,165°C
Cycle time	11 s divided into: cooling for 6 s + forging in the blocking impression for 2.5 s + forging in the finishing impression for 2.5 s
Machine	Hammer, 16 kJ
Temp. of tools	200°C
Lubrication	Water with graphite
Heat exchange	Average 10 kW/(m ² K)

Table 2. Initial-boundary conditions adopted for numerical calculations of the forging process.

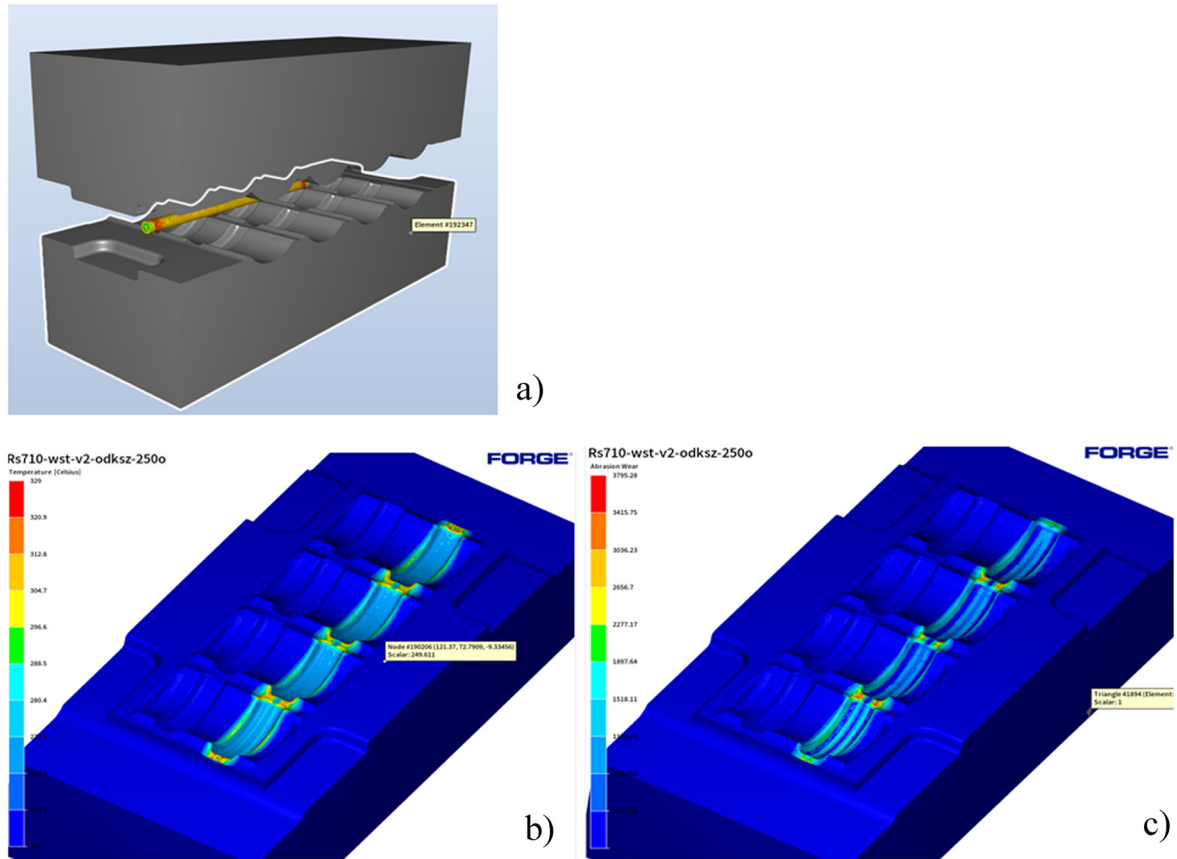


Figure 8. (a) Forging process and feed material settings, (b) temperature field distribution in the lower die in the finishing impression, and (c) abrasion wear in the lower die in the finishing impression.

The load of the maximum tool force is approximately selected, and for such a load the results of the material effort are presented. The interpretation is as follows: positive values indicate compressed areas, while negative values indicate stretched areas. In the simulation performed, the material stretching occurs at a small stress value, in contrast to compression, the values of which

reach even 1,800 MPa. The analysis of the reduced stress distribution is also performed in order to assess the von Mises pressures according to the Huber–Mises–Hencky (HMH) hypothesis (Figure 11).

The highest values are observed on the inner radius and on the surface (on which the forging number is located), reflecting the shape of the forging. Such tool loading

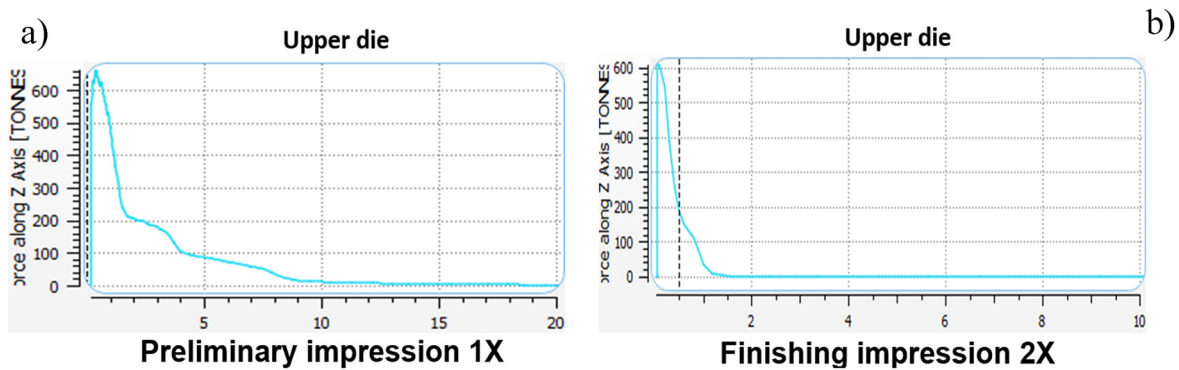


Figure 9. Force in the process of forging for (a) blocking impression and (b) finishing impression.

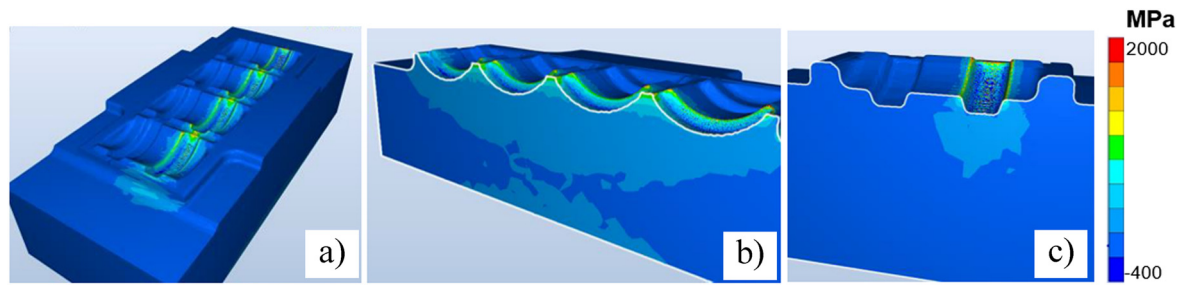


Figure 10. Distribution of hydrostatic pressure acting on the tool: (a) view of the entire lower tool, (b) longitudinal section, and (c) cross-section.

(1,500–1,800 MPa) causes stress concentration inside the tool, which is clearly visible in the cross-section. Moreover, it can be seen that in some areas the forging forces push the formed material apart causing a bending moment, while in other areas they can cause both compression and tension alternately. The analysis of tool loads during forging shows that at the moment when the forging force reaches the highest values, the reduced stresses and pressures also reach high values, which, taking into account the cyclical nature of the forging process, can intensify the pressures, especially in the near-surface areas. It should also be noted that in the case of detailed analysis of the surface layer using numerical modeling, further more advanced research work is necessary, including the development of a numerical model built from an additional surface layer reflecting the nitrided layer. Then, for the new geometry, multi-variant simulations taking into account contact phenomena are carried out.

3.3 Study of the influence of nitriding on forging tool durability

Previous studies [1,8,38], including macroanalysis combined with scanning and numerical simulations, were conducted in order to comprehensively analyze and determine the effect of the selected technique for increasing

the durability of forging tools used in industrial die forging processes on a hammer. The analyzed forging dies, which were subjected to one of the methods increasing durability (nitriding), are first subjected to a heat treatment process – hardening and double tempering in the temperature range of 500–525°C. The next step is to subject the dies to thermochemical treatment, i.e., gas nitriding. Gas nitriding is carried out in accordance with the following requirements, which are to ensure optimal operating parameters of the surface layer:

1. Thickness of the nitrided layer, max. 200 μm (core hardness +50 HV).
2. Hardness of the nitrided layer at the surface, 1,100 HV at a depth of 20 μm .
3. No layer consisting of Y' and ϵ nitrides.

The nitriding process is carried out for three sets of forging tools. A detailed analysis is carried out for a representative set, one of three, which had worked the average maximum number of forged elements (forged part with four individual forgings). The prepared forging tools are transferred to the forging production process and subsequently removed for testing after forging 1,200 pieces for their geometric analysis because the analyses during the process showed that their further use was unjustified and

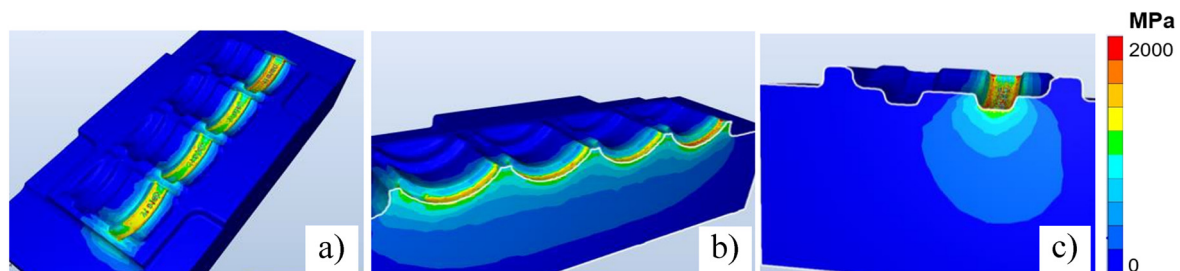


Figure 11. Distribution of reduced HMM stresses: (a) results for the whole tool, (b) longitudinal section, and (c) cross section.

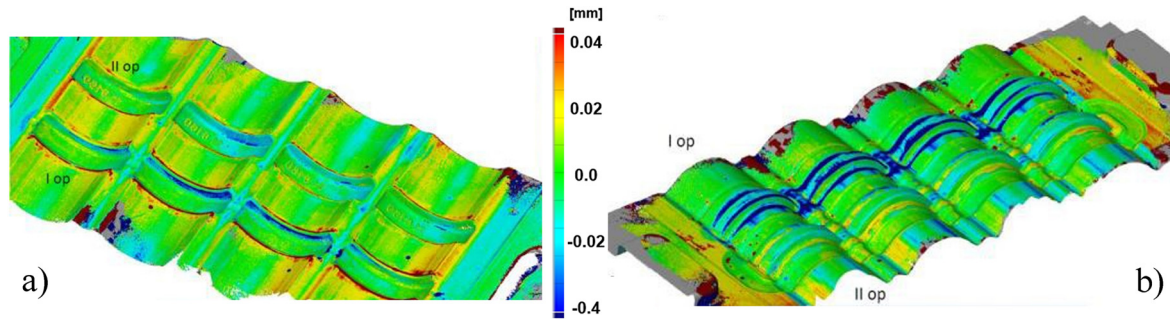


Figure 12. Geometric measurement of tools after being withdrawn from production: (a) lower die and (b) upper die.

because the forgings have defects (Figure 4c). The geometric wear is presented in Figure 12.

As can be seen, after producing 1,200 pieces of forgings, the tools experienced the greatest wear (geometric loss) in the blocking impression of the upper die (Figure 12b), for which the loss is up to 0.05 mm (navy blue). On the blocking impression, it is up to max. 0.02 mm on the upper die. A much smaller loss of material can be observed on the lower die (Figure 12a) up to max. 0.05 mm (navy blue) on the blocking impression and on the finishing impression up to max. 0.02 mm. The change in tool geometry is much smaller than for standard tools without nitriding (the wear is about 0,2 mm). Therefore, the reason for withdrawing the nitriding tools is not abrasive wear but other reasons that needed to be demonstrated.

In order to analyze changes in the surface layer, samples are taken from the forging tool in order to conduct detailed microscopic and microstructural tests. Two samples are initially taken from the forging tools. One from the preliminary impression (forging cavity) – 1× – and the

second from the finishing impression – 2×. Figure 13 shows the location where the samples are taken for testing. The die is cut into pieces and then the roughing and finishing cut. The individual die cuts are tested separately, as shown in Figures 14 and 15.

Then, after the basic preparation of the samples, they are subjected to microscopic observations. Figure 14 shows the results for the preliminary impression (1×). The microstructure analyses carried out (Figure 14) indicate numerous chippings in almost all selected areas. In addition, traces of abrasive wear can be seen (Figure 14d), especially in the vicinity of the bridge (Figure 14b). In the remaining areas, a network of thermomechanical cracks is visible (Figure 14b, f, g, h), as well as areas of micro-oxidation (Figure 14f and h). Areas with visible surface seizures (Figure 14c) and adhesion (Figure 14e) can also be observed.

The global analysis indicates micro-chipping of various sizes of falling particles, which may indicate the detachment of fractions of the nitrided layer, which is confirmed by macroscopic examinations using a 3D scanner. The 2×

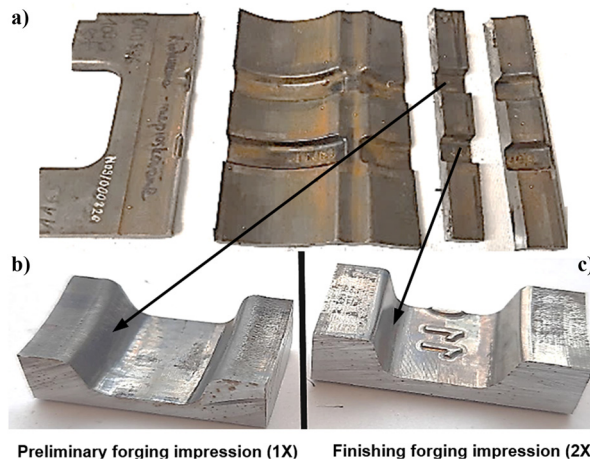


Figure 13. (a) An example of sampling locations with the samples taken from the forging tools after forging 1,200 pieces for (b) preliminary forging impression – 1× and (c) finishing forging impression – 2×.

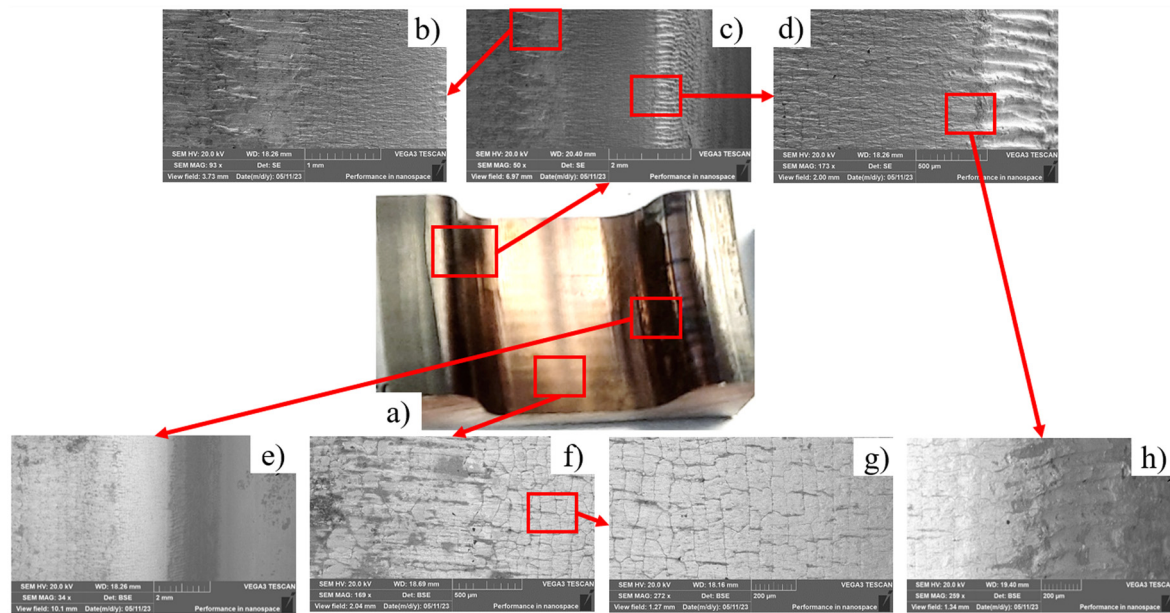


Figure 14. SEM test results for selected areas in the blocking impression – 1 $\times$ after making 1,200 forgings: (a) view of the blocking impression (1 $\times$) and (b–h) different areas of blocking impression (1 $\times$) from (a).

finishing impression is also subjected to microscopic observations. The results of SEM tests for the 2 $\times$ finishing impression (Figure 15a–c) are presented below.

Global analysis of the working surfaces indicates three main destructive mechanisms, which include primarily

thermomechanical fatigue (primary – Figure 15f and secondary – Figure 15i) and plastic deformation combined with surface oxidation (Figure 15d, e, g, and j). Small areas where adhesion occurs can also be observed (Figure 15g). Thermal fatigue probably appeared the earliest, which

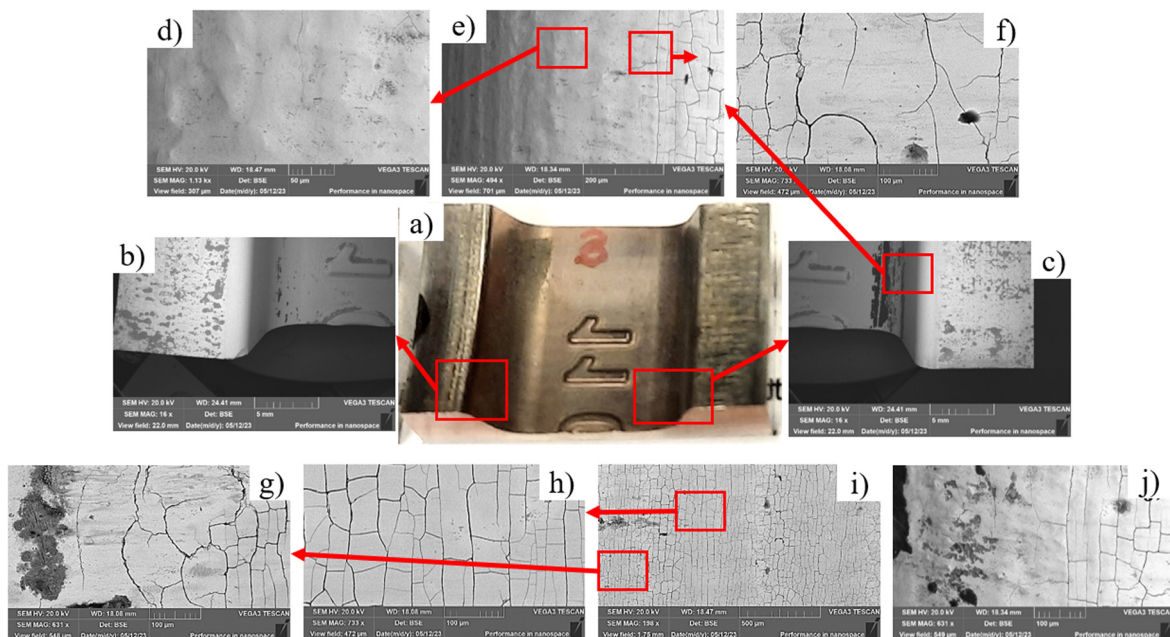


Figure 15. SEM test results for selected areas in the finishing impression – 2 $\times$ after making 1,200 forgings: (a) view of the blocking impression (2 $\times$) and (b–j) different areas of finishing impression (2 $\times$) from (a).

over time, due to cyclic mechanical loads, developed into thermomechanical fatigue and constantly progressing plastic deformation. In addition, it can be clearly seen that due to these mechanisms, particles are torn off from the surface of the impression. The crack network that forms at an early stage of the forging tool operation develops in an avalanche as a result of strong impact loads. In nitrided layers, due to increased surface hardness, resistance to wear and plastic deformation increases, but at the same time it becomes more brittle. The cycle of variable temperatures (rapid heating and cooling) causes differences in thermal expansion between the nitrided layer and the steel substrate. These differences lead to thermal stresses that initiate the formation of microcracks. An additional difference between the standard forging process on crank presses is the fact that the described process is carried out on hammers. Another important element of the forging process is the lack of ejectors used in forging dies. The manual forging process on hammers, the lack of ejectors, and the uneven time the forging stays in the die impression cause a much stronger effect on the nitrided layer than in the case of, for example, forging on crank presses and dies equipped with forging ejectors. The high deformation speed (different nature of work than in forging on crank presses), longer contact time of the forging with the tool, and uneven time caused by the lack of ejectors cause a much stronger and faster loss of the properties of the nitrided layer. Attention should also be paid to the relatively complex geometry of

the impression (ring section), additionally characterized by high accuracy, small radius, and small dimensional tolerances. This, in combination with extreme operating conditions, certainly has an adverse effect on the surface layer of the tool impressions. Taking all this information into account, we can conclude that there are significantly greater material losses in the nitrided layer, numerous cracks and chippings, which, with the increase in the number of forgings, propagate into the material. Finally, the nitrided layer, due to the loss of cohesion, disappears at some point, revealing the core material with a much lower hardness.

To sum up, we can say that there are clear material losses observed both in the area of the blocking and finishing impressions, as well as numerous microcracks. The privileged places for damage to the nitrided layer are the corners, where the material flows very intensively and the contact with the tool is long. Cracks are also located in the corners of the lower part of the impressions. Additionally, microstructural microscopic tests are carried out to analyze the microstructure of selected areas. The results obtained for the blocking impression are presented in Figure 16.

The conducted microanalyses indicate that the native material of the forging tool is characterized by a tempered martensite structure with the presence of cementite (Fe_3C) precipitates and alloy carbides. The crack network is shallow and covers only a small part of the thickness of the nitrided layer, which is confirmed by observations of the microstructure of the surface layer (Figure 14e).

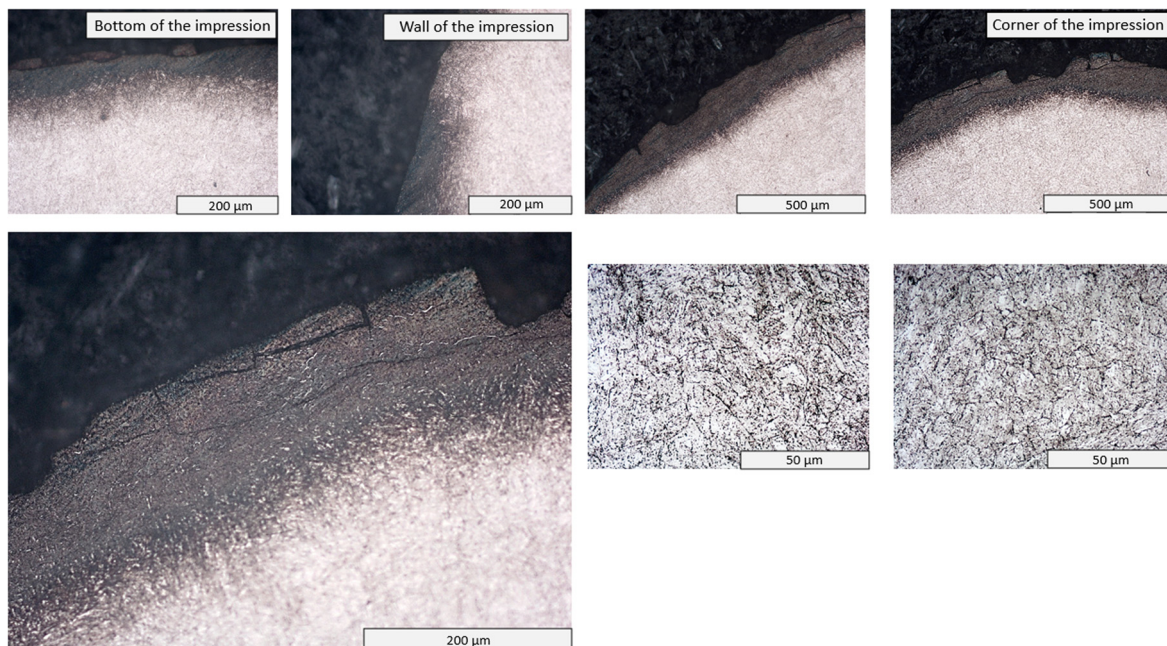


Figure 16. View of the forging tools after forging 1,200 pieces for different locations of the 1× blocking impression.

Analyzing the structure and size of the nitrided layer, it can be stated that the nitriding process is carried out correctly, while the cause of cracking and detachment of the nitrided layer particles are the difficult working conditions of the tools. In the further part of the research, the microstructure of the finishing impression is also analyzed, the results of which are presented in Figure 17. The tests and analyses carried out showed that also for the 2 $\times$ finishing impression, the microstructure of the forging tool core is tempered martensite with visible precipitation of Fe_3C and alloy carbides, i.e., it is a typical microstructure of hot work tool steel from which the forging dies are made.

For more complete analysis, the hardness of the nitrided layer is also verified for both the blocking and finishing impression. The results are presented in Figure 18. As can be seen, the hardness of the nitrided layer is at a level of about 1,200 HV at the surface, while its thickness is less than 0.2 mm, where the effective hardness can be estimated at a level of about 950–1,000 HV; such parameters confirm that the thermochemical treatment process is performed correctly.

The greatest thickness of the nitrided layer is found at the corner and is approximately 180 μm . The degradation of the nitrided layer, its numerous losses, and the lack of hardness changes indicate an extremely fast progressive destruction mechanism due to high stresses and adhesion with the forging material. As mentioned earlier, the case of

forging high-alloy austenitic steels on hammers favors adhesive wear, however in all impression was nitriding layer.

Microhardness is also verified outside the working impressions at the place of forming and shaping the flash, where there is the largest pressure, and always the nitriding layer is removed in first order. The measurement results are shown in Figure 19. The hardness of the material in the core is about 600 HV0.1, while the hardness of the nitrided layer is 1,100–1,200 HV0.1. These results prove that the nitriding process is carried out correctly.

Due to the very good deformability of austenitic steels (especially at elevated temperatures) and their strong adhesion to the tool substrate, this mechanism can accelerate tool wear. The adhesion of austenitic steels at elevated temperatures refers to their ability to adhere to other materials as a result of physicochemical processes occurring on the surface. Contact with the surface layer, which has already lost its cohesion during the forging process (the formation of a significant number of cracks perpendicular to the surface and parallel), causes the forging material to stick to the tool material that is weakly anchored to the substrate. The material in the area of a significant number of cracks is torn out of the substrate. This process continues with increasing number of forgings until the entire nitrided layer of greater hardness is removed. The greater hardness of the nitrided layer

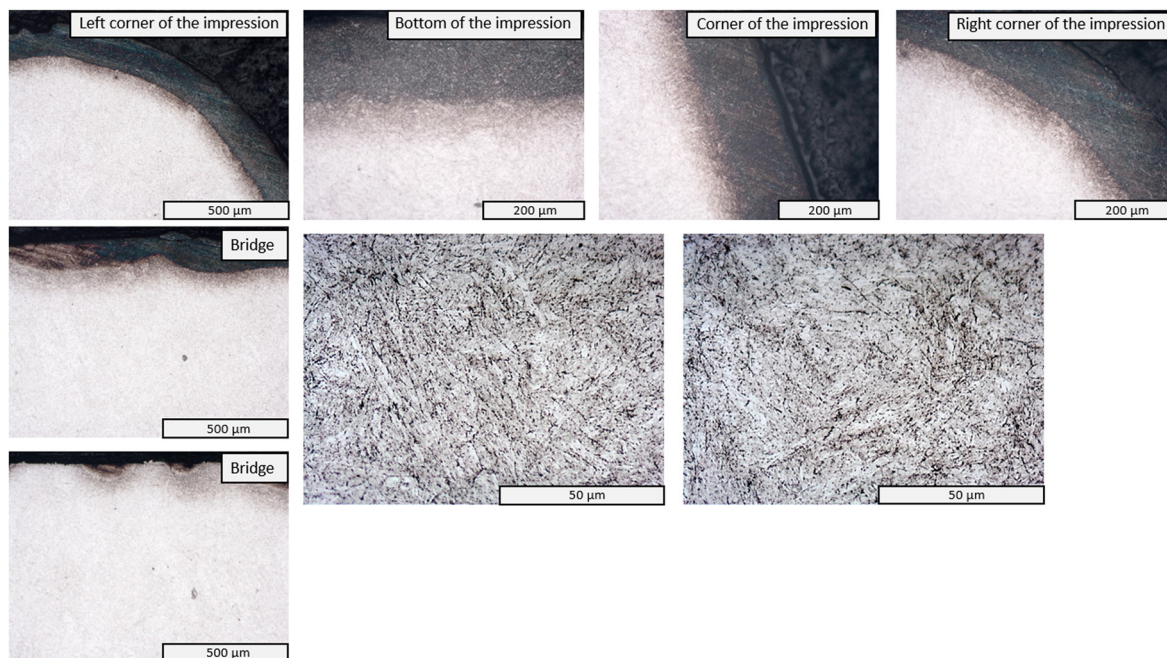


Figure 17. View of the forging tools after forging 1,200 pieces for different places of the 2 $\times$ finishing impression.

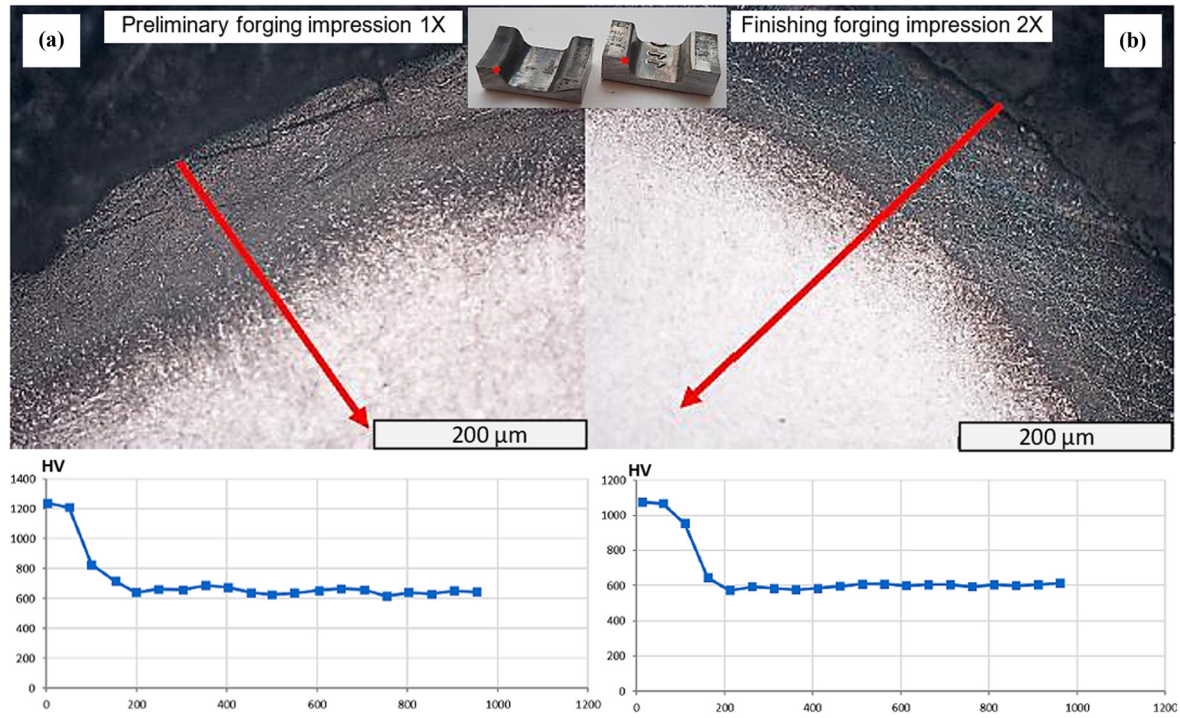


Figure 18. Microhardness measurements for (a) preliminary forging impression – 1× and (b) 2× finishing impression – 2×.

promotes the development of cracks, and the adhesive defects that arise cause the formation of further cracks due to the concentration of stresses in micro-areas. This happens so quickly that the nitrided layer does not have time to soften and remains hard and brittle until it disappears. This is confirmed by hardness measurements in areas where the nitrided layer is still present in the surface layer of the tool – its hardness is about 1,100–1,200 HV. An additional factor that can accelerate the adhesive wear of the nitrided layer is the lack of scale on the surface of hot forgings. This promotes the formation of local material bonds.

4. Summary and conclusions

This article presents the results of research on the possibility of increasing the durability of forging dies used in the production of forgings for the automotive industry by using thermochemical treatment, in particular gas nitriding, comparing the obtained results to standard tools (without nitriding). As a reference point, first, a comprehensive analysis of the technology implemented so far for tools without a nitrided layer is carried out, conducting tests for the correctness of tool manufacturing, macroscopic analyses combined with 3D scanning, and numerical modeling. The

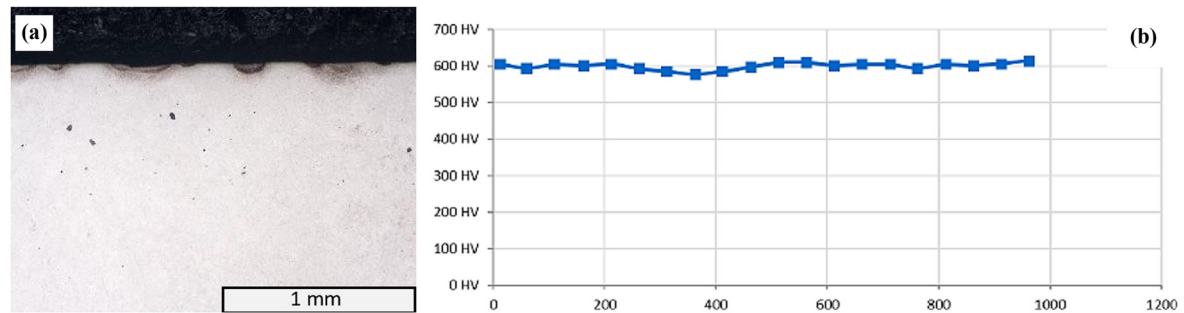


Figure 19. (a) Photo of the places subjected to the test – the place of flash formation around 2× and (b) microhardness distribution.

obtained results showed that the technology is designed correctly, although numerical simulations showed high loads in the surface layer and friction. The average durability for tools (without a nitrided layer) in standard technology is about 3,200 forged elements (so-called forging, each of which contains four individual forgings). Then, in order to assess the effectiveness of the applied method of increasing durability (nitriding of tools), operational tests are carried out for three sets of tools after thermochemical treatment under real industrial conditions and compared with the results for standard tools. The results show that nitriding, although carried out correctly, can lead to reduced tool durability due to specific working conditions, such as high cyclic thermo-mechanical loads, which trigger a number of destructive mechanisms, such as thermal fatigue, thermo-mechanical fatigue, plastic deformation, oxidation, and low adhesion. These mechanisms, combined with the “specific” geometry of the working impressions and the implementation of the forging process at high speeds on a hydraulic hammer, cause cracking and subsequent detachment of smaller and larger particles of the tool surface layer. In the case of using nitrided tools, the average durability is three times lower and amounted to about 1,100 forged elements. Based on the analysis, it was found that the nitrogen layer has a complex network of microcracks, which is successively penetrated during the forging process and subsequently removed. This in turn causes it to be visible on the finished element and causes the formed material to come into contact with the forging tool of lower hardness, which in consequence causes their faster wear. The main problem encountered during tests and studies is a network of micro-cracks, which successively transformed into deeper cracks on the preliminary impression, and these successively transferred to the finishing impression. As a consequence, this resulted in the production of products not compliant with the technical specification. Although excessive wear of forging tools on a macroscale is not visible, defects in the forgings in the form of scratches and depressions and small dents are observed on the forgings. Detailed studies have shown that austenitic steels deformed at elevated temperatures have an increased tendency to adhere to other materials (including dies made of hot work tool steels) as a result of physicochemical processes occurring on the surface. Contact of a forging made of austenitic steel with the surface layer, which has already lost its cohesion during the forging process (the formation of a significant number of cracks perpendicular to the surface and parallel), causes the deformed material to stick to the tool material weakly anchored to the substrate. The material in the area of a significant number of cracks is torn out of the substrate. This process continues with the increasing number of forgings until the entire nitrided layer with greater

hardness is removed. An additional factor that intensifies this phenomenon is the cyclic change of temperatures (rapid heating and cooling), which causes differences in thermal expansion between the nitrided layer and the steel substrate. These differences lead to thermal stresses that initiate the formation and development of microcracks, which, as the forging process progresses, cause the appearance of macro-cracks and the separation of particles and large fractions of material from the surface layer. The tests carried out and the results obtained allow the formulation of the following conclusions:

- Each technological process, especially die forging, must be analyzed individually. Solutions that work well in a given application, e.g., nitriding, may not bring the desired effects in another application.
- In the case of nitriding for the forging tools in question, the nitrogen layer is damaged very quickly by the formation of a network of microcracks. As a consequence, during plastic processing, this causes the material to be pressed into these areas, their penetration, and the formation of defective forgings. The nitriding process did not bring the desired effects in terms of increasing the durability of forging tools. For the analyzed case, the durability is obtained three times lower in relation to the standard technology of manufacturing forging tools.
- Based on the tests carried out for three sets of forging tools, it can be clearly stated that the nitriding process is carried out correctly in accordance with the specified requirements, which is confirmed by microstructural tests and hardness measurements.
- The high temperature in the hot forging process of austenitic steels in the AISI 304 grade, lack of scale, susceptibility to adhesion, and forging conditions – the rate of degradation is higher than the rate of tempering (softening) of the nitrided layer – cause accelerated adhesive wear and degradation of the surface layer of the forging tool.
- Degradation of the nitrided layer, its numerous losses, and the lack of hardness changes indicate an extremely fast progressive destruction mechanism due to high stresses (based on FEM von Mises stresses reach about 1,500–1,800 MPa) and adhesion with the forging material.
- Due to the shaped material, AISI 304 stainless steel, the dynamic process of die forging on a hammer and high

momentary pressures, reaching 6 MN, has a negative effect on the cracking of the nitrogen layer, especially in the case of geometry of impressions with small radii.

- The complicated geometry of the forging tools that reproduce the shape of the forging, the high-quality AISI 304 stainless steel used to produce the forgings, and the high requirements for shape and dimensional accuracy and quality of the forgings in this case resulted in lower hardness of the forging tools themselves, providing their higher service life compared to the hardened surface of the tools through nitriding. In the case of processes carried out for geometrically complicated forgings with small radii (for the analyzed tools, $r = 1$ mm), they are particularly susceptible to cracks in the nitrided layer.
- Based on the above, forging tools after the nitriding process are withdrawn from production despite a slight loss of material according to Figure 12 compared to non-nitrided tools (Figure 7) due to cracking of the nitrogen layer in the early stage of the production process, which leads to its penetration and chipping. These areas are filled with the input material, which in consequence causes the appearance of excess material on the forging (Figure 4c), which is inconsistent with the assumed geometry of the forging. Due to such a defect, the forging process has to be stopped because it leads to the production of products not compliant with the technical specification.

It should also be considered that the process has been carried out on hammers, for very thin forgings. Then, there are very high dynamic loads, which can lead to cracking of hard nitriding layers. In order to improve durability, it is planned to build a layer of lower hardness, unfortunately tool manufacturers are not able to fully control the thickness and hardness of the nitriding layer.

Author contributions

Conceptualization: M.H. and Ł.D.; methodology: Ł.D. and M.H.; validation: M.H. and Ł.D.; formal analysis: M.H., Ł.D., J.Z. investigation: Ł.D., M.Z., Z.G.; resources: M.H. and Ł.D.; data curation: Ł.D., M.H., M.L.; writing—original draft preparation: Ł.D., M.H., Z.G.; writing—review and editing: M.H. and Ł.D.; visualization: Ł.D. and M.H.; supervision: M.H., Ł.D., Z.G.; project administration: Ł.D. and M.H. All authors have read and agreed to the published version of the manuscript.

Conflict of interest statement

The authors have no conflicts of interest/competing interest to declare that are relevant to the content of this article.

Ethical approval

This study follows the guidelines of the Committee on Publication Ethics (COPE) and involves no studies on human or animal subjects.

Data availability statement

The datasets and material generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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