DOI: 10.24425/amm.2018.125131

M. HAWRYLUK*[#], Z. GRONOSTAJSKI*, M. KASZUBA*, J. KRAWCZYK*,
P. WIDOMSKI*, J. ZIEMBA*, M. ZWIERZCHOWSKI*, M. JANIK**

WEAR MECHANISMS ANALYSIS OF DIES USED IN THE PROCESS OF HOT FORGING A VALVE MADE OF HIGH NICKEL STEEL

The study presents a durability analysis of dies used in the first operation of producing a valve-type forging from high nickel steel assigned to be applied in motor truck engines. The analyzed process of producing exhaust valves is realized in the forward extrusion technology and next through forging in closed dies. It is difficult to master, mainly due to the increased adhesion of the charge material (high nickel steel) to the tool's substrate. The mean durability of tools made of tool steel W360, subjected to thermal treatment and nitriding, equals about 1000 forgings. In order to perform a thorough analysis, complex investigations were carried out, which included: a macroscopic analysis combined with laser scanning, numerical modelling by FEM, microstructural tests on a scanning electron microscopy and light microscopy (metallographic), as well as hardness tests. The preliminary results showed the presence of traces of abrasive wear, fatigue cracks as well as traces of adhesive wear and plastic deformation on the surface of the dies. Also, the effect of the forging material being stuck to the tool surface was observed, caused by the excessive friction in the forging's contact with the tool and the presence of intermetallic phases in the nickel-chromium steel. The obtained results demonstrated numerous tool cracks, excessive friction, especially in the area of sectional reduction, as well as sticking of the forging material, which, with insufficient control of the tribological conditions, may be the cause of premature wear of the dies.

Keywords: tool wear, tools durability, destructive mechanisms, valve engine, high nickel steel

Introduction

Exhaust valves of combustion engines in motor trucks usually operate at 700-850°C, where, in the recent years, in order to increase engine efficiency, the temperatures of their work have been increased [1]. High pressure subjects the exhaust valve to periodical thermal and mechanical loads [2-3]. Engine valves are usually made through hot plastic processing from high nickel austenitic steels or a nickel superalloy (about 80% Ni content), which characterize in high corrosion resistance in combustion gases, as well as high hardness, abrasion resistance at high temperatures and high temperature creep resistance [4].

Currently, in the valve production processes, two technologies are usually applied. One consists in local heating of the valve steel material in the form of a small diameter bar, followed by local upsetting to obtain the proper shape, the so-called 'plate' [5]. The other, less frequently used, is a forging process consisting of two operations: hot coextrusion of a long shank tipped with a preliminarily formed element called 'bulb' and next finishing forging of the valve head [6]. The first mentioned technology is quite well-mastered, yet relatively less cost-effective due to the cost of the charge material. In spite of that, in both technologies, similar materials are used; however, small diameter bars are much more expensive than larger ones, as the latter are usually rolled and the former are made through drawing or extrusion. What is more, products made in the technology of local heating and upsetting characterize in worse mechanical properties and sometimes, in the heat inflow area, as a result of a large temperature gradient, cracks appear on the product. In this process, we also observe other product flaws, such as structural changes in the heating boundary area during upsetting, cracks on the profile, overheating of the plate, laps of the plate, cracks resulting from bar surface defects, etc.

In the case of the other technology (forging with preliminary extrusion), the obtained products characterize in better mechanical properties and surface quality. This technology, however, is rarely applied, as it is a process of forging in closed dies, which is very difficult to master, requiring preparation of the preform weight with the accuracy of up to +/–1%, as well as maintaining a constant temperature and designing the proper shapes of the dies ensuring their good filling. However, the biggest problem is constituted by very high pressures, which cause problems with low die durability (in extreme cases, even up to some dozen forgings) as well as the formation of faulty products resulting from the difficulty in shaping the steel with a high content of nickel and selecting the optimal process parameters. One of the big-

* WROCLAW UNIVERSITY OF SCIENCE AND TECHNOLOGY, METAL FORMING AND METROLOGY, 5 LUKASIEWICZA STR., 50-371 WROCŁAW, POLAND
** VALVES EXTRUSION, MAHLE POLSKA
# Corresponding author: marek.hawryluk@pwr.edu.pl

gest difficulties is the increased adhesion of the charge material made of nickel-chromium steel (nickel content up to 25-35%, chromium content about 15-20%) to the tool substrate made of tool steel W360 during the hot forward extrusion process. The high pressures and temperatures, as well as the long friction path cause blocking of the extruded material in the loop of the die. Moreover, there are other methods of engine valve production, particularly of hollow valves which are constructed to be light and to conduct heat along the valve [7], or valves produced by wedge rolling and forging [8].

Currently, the most frequently used materials for the production of valves in the second mentioned technology are mainly Nimonic 80A nickel alloys [5]. The global literature contains several papers devoted to the process of forging this alloy, referring, however, mainly to the microstructural changes occurring during their deformation [9,10]. We can also find studies discussing the issue of tool durability [11]. It should be noted that all these publications concern the Nimonic 80A nickel alloy, which is very expensive [12-13]. That is why, at present, this alloy tends to be replaced by cheaper nickel-chromium steels, such as austenitic valve steels: mainly chromium nickel or high nickel steels [14,15]. The latter contain about 30% nickel, 15% chromium and 2% titanium and aluminium in an iron matrix. High nickel steels exhibit good corrosion and oxidation resistance as well as high tensile and creep strength at the temperature of up to 850°C. Their biggest advantage is the presence of intermetallic phases $Ni_3(Al,Nb)$, which are responsible for increasing the high temperature creep resistance and heat resistance. The high content of chromium significantly improves the corrosion resistance. Austenitic steels, contrary to chromium ferritic steels, as a result of grain growth, do not become so brittle, maintaining their ductility [16]. For steels of such type, the carbon content is lowered to <0,01%, as its higher content negatively affects the corrosion resistance by binding chromium into carbides. It is very beneficial to add stabilizing elements, such as titanium or niobium. Austenitic steels with a high content of nickel or chromium exhibit a significant reinforcement of the structure as a result of cold work. They become hardened much more significantly than it is observed for other steels of another structure with the same deformation degree. The reinforcement mechanism of austenitic steels is the increase of the dislocation density, cross slips and dislocation climb as a result of the operation of plastic deformation. The steel used in the analyzed process for the production of exhaust valves contains Nb (niobium) 0.52% and Ti (titanium) 0.91%. These elements play the key role. They have high affinity to carbon. Introduced into steel, they prevent the formation of chromium carbides during cooling or long-term annealing at about 700°C. The formation of chromium carbides causes the formation of microareas depleted of chromium and in consequence a decrease of the corrosion resistance. Unfortunately, the presence of intermetallic phases makes the forging process difficult, thus worsening the deformability, and their hard particles lead to a rapid tool wear [17-21]. This makes the average durability of tools used to produce valve forgings in the technology of extrusion and forging at a very low level, equalling below 500 items in extreme cases. The low durability of tools made of tool steels used for hot operations is the main problem in the case of the formation of forgings from austenitic steels. This, currently constitutes a difficult and still unsolved problem, being a significant challenge for scientists working in materials engineering as well as technologists of technological processes, including die forging. It is crucial to select the proper technological parameters, such as: the tribological conditions, including lubrication, the optimal shape of the forming tools ensuring decreased forming forces, as well as minimized residual strains. Fig. 1 shows the mean tool durability during the forging of various steels for the same forged element.

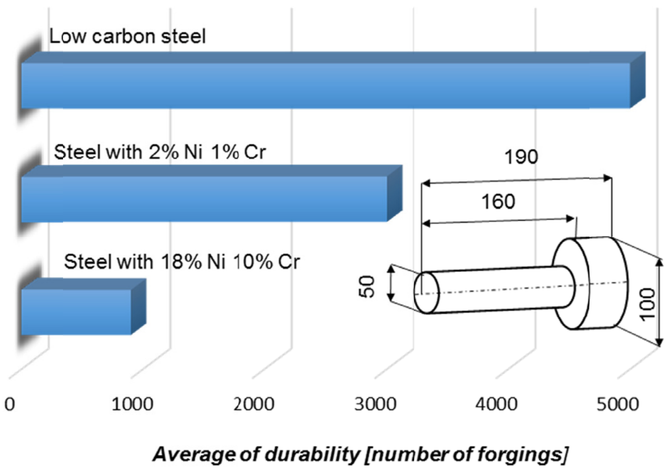

Fig. 1. Comparison of tool life for various forged materials [22]

In the case of upsetting of stainless steel 304 (18% Ni and 10% Cr), the durability was lower than one fifth of the die durability in the case of upsetting low carbon steel and lower than one third for the upsetting of steel 4340 (2% Ni and % Cr). The presented process refers to forging with a flash, which additionally demonstrates the difficulty in designing the process of forging a valve in closed dies, where the thrusts are many times higher [22].

The relatively low durability of tools used to produce valves is a consequence of many phenomena and destructive mechanisms occurring at different frequency. The most important of them include: abrasion wear, thermo-mechanical fatigue, plastic deformation, fatigue cracking, as well as adhesive wear and oxidation [23-25]. That, in combination with periodical thermo-mechanical loads which the forging tools are subjected to, as well as the dynamics and instability of the forging process, makes the forging processes one of the most difficult ones as far as the analysis of the production processes is concerned. That is why it is justifiable to perform advanced complex studies analyzing the destructive phenomena and mechanisms, as on this basis, it will be possible to take reparatory as well as preventive measures and also propose methods making it possible to improve the durability of forging tools [26-27]. Obtained results of research on the analysis of destructive mechanisms in this process will allow for the selection of effective methods to improve durability, such as: the use of surface engineering methods or the selection of other tool materials [28]. It will enable a reduction of the unitary costs of the valve forging production as well as the production of other elements in die forging processes from high nickel austenitic steels, for which the mean durability is much lower than for carbon steels.

1. Test subject and methodology

A detailed analysis was performed on dies used in I operation of hot forward extrusion of a long shank tipped with a preliminarily formed element called 'bulb'. Fig. 2a shows a CAD model together with the distribution of the areas (measure points) of the surface of the tool section, for a better understanding and analysis of the obtained test results. Fig. 2b, in turn, presents an image of one half of a worn die.

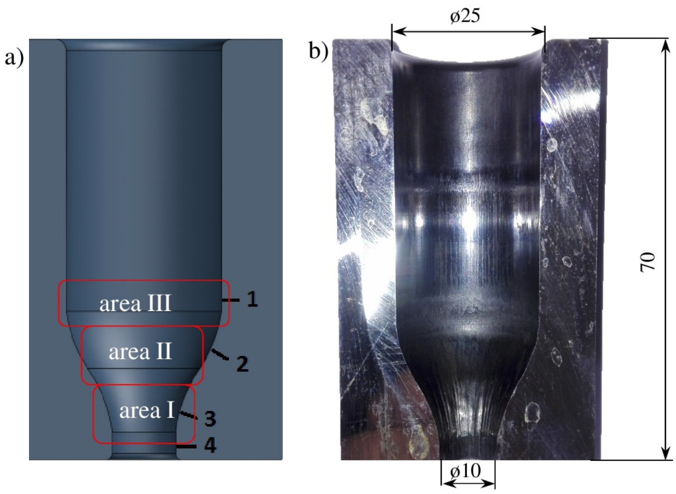

Fig. 2. View of the tool section: a) CAD model with marked selected measurement areas, including the microhardness test points, b) exemplary image of a die's half with main dimensions in mm

The dies are made of tool steel for hot operation W 360, subjected to thermal treatment, followed by gas nitriding. The surface of the impression of the ready tools characterizes in hardness at the level of about 1100HV. The ready tools are heated to the working temperature of about 200°C and then mounted on the press. The temperature of the charge material equals 1040°C. During the extrusion process, the tools are lubricated and cooled with a cooling-lubricating agent based on graphite. The mean die durability equals about 1000 forgings. A detailed analysis was performed on 2 dies, of which one produced about 900 forgings, while the other – over 1900 forgings.

During the analysis, the following research techniques were applied:

- macroscopic tests combined with a measurement of the wear/allowance degree on the working surface of the tools performed through laser scanning with a measuring arm equipped with a laser scanner and a comparison of the scan geometry with the CAD models.
- FEM (Finite Element Methods) modeling of the working conditions of the tools under different friction and temperature conditions performed in the Forge 2.0 software;
- observations of the changes taking place on the working surface with the use of a scanning electron microscope (SEM) with the magnifications exceeding 1000×;
- microstructure tests carried out in the surface layer of the tool section by the using light microscopy after its etching in nital;
- microhardness tests in the section in the function of the distance from the surface by means of the LECO microhardness tester for the evaluation of the effect of the tool working temperature on the tempering of the surface layer as well as for the verification of the applied nitriding method.

2. Results and discussion

Chapters 2.1-2.6 discuss the results of the performed complex studies.

2.1. Macroscopic tests combined with a geometrical analysis based on laser scanning

Fig. 3-4 compile comparative results for 2 dies after an increasing number of produced forgings. The macroscopic analysis consisted in observing the tool surface by means of simple optical instruments as well as recording the images with the use of a camera. Simultaneously, the same working surfaces were scanned with the laser scanner RS3 mounted on the measuring arm Romer AbsoluteArm 7520si, which enables precise scanning of the tool geometry. The obtained laser scans were compared with the CAD model, which made it possible to determine the loss and allowance values on the tool surface. The results of the macroscopic observations and the comparison of the scans have been compiled in Fig. 3-4, where the scans have been placed next to the corresponding images.

Fig. 3 shows a view and the scan of ¼ working surface of a tool which has operated through 900 forging cycles. On the tool surface, we can observe traces of abrasive wear – abrasive

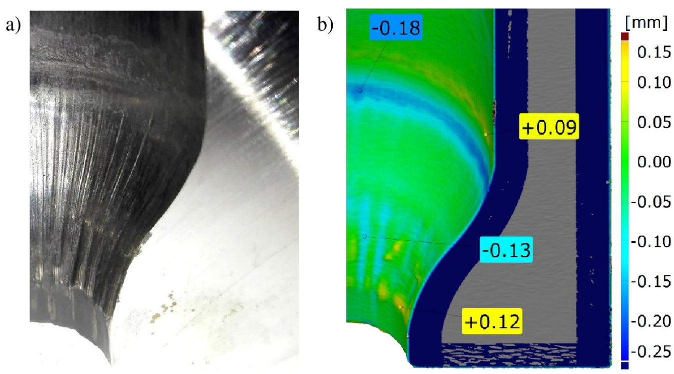

Fig. 3. The tool surface after 900 working cycles: a) macro view, b) comparison of laser scan image with CAD model

grooves, about 0,1 mm deep, formed along the direction of the forging material shift on the tool surface (area II). The biggest loss (–0.18 mm) is observed in the area of the tool's contact with the sharp edge of the charge material cut from bars (area II, point 1).

Also, we can observe locally present material allowances reaching 0.12 mm, which probably represent the areas of plastically deformed tool surface. The allowances may also mean the high nickel steel charge material being stuck to the die surface.

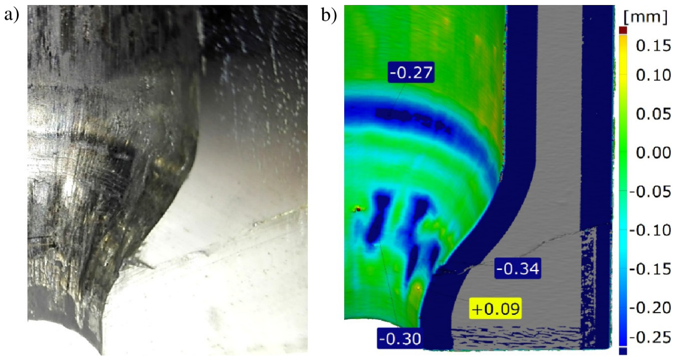

Fig. 4. The tool surface after 1900 working cycles: a) macro view, b) comparison of laser scan image with CAD model

The highest wear was observed on the surface of the tool which worked through the biggest number of forging cycles, i.e. 1900 (Fig. 4). The material losses reach 0.30-0.34 mm and are extensive. On the surface, we can also notice cracks and traces of plastic deformation in the surface layer, visible on the surface in the form of deformed cracks as well as protruding fragments constituting the allowance whose values reach over 0.15 mm.

The macroscopic analysis shows that it is possible to distinguish between a few characteristic areas of the impression. Starting from the top, we can see a clear, long and smooth, cylindrical zone, up to the moment of a clear groove in the form of a line on the circumference (circle), which is caused by the first contact of the charge material base gravitationally falling into the impression. This wear is uniform on the whole circumference of the die in area III and during the operation, its depth systematically increases. Another characteristic area (area II) marks partial minor wear occurring on the first reduction radius into the inside of the impression curvature, between points 2-3. It seems that this is the key area as far as premature wear of the tool is concerned. In this area (around point 3), we can see longitudinal scratchings, whose length can be estimated for about 4-20 mm. The probable cause of their existence is the friction of the forging material and the hard oxides present on its surface onto the tool surface during the extrusion process. During the operation, the depth and length of those scratchings increases, and the cracks and grooves formed in this way cause an increase of the surface roughness, thus increasing the friction in this area.

Also, in the same zone, we can observe non-cyclic allowances, which are caused by the sticking of the forging material, this being also confirmed by the tests with the use of a laser scanner, presented in the further section of this study. At the same time, the observations and tests performed on the surface show the presence of plastic deformations on the tool surface, especially in area I, in the form of burrs, curved cracks and deformed fragments of the surface layer.

2.2. Numerical modelling

In the simulation of the process of producing a valve forging, an axisymmetrical model was used with deformable tools in the Forge 2.0 program. The Spittel equation was used to describe the material behavior in the FORGE 2.0 program. The equation has the form:

$$\sigma_f = A e^{m_1 T} \varepsilon^{m_2} e^{m_4/\varepsilon} \dot{\varepsilon}^{m_3} \qquad (2.1)$$

where:

ε – total deformation,
$\dot{\varepsilon}$ – tensor of deformation speed,
T – temperature,
A, m_1, m_2, m_3, m_4 – coefficients.

The material data for the tools (steel W360 ISOBLOC – BÖHLER) were taken from the program database. Steel 1.4981 (X8CrNiMoNb16-16) was used as the forging material and the forging's chemical composition was typical for valve steel. Fig. 5 shows a general view of the model before and after the simulation of I forging operation.

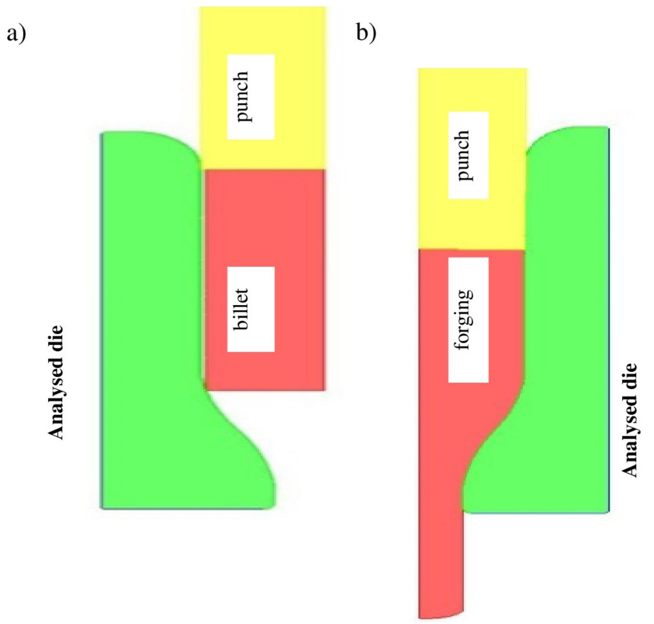

Fig. 5. General view of the model: a) before, b) after I forging operation

The data for the simulation were assumed based on the industrial process. Adopted crank press Metal Pres 700 E (chracteristic from software base) and contact time of the preform from the die before the impact – 1 s. The Treska friction model was adopted with factor f = 0.4, as well as temperatures for: input material – 1040°C, tools – 200°C, environment – 30°C. It was also adopted the heat conduction in the contact – 10 kW/m²K (marked in the program as the medium) and the heat conduction with the environment – 15 W/m² K (determined experimentally). Fig. 6 presents the distributions of deformations and temperatures on the forging in the last forging stage.

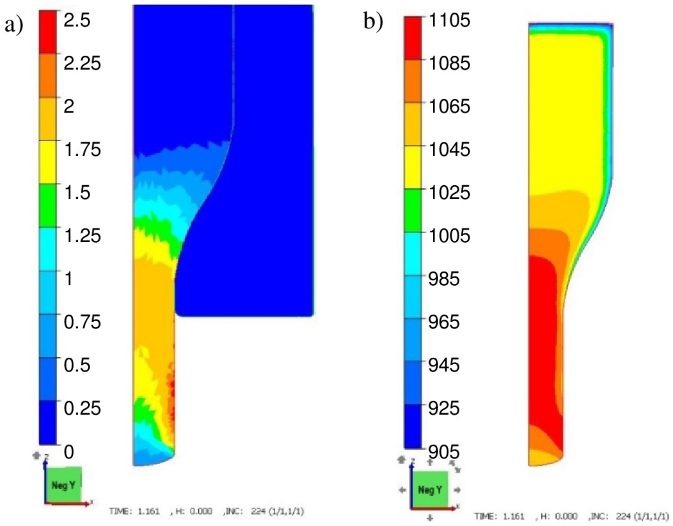

Fig. 6. Distribution of: a) plastic strain (deformation), b) temperature for the forging in the last forging stage in °C

Fig. 7 shows the temperature field distributions on the die in the final forging stage.

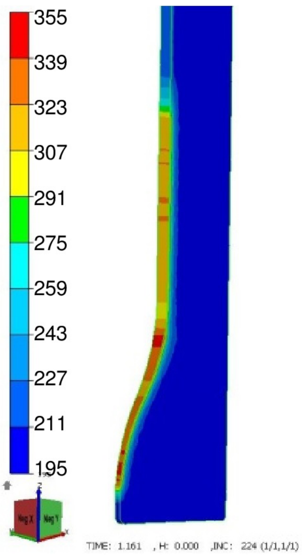

Fig. 7. Temperature distribution on the die in the last forging stage in °C

Based on the presented results, it is possible to observe that the highest temperature is present in the area of intensive deformation of the charge material (reduction of forging section). It should be noted that due to the relatively small size of both the forging and the die, these elements have a very small thermal capacity, which may cause the conditions to dramatically change in the case of instability of the forging process, e.g. too long a shutdown, or overheating of the charge/die. This is especially visible in the case of the temperature field distribution on the forging during the extrusion, where a small thermal capacity caused big differences in the forging temperature in the deformable part as well as in the contact with the cooler tools.

Fig. 8 shows the distributions of reduced stresses on the tools and the forging.

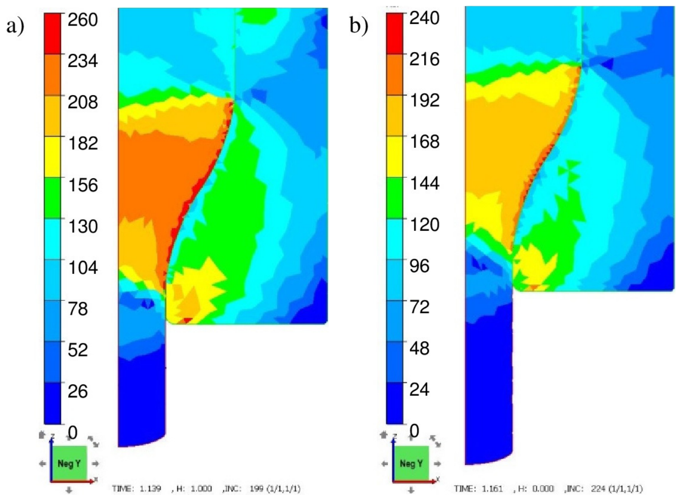

Fig. 8 Distribution of reduced stresses (von Mises): a) 1 mm to the full pocket of the punch, b) full pocket of the punch (last forging stage) in MPa

The presented distributions show not very high values of stresses, which should not cause the risk of plasticization or tool damage. The differences in the stress value can be explained by the fact that in the final stage the material fills the die pattern and the pressure is distributed on the whole surface. Much more information would be provided by the distributions of circumferential and radial stresses, as they are the ones which decide about a possible presence of longitudinal cracks on the die, which, in turn, could correlate with the cracks observed in the macro- and microstructural tests. Fig. 9 shows the path of friction on the die in the last forging stage. Based on the presented results, we can conclude that the area in the die through which the most material

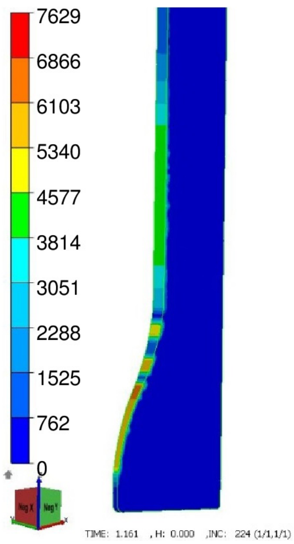

Fig. 9. Path of friction in the last extrusion stage in MPa mm

of the formed forging flows is the area which is the key zone for the process, where ridging occurs as a result of scale friction and sticking of the forging material.

Fig. 10 shows the course of the forging force in the function of the deformation time.

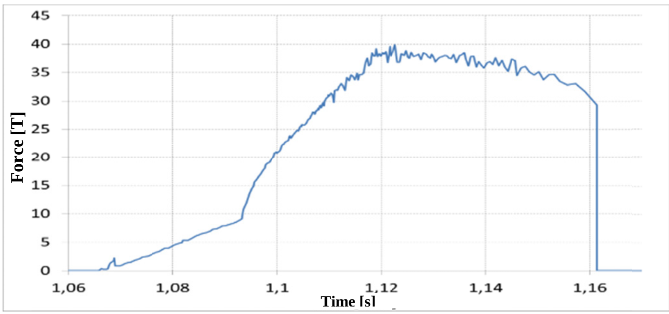

Fig. 10. Diagram of the force in I operation of extruding a valve-type element

The forging force courses obtained from the numerical modelling show that, in the case of a valve forging, the press works in the lower scope of the nominal load, which, for this forging unit, equals 700 kN, that is 70 tons.

2.3. Microstructural analysis of the surface with the use of a scanning electron microscope

During the microstructural tests, a detailed analysis was performed on two dies, 900 and 1900 forgings each, for 3 main selected tool zones for the first operation of forging an engine valve (shown in Fig. 2). Fig. 11 shows the results of the SEM analysis, after 900 forgings have been produced.

On the tool's surface (Fig. 11), after it has produced 900 forgings, we can observe oxide layers in the area of the radius and the throat (Fig. 11a-b). Layers of this type characterize in a different shade of grey during the analysis performed with the use of a BSE detector on a scanning electron microscope. In Figures 11a-b, they are visible as the darker zones in the areas between the thermal fatigue crack networks. It is also possible to notice production impurities on the surface (in the crack area). Fig. 11b shows deep grooves originating from abrasion wear. The direction of the grooves is in accordance with the direction of the forging material flow. Grooves of the same direction are visible in the other analyzed areas (Fig. 11c). Fig. 12 shows the results of the SEM analysis for 3 main selected tool areas for the first operation of forging an engine valve, after 1900 forgings.

For the analyzed die, which produced 1900 forgings, we can observe the presence of a small layer of oxides in the area of the radius and the throat (Fig. 12a-b) – there are some darker areas visible during the tests with the use of a BSE detector. The EDS analysis confirmed those areas to contain iron oxides. What is more, Fig. 12a and Fig. 12b show deep grooves originating from abrasion wear. The direction of the grooves is in accordance with the direction of the forging material flow. In this area, we can observe a large number of cracks originating from thermal fatigue, which, in some areas, are plastically deformed. This may prove a loss of stability of the surface layer and its tempering. A result of this phenomenon is a drop of hardness in this area. Grooves of the same direction are visible in the other analyzed

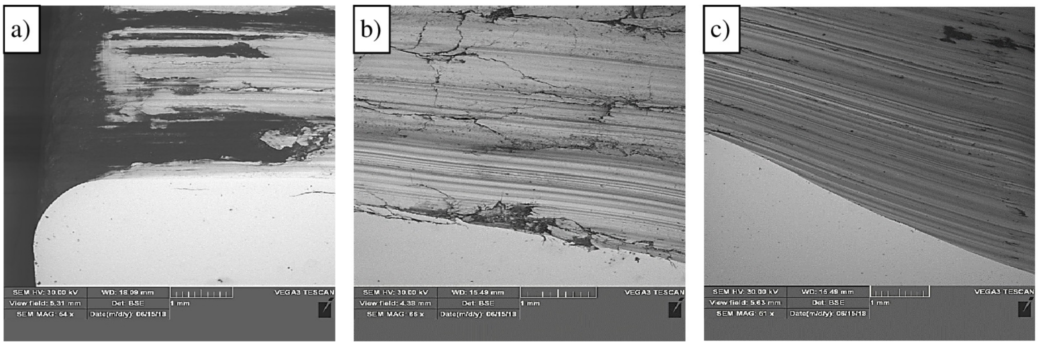

Fig. 11. View of the analyzed die surfaces after producing 900 forgings: a) zone I, b) zone II, c) zone III

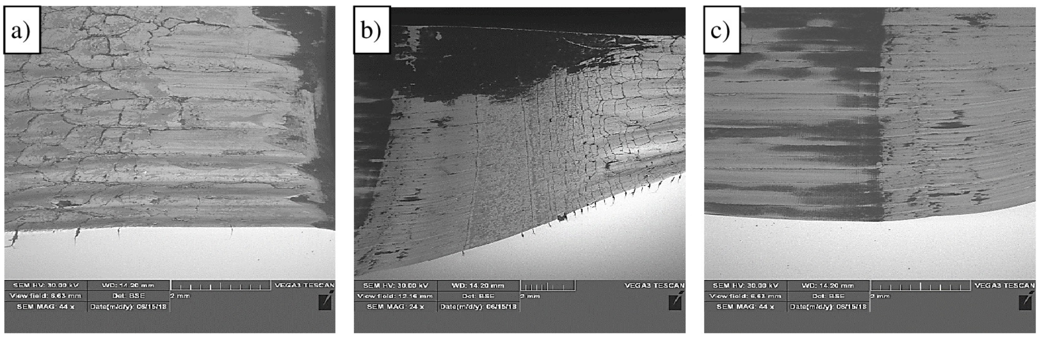

Fig. 12. View of the analyzed die surfaces after producing 1900 forgings: zone I, b) zone II, c) zone III

areas (Fig. 12c), while, in this zone, it is possible to observe an almost complete removal of the surface layer (scale and worn tool material), which was not observed for the die after 900 forgings.

The following Figures show microstructural images in a larger magnification for each of the three die zones, after 900 forgings (Fig. 11) and 1900 forgings (Fig. 12) for a more thorough comparative analysis.

2.3.1. Results for dies after 900 and 1900 forgings in zone I

Fig. 13 shows exemplary, most characteristic results for zone I (magnified) for the die after 900 and 1900 forgings (Fig. 14).

The analyzed area (Fig. 13) contains numerous grooves and scratches. In the groove pits, we can see impurities and, in some of them, a small amount of oxides. In the groove area, we can also see plastic deformations. In the thermal fatigue crack areas, it is possible to notice zones of tool material plastic deformation as well as subsurface cracks at the depth of about 150 μm.

The analyzed area (Fig. 14) contains numerous grooves and scratches. In the groove pits, it is possible to see impurities and iron oxides (which was confirmed by the EDX analysis – Fig. 14c). In the groove areas, we can notice plastic deformations, numerous cracks and tool material spallings (Fig. 14b).

In the thermal fatigue crack areas, tool material plastic deformation areas are visible (Fig. 14c) as well as subsurface cracks at the depth of about 500 μm. In the deformed material areas, we can see the presence of an additional material (Fig. 14b), which probably comes from the material of the forging. Fig. 15 shows another microstructural image, for which, additionally, the chemical composition was provided.

The analysis presented demonstrated a varying element content along the vector marked in yellow in Fig. 15. While in the diagram , the values on the left correspond to the chemical content of the tool steel for hot operations, which, beside cast

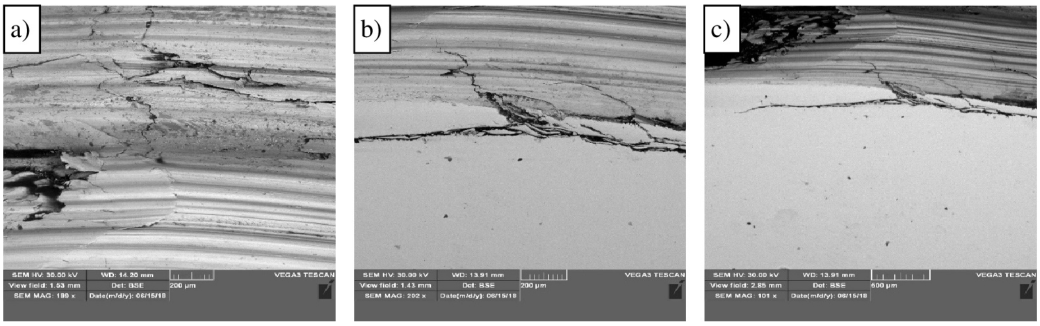

Fig. 13. Analysis of zone I for a tool which produced 900 forgings

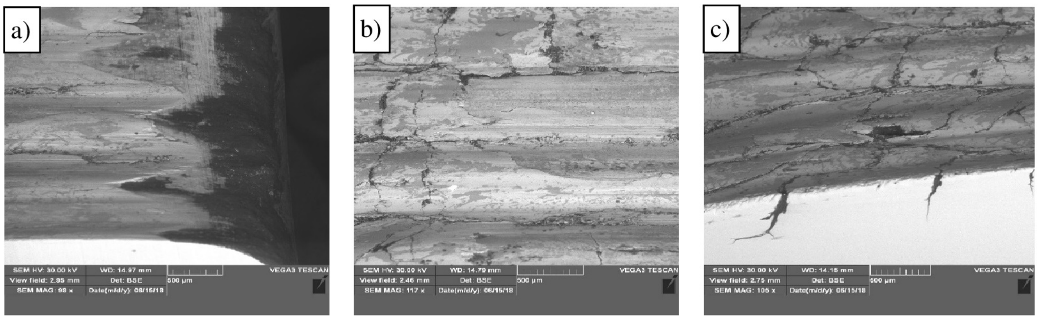

Fig. 14. Analysis of zone I for a tool which has produced 1900 forgings

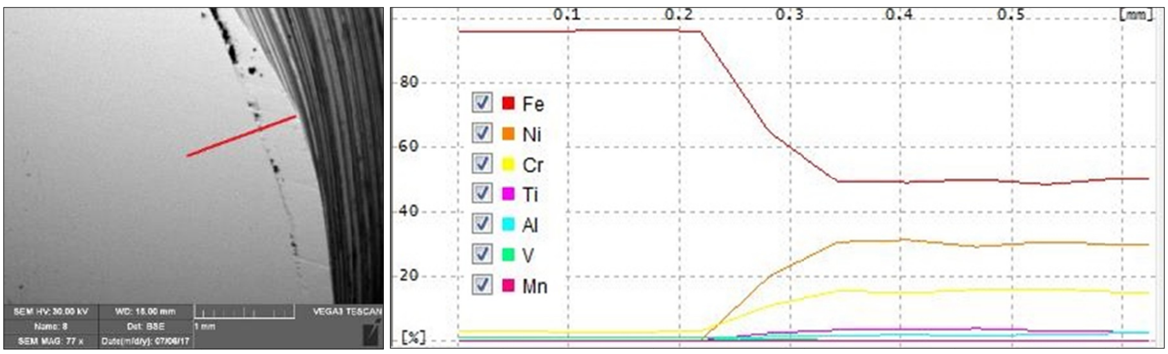

Fig. 15. Results of the chemical composition tests in the forging section for a tool which has produced 1900 forgings in zone I

steel, also contains alloy additions, such as Cr, V, Mn. A clear change in the chemical composition signifies the beginning of the forging material area, which adheres to the die surface. This material characterizes in the following contents: about 30% nickel, 15% chromium and 2% titanium in an iron matrix. This result is in accordance with the assumed chemical composition of tool steel W360 ISOBLOC and the composition of the forging material – high nickel steel. The obtained results (Fig. 15) confirm the previous observations of the forging material being stuck to the tool surface in the analyzed area. An additional material is distributed on the surface, forming a layer of a varying thickness, reaching even 0.5 mm, which forms a new working surface. An effect of the sticking (adhesion) of the shaped material to the tool is a change in the geometry of the tool section through the narrowing of the die opening, a low quality of the forging surface, excessive friction of the shaped material with the formed layer, as well as blocking of the forging during the process of it extrusion.

2.3.2. Results for dies after 900 and 1900 forgings in zone II

The Figures below show exemplary, most characteristic results for zone II (magnified) for the die after 900 (Fig. 16) and 1900 forgings (Fig. 17).

The analyzed area (Fig. 16) contains numerous grooves of different widths 25-100 μm and depths 5-25 μm. We can also notice cracks originating from thermal fatigue. The cracks propagate to the depth of about 300 μm from the surface. On the surface, it is possible to see sticking of the plastically deformed material (Fig. 16c).

The analyzed area (Fig. 17) contains numerous grooves of different widths 500-750 μm and depths 25-50 μm. We can also notice cracks originating from thermal fatigue. The cracks propagate to the depth of about 500 μm from the surface. On the surface, it is possible to see sticking of the plastically deformed material (Fig. 17a-b). In the groove and crack areas, we can observe a material in the form of oxides and impurities from the production process. The cracks filled with iron oxides originating from the tool material were confirmed by the EDX analysis. In the area of transition into the arc section, cracks without plastic deformation are visible (Fig. 17c). Their depth is about 350-500 μm. They are also filled with ion oxides coming from the tool material. This proves a relatively high temperature of the tool in these areas.

2.3.3. Results for dies after 900 and 1900 forgings in zone III

The Figures below show exemplary, most characteristic results for zone III (magnified) for the die after 900 (Fig. 18) and 1900 forgings (Fig. 19).

The analyzed area (Fig. 18) contains numerous grooves in the radial area, which fade in the further section of the tool. In the groove areas, we can see the lack of material cohesion (Fig. 18b). In the radial area (Fig. 18a), no thermal fatigue cracks were detected. Beyond the radius, no wear was observed, as well as no grooves, fatigue cracks or other traces of wear.

The analyzed area (Fig. 19) contains numerous grooves in the radial area, which fade in the further section of the tool (Fig. 19a). In the transition zone, we can notice material cracks originating from thermal fatigue (Fig. 19b). Cracks of this type

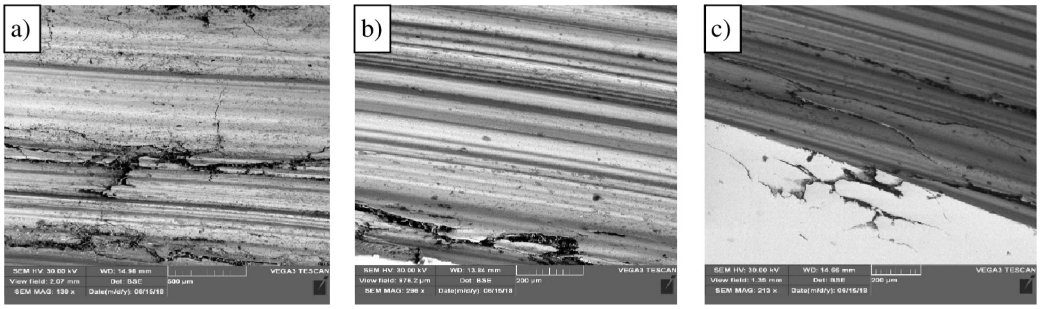

Fig. 16. Analysis of selected areas in zone II for a tool which has produced 900 forgings

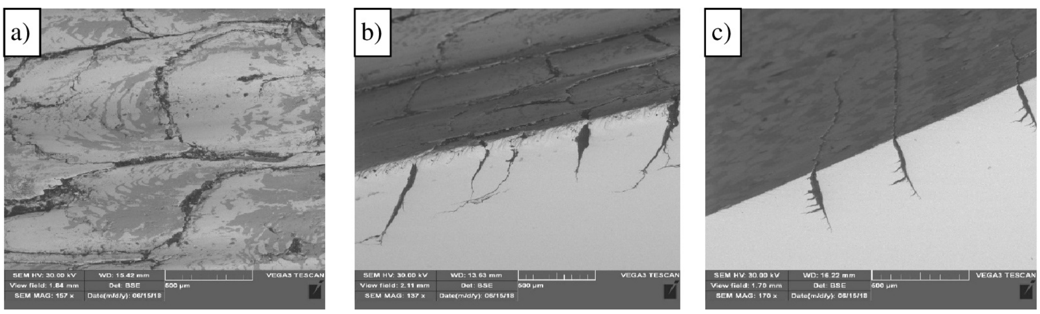

Fig. 17. Analysis of zone II for a tool which has produced 1900 forgings

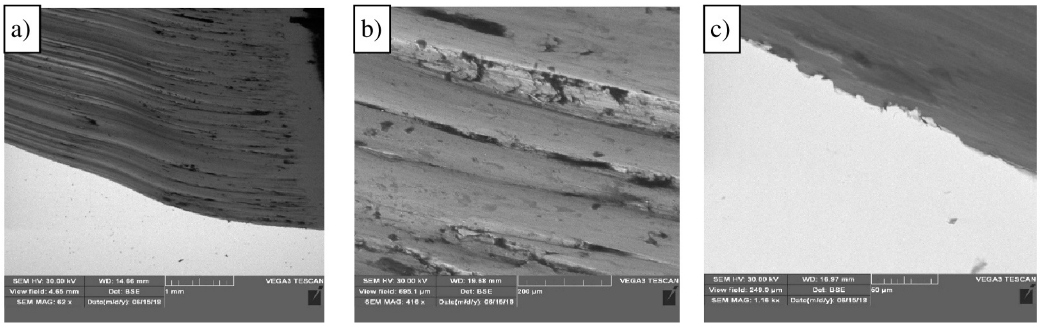

Fig. 18. Analysis of zone III for a tool which has produced 900 forgings

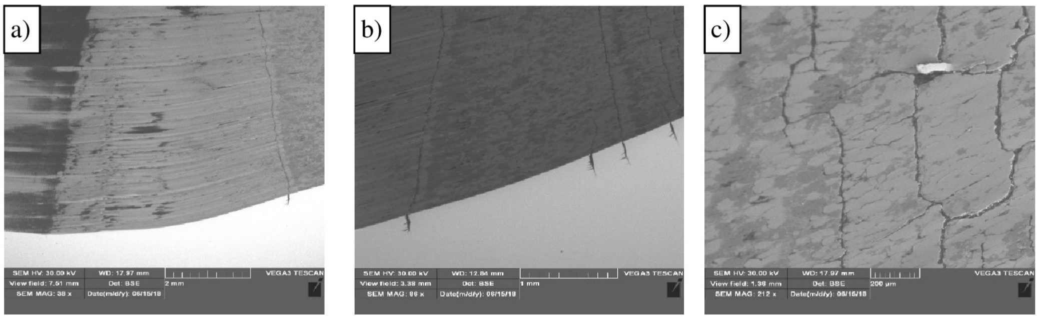

Fig. 19. Analysis of zone III for a tool which has produced 1900 forgings

were not visible for the tool which had produced 900 forgings. Also, it is possible to notice a network of primary and secondary cracks (Fig. 19c) in the transition area, covered with a small amount of oxides.

2.4. Microstructural analysis by means of a light microscope (metallographic)

Figures 20-21 show the results of a microstructural analysis of the analyzed tools (after 900 and 1900 forgings) in the three selected zones.

The performed light microscopic tests confirm the fact that the tool which has produced 1900 forgings exhibits a much higher degree of wear. The previously presented SEM investigations for the tool which has produced 900 forgings point to the presence of only a few deep cracks.

For the tools after a larger number of forgings, the cracks are much deeper; also, as it can be observed in Fig. 21a and Fig. 21c, material losses as well as a strongly deformed material in the surface layer are present. We can also notice a tendency for spalling of the diffusive nitrided layer for the tools which have produced a larger number of forgings.

2.5. Microhardness measurements

In order to determine the effect of temperature on the state of the tools, the microhardness was measured in the function of the distance from the surface in 4 selected points (Fig. 2), which produced 900 and 1900 forgings. The comparison results for points no. 1 and no. 2 are presented in Fig. 22, whereas the comparison results for points no. 3 and no. 4 – in Fig. 23. The microhardness test results presented in Fig. in the function of the distance from the working surface of the die point to a diversified state of the tool surface layer in the particular areas of the analyzed tools. In point 1 (Fig. 2), where strong abrasive wear was observed (Fig. 3-4) as well as a material loss from the surface

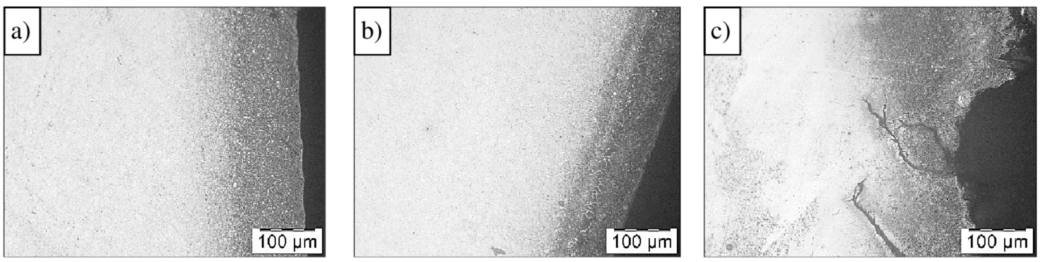

Fig. 20. Exemplary microstructural images with a visible nitrided layer and a few cracks. The tool has produced 900 forgings: a) in zone I, b) in zone II, c) in zone III

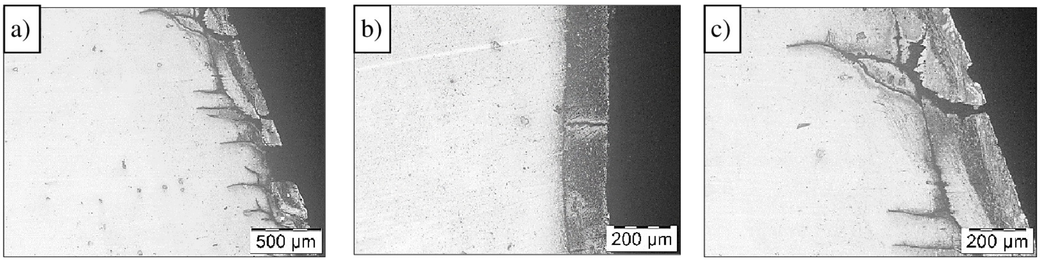

Fig. 21. Exemplary microstructural images with a visible nitrided layer and numerous cracks. The tool has produced 1900 forgings: a) in zone I, b) in zone II, c) in zone III

layer, the hardness is lowered to about 900 HV at the surface after 900 forging cycles and to about 740 HV after 1900 forging cycles. This proves a gradual removal of the nitrided surface layer in the surface of the die. At the same time, the hardness analysis in point 2 (Fig. 2) showed that the tool, through the whole operation time, remains in this area without a loss of its mechanical properties. This is confirmed by the lack of abrasive loss in this region and the presence of only a few fatigue cracks on its surface. The performed analysis confirms that the stability of the nitrided layer in this area is still high.

Fig. 22 shows visible effects of a loss of stability of the nitrided layers of the tools to the depth of about 0,2 mm after 900 forging cycles and to about 0.4 mm after 1900 forging cycles. This may prove the presence of high temperatures in the vicinity of point no. 4, caused by the highest deformation of the forging material and the highest pressures. The tempering and plastic deformation of the tool in the region are confirmed by the light microscopic analysis – Fig. 23, where one can see deformed cracks down to the depth of about. 0.5 mm from the surface.

The presented results prove the occurrence of local overheating of the shaping tools' surface layer, which results in their total tempering in such a short operation time. As it has been discussed above, the large number of losses and cracks, their

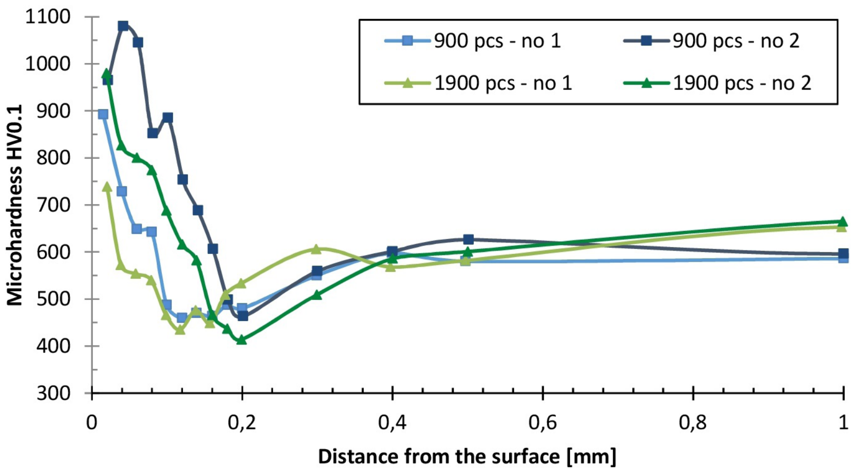

Fig. 22. Microhardness measurement results in point no. 1 and no. 2

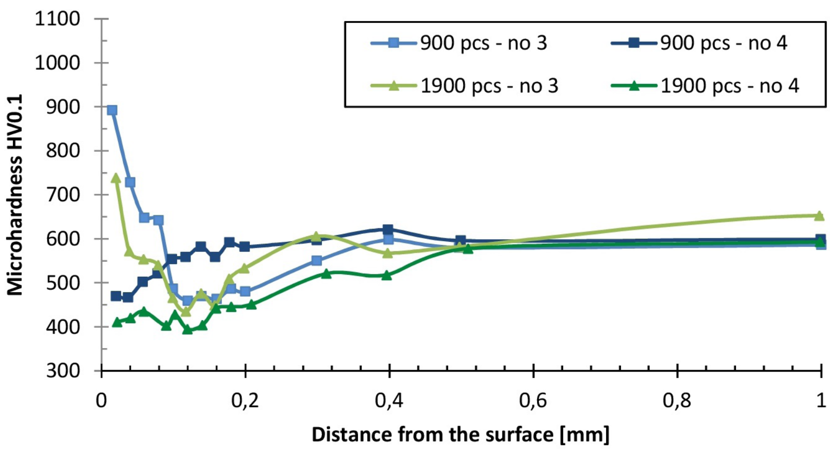

Fig. 23. Microhardness test results in points no. 3 and no. 4

depth as well as material tempering and plastic deformation in the surface layer point to a much more significant wear of the die which has produced 1900 forgings. Also, microhardness measurements were performed on the forging material stuck to the tool (Fig. 8) with the indenter load of 50 g. The hardness value was within the scope of 418-446 HV, that is 42.6-44.7 HRC.

2.6. Discussion and summary of the results

The performed complex analysis of shaping tools' wear in the process of producing an engine valve forging made it possible to determine the causes of their low durability. Based on the obtained results, the occurring destruction mechanisms were identified and their effect on the wear process was determined. The participation of the particular mechanisms was considered in three zones marked on the tool surface, in which the operation conditions significantly differed from each other.

The wear analysis was supported by numerical simulations of the examined forging process, which showed that, for the assumed industrial process conditions, the tools should not undergo wear or damage that soon. An important issue is the temperature control, as due to a low thermal capacity, resulting from the small 'size' of the charge as well as dies in the case of process instability, the conditions may dramatically change. This is visible especially in the case of the temperature field distribution on the forging during the extrusion, where the small thermal capacity caused big differences in the forging temperature in its deformable part as well as in the contact with the cooler tools. A similar situation refers to the tribological conditions, especially the assurance of the optimal die lubrication, because, as was demonstrated by the simulation results, in the case of increased friction, the shaped forging material flows not so easily, and also, the forging force in the process increases.

In zone I, the tool wear proceeded quite differently. The macroscopic observations and laser scanning of the surface did not show big geometrical changes or material losses. However, the microscopic observations by SEM and light microscopy demonstrated deep (up to 0,5 mm) cracks and numerous deformations, while the microhardness tests revealed material tempering to the hardness value of about 400-450 HV, which is lower than the hardness of the core. In this zone, the tool underwent overheating, as a result of which it lost its mechanical properties in the surface layer. What is more, the strong thrusts and immense friction caused local plastic deformation of the surface layer. In this area, the forging material was also observed to be stuck to the tool surface, which additionally increased the risk of overheating, as well as increased the friction and hindered the formation of the forgings. Zone I is the key area in the scope of durability of the analyzed tools, as it undergoes wear to the greatest degree and also due to the fact that the tool surface in this zone is directly represented on the surface of the extruded 'leg' of the valve, which is not subjected to further plastic treatment. Any damages of this surface directly lower the quality of the produced forgings. Also in this zone, too often, we can observe blocking of the forging in the die, which is a very undesirable technological problem.

In zone II, the dominating wear mechanism was also abrasive wear, which was initially revealed in the form of scratches arranged along the direction of the material flow. As a result of friction, these scratches transformed into grooves of an increasing depth and a smoothed shape. At the same time, on the tool surface, fatigue cracking phenomena occurred in the form of a dense crack network visible on the working surface of the tool. The microstructure test revealed the shape of those cracks, whose depth in zone II equalled about 0,3 mm. In the upper part of zone II (vicinity of point 2), the changes were less intensive and the material in the surface layer did not exhibit excessively lowered mechanical properties. Below, in the vicinity of point no. 3, clear scratches were observed, with the depth reaching 0,3 mm and the length of up to 20 mm. In this area, the material's hardness was also slightly lower as a result of local overheating.

In zone III, clear traces of abrasive wear were observed, at the depth reaching 0,18-0,30 mm, which is the clearly dominating wear mechanism in this area. No presence of fatigue cracks was detected, yet small (up to 0,05 mm) fragments of stuck forging material were present, and, as a result of abrasive loss, the hardness in the surface layer lowered by about 200-300 HV.

Microstructural tests of the tool surface layer in respect of cracks and other defects, as well as precipitations of alloy elements were performed. The analysis showed locally present layers of stuck material of the thickness of 0-300 μm, whose composition examined by the EDS method confirmed their origin from the forging material. The microstructural analysis revealed the presence of a nitrided layer in the surface layer of the depth of about 100 μm. Microhardness measurements of the forging material stuck to the tool were also performed. The hardness value was within the scope of 418-446 HV.

3. Conclusions

The presented results of a comprehensive analysis of the wear mechanisms of forging tools allowed to draw the following conclusions:

1. The main reason for the low durability of tools in the analyzed process is abrasive wear of the die surfaces in the zone of the greatest deformation of the material.
2. Local damages of the die working surface increases the friction of the forging material with a tool which leads to excessive adhesion of the forging material to the tool, sticking of the forging material and overheating of the dies with heat generated by excessive friction.
3. The Ni, Cr, Ti and Nb compounds contained in the material of forging, due to the affinity for the tool steel, increase the risk of sticking the forging material to the tools.
4. To increase the durability of the analyzed tools, increase their resistance to abrasion by increasing the hardness of the surface and reducing the coefficient of friction. This can be achieved through a dedicated hybrid treatment combining

nitriding with hard PVD coatings deposited on the surface of the matrices. Due to the high content of chromium in the shaped material should be used tool steels with lower contain of chromium and PVD coating eg. TiAlN.

5. The effect of increasing durability can also be obtained by careful control of the process, selection of another lubricant to reduce friction and ensuring sufficient cooling of dies in the working zone. It is suggested to change the method of lubrication by introducing a lubricant – cooling agent through the ejector to the working zone.

Acknowledgement

This study was founded by National Centre for Research and Development, Poland (grant no. TECHMATSTRATEG1/348491/10/NCBR/2017).

REFERENCES

[1] P. Forsberg, P. Hollman, S. Jacobson, Wear **271** (9-10), 2477-2484 (2011).

[2] R. Elo, J. Heinrichs, S. Jacobson, Wear **376-377** (Part B), 1429-1436 (2017).

[3] M. Priest, C.M. Taylor, Wear **241** (2), 53-65 (2011).

[4] Y.S. Wang, S. Narasimhan, J.M. Larson, S.K. Schaefer, J. Mater. Eng. Perform. **7** (1), 53-65 (1998).

[5] Z. Yuanzhia Y. Zhiminc X. Jiangpin, J. Alloy. Compd. **509** (20), 6106-6112 (2011).

[6] R. Tulsyan, R. Shivpuri, J. Mater. Eng. Perform. **4**, 161-170 (1995), https://doi.org/10.1007/BF02664109.

[7] H. Morii, H. Yoshimura, Method for producing hollow engine valve. US Patent No.8881391 B2 (2012).

[8] J. Hongchao, L. Jinping, W. Baoyu, F. Xiaobin, X. Wenchao, H. Zhenghuan, J. Mater. Process. Technol. **240**, 1-11 (2017).

[9] H.S. Jeong, J.R. Choa, H.C. Park, J. Mater. Process. Technol. **162-163**, 504-511 (2005).

[10] D. Kwon, K. Dong, Y. Kim, S. Hyeon, R. Dong J. Kim, J. Mater. Process. Technol. **113** (1-3), 148-152 (2001).

[11] B. Painter, R. Shivpuri, T. Altan, J. Mater. Process. Technol. **59**, 132-143 (1996).

[12] O. Cherniavsky, Y. Rebiakov, A. Cherniavsky, Int. J. Fatigue **103**, 415-418 (2017).

[13] M.A. Razzak, Bull. Mat. Sci. **34** (7), 1439-1445 (2011).

[14] N. Srinivasa, Y.V.R.K. Prasad, J. Mater. Process. Technol. **51** (1-4), 171-192 (1995).

[15] C. Sommitsch, R. Radis, A. Krumphals, M. Stockinger, D. Huber, Microstructure control in processing nickel, titanium and other special alloys, Microstructure Evolution in Metal Forming Processes, Woodhead Publishing Series in Metals and Surface Engineering, 337-383 (2012), https://doi.org/10.1533/9780857096340.3.337

[16] W. Wang, X. Pang, Ch. Zheng, A. A. Volinsky, Eng. Fail. Anal. **80**, 49-56 (2017).

[17] D.M. Xu, G.Q. Li, X.L. Wan, R.D.K. Misra, X.G. Zhang, G. Xu, K.M. Wu, Mater. Sci. Eng. A-Struct. Mater. Prop. Microstruct. Process. **720**, 36-48 (2018), https://doi.org/10.1016/j.msea.2018.02.018.

[18] C.Y. Lee, C.S. Yoo, A. Kermanpur Y.K. Lee, J. Alloys Compd. **583**, 357-360 (2014).

[19] K.H. Lo, C.H Shek, J.K.L. Lai, Mater. Sci. Eng. R-Rep. **65**, 39-104 (2009).

[20] M. Calmunger, G. Chai, R. Eriksson, S. Johansson, J.J. Moverare, Metall. Mater. Trans. A-Phys. Metall. Mater. Sci. **48** (10), 4525-4538 (2017).

[21] J. Zhou, Z. Sun, P. Kanouté, D. Retraint, Int. J. Fatigue **103**, 309-317 (2017).

[22] ASM Metals Handbook, Vol. **14**, Forming and Forging.

[23] C. Choi, A. Groseclose, T. Altan, J. Mater. Process. Technol. **212** (8), 1742-1752 (2012).

[24] A.Taylan, N. Gracious, S. Gangshu, Cold and hot forging fundamentals and application. ASM Int. Asm. Metals Handbook **14**, 337-338 (2005).

[25] D.H. Kim, H.C. Lee, B.M. Kim, K.H. Kim, J. Mater. Process Technol. **166** (3), 372-380 (2005).

[26] M. Hawryluk, J. Ziemba, Ł. Dworzak, P. Kaczyński, M. Kasprzak, Int. J. Adv. Manuf. Technol. **97** (5-8), 2009-2018 (2018). https://doi.org/10.1007/s00170-018-2066-y.

[27] M. Hawryluk, Z. Gronostajski, J. Ziemba, Ł. Dworzak, P. Jabłoński, M. Rychlik, Eksploat. Niezawodn. **20** (2), 169-176 (2018). http://dx.doi.org/10.17531/ein.2018.2.01.

[28] M. Hawryluk, Arch. Civ. Mech. Eng. **16** (4), 845-866, (2016). doi.org/10.1016/j.acme.2016.06.001.