Arch. Metall. Mater. **63** (2018), 2, 941-952

DOI: 10.24425/122426

M. HAWRYLUK*[#], M. ZWIERZCHOWSKI*, M. MARCINIAK*

A DESTRUCTIVE MECHANISMS OCCURRING IN THE SURFACE LAYER OF FORGING TOOLS USED IN HOT FORGING PROCESSES

In the work was presented the results of studies concerns on the destructive mechanisms for forging tools used in the wheel forging process as well the laboratory results obtained on a specially constructed test items for testing abrasive wear and thermal fatigue. The research results of the forging tools shown that the dominant destructive mechanisms are thermal fatigue occurring in the initial the exploitation stage and abrasive wear, which occurs later, and is intensified effects of thermo-mechanical fatigue and oxidation process. In order to better analysis of phenomena associated with destructive mechanisms, the authors built a special test stands allow for a more complete analysis of each of the mechanisms separately under laboratory conditions, which correspond to the industrial forging processes. A comprehensive analysis of the forging tools confirmed by laboratory tests, showed the interaction between the thermal fatigue and abrasive wear, combined with the oxidation process. The obtained results showed that the process of oxidation and thermal fatigue, very often occur together with the mechanism of abrasive wear, creating a synergy effect. This causing the acceleration, the most visible and easily measurable process of abrasive wear.

Keywords: destruction mechanisms, non-lubricated and uncooled forging tools, laboratory abrasive wear and thermal fatigue test stands

1. Introduction

Forging tools applied in industrial hot forging processes is characterized by a relatively low hardness, which is directly related to the quality as well as the cost of the production of forgings. The interconnections between the particular destruction mechanisms occurring in the case of forging tools is largely determined by the conditions of the given forging process. To a lower degree, the resistance to degradation mechanisms is dependent on the tool's construction (working surface shape), the tool's material and its proper thermal treatment as well as the treatment of the surface layer, while it is least influenced by the preform's shape [1-4]. The load of the dies and punches cyclically changes, constituting a combination of thermal and mechanical loads, which results from the contact of the hot preform material with the relatively cold tool. A special influence on the dies' hardness is exerted by the varying thermal load, which is the main reason for the crack formation as well as the physico-mechanical changes taking place on the tool's surface layer, and also the abrasive wear. In the presented case, the surface layer is the one which differs from the core material in a physical, chemical or mechanical way and which is limited by the tool's surface layer on the one side and by the core material mentioned above on the other. And so, according to the changes taking place during the operation of forging tools, the surface layer undergoes changes in respect of its geometrical location and density [5-8].

With regard to forging tools, there is the option of applying a lubricating and cooling agent. During the process of semi-free die forging (upsetting, flattening, etc.), the tools are usually not lubricated, the reason for which being the complicated flow of the deformed material. It is a different case from the one of typical die forging, where the application of a lubricant is necessary for the minimization of friction, the aim of which being to precisely fill the tool's working pattern with the deformed material. In the upsetting operation, the forger periodically removes the scale, as it can also influence durability. In this way, the operation conditions for the tools which are not lubricated or cooled are different from the conditions under which the lubricated tools work. The research conducted by the authors analyzing the forging tools' surface layer demonstrated that, in respect of the forging processes carried out at elevated temperatures, and in the case of typical tool operation conditions (lubrication and cooling), the participation of abrasive wear as the dominating destruction mechanism decreases, while the one of thermo-mechanical fatigue significantly increases. This process accelerates the abrasive wear, which is visible and easy to measure, and, as a result, the tools are eliminated from the production process. The case is slightly different with non-lubricated and non-cooled forging tools, where abrasive wear and plastic strain are the typical destruction mechanisms [8-11]. The

---

* WROCLAW UNIVERSITY OF SCIENCE AND TECHNOLOGY, DEPARTMENT OF METAL FORMING AND METROLOGY, 5 LUKASIEWICZA STR., 50-371 WROCŁAW, POLAND

[#] Corresponding author: marek.hawryluk@pwr.edu.pl

major factors influencing the thermal load of the dies are as follows: the temperature of the forged metal as well as the die, and also the contact time and the forging speed, while the mechanical load is mainly affected by: the unit pressure as well as the displacements on the friction couples' contact surfaces (relative path of friction), and also the material grade and the forging's and tool's mass [10,12]. The temperature gradient occurring between the deformed material and the tool is the cause of compressive pressure in the surface layer of the tool during the forging process, as well as tensile stresses observed after the deformation, caused by the impression being cooled. Thus, the die material is subjected to thermal and mechanical loads, which periodically vary, and this can be the cause of material fatigue and crack or scrap formation. And so, an effective load of a typical forging tool is determined by the principle of superposition of stresses caused by the changes of temperature as well as the direct mechanical load. As the forging processes are non-stationary in character, the die stress and deformation are neither homogeneous nor constant. The extreme conditions of the tool operation are characterized by the character of the load of the hot forging tool material.

Presented below are the usually observed damages of the tools, which cause their fast elimination from the production process. Abrasive wear, resulting from the material loss mainly caused by the material particles being separated from the surface. It occurrs when we observe the presence of loose or restrained abradant particles or protruding irregularities of the harder material in the areas of the elements' cooperation [5,11,13,14]. A result of the intensive periodical thermal loads caused by the alternate heating and cooling of the tool's surface, thermal stresses occur, which are the cause of the formation of a microcrack grid. This form of degradation is called thermal fatigue [15-18]. Also, the occurrence of cyclically changing mechanical loads causes a fatigue process referred to as mechanical fatigue, the intensity of which increases due to the microcrack grid caused by the thermal fatigue, thus forming macrocracks. Thermo-mechanical fatigue, where material fatigue causes local cohesion and material losses as a result of the cyclic operation of stresses in the dies' surface layers. In the stress concentration areas, we observe the formation of fatigue microcracks of the surface, which are then transformed into macrocracks [19-21]. There is another destruction mechanism which is as important as abrasive wear and thermo-mechanical fatigue and that is the plastic strain of die impressions and punches [8,11]. Oxidation wear is the degradation process of the metal elements' surface layer caused by oxide films' separation. This wear type occurrs when the intensity of oxide layer formation is higher than the intensity of surface wear (abrasion) [22]. Adhesive wear, present in the surface layer plastic deformation microareas, especially in the highest porosity peaks. In this case, we observe the formation of local metallic tackings of the friction faces. These connections degrade when the metal particles are separated or when the metal is smeared over the friction faces [9]. The type as well as the size of the admissible wear of the shaping tools‘ working patterns is determined by the process type and it influences the tools‘ operation time. And so, it is justifiable and important to conduct continuous research under laboratory and industrial conditions, which aims at explaining and more thoroughly describing the phenomena taking place during the forging tools‘ operation under different conditions. Interpreting the results of such studies and analyses can aid in the search for ways of die forging process optimization. Knowing the types of damage as well as why they occur and how to avoid them is crucial during the design of the technology as well as the construction and operation of the tools [2,8,11,23,24].

The study demonstrates the results of investigations carried out to analyze the major phenomena and mechanisms occurring during the operation of die inserts used in the first forging operation, which is upsetting non-lubricated and non-cooled tools of a disk-type forging, and also the results of laboratory tests performed on a test stand specially designed for thermal fatigue and abrasive wear examinations involving elevated pressures.

2. Industrial forging process

The industrial process of forging a spur gear consists of 3 operations: the first operation is upsetting, the second is preliminary die forging, and the third is finishing forging.

Initially, the preform is heated to 1150°C (forging temperature). The preforms whose temperature is >1200°C and

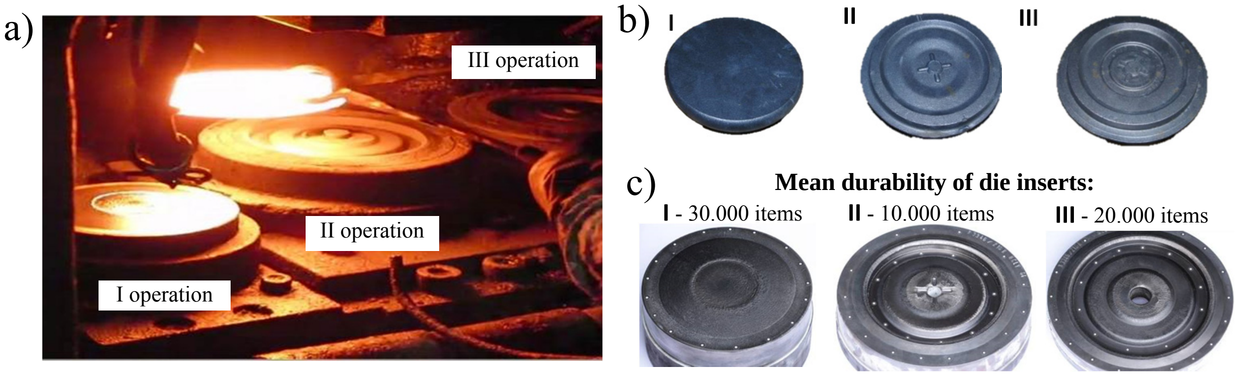


Fig. 1. a) General view of the die forging of a wheel, b) preform and forgings in particular operations, c) lower die inserts from operation: I – upsetting, II – preliminary forging, III – finishing forging

<1130°C are rejected. The tools are preliminarily heated to about 200-250°C. Figure 1 shows a view of the forging process as well as the preform and the forging obtained in the particular operations, as well as the worn lower die inserts.

The tools are heated to the desired temperature with the use of a heat waste material of about 1100°C; the heating time is about 1-1.5 hr. Between the impressions, the forgings are carried manually and the time of one cycle is 14-17 seconds. In the analyzed process, all the die inserts were made from steel WCLV (according to polish standard).The material for the forging is steel QS1920S0, which is an equivalent of steel 20HG.

The tools used in the first forging operation (upsetting) were selected for research in detail. And also for better interpretation of the occurring phenomena and as well owing to the laboratory test stands built by the authors. These die inserts characterize in a simple shape (an almost flat working surface), they are not lubricated or cooled during the forging process and their working temperature is within the range of 450-550°C, in contrast to tools from second and third operations. This operation aims at upsetting the material and removing the scale from the preform. The mean durability of the inserts for this operation is about 30 thousand forgings. The contact time of a hot forging with the lower die insert in operation I, determined based on the observations and measurements by means of a fast frame camera. The mean unit pressures, determined based on the results of the numerical simulations of the forging process previously performed by the authors, depending on the location and shape of the tool, equal from 100 to even over 1000 MPa. Due to the relatively high durability and the simple shape of the inserts from operation I, their nitriding is not cost-effective. These tools are repeatedly regenerated by way of machining and next spray-fuse alloy powder coating. As a result of a long-term operation of the tools, regardless of the number of produced forgings, the highest wear occurs in the area of the longest contact with the forged material. Such hard working conditions of forging tools have a significant effect on the complexity of the phenomena taking place during the processes of their wear.

3. Test methodology

A complex analysis of the degradation phenomena and mechanisms taking place in the surface layer of the tools was performed based on a series of investigations, such as: thermovisual measurements, scanning and analysis of working surfaces, microhardness measurements and optical microscopy and SEM tests.

3.1. Thermovisual tests

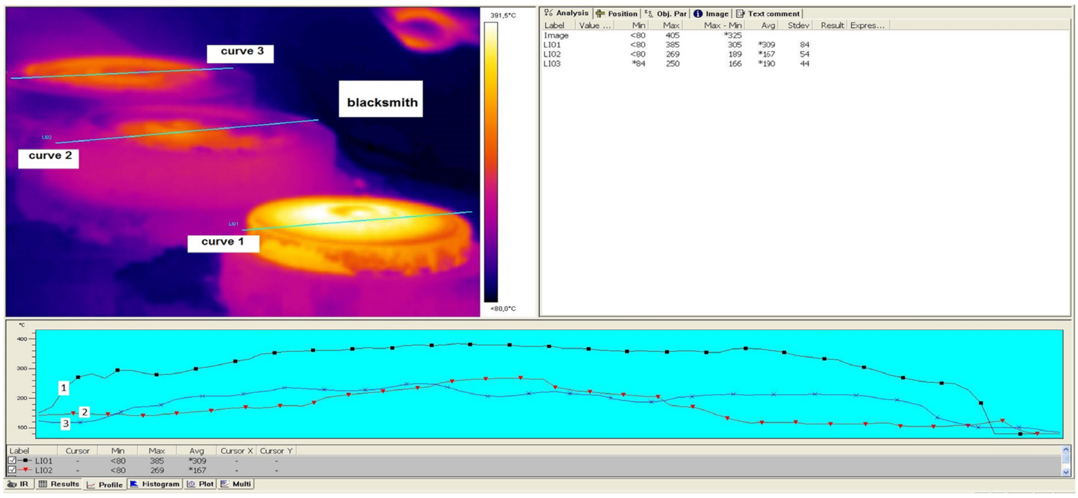
The thermovisual tests were performed with the use of the camera A320 Flir with the aim to determine the temperature distributions on the lower surfaces of the tools in the particular forging operations (Fig. 2).

The highest temperatures on the die are observed in operation I. The mean temperature of the die insert on the surface during forging, in the upsetting operation, equals about 450-550°C. The maximal temperature of the die for the second operation is about 270°C. On the die in the third operation, one can observe a more uniform distribution of the temperature course than for the die from the second operation. Here, the maximal temperature equals 250°C.

3.2. Scanning of surface working

A laser scanning tests were performed on the dies after predetermined operation periods and next a comparison of the obtained images with the CAD model or scans of new tools were made. This enabled the determination of the geometrical loss of the tool material in normal direction (its wear).

Figure 3 shows graphically the loss of tool material values of the lower dies in the first operation. One can infer from the presented scans that all the inserts wear non-uniformly, especially with a large number of forgings. This is a result of the manner (direction) of lubrication and blow-in on the side of the



Label	Value ...	Min	Max	Max - Min	Avg	Stdev	Result	Expres...
Image		<80	405	*325				
LI01		<80	385	305	*309	84		
LI02		<80	269	189	*167	54		
LI03		*84	250	166	*190	44		

Label	Cursor	Min	Max	Avg	Cursor X	Cursor Y
☑ LI01	-	<80	385	*309	-	-
☑ LI02	-	<80	269	*167	-	-

Fig. 2. Temperature distributions of the lower die inserts used in the process of forging a wheel

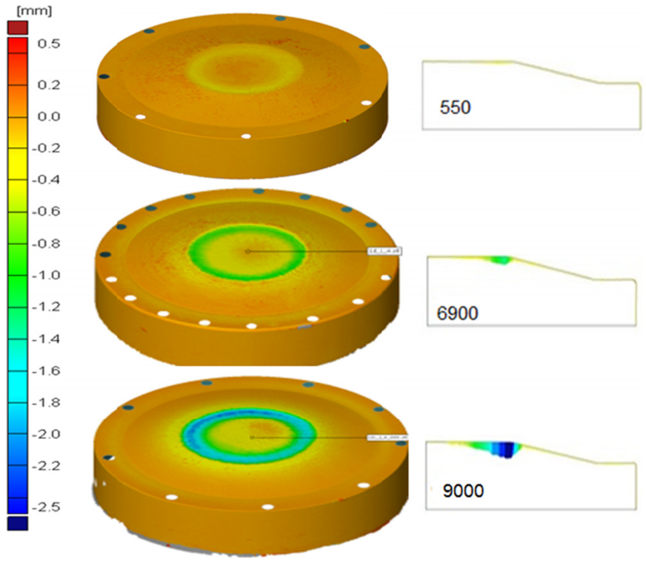


Fig. 3. Wear values for the lower die inserts used in 1st operation – upsetting

blacksmith. For the die inserts operation I, the highest wear is observed in the area of the beginning of the conic part and it equals about 1.2 mm (after 6900 forgings) and even over 2 mm (after 9000 forgings).

3.3. The hardness tests

The microhardness measurements of the discussed dies were performed with the device LECO – LM 100 AT, load 100 gram. The measurement results for exemplary lower inserts from the first operation, for 4 selected measurement points, are presented in Figure 4. These points were selected as representatives, due to their different working conditions (contact time of the forging with the tool, unit pressures, temperature field distribution, path of friction, etc.).

For the dies which produced 550 and 6900 forgings, one can notice that, at the depth of 0.2 mm, the hardness of the die is lower than the hardness of the core (Fig. 4b and 4c). For the die after producing 550 forgings, the hardness at the surface for points 1, 2 and 3 equals about 350 HV, whereas the hardness at the surface in point 4 is about 475 HV. The hardness of the core material equals about 500-550 HV. For the die, which produced 6900 forgings, the hardness at the surface for points 1,2 and 4 equals the same like for die after 550 pieces, while in point 3, at the surface, the hardness is over 500HV. The hardness of the core for this die is within the range of 550-615 HV. For the dies which produced 550 and 6900 forgings, in each measurement point, one can observe a drop of hardness at the surfaces of the examined dies, whereas for the die which produced 9000 forgings (Fig. 4d), the test results suggest that the hardness in areas 1 and 2 is higher than the hardness of the core and equals: about 620 HV for point 1 and about 770 HV for point 2. The observed increase of hardness (marked in red in Fig. 4d) can point to surface hardening of the die in this area. This might be caused by the external factors (heating and intensive cooling of the die during the process).

However, for the material of the die to be hardened at the surface (this refers to the surface layer with the depth of 0.1 mm), the temperature on the surface of the insert would have to exceed the austenization temperature – for this steel by over 1060°C. The temperature of the initial material (preform)

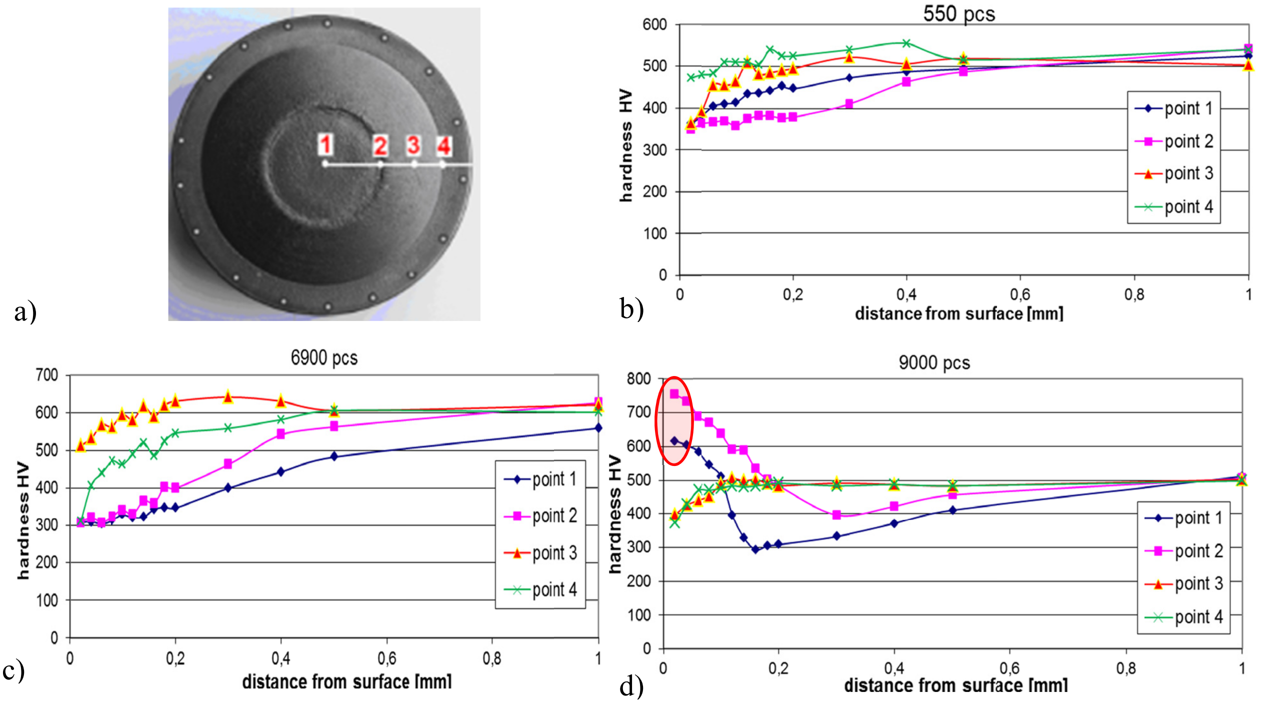


Fig. 4. The hardness distribution for inserts from the first operation: a) view of the tool with marked measurement points, b) results for an insert after producing 550 forgings, c) 6900 forgings, d) 9000 forgings

equals 1150°C (in first operation the mean temperature of tools equals about 450-550°C – based on the thermovisual tests). In turn, for points 3 and 4, one can observe a drop of hardness in the surface layer in respect of the core, which suggests material tempering (hardness less than 400 HV).

3.3.1. Effect of the annealing time of tool steel for hot operations on the hardness changes in the surface layer

As the literature suggests (Fig. 5a), as well as based on the performed investigations, with the increase of the number of forged products, the hardness in the surface layer decreases. A typical thermal treatment of this steel consists of hardening and tempering at temperatures 525-55°C. The increase of hardness after the tempering is caused by the so-called secondary hardness effect. In turn, exceeding the tempering temperature during forging causes a rapid drop of hardness. With the temperature increase, the diffusion rate increases as well, which can cause decarburization or slight oxidation in the surface layer of the tools. The observed drop of hardness in the analyzed tools induced the authors to examine the effect of the annealing time of WCLV steel on the hardness changes in the surface layer. Also, as we know, thermovisual tests enable the determination of only the temperature distribution on the surface of the tools. It is difficult or even impossible to measure the rapid changes of the temperature fields occurring during forging, especially in the surface layer. The tests were performed for different annealing times (0.5h; 1.0h; 2.0h).These times approximately correspond to the total contact times of the material of the hot gorging with the analyzed die.

Figure 5b shows the results of the laboratory analysis of the effect of time and temperature on the properties of the surface layer of the discussed steel. As one can observe, for 650°C, a large drop of hardness takes place in the surface layer. Additionally, in the area about 50μm from the surface, probably, slight decarburization occurs as well as a drop of hardness, as compared with the already tempered material of the core. The periodical exceeding of the tempering temperature which takes place in the forging process can cause exceeding of the critical hardness in the tool's surface layer. This, in turn, causes intensification of the destructive mechanisms and .

3.4. Effect of scale on the tool hardness in the forging process

During the process of hot forging, the scale accumulated on the surface of the tools and the preform is only partially removed. A part of the chipping scale remains on the tools, working as an abradant during the following hot forging cycles, thus intensifying the wear of the dies. The examinations of the chemical composition of the scale showed that it contains Fe O within the range from 45/55% to 5/95% (Fig. 6). And so, one can suppose that the scale collected from the forging contains different types of iron oxides, such as (Fe_2O_3, Fe_3O_4 and FeO).

In turn, Figure 7 shows the laminar construction of the discussed scale collected from the material of the forging.

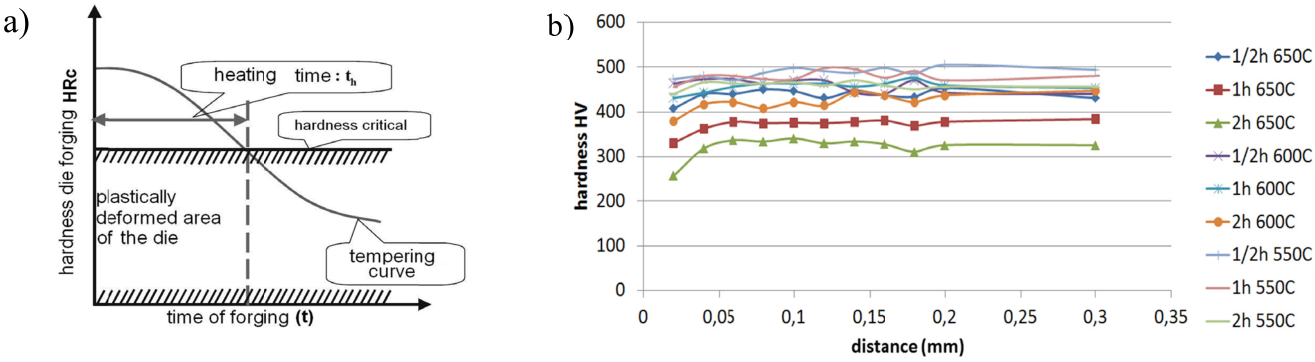


Fig. 5. a) A decrease in hardness of tool material as a function of time [25], b) hardness of WCLV steel for different annealing conditions (time and temperature) as a function of distance from the surface

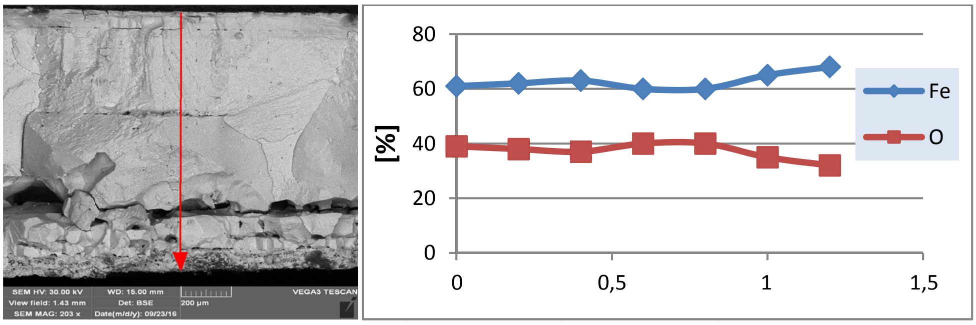


Fig. 6. Oxide layer with marked test vector and a linear distribution of oxygen and iron – sample from billet material

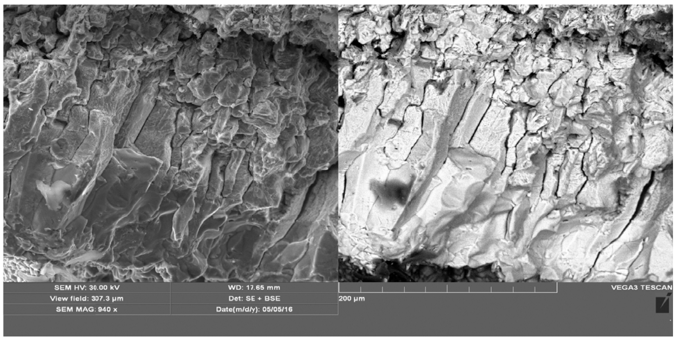


Fig. 7. Multi-layered character of mill scale on billet 20HG material

As one can see in Figure 8, the size of different particles present in the scale varies between 1.0 and about 50.0 µm. Additionally, measurements of the oxide layer were also performed. It was established that the hardness of the scale collected from the forging exceeds the hardness of the die, i.e. >550HV in the FeO layer and about 1100 HV in the Fe_2O_3layer (Fig. 8).

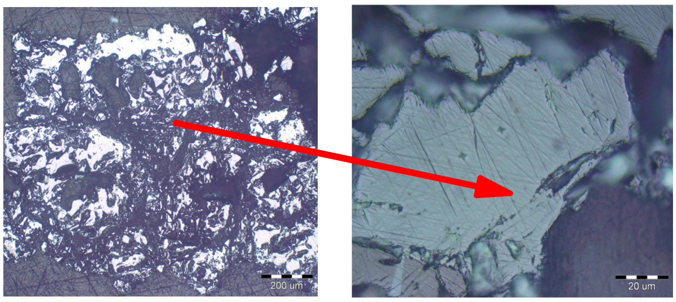


Fig. 8 .Cross microsection of the oxide layer visible and enlarging this area with the indentations obtained during microhardness tests

Considering the brittleness, the high hardness and the presence of scale during the discussed hot forging process, one can conclude that the presence of the latter intensifies the wear of the dies.

3.5. Microstructural tests

The following stage of research were microscopic tests performed by means of the electron microscope Tescan Vega 3 with a BSE and EDX Bruker Nano detector. The tests were conducted in all four areas shown in Figure 4. For the die after producing 9000-9500 forgings, one can see traces characteristic for abrasive wear (Fig. 9b).

The grooves visible in the picture were created as a result of the operation of hard scale particles moved by the forging material being formed with a high load and a high path of friction.

For the die which produced from 550 to about 1900 forgings, no cracks in the surface layer were observed. In turn, for the inserts which produced 6900 and 9000 forgings, we can observe the presence of surface cracks, 0.15-0.6 mm long. These cracks originate from thermal and thermo-mechanical fatigue (Fig. 9a).

The analysis performed on the surface layer of the die inserts used in the first forging operation demonstrated that the dominating destruction mechanism for these tools is thermal fatigue, which is observed at the initial stage of operation, and also abrasive wear, occurring a little later, and that they are intensified by the effect of thermal fatigue. Both mechanisms are the result of the extreme conditions present during the hot forging process and they originate from the periodical thermal and mechanical load changes. On the basis of what is above, we can conclude that the dominating destruction mechanisms in the case of these tools are thermal fatigue and abrasive wear, which are caused by the cyclic temperature and mechanical loads.

4. Laboratory thermal fatigue and abrasive wear test stations

For a more thorough analysis and a better understanding of the phenomena accompanying the dominant mechanisms which destroy the forging tools, the authors constructed special test stations enabling a more complete analysis of each mechanism performed separately under laboratory conditions, which correspond to the industrial forging processes [10].

4.1. Thermal fatigue test stand

Examining the material's thermal fatigue resistance under the actually occurring conditions is often not possible, and when it is, it takes a lot of time and resources. Simulation numerical

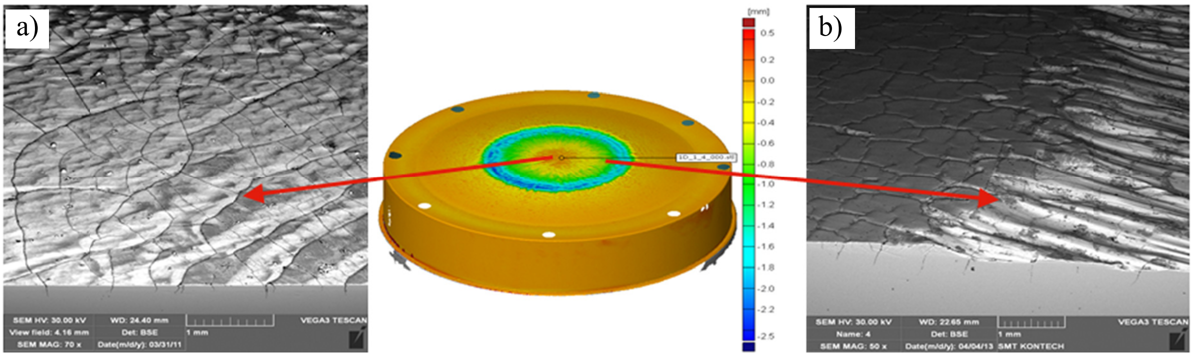


Fig. 9. Scan of the tool after 9000 forgings with a SEM image of various destructive mechanisms: a) thermal fatigue grid in area 1, b) abrasive wear in area 2

tests, which are also an option, do not always provide the possibility of a precise representation of the elements' operation conditions or the material's behavior. It is possible to recreate a similar phenomenon to that observed during the forging process under laboratory conditions. The authors have designed and constructed a tool for the physical modeling of this phenomenon, which is a special test station based on the spinning disk method. The station makes it possible to determine the ability of the material to endure a specific number of thermal changes before crack formation occurs [18].

Based on the analysis of the literature and with the use of specialized technical solutions [16,19,21] for testing the resistance to high temperature gradients and the nature of producing a disk-type forging, a test stand was built, which represented the temperature cycle of the forging dies' operation. The justification of the selection of this method are thermal fatigue tests performed on samples with a simple geometry, under easily controlled conditions, as well as the possibility to construct a numerical model representing the experimental test. The concept of the tests is based on a combination of physical and mathematical modeling of the phenomenon of thermal fatigue. During the examinations, a disk-shaped sample with an opening (made from a tool material for hot operations) is heated in the surface layer similarly to the hot forging process (Fig. 10). Details of the construction and operation of the device are presented in the paper [26].

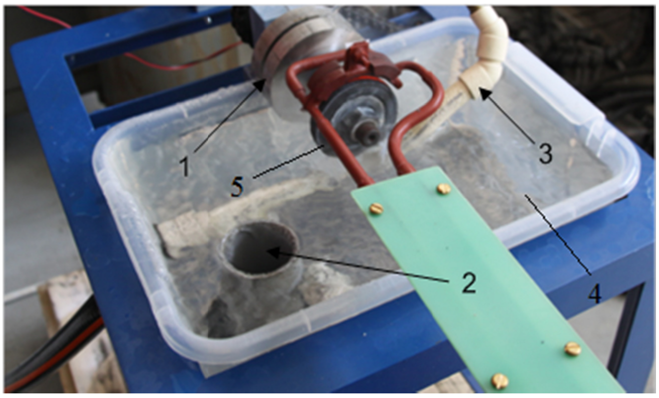


Fig. 10. The station for thermal fatigue tests: 1 – inductor, 2 – water drain with water level control, 3 – regulated water supply, 4 – container with water, 5 – sample

The heating of the sample causes the representation of the stresses which are formed during the material's contact with the forging, whereas the cooling stimulates the shock originating at the moment of removing the forging from the tool or from the application of a suspension of water with graphite (a lubricating and cooling agent), as is the case of simulations of the forging process with lubrication. In the case of testing thermal fatigue important parameters is the upper (T_{up}) and lower temperature (T_{low}) of cycle. The cycle time is regulated by way of changing the rotational speed of the sample, whereas the upper cycle temperature T_{up} is regulated by way of changing the power of the inductor generator and low temperature T_l is regulated by cooling liquid temperature.

The test station enables a fast verification of the material's resistance to thermal fatigue under controlled conditions. The resistance criterion can be the moment of the formation of first cracks or their observation after a specific number of fatigue cycles and the determination of the fatigue indicators. After the end of the tests, sample sections are collected (Fig. 11).

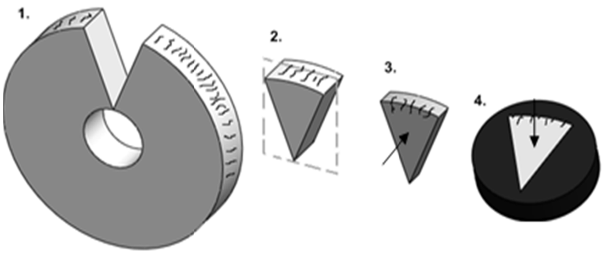


Fig. 11. Scheme of collecting a section for microscopic examinations: 1 – disk and the cut sample, 2 – cutting of the test sample, 3 – the sample after transection,4 – metallographic section

On the microsections, the depth of the formed cracks is measured by optical microscope software, and the macro-state of the surface is recorded (scanning microscope). The individual samples are then compared on the basis of two indicators: mean crack depth and crack density.

4.1.1. Test results

Fig. 12 shows exemplary results from the comparison of the behaviour of WCLV steel after increasing number of cycles for T_{up} equals 700°C and time of cycle 15 s (equal 4 rot/min). While in Fig. 13 presented exemplary results from the comparison of the behaviour of WCLV steel after 1000 cycles, depending on the change in the upper temperature of the cycle.

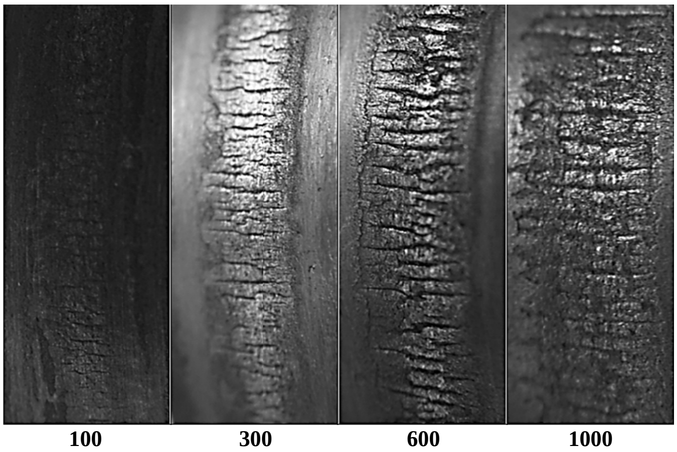


Fig. 12. Development of cracks due to thermal fatigue on the surface of the analyzed wheel samples

The conducted tests have shown that in the case of tool steel WCL, for the occurrence of fatigue cracks, the upper temperature must be at least 600°C.

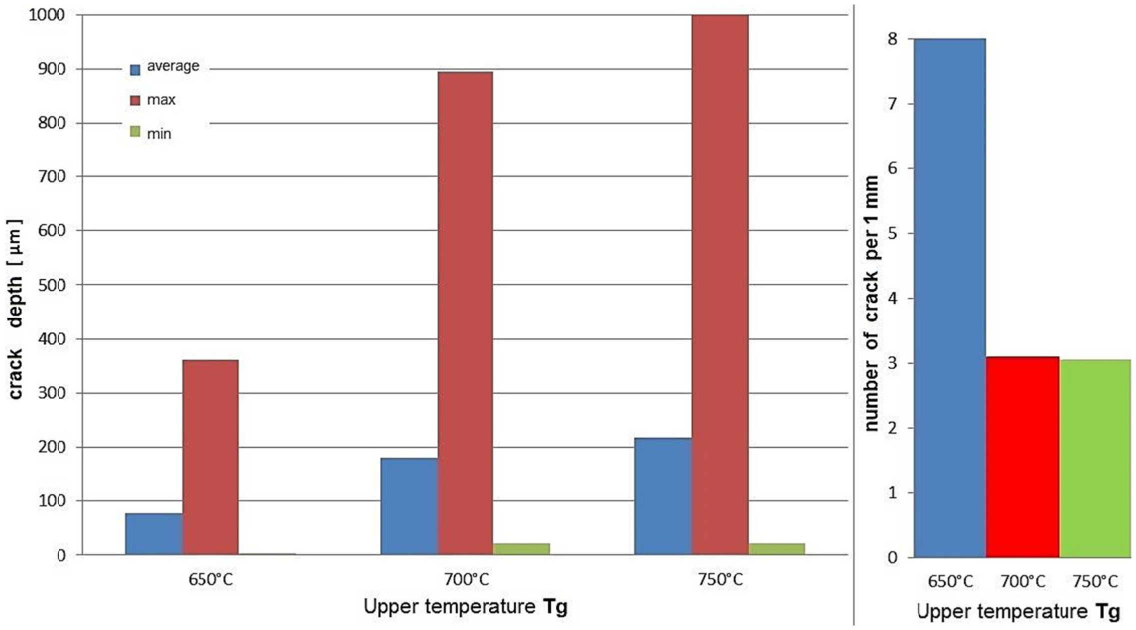


Fig. 13. Graphs showing the values of the different factors for fatigue tests after 1000 cycles

The observed maximal crack value is approximately 1 mm, when the upper cycle temperature is 750°C. The difference in the case of 700°C is minimal, equaling 0.9 mm. With 650°C, the maximal crack value is three times lower, which is also the case of the mean value, the difference being at the same level. This demonstrates the importance of the cycle temperature, not only in respect of the stresses originating from the temperature gradient, but also of the transformations occurring in the material. When the temperature increases, the amount of secondary carbides in the structure coming from the alloy additions (Cr, W, V, Mn) is reduced. The hardness of the material decreases, which results in a lowered yield point, this being confirmed by the crack density results. In the case of the samples at 650°C, we can observe the formation of a dense crack network. With higher temperatures, the number of cracks is two times lower. In the case of a harder material, initiation of new cracks occurs, while, in a tempered material, we observe a further propagation of the cracks formed in the initial phase, hence the difference in the fatigue cracks' density and depth in the case of different cycle temperatures [2].

The performed investigations showed that the density of the network is the factor which determines the durability of the dies. The more the surface is covered with a crack network, the more of the material is separated from the working surface of the tools. As a result of the flow of the forging material, the chipped off material contributes to the development of abrasive wear of the tool. Figure 14 shows an example of the described mechanism of samples after thermal fatigue tests and tool wear. Figure 14b shows the area of the tool section covered with a network of fatigue cracks.

It is the die's front which is the part subjected to the longest contact with the material heated to 1150°C. We can observe a primary network of cracks and also a secondary network, covered with oxides. What is more, we can notice the gaps from which the material has been pulled out. Figure 14c presents the area in the vicinity, with abrasive wear caused by the material's flow from the tool's central area. We can see the characteristic grooves on the surface and also loose particles. The results of the microstructure tests (Fig. 14), which are based on the SEM examinations, illustrate the importance of the compromise between the

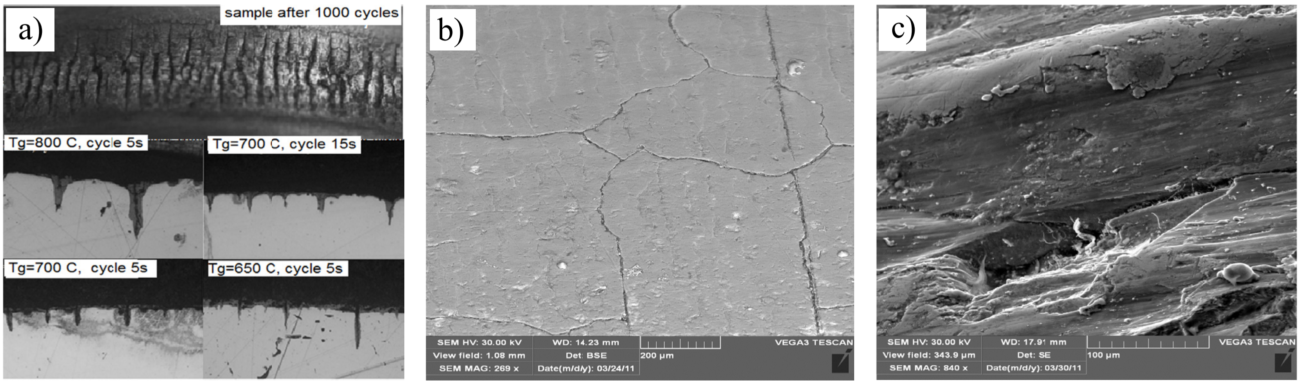


Fig. 14. A view of the surface: a) sample after tests, b)die – fatigue cracks in area 1, c) abrasively worn surface (area 2)

surface layer's hardness and the thermal fatigue resistance, which indirectly influences the die's abrasive wear value. This clearly demonstrates the usefulness of performing investigations of the surface layer's resistance to the formation of cracks originating from the temperature gradient. The test stand presented above enables examinations of the surface layer's state in respect of its application under the hot forging industrial conditions. It also makes it possible to preliminarily determine the best operation parameters (time, temperature) and also the material parameters in order to achieve a better forging tool durability.

4.2. Test station Triboforge for the analysis of abrasive wear with high pressures

The currently applied tribological machines (tribometers) are explicitly different from each other, the differences being determined by the tested phenomena, and for each simulated process, it is usually necessary to assume a separate approach to the problem [27,28]. Generally speaking, a majority of devices used in abrasive wear tests does not provide the option to approach the industrial forging process conditions. The pressures which are possible to obtain in the tests are at the level of a few MPa at best, and the maximal test temperatures are around 500°C. This makes the classic tribometers improper for abrasive wear analyses, this being the case of the forging processes. On the basis of a review of the possible solution concepts and their verification by means of numerical modeling, the authors built an abrasive wear test stand designed for high pressures (Fig. 15). The stand is based on the pin-on-ring method [29], this selection being dictated by the possibility of applying high loads, as well as the economy of the sample material when a ring shape is applied, and also the simplest heating-cooling process in respect of its implementation. Idea of the operation and construction of the device are presented in work [30].

The value of the loss of material (wear) is determined by the measurement of the change in the mass of the disk on a laboratory balance, before and after the test, as well as, based on its scanned geometry, with the use of an optical scanner – determination of the volume change. The measurement of the temperature distribution is realized by thermal camera. The station is coupled with an advanced measuring system, UNITEST, which is equipped with the CompactRio computer, with over ten modules and channels, thus making it possible to combine many sensors and measuring devices and ensure full control.

4.2.1. Tests of abrasive wear in industrial forging processes

The authors performed investigations with the use of the elaborated test station in order to compare the wear of the selected forging tool with the wear of the disk during the test. To that end, a worn upper die insert was selected, used in the first operation of forging (upsetting) of a spur gear (Fig. 16b). Based on the preliminary macroscopic analysis and the microstructural tests, it was stated that the abrasive wear is one of the dominant degradation mechanisms occurring in most areas of the working surface of this tool, used in the upsetting operation (Fig. 16a).

The slight differences between the upper and lower insert are connected with the geometry – the upper insert is completely flat and its working temperature is about 80-100°C higher. For the industrial forging process, FEM simulation was performed in order to determine the most important parameters, which enable a comparison of the abrasive wear of the tool and its simulation on the test device. These parameters include: **path of friction,** which is the value of the shift of the deformed material in respect of the selected point on the die surface, the unit pressures, the deformation and contact times, temperature, etc. On the profile

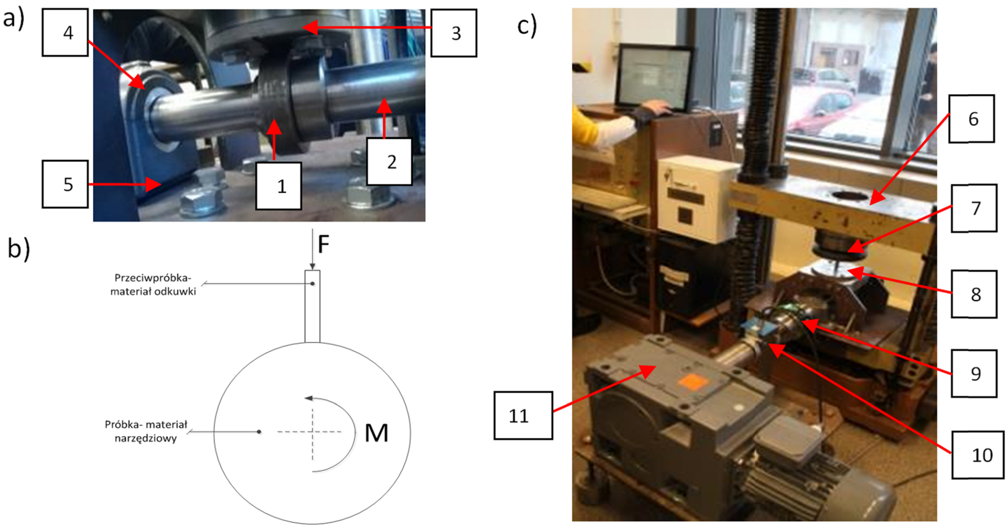


Fig. 15. a) Front view, a rotating disk (1) (steel 1.2344) fixed on a shaft (2) supported on both sides with bearings (4), replaceable die (3), force detectors (5), b) pictorial scheme of the test station c) general view of the test station: Tiratest machine beam (6), punch (7), recipient (8), coupling (9), torque meter (10) motoreducer (11) [30]

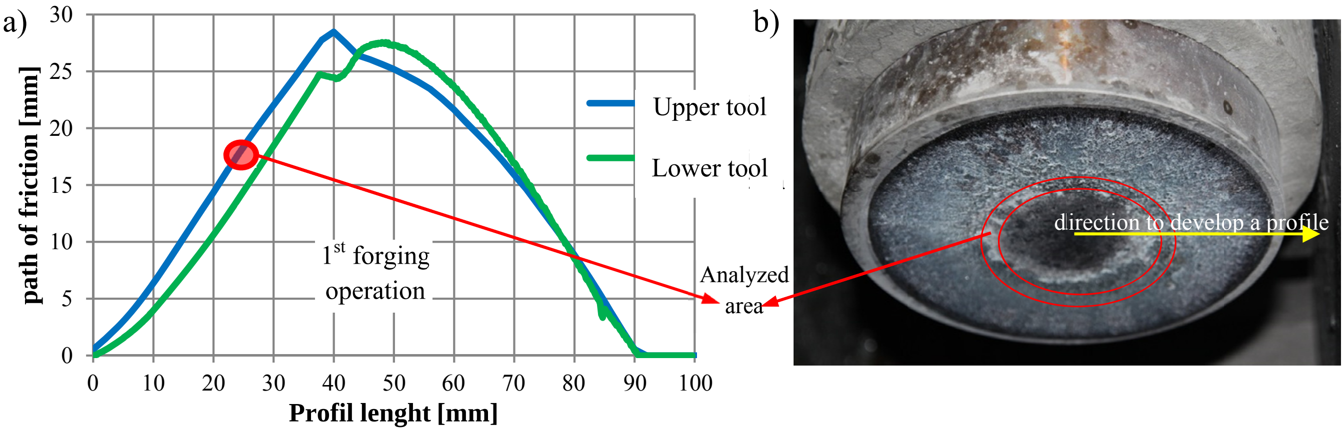


Fig. 16. a) The diagram of the dependence of the path of friction on the profile development of the tool surface determined from FEM, b) worn die (fixed in a casing) with marked direction of the profile development

of the analyzed die, the area on the bridge was selected, where intensive abrasive wear of the tool takes place (Fig. 16a), while there is no effect of other mechanisms connected with the high temperature of the forging material. The maximal pressures in this area, determined based on the simulation, equaled about 140 MPa.

Experimental tests on the elaborated test station were performed without a lubricating agent, the aim of which was to increase the wear rate and shorten the duration of the experiment. No significant effect of the environmental factors on the course of the forging processes was observed. The countersample, during the laboratory test, was pressed down to the sample made from a tool material (WCLV steel according to polish standard) with a constant force of about 7 kN, which, with the mean value of the contact field, provided the pressure of about 145 MPa, this corresponding to the load values from the analyzed area of the die (based on the FEM results, the pressures in this area equaled about 140 MPa). The most crucial comparative parameters were unit pressure values and the path of friction. The test duration was selected in such a way so that the total path of friction would be close to the path of friction which the material had completed after the total number of forgings. The total path of the test was determined based on the mean rotational speed, 4 rot/min (1 complete rotation equaled about 15 s, that is the same as the duration of the forging cycle in industrial process) as well as the dimensions of the sample.

Based on the obtained results, one can notice a comparable wear – loss of material of the disk (about 1.15 mm, Fig. 17a) and the tool in the selected area (equals about 0.95 mm, Fig. 17b).

The disk's wear is uniform, which is not the case of the die insert. The Archard model was used to determine the approximated values of parameter k; possible differences can be the result of the slightly different pressure and friction path values. The mean value of the friction coefficient (0.42) for the friction couple on the test stand (no lubricant) was determined on the basis of the measurements of pressure and force from the torque. In the case of the industrial forging process, the coefficient of friction is even lower (compared to the one assumed from FEM about 0.35). These condition differences (different temperatures in the contact during the experiment and the industrial process, different values of the coefficient of friction) are considered by parameter *k*, which is determined on the basis of the Archard

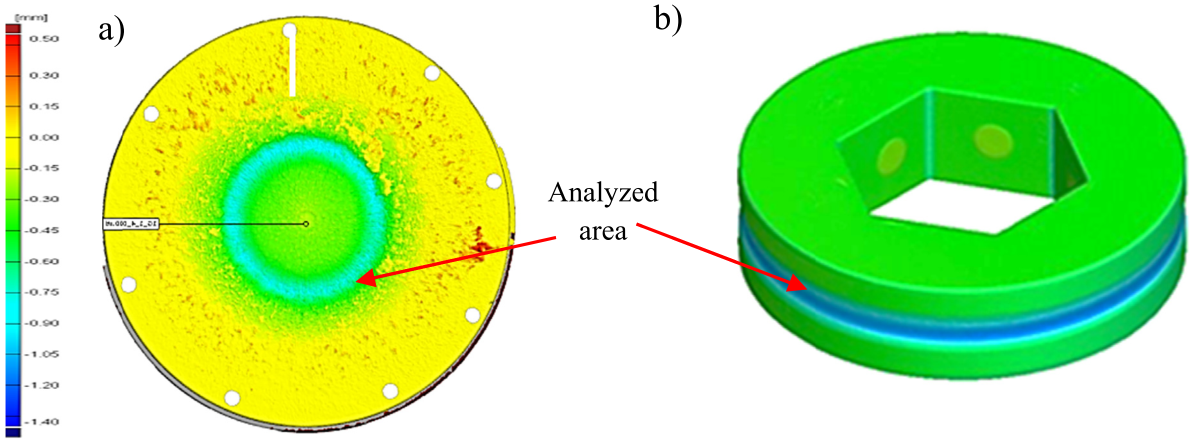


Fig. 17. Results of scanning: a) upper die in operation I of forging a wheel after 9000 forgings, b) disk in the experiment after 2200 min, which corresponds to about 8800 forgings

model. For industrial conditions k equals $5{,}06*10^{-4}$, while for laboratory tests was $4{,}88*10^{-4}$. The results obtained were previously confirmed, because in [30] the authors presented similar tests, for slightly different operating conditions, for which they obtained a high agreement between the results of laboratory tests and industrial conditions. The obtained results confirm the usefulness of the constructed test station for the examinations of abrasive wear with high pressures, for laboratory tests of materials used for the production of die inserts. The following stages of investigations will be performed with different values of pressure and path of friction for a further verification and optimization of the test station. In the future, the authors are also planning to perform a comparative analysis of different surface layers (nitrided and non-nitrided tools, a hybrid layer, subzero treatment, etc.) [10].

5. Conclusions

The investigations performed by the authors so far which regarded the analysis of forging tool durability have demonstrated that most destruction mechanisms occurring during the hot die forging processes are observed in the form of a material loss or a change in the tool surface shape. The wear intensity changes together with the process parameters, the latter depending mainly on the contact time, the values of pressure, the changes in temperature and the tribological conditions. The analyses of the die inserts working under industrial hot die forging process conditions showed the domination of abrasive wear as a degradation mechanism in the case of non-lubricated and non-cooled tools, followed by thermal fatigue, observed especially at the beginning of the operation time. In these cases, we can also see an increased participation of plastic deformations, caused by the temperature, the local tool tempering and the lowered hardness.

The tests concerning the effect of scale on the hardness of forging tools showed that the scale accumulated on the surface of the tools and the preform, during the forging process, is only partially removed. A portion of the chipping scale stays on the tools and works as an abradant during the successive hot forging cycles. In this way, it intensifies the wear of the die inserts. The crack network is often observed to chip off, causing the material to locally weaken and the surface to corrugate. This is also the cause of plastic deformation of the surface layer, which results in closing of the cracks. The investigations carried out on the special test stands, designed to analyze the thermal fatigue and abrasive wear, provided confirmation of the results obtained from the tests and observations of die inserts used under industrial conditions and made it possible to perform more thorough, separate analyses of those mechanisms. The complex studies conducted on the laboratory test stations demonstrated a cooperation of the selected mechanisms, especially observed between the thermal fatigue and the abrasive wear, which was combined with the process of oxidation.

Acknowledgements

The research has been financed by the National Centre of Research and Development (NCBiR); project no. POIG.01.03.01-02-063/12

REFERENCES

[1] T. Altan, Cold and hot forging fundamentals and application, ASM Internation, Ohio (2005).

[2] M. Hawryluk, Archives of Civil and Mechanical Engineering **16**, 845-866 (2016). http://dx.DOI:0.1016/j.acme.2016.06.001

[3] B-A. Behrens, A. Bouguecha, Ch. Buse, K. Wölki, A. Santangelo, Archives of Civil and Mechanical Engineering **16** (4**)**, 724-733 (2016).

[4] M. Hawryluk, J. Jakubik, Engineering Failure Analysis **59**, 396-409 (2016). http://dx.doi:10.1016/j.engfailanal.2015.11.008

[5] O. Barrau, C. Boher, C. Vergne, F. Rezai-Aria, Investigation of Friction and Wear Mechanism of Hot Forging Tool Steels, 6th Int. Tooling Conference, Karlstadt (2002).

[6] A. Baumel, T. Seeger, Material Data for Cyclic Loading, Suplement 1, Marterials Science Monographs, **61**, Elsevier Science Publishers, Amsterdam (1990).

[7] L. Blunt, K. Stout, Three Dimensional Surface Topography, Butterworth-Heinemann (2000).

[8] Ch. Choi, A. Groseclose, T. Altan, Journal of Materials Processing Technology **212** (8), 1742-1752 (2012).

[9] Ł. Rauch, A. Chmura, Z. Gronostajski, S. Polak, M. Pietrzyk, Archives of Civil and Mechanical Engineering **16** (3), 437-447 (2016).

[10] M. Hawryluk, Metody analizy oraz zwiększania trwałości narzędzi kuźniczych stosowanych w procesach kucia matrycowego na gorąco, Monograficzna seria wydawnicza Problemy Eksploatacji i Budowy Maszyn, ISBN 978-83-7789-410-1, Wyd. Naukowe ITE – PIB, Radom (2016).

[11] D.H. Kima, H.C. Leeb, B.M. Kimc, K.H. Kimd, Journal of Materials Processing Technology **212**, 1742-1752 (2012).

[12] A.Taylan, N. Gracious, S. Gangshu. Asm metals handbook **14**, 337-338 (2005).

[13] J.F Archard, Journal of Applied Physics **24**, 981-988 (1953).

[14] R.G. Bayer, Mechanical Wear Fundamentals and Testing, Marcel Dekker Inc., New York (2004).

[15] A. Katunin, Archives of Civil and Mechanical Engineering **11** (2), 333-342 (2011).

[16] P. Anders, S. Hogmark, J. Bergström, International Journal of Fatigue **10**, 1095-1107 (2004).

[17] http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.510.2263&rep=rep1&type=pdf [dostęp 25 stycznia 2018].

[18] A. Weroński, Zmęczenie cieplne metali, Wydawnictwa Naukowo-Techniczne, Warszawa (1983).

[19] G.A. Berti, M. Monti, Fatigue & Fracture of Engineering Materials & Structures **28** (11), 1025-1034 (2005).

[20] Y. Biriol., Ironmaking and Steelmaking **37**, 41-46 (2010).

[21] A. Grüning, M. Lebsanft, B. Scholtes, Materials Science & Engineering **527** (7-8), 1979-1985 (2010).

[22] Z. Gronostajski, M. Kaszuba, S. Polak, M. Zwierzchowski, A. Niechajowicz, M. Hawryluk, Microstructure and Processing **657**, 147-160 (2016).

[23] K. Lange, L. Cser, M. Geiger, J.A G. Kals, Journal of Engineering Manufacture **207** (11), 223-239 (1993).

[24] L. Lavtar, T. Muhic, G. Kugler, M. Tercelj, Engineering Failure Analysis **18** (10), 1143-1152 (2011).

[25] J.H. Kang, I.W. Park, J.S. Jae, S.S. Kang, Journal of Materials Processing Technology **96** (1), 53-58 (1999).

[26] Z. Gronostajski, M. Hawryluk, J. Krawczyk, M. Marciniak, Maintenance and Reliability **15** (2), 129-133 (2013).

[27] http://www.machinerylubrication.com/Read/526 [dostęp 25 września 2016].

[28] http://www.tribologia.eu/ptt/l50l/l50ls.htm [dostęp 30 marca 2013].

[29] L. Guobin, W. Jianjun, Journal of Materials Processing Technology **100**, 63-66 (2000).

[30] M. Hawryluk, M. Marciniak, G. Misiun, Maintenance and Reliability **16** (4), 600-607 (2015).