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POSSIBILITIES OF INVESTIGATING ABRASIVE WEAR IN CONDITIONS CLOSE TO THOSE PREVAILING IN INDUSTRIAL FORGING PROCESSES

MOŻLIWOŚCI BADANIA ZUŻYCIA ŚCIERNEGO W WARUNKACH ODPOWIADAJĄCYCH PRZEMYSŁOWYM PROCESOM KUCIA*

This paper presents aTriboForge – a prototype test stand for investigating abrasive wear, which unlike conventional tribometers, makes it possible to study wear under high pressures (500 MPa), i.e. in conditions close to those prevailing in industrial forging processes. The idea behind the designed and constructed prototype test stand was to most accurately reproduce the phenomena and processes acting on the surface layer of forging tools during their contact with the material being deformed. Preliminary tests were carried out on a tool material/selected forged material combination. A rotating disc made of tool steel (WCL) and a rectangular counter-sample made of the forged material (QS19-20), pressed against the disc constituted the friction pair. Thanks to a special control-measuring system integrated with the test stand it is possible to measure in real time several major parameters, such as: temperature distribution, the rotational speed of the sample, the pressure exerted by the counter-sample, the amount of wear, the sliding distance and changes in the friction coefficient value. The friction pairs would work for a fixed time of 4 hours at a constant counter-sample pressure of 10 kN (which for an average contact area amounted to about 220 MPa) at an average speed of 5 rpm (1 full rotation took about 12 s). Assuming that the key parameters describing abrasive wear are sliding distance and pressure per unit area, it has been shown that the magnitude of wear (material loss) depending on the cycle length is close to that in the actual industrial forging process. This proves the suitability of the test stand for the comprehensive analysis of the abrasive wear of forging dies.

Keywords: *abrasive tool wear, hot forging, test stand, hot tool steel.*

W pracy autorzy przedstawili prototypowe stanowisko do badania zużycia ściernego – TriboForge, które w odróżnieniu od klasycznych tribometrów pozwala na analizę zużycia w warunkachwysokich nacisków (500 MPa), czyli w warunkach zbliżonych do panujących w przemysłowych procesach kucia. Koncepcją zaprojektowanego i zbudowanego prototypowego stanowiska jest jak najdokładniejsze odwzorowanie zjawisk i procesów oddziałujących na warstwę wierzchnią narzędzi kuźniczych w kontakcie z odkształcanym materiałem odkuwki. Autorzy przeprowadzili wstępne badania dla skojarzenia: materiał narzędziowy i wybrany materiał odkuwki. Parę trącą stanowiły: obracający się krążek wykonany ze stali narzędziowej (WCL) oraz dociskana do niego próbka prostokątna z materiału odkuwki (QS19-20). Dzięki specjalnemu systemowi sterująco-pomiarowemu zintegrowanemu ze stanowiskiem możliwy jestpomiar on-line wielu istotnychparametrów(rozkładu temperatury, prędkości obrotowej próbki, siłydocisku przeciwpróbki, wielkości zużycia, drogi tarcia oraz zmianywartości współczynnika tarcia). Skojarzone próbki pracowały przez ustalony wcześniej czas 4 h przy docisku (stałą siłą około 10 kN, co przy średniej wielkości pola kontaktu wynosiło około 220 MPa), ze średnią prędkością obrotową 5obr/min (1 pełny obrót wynosił około 12 s). Przy założeniu, że najważniejszymi parametrami opisującymi zużycie ścierne są droga tarcia oraz nacisk jednostkowy wykazano, że wielkość zużycia (ubytku materiału) w zależności od długość cyklu jest zbliżonado procesu przemysłowego. Potwierdzato przydatność opracowanego stanowiska badawczego do kompleksowej analizy zużycia ściernego matryc kuźniczych.

Słowa kluczowe: *zużycie ścierne narzędzi, kucie na gorąco, stanowisko badawcze, stal do pracy na gorąco.*

Introduction

In industrial die forging processes the forging tools are subjected to extreme conditions. Many of the phenomena occurring at the contact between the tool and the forging material being formed are very violent in character and difficult to observe.Generally, the effect of degradation phenomena on the durability of forging dies is separately investigated and the degradation process has not been precisely holistically (taking all the phenomena simultaneously into account) described. An additional difficulty in an analysis of the individual phenomena is the variation in their intensity with changing process parameters and tool surface area. The latter determines the contact time, the pressures, the friction path and the changes in temperature and tribological conditions [1, 7–13, 18, 22, 27].

Owing to the intensive development of tribological sciences the degradation processes can be limited and controlled to some extent, which results in considerable savings and increased operational safety

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(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** of machines, equipment and forming tools. Special test stands, called tribometers, are often used for tribological testing. They are designed to most accurately reproduce the conditions existing in a given device (or process) and make it possible to actively record its selected parameters. Modern tribometric machines are geared towards the investigation of "mild" processes in which samples are loaded with forces of about 50 N. Currently there are practically no test stands which would fully reproduce the abrasive wear of forging dies and the tribometers being developed are at the prototype stage [3, 4, 11, 17,19].

The aim of this research was to design and build a prototype test stand capable of simulating the tribological conditions of the industrial forging process and simultaneously acquiring parameter data.

1. Concept of abrasive wear test stand

In order to identify and describe wear phenomena, not only experiments are carried out, but also several mathematical models making it possible to theoretically determine wear values have been formulated. One of the most commonly used models (being the basis for the majority of relevant equations) is the Archard model (1). Most of the research concentrates on the development and improvement of this model. The model describes abrasive wear resulting from contact between two bodies sliding against each other:

$$W = K \times \frac{F \times S}{H} \tag{1}$$

where: W – wear,
K – a wear coefficient,
F – the loading force,
S – the sliding distance,
H – the hardness of the element.

The model assumes that the wear of a given element is directly proportional to the loading force and the sliding distance and inversely proportional to the hardness of the material of which it is made. Dimensionless coefficient K is an experimentally determined quantity characteristic of each of the materials. Theoretically, its value is constant [26], regardless of the type of the investigated process, and it is in a range from 7×10^{-3} to $7\text{x}10^{-6}$ (1.3×10^{-4} for tool steel), depending on the kind of the materials being in contact and the presence of a lubricating medium [7, 11].

The Shaw model (2) represents a different approach to the wear phenomenon. It interrelates the magnitude of wear and the amount of energy dissipated as a result of friction:

$$Bu = PL\mu \tag{2}$$

where: B – a wear modulus,
P –the loading force,
L – the sliding distance,
μ – a friction coefficient,
u – the specific energy of wear.

The above equation describes how much energy is needed to produce a particle as a result of wear at given pressures, sliding distance and the magnitude of friction between the elements.

Besides the above models, there are models developed specifically to describe the wear of dies in the forging process. For example, the Kang equations or the Bahrens equations define the magnitude of wear after each forging process instance, taking into account not only the effect of temperature on material hardness, but also the decrease (due to local tempering) in tool hardness depending on the temperature impact duration [12].

Currently, there are difficulties in standardizing relevant tests because of the large scatter of the test results reported by the different research centres and the lack of repeatability of the results. Such organizations as ISO and ASTM have developed several standards and methodologies for abrasive wear testing, but they mainly apply to "mild" processes in which such factors as stresses or temperature do not reach high values. The existing tribological machines considerably differ from one another depending on the investigated phenomena and each simulated process usually requires an individual approach to the problem [7, 23]. The choice of test stand components has a key bearing on the results of tests and physical simulations. If the process is inaccurately reproduced or some factors are omitted, a measuring error is likely to occur. However, not all experiments require a fully defined testing environment. Sometimes knowledge about the general character of the process is sufficient and the use of sophisticated equipment would unnecessarily increase the research costs. With regard to the degree of reproduction of the real process, tribological machines can be grouped under three levels of simulation:

- *The first level* – the most general, supplying information about the basic parameters of the process, on the basis of which one can select the most suitable material and determine the effect of the particular factors on abrasive wear.
- *The second level* – closely connected with the values of the particular parameters. At this physical simulation level not only the mere occurrence of the given phenomena, but also their values are taken into account. The major factors in this type of simulations are: process temperature, the magnitude of stress, velocities and the type and amount of lubrication.
- *The third level* – the most faithfully reproducing the reality. Machines of this kind are, by and large, replicas of the actual workstations or their parts, except that they enable control and data acquisition.

First-level simulations and physical modelling are usually carried out in order to identify the basic principles of a given phenomenon and to determine the parameters of a given material. The second level of simulation is used in many engineering applications in which the effect of individual parameters on wear is determined. It enables one to design more efficient systems or optimize the existing ones. Although the third level does not supply all the information about a process, it is often used for practical reasons since it is easier to measure the required parameters on a real model or its reproduction without an in-depth analysis of the given phenomenon [7].

2. Survey of existing solutions described in literature

The design of a tribological machine is a complicated process in which several factors having a bearing on wear are taken into account. In order to design a second-level tribometer it is necessary to identify the key parameters of the studied phenomenon. Any divergence from the reality may result in incorrect measurement results. Therefore it is essential to take the effect of all the parameters on the process into account and identify the key parameters [7].

A survey of the designs of machines for tribological investigations, described in the literature on the subject, has been carried out. Also several test stands dedicated to the wear of dies in industrial forging processes have been identified. An example here is the test stand presented by the researchers from the University of Technology of Compiègne [20]. The present authors decided to base their solution on the disc-on-track concept enabling rotational sliding motion (Fig. 1).

According to this concept, a rotating disc (made of the die material) is pressed with a force of 50 N against the surface of a revolving track (made of the forging material). It is possible to control the relative speed of the members of the pair and their mutual sliding by means of a system controlling the motors responsible for rotation.

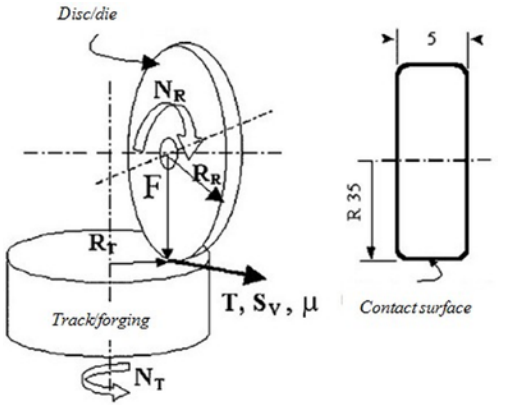


Fig. 1. Schematic of laboratory disc-on-track test stand [20]

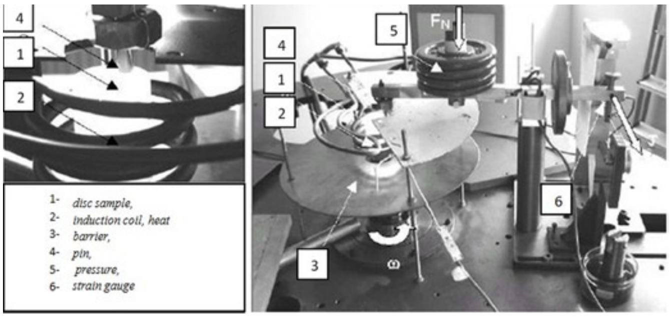


Fig. 2. Pin-on-discstand[3]

Moreover, the stand offers the possibility of heating the members to a temperature of 850°C and controlling temperature by means of a pyrometer.

Another interesting solution, based on the pin-on-disc concept, is described in [3]. A pin 20 mm in diameter, corresponding to a die, is pressed with a force of 100 N against a revolving track which is being heated through electromagnetic induction (Fig. 2).

Typically, the track is preheated and kept at a constant temperature for an hour, which is intended to produce an oxide coating. Then the test proper begins in the course of which such parameters as temperature, rotational speed and test duration are measured.

A Warm Hot Upsetting Sliding Test (WHUST)stand is described in [6]. It reproduces the die/forging contact between a cylindrical sample heated up to a temperature of 1100°C and a hot (200°C) penetrator pressed against it (Fig. 3). The tests conditions: pressures, rubbing speed, the speeds of the interacting surfaces and temperatures are similar to industrial conditions. As opposed to other test stands, this stand makes it possible to take the effect of lubrication during the test into account. Before the test the samples are coated with a lubricating film made up of graphite and water and such factors as the thickness of the lubricating film or the size of the solid particles are among the test parameters.

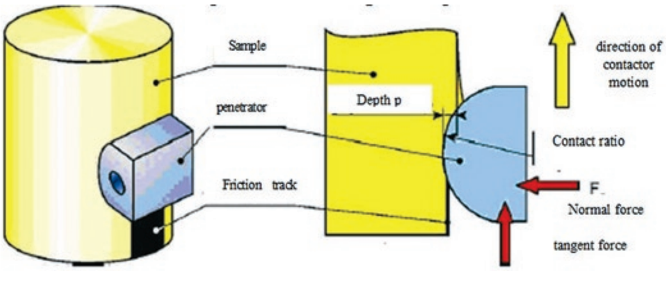


Fig.3. Schematic of WHUST device[6]

The last of the presented here solutions is described in [16]. It is based on a ring/pin friction pair. A specially designed rotating ring mimics the die. A stationary pin representing the forging is pressed against the ring. A base with a heater heats up the ring to a temperature as high as 500°C (Fig. 4). The purpose of the stand is to reproduce the conditions of the warm forging of constant-velocity universal joints.

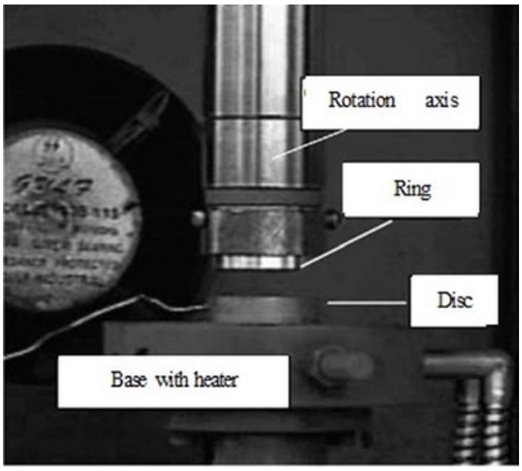
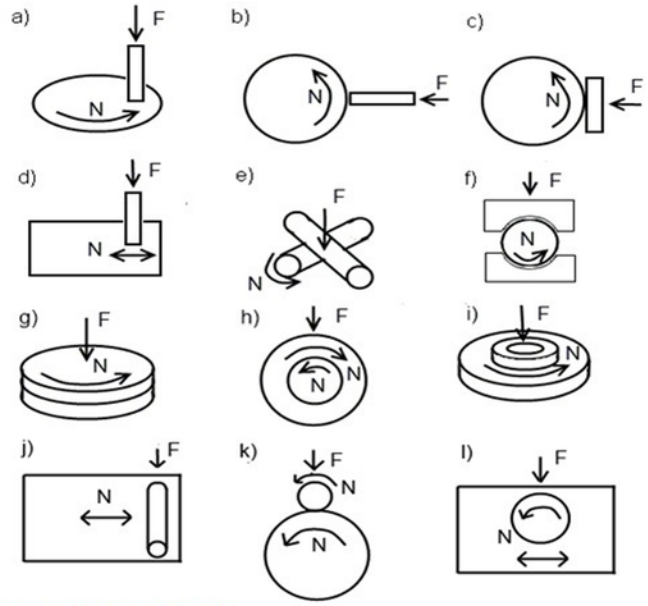


Fig. 4. Apparatus for high-temperature ring/disc wear testing [16]

Besides the prototype innovative abrasive wear test stands, also typical commercial industrial devices have been analyzed. One of the major producers of tribometric machines is Phoenix Technology Ltd [25]. The test stands and devices offered by this firm are based on typical friction pair configurations (Fig. 5).



where: F – pressure, N – displacement

Fig. 5. Wear test device configurations: a) pin-on-disc b) pin-on-ring,c) block-on-ring, d) pin-on-plate, e) cylinder-on-cylinder, f)cylinder-in-jaws, g) disc-on-disc, h) ring-on-cylinder, i) ring-on-disc, j) plate-cylinder, k) ring-on-ring), l) ring-plate

The above figure shows most of the typical tribometer friction pairs (such as pin-on-disc, pin-on-ring, etc.) and less popular configurations included in the simulation studies of forging processes.

3. Numerical modelling of abrasive wear test stand

Today IT tools (e.g. based on FEM) are frequently used to verify the basic assumptions and to determine the parameters of a test stand. The aim of numerical simulations is to verify theoretical considerations and to more precisely analyze the phenomena occurring in the course of the test as well as to prevent any structural-technological errors which may arise at the design stage [9, 11, 12,19, 24].

In order to verify and validate abrasive wear test stand assumptions the present authors built several numerical models and then ran relevant computer simulations using the MSC Marc Mentat 2013 software package. Thanks to the simulations many parameters difficult to determine analytically such as: the distribution of stress inside the disc, the way in which the plasticized sample flows, the rate of sample wear could be determined and the exchange of heat between the elements could be identified. The ultimate version of the prototype tribometer device being constructed was chosen through numerical modelling. In this device a 12 mm × 4 mm × 85 mm cuboidal counter-sample is pressed with a force of 24000 N against the edge of a disc 80 mm in diameter. At the simulation stage no cooling or heating of the sliding pair members was taken into account since the heat generated by the friction of the members was deemed representative enough of the process conditions.

3.1. Creation of model

A model, based on the plane state of stress, simulating the operation of the test stand, in which a 12 mm wide pressure exerting element acts on a disc 80 mm in diameter was built. The simulation comprises 4 contact body elements: two deformable bodies – a disc and a pressure exerting element and two stiff elements – a central element and a recipient. Moreover, similarly as in the real experiment, the contact surface of the counter-sample was appropriately shaped to ensure relatively constant contact right from the start of the test (Fig. 6).The shaft together with the disc was described as one element "disc" to simplify computations and the purpose of the hole in its centre (with the central element stuck to it) was to facilitate the definition and measurement of the required quantities. The pressure exerting element is in the recipient element described by five curves (marked green in Fig. 6).A boundary condition, in the form of pressures amounting to 500 N/mm, was defined on one edge of the pressure exerting element. The disc was made to rotate by imparting a rotational speed of 1.0472 rad/s (corresponding to 10 rpm) in the clockwise direction to the disc centre. Coulomb friction with a friction coefficient of μ=0.3 occurs between the sample and the counter-sample. The disc is made of hot-work tool steel WCLV while the pressure exerting element material is steel QS19-20. Material characteristics, such as the rate of deformation, temperature, thermal expansion, conductivity and specific heat, were defined for the two materials.

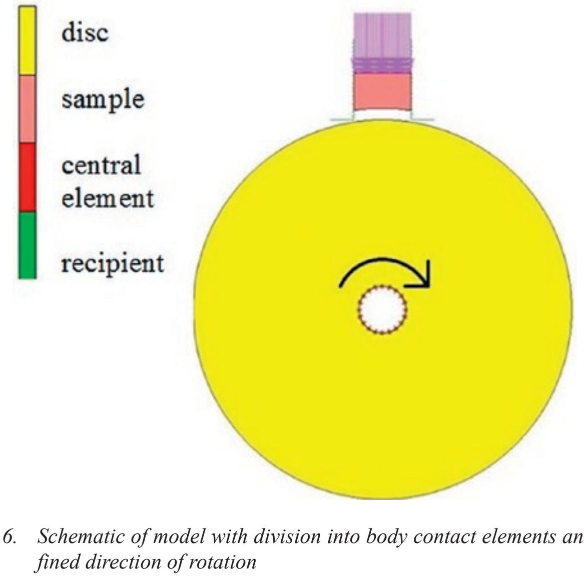


Fig. 6. Schematic of model with division into body contact elements and defined direction of rotation

A boundary condition, in the form of pressures amounting to 500 N/mm, was defined on one edge of the pressure exerting element. The disc was made to rotate by imparting a rotational speed of 1.0472 rad/s (corresponding to 10 rpm) in the clockwise direction to the disc centre. Coulomb friction with a friction coefficient of μ=0.3 occurs between the sample and the counter-sample. The disc is made of hot-work tool steel WCLV while the pressure exerting element material is steel QS19-20. Material characteristics, such as the rate of deformation, temperature, thermal expansion, conductivity and specific heat, were defined for the two materials.

In order to ensure the correct simulation of heat exchange, all the nodes were assigned a temperature of 24°C as an initial condition and a heat exchange coefficient of 20 $\mathrm{mW \cdot mm^{-2} \cdot K^{-1}}$ was introduced between the samples. Moreover, the heat exchange with the environment, whose temperature amounted to 24°C, was taken into account.

3.2. Simulation results

One of the main modelling objectives was to determine the stresses arising in the disc as a result of the action of the pressure exerting element. The distribution of the stresses in the model at the 6th second of the simulation is shown in Fig. 7.

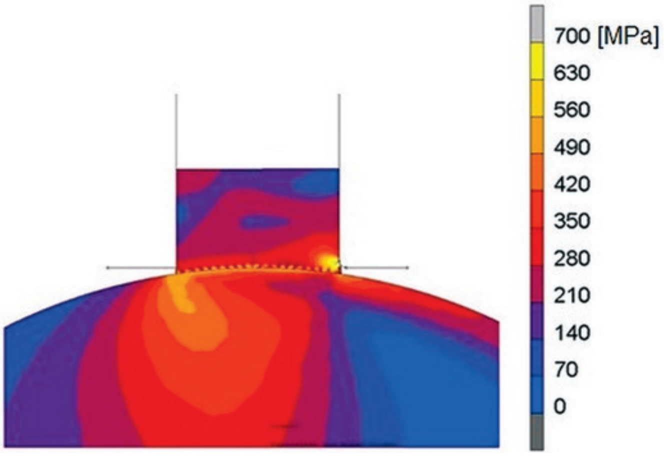


Fig.7. Stress distribution in created model

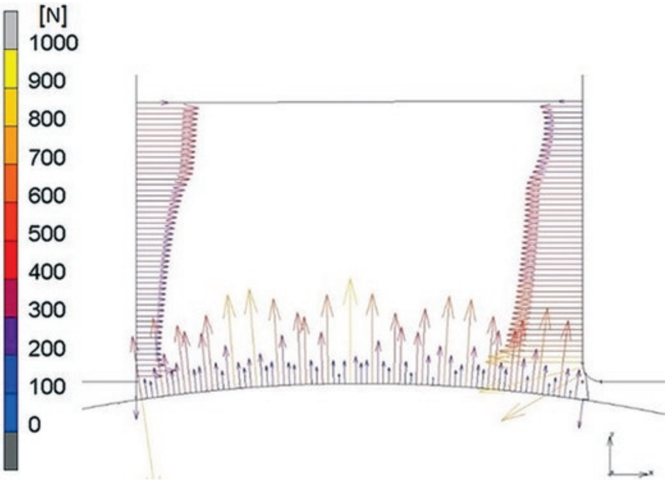


Fig. 8. Distribution of normal forces resulting from contact with counter-sample

The largest stresses in the disc occur immediately under the surface of the sample. The stress concentration (reaching 600 MPa) on the left side in the figure is the result of the superposition of the counter-sample loading force and the shaft torque, which seems to confirm the authors' theoretical analyses.

Moreover, the normal forces occurring on the inner walls of the recipient were determined for design purposes. The distribution of the forces is as shown in Fig. 8.

The simulation has shown that the right lower part of the recipient (where, consistently with the direction of rotation) the outflow of the counter-sample will take place) is most heavily loaded. Because of the action of the great forces (reaching 1000 N) combined with the relatively quick shifting of the material the wear of the recipient in this place is highly probable. This means that it is necessary to install easily replaceable dies at the exit from the container.

Then the torque in the central element, needed to make the shaft with the disc rotate was determined (Fig. 9).

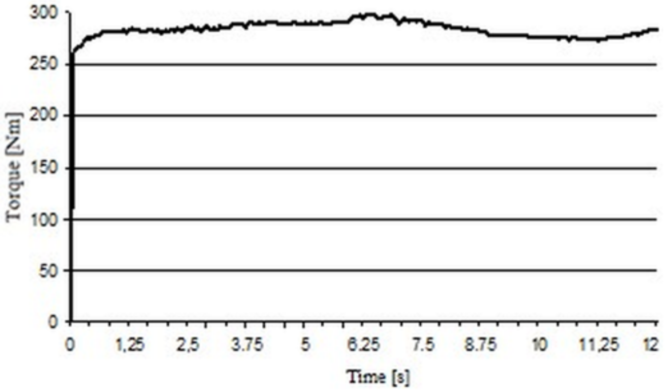


Fig. 9. Torque-time dependence in z direction z for central element

As it appears from the diagram, for a disc 80 mm in diameter and a coefficient of friction between the elements amounting to 0.3, the torque needed to make the disc rotate amounts to about 300 Nm. Another major parameter which needs to be determined is the degree of heat exchange and the temperature of the samples. In the model the temperature at the twelve second of the simulation assumes the distribution shown in Fig. 10.

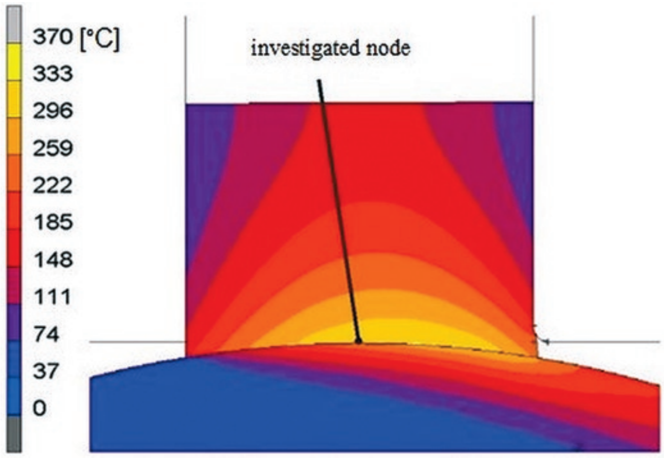


Fig. 10. Temperature distribution with marked investigated node

The temperature on the surface of the disc quickly reaches over 300°C. This means that the disc does not need to be heated and it may even be necessary to cool it.

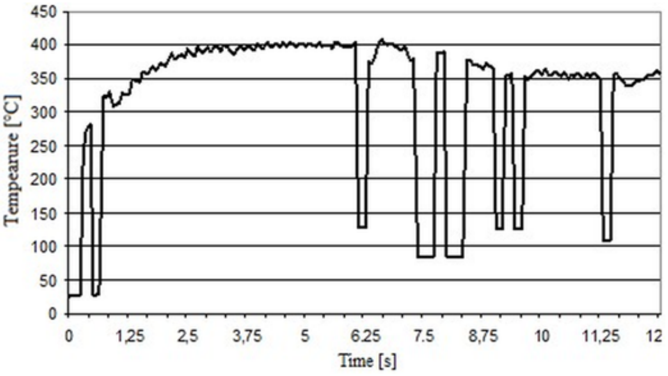


Fig. 11. Temperature-time dependence for node on counter-sample surface

Figure 11 shows the variation in temperature over time for a selected node on the counter-sample surface. The surface of the pressure exerting element quickly reaches a temperature of 350–400°C, which may necessitate additional cooling of the counter-sample. The characteristic minimum extrema in the diagram are caused by program errors connected with finite element mesh generation and do not occur in reality.

4. Test stand concept and design

When selecting test stand parameters one should take into account not only the kind and shape of the sample and those of the counter-sample, but also many other factors, such as the magnitude, direction and character of the load, having a bearing on the amount of wear not merely through the applied pressure. When designing a tribometer one should also check if the load in the physical model is constant and if it is not, whether this affects the tests. At the design stage, different ways of exerting pressure, i.e. by elastic elements, weights with a lever mechanism, or actuators, were considered [4].

Heat, the way it is supplied to the system and its exchange between the sample and the counter-sample are not less important considerations. Temperature may have a key influence on the geometry of the elements and the value of the friction coefficient and in the case of forging one should not forget the considerable effect of temperature on the behaviour of the material. When designing the test stand, both the heating and cooling of the elements and several ways of effecting them (from simple flame heating to induction heating and bath cooling, spray cooling and air-nozzle cooling) were considered [7]. Other factors, which are often neglected, include the kind and amount of lubricating medium and the effect of the environment and the surroundings on the wear of the elements and the quality of the test. The lubricating medium may affect other factors, i.e. the way the elements displace, the distribution of the load and the dissipation of heat. The environment is understood as chemical reactions affecting the wear of the elements through corrosion, and any disturbances in heat removal [23].

On the basis of the survey of the possible test-stand concepts, verified by numerical modelling, a prototype pin-on-ring stand for testing abrasive wear under high pressures was built (Fig. 12) [25]. The pin-on-ring configuration was chosen because of the possibility of applying heavy loads (which occur during forging), sample material savings in the case of the ring shape and the simplest to effect heating and cooling. Moreover, this configuration, as one of the very few, offers the possibility of bringing the counter-sample to the plastic state.

The main (tested) stand components are: rotating disc (1) 80 mm in diameter, made of WCL-type tool material, mounted on shaft (2) on both sides supported by oblique bearings (3) in split bearing retainers, via clutch (9) connected to a motor reducer (Fig. 12a). A counter-sample (made of QS19-20 forging material), fixed in 12×4×85 mm

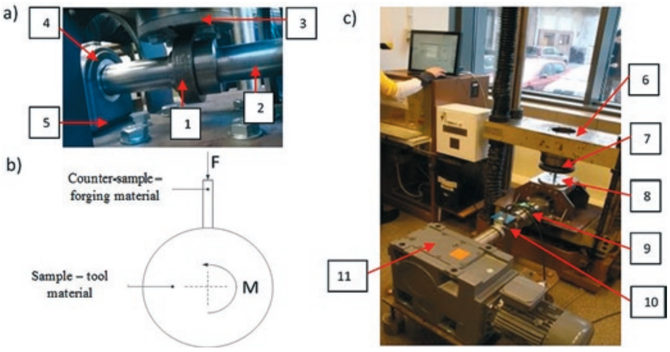


Fig. 12. a)Front view, rotating sample (WCL steel) disc(1) mounted on shaft(2) supported by bearings(4) on both sides, replaceable die(3), force sensor(5), b) schematic representation of stand, c) main view of constructed stand:Tiratest machine beam (6), punch (7), container(8), clutch(9), torque meter (10), motor reducer (11).

cuboidal recipient (8), pushed by punch (7), is pressed against the rotating disc. The pressure is exerted by TIRAtest 2300 strength tester (6). The load reaches 24 kN which is to ensure surface stress of 500 MPa. Thanks to the use of two CL-20U force sensor (5) with a measuring range of up to 25 kN under one of the bearing retainers together with DFM-30 torque meter (10) with a measuring range of up to 2000 Nm the friction coefficient can be indirectly measured in real time. The friction coefficient is calculated from a ratio of the horizontal friction force read from the torque meter to the vertical pressure force read from the sensors mounted in the supports. Thanks to a Kubler encoder 8.3651 the rotational speed of the sample can be measured and the variation in the basic quantities can be related to the sliding distance. A GKS09-3M VBR 100C12 conical-cylindrical motor reducer with MHEMAXX 100-12C1 three-phase motor (11), having an output torque of 2000 Nm (Fig. 12c), is responsible for the rotation of the disc. The latter can rotate with a speed of up to 10.25 rpm. The rotation is controlled by an ESMD302L4TXA inverter. The main specifications of the drive are shown in Table 1.

Table 1. Main specifications of motor reducer

rated power P_n	2.2 kW
rated torque M_n	14.5 Nm
rated speed n_1	1445 rpm
gear ratio i	140.921
output torque M_w	1946 Nm
output speed n_2	10.31 rpm

The wear is measured by weighing the disc on a laboratory balance before and after the test to determine the change in its mass and by scanning the geometry of the disc with an optical scanner to determine the change in its volume. The distribution of temperature is determined using a thermal imaging camera (Fig. 13).

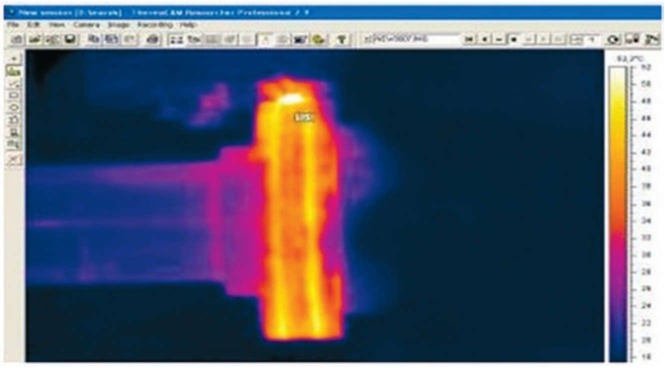


Fig. 13.Thermogram of sample

The test stand is coupled with the advanced measuring system UNITEST with a CompactRio computer with ten-twenty modules and channels whereby many sensors and measuring devices can be connected and full control can be ensured. The UNITEST system is equipped with two applications: one enabling system control, on-line measurement and results archiving and the other offering a wide spectrum of analyses of the recorded sensor signals.

5. Preliminary tests

Preliminary tests were carried out to verify the constructed prototype test stand. The tests consisted in comparing the actual wear of a selected forging tool with the wear of the disc during the test. For this purpose the bottom die used in the second operation of the hot forging of a spur gear was selected (Fig. 14b). The industrial forging process was numerically modelled to determine the path of friction, i.e. the displacement of the material being deformed relative to a selected point on the surface of the die. In the die profile an area on the bridge where the most intensive abrasive wear of the tool occurs, but where there is no influence of other mechanisms connected with the high temperature of the forging material (Fig. 14a), was selected. A simulation showed that the maximum pressures in this area amounted to about 215 MPa.

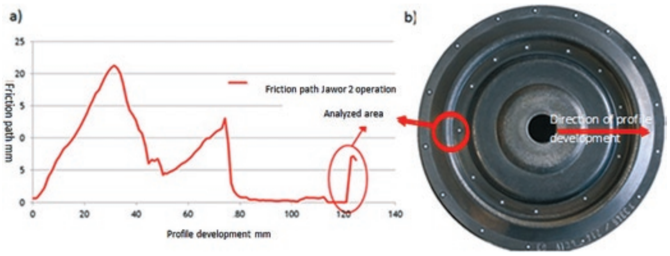


Fig. 14. a) Friction path versus tool surface profile development determined using FEM, b) worn out die with marked direction of profile development

Tests without any lubricating medium (to increase the rate of wear and shorten the test) were carried out on the test stand. No significant influence of environmental factors on the course of the forging processes was observed. During the laboratory test the counter-sample was pressed against a sample made of the tool material (steel WLC) with a constant force of about 10 kN, which for an average contact area resulted in a pressure of about 220 MPa corresponding to the actual load acting on this area of the die. Such a duration of the test was adopted that the total sliding distance was close to the sliding distance covered by the material after the total number of forged pieces.

Table 2. Main test parameters.

	Sample	Die (selected area)
Sliding distance for single forging [mm]	12	7.5
Test duration [min/number of forgings]	240/1200	6.3/1900
Pressure [MPa]	220	215
Total distance [mm]	14400	14250
Wear value [mm]	0.95	0.9
Wear coefficient k from Archard model	$5.1*10^{4}$	$4.99*10^{4}$
Coefficient of friction	0.48	0.35 (adopted in FE analysis)

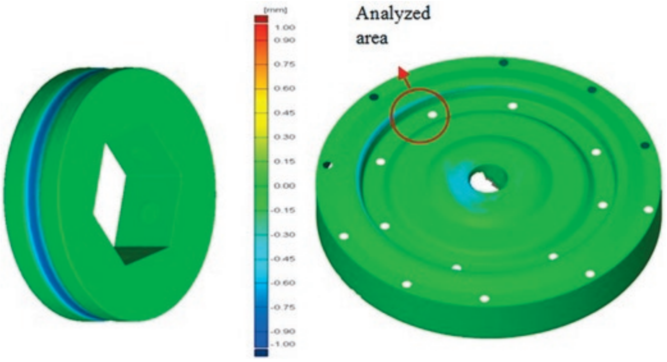


Fig. 15. Scan results: a) sample after 240 min of testing, b) second forging operation bottom die after 1900 forgings

The test total distance was determined on the basis of the average rotational speed of 5 rpm (one full rotation took about 12 seconds, i.e. the same amount of time which the forging cycle takes in industrial conditions) and the dimensions of the sample.Table 2 shows the main test parameters and their calculated values.

The above results indicate that the wear of the disc and that of the tool are similar in the selected area, amounting to about 1 mm (Fig. 15 a and b). As opposed to the die insert, the wear on the disc is uniform. However, because of the lack of a lubricating medium in the experiment, for theoretically the same number of cycles the friction distance and probably the wear would be by one third greater in the experiment than in the industrial process. The values of parameter k determined from the Archard model were similar (the small differences could be due to the slightly different pressure and sliding distance values). The (average) friction coefficient for the sliding pair on the test stand (without a lubricant) was determined on the basis of the measured pressures and the torque force. In the industrial forging process the coefficient of friction will be different (than the one adopted in FE analysis). Because of the high pressures, the lubricating film will tend to break, but on the other hand, at elevated temperatures the coefficient of friction for both the tool and the forging will decrease. All these differences in conditions (contact temperature and the friction coefficient) between the experiment and the industrial process are taken into account by parameter k determined from the Archard model. The results have shown that the test stand is suitable for laboratory tests of the abrasive wear of materials for die inserts under high pressures. In the next stage of the research tests will be carried out at different pressure and sliding distance values in order to further verify and optimize the test stand.

6. Conclusions

The designed and built prototype test stand can be used to measure many essential physical quantities (identical with the ones occurring in industrial forging processes) in real time, ensuring full control over the studied process and in-depth analyses of the degradation of forging tools through abrasive wear under high pressures.

1. The created numerical model of the constructed tribometer made it possible to determine only the basic test parameters because of the limited capabilities of the finite element method. In order to accurately determine some of the factors involved a large number of verifying tests need to be carried out on the test stand. The preliminary tests have shown the model assumptions to be valid.
2. At this moment many factors and test stand components still need to be checked and ultimately verified. There is a high probability of adhesive bonding between the sample and the counter-sample and insufficient disc and counter-sample heating and it may be necessary to introduce active cooling. These and other aspects were omitted at this stage of the research, but they are to be investigated as part of further tests and studies.
3. In the future an active system of heat supply to the test stand, with thermocouples for real time temperature measurement, is to be created. Moreover, the numerical model of the test stand will be improved so that together with experimental measurements it will make it possible to determine material coefficients by means of selected mathematical models.
4. It will be possible to use the abrasive wear test stand to investigate the resistance of the surface coating of forging tools depending on different surface engineering methods (nitriding, sub-zero treatment, the application of hybrid layers, or other, e.g. bead blasting, etc.). The test stand will also be used to study the abrasive wear of other pairs of materials [5, 21] and for other scientific and educational purposes.

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