Journal
of Achievements in Materials and Manufacturing Engineering
VOLUME 43
ISSUE 1
November
2010

Forging tools modification with graphene-like solid lubricant nanoparticles

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Received 23.09.2010; published in revised form 01.11.2010

Analysis and modelling

ABSTRACT

Purpose: Working conditions of forging tools have become severer with the years. To increase their wear and heat resistance the surface of the tool is coated by CVD/PVD methods. Relatively high friction coefficient of coatings results in high friction losses and low durability of coating films due to high shear stress at tool–workpiece interface. That is why improved self-lubricating system should be developed. Combination of modern coatings (nanostructured, nanolayers, nanocomposites, etc.) with self-lubricating tool design and application of solid lubricant MoS2 and WS2 graphene-like nanoparticles is very promising and effective way to solve existing forging tool problems.

Design/methodology/approach: Laser micro-machining technology was applied to fabricate the network of micro-channels which serve like reservoirs for encapsulation of solid lubricant nanoparticles into tool body. Wide ranges of tribological tests on T-10 ball-on-disc tester were carried out to define the optimal geometry and network configuration of micro-channels ensuring generation of a lubricious transfer film at the tribological contact.

Findings: As a result, increased tool durability and high forging precision could be reached. Analysis of failure mechanisms for different forging tools were carried out. It was found that one of the important reasons of tool wear is a high friction coefficient between treated material and the tool. Graphene-like nanoparticles of MoS2 solid lubricant were produced by Rolling Cleavage Technology. Paper consist SEM, TEM and AFM analysis of applied coatings and solid lubricant particles.

Research limitations/implications: The continuous supply to a sliding area of nanoparticles will be for the first time applied to decrease high shear stress at an interface between forging tool and treated material.The next research step will be the transfer of the developed methods of self-lubrication from samples to real cold forging tools.

Originality/value: Analysis of failure mechanisms for different forging tools were carried out.

Keywords: Forging tools; PVD/CVD coatings; Graphene-like nanoparticles; Solid lubricants; Laser micro-machining

Reference to this paper should be given in the following way:
V. Leshchynsky, M. Ignatiev, H. Wiśniewska-Weinert, J. Borowski, T. Rybak, I. Dobrovnik, Forging tools modification with graphene-like solid lubricant nanoparticles, Journal of Achievements in Materials and Manufacturing Engineering 43/1 (2010) 341-348.

1. Introduction

Working conditions [1] of forging tools have become severer with the years and it has been required for forging tools used to this end to increase the hardness, wear resistance and heat resistance. A typical shape of the tools exhibits an assembling in which a Cemented Carbides (CC) or High Speed Steel Insert (HSS) mounted into the casing. In these CC and HSS tools, the surface of the insert is ordinarily coated by a CVD/PVD methods [2].

Many factors influence component accuracy in the form of systematic and random dimensional errors in the cold forming processes. There are four important factors that affect the component systematic errors, i.e., imperfection of the material plastic flow, elastic deformation of the press system, elastic–plastic deformation and thermal behaviour of the tools and component [3]. The later two factors are the most important and relevant to process and tool design of formed components. These effects become evident during different stages in the cold forming process, typically including forming, unloading, ejection and cooling. The repetitive production cycles in the industrial practice will bring further issues of dimensional changes due to tool wear and temperature increase developed over time. Thus, the tool wear resistance is one of the most important requirements.

Generally, forging tools are required to be excellent in both of wear resistance and toughness. In the case of the coated inserts, however, there is well known that if the thickness of the hard coating is increased so as to improve the wear resistance, the toughness is deteriorated. From the other side a relatively high friction coefficient of coatings results in high friction losses and low durability of coating films due to high shear stress at an interface [4].

Wear phenomenon is usually synonymous with loss of matter. The main area of wear is the contact between the asperities present on a roughness profile. The removal of these asperities occurs according to various mechanisms such as abrasion, adhesion or fatigue contact, and depends on numerous parameters such as hardness of the surface, roughness, temperatures and lubrication [4]. Recent observations carried out on different tools in cold forging, show that all these wear mechanisms do occur at the same time on an each surface of interface [5]. The lubrication of cold forging processes depends on many parameters such as materials of tools and work-pieces, surface roughness, temperature, contact pressure and sliding velocity. The main role of the lubricant is to prevent seizure and to preserve as long as possible the integrity of tools and work-pieces by reducing the friction stresses [6]. Low friction coatings such as phosphate stearate and oil lubrication are being applied together to decrease the friction coefficient and preserve the above mentioned integrity. However, the high normal and shear stresses at the interface result in failure of both the phosphate stearate coatings and oil lubricant films. Thus the application of superior solid lubricants for these purposes is of great importance.

Lubricants play a key role in cold forging as they reduce the high frictional forces occurring at the tool–workpiece interface. Improved lubrication systems are needed, because they will help make net-shape production cost effective and affordable.

It was shown that MoS2 and WS2 nanoparticles have unique tribological properties: anomalous low friction coefficient (<0.03) and low wear rate [7]. The continuous supply to a sliding area of nanoparticles with superior lubricating properties will be for the first time applied to solve existing wear problems of forging tools. Encapsulation of solid lubricant fullerene-like nanoparticles (MoS2/WS2) into tool body (special reservoirs in certain areas of tool surfaces), their slow release to the surface is expected to alleviate both friction losses and wear, while assuring the mechanical integrity of the nanocomposite coatings for prolonged periods [8]. Friction forces and surface reactions with the environment are used to generate a lubricious transfer film at the tribological contact.

Combination of modern coating technologies with self-lubricating tool design and application of solid lubricant nanoparticles could be very promising and effective way to solve existing forging tool problems.

2. Experimental results

2.1. Worn tool analysis

Real backward extrusion punches applied by J-VST company (Czech Republic) are chosen for the wear analysis. The tool wear was studied after certain number of operation cycles using SEM images. As a result the dominating wear was defined. The typical virgin punch image of polished surface is shown on Figure 1a. Results reveal the presence of regular scratches on the surface which come from machining of the tool. These scratches are perpendicular to the main direction of metal flow during backward extrusion. Analysis of the worn-out tool surface after each 30 000-35 000 operation cycles revealed the main failure mechanisms which are typical for cold forging technology [5,6]: wear; chipping, cracking, galling (Figure 2 – 5). The first analyzed tool was taken after production of 35 000 pieces (Figure 2b). Both images show chipping of the surface layers. This chipping is localized at a maximum contact pressure zone of the backward extrusion punch and starts from scratches. Consequently, similar to [5], the cracks appear on these favorable zones and propagate parallel to the traces of machining that results in removing a hard surface layer and creation of cavities with a sharp edges. Some wear debris particles may be trapped into these cavities (Figure 2b).

A further enlarging of the cavities and creation of new ones proceed during the following exploitation cycle (65000 pieces). The accumulation of the wear particles and steel adhesion at the edges of the cavity is seen (Figure 3). The chipping of the punch surface layer implies an increase of shear stresses and friction coefficient due to adhesion and micro-welding of work-piece material [5].

The last analyzed punches are taken after a stop of production of 100 000 pieces. Abrasion tracks, scratches and intensive adhesion phenomena appeared on the surface (Figure 4). All defects are more numerous and deeper than for the preceding worn punches.

The results reveal the main degradation, which undergoes the backward extrusion tool is the chipping of surface layer and adhesion phenomena at the damaged areas. The machining scratches are very harmful factor for the tool lifetime. Their negative influence on the tool wear may be diminished by decrease of shear stresses and, consequently, friction coefficient due to change of friction regime. It is quite important at the initial stages of tool exploitation. It is clearly seen the only use of both classical phosphate lubricant coating on work-pieces and oil lubrication do not solve the problem. The creation of lubricant films withstanding high contact stresses at the piece-tool interface is of great importance.

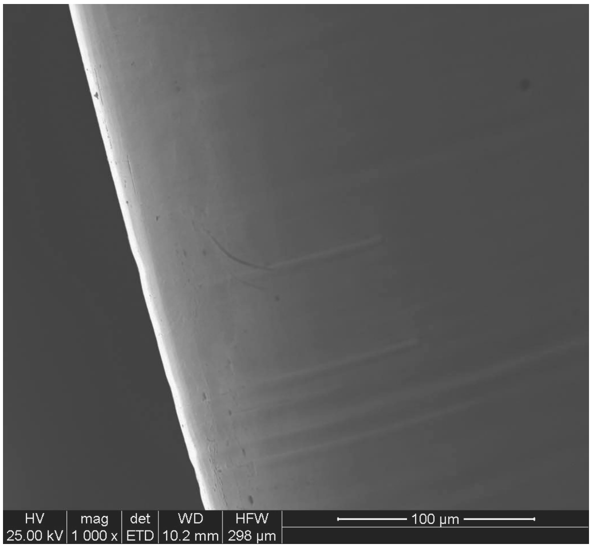
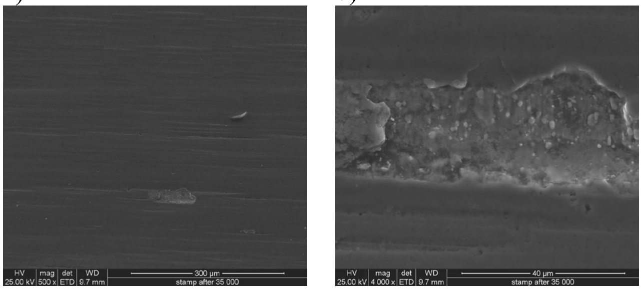


Fig. 1. SEM topography of punches of backward extrusion virgin surface


a)

b)

Fig. 2 SEM topography of the worn punches of backward extrusion after 35000 cycles

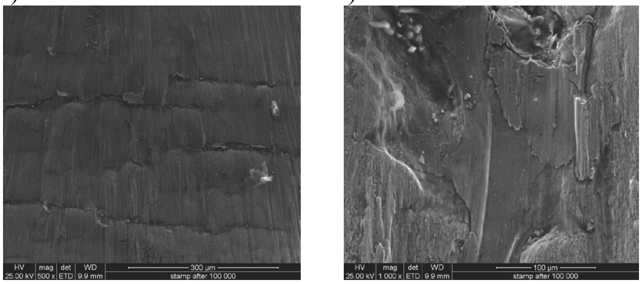

a)

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Fig. 4. SEM topography of the worn punches of backward extrusion after 100000 cycles

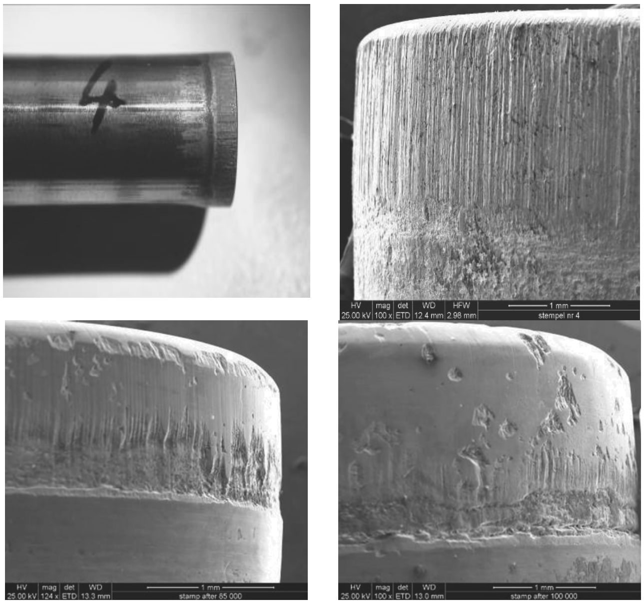

Fig. 5. SEM images of worn out working surface of forging tools

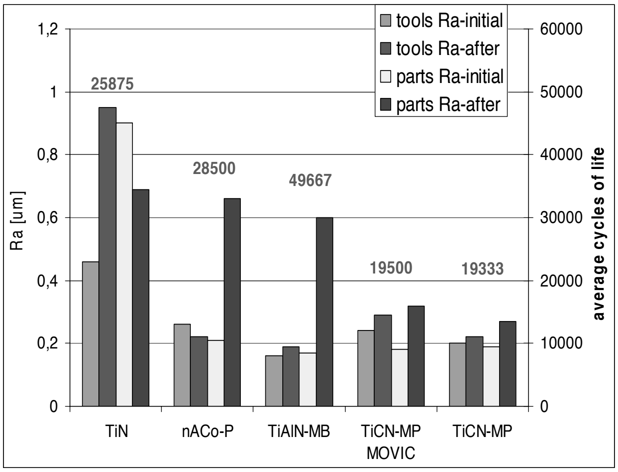

Fig. 6. Results of wear study of real backward extrusion punches

2.2. Coatings

Various types of coatings were deposited on tools surface by Gazela company: both traditional TiN coating and TiAlN and TiCN based nanocomposites which are intended for high performance tools [9]. The wear of coated tools was studied after each 20 000 operation cycles using SEM images and measurements of surface roughness before and after industrial tests (Figure 6). As a result an average cycle of life was defined for each type of coating and the most suitable coating candidate was chosen: TiAlN-MB coating which is characterised by high hardness (35 GPa) and high usage temperature (800°C) [9]. Nevertheless, this coating has relatively high (0.7) friction coefficient (Figure 9) and application of solid lubricants could lead to additional improvement of coated tools wear resistance.

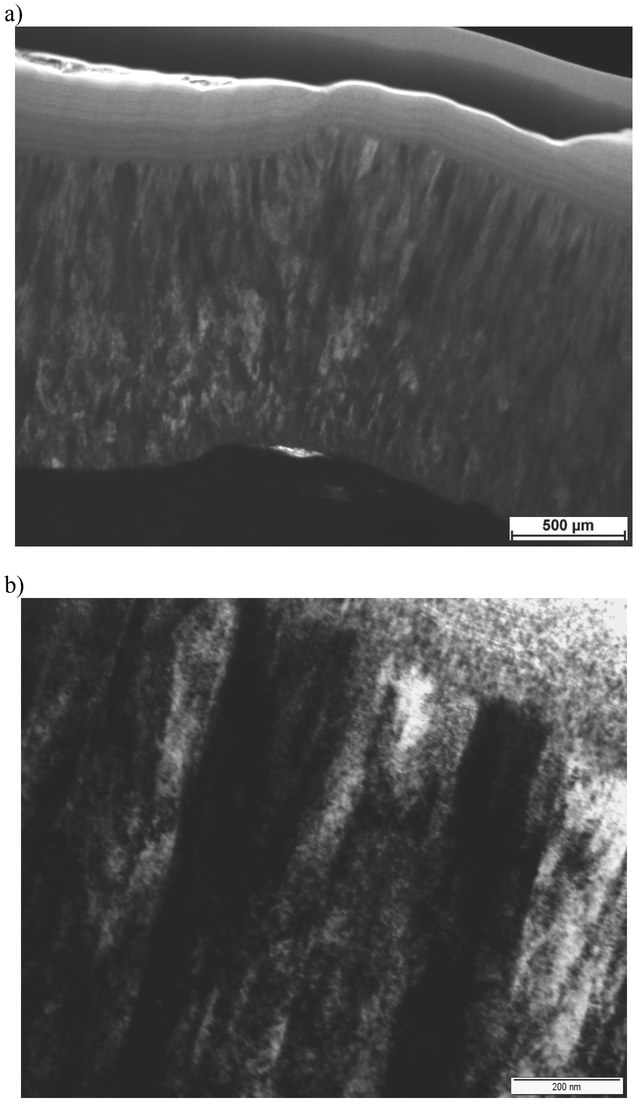

Fig. 7. HRTEM image of TiCN-NP-MOVIC coating on HS 6-5-2 steel surface: hard coating column structure and thin MoS2 top, a) b) transition zone

PLATIT Company has developed special double lubrication coating on hard basis for punching and forming tools: STARVIC®= TiCN-MP+MOVIC®, where MOVIC® is lubricating coating on MoS2 basis [http://platit.com/coatings/coating-types/optionalcoatings/starvic]. Gazela Company, like an official representative of PLATIT in Slovenia, has an experience in deposition of such type of coatings. TiCN-NP-MOVIC® coating (Figure 7) deposited by Gazela consists of TiCN layer with 3.5µm thickness and column structure and top layer with <0.5µm thickness (in some cases the thickness of top layer is 2-3 nm only). The linear microanalysis shows that the top layer is enriched with Mo and S (Figure 8) with concentrations which are close to stoichiometric composition of MoS2. It provides a good perspective to decrease friction and wear in considered forging tool application.

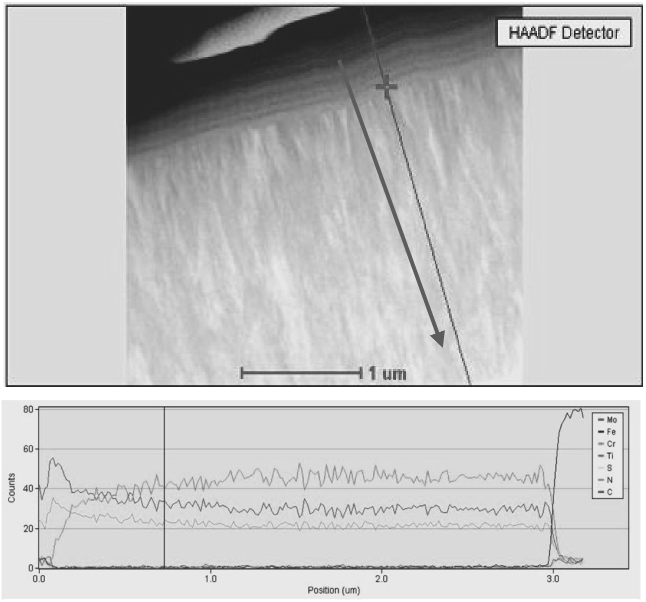

Fig. 8 The distribution of elements (Mo,Fe,Ti,S,N,C) on depth for TiCN-NP-MOVIC coating

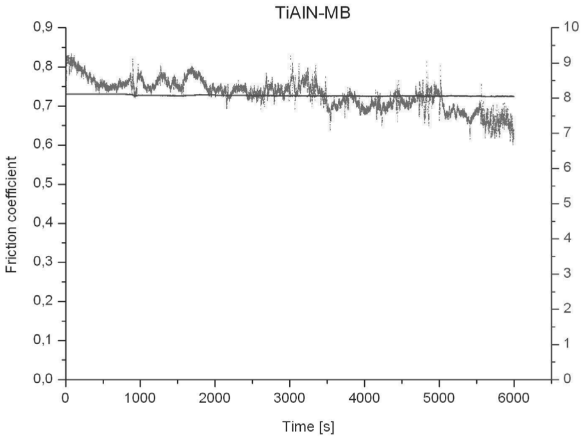

Fig. 9. Friction coefficient of ball-on-disc test of disk samples with TiAlN-MB coating

Friction tests results for TiAlN-MB coating (fig. 9)reveals high friction coefficient (0,7). At the beginning of the test its value exceeds 0,7 and falls insignificantly under 0,65 after 5000 cycles. Relatively high friction coefficient shows poor sliding behavior of the coating.

2.3. Nanoparticles

MoS2 particles of 0.1-1µm size produced of natural powder by Rolling Cleavage Technology (RCT) with home made machine [8] which allowed to obtain the graphene-like sheets in the powder mixture.

Scanning Probe Microscope (SPM) Solver Pro and the Stylus Profilometer (SP) were used to define the particle dimensions and shape (Figure 10). It was shown that MoS2 nanoparticles produced by RCT have flake-like shape. Each individual flake has layered structure. The thickness of individual graphene-like sheet is near 19 nm.

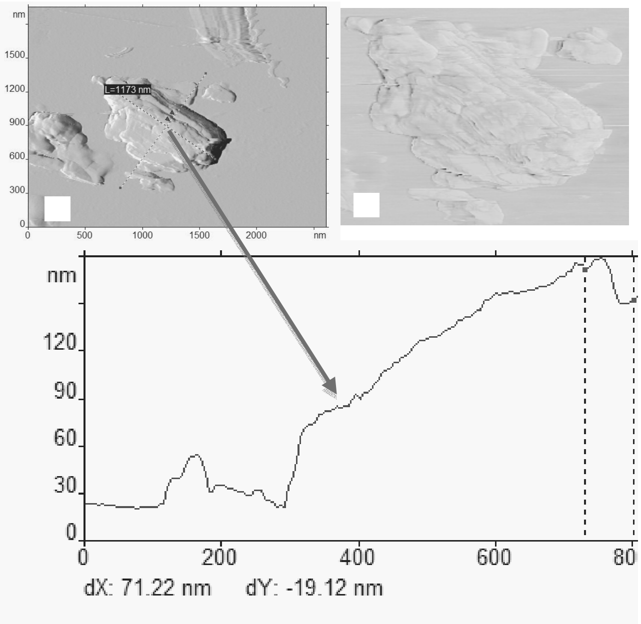

Fig. 10. MoS2 micro-flake. Left-measurement of thickness (19 nm) of single grapheme-like sheet; Right- micro-flake magnified image

The MoS2 particle mixture was incorporated into micro-reservoirs fabricated by laser micromachining on the tool working surface and on the disk samples. The tribological properties were studied with the help of ball-on-disk tester.

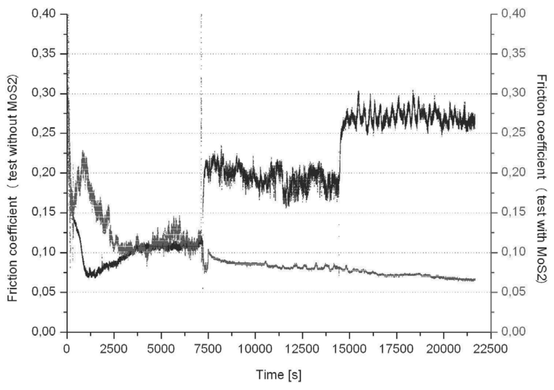

Fig. 11 Influence of MoS2 nanoparticles application into friction coefficient value for nACoP coating

The presence of MoS2 graphene-like nanoparticles on friction surface of coated disks provides much better friction behavior of the coating (Fig. 11). The friction coefficient various from 0.07 (MoS2 lubrication) to 0.27 (dry friction) at steady stage.

2.4. Laser micro-machining

To make reservoirs for solid lubricant nanoparticles on the tool surface laser engraving was chosen like a method allowing to tune the accurate microchannels geometry (depth, diameter, width and shape). High Energy, Pulsed Ytterbium Fiber Lasers has the following parameters: Wavelength-1.06 microns; Average power-10-50 W; Pulse frequency-20-200 kHz; Pulse energy-2 mJ; Pulse duration-80-500 ns; Focal spot-20 microns. These parameters allows formation of accurate micro-channel network with the following typical dimensions: width of 20-50 microns, and depth of 20 - 25 microns (Figure 12). The MoS2 nanoparticle mixture was incorporated into microreservoirs on the tool surface (Figure 13 and 14).

Four types of micro-channels network were examined to define it's optimal configuration (various radial and rectangular structures) ensuring generating a lubricious transfer film at the tribological contact resulting from slow release of solid lubricant nanoparticles from micro-channels (Table1).

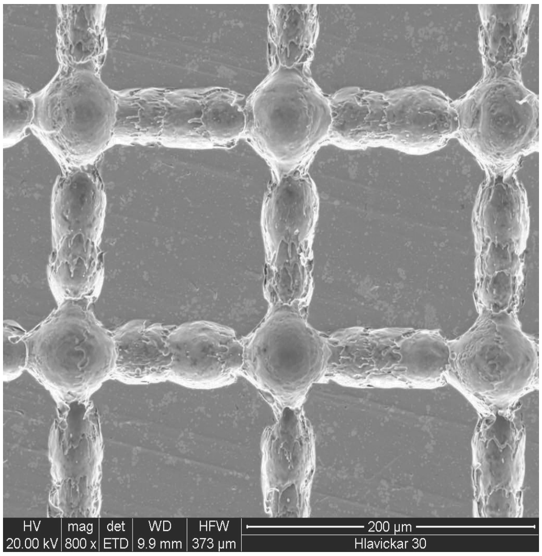

Fig. 12. SEM image of micro-channels network

Table 1.
Types of micro-dimple network on the disc samples

N	Type of pattern	Diameter, µm	Distance, µm	Depth, µm	Width, µm
1	Without laser engraving	-	-	-	-
2	Dimple pattern-2	50	300	5	
3	Dimple pattern-3	50	150	10	
4	Radial network-4		150	5	50
5	Rectangular network-5		150	7	50

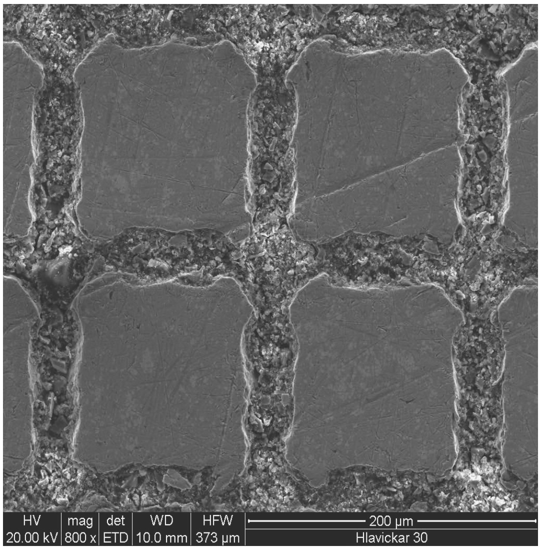

Fig. 13. SEM image of laser micro-channels with incorporated graphene-like MoS2 nanoparticles

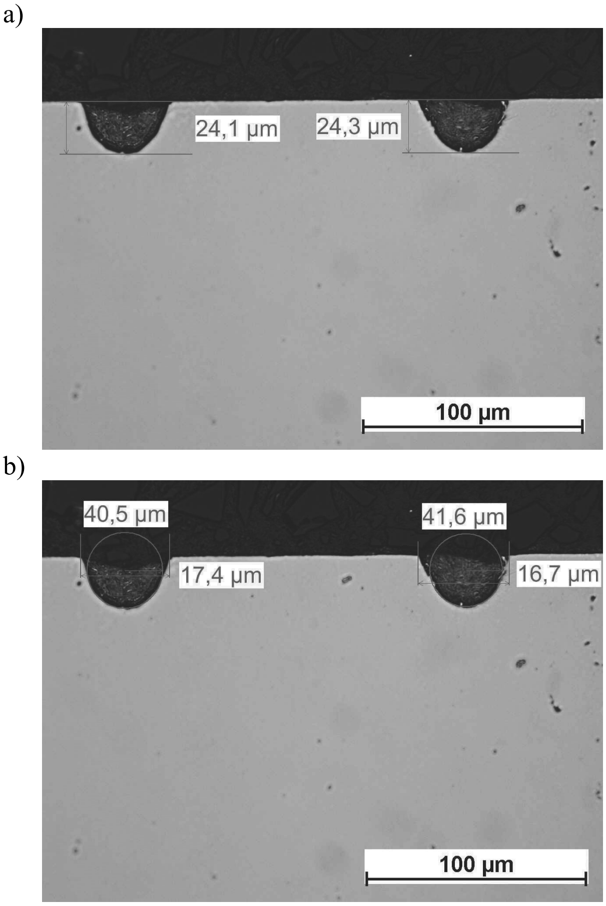

Fig. 14. Cross section of laser micro-channels surface

2.5. Self lubricating effect examination

The effect of MoS2 nanoparticle solid lubrication was studied using ball-on-disc tests with tester T-10 at normal loads 6-10N and rotation speed 200rpm. The disc samples with diameter of 40mm and the balls of diameter of 10mm are made of tool steel SW7 with hardness of 62-63HRC and. The friction coefficient and wear parameter were defined based on measurement of a friction force and ball weight.

The effect of a tool self-lubrication with solid lubricant nanoparticles is shown on SEM image of tested disc with dimples filled by MoS2 nano- and microparticle mixture (Figure 15, arrow b). The ball-on-disc test was made without oil. The solid lubrication was performed by solid lubricant film generation due to presence of solid lubricant nanoparticles in microreservoirs [7,8]. The wear track of approximately 300microns width is seen to have only the first small indication of wear scratches after 10 000 cycles running.

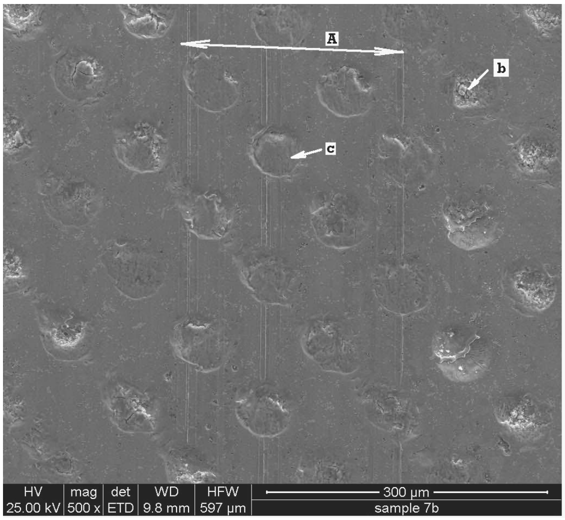

Fig. 17. Friction coefficient of surface modified with MoS2 nanoparticles incorporated into micro-channels (network configuration of type 4)

The wear debris originated from the ball are being collected in the microreservoirs during the test (arrow c), and it is mixed with solid lubricant particles. Results of the test show that self-lubricating graphene-like nanoparticles alleviate friction and decrease wear.

The friction behavior of the disc with micro-dimples of type 2 (Table 1) is shown in Figure 16. A running stage for this test is about 1500 cycles following by the friction coefficient stabilization at the value of about 0.06

The results of friction test of surface modified with MoS2 nanoparticles incorporated into micro-channels (network configuration of micro-channels of type 4) reveal the absence of the running period, and the stable friction coefficient of 0.05-0.08 is observed from the first cycles (Figure 17). It confirms the favorable role of micro-channels in permanent supplying of solid lubricant nanoparticles to sliding interface [8].

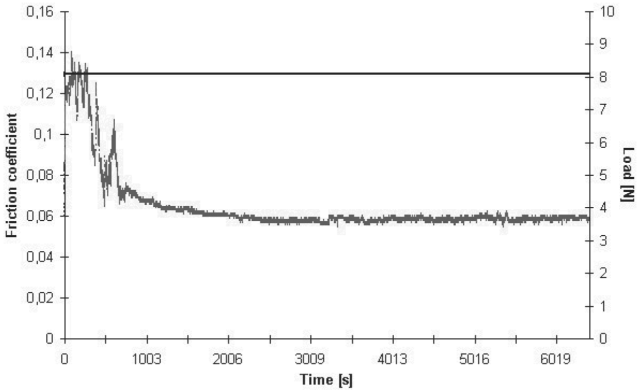

Fig. 16. Friction coefficient at ball-on-disc test of samples with micro-channels of type 2 (Table 1) filled with nanoparticles

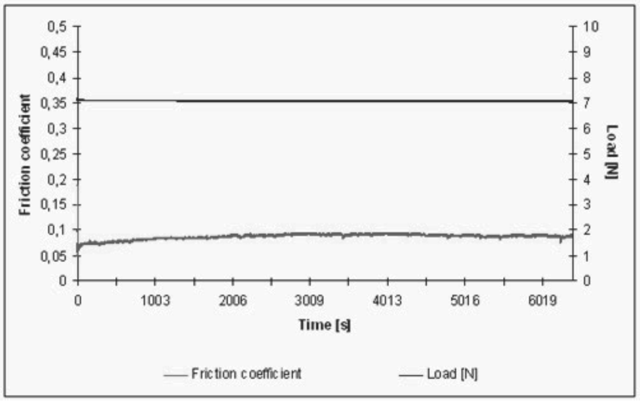

Fig. 17. Friction coefficient of surface modified with MoS2 nanoparticles incorporated into micro-channels (network configuration of type 4)

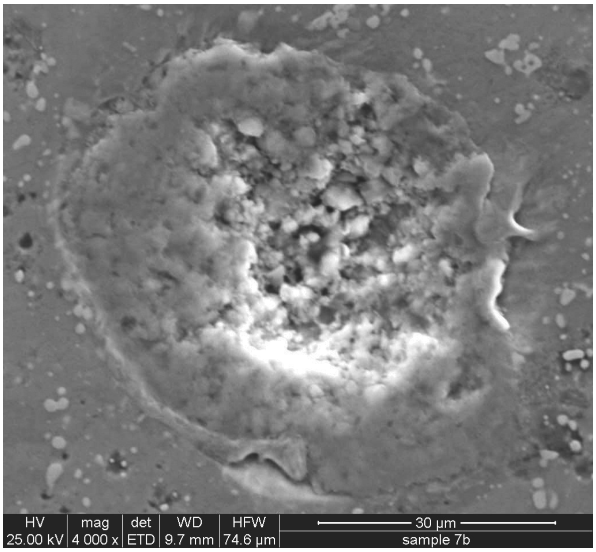

Figure 18. SEM image of micro-dimple filled with graphene-like MOS2 nanoparticles

The main role in this mechanism of boundary lubrication belongs to the process of particle circulation in the microreservoir-sliding interface system. The network configuration of micro-channels of types 4 and 5 seems to be optimal from the permanent generation of solid lubricant film. The effect of micro-dimple filling with solid lubricant and wear product particles is seen on SEM image of micro-dimple on Figure 18.

The dense area observed on the periphery of the dimple seems to contain less solid lubricant particles (grey contrast) then bright core area which contains more MoS2.

2.6. Self lubricating effect examination

The Figure 19 shows the ball wear parameter comparison for different types of micro-channel network on the discs.

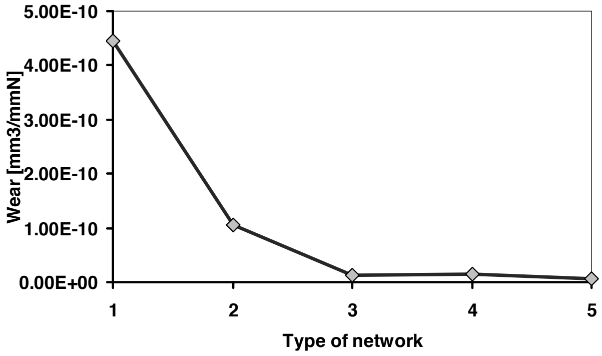

Fig. 19. Comparison of the wear parameters for different types of the micro-channel network (designations of Table 1)

The results reveal that MoS2 powder lubrication (type 1, Table1) results in maximal wear as compared with other lubrication systems using the microreservoirs for lubricant particles storage and permanent supply (types 2-5, Table 1). The geometry of micro-channel network greatly influences the wear parameters because the generation of solid lubricant film depends on the flow of solid lubricant particles at the sliding interface [8]. Utilization of this effect will allow to optimize the boundary lubrication regime, and lifetime of a friction pair.

Simple evaluation - using ball-on-disc tests at the normal loads 5-8N allows to achieve the contact normal stresses in the range 800-2000 Mpa that is equal for real contact stresses of forging operations. At the same time the sliding velocities at these tests (400 mm/s) were much higher then the metal flow rate during the forging operations. Thus, the wear behavior of the ball made of tool steel may be accepted as the wear criteria of tool [9] for the case of solid lubrication. Analysis of the data of Figure 19 clearly shows the self-lubricating effect due to nanoparticle slow release from the microreservoirs to sliding interface. The further work will be made to define this effect on real forging tool lifetime.

3. Conclusions

In the frame of the present research the following main results have been reached:

- Analysis of failure mechanisms for different forging tools was carried out. It was found that one of the important reasons of tool wear is a high friction coefficient between treated material and the tool
- graphene-like nanoparticles of MoS2 solid lubricant were produced by Rolling Cleavage Technology. It was found that RCT nanoparticles have layered graphene-like structure.
- Laser micro-machining technology was applied to fabricated the network of micro-channels which serve like a reservoirs for the storage of solid lubricant graphene-like nanoparticles in the tool surface.
- It was shown that MoS2 graphene-like nanoparticles have unique tribological properties: anomalous low friction coefficient (0.05-0.08) and low wear rate. The continuous supply to a sliding area of nanoparticles with superior lubricating properties will be for the first time applied to decrease high shear stress at an interface between forging tool and treated material.

The next research step will be the transfer of the developed methods of self-lubrication from samples to real cold forging tools.

Acknowledgements

The work has been carried out in the frame of EUROSTARS Project “New generation of forging tools” (NEGFORT). Authors are grateful to Dipl. Ing. Bohumil Jedovnicky (J-VST) for analysis of real forging tools wear problems and to research team of Instytut Obróbki Plastycznej for samples preparation and study.

References

[1] W.M. Smith, Surface Materials Processing. Second Edition, Backmann Verlag, Berlin–London–Paris–Warsaw, 2006.

[2] E.C. Lee, C.Y. Nian, Y.S. Tarng, Design of a materials processing technologies, Archives of Materials Science and Engineering 28 (2007) 48-56.

[3] H. Long, Quantitative evaluation of dimensional errors of formed components in cold backward cup extrusion Journal of Materials Processing Technology 177 (2006) 591-595.

[4] K. Holmberg, A. Matthews, H. Ronkainen, Coatings tribology-contact mechanisms and surface design, Tribology International 31/1–3 (1998) 107-120.

[5] M. Dubar, A. Dubois, L. Dubar, Wear analysis of tools in cold forging: PVD versus CVD TiN coatings, Wear 259 (2005) 1109-1116.

[6] M. Dubar, A. Dubois, L. Dubar, Wear analysis of tools in cold forging: PVD versus CVD TiN coatings, Wear 259 (2005) 1109-1116.

[7] L. Lazzarotto, L. Dubar, A. Dubois, P. Ravassard, J.P. Bricout, J. Oudin, A Selection Methodology for Lubricating Oils in Cold Metal Forming Processes, Wear 215 (1998)1-9.

[8] H. Wiśniewska-Weinert, V. Leshchynsky, M. Ignatiev, J.A. Kozubowska, J. Smalc-Koziorowska, Friction and wear with WS2 nanoparticles under mixed and boundary lubrication. Metals Plastic Forming XIX/1 (2008) 29-40.

[9] PLATIT, Nanostructured Coatings for High Performance Tools. Werkzeug Technik 1 (2003) 2-8.