Archives of Materials Science and Engineering

Volume 49
Issue 1
May 2011
Pages 40-45

International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

Comparative analysis of wear mechanism of different types of forging dies

A. Mazurkiewicz, J. Smolik*

Institute for Sustainable Technologies - National Research Institute, ul. Pułaskiego 6/10, 26-600 Radom, Poland

* Corresponding author: E-mail address: jerzy.smolik@itee.radom.pl

Received 12.02.2011; published in revised form 01.05.2011

ABSTRACT

Purpose: Hot working dies are influenced by three main factors causing their destruction: the cyclically changeable mechanical loads, intensive thermal shocks, as well as intensive friction, and erosion. The great variety of the shapes of forgings, the material they are made of (carbon steel, alloy steel, brass) and the precision of their production – whether they are supposed to undergo further treatment or are considered to be the final products – result in a variety of problems encountered in the production process. In this paper the wear mechanisms of different types of forging dies, covered by the composite layer “nitride layer / PVD coating” were analysed.

Design/methodology/approach: In order to estimate the influence of the different shapes of forgings for their wear mechanism, it was decided to that maintenance tests on two series of tools with different shapes made of DIN 1.2344 steel, coated with composite layer “nitrided layer/CrN coating” needed to be taken. The first one was designed for production of gears pre-forging and the second one was designed for the production of steel synchronizer rings.

Findings: The abrasive wear together with thermal-mechanical fatigue and plastic strain is a crucial factor of the process of wearing of forging dies for the production of forgings with high dimensional accuracy and not subject to further mechanical treatment. The variety of the shapes of the forging and the precision with which it is made have strong influence on the intensity of the abrasive wear of forging dies.

Research limitations/implications: To ensure higher effectiveness of the application of hybrid technologies of surface treatment for the increase of the durability of forging dies, the complex analysis of the influence of such various aspects of the forging process as: surface treatment, the shape of the die and the cooling and lubricating system are necessary on the development of a new generation of dies with increased operational durability.

Practical implications: The obtained results of the tests have been practically applied in the FA “Swarzędz” enterprise to increase the durability of the forging dies for steel synchronizer rings.

Originality/value: In order to ensure a required level of effectiveness of the use of layered composites of the “nitrided layer/ PVD coating” type for the increase in the durability of forging dies, it is necessary to properly select the composites on the basis of the analysis of the intensity of forging dies wear mechanisms.

Keywords: Hybrid surface treatment technology; Thin coatings; Composite layers; Forging dies

Reference to this paper should be given in the following way:

A. Mazurkiewicz, J. Smolik, Comparative analysis of wear mechanism of different types of forging dies, Archives of Materials Science and Engineering 49/1 (2011) 40-45.

METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

In the process of hot working, dies undergo an impact of three main factors causing their destruction: the cyclically changeable mechanical loading, intensive thermal loads, as well as intensive friction and erosion. In order to lower the yield point of the forged material, one needs to heat it to the temperature of 1000 to 1200°C. The cyclically changeable loading, resulting from the specificity of the forging process, makes the forging die heat up by the forged material and then cool down, also in a cyclic way. It is assessed that the temperature of the forging die surface may reach 600°C to 900°C [1]. Due to intensive, cyclic temperature changes in the surface of the forging die, which lead to thermal and structural stresses, very convenient conditions to produce a grid of cracks appear. This form of destruction of the forging die is called the thermal fatigue. All forms of structural disorder in the material of the forging die [2], e.g. carbide precipitations, point defects, dents, scratches, are locations of stress concentrations. A cyclic, changeable character of external mechanical loading, acting on the forging die during the process of production, results in fatigue phenomena known as the mechanical fatigue of the material. The intensity of the mechanical fatigue is accelerated by the cracks arisen due to the thermal fatigue, which cause an increase in the stress concentration in the zones of the cracks. The interdependence between the mechanisms of thermal and mechanical fatigues make the researchers consider them simultaneously as one process of a thermo-mechanical nature. The effective way to improve the durability of forging dies is a modification of surface properties by the constitution of layers or coatings having appropriate properties. This approach is justified by the fact that all the processes of the forging die destruction, i.e. the thermo-mechanical fatigue, plastic deformation, abrasive wear, and erosion, are located just in the surface layer of the die.

One of the most perspective directions of the development of surface engineering is related to hybrid technologies [3-4], which best fulfil the expectation of the industry concerning obtaining proper properties of the surface of tools and machine components. Hybrid technologies of surface treatment, being a combination of single processes in one multi-stage, continuous technological process, belong to the most advanced technologies in materials and surface engineering. This combination makes it possible to modify the surface properties to a considerable extent. As a result, hybrid technologies make it possible to modify the substrate surface properties and the properties of the deposited coatings. A proper selection of the properties of particular constituents of hybrid layers, i.e. the structure, chemical composition, morphology of the substrate and coating materials, gives a synergic effect.

The mostly known and widely used surface treatment hybrid technology is a combination of gas or glow-discharge nitriding process with the process of deposition of hard antiwear coatings by means of PVD methods. The effect of the hybrid technology with such a configuration is a composite layer consisting of a nitrided layer and a PVD coating deposited directly on it. The effectiveness of the "behaviour" of composite layers ("nitrided layer / PVD coating") in the process of increasing the durability of dies has been widely discussed in the literature [5-6]. One points out that their effectiveness differs depending on the properties of the nitrided layer and the deposited PVD coating.

At the same time, great variety of the shapes of forgings, the material they are made of (carbon steel, alloy steel, brass) and the precision of their production - whether they are supposed to undergo further treatment or are considered to be the final products - result in a variety of problems encountered in the production process.

2. Experimental

In order to estimate the influence of the different shapes of forgings, it had been decided to take maintenance tests on two series of tools with different shapes made of DIN 1.2344 steel, coated with composite layer "nitrided layer/CrN coating". The first one, presented in Figure 1a, was destined for production of gears pre-forging and the second one, presented in Figure 1b, was designed for the production of steel synchronizer rings.

a)

b)

Fig. 1. Two series of dies made of DIN 1.2344 steel: (a) for production of gears pre-forging and (b) for production of steel synchronizer rings

The composites selected for testing were obtained with the use of a multi-stage technology of surface treatment encompassing ion nitriding and arc-evaporation processes realised with the use of a hybrid technological device produced at ITeE-PIB in Radom (Figure 2) [7].

Fig. 2. STANDARD hybrid technological device produced at ITeE-PIB in Radom, Poland

Hybrid technological device is equipped with a working chamber with the dimensions of 800x800x800 mm with the water jacket included. It is equipped with five arc sources installed in four sides and an upper wall of the chamber and the system for the rotation of coated elements with regulated speed of 1-3 rpm. A system of vacuum pumps is attached to the working chamber. It consists of the diffusive pump with the efficiency of 8000 l/min, the Roots pump and the rotation pump, and it ensures the possibility of pumping out the chamber to the pressure of 10^{-7} mbar. The device is also equipped with the power supply system which allows the realisation of the following kinds of surface treatment: application of PVD coatings with the arc-vacuum method, ion nitriding, ion beam etching in gaseous plasma and metallic-gaseous plasma. Moreover, the device is additionally equipped with modern control and regulation systems

– pyrometric system for the control of temperature connected with PID temperature controls, blanking system of arc microdischarge on the surface of coated elements, system for the composition and dosage of the process atmospheric composition and the optical system for the control of the intensity of the ion nitriding process. The devices is also equipped with a special computer control system for the control of the technological processes including programming, control, registry, and process parameters control.

The technological parameters of the production of selected layered composited are presented in Table 1.

Maintenance tests were conducted in production conditions according: for dies designed for the production of steel synchronizer rings in FA “Swarzędz” plant and for dies designed for production of gears pre-forging in Institut für Umformtechnik und Umformmaschinen in Hannover, according to the parameters presented in Table 2.

The following material properties were determined for all obtained layered composites:

- the change in chemical composition of the PVD coating in the function of the distance from the surface (GDOES);
- the roughness of the surface (*Hommel Tester*) and the morphology of the surface (*SEM*);
- the hardness and Young’s modulus of the PVD coating (*Nano Hardness Tester*);
- the resistance to brittle cracking in the PVD scratch test (*Revetest*);
- the distribution of hardness and morphology of nitrided coating (*Neophot 32, Future TECH*).

3. Results and discussion

3.1. Materials properties

The results of metallographic tests and the established profiles of the changes of hardness in nitrided layers developed for the tested layered composites are shown in Figure 3. The nitrided layers contain the diffusion zones only, and are characterised by comparable thickness on the $g_{HV900} = 0.1$ mm level and the maximum hardness in the diffusive sphere is concerned, which for DIN 1.2344 steel amounts to 930HV.

Table 1.
Stages of production technology of layered composites on dies for the production of gears pre-forging and steel synchronizer rings

Stage	Name of the stage	Temperature T [^oC]	Voltage U_{bias} [V]	Arc current I [A]	Time t [min]	Pressure p [mbar]	Atmosphere
1	Heating	Up to 520	-	-	-	2.5	25%Ar+75%H_2
2	Nitriding	520	-	-	420	4.3	15%N_2+85%H_2
3	Soaking	520	-	-	360	4.3	100%H_2
4	Cooling	-	-	-	60	-	-
5	1) Ion etching	Up to 420	–950	5x80	1	< 10^{-4}	-
6	1) Break	-	-	-	1	< 10^{-4}	-
7	CrN Coating	2) 380-420	–200	5x80	120	3.5 x 10^{-2}	100%N_2
8	Cooling	<200	-	-	120	< 10^{-4}	-

Remarks:
1) Stages (5) and (6) are to be realised consecutively until the temperature of the substrate T=420^{o}C is reached
2) In stage (7) temperature in the range of 380-420^{o}C

Table 2.
Parameters of forging process

Type of die	Device	Forging load [T]	T_{die} [^oC]	$T_{material}$ [^oC]	Cooling
Dies destined for the production of steel synchronizer rings	Crank press	1000	200	1100	Graphite + water
Dies destined for the production of gears pre-forging	Eccentric press	3150	300	1200	Graphite + water

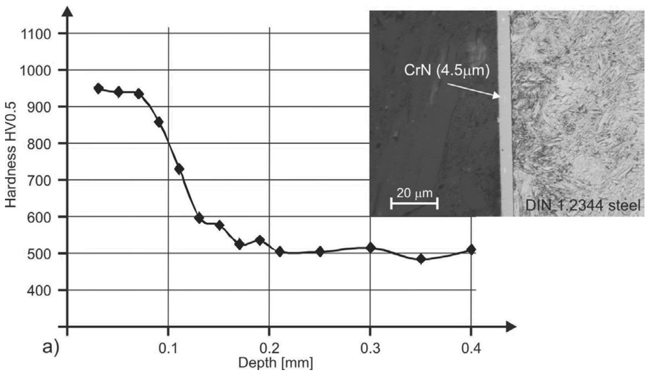


Fig. 3. The results of metallographic investigations and the changes of hardness in nitrided layers developed for the tested layered composites

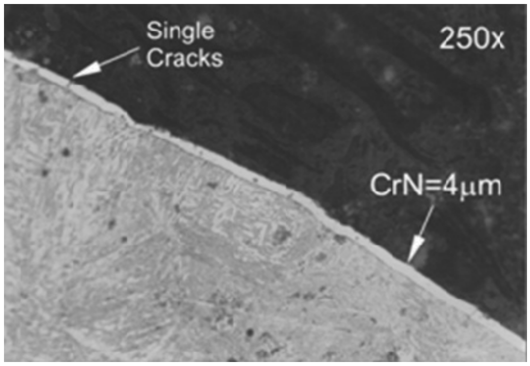
The results of conducted material investigations show that the created PVD coatings are significantly varied in relation to their hardness, Young's modulus and endurance to brittle cracking – the parameters that determine the fatigue durability of the layers. Among the two tested PVD coatings, the CrN coating was characterised by lowest hardness (2000 HV) and Young's modulus (E=245 GPa), but its resistance to cracking recorded in the scratch test ($Fc1_{CrN}$ = 20 N) was at the same time highest.

3.2. Analysis of wear mechanism of dies for production of gears

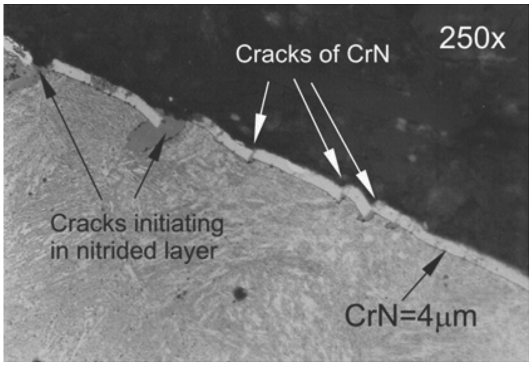
The analysis of dies with a composite layer of the type - "nitrided layer / CrN coating", revealed a very important role of the CrN coating in mitigating the wear intensity of dies. The CrN coatings reduce more effectively an influence of the temperature of the forged material on the process of tempering of the die material. Owing to this, CrN coatings prevent the decrease in the hardness of the die during the forging process, and in the effect counteract the plastic deformation of the die more effectively.

A cyclic character of the forging process causes the coating resistance to thermo-mechanical fatigue to become more vital. As a result of the fatigue phenomena, in the material of the CrN coating a dense grid of cracks occurs, and this in the effect leads to the creation of spallings, which locally decrease the coating thickness, or even cause a complete substrate uncovery. A comparative analysis of the failure intensity of forging dies with nitrided layer / CrN coating composite layers after their various maintenance time is presented in Figure 4a,b,c.

a) CrN (4 μm)/100 forgings



b) CrN (4 μm)/1000 forgings



c) CrN (4 μm)/2000 forgings

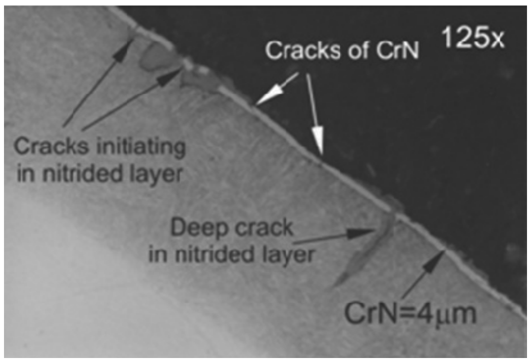


Fig. 4. The analysis of the failure intensity of forging dies with nitrided layer / CrN coating composite layers after their various maintenance time

Based on the above, it seems to be appropirate to conclude that the main role of a PVD coating as an component of a composite layer „nitrided layer / CrN coating" is to prevent from the influence of the high temperature, whose source is the forged material, and to resist the fatigue processes resulting from a cyclic character of the forging process (Figure 5).

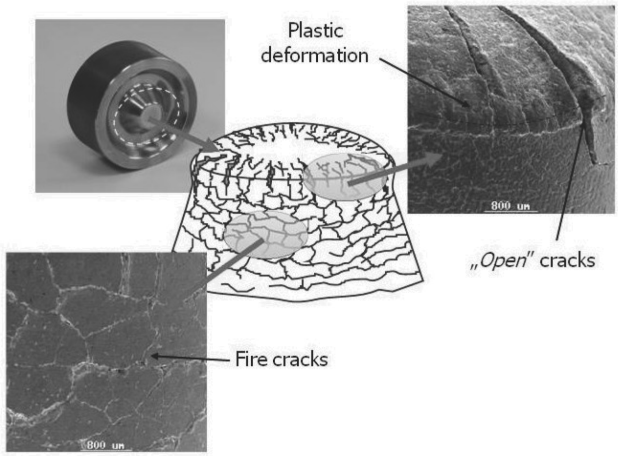


Fig. 5. The main destruction mechanism of destruction of forging dies having the hybrid layer "nitrided layer / CrN coating"

3.3. Analysis of wear mechanism of dies for production of steel synchronizer rings

For the assessment of the intensity of the die's wear, the measurement of the R radius value of the forging, presented in Figure 6 was taken every time after 250 copies of forgings were forged. The measurements were taken with the use of the 3D Wenzel Smart CMM measurement machine. According to the binding quality procedure at FA "Swarzędz", the maximum value of the R radius of the forging allowed, equaled R = 1.50 mm.

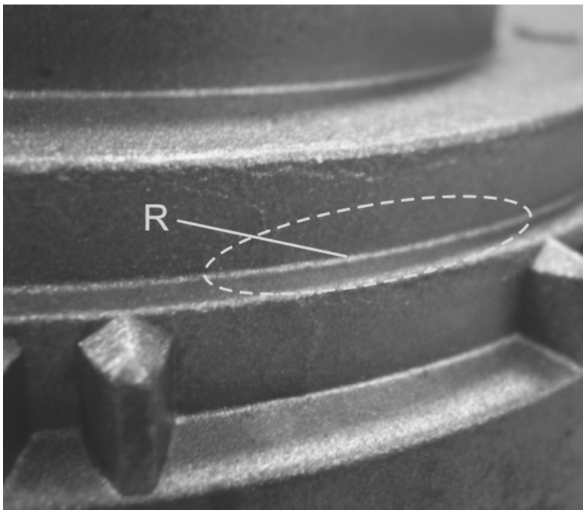


Fig. 6. Steel synchronizer rings forging with marked R radius, whose value determines the durability of the die

The results of the measurements of the changes of the R radius value of the forging, which were carried out according to the established methodology, are shown in Figure 7. The changes of the R radius value take place directly after the beginning of the forging process and their character is linear. Among the three main destruction mechanisms presented in literature that take place in hot forging and include thermal-mechanical fatigue, plastic strain and abrasive wear [8-10], only abrasive wear has a linear character and occurs directly after the beginning of the forging process. Thermal-mechanical fatigue caused by the cyclically changeable external thermal and mechanical loads, requires longer time for the energy, necessary to initiate and propagate the cracking process, to be accumulated. Similarly, the plastic strain of the die, caused by the decrease in the yield point resulting from thermal reactions, requires more time for the realisation of the tempering process with diffusive character.

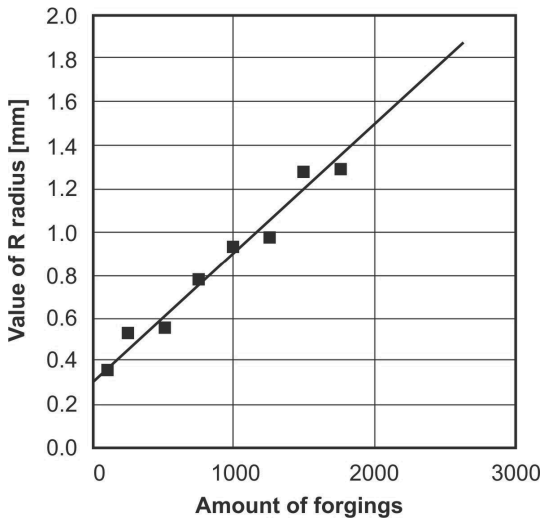


Fig. 7. Results of the measurement of the R radius value changes in the function of a number of steel synchronizer rings forgings produced for dies coated with "nitrided layer / CrN coating" layered composites

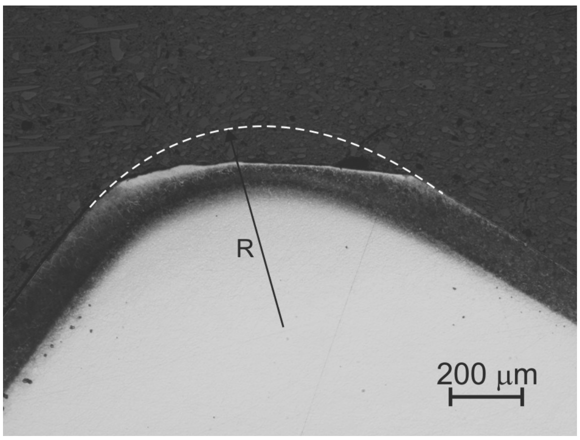


Fig. 8. The results of metallographic investigations for the die coated with a "nitrided layer/ CrN coating" layered composite after forging 2000 of steel synchronizer rings

The changes of the value of the R radius for the forgings produced with the use of forging dies coated with "nitrided layer / CrN coating" composites have a linear character in the first stage, which indicates the dominant influence of the abrasive wear in the process of their wear. Figure 8 shows the results of metallographic tests for the die coated with a layered composite of the "nitrided layer/ CrN coating" type after the process of forging steel synchronizer rings.

The visibly flat profile of the worn die and the lack of any effects of wear processes and plastic strain in the nitrided layer and the coating, indicate the dominance of the abrasive wear in the wear process of the dies for the production of steel synchronizer rings.

4. Conclusions

On the basis of the obtained results of material investigations as well as on the basis of the results of the maintenance tests, the following conclusions were drawn:

- The abrasive wear together with thermal-mechanical fatigue and plastic strain is a crucial factor of the process of wearing of forging dies for the production of forgings with high dimensional accuracy and not subject to further mechanical treatment. The variety of the shapes of the forging and the precision with which it is made have strong influence on the intensity of the abrasive wear of forging dies. The obtained results of the tests have been practically applied in the FA "Swarzędz" enterprise to increase the durability of the forging dies for steel synchronizer rings. The analysis of the results obtained, also makes it possible for them to be more widely used in relation to forging dies for the forgings in different shapes and sizes, but with similar precision with which they have been made.
- In order to ensure a required level of effectiveness of the use of layered composites of the "nitrided layer/ PVD coating" type for the increase in the durability of forging dies, it is necessary to properly select the composites on the basis of the previously conducted analysis of the intensity of the effects of individual damaging factors, such as: cyclically changeable mechanical loads, cyclically changeable thermal shocks and intensive friction.
- Properly designed hybrid technologies of surface treatment enabling the production of "nitrided layer/ PVD coating" layered composites are an effective technological solution for the increase in the durability of dies for hot forging. To ensure higher effectiveness of the application of hybrid technologies of surface treatment for the increase of the durability of forging dies, the Institute for Sustainable Technologies-National Research Institute (ITeE-PIB) in Radom and the Institut für Umformtechnik und Umformmaschinen at the University of Hanover initiated cooperation within the optimisation of the techniques of cooling and lubricating of forging dies with layered composites on their surface. The joint research program anticipates a complex analysis of the influence of such various aspects of the forging process as: surface treatment, the shape of the die and the cooling and lubricating system on the development of a new generation of dies with increased operational durability.

Acknowledgements

Scientific work financed by the Polish Ministry of science and Higher Education and carried out within the international project 271/N-DFG/2008/0 and IniTECH project ZPB/69/72766/IT2/10.

References

[1] M. Terčelj, P. Panjan, I. Urankar, P. Fajfar, R. Turk, A newly designed laboratory hot forging test for evaluation of coated tool wear resistant, Surface and Coatings Technology 200 (2006) 3594-3604.
[2] J.S. Sun, K.H. Lee, H.P. Lee, Effect of geometry and fillet radius on die stresses in stamping processes, Journal of Materials Processing Technology 104 (2000) 254.
[3] A. Matthews, A. Leyland, Hybrid techniques in surface engineering, Surface and Coatings Technology 71 (1995) 88-92.
[4] S. Takayasu, S. Kenichi, U. Shizuyo, K. Matsunami, M. Yasuoka, Development of a hybrid coating process as an advanced surface modification for cutting tools and moulds, Surface and Coatings Technology 169-170 (2003) 45-48.
[5] J. Smolik, M. Gulde, J. Walkowicz, J. Suchanek, Influence of the structure of the composite nitrided layer/PVD coating on the durability of forging dies made of steel DIN-1.2367, Surface and Coatings Technology 180-181 (2004) 506-511.
[6] P. Panjan, I. Uranjar, B. Navinšek, M. Terčlj, R. Turk, M. Čekada, V. Leskovšek, Improvement of hot forging tools with duplex treatment, Surface and Coatings Technology 151-152 (2002) 505-509.
[7] A. Mazurkiewicz, J. Smolik, Advanced technologies of surface engineering, Technological Innovations for Sustainable Development ISBN 978-83-7204-845-5, 2009.
[8] D.H. Kim, H.C. Lee, B.M. Kim, K.H. Kim, Estimation of die service life against plastic deformation and wear during hot forging processes, Journal of Materials Processing Technology 166 (2005) 372-380.
[9] H. Saiki, Y. Marumo, A. Minami, T. Sanoi, Effect of the surface structure on the resistance to plastic deformation of a hot forging tool, Journal of Materials Processing Technology 113 (2001) 22-27.
[10] O. Barrau, C. Boher, R. Gras, F. Rezai-Aria, Analysis of the friction and wear behaviour of hot work tool steel for forging, Wear 255 (2003) 1444-1454.