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Influence of the application of a PN + Cr/CrN hybrid layer on the improvement of the lifetime of hot forging tools

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ABSTRACT

This article presents the results of field tests performed on forging tools in a selected lid hot forging process. The aim of the studies was to increase the durability of hot forging tools. Different coating types dedicated to hot forging tools were proposed and first tested in laboratory conditions. Based on the laboratory test results, the PN + Cr/CrN hybrid layer was selected to improve tool durability. Tools (upper punches used in second forging operation) with a PN + Cr/CrN layer applied on them were tested in comparison with gas-nitrided tools. The hybrid layer was produced on a plasma-nitrided substrate, onto which a PVD Cr/CrN coating was deposited. All the analyzed tools were tested in industrial conditions through the manufacturing of specific quantities of forgings. Next, the wear of each tool was analyzed by surface scanning and then compared to the CAD model. All the tools were checked for changes in the surface layer under an optical and a scanning electron microscope, as well as by way of a microhardness measurement. The results obtained in industrial conditions confirmed the effect of improvement of the forging tool lifetime owed to the application of the PN + Cr/CrN hybrid layer.

1. Introduction

During its operation, the forging tooling undergoes many degradation mechanisms. Three primary factors which cause tool destruction can be distinguished in hot forging processes, i.e. intense thermal shocks, periodically changing mechanical loads and intensive friction, and in consequence, the dominant wear mechanisms are thermo-mechanical fatigue and abrasive wear (Altan, 2005). The durability of forging tools, understood as their resistance to the aforementioned destructive factors, has been researched in numerous scientific and industrial centers (Gronostajski et al., 2014). Attempts are being made to apply various methods intended to improve tool life (Hawryluk, 2016).

Nitriding is currently the most common technique of prolonging the lifetime of forging tooling. Nitriding improves tools' resistance to abrasion and fatigue strength, as well as their corrosion resistance (Uma Devi et al., 1999). Examinations of several industrial forging processes applying nitrided tools have shown that such a treatment makes it possible to improve tool lifetime several times over (Paschke et al., 2012). Studies have shown that tools must have a specific, uniform microstructure for the nitrided layer to improve tool life effectively (Wendland et al., 2014).

Mechanical working methods intended to improve the functional properties of tool surface layers include ball burnishing, or shot peening, based on cold dynamic surface working. Surface layers produced by the ball burnishing process are characterized by high absolute values of maximum internal stresses and yield point (Loh et al., 1993). Tools made of hot (and cold) work tool steel are increasingly often subjected to cryogenic heat treatment, or deep freezing (Suchmann and Niznanska, 2015). This makes it possible to rather significantly reduce the amount of retained austenite, increase hardness, and in combination with other technologies, increase tool life (Wagner et al., 2008).

The latest methods undoubtedly include hybrid technologies involving the application of two or more surface engineering techniques (Mazurkiewicz and Smolik, 2015). Hybrid techniques may combine e.g. thermochemical treatment methods and a PVD or CVD technique. Using this two mentioned microstructure components at the same time, that is a nitrided layer and a selected PVD or CVD coating, causes them to cooperate with each other, which ensures very high performance properties (Klimek et al., 2003). Nitriding increases the substrate hardness and its resistance to plastic strains, and in this way, it protects the coating from losing its internal cohesion and adhesion to the

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substrate. Simultaneously, the selected coating provides isolation for the nitrided substrate, and in this way, it limits the damage caused by external factors (Dobrzański et al., 2004). The CVD method is a process which is implemented through the chemical reaction of the gases which occurs on the surface of the substrate on which a given material is deposited. Substrate components also participate in the process of coating formation. Conventional CVD methods involve the chemical reactions taking place at 900–1000 °C, which is too high to be applied on forging tools previously subjected to heat treatment. Recently, also, a few kinds of CVD processes have been developed. Among them, the methods involving chemical deposition from the gaseous phase aided by PACVD/PECVD plasma seem to have the best prospects (Leskovšek et al., 2009) because of a lower deposition temperature, below 600 °C. There are several successful applications of PECVD coatings deposited on the nitrided layer on hot forging tools. For instance, in South Korea, investigations have been carried out of the life of nitrided tools with the PECVD-type multi-layer TiBN coatings, which obtained very good results (Myung et al., 2002). What is more, similar results in an expanded technique have been obtained in Germany (Paschke et al., 2011).

PVD methods seem to be a good alternative to CVD techniques, as, in this case, there is no problem connected with temperature. PVD methods are based on physical deposition of coatings from the gaseous phase applying low pressure, as well as different physical processes aimed at obtaining deposited couples (e.g. nitrides, carbides, borides) (Yilkiran et al., 2012). The metal or compound couples are deposited on a cold or heated substrate (Tmax = 500 °C), which makes it possible to apply coating to the tools previously subjected to thermal treatment and does not involve the risk of tempering caused by the operation of high temperature in the coating deposition process. The coating joins with the substrate due to adhesion (less often, adhesion & diffusion), and the connection depends on the surface roughness and cleanliness. At present, several dozen PVD method types and modifications are known, the PAPVD type being the most commonly used. Applying plasma in PAPVD processes additionally cleans the substrate, and this improves the adhesion of the coating to the substrate. This field of application includes several studies of the PVD coating selection (Molinari et al., 2001), and also optimization of the number of the coatings' components and the way in which they are applied (Prabakaran et al., 2014). There are many cases of the application of PVD coatings on cutting tools, published i.e. in (Ning et al., 2007) and (Pei et al., 2018), on milling tools (Okada et al., 2011) and drilling tools (Cselle et al., 2008), to increase their lifetime. Industrial applications include steel casting moulds (Wang, 1997), tools for metal injection (thixoforming) and several examples of successful applications of coatings deposited on the nitrided layer on hot forging tools, the number of which has been significantly increasing in the recent years. A remarkable example can be the industrial tests of tools with hybrid layers used in hot forging processes realized on a hammer (Podgrajšek et al., 2015). Another example of tests performed on hot forging tools with hybrid layers including test dies was conducted in Poland (Smolik et al., 2000).

In the application of PVD coatings, it is necessary to know the performance conditions, which determine the selection of the particular coating. While exploitation tests carried out on tool coatings are costly, investigations are being performed to look for research methods in which the test conditions correspond to the real working conditions. However, introducing all of these factors at the same time rather than only a few selected ones is impossible. Such mechanical properties of coatings are commonly tested as: the hardness, the hardness distribution in a normal surface cross-section, the Young modulus, and also the microstructure of the surface layer, the surface morphology and the chemical composition with the use of the EDS analysis. Very important and valuable are adhesion tests performed by means of the C-type Rockwell indentation method (Vidakis et al., 2003), and also the linear scratch method (Kacprzynska-Gołacka et al., 2014), which evaluates the influence of pressures on the cohesion of the coating and its adhesion to the substrate. Different tribological examinations are also conducted by means of the ball-on-disc or pin-on-disc method, in order to evaluate the frictional resistance of the applied coatings. The abrasive wear evaluation can be also performed by means of erosion tests, which apply a stream of loose abradant bombarding the coating surface, followed by a measurement of the formed indentation (Wu et al., 1999). The coating microstructure observations can be carried out on spherical microsections (Betiuk, 2012) or in cross-section by means of SEM or STEM microscopy. Also, there are available methods of examining the coatings' thermal fatigue, which apply repeated heating and cooling of the rotating disk on which the coating is deposited (Hawryluk, 2016). Interesting results of field tests performed on different hybrid layers and coatings were presented in the work (Navinšek et al., 2001). Although the effect of improvement of the durability of hot forging tools had been proven in several cases (Hawryluk et al., 2017a), in this study, the authors expanded the knowledge about the coatings and performed complex industrial tests to verify this effect in real industrial conditions.

The authors have conducted field tests on punches used in a hot forging process, which were improved according to two different methods for the purpose of comparing their lifetimes. These methods were: thermo-mechanical treatment through plasma nitriding and coating with a hybrid layer consisting of a nitrided layer and a PVD coating. Before the industrial tests, many laboratory experiments were performed to check the mechanical properties of the proposed hybrid layers, in order to ensure the selection of the coating type. After the selection of the hybrid layer, complex field tests were conducted for the purpose of observing and describing the possibilities of this valuable method, which increases the durability of hot forging tools.

2. Experimental procedures

The research process covered a series of activities conducted for the purpose of developing and selecting the best method of improving the durability of tools used in hot forging. The studies were divided into two stages. The first stage covered observations and comprehensive tests of the coatings under laboratory conditions. The second stage of studies concerned industrial tests conducted under hot forging conditions.

2.1. Tests of selected PVD coatings dedicated to improving tool durability under laboratory conditions

The following PN + PVD hybrid layers were subjected to the analysis: Cr/CrN, Cr/CrN/AlCrTiN and CrN/AlCrN/AlCrTiSiN. In order to determine the properties of the coatings and select the most suitable one, the following comprehensive tests were performed:

- metallographic tests and microhardness measurements of plasma nitrided (PN) layers,
- microscopic observations of hybrid layers by optical and SEM microscopy,
- measurements of hardness and Young's modulus. Tests of chemical composition changes as a function of the distance from the surface by means of the EDS linear analysis method,
- ball-on-disc abrasive wear resistance tests,
- microstructure analyses by means of scanning transmission electron microscopy (STEM),
- investigations of the phase structure of the selected multi-layered coatings.

Based on the results of the studies enumerated above, a decision was made concerning the selection of the optimal PVD coating, characterized by the most desirable mechanical properties and the highest wear resistance under laboratory conditions, from the perspective of the exploitation in the hot die forging process.