Improving mechanical properties of High speed steel by TiN/Al_2O_3 – Technical Review

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Abstract : ***Recent technological advancements for the development in surfacing of engineering materials through coating of nano materials to enhances material and mechanical properties with improved tribological characteristics is inevitable. In the present paper an attempt is made to study the feasibility of nano coating of cutting tool materials by ceramic materials. For the present study, among the variety of cutting tools, the drills with larger length to diameter ratio are selected with small drill holes. The studies were conducted based on the penetration of coated materials over drill bits, coating technologies, characterisation and experimental investigations on coated cutting tools and the cutting tools manufactured by powder metallurgy process. The various nano coating under discussion are physical vapour deposition (PVD), chemical vapour deposition (CVD), spin coating and sol - gel processes.***

Keywords - Cutting tool, Nano coating, HSS, PVD, CVD, sol-gel process, pulsed magnetron sputtering, TiN.

I. Introduction

The ancient cutting tools used by the mankind is stone, due to the continuous improvement in the technologies the cutting tool materials the need and demand of the product the cutting tool materials took several forms such as HSS, brazed carbide, tungsten carbide, solid carbide, coated tools etc., further to the advancements the cutting tool materials were designed based on the end product materials for example special cutting tool and tool materials for machining aluminium, copper, brass, phosphor bronze, mild steel, cast iron, stainless steel. These cutting tools are designed to take cutting loads under the normal cutting modes for example standards drill diameter and lengths in other terms L/D ratio of less than 5. In our present context, the survey is being conducted to drill the small hole of diameter with less than 3.0 mm and length of 50 mm. The cutting tool taken for study is of Special graded High Speed Steel (HSS) drill bits.

The desired coating method under study can be employed to perform the following machining process like drilling, milling, turning, boring, grooving, threading etc., The need for tool materials that could withstand increased cutting speeds and temperatures led to the development of high-speed tool steels (HSS). The major difference between HSS and plain high carbon steel is the addition of alloying elements to harden and strengthen the steel and make it more resistant to heat. The purpose is to obtain a cutting tool with hot hardness superior to HSS. HSS lose their hardness at 600ºC, which leads to their wide usability for higher cutting speeds [1].

Powder metallurgy process involves mixing of metal powders and additives (lubricants or binders), it is compacted by using a die under high pressure. Followed by sintering operation that proceeds with three stages, First stage being neck growth proceeded rapidly when the powder particles remain discrete. During the second, most densification occurs, the structure recrystallizes and particles diffuse into each other. In the third and final stage, isolated pores tend to become spheroidal and densification continues at a much lower rate [2].

A nano coating is a covering applied to the surface of an object, usually referred to as the substrate. Functional coatings may be applied to change the surface properties of the substrate, such as adhesion, wettability, corrosion resistance, or wear resistance. Nano coating or nano sealing is coating of an application where nano structures build a consistent network of molecules on a surface that make it super-hydrophobic or super-hydrophilic [3].

II. Survey on nano-coatings

The purpose of applying the coating may be decorative, functional, or both. The coating itself may be an all over coating, completely covering the substrate, or it may only cover parts of the substrate.

Mirvanovicoslav Rado et al. summarize the coating process, coating materials, primary reasons for using coated tools. Coated cutting tools are most widely used. Life time of the coated cutting tools is 10 times more than the uncoated tools. Nanostructured coatings are coatings with dimensions of grain size or individual layers less than 100 nm. The studied revealed the best cutting tool is not necessarily the most expensive [4]. Sergej N. Grigoriev et al. investigated and developed the concept of cutting tool material in the form of layered composite ceramics (LCC) with nano-scale multilayer coating (NMC) for machining hardened steels as well as hard-to-machining Ni-alloys. The LCC-NMC tool life exceeds that of standard coated carbide tools and standard coated ceramic tools about 2.5-8.0 times. The carbide layer provides the raised toughness and strength of tool material, the ceramic layer provides resistance of a tool material to oxidation [5].

Abrar A. Arshi et al. studied the advantages of TiN coating include high hardness, good ductility, excellent lubricity, high chemical stability and tough resistance to wear, corrosion and temperature. The studied revealed that the Tin coated tool perform better as compared to uncoated cutting tool. The effect of cutting is to reduce wear and tear of tool tip point as well as more heat dissipation to surrounding hence the increase in tool life and surface finish of the product to be machine. With increase in depth of cut the surface roughness is increased [6]. Arno Kopf et al. experiment revealed the overall gain productivity was increased and reduction of process time [7].

A.M. Pagon, et al. synthesized the high speed steel (HSS)-TiN nano-composite films from a cold-sprayed HSS-Ti cathode. The microstructure of the film depends on both the energy of the deposited flux and the substrate temperature. The result reveals the mechanical properties of HSS-TiN thin film were improved with moderate substrate bias(-200V) and high substrate temperature (>250°C). There is better property matching between the HSS tools and TiN coatings [8].

The new AlTiN-Saturn coating is characterized and its performance on cemented carbide and HSS tools compared to other commercial (Ti, Al)N films was synthesized by Mirjam Arndt et al.[9] and conclude that AlTiN-Saturn has shown an extraordinary performance in high speed cutting of hardened tool steel. The result was mainly caused by the high adhesion property and ultrafine crystalline as well as high oxidation resistance of the coating.

N. Balasubramanyam et al. studied the Nano material coating of TiN, TIC on Tungsten Carbide cutting tool and the Mechanical, Tribological properties of TiN, TIC are to be compared with uncoated Tungsten carbide cutting tool and also different coating methods are used for comparison. The result revealed that the AlCrN-T coating has a wide potential tribological application under the condition of sliding wear and AlCrN-T coating can be used with acceptable levels of productivity in the machining of aerospace and biomedical components, with adequate process parameters, lubrication and other conditions [10].

Alexey Vereschaka et al. studied the mechanical and performance properties of multilayer composite nano structured Ti-TiN-(Ti, Al and Cr) N coating with different values of thickness for wear resistant coating. The result reveals the cutting tool with thickness a 6.0 μm coating having better tool life at all cutting speeds and tool with a smaller thickness of wear-resistant layer (2.0–6.0 μm) showed a significantly smaller decrease in wear resistance with an increase in cutting speed [11].

Wei Yongqiang et al. experimented the TiN/TiAlN multilayer coatings were deposited on M2 high speed steel by a pulsed bias arc ion plating system and effect of modulation ratio on the microstructure, mechanical and wear properties was investigated. The M2 HSS discs with 30 mm in diameter and 4 mm in thickness were used as the specimen. The result reveals the TiN/TiAlN multilayer coating fabricated had the best adhesion strength [12].

Weiwei Wu et al. designed the AlCrN coating and AlCrSiN multilayer and nano composite coating are deposited on the surface of high speed steel (HSS) cutters. The result reveals for the cutting test, the worn loss of AlCrSiN coating is less than that of AlCrN coating, due to higher hardness, adhesion, wear ability and lower friction coefficient and significantly enhancement of service life of HSS cutting tools [13].

Grzegorz Skrabalaz experimented the EDM drilling performed for tool electrode diameter of 0,1 mm and workpieces of 1 mm thick and compare the coefficients are of the tool wear ratio, material removal rate / machining efficiency and machining accuracy / quality. The result reveals the round shape and very small taper angle of produced holes result from the fact that machining parameters allowed to achieve high electrode tool wear and number of holes to be drilled is relatively small, it is recommendable to keep the electrode as short as possible to perform drilling the most effectively in order to minimize the harmful effect of the forces generated by discharges on machining process efficiency [14].

The studies revealed the different types of coating process and mechanical properties of cutting tools and also the dimensions of the coating thickness, tool life the materials. From this survey the TiN coating is very effective for HSS tools and it is include high hardness, good ductility, excellent lubricity, high chemical stability and tough resistance to wear, corrosion and temperature.

III. Survey on manufacturing process of coating materials

Coating materials has a wide range of applications in rapid production industries. Very basic types of coating materials are made by sol-gel process.

M.A.Umer et al. (2011) synthesized TiN coated cBN particles by sol-gel process. CBN powder was treated in fuming concentrated sulphuric acid to which potassium nitrate was added. After washing and drying, cBN powder was further heated in air at 600◦C for 30 min.TiO_2 precursor solutions was prepared by mixing titanium (IV) isopropoxide. The solution was stirred for 30 min. The titanium isopropoxide was hydrolyzed and polycondensed to form nano sized layers on the surface of the cBN particles. The coating layer on the cBN was converted to fine TiN particles upon a thermal treatment in NH_3 gas. It was observed that an increase in the coated layer thickness [15].

M. Sundar et al. (2010) incorporated TiAlN coating by sol-gel process. Aluminium gel was prepared by adding 500 g of powdered aluminium isopropoxide into a beaker of boiling solution of 2.25 dm^3 of distilled water and 5 ml of concentrated nitric acid that was under vigorous stirring. In the preparation of the titanium gel, titanium isopropoxide Ti $(C_3H_7O)_4$ was used as the precursor. A quantity of 100 ml of absolute ethanol and 5 ml of deionized water were added to 10ml of titanium isopropoxide and then stirred vigorously for about 15 minutes. Equimolar amounts of the respectively prepared aluminium hydroxide and hydrated titanium oxide were added to urea and the resulting mixture was dissolved in a minimum volume of water and graphite, giving rise to the formation of a slurry rich in Ti, Al, N and C elements. The prepared substrate samples were mechanically coated with the slurry using K-print hand coating bars [16].

I.Piwonski, A.Ilik(2006) symphonize titania (TiO_2) surfaces by sol–gel process and Chemical vapor deposition (CVD) method was used in titania surface modification. To obtain nonporous TiO_2, titanium (IV) isopropoxide (1.1995g) was dissolved in isopropanol (13.2g). Hydrochloric acid (0.04 ml, 2 mol dm^{-3}) was added drop wise and the mixture was stirring for 2h in ambient conditions. The final sol was used to prepare the nonporous layer by dip-coating method. Substrate was immersed and withdrawn with a defined speed of 25 mm min^{-1}. After dip-coating process, prepared nonporous coating was dried for 2 h in 95°C [17].

M. Nordin et al. (1999) synthesized PVD coating of TiN/TaN on HSS. The HSS was heat treated by austenitisation at 1180°C followed by tempering 3×1 h at 560°C. All substrates were thoroughly degreased and dried with N2 gas before inserted into the coating chamber. First the substrates were resistively heated to 450°C for 60 min using an electron beam. All coatings were deposited in a commercial Balzers BAI 640R apparatus, fitted with an electron beam evaporation source (e-gun) and a planar d. c. magnetron sputtering source. Deposition of the multilayered TiN/TaN coating was performed using a hybrid process consisting of reactive electron beam evaporation (TiN) and reactive d. c. magnetron sputtering (TaN). The deposition temperature and the substrate bias were 450°C and −110 V, respectively. Field emission gun scanning electron microscopy (FEG-SEM, LEO 1530) was utilized to measure the coating thickness [18].

D. Munteanu et al. (2011) amalgamate dark Ti(C, O and N) decorative coatings onto high speed steel. The Ti(C, O and N) thin films were deposited onto high speed steel (AISI M2) and silicon substrates in a custom-made dc reactive magnetron sputtering apparatus. The films were prepared with the substrate holder positioned at 70 mm in all runs, using a current density of $100Am^{-2}$ on the titanium target (99.6% purity). A gas atmosphere composed of argon (working gas), nitrogen + oxygen (17:3 ratio) reactive mixture and acetylene were used for the depositions. During the 1h depositions the temperature was kept constant at 200°C, using an external heating resistance. The atomic composition of the deposited sample was measured by electron probe micro analysis (EPMA) in a Cameca SX-50 apparatus. The film thickness was measured by CALOTEST method [19].

M. Keunecke et al. (2010) harmonizes TiAlN coating by d. c. pulsed magnetron sputtering. The deposition processes for nitride coatings consisted of five main steps: (i) heating (ii) Ar ion etching for substrate cleaning; (iii) sputter deposition of an adhesion improving layer by increasing of the reactive gas flow gradually from zero to 200 sccm or 300 sccm, respectively, for pure TiAlN coatings and increasing the target power up to maximum values and (iv) gradually increasing the substrate bias with 1 V/min starting from −30 V d.c. up to the maximum selected bias value; and finally (v) the deposition of the modified TiAlN coating under constant process conditions [20].

A. Ghasemi et al. (2010) synthesized TiO_2-CeO_2 composite coatings by sol-gel method. Titanium oxide sol is prepared by mixing ceric ammonium nitrate and titanium but oxide to get the molar ratio of 1:10 between Ce: Ti in ethanol. The mixture stirred vigorously at room temperature for 30 min. In the next step, small amount of distilled water was added to the mixture to accelerate hydrolysis and condensation.

Then the suspension stirred for 10 h until it turns to a clear solution. In order to obtain a Ce^{2+} rich solution, the prepared TiO_2–CeO_2 sol was aged for 8 days at room temperature with humidity of (50±5%). Within a few days, the color of the solution changed from deep red to pale yellow, indicating a reduction of Ce^{4+} by ethanol. The TiO_2–CeO_2 composite films were deposited on 316L stainless steel substrates using spin coater (Model: TC100, MTI corporation, USA) at spinning rate of 3000 rpm. Then the samples were dried for 1h at 100°C. The samples were coated and dried for three times. The coated specimens were heat treated inside a muffle furnace at different temperatures of 300,400 and 500°C for 1h in atmospheric condition. Heating and cooling rate were adjusted at 60°C/h [21].

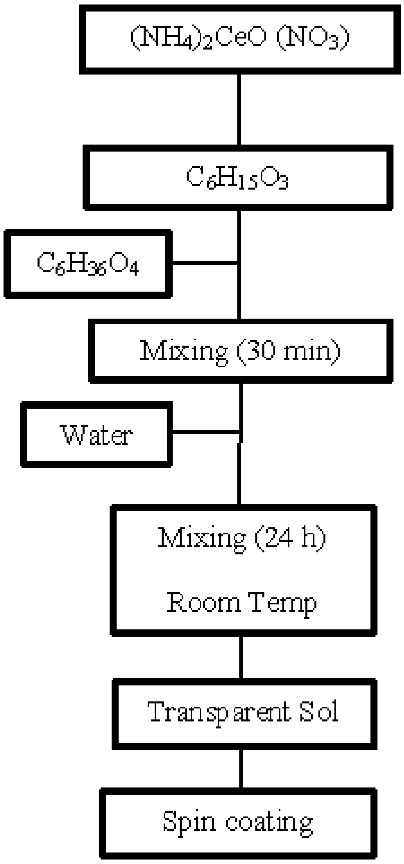

Fig.1 Flow diagram of TiO_2-CeO_2 coating process by the sol-gel method [21].

T. Ezz et al. (2007) orchestrate TiN coatings by laser/sol-gel process. EN43 mild steel in the as-received annealed state was used as a substrate. Samples were polished with different sizes of emery paper and cleaned with ethanol to remove any contaminants on the surface and then it was sand blasted. Titanium isopropoxide Ti $(C_3H_7O)_4$ (TIPP) was used as the precursor for titania gel preparation. One hundred microlitres of absolute ethanol was added to 10 ml of TIPP with stirring for 15 min during which 5 ml deionized water was added. The gel was then filtered with a grade 42 filter paper to produce a finely divided amorphous powder. It was assumed that the powder was hydrated TiO_2. Urea, dissolved in a minimum volume of water (2 g of urea dissolves in 5 ml of water), and graphite were then added to the filtered powder to obtain a slurry. Two mixtures with different molecular ratios were used in the process. Samples were mechanically coated with these mixtures using K-print hand coating bars and the thickness was controlled to be of the order of 0.2 mm [22].

Y. Sen et al. (1999) manufacture CrN coatings on high-speed steel (HSS) by physical vapour deposition (PVD). Before coating, the samples were wet-ground with 1000 grit emery paper and then polished with 1 mm diamond paste. All samples were then ultrasonically cleaned in alkaline solution, degreased, rinsed in distilled water and dried using propanol. The first step of the deposition process involved evaporation of the chromium target and acceleration of the chromium ions towards the substrate by applying a high negative bias of 1000 V to the substrate. In this step the sputter cleaning and heating of the substrate to the desired coating temperature were achieved. After reaching a substrate temperature of 450 °C, deposition was started by decreasing the bias voltage to 120 V. A thin chromium film was formed at this stage of the process. Reactive gas, nitrogen, was introduced into the vacuum chamber in order to start CrN deposition. The nitrogen gas pressure during the coating procedure was 5 mtorr and the total deposition time was 30 min. It concluded the thickness of the CrN coatings varied between 1.6 and 2.0 mm [23].

From this survey we understood different types of coating process such as sol-gel process, PVD, CVD. Comparing to all the three, PVD is more suitable for our experiments.

IV. Studies on characterization of coated materials

Characterization of the cutting tool material includes the tribological test. Tool life is also analysed.

L.Settinari et al. had done nano composite coatings of AlTiN or AlCrN in a matrix of Si3N4 are done by cathodic arc PVD. Wear analysis were performed using a SEM with tungsten filament, equipped with ISCS microprobe for elemental analysis. Coated tool is tested under specific parameters by contour milling operation in a milling machine. Ti based coatings have greater wear resistance. Investigation reveals that at high temperature wear is mainly due to oxidation phenomena, leading to surface modifications [24].

Akash Singh et al. have identified that the coatings were deposited in the deposition temperature range 300–873 K using the pulsed magnetron sputtering technique. ZrN coatings prepared at higher deposition temperature show lower value of coefficient of friction (COF).

ZrN coatings were characterized by X-ray diffraction. Higher crystallite size of the coatings at 873 K could possibly reduce the COF to lower values (~0.1) due to the reduction in the surface roughness. ZrN coatings tested with steel ball showed lower COF value due to the formation of the tribo layer on the coating [25].

Miroslav Piska et al. focussed on the analysis of physical parameters of loading such as torque moment, total energy and specific energy of the taps measured with the piezo- electrical dynamometer kistler 9272. The combination of PVD TiN+DLC surface coatings can be recommended for a very effective and safe tapping in the steels, even in the hardened state. A very good accuracy in the range of IT 9-10 for the threads made by both technologies, roughness Ra<1.6 μm, tool life for production of 1,000 threads (for forming operation) and 600 threads (when cutting) is expected while coating [26].

J.A. Canteli et al. characterized the cutting performance of High speed steel matrix with hard phase TiCN were analysed. The cermet was compared with the reference material M2 without reinforcement and with commercial HSS M2. Orthogonal cutting test were carried out at constant speed and feed rate of 30m/min. Tool life was increased one order of magnitude in the case of the cermet when compared with the reference material M2 and the commercial HSS. Flank wear and chipping at the cutting edge are diminished in the cermet. Rounded or chamfered edge can also prevent the chipping wear even when the rake angle is positive [27].

Karol Vasilko et al. have identified high speed steel cutting tools are widely used material for lower cutting speeds. Their aim is to reduce the residual stress for new cut-off tool caused by heat processing and sharpening. The increase of the rake angle size means that the cutting force decreases significantly. The freezing treatment was made by nitrogen of the temperature of –190°C. The time of freezing is 30-90 minutes taking into account the tool size. The change of cutting materials, the construction and technological modifications can considerably influence cutting tool life. When combining the tool coating and freezing treatment, the achieved tool life was up to eight times longer [28].

R. K. Choudhary et al. had used AlN as coating material to grow on stainless steel by magnetron sputtering. Grazing incidence X-ray diffraction measurement revealed that formation of mixed phase (wurtzite and rock salt) AlN was favoured at low discharge power and substrate negative biasing. Secondary ion mass spectroscopy showed presence of oxygen in the coatings. Wear test showed improved wear resistance of the coatings obtained at higher substrate bias. The thickness of the coatings was calculated by the weight gain method assuming the density of the deposited AlN to be same as that of bulk AlN (3.26 g/cm3). Wear test were performed by using computer controlled reciprocating sliding machine. It is possibly to obtain high crystalline and adherent AlN coatings on stainless steel. COF is higher in higher substrate bias and it is negligible in various sliding frequencies [29].

Wei Liu et al. have characterised the coated material by wear mechanism study. The effects of the cutting speed on tool life, wear mechanism and surface quality of the work pieces were studied through high speed face milling tests. The uncoated Si3N4 cutting inserts life decreased as the cutting speed increased in face milling test. CrAlN and TiAlN coated cutting inserts were conducted by high speed face milling showed that the tool life is increased as the cutting speed also increased. During this high speed, the coating material did not peel off. CrAlN and TiAlN coated cutting inserts had improved the tool life of the uncoated cutting inserts by 138–150% and 32–65%. CrAlN and TiAlN coated tools was almost similar to the tools produced at the cutting speed of 600 m/min [30].

C.Y.H. Lim et al. had compared the behaviour of titanium nitride (TiN) coated and uncoated high speed steel (HSS) tool inserts during turning. It is well known that thin, hard coatings can reduce tool wear and improve tool life and productivity. The coated tool inserts machining under certain conditions had an average of 1.5 times more resistant to crater wear than the uncoated tools. The application of TiN coatings onto HSS tool inserts broadens the range of cutting speeds and feed rates within which acceptable rates of crater wear occurs during dry turning of steel work pieces [31].

Guangming Zheng et al. were carried out the sliding friction and high-speed turning experiments in dry conditions to reveal the antifriction characteristics and wear mechanisms of the TiAlN/TiN coated tool against high-strength steel. The value of flank wear width was measured in the turning tests. The microstructure of the worn surfaces was observed by using ESEM. During sliding process friction coefficient increases in applied load, but it decreases while the sliding speed increases. During the dry turning process, the combined action of the peeling off, chipping, adhesion, mechanical scratch, element diffusion and oxidation was the main wear mechanism of the TiAlN/TiN coated tool. Especially on the rake face TiO_2 was formed and cutting performance had increased [32].

E.D. Kiosidou et al. had examined various representative models of finite length diffusion impedance, in order to find the optimum description for dissolved oxygen diffusion, during corrosion of scribed coated steel in cyclic salt spray conditions, at 6, 8 and 12-week intervals. Oxygen would diffuse through the porous corrosion layer and reduce on the magnetite layer, lying on top of the electrode surface. The selected model for each curve exhibited minimum gooness of fit values for both PSO and CNLLS procedures, a diffusion layer thickness compatible to the corrosion products layer, as observed by stereoscopic observations and kinetic parameters that could be ascribed to a charge transfer/ double layer time constant [33].

From this survey, we conclude that TiN coating in HSS cutting tool had effectively increased the tool life and cutting parameters.

Conclusion

The research survey indicates that parameters related to tool life and performance; it was observed that tool damage is a major phenomenon which affects the drilling tool life and surface finish of the holes in the work piece. It was followed by hard coating substances like TiN, TiC and Al_20_3 which improved the cutting tool capabilities. Also, studies revealed that the performance and life of the drilling tool is high in case of coated tool when compared to the uncoated tool. The recent studies and researches focus on the development of cost effective coatings on the drilling tool by conducting various drilling experiments. Following the experiments made in the past TiAlN and CrN coated tool performs better and reduces wear thereby increasing the tool life to greater extent. These hard coating enable high speeds accurate drilling, reduces the tool wear and increases the length to diameter ratio and increases heat dissipation on the surface of the drilling tool which increases the tool life. Thus coating on cutting tool improves the surface roughness, chemical stability, and tool life.

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