Surface Engineering - Applied Research and Industrial Applications
Room Palm 5-6 - Session IA3-WeM

Innovative Surface Engineering for Advanced Cutting and Forming Applications

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8:00am **IA3-WeM-1 How to Design a Coating for Metal Sheet Deformation Starting from Cutting Tools***, **Alessandro Bertè (berte@lafer.eu)**, P. Colombi,* Lafer Spa, Italy **INVITED**

Metal sheet transformation processes still represent a fundamental sector of activity for the mechanical industry and for PVD coatings as well, as the latest have a primary role in reduction of production costs, thanks to the increase of the life of the mold and the reduction of friction during the molding phase.

Lafer has always invested in research for innovative surface treatments including coatings, aimed to improve the state of the art, in order to increase wear resistance of the moulds.

This research focuses on the mold throughout its entire life cycle, starting from its machining process and ending to its application on the field.

For this reason, the goal is twofold: namely to develop a coating for cutting tools used during mold construction while creating a high-performance coating for ferrous metal sheet deformation.

The starting point concerned the cutting tool: once the geometry and the material to be machined were defined (1.2379 steel hardened to 62 HRC), the influence of cutting edges preparation, coating and post-finishing techniques were investigated with the aim of minimizing tool wear.

Various coatings formulations on the market, specific for this application, were tested (AlTiN, AlCrN, AlTiSiN) and subsequently an AlTiSiN-based coating was developed using HiPIMS technology: the study allowed the improvement of the thickness uniformity, increasing the coating adhesion while optimizing its hardness and elastic modulus.

All the tested solutions were compared in terms of the wear of the cutting edges, finding that the HiPIMS AlTiSiN coating reached the best performances.

The second part of the project concerned the mold: a demanding geometry for ferritic metal sheet molding was identified and the cutting tools for the machining of the mold were prepared with the method defined above.

Field tests were carried out by comparing the uncoated mold against the current Lafer solution on the market (TiAlCN), based on the number of compliant produced parts.

Subsequently, a new TiCN-based coating deposited with arc technology was developed: the various tests led to a reduction of the friction coefficient and coating wear rate and increase of its fatigue resistance, measured through multiple impacts technique.

A molding comparison between the new and the actual solutions was carried out: the new coating led to a reduction in lubricant consumption and a significant increase in the number of produced parts.

Future developments will investigate the joint effect of a surface hardening process underneath the newly developed PVD coating and its performances with different types of metal sheet materials.

8:40am **IA3-WeM-3 Effect of Current Density on the Pulsed-DC Powder-Pack Boriding Process (PDCPB)***, I. Campos-Silva,* ***J.L. Rosales-Lopez (jrosales96@hotmail.com)****, M. Olivares-Luna, K. Chaparro-Pérez, E. Hernández-Ramírez,* Instituto Politécnico Nacional, Mexico*; A. Contreras-Hernández,* Tecnológico Nacional de México/Instituto Tecnológico de Tuxtepec, Mexico

In this study a novel method denominated pulsed-DC powder-pack boriding process (PDCPB) was used to develop FeB/Fe_2B layers on the surface of an AISI 316 L steel. The layers were obtained at 1123 - 1223 K, exposure times of 1800 – 7200 s for each temperature, employing current densities around of 230 and 460 $mA\cdot cm^{-2}$ with polarity inversion changes of the electric field of 10 s over the material's surface. A boriding agent composed by 70% B_4C, 20% SiC and 10% KBF_4 was used for the entire set of experimental conditions. The diffusion/electromigration-controlled growth of the FeB/Fe_2B layers on the AISI 316 L steel was validated by the "Mean Diffusion Coefficient" model. A positive effect of the current density on the boron activation energies of FeB and Fe_2B (~157 and ~165 $kJ\cdot mol^{-1}$ for the results obtained on 230 $mA\cdot cm^{-2}$, and ~150 and ~147 $kJ\cdot mol^{-1}$ at 460 $mA\cdot cm^{-2}$, respectively) were obtained; these results were lower (20% for the current intensity of 230 $mA\cdot cm^{-2}$ set and 26% for the current intensity of 460 $mA\cdot cm^{-2}$, respectively) than those reported for conventional powder-pack boriding process.

Furthermore, during the heating and electric field induction periods of the PDCPB, the temperature between the electrodes (T_E) and the electrical resistivity of the boriding agent (E_R) were sampled. In the same way, the induction of the electric field during PDCPB was possible due to KBF_4 percolation in the boriding agent and the transformation of part of the electron flux kinetic energy into heat (Joule effect), reducing drastically the E_R.

9:00am **IA3-WeM-4 Challenges Dealing with Industrial Coating Development and Tailor-Made Production***,* ***Klaus Pagh Almtoft (kpa@dti.dk)****, B. Christensen,* Danish Technological Institute, Denmark **INVITED**

The materials requirements of manufacturing industries encourage job coating companies to develop and adapt improved coatings or customize existing ones for emerging markets. The combination of coating research and development (R&D) for industrial applications, tailor-made coating solutions and job coating presents several practical challenges and opportunities.

One of the primary challenges in practice is translating R&D outcomes into scalable production processes. While the laboratory environment enables precise coating control and optimization, replicating these conditions on an industrial scale often proves difficult. Factors such as process variability, equipment limitations, the influence of complex geometries of real parts, and time and cost constraints can significantly impact the feasibility of implementing new coating technologies and processes. Different time scales between R&D and production may further complicate the process. In the pursuit of a solution, understanding every detail of the underlying science is not always feasible. A pragmatic approach can expedite the development process but requires a high expertise to avoid pitfalls.

Tailor-made solutions, while offering a high degree of customization, come with their own set of challenges. In daily PVD job coating operations, low volume production of certain parts demands flexibility and often non-standardized batches – frequently with mixed types of parts. This increases the need for skilled and highly experienced people to ensure consistent coating quality and performance. Additionally, coating processes developed for such applications need to be sufficiently robust to ensure the desired functionality, even when the geometrical setup of the coating system varies. In some cases, the use of simulation tools aids in optimizing batch setups to ensure sufficient coating homogeneity or thickness on the critical surfaces of components.

Despite these challenges, the potential benefits of customized coating solutions are substantial and serve many customers having a limited number of parts. By aligning R&D efforts more closely with production realities, it is often possible to accelerate the development of tailor-made PVD coatings and improve their production adoption.

This talk discusses some of the complexities encountered in bridging the gaps between R&D and production, focusing on applied customized sputter coating solutions and regular job coating. Practical examples of R&D using industrial scale DCMS and HiPIMS coatings for machine components and tools will be used as cases.

9:40am **IA3-WeM-6 a Comprehensive Study of HiPIMS Coated Tool and Microtool Performance: From Edge Preparation to Micro-Machining Tests***,* ***Pablo Díaz Rodríguez (pablo.diazr@nano4energy.eu)****, J. Santiago,* Nano4Energy, Spain*; A. García,* Nano4Energy, Colombia*; I. Fernández, A. Wennberg,* Nano4Energy, Spain*; P. Collignon,* PD2i, France*; Á. Guzmán, D. Sanmartín, J. Molina-Aldeguia,* Universidad Politécnica de Madrid, Spain*; M. Monclus,* IMDEA Materiales, Spain

The high standards and requirements demanded in high-speed machining (HSM) applications – some examples are the precise manufacturing of IC Molds or biomedical devices - comprise a delicate control of the tool preparation as well as coatings design and finish, especially in the case of microtools with a diameter below the millimeter.

The work developed covers not only the coating step, but also the preparation of the tool, focusing on:

a) Microtool cutting edge preparation.

b) HiPIMS deposition, as the use of this technology allows the preparation of hard coatings with high smoothness, low density of defects, and good homogeneous coverage of 3D intricate parts (thus able to match the low tolerances required for micromachining) makes this technology ideal for these applications. The tested coatings are based on Si- and B- containing AlTiN and were deposited in different sets of tools, according to their specific requirements, attaining hardness values of 35 GPa and good adhesion. Moreover, oxidation studies were performed to determine the stability of these coatings, analysing, and comparing the results in terms of SEM, TEM, and XRD, observing a greater oxidation resistance for the Al containing coatings.

c) Machining tests, which, in addition to mechanical properties analysis, provide information regarding the performance of the coatings under operation conditions. The materials selected for machining are Hardened Steel (HRC60) and Ti6AlV4 alloy, and the finishing of the machined parts, as well as the wear suffered by the tool is analyzed.

11:00am **IA3-WeM-10 Effect of Phase Separation in the Anticorrosion Performance of AlCrFeNi High-Entropy Alloy***, **Chih-Chen Lee (janislee0123.en12@nycu.edu.tw)**, I. Tasi,* National Yang-Ming Chiao Tung University, Taiwan*; H. Chen,* Michigan State University, Taiwan*; C. Chen,* National United University, Taiwan*; S. Chen,* National Yang-Ming Chiao Tung University, Taiwan

Due to reaching net-zero emissions, offshore wind power is one of the methods to get clean energy. To improve the anti-corrosion performance of wind turbine towers, researchers are always seeking the candidates to enhance or replace the stainless steel 316 base material. In our study, we found that AlCrFeNi HEA exhibited a better anti-corrosion performance than SS 316 in both the salt spray and acid immersion test. Especially, its corrosion resistance could be significantly improved by controlling the phase ratio. Gas-atomized HEAs can retain the ideal high-entropy state owing to the sluggish effect and rapid cooling process. The as-atomized AlCrFeNi powders presented a superior resistance to acid solutions, but weakened after experiencing high temperature environment. Through careful investigations, it was found that Al and Ni elements have the lowest mixing enthalpy, promoting the preferential formation of AlNi phase from the uniformly distributed matrix. As a result, ordered AlNi and FeCr phases are formed within the BCC structure. It has a chemical composition closely matching the designated component ratios, composed of a BCC/B2 phase composed of AlNi and a BCC/A2 phase composed of FeCr. From the acid immersion test, we found that the rich AlNi phases were preferentially corroded, decreasing corrosion resistance. Furthermore, argon gas was commonly used to atomize the melt and has a lower specific heat capacity, which allows sufficient time for melted droplets to form spherical shapes with better flowability due to cohesive forces. The AlCrFeNi HEA powder produced by gas atomization exhibits a good anti-corrosion performance because it maintains the initial high randomness phase and prevents the segregation of elements. It also shows a spherical shape and excellent flowability, making it suitable for coating applications in harsh environment.

Keywords: High-entropy alloys, Gas atomization, AlCrFeNi, Annealing, Phase transition, anti-corrosion performance

11:20am **IA3-WeM-11 Surface Conditioning and New Applications Using Advanced Plasma Etching Technology***, **Dominic Stangier (dominic.stangier@oerlikon.com)**,* Oerlikon Balzers Coating Germany GmbH, Germany

Plasma etching plays an essential role for the vacuum-based cleaning of tools and components to remove native oxide films and small contaminations. This inherent treatment of the substrate material prior to every PVD process directly influences the adhesion and consequently the overall performance of the substrate coating compound. Therefore, different processes such as glow discharges and metal ion etching methods are commonly conducted, which are however on the one side strongly limited in their etching rate as well as performance and on the other side lead to macro defects on the surface of the substrate significantly reducing the performance of the coated tools. To overcome these challenges an improved etching process, which combines the high plasma density of cathodic arc evaporation with a noble gas-based glow discharge called advanced Arc Enhanced Glow Discharge (AEGD) is used. In this context, the unique possibility to independently control the bias potential and freely modulate the pulse pattern with a simultaneous scalable plasma density for the etching process open up a broad field of new pre-treatment options for PVD coated tools.

Fundamental investigations for the limits and correlations of the aforementioned etching parameters on the surface condition, near subsurface region and the coating adhesion of nitrides are conducted using cemented carbide substrates. The etching rate is directly linked to the applied bias level as well as to the current used on the cathode and anode. As a result of the high etching rates, a new approach for a targeted cutting edge preparation for micro tools is presented, showing the possibility of generating asymmetric cutting edge shapes (form factors up to $K = 2.7$). The performance is evaluated in milling tests, proving a reduction of the process forces for milling HSS (62 HRC). Furthermore, for tool steels an adjusted composition of the plasma allows the nitriding of the surface near region, which also leads to improved performance of coating systems for dies and molds. Thus, the presented investigations prove the extended possibilities and application fields offered by the advanced AEGD technology.

11:40am **IA3-WeM-12 Advances in Microhard Machining: From Etching-based Asymmetrical Cutting Edge Preparation to Cutting Performance of TiAlN-based Thin Films***, **Nelson Filipe Lopes Dias (filipe.dias@tu-dortmund.de)**, A. Meijer, C. Jäckel, D. Biermann, W. Tillmann,* TU Dortmund University, Germany

Micromilling of hardened and tempered tool steels offers significant potential for die and mold manufacturing due to the high precision in dimension and shape of filigree geometries combined with high surface integrity. Nevertheless, the high hardness of these steels impose considerable thermo-mechanical loads on the cutting edge of micromilling tools. Hence, it becomes essential to employ an adapted combination of cutting edge preparation alongside the application of wear-protective PVD thin films with improved properties. This integrated approach is crucial for enhancing cutting performance and prolonging the service life of tools when machining hard materials. Arc-enhanced glow discharge (AEGD) ion etching emerges as a promising pretreatment, serving not only to enhance thin film adhesion, but also to produce asymmetrical cutting edge geometries in small scale for micromilling tools of ultrafine-grained WC-Co cemented carbide. Already 15 min of AEGD ion etching yields in considerable cutting edge rounding and the formation of asymmetrical shapes with form-factors $K \geq 2$. The obtained cutting edge geometries promote favorable cutting behavior in terms of process forces and wear development in machining tests of a hardened and tempered powder metallurgical high-speed steel (AISI M3:2). In addition to the AEGD ion etching pretreatment, the effectiveness of micromilling tools substantially relies on the application of a protective PVD thin film with enhanced tribo-mechanical properties. Both the selection of the TiAlN-based thin film system and the employed sputtering technology play pivotal roles in determining the cutting performance of the coated tools. In comparison to the traditional TiAlN, quaternary TiAlSiN and TiAlTaN thin films exhibit superior wear resistance for micromilling tool steels with high hardness and carbide content. The use of high power impulse magnetron sputtering (HiPIMS) further enhances cutting performance and wear resistance, particularly for TiAlSiN. To overcome the low deposition rates of pure HiPIMS processes, a hybrid approach combining direct current magnetron sputtering (dcMS) with HiPIMS is a viable alternative, taking advantage of the benefits of both processes. This hybrid dcMS/HiPIMS technique also proves beneficial in producing TiAlN-based thin films that exhibit improved cutting performance and wear resistance compared to pure dcMS thin films. These findings emphasize the importance of a coordinated approach involving ion etching and PVD deposition for effectively reducing wear and process forces in micromilling difficult-to-machine materials.

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