Study of Wear & Corrosion Resistance of Cold Sprayed Components

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***Abstract* – There is a major loss of material and process is observed in engineering application due to corrosion and wear. As the operating conditions are varying enormously, the mechanical component undergoes wear and corrosion for achieving wear resistant coating. Previously hot metal spray technique is used, which is now a day replaced with cold spray. There are many advantages of it over hot spray such as avoid melting and solidification, negligible thermal induced stress on substrate, avoid undesirable phases, avoid oxidation and higher deposition efficiency, good surface finish etc. There is a brief enlightening on wear mechanisms observed (corrosion, fatigue, adhesive and abrasive wear). In this technique the deposition efficiency is more. It's Deposition Efficiency increases as the velocity of powder is increased. It can coat 5 – 50 mm ultra thick coating to serve its purpose. The case study shows utilization of cold spray technique and different material which coats substrate and their results. This case study is of orthopedic implants and effect of cold spray coating of different metals and their positive effects on human body. It shows that Tantalum gives a better wear resistance, good bio compatibility as well as long life (50 years). As Ta is having high surface energy, there is a better interaction between cell and material.**

Index Terms - Ta, GLC, DLC, Wettability

I. Introduction

Thermal Spray technology is used extensively in defence, aerospace and gas turbine industries. Typical applications include fabrication of components, preparation of protective surfaces, refurbishment of mis-machined and service-damaged parts, etc. Recently, a new Thermal Spray process, known as Cold Spray process, has been introduced to produce metal, alloy, and composite coatings with superior qualities. Cold Spray process uses high velocity rather than high temperature to produce coatings, and thereby avoid/minimize many deleterious high temperature reactions, which are characteristics of typical Thermal Sprayed coatings. Typical advantages of Cold Spray coatings include compressive rather than tensile stresses, wrought-like microstructure, near theoretical density, oxides and other inclusions -free coatings, etc. Moreover, the footprint of the cold spray beam is very narrow yielding a high-density particle beam, which results in high growth rate of coating thickness with better control over the shape of the coating, without masking requirements. These advantages can be gainfully exploited for producing engineered bulk forms and coatings for many strategic and other high tech applications.

Cold Spray is a relatively young process and still considerable R&D efforts are needed to understand and control the process, as well as develop engineered coatings with desired properties for specific applications. The last few years have seen exponential growth of cold spray R&D around the globe. Considerable R&D efforts are being undertaken at various laboratories, academic institutions, and industries. These studies include process diagnostics and modelling of the process and the jet, modelling of the coating formation, spray optimization and application coating development. Europe, in particular, Germany is leading the technology development and applications.

The basic principle of cold spray is simple (Fig. 1). When a particle-laden gas jet impinges on a solid surface, three different phenomena occur, depending on the particle velocity (Vp). When Vp is low, the particles simply reflect (bounce) off the surface. When Vp reaches moderate values, solid particle erosion of the surface occurs. When Vp exceeds a critical value (which varies with particle and substrate materials – typically in the range of 500-900 m/s), particles plastically deform and adhere to the substrate/one another to form an overlay deposit, analogous to thermal spray coatings. Russian scientists, carrying out supersonic wind tunnel tests, first observed this phenomenon.

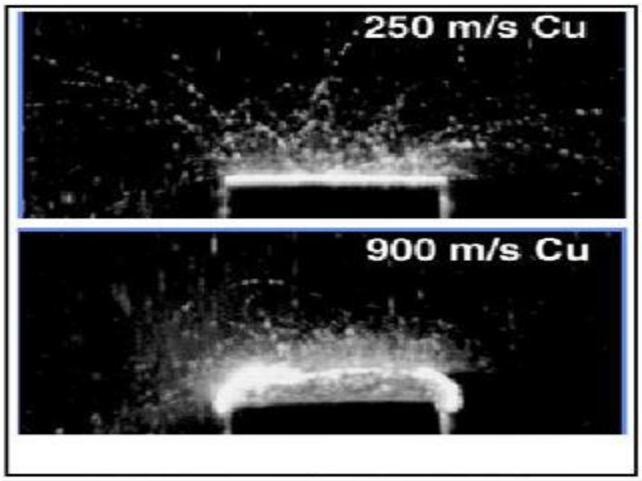


Fig 1 basic principle of cold spray

Cold spray process uses a high pressure, high velocity gas jet to impart the velocity for the coating particles. A high-pressure jet, preheated to compensate for the adiabatic cooling due to expansion, is expanded through a converging/diverging nozzle to form a supersonic gas jet. Powder particles, transported by a carrier gas, are injected into this gas jet. Momentum transfer from the supersonic gas jet to the particles results in high velocity particle jet. These powder particles, on impact onto the substrate surface, plastically deform and form interlinking splats, resulting in a coating.

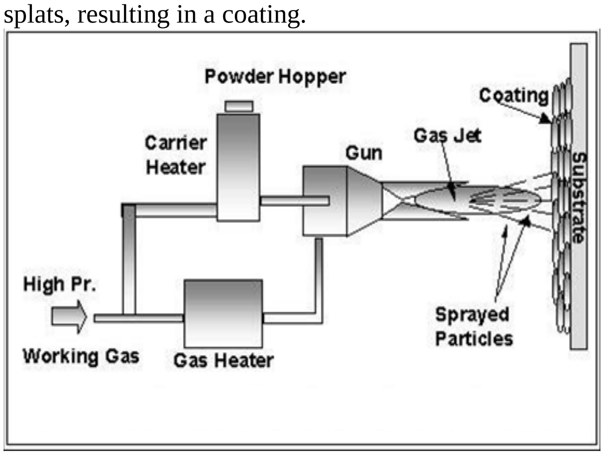


Fig 2 Schematic representation of cold spray process

II WEAR MECHANISM

A. Adhesive Wear

If the contact interface between two surfaces under plastic contact has enough adhesive bonding strength to resist relative sliding, large plastic deformation caused by dislocation is introduced in the contact region under compression and shearing. As a result of such large deformation in the contact region, a Fig 2

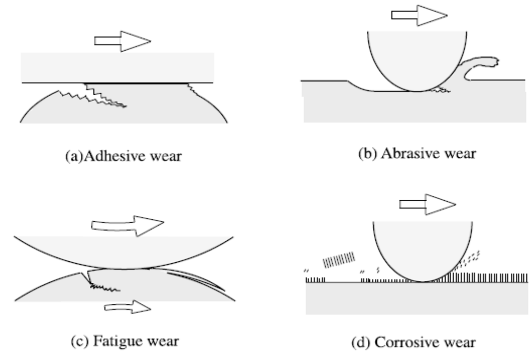


Fig 3 Schematic images of four representative wear modes

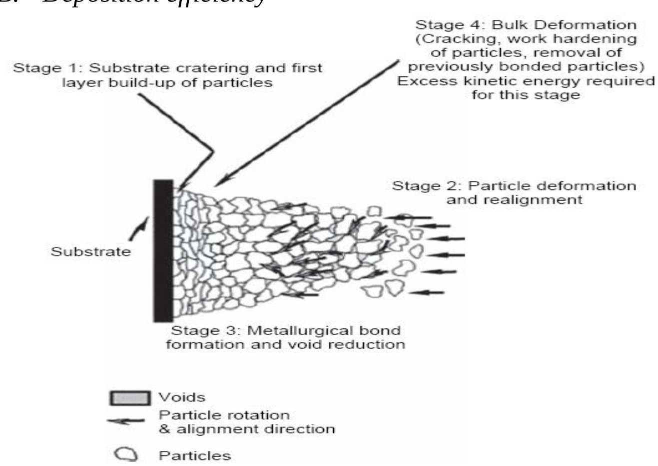
Crack is initiated and is propagated in the combined fracture mode of tensile and shearing. When the crack reaches the contact interface, a wear particle is formed and adhesive transfer is completed. This type of wear, which occurs when there is enough adhesive bonding at the contact interface, is called adhesive wear.

III PROCESS RELATED FACTORS AND SIGNIFICANCE

A. Adhesion mechanism

To clarify an adhesion mechanism of the sprayed particle onto substrate surface, evaluation of adhesion strength of an individual particle by nano-scratch testing was conducted. To do this, cold spraying of copper particle onto mirror polished steel substrate was carried out by traversing the spray torch quite rapidly under the designated spraying conditions. By this method, particles adhered onto substrate separately and it can be scratched one by one easily. The shear load was measured by this equipment and the actual shear stress can be given by measuring the bonded area of the particle after scratching.

B. Deposition efficiency



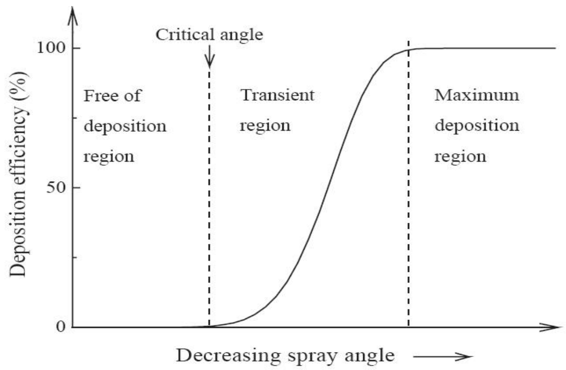


Fig 4 The schematic view of different region of particles on substrate

Second, adhesion of particles depends on many factors: area of the contact surface, crater depth, plastic strain, yield stress, pressure and temperature at the contact boundary, etc. In turn, these factors are affected by the impact velocity of the particle. Therefore, it seems logical to assume that these parameters reach their critical values at velocities close to the critical one or their dependence on velocity becomes different. Postulating of some adhesion criterion requires these critical values and conditions to be determined. But in the simplest way the deposition efficiency calculated experimentally as follow:

$$kd = \Delta ms/Mp \quad (1)$$

where **Δms** is change of weight of a substrate and **Mp** is weight of all particles interacting with a substrate.

IV CASE STUDY ON ORTHOPAEDIC IMPLANTS

Hee Ay Ching et al [4] discussed that coatings are normally used to improve the surface properties of the substrate without changing the bulk materials. Moreover, coatings can act as an effective barrier to minimize the release of ions attributing to tribo-corrosion. It can increase the hardness along with excellent surface finishing, thus reducing the friction and wear rate. However, one limitation of coatings is their adhesion to the substrate allowing the interactions of chemical bonds between the layers. Moreover, their abilities in cyclic loading condition are still being researched. It is necessary to define coating dimensions (thickness, hardness and surface finish) which have an ability to protect the substrate from the excessive wear (abrasive, fatigue and corrosive) and to provide a low friction transferring film on the opposing surface.

This review focuses on four main types of coatings which are Ta, GLC, DLC and TiN. DLC and TiN have been used in many orthopaedic applications. GLC possess both hardness and flexibility. Porous Ta is found to have a similar material structure to bone. Ta is a biocompatible metal and it possesses excellent corrosion resistance with low ion release. It is also suitable in the coating of implant surface among most of the materials used in hip or knee implants such as stainless steel, ceramic, cobalt–chromium and titanium alloys. Balagna et al presented the work on Ta-rich coating deposited on cobalt–chromium–molybdenum (CoCrMo) alloys through a thermal treatment in molten salts. Ta coating with thickness less than 1μm is a suitable implant for the substitution of joints owning to its good wear resistance. The surface TiN was first introduced back in the 1980s for ceramic coating of artificial hip and knee replacements. TiN coating in golden colour is normally deposited by PVD or laser deposition. Tribological testing showed a very good wear rate for TiN against PE. In addition, it exhibits an increase in hardness and a decrease in metal ion release from the substrate. The ceramic layer reduces the release of metal ions into the patient's joint space and minimizes bacterial proliferation.

A. Tribological outcome of coating

Many attempts have been made to minimize the friction and wear of implant materials including the use of different sizes, shapes and clearances (design parameters) in artificial hip or knee implants. Hip simulator testing has shown that metal on metal bearing has a conferrable low linear (40 times) and volumetric (200 times) wear than a metal-on-UHMWPE couple. However, a few studies have shown evidence of high toxicity due to generated metallic or UHMWPE particles. Therefore, an appropriate coating does not only improve upon friction and wear but also increases the acceptability of implanted joints. Wear damage to the articulating surface is associated with the frictional forces at the interface. The coefficient of friction depends on the materials and the surface finish of the articulating surfaces in the lubricating regime. A better wettability will increase the lubrication, thereby decreasing the coefficient of friction and subsequently reducing the wear.

Ta coating with a lower surface roughness value gives a better wear rate. Ta coated on CoCrMo with a surface roughness of 5–12 nm exhibited a lower wear rate in the range of 4×10^{-7}–5×10^{-7} $mm^3\ N^{-1}\ m^{-1}$ compared to Ta coated on the biodur alloy with 40 nm of surface roughness and wear rate in the range of 0.755×10^{-4}–1.249×10^{-4} $mm^3\ N^{-1}m^{-1}$. GLC coatings have high adhesion normally associated with a high ion current density magnetron sputter ion plating system. Low wear rates can be obtained when high hardness is combined with low friction. The excellent mechanical properties with good adhesion of the GLC coatings will result in high load-bearing capacity. GLC has a wear coefficient about ten times lower than conventional hydrogenated DLC coatings. GLC also has a lower coefficient of friction. Adhesion tests were used to reveal the quality of the coatings in terms of their abrasive wear potential in artificial joints. The surface scratch resistance of GLC coating prevents implant damage at excessive contact load up to 140 N. The scratch formation is minimal, which results in a substantial reduction in wear at 3×10^{-8} $mm^3\ N^{-1}m^{-1}$ as opposed to DLC coatings.

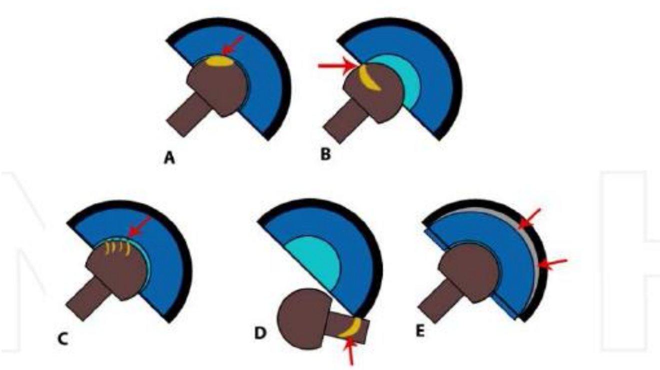
Surface wettability is determined using water contact angle measurement. A low water contact angle gives a hydrophilic surface which can generally provide better adhesion. However, the hydrophilic surface has the tendency to attract more water molecules from the atmosphere if the humidity is high. The adhesion strength between the film and the substrate will decrease with the presence of water molecules on the solid substrate. Tribological tests showed that a higher hardness in the intermediate layers gives better penetration resistance to soft UHMWPE film, reduces the contact area of the ball and promotes wear durability.
Wear and friction are greatly reduced by using DLC in total hip and knee replacement devices. The wear rate and the coefficient of friction of the coated surface are measured using a commercial ball-on-disc tribometer. Wear test is carried out in a rotating vessel with UHMWPE discs immersed in bovine serum (b-9433, Sigma Aldrich). Wear factors, *k* can be calculated using the following equation:

$$k = 2r\,A/Ls, \qquad (3)$$

where ***r*** is the wear track radius, ***A*** is the average worn area, ***L*** is the applied load and **s** is the sliding distance .

The wear rate of the coating is very dependent on the variables like liquid lubrication, temperature and DLCH composition. The wear rate decreased with the sliding distance. An initial polishing of the sample and an associated increment of the contact area result in reduced contact pressure. Cross linked UHMWPE and pristine UHMWPE showed improved wear resistance compared to uncoated materials, which made them suitable for substrate with thin coatings. DLCH is an ideal option in modular implants as it provides better wear resistance and good adhesion to the substrates.

Compatibility of coating materials with surrounding tissue



The modes of wear for a total hip arthroplasty: A: Mode 1 or normal wear, B: Mode 2 or subluxation wear, C: Mode 3 or third body abrasive wear, D and E: Mode 4
Courtesy: Hamid Reza Seyyed Hosseinzadeh et al

The biocompatibility of coated surfaces can be judged by bacterial adhesion, wettability, cell growth rate on the surface and cell death rate by the wear generated debris. Hydrophobic surfaces (contact angle higher than 90deg) are good for bearing materials used in an acetabular prosthesis component in joint replacement. It was suggested by the researchers that films with low hydrogen content and hydrophobic properties increased the rate of bactericidal activity. A coating with antibacterial properties is extremely important in reducing the risk of infection. Ta is a biocompatible metal that possesses a porous structure similar to spongious bone as the commercial trabecular Metal for various orthopaedic applications. It is suitable for cell adhesion, proliferation and differentiation and deposited Ta oxide and nitride could be applied in cardiac and vascular devices. Pure Ta has a lower bacterial adhesion compared to commercially available materials used in orthopaedic implants. This is due to higher wettability of Ta surface in both distilled water and cell media with contact angle of 51deg and 48deg, respectively. Furthermore, the study confirms that the Ta surface has better interaction between cell and material as Ta has higher surface energy. The low porosity of Ta surface has sharp interface between coating and the interface, resulting in high fatigue resistance, which is applicable to early biological fixation. However, we could not find any paper that studied the protein deposition rate and synovial fluid contact angle on Ta coated surfaces. GLC coatings have shown no biocompatibility problem when tested for use in artificial hip joints. The GLC coated hip joints will have an estimation of at least 50 years compared to uncoated joints with the usage of about 10 years. Generally, it can be used in knees and other joints.

V. CONCLUSIONS

A number of materials have already proven to be suitable for deposition by cold spray from decorative articles to biomedical, automotive, power plants and space industries. Extensive research is required to design the optimum parameters like nature of gas, temperature control, nozzle design and its material and also prediction of critical velocity for different particle/substrate combinations. The research area of mathematical modelling to optimize various design parameters is still open to expand this process to more non-traditional applications. Research is required on deposition of hard and brittle ceramic materials by cold spray.

It is observed that by using CS we can resist corrosion as well as improves its texture.

By cold spray we can reduce friction by controlling wettability by precisely selecting material.

We can improve thickness of objects in many industrial applications.

We can effectively minimize friction in orthopaedic implants.

Porosity can be minimized by using gases like helium which imparts more kinetic energy to particle.

Thermal conductivity can vary by depositing other elements.

This can be effectively used with many metals combination.

Further study could consider with other parameters like s protein deposition rate and synovial fluid contact angle on Ta coated surfaces. The ongoing work is mainly on deposition efficiency and homogeneity of material. One can go with detailed analysis and study of Inconels and Tantalum spraying for minimum and effective coating for any application. Another way to put forward is to improve cold spray durability with brittle material with minimum Helium usage.

Carry out experimentation for different types of combination for more competent data. The cold spray coating process has huge potential of growth with more applications in new areas like in boiler industry, to increase the life of boiler tubes by prevention from high temperature corrosion in aggressive chlorine and sulphate based environments.

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