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## **CONTROLLED HVOF HARD COATINGS REMOVAL METHOD**

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### **ABSTRACT**

There is an increasing demand for recoating of the expensive coated components like turbine blades, rollers and pumps. For economical recoating an efficient coating removal (stripping) method is required. This paper presents the development of the adaptive Abrasive Water Jet (AWJ) stripping method. The method was applied to remove the WC-CoCr and Cr<sub>3</sub>C<sub>2</sub>-NiCr HVOF coatings in a controlled manner. In the test run the coating thickness was reduced (stripped) down to 10-20 µm without damaging the base material. Aluminum oxide powder (Al<sub>2</sub>O<sub>3</sub>) was applied as an abrasive. With this novel method the use of the environmentally problematic chemicals can be significantly reduced or entirely avoided.

A fast measuring system capable to measure the coating thickness non-destructively with adequate accuracy was integrated to the AWJ removal cell. The recorded coating thickness values were applied to control the power of stripping and to stop the stripping before the coating is completely removed thus preventing the unwanted base material erosion. The applied measuring technique depends on the coating and base materials. The eddy current or X-ray fluorescence methods can be applied to measure the coating thickness. The measurement results of samples with magnetic substrate are described. Two industrial applications of the AWJ method are given, one focusing on the method validation and the future prospects in the aircraft industry (KLM) and another on the coating removal of the components applied in the process industry (HT Lasertekniikka).

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## **1. INTRODUCTION**

Hard coatings are widely used to protect various industrial components from wear and corrosion. Electroplating, especially hard-Chromium is often used coating for wear resistance applications. Due to the environmental problems associated with this process (hexavalent Chromium) an increasing concern has lead to the search for alternative coating methods. Thermal spraying is becoming increasingly popular, especially HVOF (High-Velocity Oxygen-Fuel) spraying of hard metals, such as WC-Co and Cr<sub>3</sub>C<sub>2</sub>-NiCr. Due to the harsh environment where coatings are used, coating can be damaged and a need for recoating of components exists. Whilst HVOF process gives excellent coating due to the very high adhesion and dense structure it is very difficult to remove.

The current methods to remove HVOF coating are chemical stripping or mechanical grinding. Chemical stripping of HVOF coatings is environmentally damaging and typically requires high temperature or electro-chemical baths and immersion times in the range of a couple of hours till days (depending on the coating thickness) [1]. Water jet removal is an attractive method, although it is relative aggressive towards the base material. High pressure water jet removal combined with abrasives was considered to offer a potential solution for a fast, accurate and environmentally friendly method of HVOF coating removal.

Typically used coating thicknesses in HVOF hard metal coatings are between 150-300 µm. More often used base materials are low carbon or stainless steels in the general industry and super alloys in the aircraft industry. Due to the fact that hardness of HVOF coating is much higher compared to the substrate, the removal rate of coating and base material varies largely with abrasive water jetting. This is imposing a problem: Once the interface is reached, there is no inherent physical reason for the coating removal to stop at the interface. To be able to select the removal parameters and to stop the removal before the interface between the coating and the substrate has been crossed, a method to measure the coating thickness is needed. Monitoring of the coating thickness during the removal process with a fast and reliable measurement method enables controlled and efficient coating removal.

The main purpose of the work introduced in this article was to develop a procedure to remove HVOF sprayed hard coatings. An ultra high pressure (UHP) water jet system together with abrasives was used for this purpose and an Abrasive Water Jet (AWJ) coating removal method was developed. Such method can be applied effectively only for wore or damaged coating area instead of the whole work piece. Combined to the AWJ method a sensor system to control the material removal rate was developed to prevent unwanted removal of base material. Two industrial key players were behind the project. KLM was interested in abrasive system which can be retro fitted to KLM's existing water jetting equipment and HT Lasertekniikka was interested in finding new applications for their existing water jet cutting robotic system.

## **2. EXPERIMENTAL PROCEDURE**

### **2.1 Abrasive Water Jetting**

The Abrasive Water Jet process is based on the fact that the high-velocity water jet is ejected through a mixing chamber, where the passing through water jet generates vacuum which sucks abrasive to the water jet from the abrasive line. The abrasive continue to mix to the

water jet and abrasives are accelerated in the following mixing tube. Mixing tube (= focusing tube or slurry nozzle) focus the AWJ into a coherent stream/jet and it directs the stream towards the required point on the target surface. From the AWJ nozzle end there is a needed stand-off distance where some energy is lost as the AWJ stream moves through the air or other fluid. When the jet reaches the target surface the remaining power in the jet is applied in the removal of material. A schematic view of system generating AWJ is shown in Figure 1.

## **2.2 Material Removal Mechanism**

The basic material removal mechanisms in AWJ techniques are very similar to erosion and especially to the slurry erosion. Two common mechanisms of the particle erosion are abrasion and fracture. The abrasive erosion is typically associated with shallow angles, while fracturing is usually associated with the large angles of particle impact. The principles of the erosion depend on whether the target material is ductile or brittle. The ductile erosion is defined as a cutting process in which the abrasive particles cut the eroded material causing volume loss. The brittle erosion is described as a deformation or cracking process in which the abrasive particles remove material by forming a network of intersecting cracks from which material eventually breaks out as a result of direct particle impact. For materials such as soft steel, the erosion is predominantly ductile, while for hard steel the process is predominantly brittle erosion. For glass, ceramics and rock, the erosion is best described primarily as a brittle erosion process [4, 5].

There are four sub-mechanisms for removing material from a target surface by solid-particles. These mechanisms are cutting, fatigue, melting and brittle fracture. These mechanisms do not work separately, but in combination. The importance for the particular erosion process depends on several factors, such as impact angle, particle kinetic energy, particle shape, target material properties and environmental conditions. The impact of single solid-particles is the basic event in the materials removal by AWJ.

## **2.3 Test facility and parameter selection**

In this project a commercially available AWJ working cell with a robot was used. A robot program was applied to use locally measured coating thicknesses to adjust the stripping power during the stripping. Depending on the used HVOF coating or base materials different type of coating thickness measuring devices can be applied. The main parameters varying the effectiveness of the stripping performance of Abrasive Water Jet are [6]:

- Water: Surface tension, viscosity, pressure, flow rate.
- Water jet: Shape, orifice diameter, mixing tube length, diameter and stand-off distance.
- Abrasive feeding: Air density and velocity, abrasive density, feed rate and particle size and shape.
- Traverse speed and target material strength.

In this project the parameter matrix was too large to allow the experiment of all factors to achieve optimized parameters. Therefore a Taguchi algorithm (i.e. parameter estimation/calculation) was used to reduce the test matrix. Taguchi or other similar algorithms are normally used to predict the influence of parameter changes to the actual process [7]. Single grooves into HVOF sprayed hard coatings were machined using this

optimization results. Machined grooves were then inspected and feedback to the Taguchi calculations was made.

A very large number of different types of abrasives are used in the AWJ cutting. Most of the AWJ-shops use garnet (90%), followed by olivine (15%), slag (15%), aluminum oxide (11%) and silica sand (11%). Most users have found garnet to be the best for them in terms of cost, cutting speed, mixing tube life and health hazards. Most of the AWJ users prefer abrasive mesh sizes #50, #60, #80 and #100 [8].

In this project white angular corundum,  $Al_2O_3$  (aluminum oxide), was used because it is possible to recycle or re-use the corundum and the aviation industry generally are not using i.e. steel (Fe) containing abrasives like garnet.

## **2.4 The applied test specimens and measurement techniques**

Altogether 83 specimens with different coating thicknesses and different coating and substrate materials were fabricated and studied. The applied substrate materials were low carbon steel (S355J0), AISI 304, AISI 316 and aluminum. The applied coating materials were  $75Cr_3C_2-25NiCr$ ,  $WC-10Co_4Cr$ ,  $WC-Ni$  88/12 and Hastelloy C. The coated surface of some specimens was ground to see the effect of the surface roughness. Additionally some turbine blades were studied.

The coating thickness of the fabricated specimens was measured using eddy current, ultrasonic and X-ray methods, altogether six different measuring techniques. The purpose of these measurements was to screen the applicable methods and techniques and to optimize the selected techniques.

The coating thickness of specimens with magnetic substrate were measured using a standard low frequency coating thickness gauge, the multifrequency (scanning frequency) eddy current technique, the ultrasonic technique based on material characterization probe and the X-ray fluorescence.

The coating thicknesses of specimens with the non-magnetic substrate were measured using a standard single frequency eddy current device, the multifrequency eddy current technique, the ultrasonic technique based on material characterization probe and the X-ray fluorescence.

The low frequency eddy current thickness gauge was applied in the first stripping tests. Thus only this technique is described more closely and the results of this technique are given in this paper.

### **2.4.1 Eddy current method**

The eddy current method is based on the interaction of the alternating magnetic field of the eddy current probe and the eddy currents induced in the electrically conducting specimen. The specimen composed of electrically conductive material has a dramatic effect on the electrical impedance of the eddy current probe, when the probe is set in the immediate proximity of the specimen. If the specimen is of magnetic material (like ordinary low carbon steel) the probe inductance is increasing strongly, as shown in the Figure 2. If the specimen is of nonmagnetic material (like ordinary stainless steel) the probe inductance is decreasing. In the Figure 2 the horizontal axis gives the normalized resistance and the vertical axis the

normalized inductive reactance of the probe. The impedance is normalized by dividing with the reactance of the probe when in the air and far from any conductible object. The detailed behavior of the probe impedance depends on the frequency of the driving current of the probe, the conductivity and magnetic permeability of the specimen as well as the probe size.

The distance between the probe and specimen (lift off) has the by far strongest effect on the probe inductance. When the permeability of magnetic material is decreasing, the probe impedance is approaching to the value achieved when the probe is set on a specimen of nonmagnetic material with equal conductivity. When the conductivity of nonmagnetic material is decreasing, the probe impedance is approaching the probe impedance in air. The smaller the conductivity of nonmagnetic material the smaller is the change of the probe impedance when the probe is set on the specimen.

#### 2.4.2 The low frequency thickness gauge

In this study the ordinary low frequency eddy current coating thickness gauge was applied to measure the thickness of the coating on ferromagnetic substrate. This gauge gives directly the coating thickness in micrometers. The gauge is actually measuring distance of the probe "face" from the ferromagnetic substrate material. Thus the probe must be in contact with the surface (or at fixed distance from the surface) during measurement. Any deviation of the distance or tilt of the probe gives rise to an error. Reference specimens of proper materials are not needed. Only ferromagnetic plate and plastic sheets with known thickness are needed for calibration. This kind of a gauge is quite cheap and simple to use.

The operation principle of the standard eddy current coating thickness gauge is based on low frequency eddy current method (sometimes called inductive method). This kind of a device is just measuring the inductance of the probe (lift off between the probe and the specimen). Due to very low frequency, the conductivity of the thin coating on the substrate of magnetic material like ordinary carbon steel has no remarkable effect on the probe inductance. Thus the thickness of a conductive or isolating coating material can be measured. Reference specimens of proper materials are not needed. The coating material to be measured must not be magnetic. This is prerequisite of the application of all eddy current methods for coating thickness measurement. Cracks or pores in the coating have no effect on the measured coating thickness values when standard thickness gauge is applied. Cracks extending to the substrate material give rise to serious errors in coating thickness measurement. The standard eddy current coating thickness gauge can not be applied to measure the thickness of conducting coating if the substrate is of non magnetic material like ordinary stainless steel.

### 3. RESULTS AND DISCUSSION

#### 3.1 HVOF Coating Removal by AWJ

Comparing the literature survey of made AWJ cutting processes research to the effects learned during AWJ stripping development we found some process similarities [2, 9]. The abrasive material characteristics like shape and hardness influence on the coating removal speed. The coating removal speed can be increased by:

- Increasing the working water pressure.
- Decreasing the traverse speed.

- Increasing the abrasive feed rate. Optimum feed rate for used coatings can be found.
- Decreasing the abrasive size. Optimum abrasive size for used coatings can be found.

An example of stripped coating depth and profile when three different parameter sets were applied is shown in Figure 3. The depths and shapes of the grooves were measured by using the mechanical profile meter.

The optimal working parameters for precise stripping process were found in the project. The coating thickness can be measured and by using that data the tested HVOF coatings were removed in a controlled way.

### **3.2 Measuring Optimization**

Hundreds of coating thickness measurements of fabricated samples was carried out. Several eddy current techniques were studied. Eddy current techniques were the fastest and the most versatile techniques. The measurement time may be as short as 10 ms. The best results were achieved with the multifrequency eddy current method when the substrate was not magnetic and the coating thickness was 50-100  $\mu\text{m}$  or more. When the coating thickness was 50-150  $\mu\text{m}$  or less the best results was achieved with the X-ray fluorescence when the substrate was not magnetic. The range of multifrequency and X-ray fluorescence techniques depends on the applied coating and substrate materials. When the substrate was of low carbon steel (ferromagnetic) the best results were achieved with ordinary eddy current low frequency coating thickness gauge.

In the following only the results of eddy current coating thickness gauge are given. An example of the achieved accuracy is given in the Figure 4. The true thicknesses and the thickness measured by eddy current gauge are given. The substrate material was of ferromagnetic low carbon steel.

The true coating thickness was measured with a microscope after the specimens were cut into two equal parts. After preparation of the cross section samples it was slightly problematic to decide whether the coating thickness was the maximum thickness or medium thickness. The applied thickness gauge measures the maximum thickness and other applied methods measure more or less the medium thickness (results not reported here). The roughness of the coating surface and the roughness of the interface between the coating and the substrate was approximately  $\pm 20 \mu\text{m}$ . To define the true coating thickness some visual averaging of rough surfaces had to be done.

The measured and the true coating thickness values had a very good correlation, Figure 4. The accuracy was good even when the coating thickness was small (10 - 25  $\mu\text{m}$ ). As a matter of fact the accuracy may be better than that achieved by microscopic inspection when visual averaging had to be used. If the surface of the specimen is curved, the measured thickness values will be erroneous if it is not compensated by using a reference block with curved surface. Repair welds of the substrate material may produce such large deviations in the permeability of the ferromagnetic substrate that a remarkable error is produced.

## **4. CONCLUSIONS**

### **4.1 AWJ Stripping**

Typically used HVOF sprayed hard coatings, WC-CoCr and Cr<sub>3</sub>C<sub>2</sub>-NiCr, were removed by using an AWJ method in a controlled manner. Process parameter selections were carried out by using a Taguchi method to select the stripping parameters. The optimum working parameters for precise stripping were determined. After the measurement of the coating thickness the robot program applied the measured local coating thickness values to adjust the AWJ process parameters during the stripping cycle.

#### **4.2 Measuring Optimization**

Altogether 83 specimens with different coating thicknesses and different coating and substrate materials were fabricated and studied. Three measurement methods and six techniques were studied. The eddy current techniques are the fastest and the most versatile techniques. Eddy current techniques can also be applied for online measurement. The measurement time may be as short as 10 ms. When comparing the results achieved with different methods and techniques it became evident that gauge technique gave the best results when the substrate consisted of low carbon steel. The gauge is cheap and straightforward to use and the measurement is quite fast. No reference specimens of proper materials are needed. The measurement range was the largest and the accuracy was the best. Even the thickness on thin coatings with thicknesses of 10 to 25 µm could be measured with a good accuracy. Cracks in the coating do not produce error.

Specimens with carbon steel substrate were applied in the first stripping experiments. For coating thickness measurement standard eddy current thickness gauge was successfully applied. The power stripping process was controlled using the coating thickness values measured by gauge. The movement and control of the cutting nozzle and the gauge were manipulated by the same robot.

#### **4.3 Business Potential of AWJ Stripping**

Now developed technique offers project partners like KLM and HT Lasertekniikka new markets and new, more environmentally friendly, HVOF stripping method. HT Lasertekniikka is going to use this technique for stripping of process components with difficult shape and by that way increases their market potential. KLM sees this as a bit wider issue because not only HVOF sprayed coatings are a potential removable coating for AWJ, but also LPPS sprayed coatings, plating (galvanic coatings), industrial contamination coatings (corrosion, scales, glass, concrete, etc.) can be considered.

### **5. ACKNOWLEDGEMENTS**

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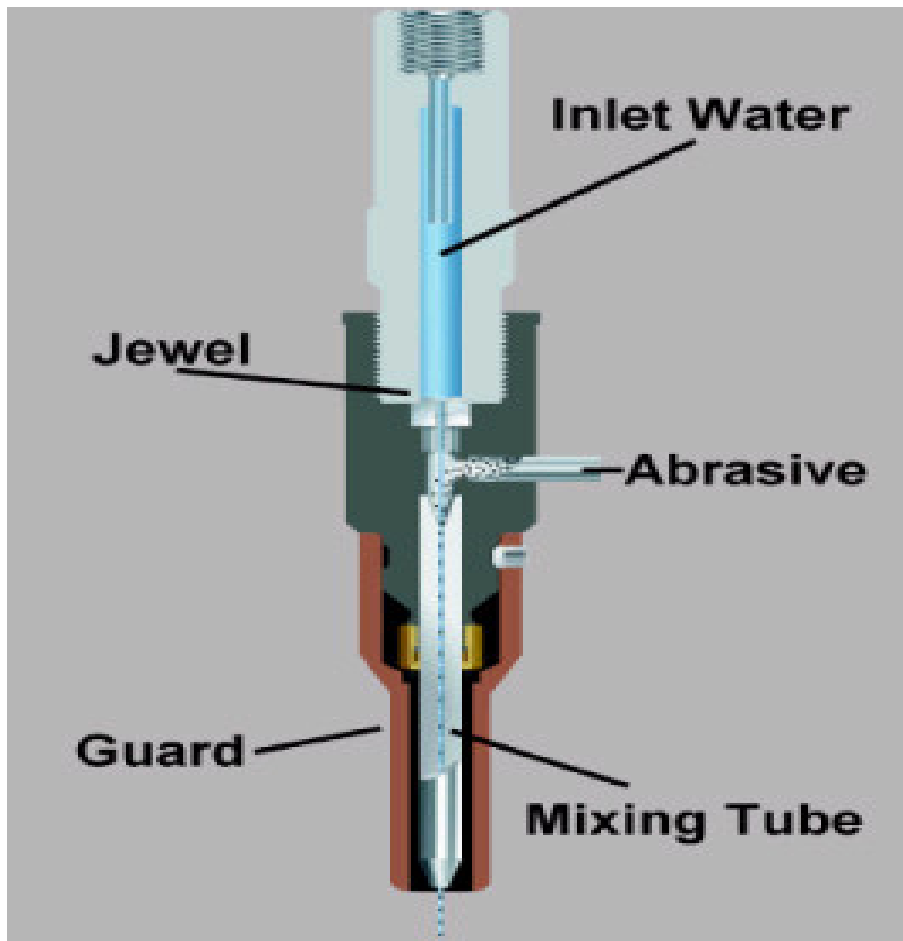
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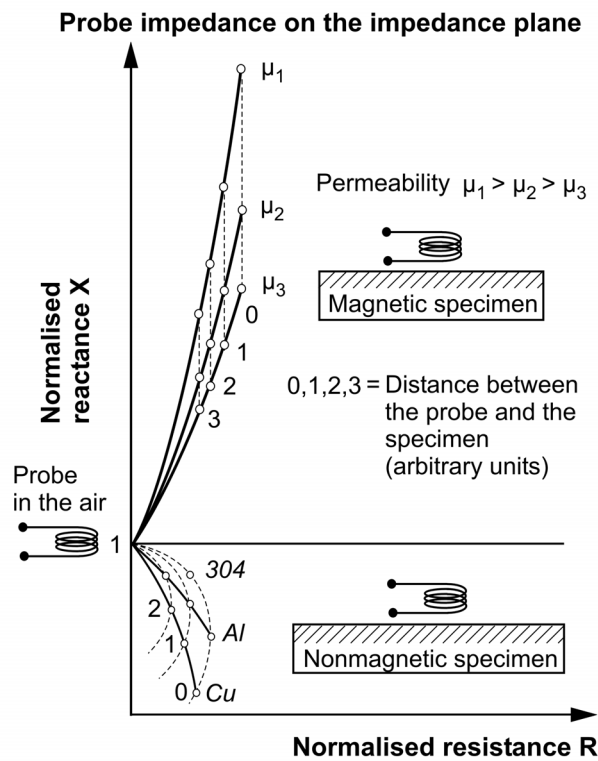
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## **7. GRAPHICS**



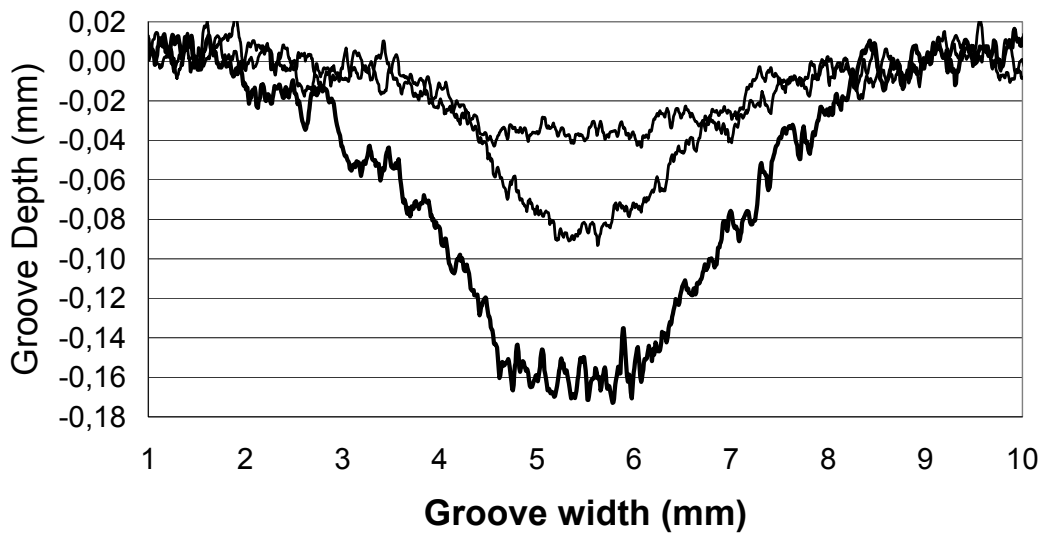


**Figure 1.** The principle of used AWJ cutting nozzle [3].

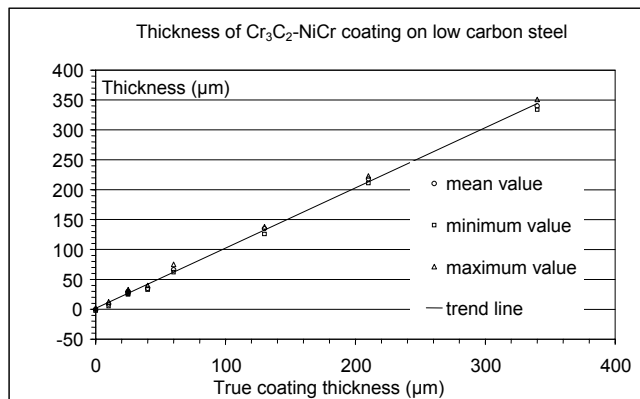


**Figure 2.** The schematic view of the changes of the eddy current probe impedance when the probe is set on the surface of a magnetic and a nonmagnetic specimen.

### Groove shape and depth measurements, Example



**Figure 3.** An example of stripped single pass groove profiles of  $\text{Cr}_3\text{C}_2\text{-NiCr}$  coating using three different coating removal parameters.



**Figure 4.** The coating thickness of the fabricated specimens measured with the eddy current thickness gauge vs. true coating thickness. Ten measurements were carried out on the middle of each sample.