MANUFACTURING ENGINEERING IN THERMAL SPRAY TECHNOLOGIES BY ADVANCED ROBOT SYSTEMS AND PROCESS KINEMATICS - HIGH END COATINGS FOR KEY COMPONENTS IN AUTOMOTIVE TO NUCLEAR POWER ENGINEERING –

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Abstract: For high process reproducibility and optimized coating quality in thermal spray applications on complex geometries, APS (Atmospheric Plasma Spraying), HVOF (High Velocity Oxygen Fuel) and further torches are guided by advanced robot systems. The trajectory of the torch, the spray angle and the relative speed between torch and component are crucial factors which affect the coating microstructure and phase composition as well as the mechanical, thermophysical and electrophysical properties and especially the residual stress distribution. Thus the requirement of high performance thermally sprayed coatings with narrow dimensional tolerances leads to challenges in the field of robot assisted handling, and software tools for efficient trajectory generation and robot programming are demanded. By appropriate data exchange, the automatically generated torch trajectory and speed profile can be integrated in FEM (Finite Element Method) models in order to analyze their influence on the heat and mass transfer during deposition.

Key words: Trajectory generation, Robot programming, Heat and mass transfer, Numerical simulation, Tolerances and quality, Residual stresses.

1. INTRODUCTION

Plasma physics and material science have dominated academic research in thermal spray technologies in recent decades. Value adding by creation and manufacturing of competitive products with advanced coating technologies employed needs a state of the art approach in manufacturing engineering. Thinking in process chains and managing all steps of them with a focus on product performance, reliability and customer satisfaction is an indispensable methodology for modern manufacturing engineering with complex high technologies. Materials mechanics and the understanding of process induced residual stresses and their interaction with operational load stresses are further issues in product development of coatings and layer composite structures. Intensive heat and mass transfer up to supersonic conditions have a distinct influence on coating properties. The same is true for the torch trajectories and robot kinematics programming with their influence on local resolution of these parameters and subsequently on the achievable dimensional tolerances and reproducibility in industrial processes.

The trajectory of the torch, the spray angle and the relative speed between torch and component are crucial factors for high process reproducibility and optimized coating quality in thermal spray applications on complex geometries, APS (Atmospheric Plasma Spraying), HVOF (High Velocity Oxygen Fuel) and further torches are guided by advanced robot systems. The control of the process kinematic is crucial to obtain the desired coating properties, such as microstructure and phase composition as well as the mechanical, thermophysical and electrophysical properties and especially the residual stress distribution. It enables the deposition of a wide range of materials on components in order to feature specific in-service properties for functional and structural applications, [1]. Thus the requirement of high performance thermally sprayed coatings with narrow dimensional tolerances leads to challenges in the field of robot assisted handling and software tools for efficient trajectory generation and robot programming are demanded. By appropriate data exchange, the automatically generated torch trajectory and speed profile can be integrated in FEM (Finite Element Method) models in order to analyze their influence on the heat and mass transfer during deposition.

Last not least the process variants have to be matched to meet the best fit of functional requirements of the coating product in its specific application field.

The present work describes developed software tools for off-line programming of the handling robots and their coupling with numerical simulations of heat transfer considering the generated trajectories and real component geometries, with the aim of control the influence of torch handling on coating properties. To demonstrate the potential and benefit of the software tools for industrial product development, different case studies are introduced in the fields of free-form geometry of a sigma kneader blade, ship propulsion and the kinematic optimization for the coating of copper chevrons for nuclear power plant engineering.

2. INFLUENCE OF TORCH HANDLING ON COATING PROPERTIES AND RESIDUAL STRESS DISTRIBUTION

The process kinematic defined by the parameters of the robot program, such as torch trajectory, speed profile and spray angle play a crucial role on mass and heat transfer during deposition and influence therefore the coating properties. The thermal energy of the high energetic process gases and high temperature of the particles and the torch trajectory determine the state of local temperatures and thermal gradients during deposition, which is related with the residual stress distribution in coating and substrate.

The kinematic process parameters define the relative movement between spray torch and the substrate during deposition, being the most relevant parameters the spray angle, spray distance, spray velocity and spray patch, see figure 1.

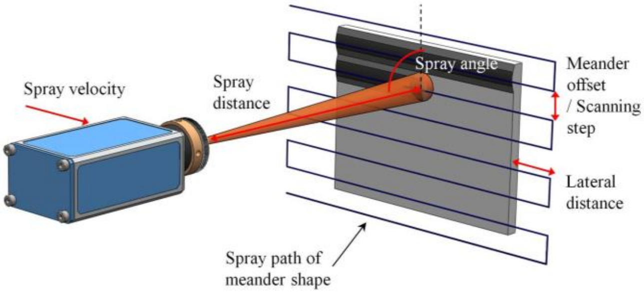

Fig.1. Main kinematic parameters, [2].

The spray angle is defined as the angle between the symmetry axis of the spray torch and the surface of the substrate. It is a factor affecting the splat formation, coating microstructure, adhesion, hardness and porosity. Thus the spray angle is especially important if complex surfaces and component geometries have to be thermally coated. The influence of spray angle on coating thickness was analyzed experimentally spraying WC-Co with spray angles varying from 90° to 30°, see figure 2. The coating thickness strongly decreases with the spray angle. Low spray angles are associated with higher tangential velocities and therefore, higher probability for the particles to rebound at impact with the substrate. In this way, the deposition efficiency might be lower and maximum coating thicknesses are obtained for spray operations perpendicular to the substrate surface, [4]. The coatings were produced by using the HVOLF K2 torch (GTV GmbH, Germany) with kerosene as fuel gas.

The influence of the spray or standoff distance on the resulting coating have been extensively analysed in the literature for different spray materials and thermal spray processes.

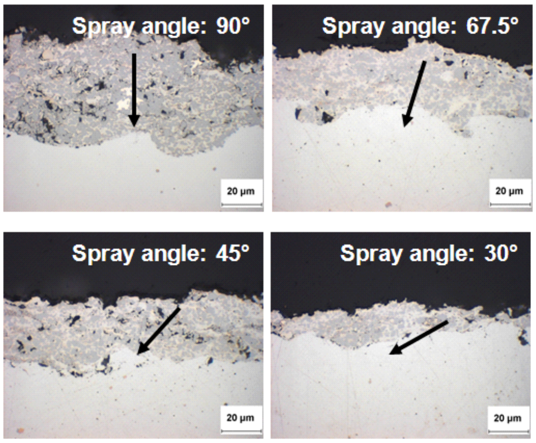

Fig. 2. Influence of the spray angle on the coating thickness, [3].

Since the spray distance controls the in-flight time of the particles in the high-energy jet or flame until the impact on the surface, the so-called dwell time, it also determines the particle temperature and velocity at impact on the substrate. Therefore, the coating build-up process is significantly influenced by this parameter, which provides the optimized thermal and kinetic energy of the particles for the required coating properties. Too short spray distance can result in insufficiently melted particles impacting the substrate, while too high distances can lead to early solidification by non-desired cooling of the already melted in-flight particles, [5].

The displacement speed of the torch, the so-called spray velocity, is the speed of the torch relative to the substrate. These conditions influence the amount of matter deposited per coating cycle, i.e. coating thickness, and the thermal history of the coating composite during the process since they define the residence time of the jet or flame focus on the substrate.

The last important kinematic parameter is the spray path, which is the sequence of relative displacements of the spray torch to the substrate to cover its entire surface during the coating process. This parameter has a distinct influence on the resulting coating properties, as the lateral or local resolution of heat and mass transfer during coating deposition affects the coating properties. A meander-shaped spray path is commonly used in thermal spraying, see figure 1. Such a path is composed by equidistant and parallel horizontal passes of the torch with respect to the substrate. The distance between each two consecutive passes is known as scanning step, and it determines the overlapping of the coating material beads deposited in consecutive passes and, therefore, the coating thickness, [6].

The effect of the spray path for the deposition of thermally sprayed film heaters on glass ceramic substrates used for cooking plates deposited via APS is analyzed in order to improve the coating characteristics in service. Two paths are analyzed.

Path type “A” represents a meander-shaped spray path, while type “B” is a modified meander-shaped spray path, which describes a top-down-top movement with respect to the substrate for each coating cycle, leading to a lower-temperature gradient within the component. The IR images in correspond to the coating temperatures in working conditions, see figure 3. It can be observed that the sample sprayed with the path type “B”, which gives rise to a more homogeneous heat distribution in the composite during spraying, presents a uniform heating of the operating film, while the sample sprayed with the typical meander shaped spray path shows hot spots with overheating during its functioning, [7].

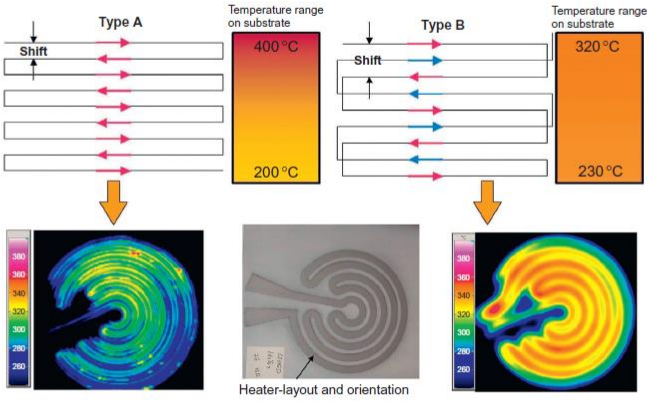

Fig. 3. Analyzed spray paths and their effect on the surface temperature distribution and IR images showing coating temperature distribution in working conditions for the case study of film heaters for cooking plates, [7].

Therefore, the heat management during spraying operations by the optimization of the process kinematic is quite important to the coating properties, such as the residual stresses. An example is especially relevant on coatings on borosilicate glass and glass ceramic substrates due to the specific thermophysical properties of these materials, that is, low thermal expansion coefficient, [8]. In the experiments, the high residual stresses lead to the breakage of the coated tubes during the cooling down after the deposition process. By adapting the spray torch path and the cooling system with compressed air nozzles, the thermal gradients in the substrate and coating during spraying, as well as the reached temperatures, could be reduced, leading to lower residual stresses and higher process security, see figure 4.

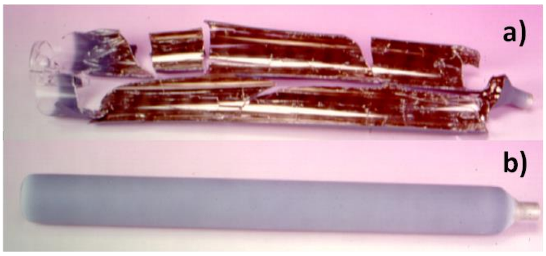

Fig. 4. a) Broken and b) operational coated ozonizer glass tube (Al/Si and Al2O3/TiO2) due to different residual stress situations, [9].

3. OFF-LINE GENERATION OF COORDINATES TRAJECTORIES OF ROBOT

In thermal spray applications the torch guide is required to describe a defined trajectory with an appropriate speed profile, spraying distance and relative orientation between torch and substrate. Due to the influence of the torch trajectory on the coating properties, software tools for efficient and flexible robot programming are needed. In the present work, an off-line programming system with modules for the acquisition of the surface geometry and generation of trajectories is proposed. In order to ensure homogeneous coating properties, the real geometry of the surface to be coated has to be acquired and processed. The geometrical data of the surface to be coated can be obtained from CAD models or acquired by 3D scanning using optical or tactile coordinate measurement systems. As case study the free-form geometry of a sigma kneader blade was considered. The point cloud is obtained by laser scanning system ModelMaker Z (Descam 3D Technologies GmbH, Germany), see figure 5.

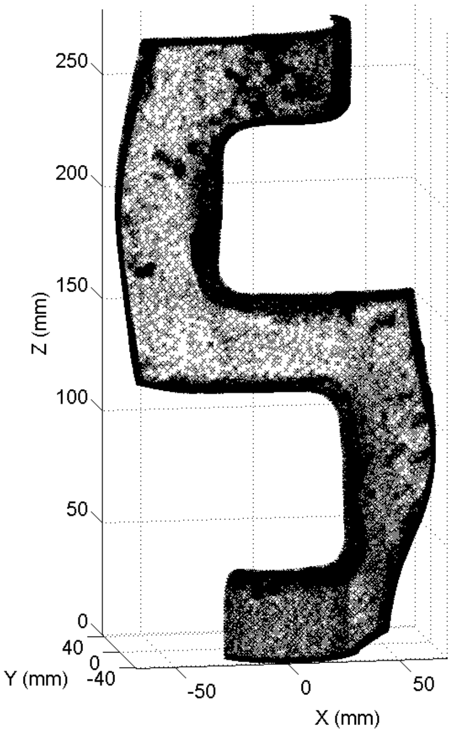

Fig. 5. Point cloud of free-form surface obtained by laser scanning of a sigma kneader blade, [13].

The resulting point clouds are processed into a mathematical description of the surface. By extracting a mesh of regularly distributed spatial points, the path of the powder loaded jet on the component as well as normal vectors for calculation of the torch orientation during coating can be obtained, see figure 6. Since the coordinates of the spatial points and normal vectors are referred to the coordinate system of the CAD model or measuring device, tools for coordinate transformation have to be programmed with a view to the implementation in the real workcell. The required subroutines were developed at the IMTCCC by using the computing environment and programming language MATLAB (The MathWorksTM, USA).

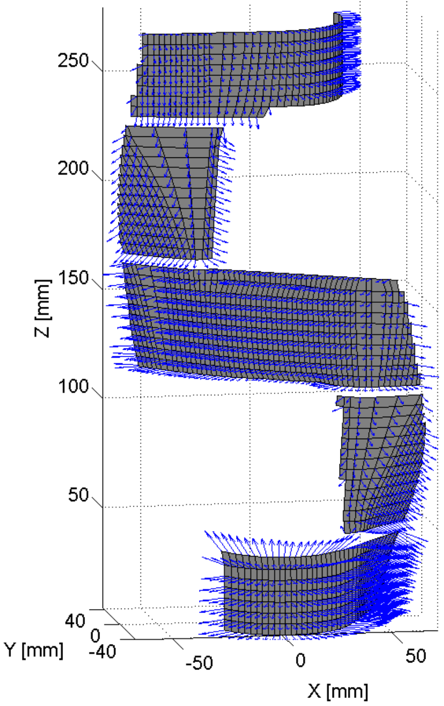

Fig. 6. Normal vectors on free-form surface for calculation of torch orientation during coating of a sigma kneader blade, [2].

Coming up next, a meander trajectory was calculated. The obtained path of the jet on the surface to be coated includes the coordinates acquired by the 3D coordinate measurement system. Finally, program code was generated for the implementation of the trajectory in the workcell. For this application the trajectories were programmed by using the language V+® (Adept Technologies Inc., USA). The torch handling was performed by means a RX-170 (Stäubli Tec-Systems GmbH, Germany) robot arm. By following the presented methodology, codes for different substrate geometries and robot programming languages can be generated, as for example the case study of free-form geometry of a ship propeller, see figure 7.

4. COUPLED OFF-LINE ROBOT PROGRAMMING AND NUMERICAL SIMULATION OF HEAT TRANSFER

The analysis of heat and mass transfer is an essential tool for a better planning of process design and torch trajectories. Particularly the influence of the generated torch trajectory and speed profile on the heat transfer and temperature distribution can be analyzed by numerical simulation.

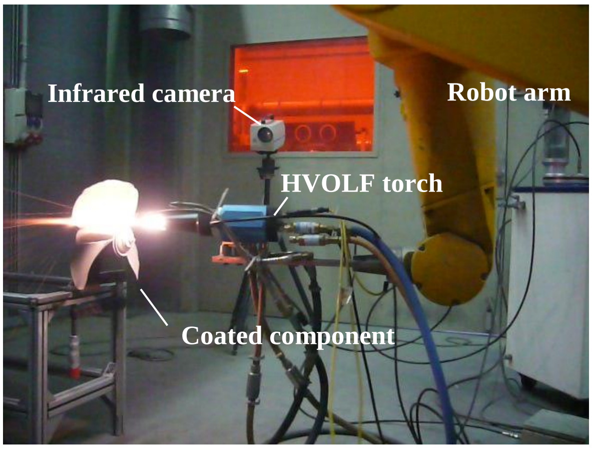

Fig. 7. Implementation of generated code for coating process at IMTCCC facilities for a ship propeller, [14].

Due to the impacting gases and impinging particles the component and coating system are subjected to high thermal load. As the initial step of a process design for numerical simulation of temperature distribution during coating, the heat transfer coefficient between impinging gases and substrate is required. Also the impacting particles and the heat dissipation by convection and radiation play a role on the total thermal load. The calculation of the contribution of gases and particles to the total thermal load was done by considering approaches presented in previous works, [10, 11], and CFD simulations of the combustion and in-flight behaviour of gases and particles. In the presented work of free-form geometry of a ship propeller, the FEM meshes are created by using the collected geometrical data (by CAD model or coordinate measurement device) of the surfaces to be coated. For the mesh definition and numerical simulations ANSYS® and ABAQUS® were used.

Coordinates of spatial points of the generated trajectory and corresponding process times were transferred in ASCII format to the numerical simulation software. Thus the generated jet trajectory is correlated with nodes of the finite element model. In order to model according to real conditions, the thermal load was modelled as heat flux. The corresponding surfaces where heat flux is applied can be obtained on basis of the previously defined nodes and by considering the diameter of the impacting spray jet. The heat transfer during deposition can be simulated for different meander trajectories, torch velocities and total heat flux. For model validation calculated temperatures on selected nodes were compared with temperature measurements by infrared thermography, see figure 8.

Temperatures can be calculated also on the complete component surface to obtain time dependant temperature distributions, gradients and corresponding stresses. Thus the influence of the component geometry on heat transfer can be considered for further process optimization. The obtained temperature distributions for the case study ship propeller at different process times are show, see figure 9.

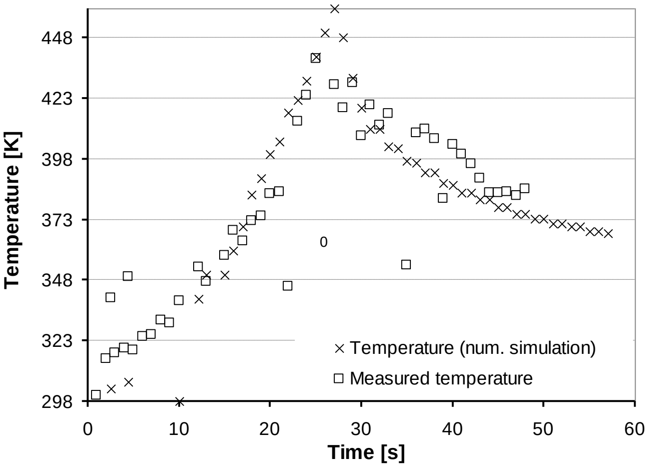

Fig. 8. Numerical simulation of node temperature for model validation, [14].

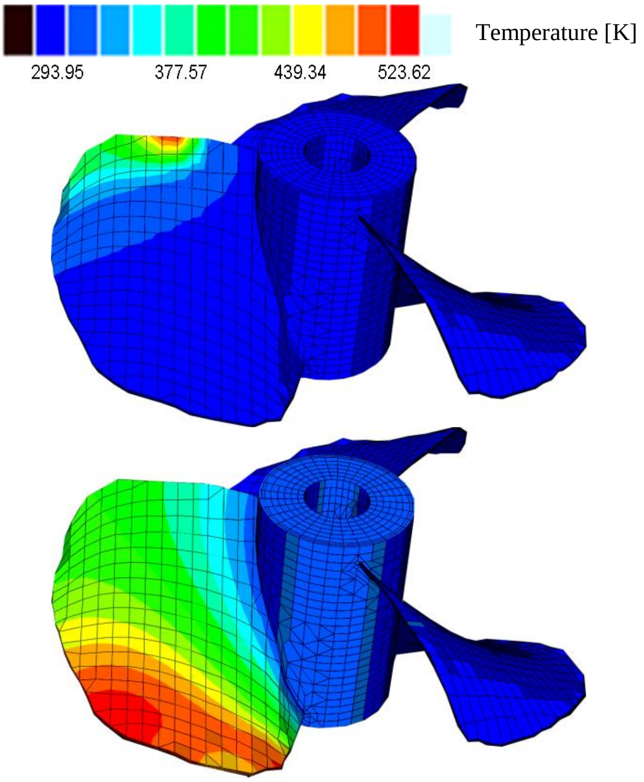

Fig. 9. Numerical simulation of temperature distribution during coating of a ship propeller, [14].

Further works were developed for geometrical models created and meshed in ANSYS Classic. However, the functions available for this aim are more limited than in CAD programs. For this reason, in this work the model of the guiding blade for a newspaper folding machine was created in SolidWorks® (Dassault Systèmes SolidWorks Corp., USA) and imported to ANSYS as .igs data. It is recommended to mesh the surface of the substrate which is coated with hexahedral elements with the size of the meander pass, as indicated by Cai et al., [12]. In this way, there are nodes in the finite element model located at the trajectory of the robot and they assure a better fitting of the locations of eat loading in the simulation with reality. However in some cases, a refinement of the mesh to improve the calculation accuracy is required or due to the component geometry other element types need to be used, see figure 10.

For the case of the previous model, deposition processes using both the horizontal and vertical meanders were simulated for 5 mm offset and 300 mm/s spray velocity, see figure 11. A transient thermal problem has been modelled, in which the thermal loads and their locations are functions of time. Macros were programmed to read the files generated from MATLAB with information about the loading steps, nodes and torch orientation.

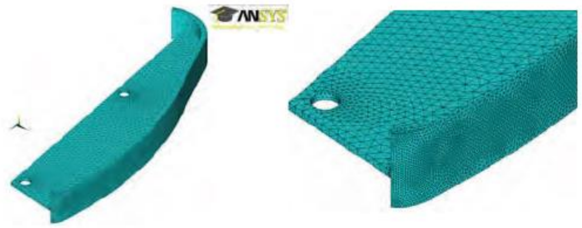

Fig. 10. Model of the guiding blade for a newspaper folding machine, imported to ANSYS and meshed, [2].

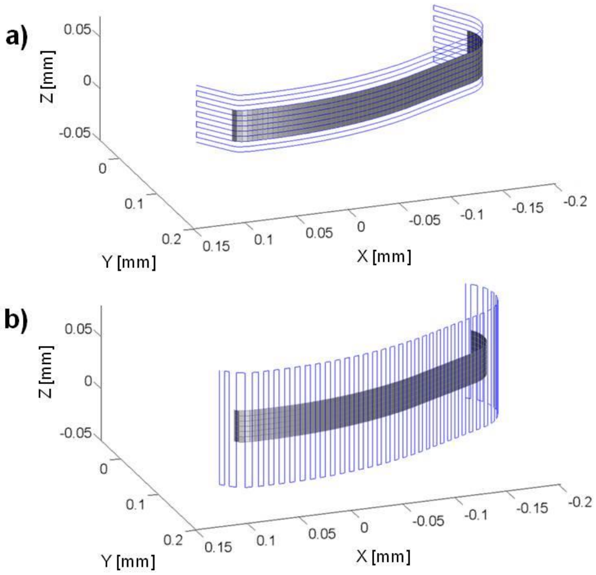

Fig. 11. Representation of the a) horizontal meander and b) vertical meander path programmed in MATLAB on the guiding blade, [2].

The heat transfer process by Atmospheric Plasma Spraying is simulated by applying a thermal surface load on the substrate surface. The moving hot spot describes the programmed spray path and gives the heat contribution from the plasma and the particles. The thermal load correspondent to the plasma is applied on each node as a Gaussian distribution of heat flux on the defined area of the hot spot. In the case of the guiding blade, the torch is perpendicular to the substrate during the whole trajectory. However, as the substrate surface is not planar, the local coordinate system has to be reoriented at each node in order to maintain the perpendicularity. Moreover, a condition has to be imposed related to the area on which the thermal load is applied. Considering the area of the hot spot on the perpendicular plane to the plasma jet axis at each node, its projection on the substrate surface is the area on which the thermal load is applied. For zones of the substrate surface with strong curvature, the projection of the hot spot can give rise to much larger loading areas than what is actually coated. For this reason, only the nodes contained in the projection of the hot spot on the substrate surface with a distance to the origin of the local coordinate system lower than 1.5 times the radio of the hot spot, were selected to apply thermal load. Results of the temperature distribution during spraying for horizontal and vertical meander are obtained, see figure 12.

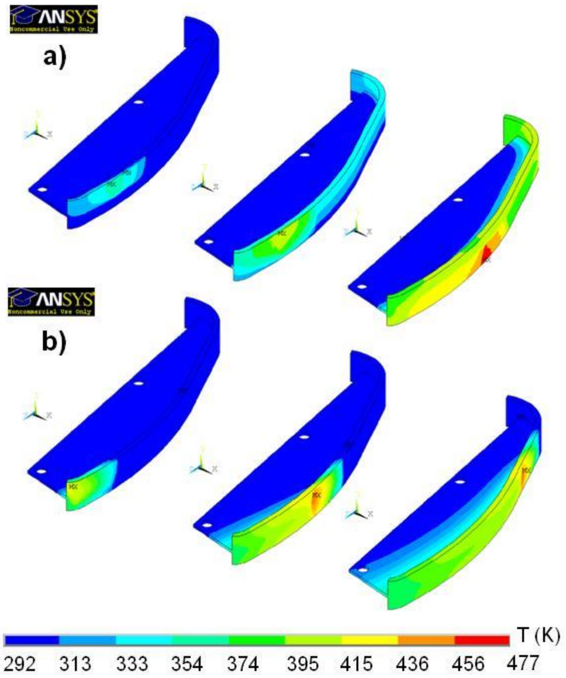

Fig. 12. Simulated temperature distribution during spraying for a) horizontal meander, b) vertical meander, [2].

5. KINEMATIC OPTIMIZATION FOR COMPLEX GEOMETRIES

Recently, as case study the complex geometry of a copper chevron for nuclear fusion reactor was considered. Due to the relatively high strayfield radiation (140 GHz) from the electron cyclotron radio frequency heating system to which the W7-X cryopumps are expected to be subjected, coating systems acting as an efficient absorber for 140 GHz radiation have been developed for the water-cooled baffle shield in order to reduce the thermal load on the liquid N shield and the liquid He cryopanel, [15]. Several types of oxide ceramic coatings were applied on planar copper substrates by Atmospheric Plasma Spraying, in order to study the high frequency microwave absorption at 140 GHz, the coating adhesion, the coating mechanical stability and the thermal resistance up to 200°C. The influence of the process parameters on the coating properties and microwave absorbing capability was analyzed. It was found that film thickness and microstructure of the sprayed coatings have a significant influence on microwave absorption behaviour, which in turn depended on the spray parameters and kinematics, such as spray angle, spray distance, meander offset and number of cycles. Finally, Al_2O_3/TiO_2 coatings where optimized to cover the complete copper chevron surface, with a variation in number of cycles for each spray angle (30°, 50°, 70° and 90°) in order to reach the appropriate coating thickness, analyzing is of overlapping of the coating operations with different angles and variation of the meander offset (1.5, 2, 2.5, 3, 4.25 mm). The optimized final robot kinematic where determined and samples were coated with optimal angles of 90 angle of impact of 20° and a flat angle of impact of 39°, which in combination allow a homogeneous coating thickness in all the surfaces of the copper chevrons, see figure 13.

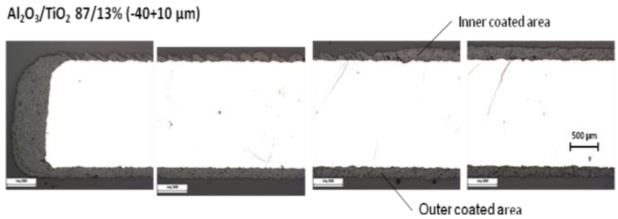

Fig.13. Details of coating thickness in different surface segments of complex copper chevrons for cryo pump absorbers in nuclear fusion reactors, coated by optimized robot kinematics.

Finally, mock-up are coated showing a homogeneous coating thickness in all the surfaces with absorption values over 90% for the 140 GHz probing beam, see figure 14.

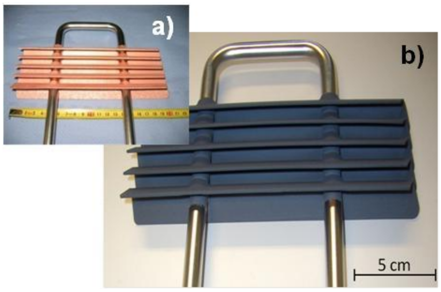

Fig. 14. a) Initial uncoated and b) optimized kinematic coating copper chevrons with neutron absorber functionality in nuclear fusion reactor, [15].

6. SUMMARY AND CONCLUSIONS

The production of net shape, high performance thermally sprayed coatings for high applications requires advanced automation systems. The torch trajectory, speed profile and spray angle are important process parameters as the demand of spraying complex-shaped parts increases. Due to the influence of these parameters on the temperature distribution during deposition, residual stresses development and final coating properties, software tools for efficient and flexible robot programming are required.

An approach for trajectory generation and off-line robot programming is presented. In order to consider the real component geometry, CAD tools and optical or tactile coordinate measurement systems can be used to provide the required data for the off-line programming of handling devices. Specific software tools were developed for processing the substrate geometry, coordinate transformation and calculation of normal vectors and trajectories for thermal spraying applications.

By the integration of modules for numerical simulation, the heat transfer during coating process can be analyzed. The proposed interconnection of the modules for the programming of the handling devices with the numerical simulation is a first step in the development of completely virtual workcells for thermal spraying. By control assisted coating deposition, the process parameters as well as the velocity and temperature of gases and particles can be on-line supervised, displayed and recorded. Coating experiments assisted by on-line diagnosis were performed for validation of the developed models and software tools.

Optimized robot kinematic is developed for complex copper chevrons with coating functionality in nuclear fusion reactor.

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