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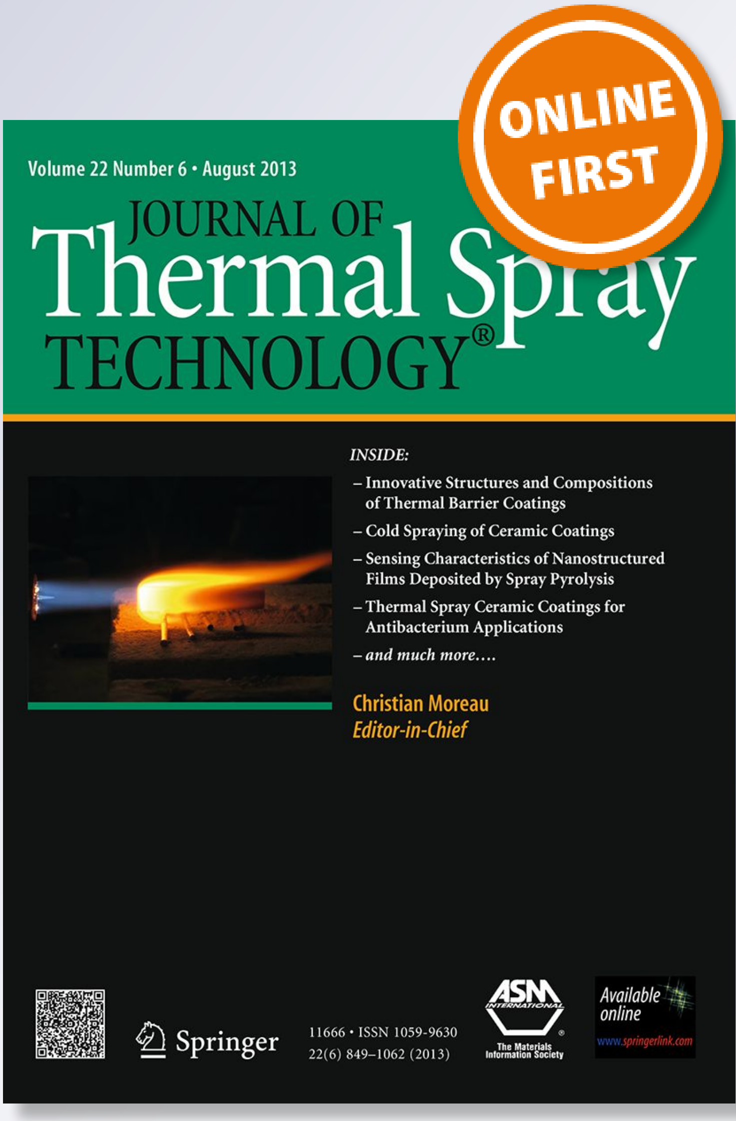

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A Robot Trajectory Optimization Approach for Thermal Barrier Coatings Used for Free-Form Components

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Abstract This paper is concerned with a robot trajectory optimization approach for thermal barrier coatings. As the requirements of high reproducibility of complex workpieces increase, an optimal thermal spraying trajectory should not only guarantee an accurate control of spray parameters defined by users (e.g., scanning speed, spray distance, scanning step, etc.) to achieve coating thickness homogeneity but also help to homogenize the heat transfer distribution on the coating surface. A mesh-based trajectory generation approach is introduced in this work to generate path curves on a free-form component. Then, two types of meander trajectories are generated by performing a different connection method. Additionally, this paper presents a research approach for introducing the heat transfer analysis into the trajectory planning process. Combining heat transfer analysis with trajectory planning overcomes the defects of traditional trajectory planning methods (e.g., local over-heating), which helps form the uniform temperature field by optimizing the time sequence of path curves. The influence of two different robot trajectories on the process of heat transfer is estimated by coupled FEM models which demonstrates the effectiveness of the presented optimization approach.

Keywords heat transfer analysis · off-line programming · thermal barrier coatings

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Introduction

The thermal spray process can be applied to deposit a broad range of materials (metals, carbides, ceramics, plastics, etc.) in molten, semi-molten or solid states on components to create a functional film with optimum properties (Ref 1-3). This technology is extremely effective at prolonging the service life of the products, decreasing machinery downtime, and increasing performance in a great variety of industrial applications. For high reproducibility and optimum deposition quality of complex components (e.g., a gas turbine blade), thermal spray processes are usually guided by programmed industrial robots. Therefore, a well-designed robot trajectory should first ensure an accurate control of some process parameters in thermal spraying (e.g., scanning speed, spray distance, scanning step, etc.) to fulfill the coating quality requirements (e.g., coating thickness uniformity, etc.).

During the thermal spray process, heat and mass transfer plays a crucial role in the development of residual stresses, which in turn has a vital influence on a large number of coating properties such as adhesion stress, hardness, formation of microcracks, and tribological behavior (Ref 1). Thus, heat and mass transfer analysis should be taken into account during the trajectory generation process, which helps to minimize thermal gradients in the component and balance the surface temperature distribution. With this aim, a mesh-based trajectory generation strategy is proposed in this work to generate a series of path curves. A coupling between the robot trajectory and thermal source is developed to predict the thermal history of workpieces under different meander trajectories.

Publications dealing with the same topic are considered in this work. The influence of robot trajectory on thermal history was first investigated by Nylén et al.

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(Ref 4). They developed a heat transfer model between the plasma torch and the component using the finite element method (FEM). A mathematical model of a plasma torch and a simplified stochastic model in two dimensions was proposed. Then, the temperature gradient in the component as a function of time was calculated using FEM. A. Candel et al. presented a software package for improved trajectory generation in thermal spraying. The developed trajectories can be used to analyze the influence of the torch trajectory as well as the scanning speed on the temperature distribution of the coating surface during the thermal spray process (Ref 5). Liu et al. developed a finite element model for the transient analysis of the residual stress formation during the thermal spray process. This model allows the simulation of the transient heating, stress state distribution and deflection of the specimen during the coating manufacturing (Ref 6). Other works dealing with similar topics are also considered (Ref 7, 8). These studies do not include the robot movements during the thermal transfer analysis, which is a key factor affecting the temperature distribution. As a matter of fact, the acceleration and deceleration of robot motion at each direction change can cause the variation of the scanning speed, and thus the real robot movements should be simulated before the prediction of the heat transfer behavior.

This work aims to determine the optimal robot trajectory through a coupling between a sampled robot trajectory and the corresponding thermal history. For this purpose, the influence of different meander trajectories on the temperature distribution of the component is investigated.

Trajectory Generation via Off-Line Programming

The programming of an industrial robot occurs via two steps, which are the Lead-through method and Off-line Programming (OLP). The Lead-through method is the most used in the industrial area, especially for simple movements. The torch and its assembly are first installed on the robot wrist. The operator uses a handheld control and programming unit, called a tech pendant, which allows manual jogging of the robot and moves the TCP (Tool Center Point) to the desired position, and then memorizes these positions in a series of movement instructions (Ref 9). OLP refers to the procedure of transferring robot programs that are created through graphical models to actual robot cells. It helps users generate the optimal robot trajectory by analyzing robot behaviors, joint reachability and collision detection between objects. Then, the specific task is executed by passing through a series of target points that are generated by OLP.

OLP software provides capabilities for combining the robot system and the CAD model. Thus, the first step toward trajectory planning operations is to obtain the CAD data of the workpiece. Reverse engineering is one of the keys of advanced manufacturing technology, which is often adopted for curved surface reconstruction. Thus, a tactile coordinate measurement system is usually used for data acquisition operations. Then, the curved surface to be coated is characterized as a large volume of point cloud. By fitting the discrete point cloud, the high-quality CAD model is reconstructed and then converted to standard formats (e.g., stl) for data processing. In the OLP software, a virtual workshop floor identical to the real robot cell is set up by building or importing geometric models such as a spray torch, the CAD model of component and other accessories. The position of the CAD model and the installation position of the spray torch have to be calibrated to be consistent with the real robot cell. In this step, several reference points must be selected to calculate the space distance and space angle. Then, the operating position of 3D model is adjusted by the inner transfer and rotation matrix of the OLP software. A typical virtual workshop built up in RobotStudio™ is shown in Fig. 1.

Normally, a robot trajectory is represented via a set of target points that consist of three aspects: target point location, target point orientation and target point sequence. Some research efforts have been made to determine the target point location. Most of these efforts are based on Boolean operations or a parametric surface (e.g., Bezier surface, B-spline surface) interpolation (Ref 10-12). A target point generation approach based on the mesh data of a sculpture surface is employed in this work. The 3D model of a free-form component (shown in Fig. 2) is imported into the preprocessor module of ANSYS. One coating surface can be obtained via reconstruction or decomposition operations, as shown in Fig. 3. The mapped mesh generated by the preprocessor unit has regular and uniform transition curves, which are suitable for representing the torch movements during the thermal spraying process. For complex components, the coating surface needs to be patched and/or reconstructed to some fairly regular quadrilateral pieces to generate the mapped mesh (Ref 3). The element size is proposed to be equal to the value of the scanning step. Thus, the robot target points will be situated at varying positions of finite element model nodes. In this case, an element size of 8 mm is used to generate a mapped mesh on the coating surface (shown in Fig. 3).

During thermal spraying, the spray angle between the axis of the spray torch and the coating surface usually remains at 90°, which appears to be a difficult problem for complex sculpture surfaces. Thus, in the preprocessor, the

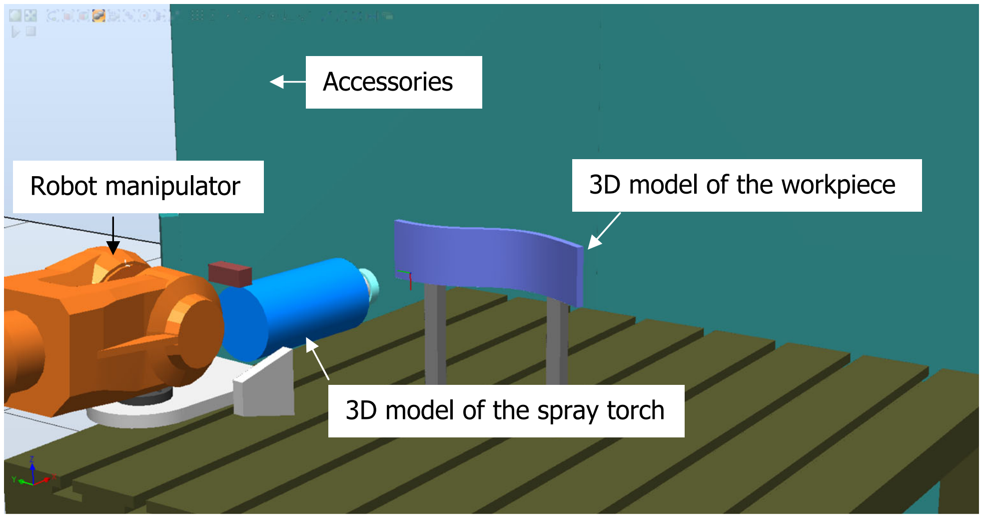
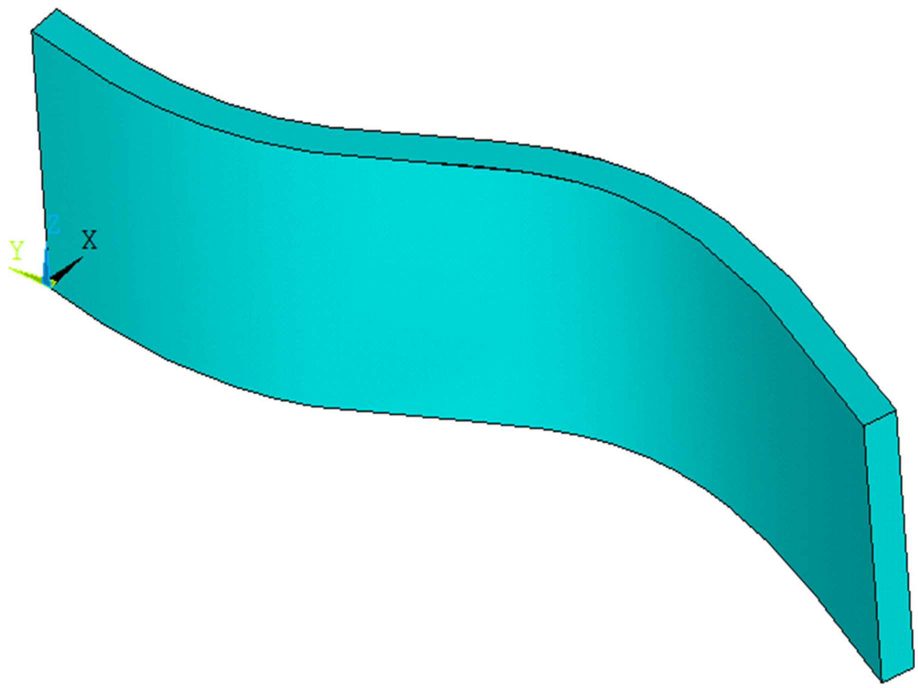


Fig. 1 Typical virtual workshop in the OLP software

Fig. 2 3D model of the coating surface



normal vector to the coating surface is acquired by performing a three-dimensional rotational transformation of the node coordinate system (shown in Fig. 4). Thus, the spray angle can be calculated via a rotation matrix or a normal vector. In this case, a spray angle of 90° is kept. Then, the node data including node location and node coordinate orientation are stored in an ASCII format, which is imported into RobotStudio™ via the developed software package to create target points. After calibration operations, a series of path curves (shown in Fig. 5) are generated on the coating surface.

Coupling Between Robot Trajectory and Corresponding Thermal History

During a thermal spraying process, the spray torch, mounted on the terminal of the robot axis, moves along with the robot movements. Therefore, different meander trajectories will affect the heat and mass transfer to the component and, to a great extent, determine the temperature gradient on the component. This effect is very important for coating of substrate materials with complex thermo-physical behaviors (Ref 11). Thus, research on the

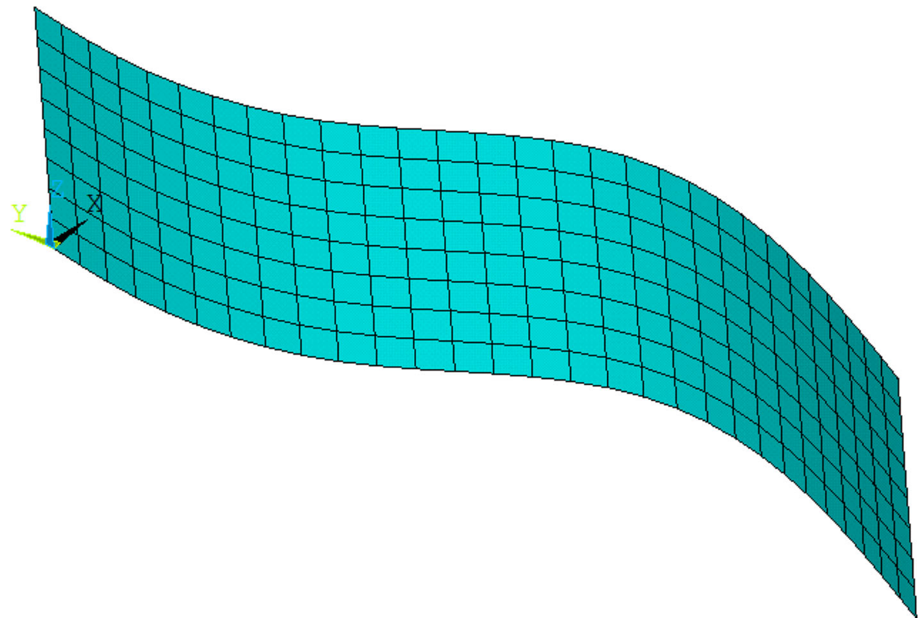


Fig. 3 Mapped mesh on the coating surface

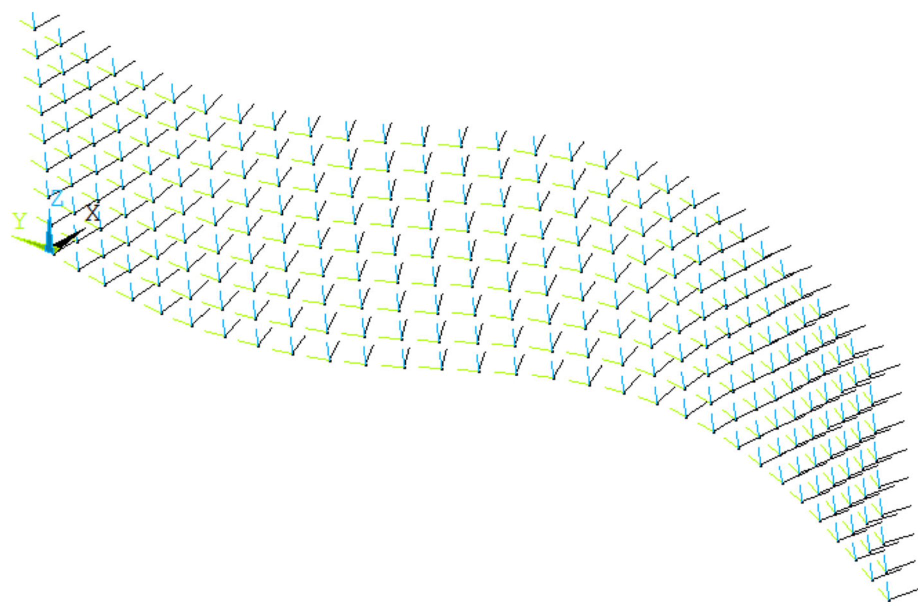


Fig. 4 Set of targets normal to the surface

variant of meander trajectories is of great significance for the coating properties.

In this study, two types of meander trajectories are generated, based on the different path curves connection method, as shown in Fig. 6. From Fig. 6(a), trajectory A is a typical thermal spraying path. The path curves are sequentially connected according to their location in 3D space. Scanning moves alternately from left to right and from right to left, with a scanning step of 8 mm between every two successive path curves. The trajectory passes through the coating surface from bottom to top. Trajectory B is shown in Fig. 6(b), in which the robot trajectory can be seen as a screw motion along the centerline of the path curves. The spray gun moves from the middle to the two edges of the component to realize the full coverage of the coating surface.

Then, the generated robot trajectories are simulated in RobotStudio™. A Sulzer Metco F4 type spray torch is modeled and guided by a IRB2400-16-25 robot (ABB, Sweden). The scanning step is set to 8 mm, and the over-length is set to 100 mm. A scanning speed of 400 mm s^{-1} is defined at all the target points. A spray distance of 12 mm and a spray angle of 90° are kept. During the simulation process, the realtime Tool Center Point (TCP) velocity and position are recorded every 0.024 s. The TCP velocity history for different types of meander trajectories

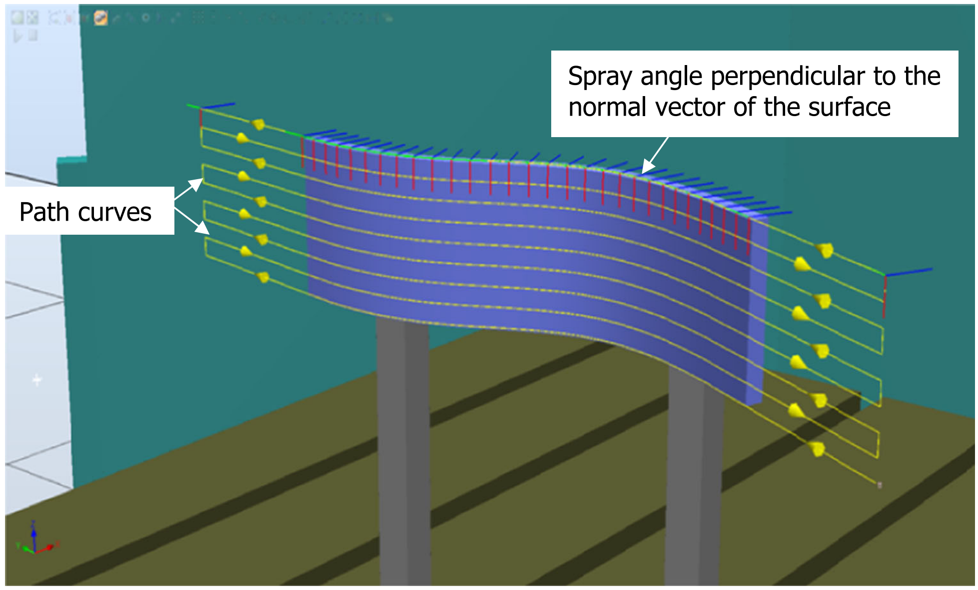


Fig. 5 Path curve generation based on the node data

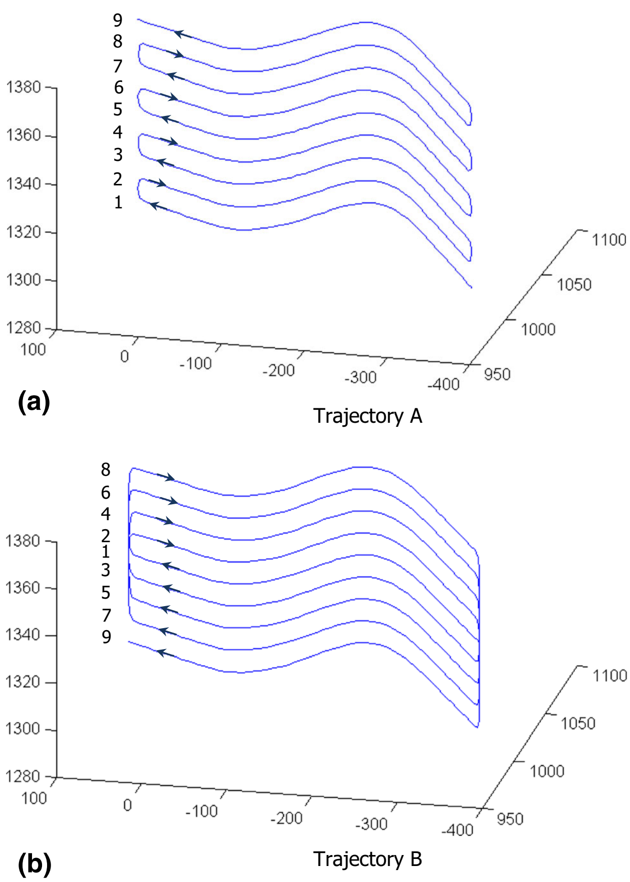


Fig. 6 Two types of meander trajectories

is presented in Fig. 7. At the beginning of a single path curve, the robot accelerates from 0 mm s^{-1} to almost 400 mm s^{-1}, represented by the blue points in Fig. 7(a) and (b). The red points represent that a scanning speed of nearly 400 mm s^{-1} is sustained while the robot passes through the coating surface. The scanning speed decreases from 400 to 200 mm s^{-1} at the other side of the path curve. It can be observed from Fig. 7 that the user-defined TCP speed cannot always be maintained during the spraying process. This phenomenon is probably caused by curvature changes of the coating surface or by abrupt TCP direction variations. However, these sampled TCP data are closer to the real situation because they allow the taking into account of the robot dynamics.

In this simulation, the TCP position is extended from the outlet of the spray gun nozzle to the coating surface, considering a spray distance of 12 mm. For this reason, the TCP and the thermal source will meet at a common point on the coating surface. Thus, the thermal source position versus time can be defined, based on the real-time TCP data. The sampled TCP position under fixed intervals is stored in an ASCII format for reading back by a user-defined module of ANSYS/FLUENT. Based on that, a coupling between the robot trajectory and the thermal source can be developed.

Thermal History of Different Meander Trajectories

Numerical simulation is implemented to analyze the thermal history according to the simulated TCP position in Fluent. An aluminum substrate (0.01 m in width, 0.075 m in height, and 0.272 m in length) is used, and the spray powder is Alumina Amperit 742.3 (97 wt.% Al_2O_3, 3 wt.% TiO_2) with a size distribution of −45 to +15 μm. A Sulzer Metco F4 torch with a 0.006-m internal diameter is employed with an Ar/H_2 (35/8 SLM) plasma gas mixture. A spray distance of 0.12 m and a torch–substrate velocity of 400 mm s^{-1} are applied. The electric arc current is set to 500 A. A carrier gas (Ar) flow rate of 3.5 SLM and a powder feed rate of 30 g min^{-1} are considered in the experiment. Table 1 shows the material properties of the spray powder and substrate of two models. The heat transfer of natural convection is considered in this model, and the convection coefficient is varied from 3 to 10 W m^{-2} K^{-1} for a substrate whose temperature varies from 322 to 572 K (Ref 12).

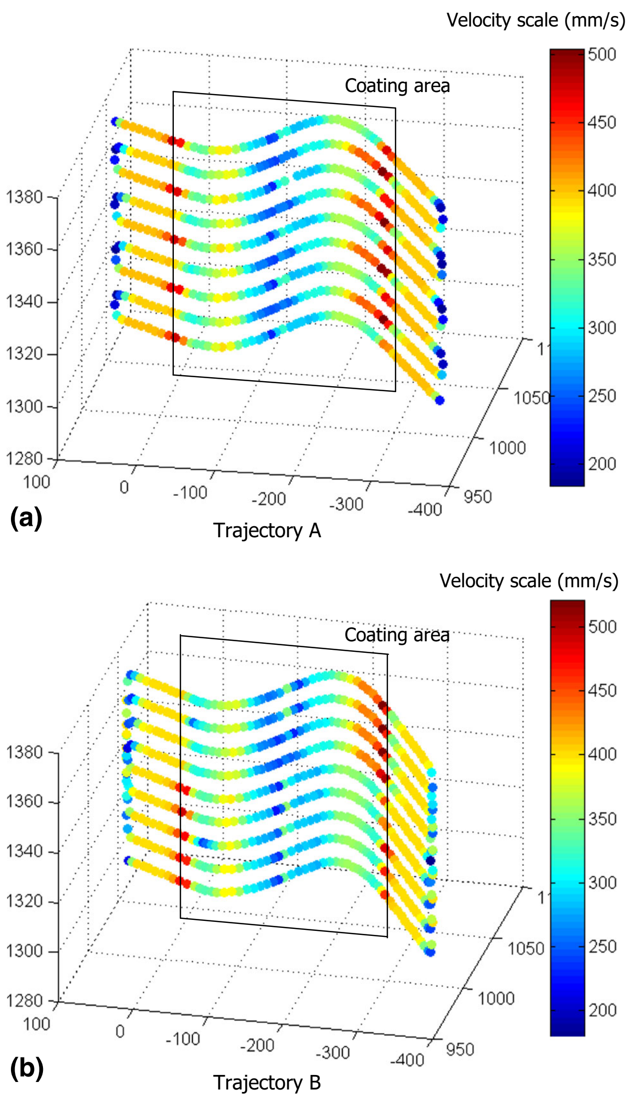


Fig. 7 Sampled TCP speed

Figure 8 illustrates the obtained plasma torch isotherms and particle trajectories for a stand-off distance of 0.12 m (Ref 13). The considered particle size is 25 μm, and a particle impact offset of 0.005 m is observed from the centerline of the torch.

The thermal source, considering the effect of sprayed particles, can be shown as follows:

$$\Psi(r) = 7.93 \exp\left(\frac{-r^2}{2\sigma^2}\right)\left(\mathrm{WM\ m^{-2}}\right) \quad \text{(Eq 1)}$$

where σ is the Gaussian profile dispersion parameter (mm), which equals 0.005 m. The thermal flux transferred from the plasma jet can be estimated from (Ref 14), and it is fit via:

$$\emptyset(r) = \emptyset_{0/\left(1+(r/R_0)^2\right)} \quad \text{(Eq 2)}$$

where the value of thermal flux is 0.56 MW m^{-2}, and R_0 is 0.02 m at a spray distance of 0.12 m; these coefficients are taken from Ref 15.

The simulation is based on an ambient temperature of 288 K. An element size of 0.5 mm is applied to the finite element model. Figure 9 shows the obtained surface temperature fields after thermal simulation in Fluent via loading trajectories A and B separately. The duration time of the simulation process for trajectory A is 12.6 s, and a maximum surface temperature of 362 K and a minimum surface temperature of 327 K are observed. The time of the simulation process for trajectory B is 13.3 s, the maximum

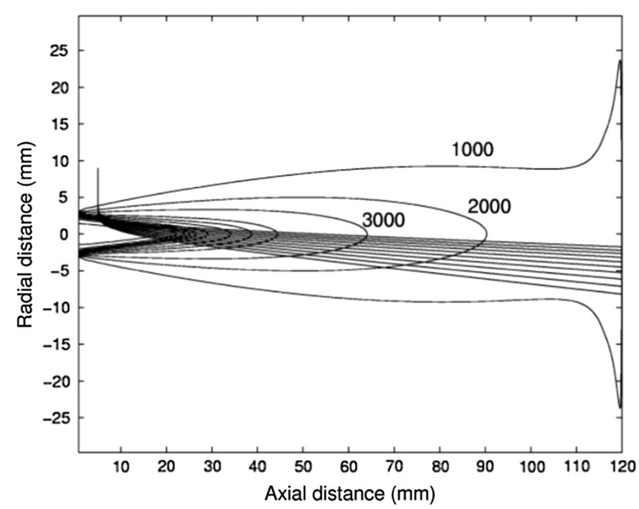


Fig. 8 Plasma torch isotherms and particle trajectories for a spray distance of 0.12 m

Table 1 Thermal properties of materials

Materials	Density, kg m^{-3}	Specific heat, J kg^{-1} K^{-1}	Thermal conductivity, W m^{-1} K^{-1}
Substrate/aluminum	2700	897	237
Coating/alumina	3960	753	36

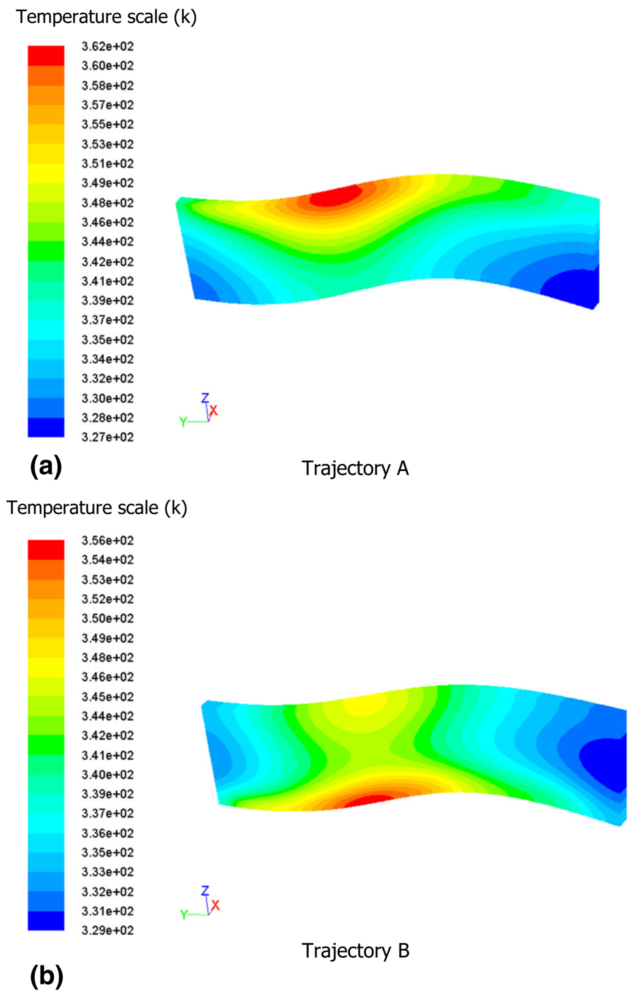


Fig. 9 Surface temperature field (k) of two meander trajectories

surface temperature reached is 355 K, and the minimum surface temperature is 329 K. The standard deviation of the surface temperature created by trajectories A and B equals 8 and 6 K, respectively, which confirms that trajectory B helps balance the temperature distribution on the coating surface. Using the analysis of temperature distribution on the coating surface, the thermal gradient in the component and residual stress distribution can be calculated, which helps perform further trajectory optimization such as the application of artificial intelligent technologies.

Conclusions

In this work, a mesh-based trajectory generation approach is introduced and a specific package is developed to achieve data exchange between ANSYS and RobotStudio^{TM}. Then, robot target points are generated based on the surface mesh data. Different meander trajectories are simulated in an off-line programming environment. The recorded real-time TCP position is employed as the displacement of the thermal source in Fluent. Then, a coupled model between the robot trajectory and the corresponding thermal history is developed to analyze the temperature distribution during the thermal spraying process, which helpsto determine the optimal robot trajectory.

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