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The Effect of Robot Kinematics on the Coating Thickness Uniformity

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The torch speed is one of the most important operating parameters in thermal spraying. Generally, in order to keep a uniform coating thickness, the movement of the torch should be constant. Nevertheless, when the torch follows a large trajectory angle, the torch speed will decrease significantly, which leads to an irregular coating thickness. This phenomenon is caused by the weight of different devices fixed on the robot and the combination of the robot's six axes. It is therefore necessary to optimize robot kinematics behaviors in this case. In this paper, the works concentrate mainly on the relationship between the robot kinematics property and the coating quality to find an adequate model for the torch speed optimization. An add-in program based on RobotStudio™ (ABB, Sweden) is developed to determine and optimize the spray trajectory. The optimal trajectory was verified by both the simulations and the experiments.

Keywords coating quality, optimize spray trajectory, robot kinematics, RobotStudio™, torch speed

1. Introduction

High-accuracy robot systems are widely used in modern thermal spray applications in recent years (Ref 1). When using a robot in thermal spraying, the trajectory generation represents an important part of the work. The generation of robot trajectory on 2D surface in thermal spraying is traditionally made by methods such as point-by-point or teaching-playback. But the demand for coating on 3D surface has increased over the last few years. It requires hundreds of points in the trajectory and different orientation for each point, so it is very difficult to create such a trajectory by manual point-by-point programming method (Ref 2, 3). With the development of the robotics, the robot manufacturers provide software for off-line programming, such as RobotStudio™, which is a simulation and off-line programming software of ABB Company. A virtual workshop can be elaborated and the robot program can be prepared and simulated with RobotStudio™. The turning status of 6 axes can be easily obtained while simulating the robot movement. This helps us to evaluate robot kinematics behavior during the spraying process which is used as the basis of optimization. In this paper, an ABB robot and the off-line programming software RobotStudio™ will be considered.

There are some important operating parameters in thermal spraying, for example, the torch speed, the stand off distance, spray angle, etc. The torch speed is one of the most important operating parameters in thermal spraying. In order to ensure the required quality of coatings, the movement of torch should be constant and the spray direction should be as close to normal as possible to the coating surface. However, when the torch follows a trajectory on a curved workpiece, if there is a large change of the torch orientation, the torch speed will be obviously decreased. This phenomenon can be explained by an uncoordinated combination of robot's six axes. Moreover, the movements that require a great torque in the robots' axes will not be correctly implemented due to some technical limitations associated with the servos. The kinematics behavior of the robot is thus of prime importance in the program execution, so it is necessary to optimize robot kinematics behaviors in this case (Ref 4). In this study, several methods will be proposed to optimize the robot movement in order to keep a uniform coating thickness.

2. Problems and Optimized Methods

As we know, in thermal spraying, the coating properties such as coating structure and surface profile (e.g. coating thickness) are highly influenced by the torch speed. Generally, in order to keep the coating thickness uniformity, the movement of the torch should be constant. But in certain case for example, to coat the sample shown in Fig. 1(a), the robot could not keep the speed as it should be.

In this study, a 1 mm thick stainless steel sheet with an angle 90° as shown in Fig. 1(a) was used as the substrate in our simulations and experiments. According to our previous tests, when the torch follows a trajectory which contains a large angle, the torch has to change its orientation rapidly. In this condition, it is not always possible for the robot to keep the torch speed, which leads to an

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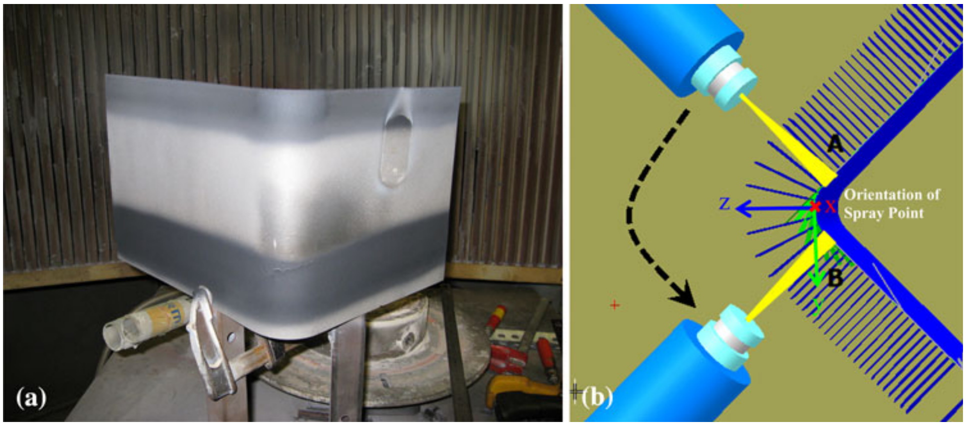

Fig. 1 (a) Real workpiece with a large angle and (b) trajectory with a large angle

irregular coating thickness. This is probably caused by two reasons.

The first is perhaps that the different devices fixed on the robot arm have a big inertia, which can prevent the robot arm from respecting the designed speed. It means the torch speed cannot always reach the planned value. The weight of all the devices fixed on the robot including the torch, the pipes and the cables were measured, which is about 9.7 kg in total in our experiments.

The second one is that a rapid change between linear and curved trajectory leads to a high individual axis acceleration, which can result in a strong vibration of robot arms and then deviate the torch trajectory. As shown in Fig. 1(b), there are many spray points in the trajectory which was created in RobotStudio™, the orientation of each spray point is different, blue color represents *z*-axis, green color represents *y*-axis, and red color represents *x*-axis. From A to B the distance is about 55 mm, and the planned torch speed is 500 mm/s, so the robot should take 0.11 s to pass these two points. That means that it must turn 90° in 0.11 s when combining all 6 axes. This should exceed the performance limit of the robot.

According to our experience, the influences of torch and cable weights on torch speed are small and it is difficult to solve this problem. Anyway it will be verified later by our experiments. Thus, our works will focus on estimating the effects from the second reason. Two strategies are proposed for optimizing the kinematics behavior in this paper in order to solve this problem.

2.1 Optimizing the Spray Trajectory by Changing Torch Setup

Based on the robot kinematics theory, the action of the robot is a combination of six individual axes: any complex action such as moving the torch from one point to another point can be decomposed in a series of axis movements (Ref 5). The position of the robot and its movements are always related to its tool coordinate system, i.e. the Tool Center Point (TCP) and tool orientation. TCP is defined as the impact point of material jet on the substrate in thermal spraying, which should scan all the surface of workpiece during the process (Ref 6). In fact, in the robot controller system, the speed parameter is defined as TCP speed which decides the torch speed in thermal spraying. In this paper, the TCP speed obtained from RobotStudio™ is called simulated TCP speed, and the TCP speed collected from robot controller is called real TCP speed. Different torch setup system including clamp position, torch direction, etc., will change TCP definition directly. For the same trajectories, different TCP definitions will bring different load distributions to six axes. That means a little change of TCP definition will change the relative movements of six axes as well as robot kinematics behaviors.

To explore the effect of the proposal mentioned above, two torch setup systems were tested. Figure 2(a) shows a conventional torch setup and Fig. 2(b) shows the simulation in RobotStudio™. The software RobotStudio™ allows simulating the process sequence. It is possible to test the robot movement collisions, the TCP speed, the movements of six axes and other problems during the simulation. For a given workpiece, the spray trajectory is created by the following two steps. In the first step, the way according to which the Computer Aided Design (CAD) imported data or the combination of some simple shapes is used for modeling the workpiece in RobotStudio™. In the second step, Thermal Spray Toolkit (TST) (Ref 7) is used to auto-generate the spray trajectory as described in Fig. 1(b). The orientation of each point is perpendicularly positioned to the workpiece surface. Here, a six degree of freedom ABB robot (IRB4400_45) was used in our simulations and experiments.

The movements of each axis recorded as ''rotation angle'' while the robot realizes the spray program for one pass by using conventional torch setup in simulation are shown in Fig. 3. The angular velocities of axes corresponding to every sampling point by using the conventional torch setup are calculated from Fig. 3 and shown in Fig. 4.

For a normal six-axis robot, the performance of each servo is different. Table 1 describes the maximum angular

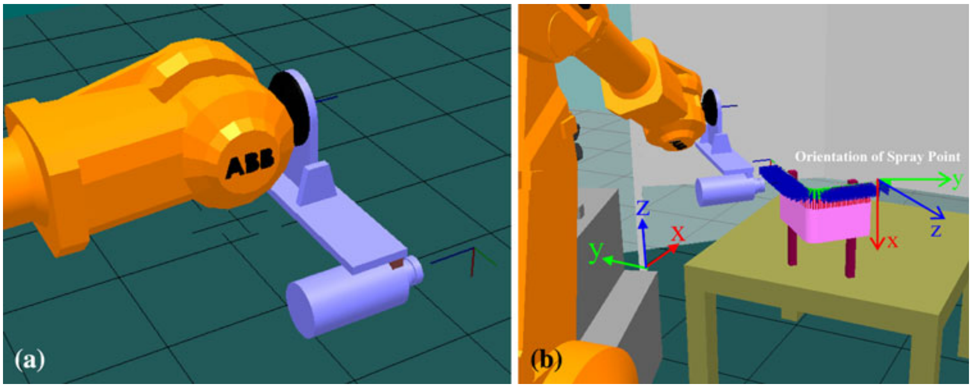

Fig. 2 (a) Conventional torch setup and (b) simulation in RobotStudio™

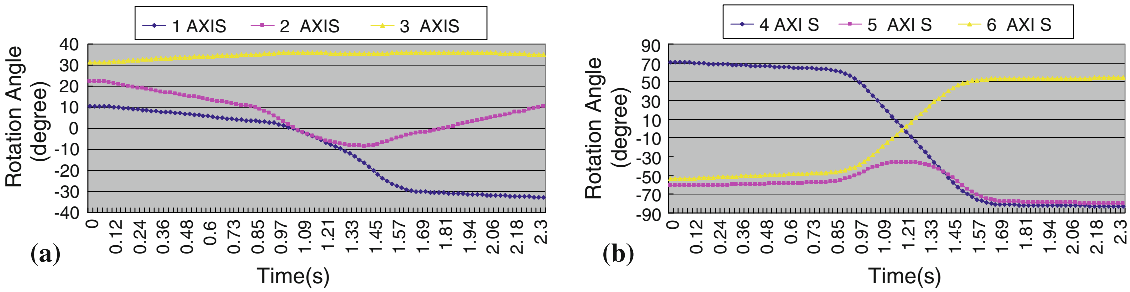

Fig. 3 Movements (rotation angle) of 6 axes vs. the time with conventional torch setup for (a) axes 1-3 and (b) axes 4-6

velocity of each axis and the working range of each axis in rotation for an ABB Robot IRB 4400-45.

As shown in Fig. 4 and Table 1, axes 4, 5 and 6 were loaded with the biggest movement of the torch, axis 4 reached its performance limit in the action and axis 5 is close to its maximum. So the purpose of optimization is to reorientate torch setup in order to combine the movements of axes 4 and 5 into axis 6 which is more preferment than the other axes as shown in Table 1. It can be obviously noticed that the biggest orientation changes happened in the plane X-Y, so the wrist plane of axis 6 should be superposed in X-Y for this purpose.

Figure 5 shows the optimized torch setup and the same simulation with optimized torch setup. Figure 6 shows the movement of each axis after optimization. Figure 7 shows the calculated angular velocities of six axes corresponding to every sampling point after optimization. As shown in Fig. 7, the angular velocity increases slightly for axes 1, 2 and 3; however, the angular velocity decreases greatly for axes 4 and 5. It is clear that axis 6 was distributed more movement load than the other axes. As mentioned earlier, axis 6 is the most flexible axis in all axes, so it is reasonable to let axis 6 assume the well-proportioned task. And this kind of movement load distribution should improve TCP speed.

For a deeper investigation, a comparison parameter called Motion Quantity (MQ) was defined for analyzing the robot work efficiency. MQ is the summation of the rotation angle per unit path length. Mathematically, it can be represented as:

$$\mathrm{MQ} = \frac{\int_0^t \omega dt}{l} \qquad \text{(Eq 1)}$$

where ω is the angular velocity of axis, t is the robot moving time and l is the robot moving distance counted by meter. To make an objective and convenient assessment of robot work efficiency, the weighted mean of MQ is chosen as an estimation criterion which is expressed as follows:

$$\overline{\mathrm{MQ}} = \frac{\sum_{i=1}^{m} w_i \mathrm{MQ}_i}{m} \qquad \text{(Eq 2)}$$

where m is the number of quantity of axis, w_i is the reciprocal of the maximum angular velocity of the axis i, MQ_i is the MQ of the axis i.

According to Eq 1 and 2, $\overline{\mathrm{MQ}}$ without optimization is 31.03 and $\overline{\mathrm{MQ}}$ with optimization is 18.35. This result reveals that the optimized torch setup can lead to a less $\overline{\mathrm{MQ}}$ per axis and further explains that the sacrifice of axis 6 leads to a global optimization so that the robot work efficiency is improved.

2.2 Optimizing the Spray Trajectory by Modifying the Angle Between Two Adjacent Points

This method aims at improving the trajectory which contains a large angle. If the workpiece has a curved

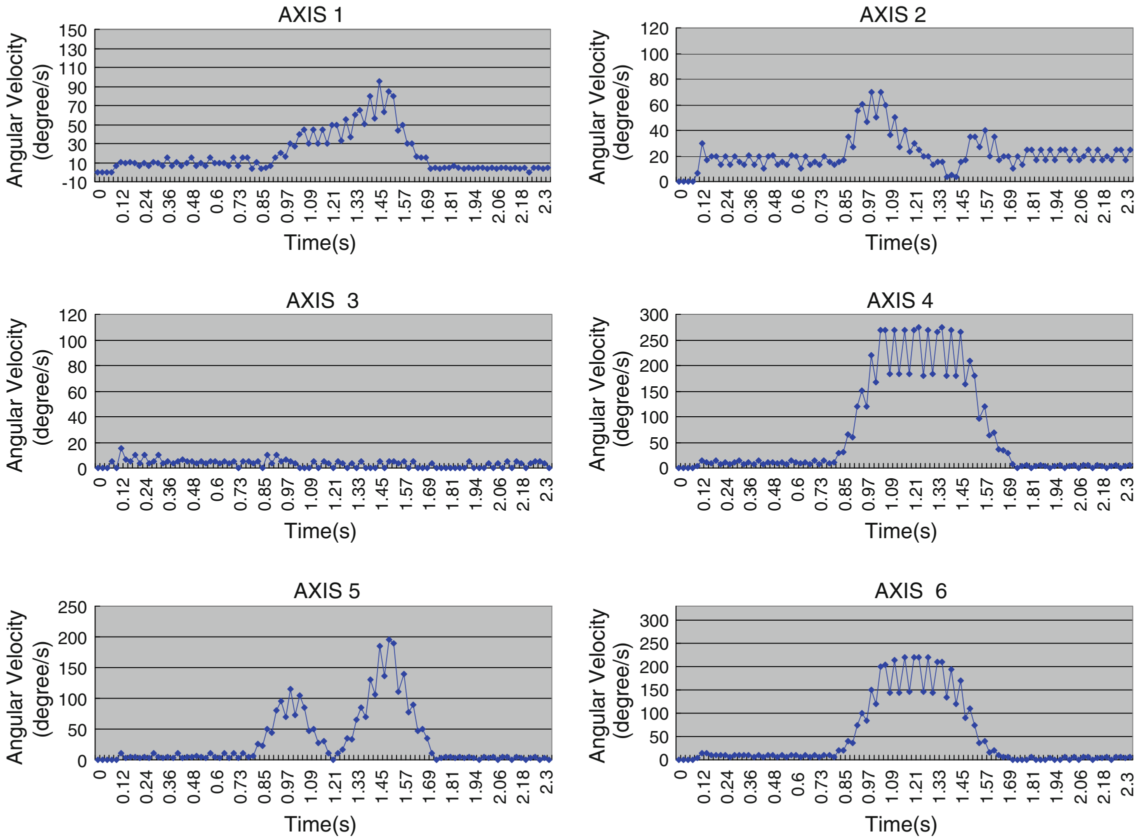

Fig. 4 Angular velocity of 6 axes with conventional torch setup

Table 1 Maximum angular velocity and working range of each axis

Axis name	Maximum angular velocity, °/S	Working range, °
AXE 1	150	+165 to −165
AXE 2	120	+95 to −80
AXE 3	120	+65 to −60
AXE 4	225	+200 to −200
AXE 5	250	+120 to −120
AXE 6	330	+400 to −400

surface with a large angle as shown in Fig. 1(a), the robot has to do a sudden change of orientation when passing the large angle zone. The TCP speed decreases then significantly. This quick change of torch orientation must be avoided. Thus, it is necessary to keep a smooth and slow change of torch orientation in order to keep a constant linear speed. The method is to assign the deflexion of the torch orientation before and after the large angle zone and insure that robot passes the angle little by little. This is done through changing the orientation of point after setting the maximum angle between each neighboring point. The spray angle will not be kept 90° with this method, but the TCP speed is close to constant.

For this application, an add-in program based on RobotStudio™ was developed for determining and optimizing the spray trajectory (Ref 8). The following steps are performed by the program for optimizing the spray trajectory: Firstly, choosing the reference point which is in the center inflexion in the trajectory. Then, setting the optimization fitness value: the maximum intersection angle between two normal directions of adjacent points. The fitness value is set to 2° in this experiment. Finally, the new orientation of each point which satisfies the above fitness is calculated and executed by the program automatically.

Figure 8(a) shows the trajectory without optimization, and Fig. 8(b) describes the trajectory with optimization. It is clear that the movement of torch becomes smoother after optimization. To figure out the influence of the fitness variation on the performance of the algorithm, a pre-evaluation with varying settings for the threshold ranging from 1 to 10° was conducted. In general, a smaller intersection angle threshold results in a smoother trajectory, which helps to stabilize the TCP speed, but it also increases the number of optimized points. From the evaluated values for our case, 2° seems the best in terms of the TCP speed stability and the number of optimized point.

3. Experiments and Discussion

In the last section, two methods were proposed to improve the stability of TCP speed and some preliminary

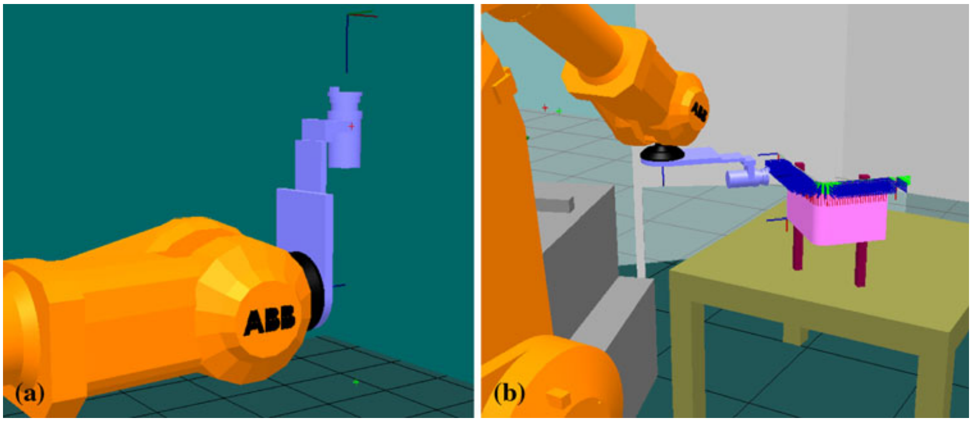

Fig. 5 (a) Optimized torch setup and (b) simulation in RobotStudio™

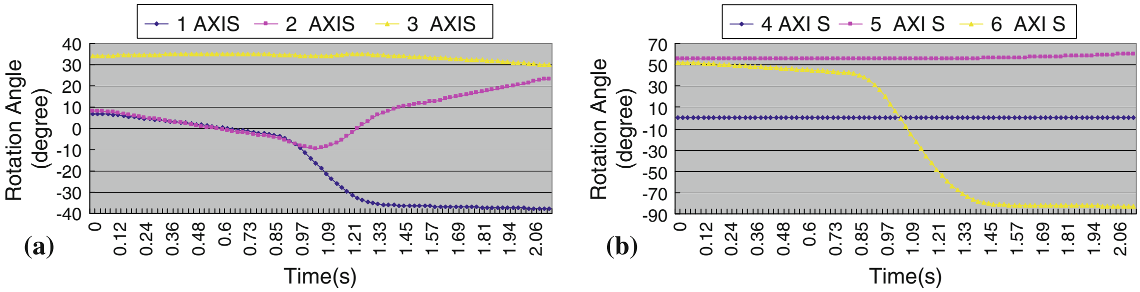

Fig. 6 Movements (rotation angle) of 6 axes with optimized torch setup: (a) axes 1-3 and (b) axes 4-6

analyses were carried out to validate our proposals. In this section, TCP speed and coating thickness uniformity will be analyzed with the help of simulations and experiments with a typical atmospheric plasma spray (APS).

A coating system was designed to apply this experiment. The ABB robot IRB 4400_45 was used to transport the APS torch F4 and the optimized torch setup was applied.

The main spray parameters of experiment are listed in Table 2.

3.1 Load Testing

As mentioned above, the weights of devices fixed on the robot may prevent the robot arm from running. Two comparison tests were performed to find the influence. The real TCP speeds were recorded by means of an acquisition card set in the control console (Ref 9). One was registered without torch; another was with the torch and cables. These speeds faithfully reflect the influence of load. Figure 9 shows these two speeds.

From these recorded speeds, it can be found that the real TCP speed with the torch is almost the same as that without the torch. That means that the inertia does not slow down the TCP speed. But both speeds are only 300 mm/s, less than the designed value: 500 mm/s. It is probably due to the total scanning course or the scanning course is too short for the robot to accelerate to 500 mm/s. Anyway the influence of device weights is very minor for this robot. So it is not necessary to consider this factor when using this robot. Moreover, the robot used in this study is relative heavy compared to the torch; the robot can support 45 kg on the axis 6 and the torch and cables are only 9.7 kg. If the robot was smaller, this speed decrease had to be considered.

3.2 TCP Speed Optimization for the Curved Workpiece

3.2.1 Simulated TCP Speed Analysis. A statistic method was used to treat the data to compare the stability of simulated TCP speed. The coefficient of variation (CV) is considered as an effective criterion. The mathematical expression of CV is as follows (Ref 10):

$$\mathrm{CV} = \frac{S}{\overline{X}} \times 100\% \qquad \text{(Eq 3)}$$

where S is the standard deviation (SD) and $\overline{X}$ is mean speed.

Figure 10 shows the simulated TCP speed variation recorded during the first simulation based on our first proposal: optimizing the spray trajectory by changing torch setup. These data come from RobotStudio™ simulation. Due to the limit of the processing performance of the robot controller, the maximum simulated TCP speed is around 350 mm/s, whereas the planned TCP speed was

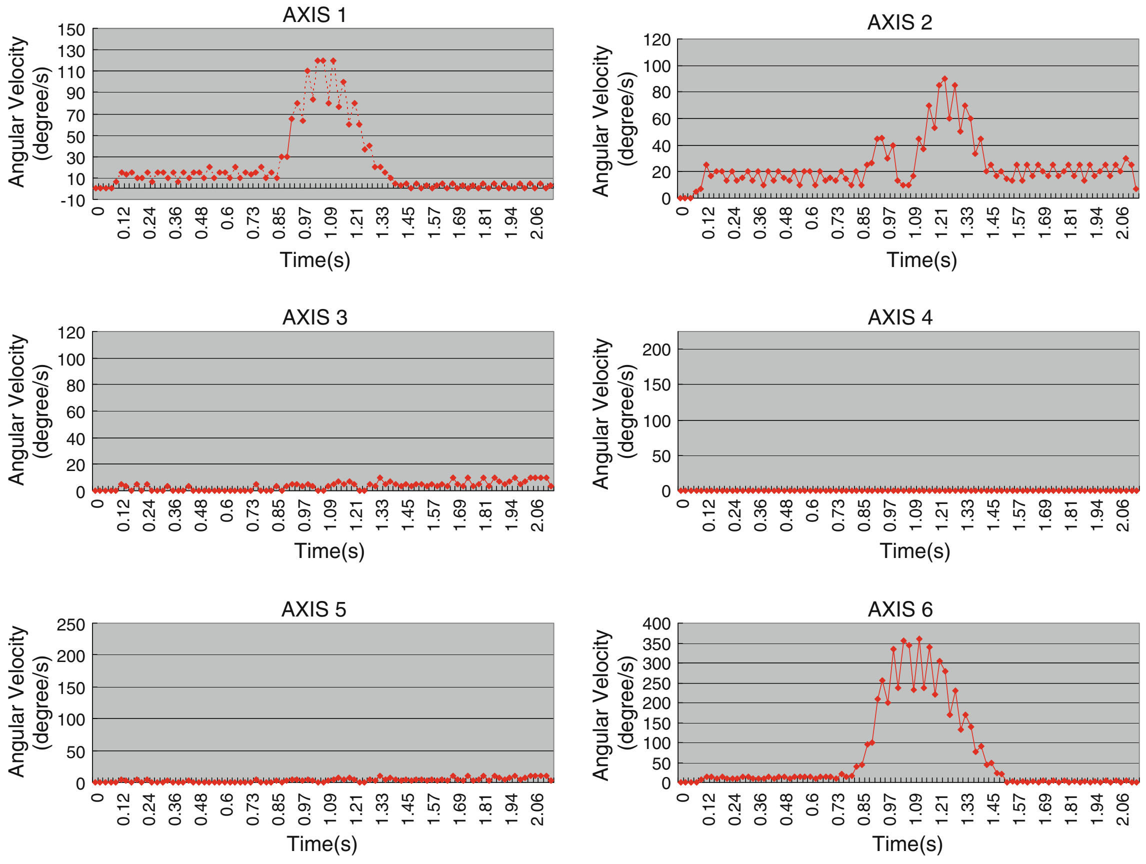

Fig. 7 Angular velocity of 6 axes with optimized torch setup

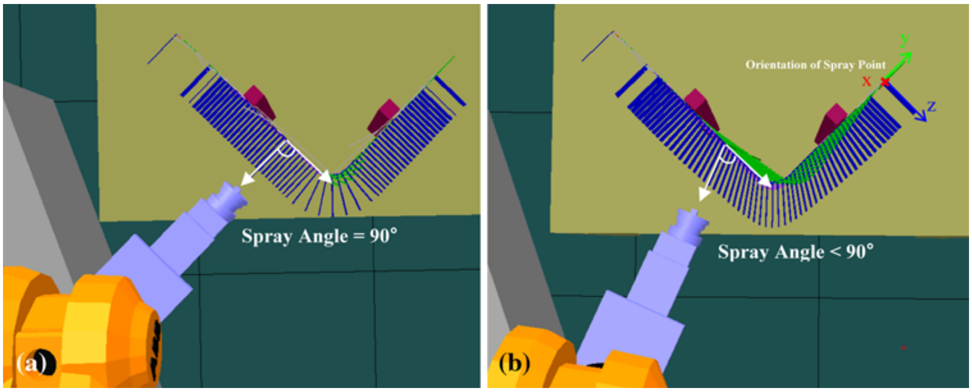

Fig. 8 (a) Trajectory without optimization and (b) trajectory with optimization

Table 2 Main experimental spray parameters

Plasma gun	F4
Input power, kW	29.4
Argon flow rate, L/min	30
H_2 flow rate, L/min	8
Powder	Al_2O_3/TiO_2 (−45 + 22.5)
Powder injection, mm	1.8
Powder feed rate, g/min	35
TCP speed, mm/s	500
Stand off distance, mm	120
Number of pass	20

500 mm/s. After optimization, the simulated TCP speeds increase when passing the large angle zone by comparing Fig. 10(a) and 10(b).

Table 3 shows CV of two results. From this statistical analysis, it is believed that the torch setup optimization can accelerate as well as stabilize the spray torch obviously. This conclusion not only validates our previous analysis: the optimized torch setup can increase work efficiency and avoid exceeding the robot limitation but also confirms that a judicious choice of torch setup can

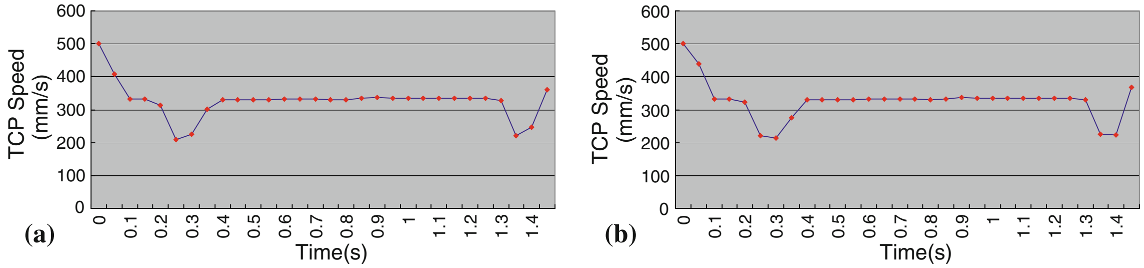

Fig. 9 Real TCP speed (a) without torch and (b) with torch and cable

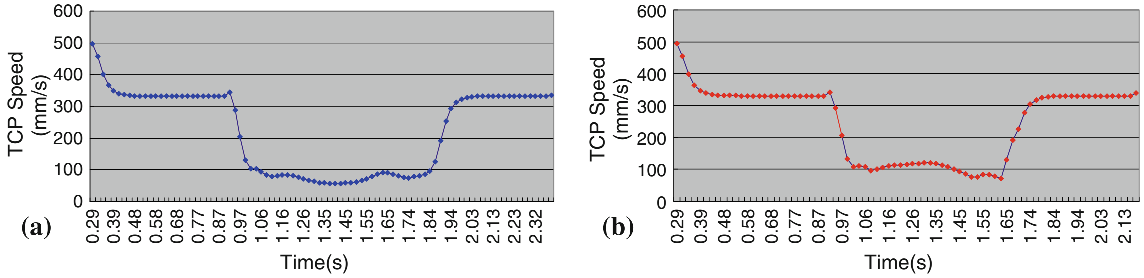

Fig. 10 Simulated TCP speed of (a) conventional torch setup and (b) optimized torch setup

Table 3 Statistic parameters of torch setup optimization

Parameters	Without optimization	With optimization
Mean	225.1	249.4
SD	129.9	114.6
CV	0.58	0.46

optimize the TCP speed. Although the improvement is not probably radical, the result shows clearly the importance of the torch setup design. The torch setup should be designed according to the trajectory directions. The following principle should be followed: try to let axis 6 turning in the same plane where the trajectory is so that the axis 6 can share the motion quantity of other axes, and the possibility that the robot exceeds its limit is reduced.

The second simulation is for our second proposal: optimizing the spray trajectory by modifying the angle between two adjacent points. The simulated TCP speeds in two different coating processes with and without point optimization are shown in Fig. 11, respectively. These data were also recorded from the simulation in RobotStudio™ and the optimized torch setup was used.

Here, the previous treatment method, the CV, is still used. Table 4 shows the CV of two results. The CV with optimization is much smaller than that without optimization. It indicates that the second optimization proposal is very effective. It is obvious from Fig. 11(b) that the simulated TCP speed is more homogeneous especially when the torch passed the large angle zone.

3.2.2 Experimental Results. As it is well known, experiment is the best criterion for testing the correctness of our solutions. Furthermore, RobotStudio™ is not fit for checking the coating quality. Therefore, after analysis for simulation, an APS experiment is carried out.

Previous analysis of simulation revealed that both optimization methods can make the TCP speed more constant. Thus, both proposed optimizations were applied in this experiment to reach a good spray coating quality with a homogeneous coating structure as well as a constant thickness.

Two plasma sprayings were carried out with the conditions listed in table 2; one was done without optimization (see Fig. 8a), another was done with optimization (see Fig. 8b). The workpiece and coating after spraying are shown in Fig. 1(a). The workpiece is sampled in equal interval in the length direction for thickness measurement, and the position of each sample corresponds with the position of each spray point on the trajectory. Figure 12 shows the coating thicknesses without and with optimization.

It can be seen clearly from Fig. 12 that the coating without optimization is very thick in the center. The thickness is about 2 mm in this region while the thickness of other regions is about half. This zone corresponds to the concave zone where the TCP speed is very slow as shown in Fig. 11(a). The coating thickness after optimization does not have this variation and is rather homogeneous.

The coating thickness in the flat area is about 0.7 mm. Figure 13 shows the spray angle at each point on the trajectory after optimization. In the curve area A, the TCP speed is almost the same, the spray angle was changed, and the coating thickness is nearly 0.7 mm and almost uniform, so the change of spray angle has not much influence on the deposition efficiency for this material, only the TCP speed affects the uniformity of the coating.

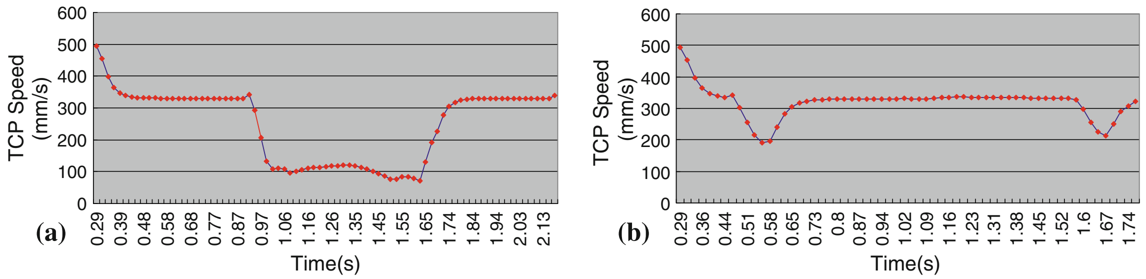

Fig. 11 Simulated TCP speed (a) without optimization and (b) with optimization

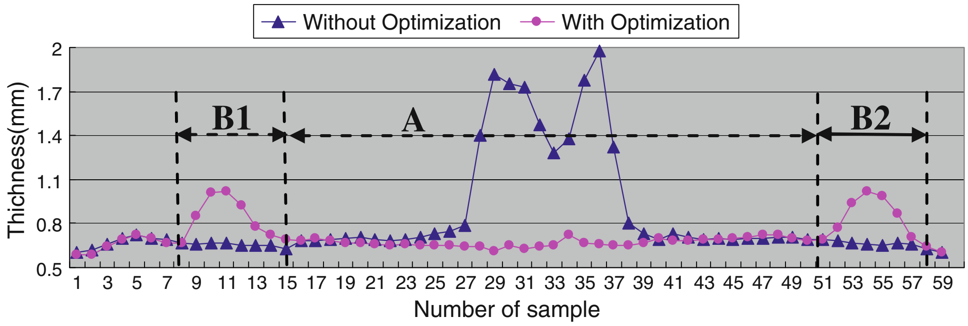

Fig. 12 Thickness of each sample on workpiece in coating length direction

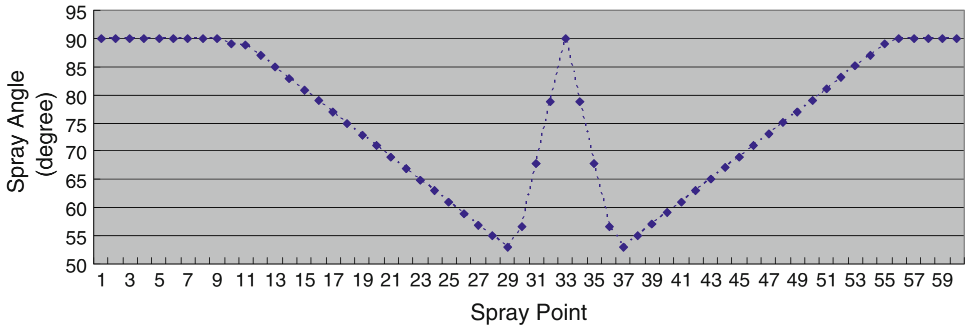

Fig. 13 Spray angle at each spray point

Table 4 Statistic parameters of point optimization

Parameters	Without optimization	With optimization
Mean	225.1	319.5
SD	129.9	49.5
CV	0.58	0.16

In the curve area B1 and B2, the coating is relatively thick compared to the curve area A; this is due to a decrease of speed in a short period and this decrease was probably caused by the beginning of variations of spray angle as shown in Fig. 13. This variation will be explored and optimized in our further work. Globally, the coating is improved by the optimization even there are two little variations

Table 5 Statistic parameters of the coating thickness uniformity

Parameters	Without optimization	With optimization
Mean	1.04	0.82
SD	0.37	0.09
CV	0.36	0.10

Here, the CV is once again fit to analyze the coating thickness uniformity. As described in Table 5, it is obvious that CV with optimization is less than that without optimization. As expected, this result indicates the coating thickness uniformity is improved by our solutions.

To investigate the effect of spray angle on the microstructure of coatings, cross sections of four samples with

Table 6 Porosities of the coatings

	1	2	3	4	5	Average
Spray angle 90°, %	4.95	6.85	6.4	5.36	4.87	5.686
Spray angle 80°, %	5.31	5.67	3.1	4.19	3.99	4.452
Spray angle 70°, %	4.88	4.11	4.07	3.47	4.97	4.3
Spray angle 60°, %	3.81	2.7	3.5	6.05	7.06	4.624

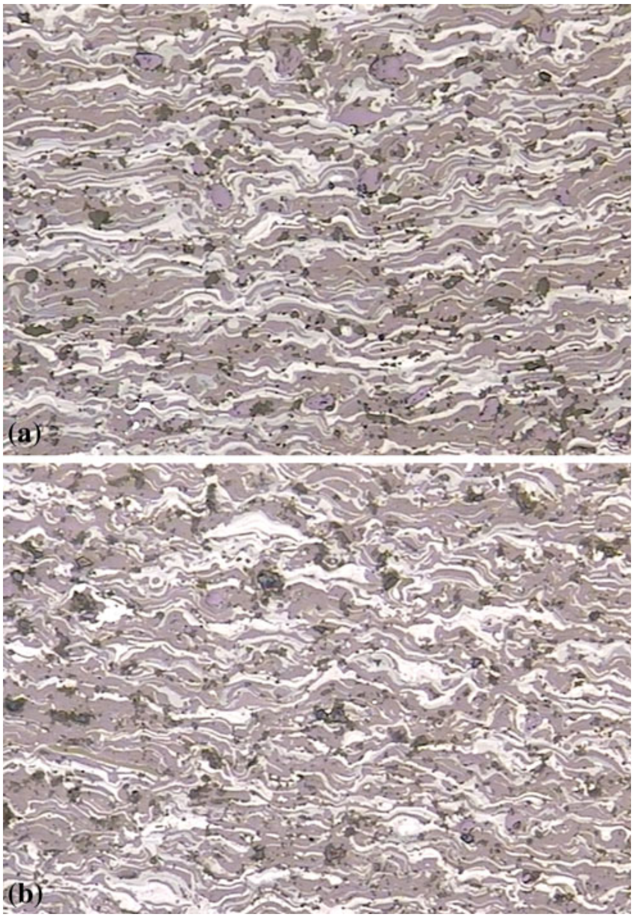

Fig. 14 Scanning electron micrographs of a coating cross-section for (a) spray angle 90° and (b) spray angle 60°

different spray angles were analyzed by optical microscopy (Nikon, Japan) and porosity measurements were done by image analyse software (Scion Image). The porosity measurements for each sample were carried out from five micrographs and shown in Table 6.

According to the statistical method ANOVA *F*-test (Ref 11), the *F* value calculated from these four porosities is equal to 1.1. Compared to the table of *F*-test critical values, the result is significant at the 28% significance level. Normally if the significance level is upper than 5%, it can be deduced that these four porosities have no significant differences. It means that spray angle, in this range, has no or slight influence on the porosity.

Figure 14 shows the typical scanning electron microscope (JEOL, Tokyo, Japan) images of coatings. It can be found that there is no difference between the coating sprayed with 90 and 60°.

4. Conclusions

The high-performance thermally sprayed coatings require advanced automation systems. The TCP speed stability is becoming an important process parameter as the demand for high-quality spray coating. In this paper, the reasons for inconstant TCP speed while the workpiece has a curved surface were investigated. Consequently, based on these analyses, two optimization methods to keep the TCP speed are proposed. One is the improvement of torch setup system; in such way the flexible axis can share more motion quantity in order to reduce the total motion quantity. Furthermore, the design of torch setup should be adapted to the concrete trajectory. Another is to change the point orientation before and after the curve zone to distribute this large angle into the whole trajectory. The simulations and experiments are implemented for the different scenarios. The conclusions from simulations and experiments verify that these two optimization methods can improve effectively the coating quality.

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