Experimental Investigation on the Spray Characteristics of a Robotic Spray Paint Gun Used for Car Repaint

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***Abstract*— When using a spray gun, grasp the distance between the object and the spray gun and the overlap of painting by spray distance, and well-balanced paint quality results can be obtained when maintenance painting work is performed. The width of the spray pattern is formed in a vertically long elliptical shape and when the spray gun moves, it is difficult to form a paint film at the edge of the paint because the discharged pressure is low and the density of the paint is low. The paint sprayed with the spray gun has the property that the central part of the object to be coated is the thickest and becomes thinner toward the edge due to the difference in density. In order to obtain a target coating film thickness with a set number of sprays, the width of the coating pattern for each spray distance must be considered. On the standard painting conditions for automobile repair painting, when the distance between the object to be coated and the spray gun is about 12 to 15 cm and when the feed speed of the spray gun is about 0.3 ~ 0.5 m/s, it is possible to form the thickness of the coating film according to the paint manufacturer's manual.**

***Index Terms*—Coating thickness, spray pattern width, spray distance, paint work, spray gun**

I. Introduction

Car painting includes new car painting that is applied to the production line and maintenance painting after the release of new cars.

Maintenance painting [1] often occurs upon damages from accidents while driving or damages to the external paint face of the car due to the usage environment. Car maintenance paint is classified into oil-soluble [2] and water-soluble [3] paint, with the global trend recommending the use of water-soluble paint to protect the atmospheric environment.

Oil-soluble and water-soluble paint are classified depending on whether thinner or water was used as the diluent of the base paint, which determines the color of the coating. Water-soluble paint is environment friendly compared to oil-soluble paint due to its lower amount of volatile organic compound emission, relatively free in color expression, and excellent in its brightness and Chroma. Also, while the customer demand for more beautiful cars with more shining increase the tendency of using metallic (powered silver) paint as opposed to solid paint, even if the same pigment combination ratio is used for the maintenance painting, the color expression is often different from the color of the original paint depending on the spray method used by the operator such as spray distance, pressure, angle, etc. This is why a lot of color differences occur during water-soluble maintenance painting depending on the proficiency of the worker. Significant differences in color expression occur, despite color matching and mixing [4] depending on the painting method used by the worker.

Even when the same maintenance painting worker paints the same color, the color expression completely changes depending on the painting method [5] such as the number of sprays, width of overlapping, spray distance, etc. As a result of this, two-color phenomenon occurs between the existing panel and the maintenance paint panel, causing significant differences in the brightness and Chroma which may cause customer complaints. Despite efforts by the maintenance painting worker to identify the causes of two-color phenomena, since it is difficult to find the cause, they tend to repeat the process of mixing, spraying, etc. If the two-color phenomenon is caused by an issue in the spray process, the worker may repeat mixing and spraying and waste time and materials without recognizing this. Unlike oil-soluble paint, water-soluble paint requires operation methods and painting manuals that consider the characteristics of water-soluble paint [6][7] and following the correct spray gun use method to reproduce paint quality and highest quality of color expression [8][9].

Darwish et al. (2019, 2018) explained the size distribution of the droplets [10][11]. They stated that the droplet size became more uniform by enlarging the lateral distance. Oswald et al. (2019) demonstrated that the elongational resistance flow influences the disintegration process in the bell atomizer [12]. Shen et al. (2019)

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reported the droplet disintegration process and the non-Newtonian fluid behavior that is injected into the orifice and bell surface[13]. Pendar and Pascoa (2020, 2021) investigated the fundamental flow behavior around the sprayer[14][15].

This study experimentally investigated the method for using spray guns, which are always used for maintenance painting, in terms of their spraying characteristics [16-18].

II. Experimental Equipment and Method

To check the spray characteristics of essential maintenance painting equipment spray gun and the paint transfer face characteristics from the spray work, this study investigated the effective width of the transfer after spraying on 1mm graph paper and sprayed on a sheet of W(500mm) XL cut in 5mm vertical intervals to measure the weight and thickness of the paint.

Also, since actual car panels could not be used, the spraying was done on W(300mm)×L(300mm)×T(0.8mm) cold-rolled steel sheet specimen, which is identical to the car steel sheet material, after which the coating thickness, weight, etc. were measured.

A. Experimental Equipment

This study was done inside the Autonomous spray booth of the automatic equipment to maintain the spray work environment constant.

The Gravity type spray gun by SATA was used for the experiment, and HVLP(High Volume Low Pressure) technology-applied spray gun with nozzle size Φ1.3mm which is used most often in maintenance painting as well as RP(Reduced Pressure) method spray gun with fast operation speed and nozzle size Φ1.3mm used for the overspray [11]. Also, the pressure of the spray gun was kept constant using a digital pressure gauge and regulator.

Water-soluble paint by company K for maintenance painting was used(Table V), and the experiment was done using a specially manufactured 3D painting robot (Fig. 1) with its specifications outlined in Table I to maintain spray gun transport speed, the distance between the spray gun and the target, etc. constant and thereby acquire reliability.

To measure the mass of paint that has been applied to the target after the spray work is completed, a high-precision digital scale (GF-603A) with sensitivity up to 0.001g was used – specifications are outlined in Table II. Also, the coating thickness was measured using a Dry Film Thickness (DFT) measuring instrument (Elcometer 456) with specifications outlined in Table III.

B. Experiment Method

The spray gun was attached to a 3D painting robot that was specially manufactured to allow automatic control of the spray gun, the ideal distance between the spray gun-arrival face for each transfer speed and the transfer speed that satisfies the standards in the painting manual of the gun manufacturer were identified, after which this experiment was conducted considering the spray width, pattern, and arrival rate. The experimental conditions are outlined in Table IV.

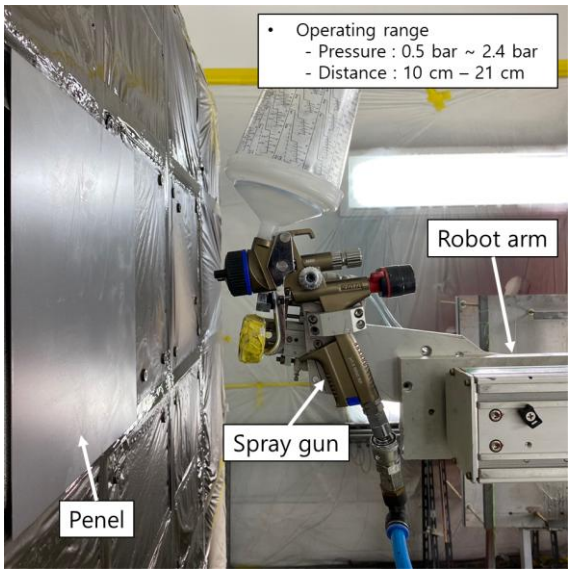

Figure 1. 3D painting robot.

TABLE I. 3D Painting Robot Specifications

3D ROBOT		
X-axis	Model	RBC-21HSA
	Stroke	1100-N7KN
	Motor	HC-KFS43 KFS/AC 400W
	Encoder	INC/5CLD/131072
	Gear ratio	20
	Max. rpm	1350
	Moving speed	0.1~0.7m/s
Y-axis	Stroke	900
	Motor	HC-KFS23
	Input	3 AC 118V 1.1A
	Output	200W IEC60034-1'99
	3,000rpm IPC.I.B 1.0kg	
	Moving speed	0.1~07m/s
Z-axis	Stroke	500
	Moving speed	0.1~0.5m/s

TABLE II. Electronic Scale

Digital electronic scale	
Model	GF-603A
Weight	620g
Minimum weight	0.001g
Straightness	±0.002g
Stable time	1.2Second

TABLE III. The Specifications of Digital Dry Film Thickness Gauge

Digital electronic scale	
Model	Elcometer A456C
Range	0~1500 ㎛
Accuracy	±1~3% or ±2.5 ㎛
Resolution(0~100 ㎛)	0.1 ㎛
Resolution(100~1500 ㎛)	1 ㎛

1. The experiment was done in a spray booth specific for water-soluble painting to maintain the temperature, humidity, and wind speed inside the spray booth constant.
2. The spray gun and the target were placed in parallel and the angle of the spray was perpendicular to the target.
3. The spray result was obtained using 1mm graph paper and sheet paper cut in 5mm intervals, while the painting of the metal sheet was done using a panel of 300mm×300mm size.
4. The transfer speed of the spray gun was set between 0.2 ~ 0.7 m/s in 0.1 m/s increments to measure the arrival face coating thickness and paint weight for each spray distance of 80mm, 100mm, 120mm, and 150mm. For horizontal back and forth spraying, the comparison was made by dividing into 50mm and 75mm for vertical overlapping on the arrival side.
5. The pattern width based on the distance between the spray gun and the target was classified into base coat and clear coat, where repeated experiment of spraying, drying by heating, and measuring the weight of sheets cut in 5mm fragments was used to check the weight distribution characteristics of the coating.
6. Water-soluble base coat was painted twice using the WET ON WET method, and the fresh off time during paint work was 10 minutes for the base coat and 10 minutes for the clear coat. 10 minutes of setting time was applied after completion of the paint, and the heating to dry the paint was done for 30 minutes at 60 ℃. The manual by the paint manufacturer is outlined in Table V.
7. For the measurement of coating thickness for water-soluble base coat and clear coat, the method in ⑥ was applied before using Dry Film Thickness (DFT) measuring equipment (Elcometer 456). In measuring the thickness of the coating that has arrived at the panel, the average of measurements obtained from 5 locations was used in accordance with the testing methods specified by KS M ISO 1984012), KS M ISO 280813) and SSPC-PA2.

TABLE IV. EXPERIMENTAL CONDITION

Temperature		25 ℃	
Humidity		67%	
Velocity of wind		0.7m/s	
Viscosity of	Base coat	16sec	
	Clear coat	18sec	
Paint		2K PUR Clear coat	
		1K Water Base coat	
Spray gun type	Base coat	Gravity type	HVLP
	Clear coat		RP
Nozzle size		1.3mm	
Baking		60 ℃×30 min	
Panel (Width×Length×Thickness)		300 mm × 300 mm × 0.8 mm	
Air pressure	Base coat	2.0bar	
	Clear coat	1.5bar	
Gun speed		0.3~0.7m/s	

TABLE V. WATER BASE, CLEAR COAT APPLICATION GUIDE

Base coat	Mixing ratio(vol)	100 : 25~60%
	Wet coat	2~3
	Fresh time	Air blowing
	Setting time	10~20 min
	Dried film	10~20 ㎛
Clear coat	Mixing ratio(vol)	3 : 1
	Wet coat	1.5
	Fresh time	5~10 min
	Setting time	10 min
	Baking	60 ℃×30 min
	Dried film	50~60 ㎛

III. EXPERIMENT RESULTS AND CONSIDERATIONS

Spray testing 3D paint robot that can control the transfer speed, spray distance, overlapping width, pressure, etc. of the spray gun at constant levels allowed identification of the coat formation for water-soluble base coat and clear coat as well as the spraying characteristics of the spray gun. Identifying the spray characteristics of the spray gun and the appropriate settings for the spray gun such as transfer speed, distance from the target, and width of paint overlapping was possible through the experiment, which helped identify the optimal spraying method to obtain a high-quality maintenance paint area with even distribution. The summary of this analysis is as follows.

A. Transfer Speed and Distance Considering the Coating Thickness

According to the clear coat painting manual, spraying was done twice using the Wet on Wet method, then the thickness of the coating that reached the panel was measured to check the appropriate distance between the spray gun and the target. At this time, if the distance between the spray gun and the object to be coated is too close, the paint seated on the object to be coated accumulate with each other, and the phenomenon of flowing down becomes stronger, making it difficult to use. Therefore, the spray gun and the object to be coated become difficult to use. The experiment was conducted with the minimum distance between them set to 8 cm.

When this distance was 8cm, the width of the pattern of paint sprayed from the gun was too narrow, causing the paint that has landed on the target to accumulate or flow immediately after spraying. Also, the air pressure that was released along with the paint caused the paint to go outside the effective spray range and result in irregular arrival rates. When the distance was 15cm, while paint flow or accumulation did not occur, the atomization of the sprayed paint and the lowering of pressure after spray resulted in a large amount of paint that failed to arrive at the panel and was lost.

In conclusion, the appropriate transfer speed of the spray gun with a low failure rate that follows the manual of the spray gun was 0.3~0.5m/s, and the appropriate distance between the spray gun and the target was

determined to be 10~15cm for good quality painting. Also, since the number of repetitive overlapping of paint on the target directly affected the thickness of the coating, it was confirmed that painting must be done while considering the number of overlaps on the spraying side.

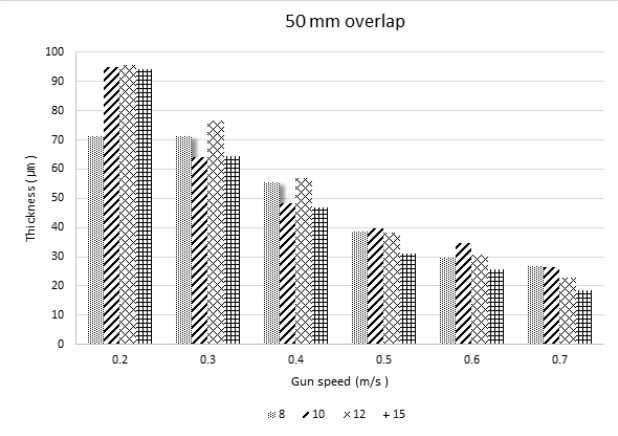

Figure 2. Thickness of coating film

B. Paint Distribution on the Arrival Face

The paint sprayed from the spray gun was identified to have a parabolic shape as seen through the high-speed camera image Fig. 3 before landing on the target. The parabolic spray pattern width becomes longer and broader as the distance from the target increases, narrowing with the decrease in this distance. For the paint that is sprayed due to pressured air, it arrives at the target with higher pressure at shorter distances while the amount that reaches the target significantly decreases with the increase in distance due to lower pressure.

When the direction of spray gun movement is left-right and the spraying is done perpendicularly (up-down), the distribution of paint that arrived at the target, as seen in Fig. 4 and Fig. 5, had the highest coating thickness in the center regardless of the spray distance (8, 10, 12, 15cm), and the thickness of the coating was less near the two ends due to lower pressure and consequent lowering of the arrival rate. Meanwhile, for both the base coat and clear coat paint, the spray that was applied to the surface was concentrated at a lower point in comparison to the center that is parallel to the spray nozzle, because of the movement of the air inside the paint booth going from top to bottom at a speed of around 0.7m/s and also due to the effect of gravity.

In the distribution chart for the paint on the arrival face, the base paint had less spreading due to fast drying of the solvent to result in an uneven curve, while the clear paint had a relatively smoother curve due to its high spread ability.

C. Change in Coating Thickness Based on Overlapping Distance and Spraying Distance

The clear coat was painted twice using the Wet-on-Wet method, and when the experiment was conducted with the spray arrival face overlapping distance of 30mm, 50mm, and 75mm in combination with the distance between the target and the spray gun as 10cm, 12cm, or 15cm. The result of the experiment is displayed in Fig. 6.

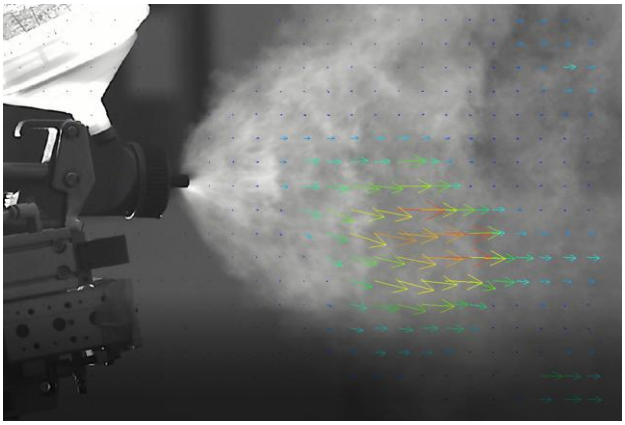

Figure 3. Spray pattern width measurement.

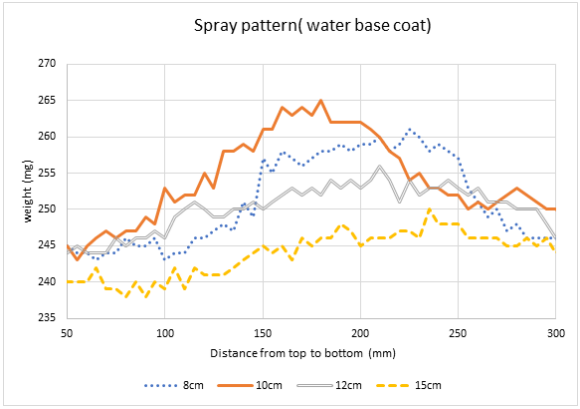

Figure 4. W-base coat paint film weight.

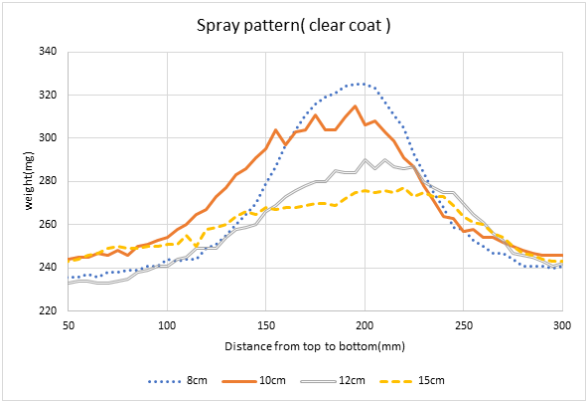

Figure 5. Clear coat paint film weight.

With more overlapping in the paint face and a shorter distance from the spray gun, the thickness of the coating increased, while less overlapping and longer distance resulted in thinner coating. Also, with more paint overlapping and closer spray gun distance, the paint experienced a flowing phenomenon, and although the opposite condition had less flowing of the paint, the thickness of the coating became thin which required an increase in the number of paints. In conclusion, the thickness of the coating increased with smaller distance between the spray gun and target, and vice versa.

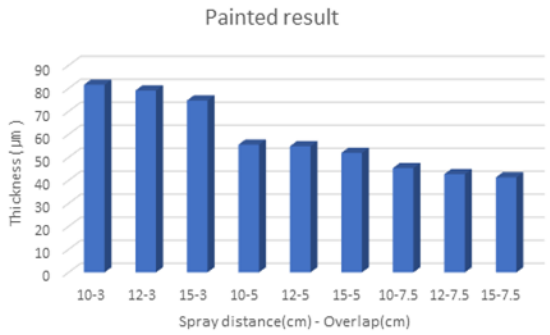

Figure 6. Painted result

D. *Leveling from Paint Overlapping and Spray Distance*

The paint applied on the target moving to create a smooth even coating is called Leveling, and the coating is said to have good leveling if there aren't a lot of microscopic bumps on the surface such as brush marks, orange peels, waves, etc.

When the clear coat was sprayed with 30mm, 50mm, and 75mm arrival face overlapping, the leveling was best at 30mm paint overlapping as shown in Fig. 7 but significant paint flow was observed with the thickening of the paint coating.

With 50mm overlapping, as shown in Fig. 8 leveling was satisfactory in all three distances of 10cm, 12cm, and 15cm between the spray gun and the target with no paint flow.

For 75mm paint overlapping, while there was no flowing phenomenon, there was poor leveling and a valley formed at the center of the paint overlapping as shown in Fig. 9. Also, the formation of the valley refers to a lack of paint that arrives at the target, and as seen in Fig. 10, it was to a point where the color of the channel below the base coat was visible in stripes in the direction of the spray.

In conclusion, the appropriate spray distance appeared to be between 12 ~15cm as no valleys are formed with the increase in overlapping.

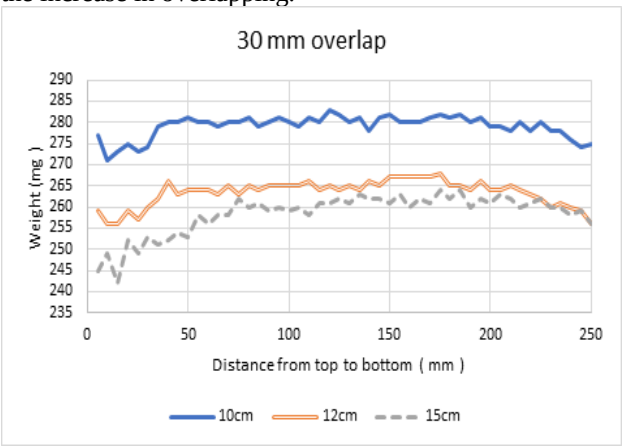

Figure 7. W-base coat 30mm overlap paint film weight

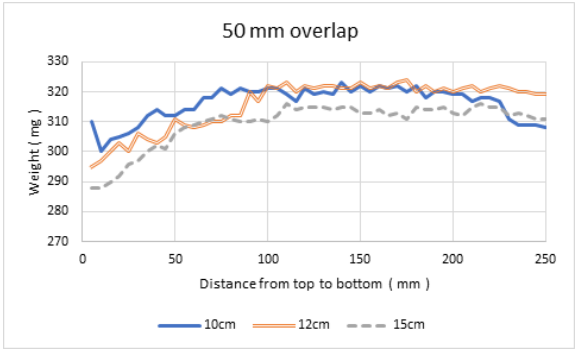

Figure 8. W-base coat 50mm overlap paint film weight

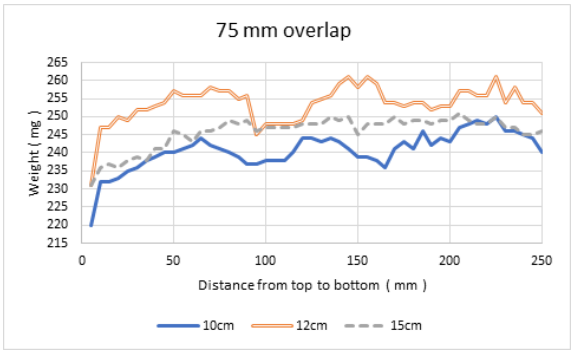

Figure 9. W-base coat 75mm overlap paint film weight

Figure 10. W-base coat color difference

E. *Effective Spray Width Based on Spray Distance*

As seen in Fig. 11, the paint is sprayed in a curve shape from the nozzle of the spray gun. Within the effective range where painting quality can be assured, the width narrowed with shorter spray distance and increased with more distance, while the thickness of the coating at the arriving face was thicker in the center and thinner towards the edges.

The specifications provided by the manufacturer of the spray gun used in this experiment states a maximum spray width of 30cm in atmospheric pressure of 1.5~2.0 bar and distance of 15~20cm from the target, but when spraying was done with a transfer speed of 0.3m/s and spray distance of 15cm, the maximum spray width measured by spraying in a stationary state for a certain period of time was different compared to when the spraying was done while moving as shown in Fig. 12.

While transferring the spray gun with the same speed as in Fig. 12 to a graph paper, the relationship between the effective width during transfer and maximum width in a stationary state, as shown in Fig. 13, was where the width of the effective arrival face during transfer was around 4cm less in average compared to the maximum spray width.

During actual maintenance painting, the paint is sprayed while moving the spray gun at a constant speed with the overlapping that results in good leveling upon consideration of arrival spray characteristics of the paint, so the spray width during the transfer of the spray gun is the actual effective spray width. To obtain the desired coat thickness, the effective spray width that changes depending on the distance between the target and the spray gun must be considered to decide the overlapping distance and the number of paints.

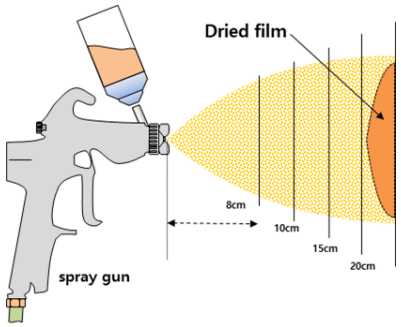

Figure 11. Spray gun spray width

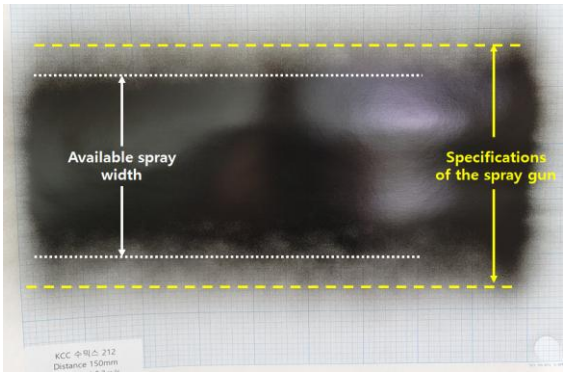

Figure 12. Spray pattern width

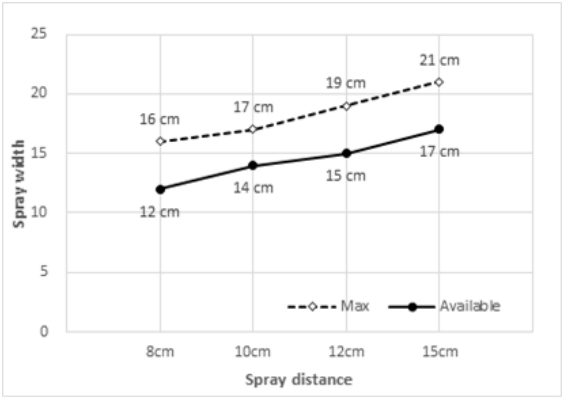

Figure 13. Available spray width

IV. Experiment Results and Considerations

After attaching the spray gun to a specially manufactured 3D painting robot for automatic spray gun control, the transfer speed, spray distance, overlapping width, spray pressure, etc. were kept constant while observing the arrival face after applying the paint on the target. The following conclusions were deduced on the characteristics of the spray gun, characteristics of the arrival face, and the precautions during spray work.

1. Under standard conditions, the ideal spray distance was around 12~15cm, with the spray gun transfer speed at 0.3 ~ 0.5m/s, which are different from the values generally used and specified in the data.
2. The distribution of the paint arrived at the target was thicker in the center towards the location of the nozzle and thinner towards the edges due to less painted amount, while the thickest area was slightly oriented downwards from the center due to the movement of internal air and effect of gravity.
3. The width of the paint sprayed on the arrival face during the transfer of the spray gun is different from the maximum width provided in the data, and thus the effective width during transfer must be confirmed as this is used during the actual maintenance painting.
4. Since the sprayed paint arrives at the target in a projected manner, the overlapping width on the arrival face during spraying should be between 30 ~ 50mm for ideal leveling.

Identifying the characteristics of the spray gun and the formation of the coating on the arrival face before performing maintenance painting can create a more efficient coating of higher quality, and is also expected to decrease atmospheric environmental contamination by reducing the amount of paint used.

In the future, further research will be done to prove the two-color phenomenon depending on the metallic particle arrangement on the arrival face and to identify spraying methods where the spray worker can control the arrangement of these metallic particles.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Woonsang Lee and HaengMuk Cho conducted the research and wrote the paper; Woongsang Lee analyzed the data. All authors had approved the final version.

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