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Key Factors Affecting the Performance of RFID Tag Antennas

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1. Introduction

Bar codes and Radio Frequency Identification (RFID) both belong to a group of technologies called Automatic Identification and Data Capture. People have all become very aware of bar codes as they have permeated our existence in the last 25 years. In fact, it is tough to buy something in a store that does not use bar codes these days. But bar codes have four disadvantages: you have to be able to see them, the bar code cannot be written on or defaced, you cannot change the data once they are printed, and they take up space on the object they are printed on. To eliminate those disadvantages, RFID is the solution. RFID is a means of capturing data about an object without using a human to read the data. Along with Smart cards, and Magnetic Stripe technology and a host of others, this is a method of automating our need for data. Recently, the technique of RFID grabs people's attention because it captures data about an object without using a human to read the data.

Individual RFID tags must be cost-efficiency for these applications (usually less than one to two cents). The cost of antennas is a crucial factor in the mass production of antennas. To reach this goal, emphasis has been placed on the development of printed electronics technologies to enable the manufacturing of RFID tags in an economically competitive way (Hodgson, n.d.; Björninen, et al., 2009). Various printing processes has been or is currently being used for producing a number of electronic components such as printed circuits, displays, RFID antennas, batteries, etc. Printing techniques such as flexographic, offset and gravure are suited for mass production, while screen printing and ink-jet printing have been identified as processes that could be employed for printing the antennas in order to bring down the cost of RFID tags (Sangoi, 2004; Subramanian, 2005). Screen printing enables very thin printing and also very thick films. It has been used for a long time to print circuits and remains interesting for electronic printing. In the future, different printing methods are likely to co-exist in the printed electronics market. The choice of printed electronics technologies will base on the normal parameters such as run length, feature size and variable data requirements (Blayo & Pineaux, 2005; Parashkov, et al, 2005).

Three requirements of printed electronics are resolution, accuracy of position, and amount of material deposited (i.e., thickness and content of active particles). Although the achievable resolution with screen printing (usually under 50 lines per centimeter) is not sufficient for high-performance electronics, it is still applicable to print gates for TFTs, dielectrics, and semiconductors. In printed electronics, silver particles are often used to form the conductive layer. Thin conducting layers are preferred to maintain low manufacturing costs while maintain good radiation efficiency (Parashkov, et al, 2005; Björninen, et al., 2009). Therefore, the amount of silver and the thickness of the conductive layer need to be well defined. Previous works have shown that decreasing conductor thickness increases losses and thereby decreases efficiency and results to weaker backscatter from the tag. Gao and Yuen's paper (2009) exam the effects of printing thickness on the performance of UHF RFID tags and found out that the 10 μm thick RFID antenna exhibits relatively good radiation efficiency. Koptioug et al.'s paper on "On the Behavior of Printed RFID Tag Antennas, Using Conductive Paint" indicated that with conductive layers of thickness beneath 10 μm, a commercially available silver-based paint with finite conductivity showed low radiation efficiency at high frequency. The thinner printed silver paste RFID tag antenna is a potential solution for low cost RFID tags. However, the print quality needs special attention when RFID tags are printed using very thin conducting layers.

1.1 Needs of the study

RFID technology has been around for many years, but it is only in the past few years that we have seen a surge in its acceptance and a massive growth in its use. However, RFID has not been able to replace the current bar code system yet because of the high production cost of RFID tags, especially the cost of printing RFID tag antennas. Printing the antennas is the most critical part of producing an RFID tag. The high production cost problem of printing RFID tag antennas can be eliminated if the conventional screen printing process can be applied to perform the printing tasks effectively. According to literatures, screen printing technology can be used for RFID tag printing, providing significant time and cost savings compared to traditional etching technology. Therefore, there is a great need to investigate the possibility of applying screen printing method to print RFID tag antennas to perform the task of automatic identification and data capture.

1.2 Purposes of the study

This study was a true experimental research in nature and aimed to investigate the process consistency and accuracy of printing RFID tag antennas via the screening printing method with a conductive ink, silver-based (Ag) ink, on PET, PVC, and Wet Strength paper. The target values of RFID frequency in this study were set at 13.56 MHz (HF). The purposes of the study were triple fold:

1. to establish the specifications of antenna ink film thickness and ink density,
2. to compare the solid ink density, ink film thickness, and impedance differences in process consistency and capability of printing RFID antennas on the three different substrates, and
3. to determine the optimal substrates for RFID tags using screen printing technology with conductive inks, in terms of process capability.

The reason of selecting PET and PVC as substrates is that they have high transparency and rigidity. Currently, PET and PVC have been frequently used as substrate materials of RFID tags. The reason of choosing Wet Strength paper is that it is commonly used in the package industry, and its low cost is also suitable for mass production of RFID tags.

1.3 Limitations and assumptions of the study

The following limitations must be considered when interpreting the results of this study:

4. The RFID antenna used in this study was not randomly selected; instead it was specially designed for the study.
5. The company taking part to help the screen printing production for the study had their own experienced printing crews; the authors did not actually perform the printing process in every detail. This study assumes that there were no operator effects on solid ink density and ink film thickness, although only one experienced operator ran the press during the experiment.
6. The make, ages, and physical conditions of the press machine used to run the experiment were not studied. Their effects on the results were therefore not discussed.
7. The type of Ag inks, three substrates, and chips were held as constants. This research did not investigate the consistency of the materials; and therefore, their effects on the results of this study were not explored.
8. Since the pressroom temperature and relative humidity were well controlled, their effects on the experimental results were not studied. It is assumed that there were no temperature and humidity effects on the results of the study.

2. Methodology

This study was a true experimental research in nature and aimed to investigate the process consistency and capability of printing RFID tag antennas via the screening printing process

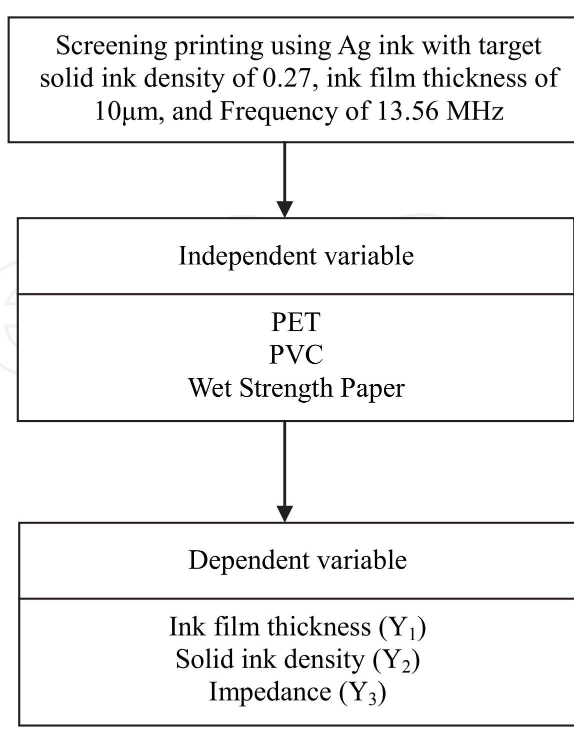

Fig. 1. Research framework

with a conductive ink, silver-based (Ag) ink, on PET, PVC, and Wet Strength paper. The research framework is displayed in Figure 1. The three factors were PET, PVC, and Wet Strength paper. The dependent variables were the solid ink density (SID), ink film thickness (IFT), and impedance (IMPED) of the printed RFID tag antennas.

2.1 The test form

A single color test form for the tag antenna was designed for this study (as shown in Figure 1). The test form is 45mm x 76mm in size and was designed for the frequency of 13.56MHz.

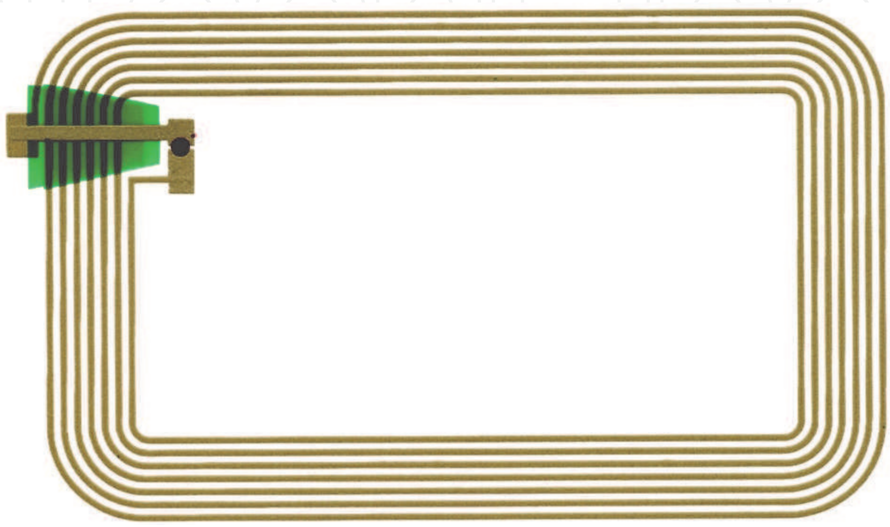

Fig. 2. Antenna design (13.56MHz, 45mm x 76mm) for the study

2.2 Experimental materials

This section describes the experimental procedures for the study. It consists of the screen printing plate materials (see Table 1), substrates (see Table 2) and press setting (see Table 3) for the experiment.

Materials	Description
Fabric Material	PET
Mesh Counts	300 meshes / inch
Mesh Angle	45 degree
Screen Tension	25 N/cm
Thickness of Sensitized Emulsion	25µm

Table 1. Screen plate-making material used for the experiment

Substrates	Manufacturer	Specification
PET (Polyethylene Terephthalate)	NAN YA Plastic Corporation	Thickness: 200µm
PVC (Polyvinyl Chloride)	NAN YA Plastic Corporation	Thickness: 300µm
Wet Strength Paper	HO Zone Paper Inc.	gsm: 80
Silver-based (Ag) Ink,	Flint Conductive Ink for Screen Printing	

Table 2. Substrates and ink used in the study

Item	Description
Press (semi-automatic)	Liang-Chen Mechanical Company
Screen Printer	Mini-Angel Company in Taipei
Press Operator	Mr. Lou
Relative Humidity	46~50%
Temperature	25℃
Blade hardness	70 degree
Squeegee Angle	75 degree
Squeegee Speed	30 m/min

Table 3. Screen printing press setting for the study

After receiving the test form, the participating screen printer was asked to print the test form based on their in-house standard operating procedures and conditions. During the press runs, the research team was present all the time to monitor the whole operation process to make sure that the press run was well-controlled.

2.3 Experimental procedure

Two print tests were run with the first operation serving as a pilot test to familiarize the press operator with printing the test form, while the second operation served as the actual printing experiment where printed RFID tag antennas were sampled. After the first press run, the press was shut down and cleaned, the run counter was set to zero, and the desired materials and conditions were made ready for the next run.

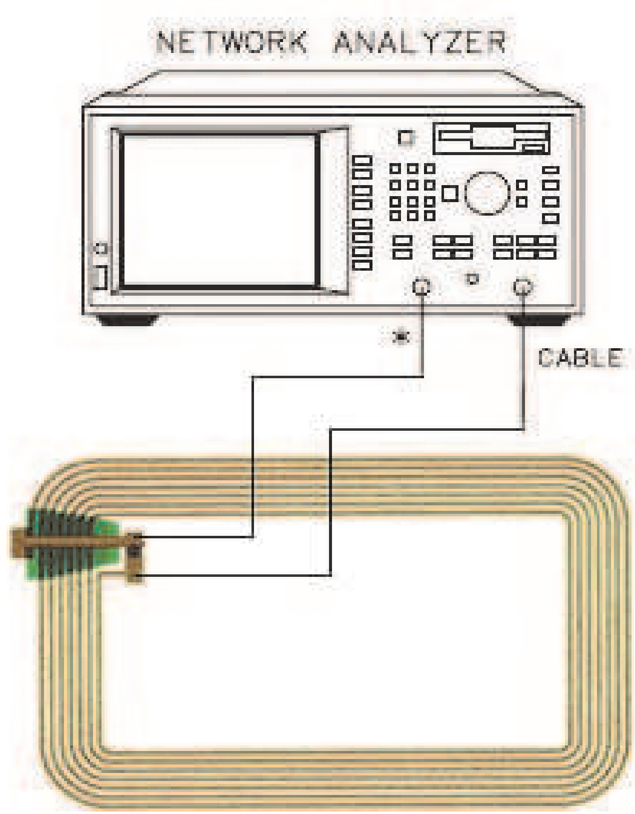

Fig. 3. The diagram of antenna impedance measurement

One hundred printed tags were collected for each press run after the press was determined to be at equilibrium and the desired solid ink density of .27 and ink film thickness of 10 microns (µm) (according to the practical experience of the participating screen printer of the study) were achieved. Consequently, a total of 300 printed tags were gathered for the three runs; and then, 50 printed tags were systematically sampled for each of the three substrates for a total sample size of 150 (3*50). Finally, an X-Rite® 530 reflective spectrodensitometer using Murray-Davies equation (n=1) was applied to measure solid ink density (SID) of the printed tags for this study. It is important to note that each specific measured area on the sampled tag was read five times to reduce the measuring error. Thus, the final data entered onto computer for the analysis was a mean of five readings from the X-Rite® 530. The ink film thickness of the printed antennas was measured by a high-accuracy digimatic indicator. The impedance of the printed tag antennas was read using a HP 8714ET RF Network Analyzer (T/R) (300 kHz to 3 GHz) (see Figure 3. below). The target frequency to be achieved was 13.56 MHz. Finally SPSS 14 and Minitab 14 statistical software packages were used for data analyses.

3. Results and findings

This section describes the overall results and findings obtained through data analyses. The first sub-section exhibits the descriptive statistics for all the measurements. The second sub-section shows the analyses of variance to test the hypotheses whether there was a significant difference in solid ink density, ink film thickness, and impedance of the antennas among the three substrates of the study. The last sub-section analyzes the process consistency and capability for printing RFID antennas on PET, PVC, and Wet Strength paper, respectively.

3.1 Descriptive statistics

Solid ink density (SID) refers to the light-stopping power of color on substrates, measured through the complementary-colored filter. In conventional printing workflows, the setup of solid ink density is a vital factor to achieve an optimum print. Once the right amount of solid ink density is determined, the RIP software automatically optimize the steps for the target linearization, that is, enables a printer to deliver ink on a particular media optimally so that an image's tones can be correctly reproduced. Different linearization settings and profile combinations will affect the final prints. Solid ink density measurement provides an effective means of monitoring and controlling ink film thickness (Tritton, 1997, pp.95-96).

Ink film thickness (IFT) is the most significant of the process variables and the one most easily adjusted during printing: it can be seen affect many print attributes such as tone transfer and print density (Tritton, 1997, pp.141-142).

Impedance is a measure of opposition to a sinusoidal alternating electric current. The concept of electrical impedance generalizes Ohm's law to AC circuit analysis. Unlike electrical resistance, the impedance of an electric circuit can be a complex number, but the same unit, the ohm, is used for both quantities. (Wikipedia, Wikipedia. Retrieved February 26, 2007, from http://en.wikipedia.org/wiki/Electrical_impedance#Definition_of_ electrical_ impedance)

Table 4 shows the SID, IFT, and impedance basic statistics (mean, standard deviation, minimum, maximum, and 95% Confidence Interval of the mean) of the PET, PVC, and Wet

Strength paper. The overall average SID value of the PET was .266 with a standard deviation of .006, .280 for PVC with a standard deviation of .005, and .266 for Wet Strength paper with a standard deviation of .005. The average IFT value of PET was 8.860μm with a standard deviation of .783, 11.300 for PVC with a standard deviation of .741, and 8.670 for Wet Strength paper with a standard deviation of .688. As for the antenna impedance, the average number was 27.690 ohm with a standard deviation of 1.687 for PET, the average was 26.135 with a standard deviation of 1.142 for PVC, and the average was 27.428 with a standard deviation of 1.183 for Wet Strength paper. It is important to note that the 95% confidence intervals (95% C.I.) of the means of SID, IFT, and impedance for the three substrates are listed in the very right-hand side column of Table 4. However, Table 4 could be used for the specifications for screen printers to print RFID tag antennas using Ag ink.

Observed Attribute	N	Mean	Std. Dev.	Min.	Max.	95% C.I. of Mean
PET_SID	50	0.266	0.006	0.255	0.280	(0.264, 0.267)
PVC_SID	50	0.280	0.005	0.270	0.290	(0.279, 0.282)
wet_SID	50	0.266	0.005	0.260	0.275	(0.264, 0.267)
PET_IFT	50	8.860	0.783	7.250	10.500	(8.638, 9.082)
PVC_IFT	50	11.300	0.741	10.000	13.000	(11.090, 11.510)
wet_IFT	50	8.670	0.688	7.500	10.250	(8.475, 8.866)
PET_IMPED	50	27.690	1.687	24.858	31.034	(27.211, 28.170)
PVC_ IMPED	50	26.135	1.142	25.719	30.960	(25.810, 26.460)
wet_ IMPED	50	27.428	1.813	25.051	31.034	(26.913, 27.944)

Table 4. Descriptive statistics of solid ink density, ink film thickness, and antenna impedance on the different substrates

3.2 Hypothesis testing

In this section, One-way ANOVA and Box-plot statistical procedures were employed to determine whether the differences in solid ink density (SID), ink film thickness (IFT), and impedance readings of the RFID tag antennas printed using screen printing with Ag ink on the PET, PVC, and wet strength paper were significant. The hypothesis being tested was whether the reading difference among the substrates was equal to zero. The significant level (α) was set at .05 for all tests. The results for the SID, IFT and impedance are exhibited in Table 5, Table 6, and Table 7, respectively.

Hypothesis testing on the SID difference for the three substrates

The hypothesis for testing the SID reading difference on the three different tag antennas is:

$$\mathrm{Ho}: \mu_{\mathrm{PET\_SID}} = \mu_{\mathrm{PVC\_SID}} = \mu_{\mathrm{wet\_SID}}$$

$$\mathrm{Ha}: \mu_{\mathrm{PET\_SID}} \neq \mu_{\mathrm{PVC\_SID}},\ \mathrm{or}\,\mu_{\mathrm{PET\_SID}} \neq \mu_{\mathrm{wet\_SID}},\ \mathrm{or}\,\mu_{\mathrm{PVC\_SID}} \neq \mu_{\mathrm{wet\_SID}}$$

As shown in Table 5, the significant value of p is .000 < .05 (α) and therefore the ANOVA suggests that Ho be rejected, i.e., at least one pair of the mean SID values is significantly different at .05 level. Examining the bottom part of Table 5 (95% Confidence Interval for Mean) in detail, one can conclude that there existed significantly different SID readings between the pair of PET and PVC tags and the pair of PVC and Wet Strength paper tags. In addition, the differences in SID readings were not significant at .05 level between PET and Wet Strength paper tags.

Source	DF	SS	MS	F	P
Factor	2	0.007	0.004	120.090	0.000
Error	147	0.004	0.000		
Total	149	0.011			

S = 0.005420   R-Sq = 62.03%   R-Sq(adj) = 61.52%

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                                 Individual 95% CIs For Mean Based on Pooled StDev
Level     N     Mean    StDev   --+---------+---------+---------+-------
PET_SID  50  0.26560  0.00586  (--*--)
PVC_SID  50  0.28010  0.00539                            (--*--)
wet_SID  50  0.26550  0.00497  (--*--)
                                --+---------+---------+---------+-------
                                0.2650    0.2700    0.2750    0.2800
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Pooled StDev = 0.00542

Table 5. Hypothesis testing on the SID difference among the three substrates

Likewise, the two straight lines originated from PVC_SID box in Figure 4 (the box plot of SID readings for the three substrates) indicate the two pairs substrates with significantly different SID reading were (PET, PVC) and (PVC, Wet). Among the three substrates, PVC has the highest SID mean values than the other two substrates have.

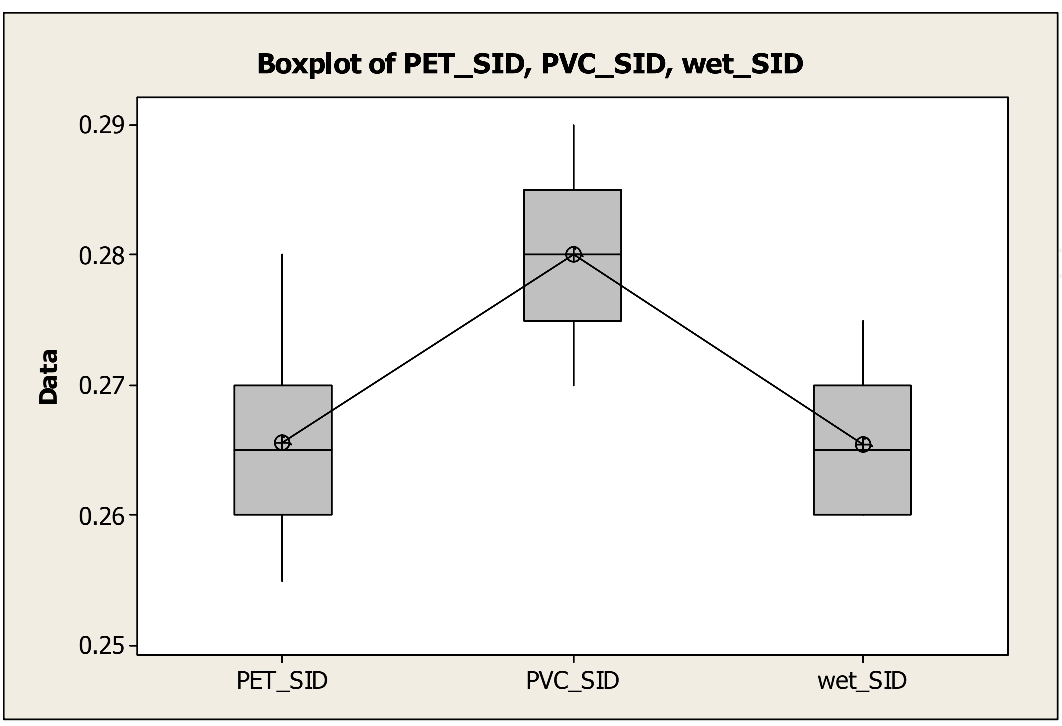

Fig. 4. Box plot of SID readings for the three substrates

Hypothesis testing on the IFT difference for the three substrates

The hypothesis for testing the IFT reading difference on the three different tag antennas is:

$$\text{Ho}: \mu_{\text{PET\_IFT}} = \mu_{\text{PVC\_IFT}} = \mu_{\text{wet\_IFT}}$$

$$\text{Ha}: \mu_{\text{PET\_IFT}} \neq \mu_{\text{PVC\_IFT}},\ \text{or}\ \mu_{\text{PET\_IFT}} \neq \mu_{\text{wet\_IFT}},\ \text{or}\ \mu_{\text{PVC\_IFT}} \neq \mu_{\text{wet\_IFT}}$$

Source	DF	SS	MS	F	P
Factor	2	215.110	107.555	197.450	0.000
Error	147	80.075	0.545		
Total	149	295.185			

S = 0.7381 R-Sq = 72.87% R-Sq(adj) = 72.50%

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                               Individual 95% CIs For Mean Based on Pooled StDev
Level     N    Mean  StDev  ----+---------+---------+---------+-----
PET_IFT  50   8.860  0.783    (--*-)
PVC_IFT  50  11.300  0.741                                 (-*--)
wet_IFT  50   8.670  0.688  (-*--)
                            ----+---------+---------+---------+-----
                              8.80      9.60     10.40     11.20
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Pooled StDev = 0.738

Table 6. Hypothesis testing on the IFT difference among the three substrates

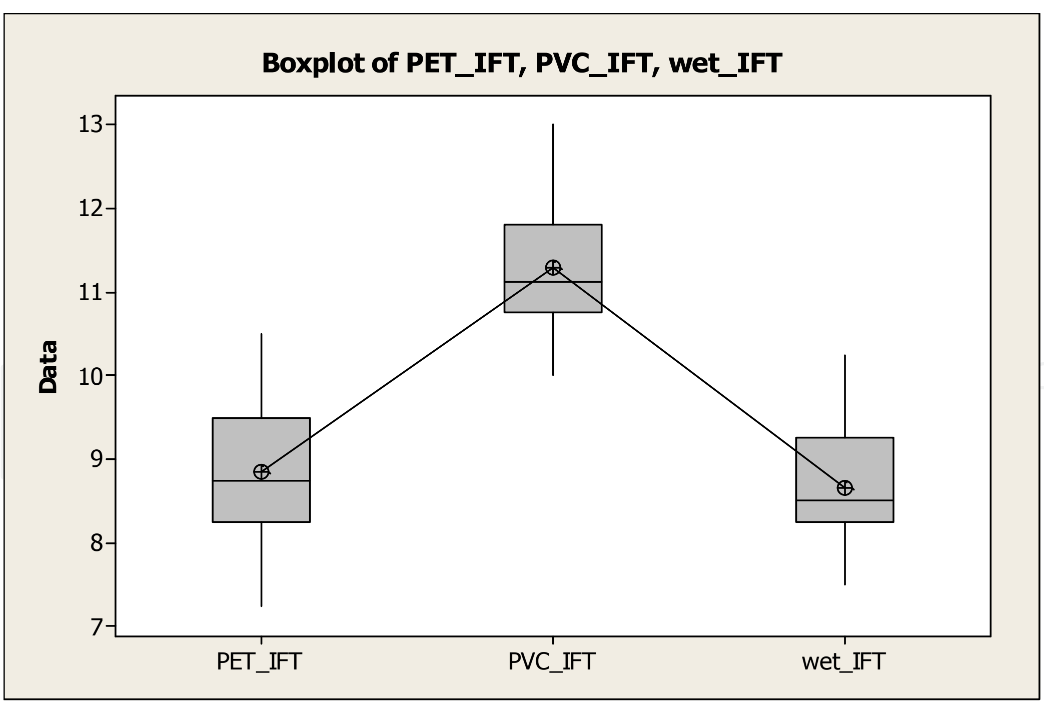

Fig. 5. Box plot of IFT readings for the three substrates

As shown in Table 6, the significant value of p is .000 < .05 (α) and therefore the ANOVA suggests that Ho be rejected. That means that at least one pair of the average IFT values is significantly different at .05 level. If we examine the bottom part of Table 6 (95% C. I. for

Mean), we can conclude that there were significantly different IFT readings between the pair of PET and PVC tags and the pair of PVC and Wet Strength paper tags. Moreover, the differences in IFT readings were not significant at .05 level between PET and Wet Strength paper tags.
The same conclusions could be drawn if we examine Figure 5 in detail: the two straight lines originated from PVC_IFT box in Figure 5 (the box plot of IFT readings for the three substrates) indicate that the IFT readings of PET and PVC were significantly different at .05level, and those of PVC and Wet Strength paper were also significantly different. Among the three substrates, PVC has the highest IFT mean values than the other two substrates have.

Hypothesis testing on the impedance (IMPED) difference for the three substrates

The hypothesis for testing the IFT reading difference on the three different tag antennas is:

$$\mathrm{Ho}: \mu_{\mathrm{PET\_IMPED}} = \mu_{\mathrm{PVC\_IMPED}} = \mu_{\mathrm{wet\_IMPED}}$$

$$\mathrm{Ha}: \mu_{\mathrm{PET\_IMPED}} \neq \mu_{\mathrm{PVC\_IMPED}},\ \mathrm{or}\ \mu_{\mathrm{PET\_IMPED}} \neq \mu_{\mathrm{wet\_IMPED}},\ \mathrm{or}\ \mu_{\mathrm{PVC\_IMPED}} \neq \mu_{\mathrm{wet\_IMPED}}$$

Source	DF	SS	MS	F	P
Factor	2	69.33	34.66	13.98	0.000
Error	147	364.57	2.48		
Total	149	433.90			
S = 1.575 R-Sq = 15.98% R-Sq(adj) = 14.84%					

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                                     Individual 95% CIs For Mean Based on Pooled St
           Dev
           Level       N    Mean  StDev  ---+---------+---------+---------+------
           PET_IMPED  50  27.690  1.687                      (------*-----)
           PVC_IMPED  50  26.135  1.142  (-----*------)
           wet_IMPED  50  27.428  1.813                   (-----*-----)
                                         ---+---------+---------+---------+------
                                         25.90     26.60     27.30     28.00
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Pooled StDev = 1.575

Table 7. Hypothesis testing on the IFT difference among the three substrates

As shown in Table 7, the significant value of p is .000 < .05 (α) and therefore the ANOVA suggests that Ho be rejected. That means that at least one pair of the mean IFT values is significantly different at .05 level. Examining the bottom part of Table 7 (95% C. I. for Mean) more closely, we can conclude that there were significantly different impedance readings between the pair of PET and PVC tags and the pair of PVC and Wet Strength paper tags. In addition, the differences in impedance readings were not significant at .05 level between PET and Wet Strength paper tags.
The same conclusions could be drawn if we examine Figure 6: the two straight lines originated from PVC_IMPED box in Figure 6 (the box plot of IFT readings for the three substrates) indicate that the impedance readings of PET and PVC were significantly different at .05level, and those of PVC and Wet Strength paper were also significantly different at .05 level. Among the three substrates, PVC has the lowest impedance mean values than the other two have. It is important to note that the box plot of PVC_IMPED in Figure 6 shows that the impedance variation (the height of the box in the middle of the PVC_IMPED) of PVC was extremely small compared with that of the other two substrates.

3.3 Capability study

The section is to discuss the process consistency and capability of the observed attributes for the three types of substrates. The tools used to analyze the consistency for each variable are Individual Control Chart (I Chart), Moving Range Charts (MR Chart), and Capability Analysis.

Interpretation of the relative PCR (Cp or Pp)

In capability analysis, overall capability depicts how the process is actually performing relative to the specification limits. Potential capability depicts how the process could perform relative to the specification limits, if shifts and drifts could be eliminated. The difference between the two represents the opportunity for improvement. Without both overall and potential estimates, it is hard to identify the size of the opportunity. Process capability is a measure of how capable a process is of meeting specifications. A Cp index (PCR) of 1 means that a process is exactly capable of meeting specifications, while less than 1 means that it is outside specification limits. Ideally, one would like to see a Cp much larger than 1, because the larger the index, the more capable the process. Some practitioners consider *1.33* to be a minimum acceptable value for this statistic, and few believe that a value less than 1 is acceptable (Ryan & Joiner, 1994).

Determination of the lower specification limits (LSL) and upper specification limits (USL)

Due to the lack of historical parameters of LSL and USL for the observed attributes (SID, IFT, and impedance) for RFID tag antennas using screen printing with Ag ink on the three substrates, a method of determining the proper LSL and USL is necessary. In this study, the LSL and USL for each attribute are determined based on the following procedures (Hsieh, 2003; Montgomery, 1997, pp. 180-229):

1. Construct the trial I and MR control chart of each attribute for the four plates.
2. Examine every control chart; if it is in control, then use the lower control limit (LCL) and upper control limit (UCL) as the LSL and USL. If it is in out-of-control condition (for most cases), reconstruct the control chart after eliminating all out-of-control points in the initial charts to obtain the revised values for mean, LCL, and UCL.
3. For each attribute, the difference between revised LCL and UCL of each plate obtained in the previous step is computed and named $6\sigma_{\mathbf{revised}}$, i.e., $UCL_{\mathbf{revised}}$ - $LCL_{\mathbf{revised}}$ = $6\sigma_{\mathbf{revised}}$. Then $3\sigma_{\mathbf{revised}}$ of each plate is computed for the purpose of obtaining the "average $3\sigma_{\mathbf{revised}}$" of the four plates, $3\hat{S}_{\mathbf{revised}}$ namely, i.e.,
$$\mathbf{3\hat{S}_{revised} = (3\sigma_{revised/PET} + 3\sigma_{revised/PVC} + 3\sigma_{revised/wet}) / 3.}$$
4. For each attribute, the final LSL and USL are obtained by subtracting from and adding to the $3\hat{S}_{\mathbf{revised}}$, the revised mean of each plate, i.e.,
$$\mathbf{LSL_{final} = Mean_{revised} - 3\hat{S}_{revised}}$$
$$\mathbf{USL_{final} = Mean_{revised} + 3\hat{S}_{revised}}$$
5. The $LSL_{\mathbf{final}}$ and $USL_{\mathbf{final}}$ were then used to assess the relative Process Capability Ration (PCR) for the *revised* individual measurement control chart (I-Chart) of each attribute for the three substrates.

The revised control limits ($UCL_{\mathbf{revised}}$ and $LCL_{\mathbf{revised}}$) for the three attributes (SID, IFT, IMPED) of the three substrates are displayed in Table 8. Table 9 shows the $3\hat{S}_{\mathbf{revised}}$ of the attributes computed from Table 8 by taking the average $\sigma_{\mathbf{revised}}$ of the three substrates. The $LSL_{\mathbf{final}}$ and $USL_{\mathbf{final}}$ of the attributes for the three substrates are then computed and exhibited in Table 10.

	PET		PVC		Wet Strength Paper	
	$LCL_{revised}$	$UCL_{revised}$	$LCL_{revised}$	$UCL_{revised}$	$LCL_{revised}$	$UCL_{revised}$
SID	0.249	0.282	0.266	0.294	0.253	0.278
IFT	6.960	10.760	9.455	13.145	6.811	10.529
IMPED	23.080	32.300	25.624	26.080	22.100	32.760

Table 8. The revised control limits of the attributes for the substrates

	$3\hat{S}_{revised}$
SID	$(3\sigma_{revised\_PET\_SID} + 3\sigma_{revised\_PVC\_SID} + 3\sigma_{revised\_wet\_SID}) / 3$ = (0.017 +0.014 +0.013) / 3 = 0.015
IFT	$(3\sigma_{revised\_PET\_IFT} + 3\sigma_{revised\_PVC\_IFT} + 3\sigma_{revised\_wet\_IFT}) / 3$ = (1.900 + 1.845 +1.859) / 3 = 1.868
IMPED	$(3\sigma_{revised\_PET\_IMPED} + 3\sigma_{revised\_PVC\_IMPED} + 3\sigma_{revised\_wet\_IMPED}) / 3$ = (4.610 + 0.228 + 5.330) / 3 = 3.389

Table 9. The $3\hat{S}_{revised}$ of the attributes computed from Table 8

	PET		PVC		Wet Strength Paper	
	LSL_{final}	USL_{final}	LSL_{final}	USL_{final}	LSL_{final}	USL_{final}
SID	0.251	0.281	0.265	0.295	0.251	0.281
IFT	6.992	10.728	9.432	13.168	6.802	10.538
IMPED	24.301	31.079	22.463	29.241	24.041	30.819

Table 10. The LSL_{final} and USL_{final} of the attributes for the substrates

Capability analysis for solid ink density (SID)

The capability analyses of solid ink density for the substrates are exhibited in Figure 7, Figure 8, and Figure 9. As shown in those figures, PVC has the highest relative PCR value (Cp = 1.04), followed by the Wet Strength paper (Cp = 1.02), and PET (Cp = .95). Therefore, this study concludes that the PVC and Wet Strength paper are barely acceptable substrates for printing consistent ink density because their relative PCR are only slightly higher than 1.00. Figure 7 also implies that PET is not an acceptable substrate for printing consistent SID for RFID tags due to the low Cp value (Cp = .95).

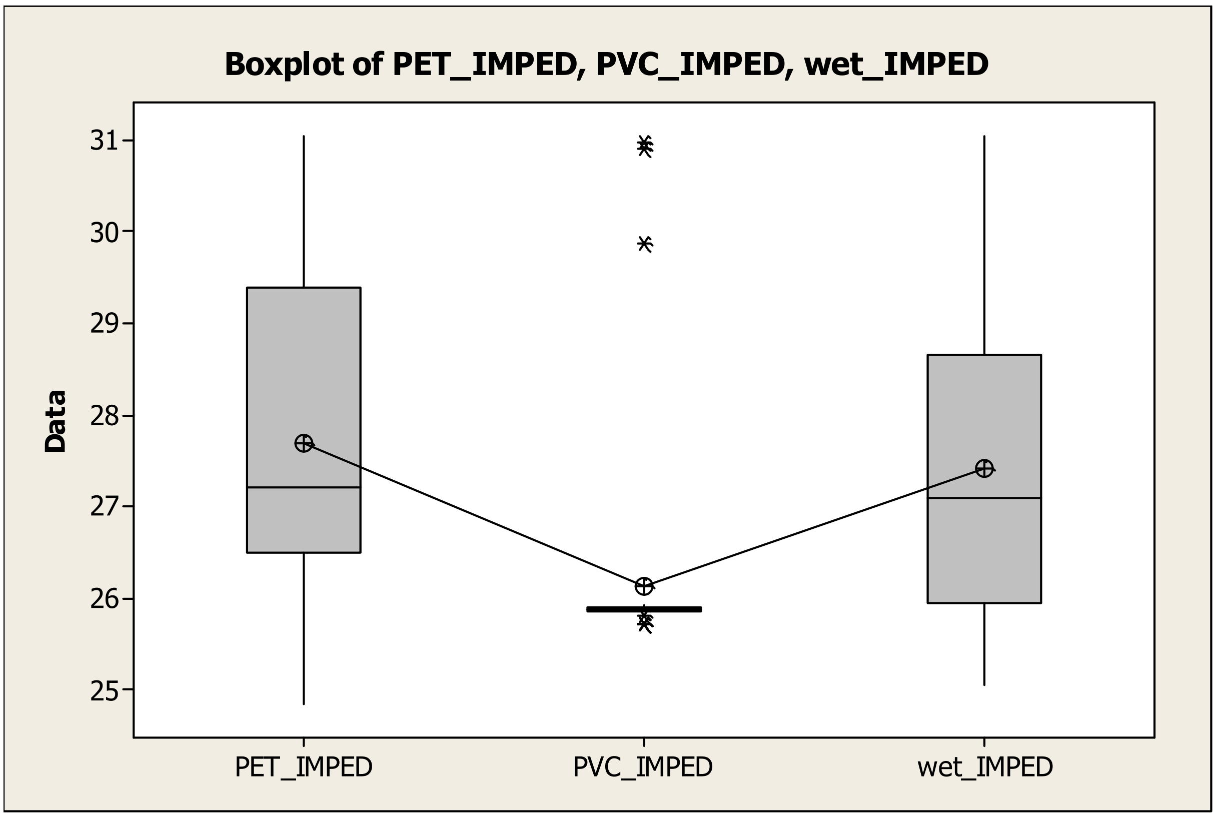

Fig. 6. Box plot of impedance readings for the three substrates

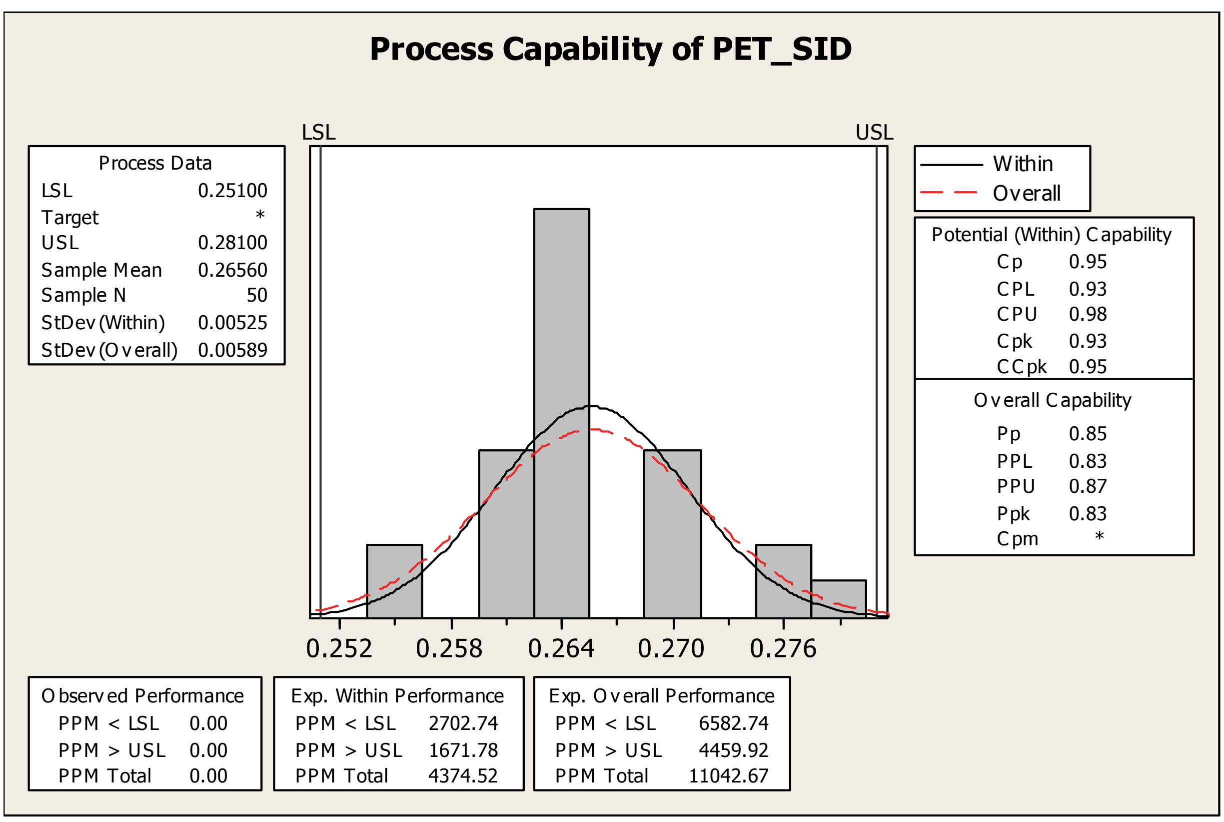

Fig. 7.

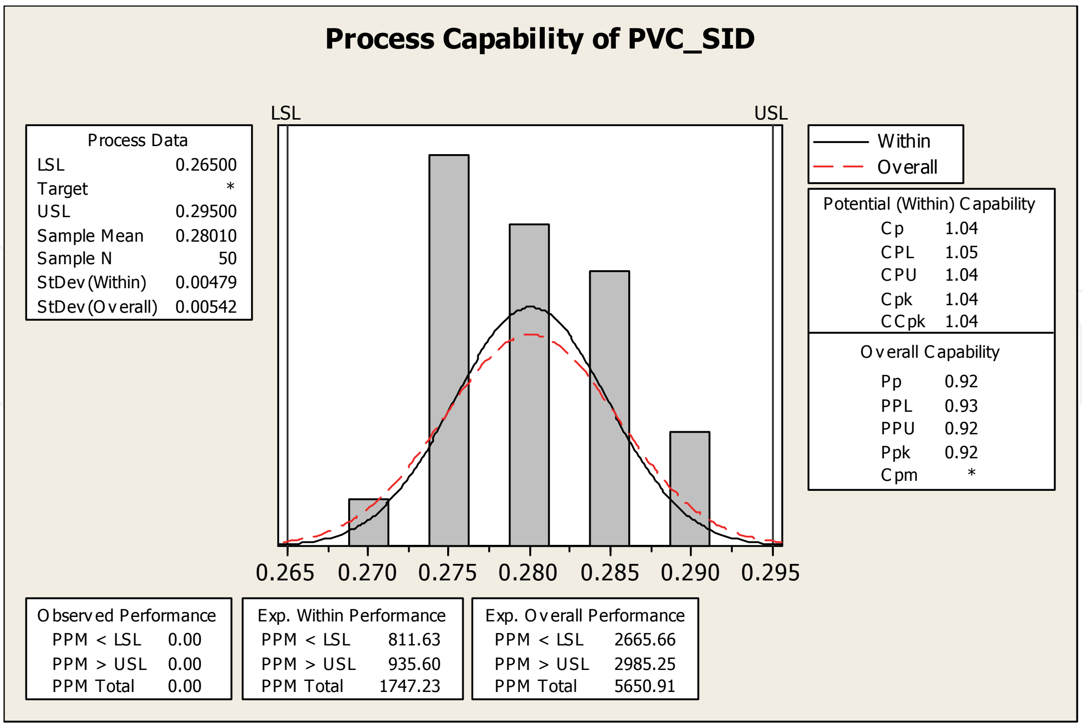

Fig. 8.

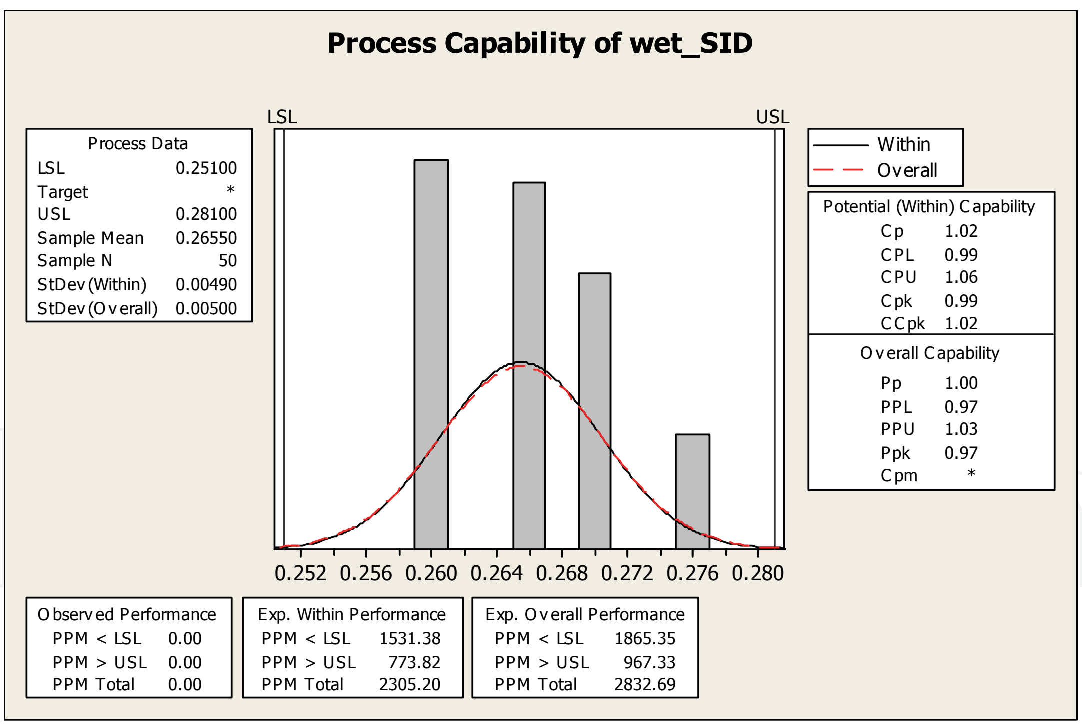

Fig. 9.

Capability analysis for ink film thickness (IFT)

The capability analyses of ink film thickness for the substrates are shown in Figure 10, Figure 11, and Figure 12. As shown in those figures, PET has the largest relative PCR (Cp = 1.10), followed by the PVC (Cp = 1.01), and wet strength paper (Cp = .98). Therefore, this study concludes that the PET was the most acceptable substrate for printing consistent ink film thickness among the three substrates in terms of relative PCR. Due to the small Cp value (.98) of Wet Strength paper, the study concludes that Wet Strength paper might not be an acceptable substrate for printing consistent ink film thickness. However, the Cp value of PET (1.10) is smaller than 1.33; that means that PET is only acceptable, but not necessary satisfied, as the substrate for printing consistent ink film thickness.

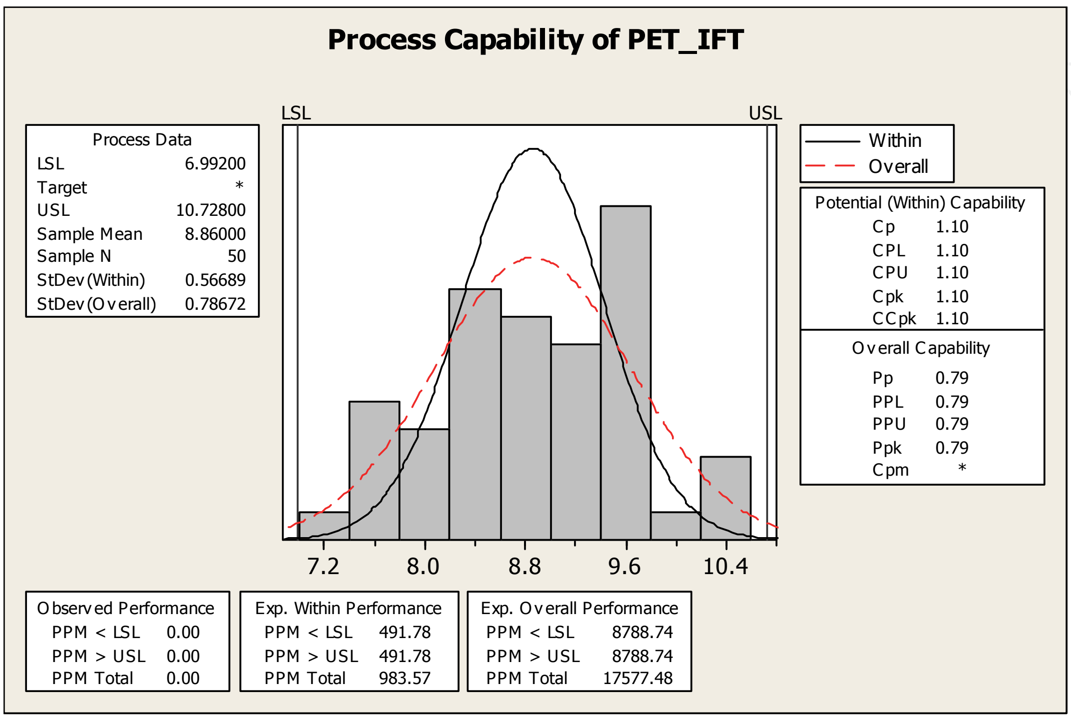

Fig. 10.

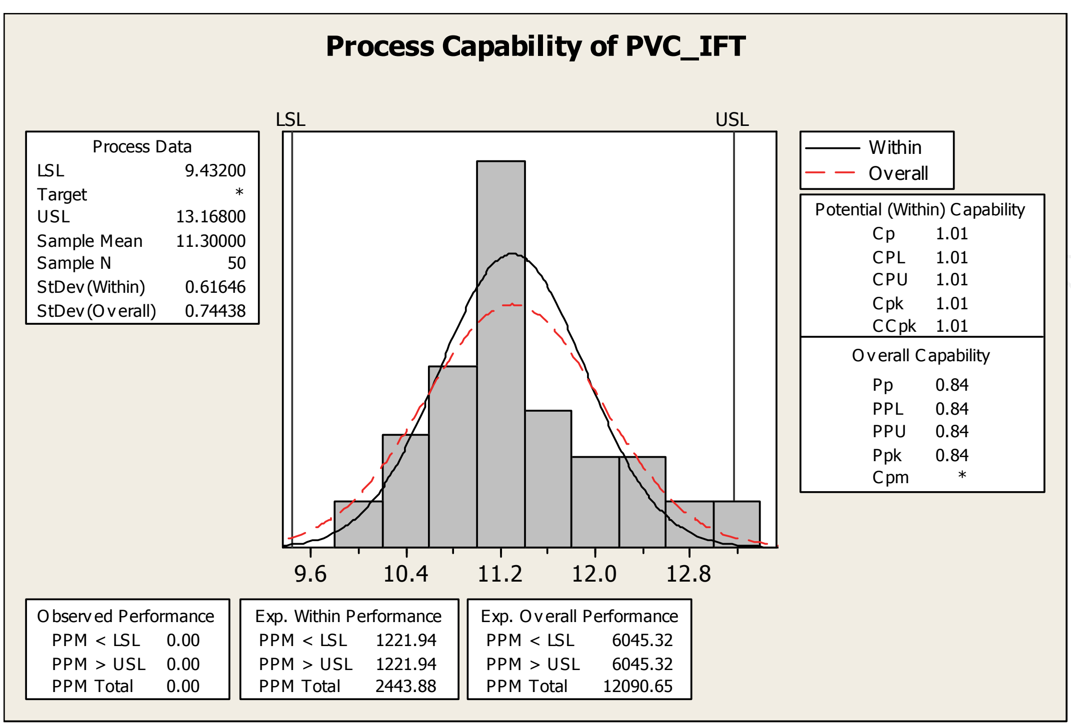

Fig. 11.

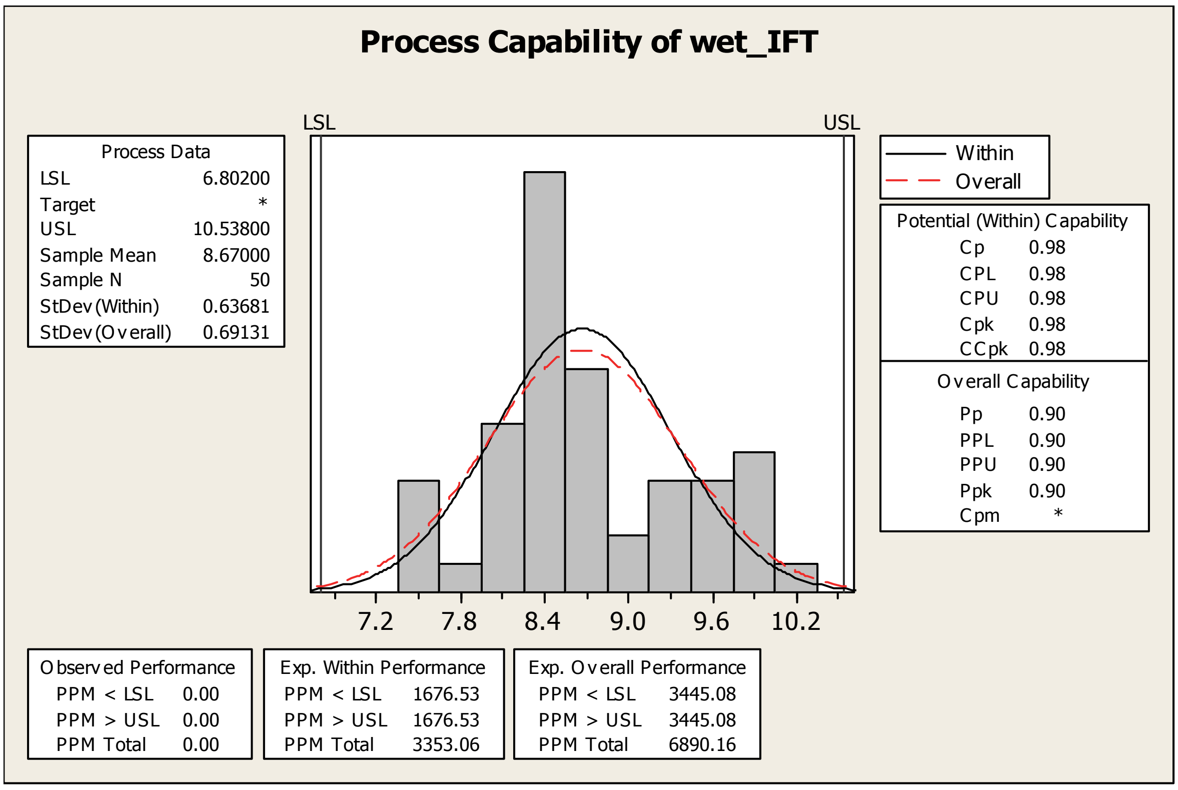

Fig. 12.

Capability analysis for impedance (IMPED)

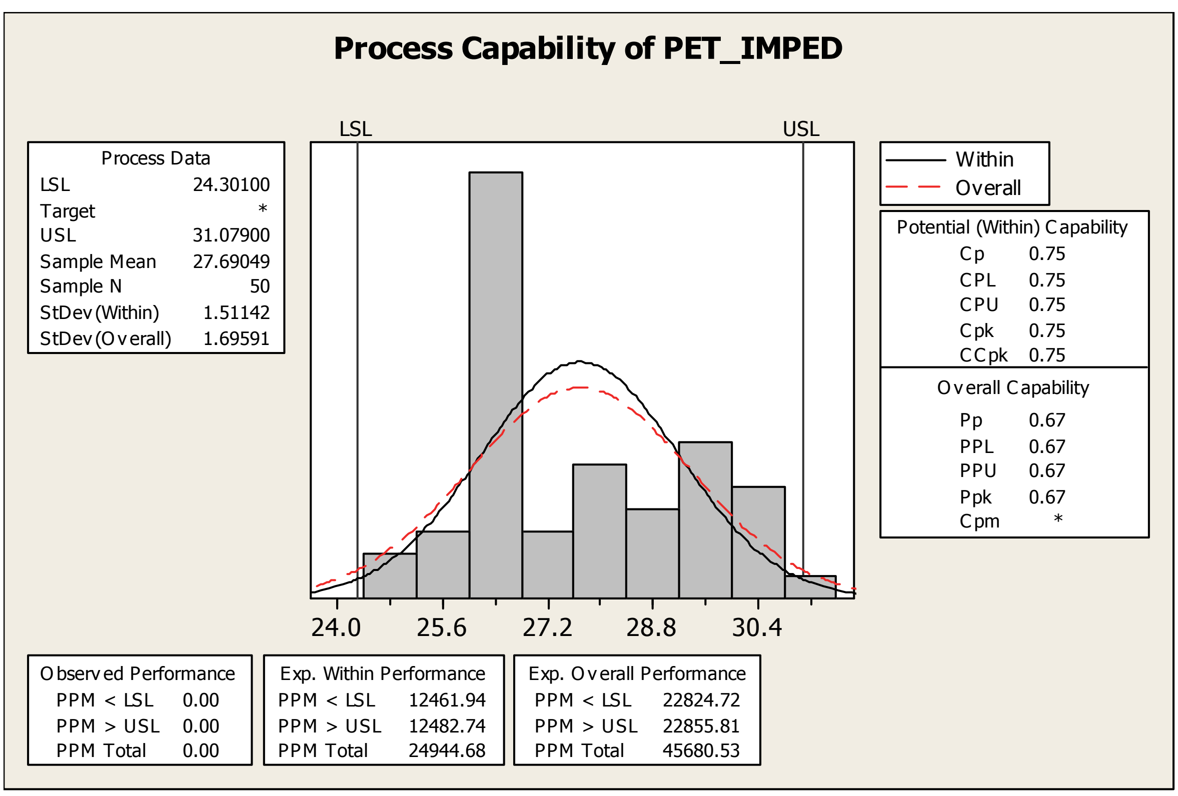

Fig. 13.

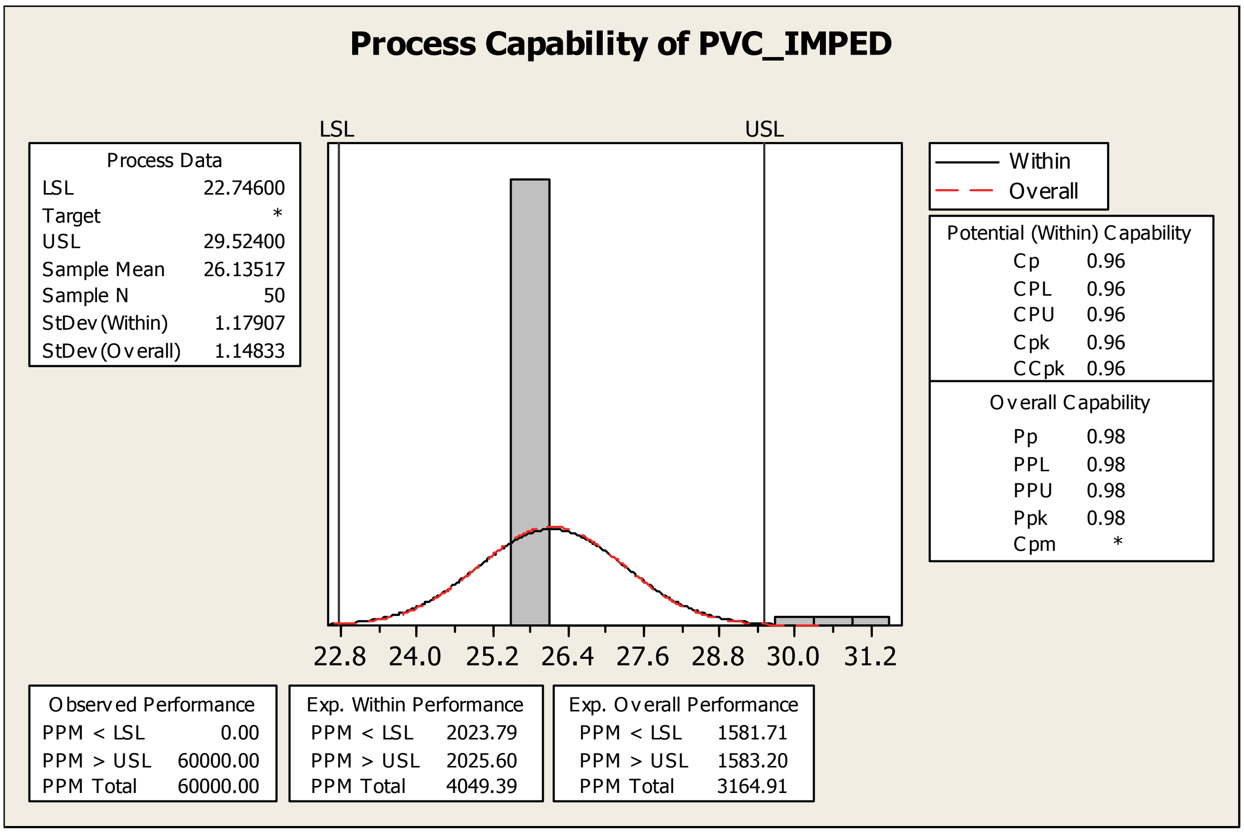
Process Capability of PVC_IMPED
LSL
USL
Process Data
LSL 22.74600
Target *
USL 29.52400
Sample Mean 26.13517
Sample N 50
StDev(Within) 1.17907
StDev(Overall) 1.14833
Within
Overall
Potential (Within) Capability
Cp 0.96
CPL 0.96
CPU 0.96
Cpk 0.96
CCpk 0.96
Overall Capability
Pp 0.98
PPL 0.98
PPU 0.98
Ppk 0.98
Cpm *
22.8 24.0 25.2 26.4 27.6 28.8 30.0 31.2
Observed Performance
PPM < LSL 0.00
PPM > USL 60000.00
PPM Total 60000.00
Exp. Within Performance
PPM < LSL 2023.79
PPM > USL 2025.60
PPM Total 4049.39
Exp. Overall Performance
PPM < LSL 1581.71
PPM > USL 1583.20
PPM Total 3164.91

Fig. 14.

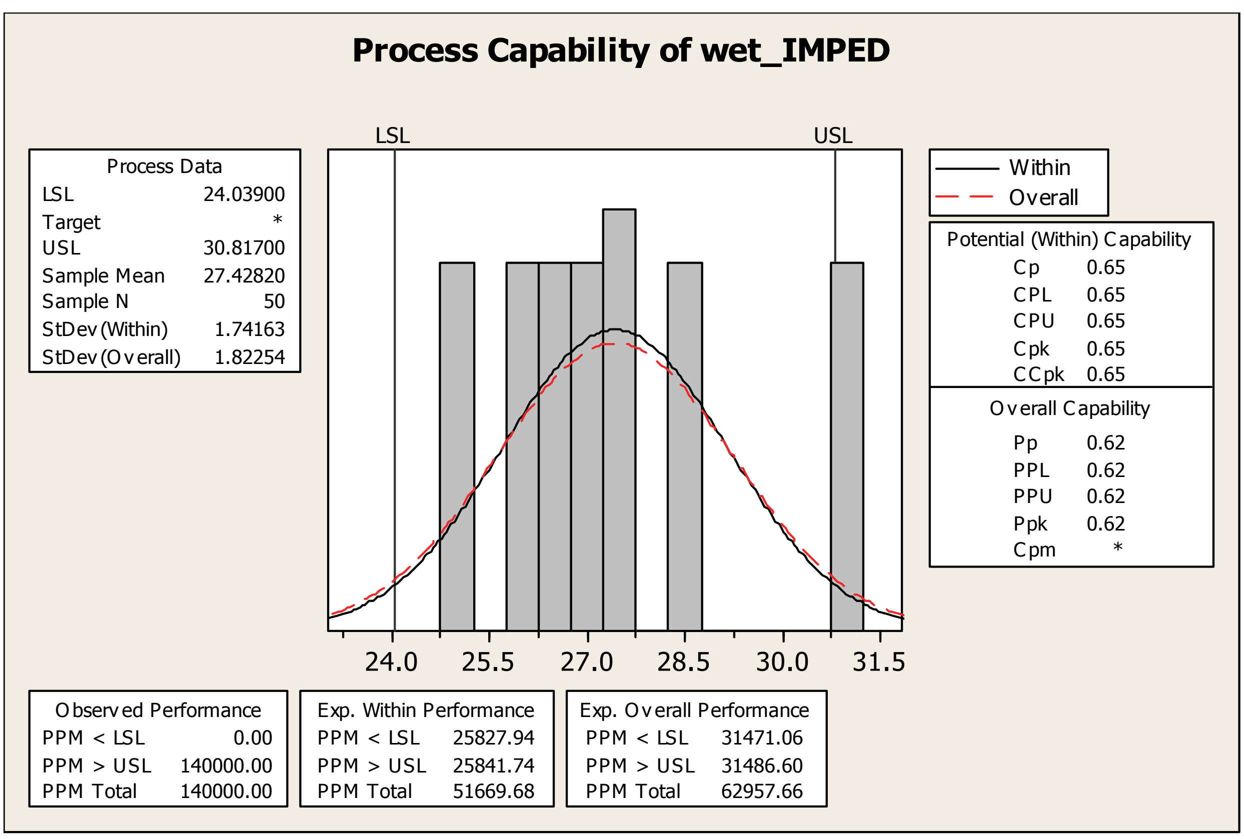
Process Capability of wet_IMPED
LSL
USL
Process Data
LSL 24.03900
Target *
USL 30.81700
Sample Mean 27.42820
Sample N 50
StDev(Within) 1.74163
StDev(Overall) 1.82254
Within
Overall
Potential (Within) Capability
Cp 0.65
CPL 0.65
CPU 0.65
Cpk 0.65
CCpk 0.65
Overall Capability
Pp 0.62
PPL 0.62
PPU 0.62
Ppk 0.62
Cpm *
24.0 25.5 27.0 28.5 30.0 31.5
Observed Performance
PPM < LSL 0.00
PPM > USL 140000.00
PPM Total 140000.00
Exp. Within Performance
PPM < LSL 25827.94
PPM > USL 25841.74
PPM Total 51669.68
Exp. Overall Performance
PPM < LSL 31471.06
PPM > USL 31486.60
PPM Total 62957.66

Fig. 15.

The capability analyses of impedance of the printed antennas for the substrates are shown in Figure 13, Figure 14, and Figure 15. As shown in those figures, PVC has the largest relative PCR (Cp = .96), followed by the PET (Cp = .75), and wet strength paper (Cp = .65). Therefore, this study concludes that the PET, PVC, and wet strength paper are all unacceptable substrates for printing RFID antennas to achieve consistent impedance because their relative PCR are all smaller than 1.0. The worst substrate to deliver consistent impedance of the antenna is Wet Strength paper (Cp = .65).

4. Conclusions and recommendations

Substrate is definitely a dominant variable affecting the printability of printing antenna of RFID tags. The results of study can assist the printing industry in determining the optimal substrates for printing RFID tags using screen printing technology with conductive ink. It is wise to apply screen printing technology to print the antennas of RFID tags to reduce the production time and cost. Based on the experience of the study, screen printing is an optimum printing method, in terms of process consistency and capability, to save money and simplify the manufacture process for RFID tags. The key issue is to choose proper materials for the substrate.

To sum up, the specifications of antenna ink film thickness and ink density to achieve HF (13.56 MHz) frequency were reported respectively when the RFID antennas were printed on PET, PVC, and Wet Strength paper using screen printing. In addition, the consistency and capability of the three processes were analyzed and compared. It is hoped that the study can assist screen printers in determining the optimum substrates for printing RFID tag antennas. This study evaluated the consistency and capability performance on solid ink density, ink film thickness, and impedance of printed antennas for three commonly adopted RFID tag substrates in Taiwan. The overall specifications of the solid ink density (SID), ink film thickness (IFT), and antenna impedance (IMPED) for PET, PVC, and Wet Strength paper are displayed in Table 4. These real-world specifications could be incorporated into RFID tag production process as an evaluation mechanism to ensure the screen printers in Taiwan meet required quality levels.

	PET		**PVC**		**Wet Strength Paper**	
	Cp	Pp	Cp	Pp	Cp	Pp
SID	0.95	0.85	1.04	0.92	1.02	1.00
IFT	*1.10*	0.79	1.01	0.84	0.98	0.90
IMPED	0.75	0.67	*0.96*	0.98	0.65	0.62

Note: 1 Cp denotes the potential capability; Pp denotes the overall capability
2.Underlined Cp values denote the largest Cp in the group.

Table 11. Summarized Relative PCR (Cp Value) of the attributes for the three substrates

Based the presentation of Figure 7 to 15, Table 11 summarizes the capability performance of the substrates, in terms of relative Cp indexes, in solid density (SID), ink film thickness

(IFT), and antenna impedance (IMPED). As shown in Table 11, the PVC and Wet Strength paper appear to be barely capable of yielding consistent SID because their SID Cp values are just over 1.00 (1.04 for PVC, 1.02 for Wet Strength paper). As to PET, its Cp value is .95 (<1.00) and that means PET is not an acceptable substrate for printing RFID tag antennas in terms of process consistency. According to Table 11, this study concludes that the Wet Strength paper is not a suitable substrate to print consistent IFT and impedance attributes for RFID tags because it had smallest IFT and IMPED Cp value among the three substrates, and its Cp values for IFT and impedance attributes are both smaller than 1.00. This study therefore concludes that the Wet Strength paper is the least capable substrate of producing consistent results in ink film thickness and antenna impedance. Table 11 also indicates that the PET is the most capable substrate for printing consistent ink film thickness among the three substrates in terms of relative PCR.

However, as shown in Table 11, none of the three substrates was capable of producing consistent antenna impedance. Therefore the study recommends that a further research be necessary to investigate the possible special variations in the screen printing process to print PET, PVC, and Wet Strength paper using Ag ink, based on the low Cp values of the antenna impedance for the three substrates.

5. Acknowledgements

We wish to express our sincere gratitude to all participants in this study who invested time and materials in the effort to help us finish this research. Sincere appreciation is also expressed to the Nation Science Council (NSC) of Taiwan who mainly provided financial support to this research. The completion of this research could not have been accomplished without the help from my research assistants, Hui-Wen Cheng, Hui-Ping Liou, Chung-Yin Yang, Mandy Wu, and Yi-Li Wang. I would like to take this opportunity to express my thanks to them.

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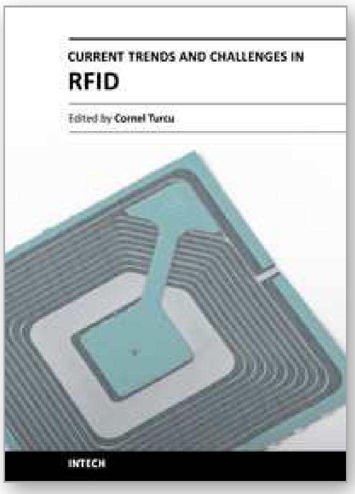

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With the increased adoption of RFID (Radio Frequency Identification) across multiple industries, new research opportunities have arisen among many academic and engineering communities who are currently interested in maximizing the practice potential of this technology and in minimizing all its potential risks. Aiming at providing an outstanding survey of recent advances in RFID technology, this book brings together interesting research results and innovative ideas from scholars and researchers worldwide. Current Trends and Challenges in RFID offers important insights into: RF/RFID Background, RFID Tag/Antennas, RFID Readers, RFID Protocols and Algorithms, RFID Applications and Solutions. Comprehensive enough, the present book is invaluable to engineers, scholars, graduate students, industrial and technology insiders, as well as engineering and technology aficionados.

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