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Improvement inconsistency of the metallic film thickness of computer connectors

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ABSTRACT

The variation of the film thickness and associated increase in cost are vital problems to computer connector producers. However, no scientific adjustment method is currently available. Transfer function and engineering process control are proposed to adjust the production processes for improving the quality of the metallic film of the connectors and reducing the cost of production. The analyses of the confirmatory experiments from using the two proposed approaches show significant gains in quality improvement and cost reduction. Furthermore, the engineering process control approach reveals a better improvement over the transfer function approach. Thus this approach is recommended to improve the quality of the film thickness and reduce the production cost in the computer connector industry

1. Introduction

Computer connectors are used for connecting main system hardware to the peripheral components. The connector terminal is one of the most important parts of the computer connectors. In order to increase the electrical conductivity of the terminals, it is a common practice to electroplate a thin gold film on the surface of the terminals using halo-gold ($KAu(CN)_2$). In general, the production processes and production conditions are based on engineers' (subjective) judgment without any precise production specification. This typically results in substantial variation of the film thickness and an increase of the cost. Thus, an effective adjustment of the production processes conditions is required in order to eliminate the variation of film thickness and reduce the cost.

The current research proposes an effective method to improve the consistency of the film thickness. Based on the collected data, it was found that the gold film thickness is strongly affected by the gold concentration in the electroplating tank. The objective of this study is to build a model relating the gold film thickness and the gold concentration. The gold film thickness can then be controlled by adjusting the gold concentration in order to produce a film thickness as close to the target value as possible and to reduce the cost. The variation of the film thickness due to gold concentration is, however, time dependent. A statistical relationship is defined using a transfer function – a function between the film thickness and the gold concentration. The gold concentration is adjusted and varied with a period of 1 h. It was found that both high quality gold film and the reduction of the halo-gold consumption can be achieved.

Furthermore, a statistical correlation between the film thickness and gold concentration using the transfer function aided by engineering process control is also proposed. Based on this correlation, it was found that a better film quality and a lower gold consumption can be obtained, compared to that obtained from the method using the transfer function.

This paper is organized as follows. Section 2 describes the problems encountered and the current situation. Section 3 discusses the data collection and data process. Two improvement methods of adjusting the gold concentration are proposed in Section 4. Section 5 compares the quality and the cost, using these two proposed methods. The final section is the conclusion and suggestions derived from this study.

2. Description of problems encountered and current situation

As previously mentioned, the thickness of the gold film on the surface of the terminals strongly affects the stability of signal transfer between the computer main hardware and its peripheral components. A thin film will result in an unstable signal transfer and the terminals must be re-processed or discarded. On the other hand, a thick film results in a waste of gold and a higher production cost. Current engineering practice for the production of the gold film is based on engineers' subjective judgment. The drawback of this practice is the substantial variation of the thickness, either too thin or too thick. The main purpose of this study is to find a method to control the film thickness and to adjust the process periods for cost reduction.

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The current production process of the terminals is based on a series of electroplating processes. A number of factors are believed to be relevant to the gold film thickness. These factors include: (1) current, temperature, degreasing agent and processing speed at the electrolysis/degreasing station, (2) temperature, sulfuric acid and its speed at the acid activation station, (3) current, temperature, pH value, nickel solution and its speed at the nickel plating station, (4) current, temperature, pH value, pre-gold solution and its speed at the pre-gold plating station, (5) current, temperature, pH value, gold solution and its speed at the gold plating station, and (6) current, temperature, pH value, tin/lead solution and its speed at the tin/lead plating station. Based on the Faraday Law of electroplating, the thickness of gold film on the terminals is affected by temperature, current, speed of solution, and concentration of gold.

The current process conditions employed are: a temperature of 60 °C, a speed of 20–25 ft/s, and an electric current of 3.0–7.0 A. However, the current and speed depend on the gold concentration. During operation, the gold concentration decreases as gold forms on the terminals, and it is a common practice to supply more halo-gold every 24 h. Once halo-gold is re-supplied, the gold concentration will temporarily increase. A few minutes, after re-supply of halo-gold, six film thickness measurements are taken.

If all the measured values of the film thickness are below target value, there are two ways to adjust the process. One way is to reduce the speed so that the film thickness on the terminals will be increased. The film thickness at six points will be measured again after the speed is reduced. However, it is necessary to keep the speed above 20 ft/s before the action of adjustment is taken. Another way to adjust the process is to increase the current instead of reducing the speed so that the film thickness on the terminals can be increased, if the speed is indeed below 20 ft/s. The film thickness at six points will be measured again after the current is increased. Moreover, it is also necessary to keep the current below 7.0 A before the current increases in order not to burn the terminals. If it is indeed above 7.0 A, then the halo-gold is supplied instead of increasing the current. Once the halo-gold is supplied, production processes are adjusted as mentioned above.

If all the measured values of the film thickness are above the target value, there are two ways to adjust the process. One way is to increase the speed so that the film thickness on the terminals can be reduced. The film thickness at six points will be measured again after the speed is increased. However, it is necessary to keep the speed below 25 ft/s before the action of adjustment is taken. If the speed is indeed above 25 ft/s, it will result in a decrease in quality of the films on the terminals. Thus, another way to adjust the process is to decrease the current instead of reducing the speed to decrease the film thickness. The film thickness at six points will be measured again after the current is decreased. Moreover, it is necessary to keep the current above 3.0 A before the current is decreased in order to assure the quality of the electroplating of the films. If it is indeed below 3.0 A, then the current will not be reduced and no further action of adjustment will be taken. If all the measured values of the film thickness are close to the target value, then no further action during production processes will be taken.

Quality assurance personnel take samples every 2 h to record the film thickness at six points of each terminal. Then the $\overline{X} - R$ control chart is plotted using only one value out of these six measurements in order to control the film thickness. Meanwhile, the values of temperature, speed, and electric current are also recorded.

Since the measurement is taken every 2 h by quality assurance personnel (regardless of engineers' production processes), the information of the film thickness is obtained under various production processes, and the quality of the terminals varies accordingly. The only measurement of production cost is the halo-gold supplied. Therefore, the data collected by quality assurance personnel would not reflect the quality of the film and the production cost under steady operation, because the process is being adjusted continuously. The collected data would not be utilized to provide an accurate analysis. In the next section, some problems that occurred during data collection processes by quality assurance personnel will be discussed and an improved method will be described.

3. Data collection and data management

Based on the process adjustment methods and the data collection approach, several comments are made:

1. It is inappropriate to take measurements of the film thickness every 2 h since the varying conditions of the production processes. The condition of the production process before the halo-gold is supplied is different from that of after the halo-gold is supplied. Hence, these processes should be considered as two different production processes. The appropriate method for quality assurance is to collect data and take control actions whenever the halo-gold is supplied. The same procedures should be repeated everytime the halo-gold is supplied.

2. It is recommended that measurements be taken every 30 min instead of every 2 h in order to collect more data and reflect the current conditions of the production processes.

3. As the film thickness deviates from the target value, the common practice is to adjust the current or the speed, in order to bring the film thickness to the target value. However, the main factor that affects the film thickness is the gold concentration. Furthermore, the cost of the halo-gold accounts for up to 90% of the total production cost of the terminals. Therefore, it would be more cost effective for terminal production if the halo-gold concentration can be effectively adjusted. The current and speed can be held constant in order to reduce the variation of the film thickness. It is also recommended that the gold be recorded.

4. The $\overline{X} - R$ control chart is obtained from only one value of the film thickness at six observation points, and the value at this point may not reflect the conditions at the other five observation points. It is recommended that the film thickness be controlled at six observation points simultaneously.

In summary, it is proposed that the data collection be as follows:

(1) Data will be collected once the conditions of the production processes are stable (a temperature of 60° C, a current of 4.0 A, and a speed of 20 ft/s) after the halo-gold is supplied. The action of data collection will continue until the next occasion halo-gold is supplied.
(2) Measurement be taken every 30 min, and one terminal will be measured.
(3) The gold concentration be recorded during data collection.
(4) The film thickness of all the six observation points on each terminal be recorded.

Based on 30 subgroups of data of the film thickness measured from the six observation points, a matrix of the correlated coefficients is shown in Table 1. It can be seen from the table that the values of the film thickness measured from the six observation points are strongly correlated. A Hotelling T^2 control chart [1] is developed based on the information of the film thickness measured from the six observation points in order to guarantee a steady production process. As shown in Fig. 1, the production processes are within the range of control in the Hotelling T^2 control chart. Based on the information under steady operation, a transfer function can thus be obtained to provide a functional relationship between the gold concentration and the gold film thickness.

Table 1
Correlation coefficients of the film thickness measured from the six observation points

Observation points	Right side 1	Right side 2	Right side 3	Back side 1	Back side 2	Back side 3
Right side 1	1.000	0.721	−0.037	0.551	0.645	0.055
Right side 2	0.721	1.000	0.086	0.786	0.715	0.157
Right side 3	−0.037	0.086	1.000	0.240	0.077	0.366
Back side 1	0.551	0.786	0.240	1.000	0.812	0.271
Back side 2	0.645	0.715	0.077	0.812	1.000	0.143
Back side 3	0.055	0.157	0.366	0.271	0.143	1.000

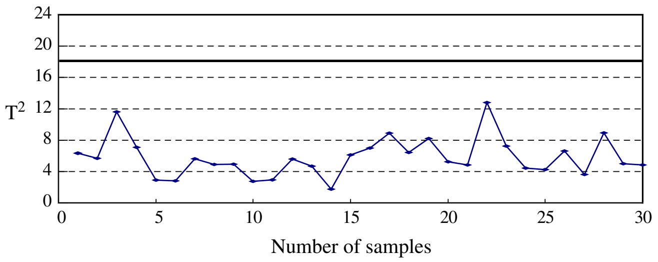

Fig. 1. Hotelling T^2 control chart.

Furthermore, the influence of the gold concentration on the gold film thickness can be obtained using engineering process control (EPC). The two methods mentioned above will result in a relationship between the gold concentration and the gold film thickness for the engineers to control the film thickness as close to the target value as possible, and the production cost will also be reduced.

4. Two approaches for process improvement

The two proposed methods for controlling the film thickness to be as close to the target value as possible, are described as follows.

4.1. Determine the statistical relationship between the film thickness and gold concentration using a transfer function model

A transfer function model [2] relates an output series to one or more input series. First, we determine the common factors for the film thickness measured at six observation points using the method of factor analysis [3]. The common factors are regarded as the output series while the gold concentration is one input series. Then, the relationship between them is determined using the transfer function model. Based on the derived transfer function model, the gold concentration is adjusted within a period of 1 h. The detailed procedure is described below, step by step.

4.1.1. Factor analysis

The multivariate statistical technique of factor analysis (for example [4]) can efficiently reduce a large number of variables to small set of new variables and explore the correlation structure among the original variables. The new variables preserve the information of the original variables. It can be seen from Table 1 that the values of the film thickness measured from the six observation points are correlated. Hence, the new variables of the film thickness measured from the six observation points may be determined using the factor analysis technique. The new variables are independent and represent the film thickness on the six observation points.

Before factor analysis, however, we use Bartlett test [5], to assess the appropriateness of factor analysis. The Bartlett test assesses whether the correlation matrix has significant correlation among at least some of the variables. The Bartlett test of Chi-Square = 85.8 is significant at the 0.01 significance level. This indicates that the data of film thickness on the six observation points has significant correlation and is very appropriate for factor analysis.

Next, the factor analysis technique is applied to identify the underlying structure of the variable relationships. Based on the correlation matrix, it is transformed through estimation of a factor model to obtain a factor matrix. The loading of each variable on the factors are then interpreted to identifying structure of the new variables. In doing so, we have to extract the factors using principal component method and select the number of factors to represent the underlying structure of relationships. Table 2 shows the information regarding the six factors (F_1, $F_2,\ldots,F_6$) and their relative explanatory power as expressed by their eigenvalues, the percentage of variance and the cumulative percentage of variance. The eigenvalues are thus used to assist in selecting the number of factors. We apply the latent root criterion to decide the number of factors, two components (F_1 and F_2) with eigenvalue greater than one will be retained. Furthermore, the two components retained represent 75.83% of the total variance of the gold thickness measured from the six observation points.

Since factors F_1 and F_2 are linear combination of the film thickness on the six observation points ($X_1, X_2, X_3, X_4, X_5, X_6$), they can be expressed by the following equations.

$$F_1 = 0.4432X_1 + 0.5066X_2 + 0.1126X_3 + 0.5096X_4 + 0.4985X_5 + 0.1616X_6 \quad (1)$$

$$F_2 = -0.2611X_1 - 0.1098X_2 + 0.6965X_3 + 0.0788X_4 + -0.1037X_5 + 0.6463X_6 \quad (2)$$

Using Eqs. (1) and (2), the values of F_1 and F_2 for the 30 subgroups of data of the film thickness are calculated and shown in Table 3. To understand the relationship between F_1 and F_2 and gold concentration (C) under varying data sampling time (t), the scatter plots for F_1, F_2, C and data sampling time are plotted (see Figs. 2–4). From Figs. 2 and 3, it can be seen that F_1 and C have similar decreasing trends. This indicates that F_1 and C are related under varying data sampling time. However, Fig. 4 shows that F_2 and C have no correlation on data sampling time. Hence, we will focus on the correlation between F_1 and C. Now, F_1 is regarded as output variable and the C is input variable. Since F_1 is affected by the gold concentration only in terms of its present and past values, the transfer function model is thus used to express their relationship.

4.1.2. Transfer function model

The purposes of transfer function modeling are to identify and estimate the transfer function $V(B)$ and the noise model N_t based on the available information of the input series C_t and the output series F_{1t}, t = 1, 2, 3... The procedure to obtain the estimated transfer function model and the noise model is described as follows:

(1) Determine the appropriate impulse response function and noise model.

After fitting and testing the order 10, 11, and 12 impulse response function, we find order 11 is the best. Hence, the order 11

Table 2
Varimax rotated component analysis factor loading matrix

Six sides	F_1	F_2	F_3	F_4	F_5	F_6
Right side 1	0.4432	−0.2611	0.0746	0.7550	0.2847	−0.2808
Right side 2	0.5066	−0.1098	−0.0126	0.1068	−0.7077	0.4679
Right side 3	0.1126	0.6965	−0.6585	0.2412	0.0700	0.0747
Back side 1	0.5096	0.0788	−0.0943	−0.4558	−0.1757	−0.6976
Back side 2	0.4985	−0.1037	−0.0487	−0.3867	0.6171	0.4562
Back side 3	0.1616	0.6463	0.7413	0.0567	0.0397	0.0438
Eigenvalue	3.1942	1.3553	0.6342	0.4312	0.2645	0.1206
Percentage of variance	53.2385	22.5929	10.5714	7.1911	4.4023	2.0068
Cumulative percentage of variance	53.2388	75.8307	86.4015	93.5929	97.9947	100.0000

Table 3
The values of F_1 and F_2 under various gold concentration

Time point	Right side 1	Right side 2	Right side 3	Back side 1	Back side 2	Back side 3	F_1	F_2	Gold concentration
1	19.45	18.93	16.13	18.68	19.08	16.08	41.65	13.96	14.78
2	18.48	19.60	16.20	18.08	17.65	15.75	40.49	14.08	14.52
3	17.33	18.58	16.45	18.50	19.13	15.55	40.41	14.42	14.38
4	19.55	20.05	16.38	18.50	18.80	16.28	42.09	14.13	14.48
5	19.33	19.78	16.05	18.90	18.88	16.03	42.02	13.85	14.23
6	19.85	19.48	15.95	18.15	18.93	15.75	41.69	13.44	14.12
7	18.90	18.53	15.20	17.73	19.13	15.38	40.52	12.97	14.33
8	18.53	19.48	16.20	18.93	18.95	15.23	41.45	13.68	14.57
9	20.03	19.88	15.50	19.40	19.95	15.28	42.99	12.72	14.64
10	19.53	19.50	16.13	18.60	19.38	15.43	41.98	13.42	14.36
11	19.58	19.73	15.50	18.83	19.00	16.00	42.06	13.37	14.03
12	19.60	19.60	15.10	18.98	18.98	15.98	42.03	13.10	13.50
13	19.78	19.58	14.73	18.70	19.10	15.08	41.82	12.18	13.76
14	19.00	19.35	15.30	17.95	18.93	15.43	41.02	12.99	13.43
15	19.30	19.80	14.88	17.83	18.48	14.73	40.93	12.15	13.53
16	18.55	19.23	15.00	17.70	18.78	14.50	40.37	12.31	13.12
17	20.70	19.73	14.98	17.65	18.65	14.85	41.54	11.92	13.02
18	18.40	19.53	14.63	18.43	18.48	15.30	40.76	12.66	12.85
19	19.20	18.80	15.20	17.08	18.78	15.80	40.36	13.12	12.51
20	18.25	19.30	16.05	17.78	17.40	15.98	39.99	14.22	12.75
21	18.58	18.43	16.10	17.28	17.20	15.03	39.18	13.63	12.49
22	19.13	18.70	16.23	17.48	17.18	14.50	39.59	13.22	12.44
23	18.00	17.95	15.80	17.50	17.00	15.78	38.79	14.15	12.13
24	17.08	18.30	15.90	17.13	17.20	15.30	38.40	14.06	12.31
25	18.30	18.48	14.85	16.93	16.78	15.35	38.61	13.05	11.73
26	18.35	17.85	14.88	16.43	16.68	15.50	38.04	13.19	11.35
27	18.03	18.38	15.58	16.65	17.60	15.43	38.80	13.58	11.48
28	17.25	18.03	14.30	17.08	17.13	15.05	38.06	12.78	11.67
29	17.65	18.53	15.50	16.65	17.05	15.73	38.48	13.86	11.28
30	18.10	17.95	15.80	16.48	17.40	15.20	38.42	13.63	10.98

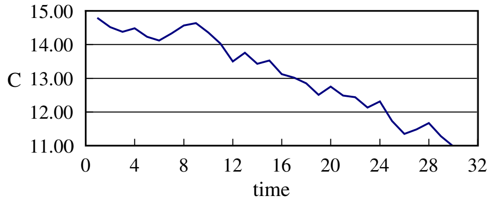

Fig. 2. Gold concentration over time.

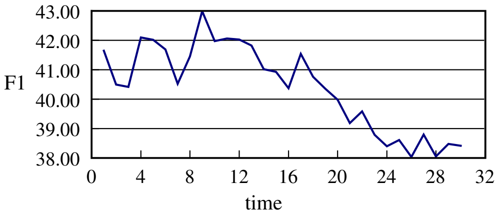

Fig. 3. Common factor F_1 over time.

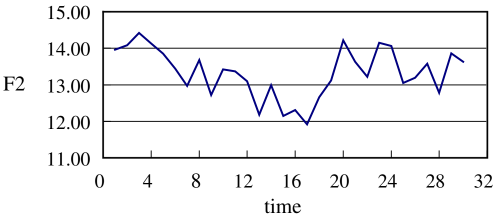

Fig. 4. Common factor F_2 over time.

impulse response function with the noise model following AR(1) model is expressed as follows.

$$F_{1t} = CNST + (v_0 + v_1 B + v_2 B^2 + \cdots + v_{11} B^{11}) C_t + \{1/(1 - \phi B)\} N_t \tag{3}$$

That is $V(B) = v_0 + v_1 B + v_2 B^2 + \cdots + v_{11} B^{11}$.

The estimated models are obtained using the SCA package (see Table 4).

From the ACF (auto-correlation function) and PACF (partial auto-correlation function) of the noise model, it is found that the

Table 4
Impulse response weights and coefficients of noise model

Parameter	Label	Variable name	Num./Denom.	Factor	Order	Constraint	Value	Std error	*T* value
1	CNST		CNST	1	0	None	22.6079	2.4552	9.21
2	V0	C	NUM.	1	0	None	−.3789	.5921	−.64
3	V1	C	NUM.	1	1	None	−.9229	.4209	−2.19
4	V2	C	NUM.	1	2	None	.1618	.4100	.39
5	V3	C	NUM.	1	3	None	−1.1200	.3802	−2.95
6	V4	C	NUM.	1	4	None	.7202	.3809	1.89
7	V5	C	NUM.	1	5	None	.4654	.4731	.98
8	V6	C	NUM.	1	6	None	.0310	.4860	.06
9	V7	C	NUM.	1	7	None	1.3733	.6533	2.10
10	V8	C	NUM.	1	8	None	−.0853	.4771	−.18
11	V9	C	NUM.	1	9	None	1.0242	.4413	2.32
12	V10	C	NUM.	1	10	None	1.2715	.3838	3.31
13	V11	C	NUM.	1	11	None	−1.3900	.4900	−2.84
14	ϕ	FAC1	D-AR	1	1	None	.5241	.2647	1.98

fitted MA(1) model is appropriate. The ACF of Eq. (3) shows that the residuals are close to white noise. This means that the fitted impulse response function and the MA(1) noise model are appropriate.

(2) Verify the order of the transfer function model.

Since the transfer function $V(B) = v_0 + v_1B + v_2B^2 + \cdots + v_{11}B^{11}$ may contain an infinite number of coefficients, the transfer function $V(B)$ is represented in the following form (Eq. (4))

$$V(B) = \frac{w_S(B)B^b}{\delta_r(B)} \tag{4}$$

where $w_S(B) = w_0 - w_1B - \cdots - w_SB^S$, $\delta_r(B) = 1 - \delta_1B - \cdots - \delta_r\ B^r$ and b is a delay parameter representing the actual time lag that elapses before the impulse of the input variable produces an effect on the output variable.

The corner table method [6] is used to verify the order (r,s,b) of the transfer function in Eq. (4). The corner table (see Table 5) is obtained using the SCA package, and shows that the transfer function with $r = 2$, $s = 3$ and $b = 2$ is appropriate. Hence, the transfer function is temporarily expressed as Eq. (5).

Table 5
Corner table

	1	2	3	4	5	6
0	−.35	.12	−.04	.01	−.00	.00
1	−.15	.32	−.13	.15	−.08	.07
2	.86	.69	.79	.98	1.01	1.06
3	−.33	−.62	.43	1.01	.08	−.98
4	.85	.77	1.04	1.01	.98	.92
5	.13	.47	.70	−.00	.52	−.24
6	−.54	.18	.47	−.36	.28	.20

$$\begin{aligned} F_t &= CNST + \tfrac{w_0+w_1B+w_2B^2}{1-\delta_1B-\delta_2B^2-\delta_3B^3}B^2C_t + (1-\theta B)a_t \\ &= CNST + \tfrac{w_2B^2+w_3B^3+w_4B^4}{1-\delta_1B-\delta_2B^2-\delta_3B^3}C_t + (1-\theta B)a_t \end{aligned} \tag{5}$$

(3) Estimate the coefficients of the transfer function using conditional maximum likelihood estimation

The estimated coefficients of the transfer function can be obtained using the SCA package (see Table 6). The transfer function is determined as Eq. (6).

$$\begin{aligned} F_t = 20.5213 + \frac{0.9953B^2 - 0.1845B^3 + 0.5124B^4}{1 - 0.1043B + 0.3905B^2 - 0.3953B^3}C_t \\ + (1 + 0.2350B)a_t \end{aligned} \tag{6}$$

To verify that the transfer function model is appropriate, we check the ACF of the residuals of Eq. (6) and the CCF of gold concentration. They show that all ACF and CCF (cross-correlation function) are less than twice their standard deviation. Consequently, the fitted transfer function in Eq. (6) is appropriate.

The adjustment policy for gold concentration can be determined based on the derived transfer function model. Before determining the adjustment policy for gold concentration, the prediction model for gold concentration needs to be found.

4.1.3. The prediction model for gold concentration

Fig. 2 indicates that the gold concentration decreases over time. The data analysis results for gold concentration, using the SCA package, show that the ACF follows a decreasing cosine function; the PACF is significant at the first time lag; the EACF (extended auto-correlation function) of the gold concentration supports the AR(1) model. All these results indicate that the appropriate model of gold concentration is AR(1) (Eq. (7)).

$$(1 - \phi_1B)C_t = \alpha_t \tag{7}$$

Table 6
The estimated coefficients in the transfer function

Parameter	Label	Variable name	Num./Denom.	Factor	Order	Constraint	Value	Std error	*T* value
1	CNST		CNST	1	0	None	20.5213	2.2114	9.28
2	W2	C	NUM.	1	2	None	.9953	.3699	2.69
3	W3	C	NUM.	1	3	None	−.1845	.5461	−.34
4	W4	C	NUM.	1	4	None	.5124	.4120	1.24
5	δ_1	C	DENM	1	1	None	.1043	.2115	.49
6	δ_1	C	DENM	1	2	None	−.3905	.1593	−2.45
7	δ_1	C	DENM	1	3	None	.3953	.1686	2.34
8	θ	FAC1	MA	1	1	None	−.2350	.1987	−1.18

Table 7
The estimated coefficient of gold concentration model

Parameter	Label	Variable name	Num./Denom.	Factor	Order	Constraint	Value	Std error	T value
1	ϕ	C	AR	1	1	None	.9902	.0035	284.46

Next, CMLE (conditional maximum likelihood estimation) is employed to estimate the coefficient ($\hat{\phi}_1$) in the AR(1) model and obtain $\hat{\phi}_1 = 0.9902$ (Table 7). So the fitted AR(1) model is

$$(1 - 0.9902B)C_t = \alpha_t \tag{8}$$

Since all ACF of residuals are less than twice its standard deviation, the fitted prediction model of gold concentration is acceptable.

4.1.4. Adjustment policy of the gold concentration

To control the film thickness as close as possible to the target and to reduce the cost of halo-gold consumption, the gold concentration is adjusted every 1 h based on the derived transfer function.

The lower specification limit of the film thickness is $15u''$. If film thickness is $15u''$ at all six observation points then the common factor F_1 is 33.48 (from Eq. (1)). When the target value (or minimum value) of F_1 is set to 33.48, the risk of defective films could be high. If the film thickness is set on $15.5u''$ at all six observation points then the common factor F_1 is 34.61 using Eq. (1). To avoid defective film, the target value of F_1 is set to 34.61 and the gold concentration is adjusted every 1 h based on the derived gold concentration model.

Using the derived transfer function (Eq. (6)) and the derived gold concentration model (Eq. (8)), the gold concentration is 9.20 g/l when F_1 = 34.61. Consequently, the gold concentration should be controlled higher than 9.20 g/l in the process.

The gold concentration is calculated as 9.383 g/l at the start (t = 0) of the production using Eq. (8). After 1 h (t = 1) from the start of the production, the predicted gold concentration ($\hat{C}_1$) is 9.3 g/l. By putting $\hat{C}_1 = 9.3$ g/l in the derived transfer function, the predicted common factor $\widehat{F}_{11}$ is 34.78. After 2 h (t = 2) from the start of the production, the predicted gold concentration ($\hat{C}_1$) is 9.21 g/l. By putting $\hat{C}_2 = 9.21$ g/l in the derived transfer function, the predicted common factor $\widehat{F}_{12}$ is 34.62. Similarly, the $(\hat{C}_1, \hat{F}_{11})$ and $(\hat{C}_2, \hat{F}_{12})$, the predicted gold concentration, predicted common factor, and predicted film thickness can be computed for any time from the start of production Since gold concentration decreases over time after the start of the production, we propose to add halo-gold every hour to keep the gold concentration close to the initial value 9.383 g/l. The cost of halo-gold is estimated using the formula: "gold consumption = change in gold concentration × volume of gold solution tank". Since the ratio of gold to halo-gold is 1:0.6825 and the cost of halo-gold is NT$250/g, the total cost of halo-gold consumption is estimated to be around NT$242,000/day.

4.2. Engineering process control method aided by transfer function model

Engineering process control (EPC) [7] is the approach of adjusting a manipulatable process variable to keep the process output on target or minimize the variability of the output around the target. Similar to the transfer function model, the common factor (F_{1t}) is regarded as the output variable at time t, and the sum of all the adjustments of gold concentration, through time t ($\sum_{i=1}^{t} C_i - C_{i-1}$), is regarded as a manipulatable variable (X_t). The EPC method is applied to determine the dynamic model between F_{1t} and X_t. Then the output variable F_{1t} in the derived dynamic model can be predicted, aiding by the derived transfer function (Eq. (6)) and the appropriate gold concentration adjustment can thus be determined to reduce the variation of film thickness and cost of halo-gold consumption.

4.2.1. Engineering process control approach

Using the EPC method, the model for F_{1t} and X_t at time t is expressed as

$$C_i - C_{i-1} = -\frac{\lambda}{g}(F_{1i} - T), \quad i = 1, 2, \ldots, t, \ldots \tag{9}$$

$$X_t = \sum_{i=1}^{t}(C_i - C_{i-1}) = -\frac{\lambda}{g}\sum_{i=1}^{t}(F_{1i} - T) \tag{10}$$

where λ is the weight factor in the disturbance model, g is the process gain, and T is the target value.

The determination of T, the estimation of λ and g, and the prediction of F_{1t} can be obtained as follows.

(1) The determination of target value T

As in Section 4.1.4, F_{1t} is 34.61 when all film thickness are $15.5u''$. The target value of F_{1t} is set at 34.61.

(1) The estimation of g

Figs. 2–4 show that the correlations for F_{1t} and C_t are linear and dependent on time. The regression model with an error term following ARIMA(1,0,1) is thus fitted (Eq. (11)). However, the ACF and PACF of residuals show the slope parameter β_1 is significant but the parameters, θ and ϕ, in the ARIMA(1,0,1) model are not significant. Hence, the estimated g is the estimated β_1, that is $\hat{g}$ = 1.08.

$$F_1 = \beta_0 + \beta_1 C + \varepsilon hatF_1 = 26.196 + 1.08\hat{C} \tag{11}$$

(1) The estimation of λ

Let $F_{1t} - T = N_t$ where N_t is the disturbance. Montgomery and Mastrangelo [8] suggest that N_t can be expressed by an EWMA (exponentially weighted moving average) model, because EWMA model approximates an ARIMA(0,1,1) with $\lambda = 1 - \theta$. The fitted ARIMA(0,1,1) model of N_t has an estimate of $\hat{\theta}$ =0.3484. From the ACF of residuals of the ARIMA(0,1,1) model, we found no ACF greater than twice the standard deviation, and so the fitted ARIMA(0,1,1) model (Eqs. (12) and (13)) is acceptable. Hence, $\hat{\lambda} = 1 - \hat{\theta} = 0.6516$.

$$\hat{N}_{t+1} = \hat{N}_t + \lambda(N_t - \hat{N}_t), \quad 0 < \lambda \leqslant 1 \tag{12}$$

$$(1 - B)N_t = (1 - \theta B)a_t \tag{13}$$

(1) Prediction of output variable

To make the output variable (common factor F_{1t}) as close to the target value as possible, the derived prediction model of gold concentration (C_t) (Eq. (8)) is used to predict the gold concentration at time t ($\hat{C}_t$). Then, the predicted $\hat{C}_t$ and the derived transfer function (Eq. (6)) are used to predict factor F_{1t}. Finally, the adjusted gold concentration at time t (X_t) can be determined using the predicted F_{1t} and the derived dynamic model (Eq. (10)).

Table 8
Quality and cost comparison among current and the proposed two adjustment approaches

		Current situation			Adjustment of transfer function			Adjustment of EPC		
predicted thickness	Average thickness (M)				15.548			15.439		
	Standard deviation (S)				0.036			0.031		
	Defective(P)	0						0		
	Cost of Halo-gold consumption				NT$225,000 per production/day			NT$223000 per production/day		
confirmation results		M	S	P	M	S	P	M	S	P
	Right side1	18.79	0.882	0	15.71	0.330	0	15.72	0.301	0
	Right side 2	19.03	0.673	0	15.68	0.330	0	15.62	0.312	0
	Right side 3	15.55	0.596	23.33	15.71	0.303	0	15.63	0.309	0
	Back side1	17.86	0.835	0	15.71	0.311	0	15.58	0.298	0
	Back side 2	18.25	0.940	0	15.67	0.297	0	15.66	0.286	0
	Back side 3	15.44	0.460	13.33	15.70	0.321	0	15.53	0.334	0
	Total average	18.109			15.693			15.633		
	Total standard deviation	0.655			0.154			0.135		
	Total defective	0			0			0		
	Cost of Halo-gold consumption	NT$286000			NT$229000 per production/day			NT$225000 per production/day		

4.2.2. Adjustment of the gold concentration

As discussed in Section 4.1.4, the target value of F_{1t} is set at 34.61 when all film thickness are 15.5u''. To avoid defective film, the gold concentration is adjusted every hour.

We set the gold concentration to $C_0 = 9.20$ g/l on the start of the production. After 1 and 2 h from the start of the production, the predicted gold concentration are $\hat{C}_1 = 9.1098$ g/l and $\hat{C}_2 = 9.0206$ g/l using the derived prediction model of gold concentration (Eq. (8)). The predicted common factor $\hat{F}_{11} = 34.4898$ and $\hat{F}_{12} = 34.3509$ are obtained, using the derived transfer function (Eq. (6)). Consequently, after 2 h from the start of the production the adjusted gold concentration is $\hat{X}_2 = 0.2289$, by putting the $\hat{F}_{11} = 34.4898$ and $\hat{F}_{12} = 34.3509$ in the Eq. (10). The predicted gold concentration ($\hat{C}_t$), common factor ($\hat{F}_{1t}$) and the adjusted gold concentration ($\hat{X}_t$) at any time can be obtained using the proposed approach. The estimated cost of halo-gold consumption is about NT$223,000 per production line/day.

4.3. Confirmatory experiments for the two proposed approaches

Based on the results from those two proposed methods, the gold concentration adjustments were performed on the real production lines. The conditions of the production processes were set at a temperature of 60 °C, a current of 4 A and a speed of 20 ft/s. The production started at 8 AM and the gold concentration was set at 9.383 g/l for the first proposed method (transfer function). The samples were taken at time 8:30 AM, 9:00 AM, 9:30 AM,...,7:30 PM, and 8:00 PM. The observed gold concentration and the measured film thickness on the six observed points were also recorded. The halo-gold was added to maintain the gold concentration at 9.383 g/l at time 9:00 AM, 10:00 PM, 11 AM...,6:00 PM, and 7:00 PM. A confirmatory experiment for the second proposed method (EPC) was the same as that of the first proposed approach.

5. Quality and cost comparison for the proposed two adjustment approaches

The analysis results based on the collected data for the film thickness quality and the cost of halo-gold using the two proposed methods are illustrated in Table 8. Table 8 shows (1) the predicted results of thickness and the cost and (2) confirmation results of thickness and the cost using the two proposed adjustment approaches. The confirmation results are close to the predicted results of the two proposed adjustment approaches. This indicates that the improvement effect of the proposed approaches is reliable. Compared to the current adjustment, the average thickness is much closer to the target thickness; the standard deviation of thickness is much smaller, and the defect reduced to zero by using either of the two proposed adjustment approaches. Moreover, the production cost savings are a minimum of NT$41,000 per production line/day. Fox Company has 24 production lines per day, so the production costs may be saved at least NT$984,000 per day.

Table 8 reveals that the two proposed approaches significantly improve the quality of the metallic film of the connectors and reduce the cost of production. However, the engineering process control approach is slightly better than the transfer function approach in the quality of the metallic film and cost reduction. Hence, the engineering process control approach is recommended to adjust the production process for improving the quality of metallic film and cost reduction.

6. Summary

The variation of the film thickness and the cost are important to many industry of computer connector. However, the production processes and production conditions are currently available only through engineers' subjective judgment. Two adjustment approaches, transfer function and engineering process control, have been proposed to control the film thickness to be close to the target value. The data analyses results of confirmatory experiments of the two proposed adjustment approaches reveal substantial improvement in film quality and cost reduction, as compared to the current situation. Moreover, the engineering process control approach has better film quality and cost reduction than the transfer function approach and hence is recommended.

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