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Automated optical inspection of liquid crystal display anisotropic conductive film bonding

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Abstract. Anisotropic conductive film (ACF) bonding is widely used in the liquid crystal display (LCD) industry. It implements circuit connection between screens and flexible printed circuits or integrated circuits. Conductive microspheres in ACF are key factors that influence LCD quality, because the conductive microspheres' quantity and shape deformation rate affect the interconnection resistance. Although this issue has been studied extensively by prior work, quick and accurate methods to inspect the quality of ACF bonding are still missing in the actual production process. We propose a method to inspect ACF bonding effectively by using automated optical inspection. The method has three steps. The first step is that it acquires images of the detection zones using a differential interference contrast (DIC) imaging system. The second step is that it identifies the conductive microspheres and their shape deformation rate using quantitative analysis of the characteristics of the DIC images. The final step is that it inspects ACF bonding using a back propagation trained neural network. The result shows that the miss rate is lower than 0.1%, and the false inspection rate is lower than 0.05%. © 2016 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.OE.55.10.103109](https://doi.org/10.1117/1.OE.55.10.103109)]

Keywords: anisotropic conductive film; conductive microspheres; differential interference contrast; back propagation; automated optical inspection.

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1 Introduction

Anisotropic conductive film (ACF) bonding is a key packaging process in the liquid crystal display (LCD) module industry. It refers to the process that an integrated circuit or flexible printed circuit is assembled onto indium tin oxide (ITO) glass substrates of LCD modules with the ACF.^{1,2} The ACF is a film that consists of adhesive epoxy matrix and fine conductive microspheres. The conductive microspheres are metal-coated polymer spheres with 5 to 10 μm in diameter, and the adhesives are thermosetting resins.³ In ACF bonding, the conductive interconnection is achieved through conductive microspheres trapped between the bumps and the corresponding substrate pads.⁴ Recently with development and competition in the LCD industry, the quality of LCDs is becoming more and more important. As packaging is an important part of the production process, it is crucial to inspect the quality of ACF bonding. The quality of ACF bonding is affected by the quantity and the shape deformation rate of conductive microspheres, which determine the interconnection resistance.⁵ However, it is too difficult to inspect these trapped microspheres because they are too small. Due to this reason, many factories inspect ACF bonding by electrical measurements instead. However, this electrical measurement has many problems, such as it has low efficiency.

Prior work has extensively studied the mechanism of ACF bonding and how to improve the conduction of ACF bonding. In Ref. 6, Yim has pointed out that the quantity of conductive microspheres trapped between the bump and ITO glass substrate pad should be large enough, but how to inspect the quantity is still an unresolved issue. In Ref. 7–9,

the parameters, including the conductive microsphere diameter and the bonding force, are analyzed with nonlinear and temperature-dependent material properties and it is shown how the parameters affect the resistance, but how to inspect whether the bonding force is acceptable still remains open. In Refs. 10–14, the authors have discussed the formation mechanism of interconnection resistance, but how to inspect the connective zones of the conductive microspheres and the shape deformation rate of the conductive microspheres is not presented. In Refs. 15 and 16, a system has been developed to inspect the interconnection conductivity using the connective area (CA), but the proposed method to obtain the CA is not very accurate due to the limitations of its imaging and calculation. Other studies have researched some advanced methods to inspect some specific goals in other fields. In Refs. 17 and 18, an artificial neural network method has been designed to automatically inspect the fungi under complex microscopic fecal images. It can be used to identify whether ACF bonding is acceptable by inspecting the quantity of the conductive microspheres, the shape deformation of conductive microspheres, and so on. But in ACF bonding, it is difficult to obtain the shape deformation of conductive microspheres by conventional image acquisition methods. So despite the above work, we have not found a way in the literature to quickly inspect whether ACF bonding is acceptable.

In this study, a method has been designed to inspect ACF bonding conductive microspheres based on differential interference contrast (DIC) and back propagation (BP) neural networks. The method has three steps. The first step is that it acquires images of the detection zones using a DIC imaging

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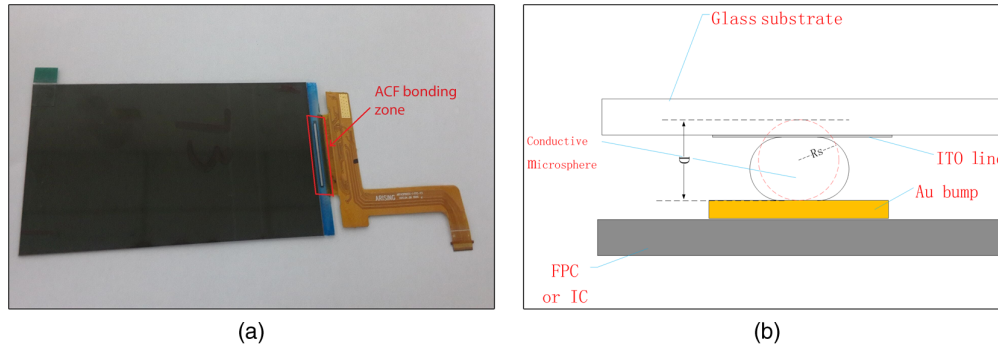


Fig. 1 LCD ACF bonding processing: (a) an LCD module and (b) ACF bonding.

system. The second step is that it identifies conductive microspheres and the shape deformation rate using quantitative analysis of the characteristics of DIC images. The final step is that it inspects ACF bonding using a BP trained neural network.

2 Methods and Theoretic Results

2.1 Imaging Analysis

Due to the fact that conductive microspheres are too small and are trapped between bumps and the corresponding substrate pads, as shown in Fig. 1, an optical system has been designed to take images of them based on DIC, as shown in Fig. 2. The light source of the imaging system is of low coherence and the illuminance is uniformly distributed.

When a uniform illuminance distribution polarized light is used, the surface reflection function of the sample can be expressed as $f(x, y) = A_0 \exp[j(2\pi/\lambda)\phi(x, y)]$, where A_0 is the amplitude of polarized light, $\phi(x, y)$ is the optical path

difference (OPD) function caused by the surface of the sample, and (ξ, η) and (x, y) are the coordinates of the object plane and the image plane, respectively. The amplitude point spread function of the DIC imaging system can be expressed as¹⁹

$$h(x, y) = \frac{1}{2} \delta\left(x - \frac{\Delta X}{2}, y\right) \exp(-j\Delta\theta_0) + \frac{1}{2} \delta\left(x + \frac{\Delta X}{2}, y\right) \exp(j\Delta\theta_0), \quad (1)$$

where ΔX is the shear of the DIC imaging system and $2\Delta\theta_0$ is the bias of the DIC imaging system. Because the light is of low coherence, coherence can occur only between e-ray and o-ray split from the same ray. From the linear spatial constant characteristics of the DIC imaging system, we can get the coherent intensity $I(x, y)$ as in Eq. (2).¹⁹ When ΔX is small enough, $I(x, y)$ can be expressed as Eq. (3)

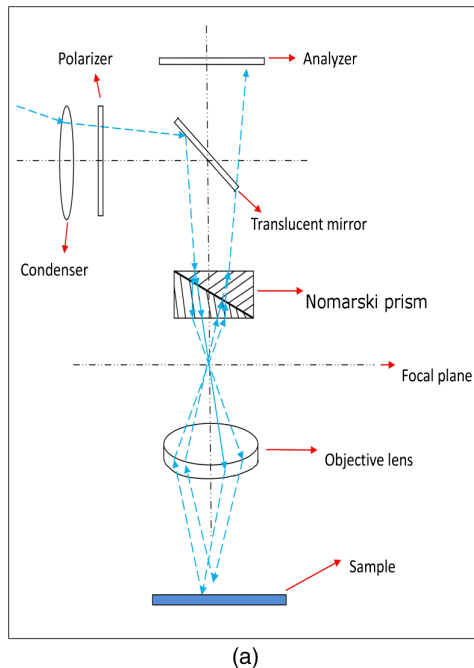
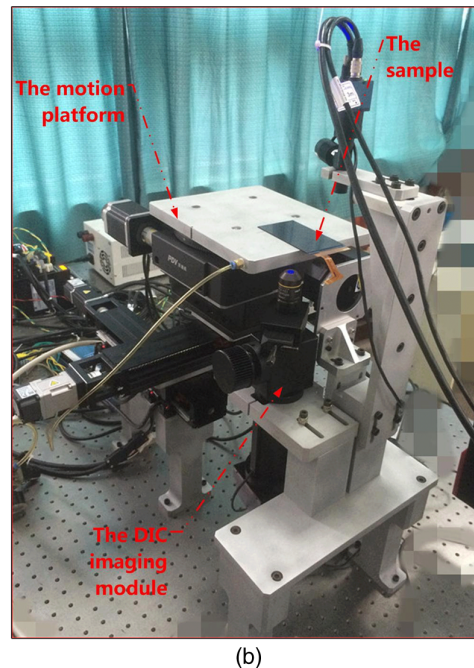


Fig. 2 Imaging system: (a) DIC principle and (b) the experimental device.

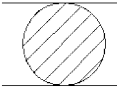
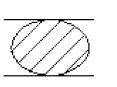
Shape deformation				
Deformation rate	<20%	20% to 50%	50% to 80%	>90%
Result	NG	OK	OK	NG

Fig. 3 A reference table for percent deformation.

$$\begin{aligned}
 I(x, y) &= \left| \iint f(\xi, \eta) h(x - \xi, y - \eta) d\xi d\eta \right|^2 \\
 &= |f(x, y) * h(x, y)|^2 \\
 &= \left| \frac{1}{2} \exp \left[j \frac{2\pi}{\lambda} \varnothing \left(x - \frac{\Delta X}{2}, y \right) \right] \exp(-j\Delta\theta_0) \right. \\
 &\quad \left. + \frac{1}{2} \exp \left[j \frac{2\pi}{\lambda} \varnothing \left(x + \frac{\Delta X}{2}, y \right) \right] \exp(j\Delta\theta_0) \right|^2 \\
 &= \frac{1}{2} \exp \left\{ j \left[\frac{2\pi}{\lambda} \varnothing \left(x - \frac{\Delta X}{2}, y \right) - \Delta\theta_0 \right] \right\} \\
 &\quad + \frac{1}{2} \exp \left\{ j \left[\frac{2\pi}{\lambda} \varnothing \left(x + \frac{\Delta X}{2}, y \right) + \Delta\theta_0 \right] \right\} \\
 &= \cos^2 \left\{ \frac{\pi}{\lambda} \left[\varnothing \left(x - \frac{\Delta X}{2}, y \right) - \varnothing \left(x + \frac{\Delta X}{2}, y \right) \right] - \Delta\theta_0 \right\},
 \end{aligned} \tag{2}$$

$$I(x, y) = \cos^2 \left[\frac{\pi \Delta X}{\lambda} \frac{d\varnothing(x, y)}{dx} - \Delta\theta_0 \right]. \tag{3}$$

From the above, we know that:

1. The coherent intensity of the DIC imaging system $I(x, y)$ is based on the gradient of the direction of the shear when the shear and the bias are constant.
2. The coherent intensity of the conductive microsphere image $I(x, y)$ is based on the orientation gradient of the conductive microsphere surface.

2.2 Shape Deformation of Conductive Microspheres

As noted above, the conductive microspheres trapped between the bump and the pad affect the interconnection resistance in ACF bonding. The deformation rate of a conductive microsphere can be expressed as $K = \Delta D/D$, where $D = 2R_s$ is the diameter of a conductive microsphere and R_s is the radius of a conductive microsphere. Figure 3 is a reference table from an LCD module factory. From Ref. 5, it is noted that the quantity and the deformation rate of

these trapped conductive microspheres will affect the interconnection resistance.

When the deformation rate is K in the radial shear direction, the distance between the upper and lower contact can be expressed as

$$h = (1 - K)D = 2(1 - K)R_s = 2R_d. \tag{4}$$

So the radius R_d can be expressed as

$$R_d = \frac{h}{2} = (1 - K)R_s. \tag{5}$$

Because the volume of the microsphere does not change, we obtain the below equation

$$\frac{4\pi R_s^3}{3} = \pi \int_{-h/2}^{h/2} \left[\sqrt{\left(\frac{h}{2}\right)^2 - z^2} + R_c \right]^2 dz. \tag{6}$$

Then, the radius R_c can be expressed as¹⁰

$$R_c = D \frac{\frac{-\pi(1-K)}{4} + \sqrt{\left[\frac{\pi(1-K)}{4}\right]^2 - 4\left[\frac{(1-K)^2}{6} - \frac{1}{6(1-K)}\right]}}{2}. \tag{7}$$

The relation between R_d and K and R_s and the relation between R_c and R_s and K are shown in Fig. 4.

So the OPD in the radial shear direction can be expressed as

$$\begin{aligned}
 \varnothing(x, 0) &= \begin{cases} 0, & 0 \ll |x| < R_c \text{ or } R_c + R_d \ll |x| \\ 2\sqrt{R_d^2 - (x - R_c)^2}, & R_c \ll x < R_c + R_d \\ -2\sqrt{R_d^2 - (x + R_c)^2}, & -R_c > x \gg -R_c - R_d \end{cases}
 \end{aligned} \tag{8}$$

When the shear ΔX is small enough, the coherent intensity in the radial shear direction can be expressed as

$$I(x, y_0) = \begin{cases} \frac{1}{2} \cos(2\Delta\theta_0) + \frac{1}{2}, & 0 \ll |x| < R_c \text{ or } R_c + R_d \ll |x| \\ \frac{1}{2} \cos \left[-4 \frac{\pi \Delta X}{\lambda} \frac{x - R_c}{\sqrt{R_d^2 - (x - R_c)^2}} - 2\Delta\theta_0 \right] + \frac{1}{2}, & R_c \ll x < R_c + R_d \\ \frac{1}{2} \cos \left[4 \frac{\pi \Delta X}{\lambda} \frac{x + R_c}{\sqrt{R_d^2 - (x + R_c)^2}} - 2\Delta\theta_0 \right] + \frac{1}{2}, & -R_c \gg x > -R_c - R_d \end{cases} \tag{9}$$

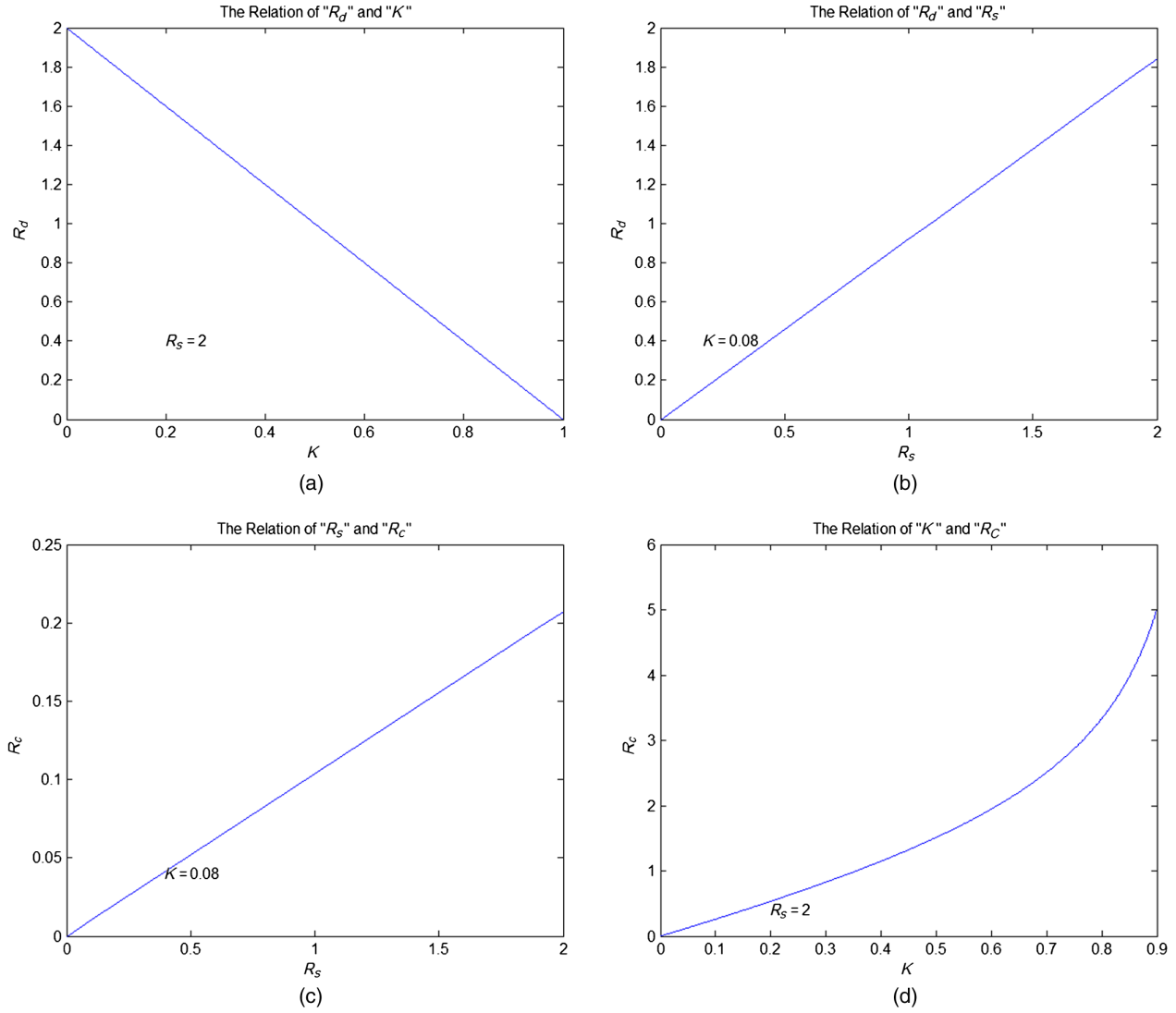


Fig. 4 The relation between R_d , K , and R_s and the relation between R_c , R_s , and K , where (a) the relation between R_d and K , (b) the relation between R_d and R_s , (c) the relation between R_c and R_s , and (d) the relation between R_c and K .

For the scan camera pixel, the physical distance represented by the scan camera pixel is ε , the gray intensity of the scan camera pixel in the shear direction can be expressed as in the below equation, as shown in Fig. 5

$$I_{\text{det}}(n) = \int_{x(n)}^{x(n)+\varepsilon} I(x, y_0) = \sum_n^{n+\left[\frac{\varepsilon}{\Delta X}\right]} I(x, y_0). \quad (10)$$

From Eq. (8), it is noted that the OPD $\Delta\phi$ between e-light and o-light has the relation, as shown below:

$$-2\sqrt{2R_d\Delta X - \Delta X^2} \ll \Delta\phi \ll 2\sqrt{2R_d\Delta X - \Delta X^2}. \quad (11)$$

From Eqs. (7) and (9), it is noted that the distance between the bright spot and the dark spot can be expressed as

$$\begin{aligned} \text{Dis} = 2R_c + \sigma R_d = R_s \left\{ \sigma(1-K) + \frac{-\pi(1-K)}{2} \right. \\ \left. + 2\sqrt{\left[\frac{\pi(1-K)}{4}\right]^2 - 4\left[\frac{(1-K)^2}{6} - \frac{1}{6(1-K)}\right]} \right\}, \end{aligned} \quad (12)$$

where

$$\sigma = \left\{ \frac{2\Delta\theta_0}{[A^2 + (2\Delta\theta_0)^2]^{1/2}} + \frac{\pi - 2\Delta\theta_0}{[A^2 + (\pi - 2\Delta\theta_0)^2]^{1/2}} \right\}, \quad (13)$$

where $A = 4\pi\Delta X/\lambda$.

From the above, we know that:

1. R_c is a monotonically increasing function of R_s and K .
2. There are bright and dark spots (D_BDS) in the shear direction in the conductive microsphere DIC images.

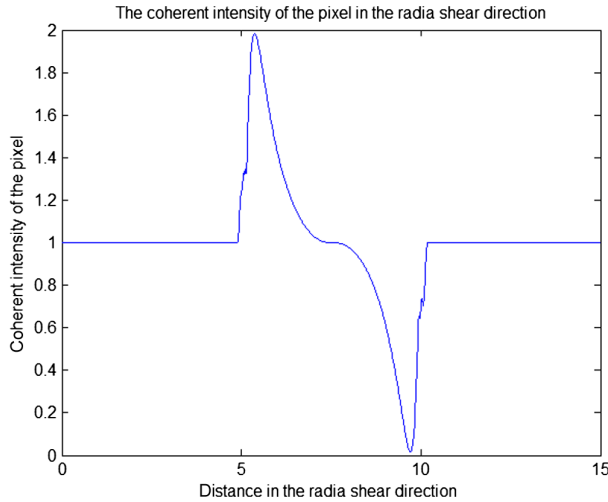


Fig. 5 The coherent intensity of the pixel, where $R_s = 5 \Delta X = 0.05$, $\varepsilon = 0.7$, and $2\Delta\theta_0 = \pi/3$.

3. The distance between the D_BDS is affected by the shape deformation rate K when the radius R_s is constant.
4. The gray value of the D_BDS has a limit depending on the shape of the target.

2.3 Identification Methods

Different factories have different standards on the quality of the LCD modules and it is difficult and time-consuming to obtain the inspection parameters manually. An automatic inspection algorithm is designed to inspect whether ACF bonding on the bumps is acceptable using a BP trained neural network to automatically obtain the inspection parameters for different factory standards. The BP neural network designed to self-adaptively obtain the parameters of the inspection system is very useful in the actual production process. The inspection system has two stages. The first stage is to identify acceptable conductive microspheres, no-good (NG) conductive microspheres, and the impurities on each bump with the information in Table 1. The second stage is to identify whether ACF bonding is acceptable by a BP trained neural network, as shown in Fig. 6.

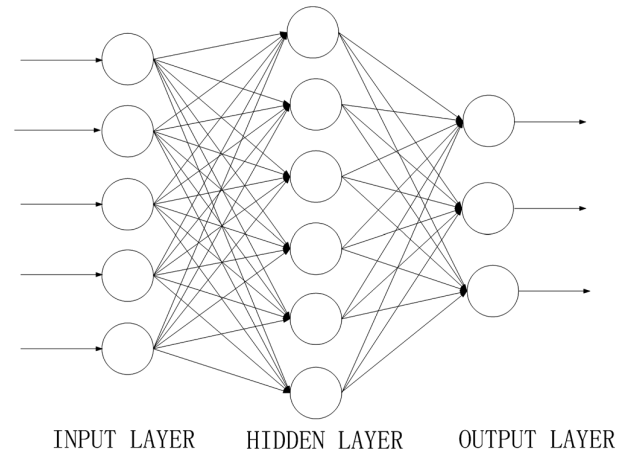


Fig. 6 The BP neural networks.

The BP neural network is composed of an input layer, a hidden layer, and an output layer. The BP neural network has four input nodes and two output nodes. The membership value is the ideal output from the BP neural network. The neural network is trained with the samples, and then the membership function is obtained. The samples are images from the LCD modules, which contain 1000 OK bump images, 1000 NG bump images, and 1000 impurity (IM) bumps. The IM bumps are always caused as the bumps contain impurities. Those bumps have already been checked by the LCD module factory. All these bump images are used to train the BP neural network, until the output of all networks meets the accuracy requirements. The steps to identify whether ACF bonding is acceptable on the bumps are as follows:

- Step 1: Get each bump region from the images of ACF bonding on the ITO glass substrate.
- Step 2: Inspect OK conductive microspheres, NG conductive microspheres, and the impurities on each bump with the data in Table 1.
- Step 3: Calculate the quantity of OK conductive microspheres (N_{OK}), the quantity of NG conductive microspheres (N_{NG}), the quantity of the impurities (N_{IW}), the effective contact area of OK conductive microspheres (S_{OK}), and the effective contact area

Table 1 The main components of the experimental device.

Component	Brand	Model	Property
DIC prism	Olympus, Japan	U-DICR	
Objective lens	Olympus, Japan	LMPLFLN10XBD	10×
Servo motor	Panasonic, Japan	MHMD022G1U	200 W
Servo driver	Panasonic, Japan	MADHT1507	
Illuminant	Cree, Durham	CLM1S-GKW	5W 450 to 455 nm
Computer	Advantech, China	ACP-4000MB/ASMB-784	700W/I7-4770S/8G/1T
Camera	Teledyne DALSA, Canada	ES-80-04k40-00-R	68 kHz COMS
Frame grabbers	Teledyne DALSA, Canada	OR-X4C0-XPFO0	



Fig. 7 Some of the inspection zone.

of NG conductive microspheres (S_{NG}) on each bump.

- Step 4: Inspect whether ACF bonding of each bump is acceptable using the BP neural network, which has already been trained with the samples checked by the LCD module factory.

Table 2 Image features of conductive microspheres under different conditions.

	OK	EP	IP	Impurities
CA	84	103	65	206
D_BDS	6	8	4	20
GV_BS	192	143	255	255
GV_DS	86	117	51	64

3 Experimental Results and Analysis

As shown in Fig. 7, the image is taken from LCD modules by the experimental device, which contains the main components as shown in Table 1. From Sec. 2, it is noted that there are differences in image features of conductive microspheres under different conditions, such as differences in the CA, the distance between the D_BDS, the gray value of the bright spots (GV_BS), and the gray value of the dark spots (GV_DS).

As shown in Table 2 and Fig. 8, it is noted that the results of the experiment conform to the theoretical analysis in Sec. 2. There are differences in image features of conductive microspheres under excessive pressure (EP), insufficient pressure (IP), and OK pressure conditions. From Fig. 8, we can see that there is bright and dark spot symmetry in the OK conductive microspheres area and the NG conductive microspheres area, but not in the impurities area. The impurities have the largest distance between the bright and dark

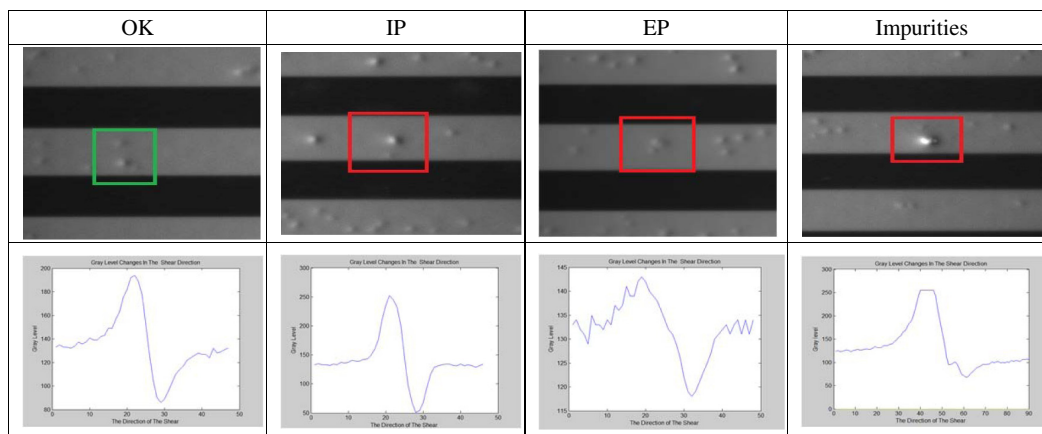


Fig. 8 Analysis of results.

Table 3 Relation of image features under different conditions.

	Relation
D_BDS	$DBDS_{EP} > DBDS_{OK} > DBDS_{IP}$
CA	$CA_{EP} > CA_{OK} > CA_{IP}$
GV_BS	$GVBS_{IP} > GVBS_{OK} > GVBS_{EP}$
GV_DS	$GVDS_{EP} > GVDS_{OK} > GVDS_{IP}$

Note: $DBDS_{EP}/CA_{EP}/GVBS_{EP}/GVDS_{EP}$ are $D_BDS/CA/GV_BS/GV_DS$ of conductive microspheres under EP, respectively. $DBDS_{IP}/CA_{IP}/GVBS_{IP}/GVDS_{IP}$ are $D_BDS/CA/GV_BS/GV_DS$ of conductive microspheres under IP, respectively.

spots, high GV_BS, a low GV_DS, and the largest area without a good symmetry of the bright and dark spot.

From Table 2 and Fig. 8, we can also obtain the relation of image features when conductive microspheres are under different conditions, as shown in Table 3.

We have tested 30,000 LCD module bumps, which are from LCD module factories. There are 2194 NG bumps, 27,783 OK bumps, and 23 IM bumps. The results show

that the system can inspect conductive microspheres and ACF bonding in the inspection zones in 0.8 s. The miss rate is lower than 0.1%, and the false rate is lower than 0.05%, as shown in Table 4 and Fig. 9.

4 Discussion and Conclusion

In this paper, an automated optical inspection (AOI) inspection method has been designed to inspect the result of ACF bonding on glass based on a DIC optical system and BP neural networks, which is reported for the first time. It can obtain conductive microsphere deformation information and gain the inspection parameters self-adaptively for different kinds of LCD modules. The theoretical analysis has proven that there will be differences in gray value and the distance between the bright spots and the dark spots in the DIC images if the microsphere deformation is different, and experiments have verified this observation.

Compared with the traditional methods used to inspect ACF bonding, the AOI processing method in this paper can inspect the deformation of trapped conductive microspheres by innovatively using quantitative DIC analysis. It outperforms traditional inspection. Simultaneously, it can quickly and self-adaptively obtain the parameters of the

Table 4 Test results.

		OK bump		NG bump		IM bump		Total
Standard result from the factory		27,783		2194		23		30,000
Test result	Right result	27,754	27,739	2223	2193	23	23	30,000
	False result	15		30		0		
Miss rate				0.05%				
False rate				0.1%				

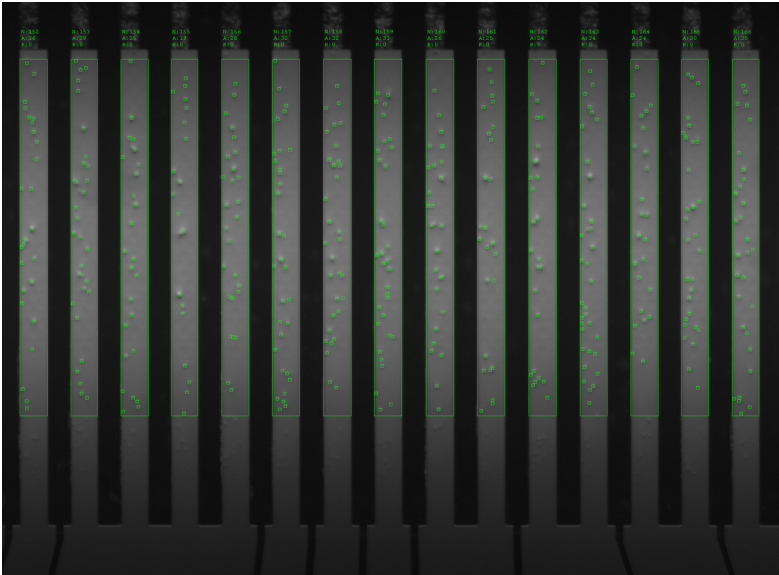


Fig. 9 A detecting result.

inspection system for different factory standards using the BP neural network. Future work includes researching how the shear amount of DIC prisms and the light source in the inspection system will affect the DIC imaging to improve the inspection performance.

Acknowledgments

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