Study on Chip Components Assembly Quality Fuzzy Fault Diagnosis System Based on Solder Joint Shape Theory

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Abstract: - The quality of surface mount technology (SMT) product solder joint was key factor for SMT products. In this paper, for chip components, a fuzzy fault diagnosis principle of SMT products was analyzed. And the total framework of fault diagnosis system was built based on solder joint shape theory. Geometrical shape parameters which reflected chip components solder joint quality were analyzed and determined. Through building the solder joint shape prediction model, finite element analysis of thermal stress and life prediction were done with chip components solder joint, and then reasonable solder joint shape was determined. Based on fuzzy theory, fuzzy fault diagnosis was accomplished and defects of solder joint were detected. Finally, a fuzzy fault diagnosis system of chip components was developed and a case was studied to testify its correctness.

Key-Words: - Chip components, Assembly quality, Solder joint shape, Fault diagnosis, Fuzzy technology

1 Introduction

As a new assembly technology, SMT has been widely used and well developed in the electronics field. It has the characteristic of high density, fine pitch, high precision and superior reliability. And the SMT has provided wide applications for the smaller, lighter and thinner electronic product and plays an important role in the present electronic product manufacturing. It is necessary to study the solder joint quality of SMT products because the solder joint quality directly affects the stability and life of electronic product and its whole quality. And the reliability of the solder joint quality is a key to the reliability of the SMT product.

There are many factors which affect the solder joint reliability, including the solder joint structure, the material CTE, and the fatigue creep capability of soldering material, the conditions of the heat/machine load for solder joint and so on[1][2]. Among these factors, the solder joint fault is the key to the reliability of the solder joint. And the solder joint faults include pseudo soldering, solder bridge, solder ball, tombstoning, collapse and so on.

Taking the chip components as the analyzing object, the fuzzy fault diagnosis technology of the assembly quality was proposed in this paper. The real 3D- shape of solder joint can be obtained by CCD (charge coupled device), and compared with the logical shape. Then chip components assembly solder joint faults can be real-time diagnosed accurately according to fuzzy rules and ratiocinations.

2 SMT Solder Joint Shape Theory

2.1 Solder joint shape

The SMT solder joint quality depends on many factors that include the solder joint 3D-shape, solder joint inner quality, matching between material and the mechanical performance of the soldering materials and so on. conclusions gained by researchers show that solder joint quality directly relates to the solder shape.The solder joint shape is the geometry dimension of melting solder material concreted on the joint between components pins and the plate of the PCB, and the shape between the metal surface contact angle and solder material round-angle, solder joint shape is the appearance shape that the solder has formed. Solder joint shape is directly relates to the dimension and shape of the soldering pins and plates, solder joint characteristics, soldering temperature and solder material quantity, and so on.

2.2 Solder joint shape theory

Theoretically, when the main factors which affect the solder joint 3D-shape are fixed and the only logical solder joint shape will be obtained. If one or more main factors have a permissible range, then the corresponding logical solder joint shape will have the permissible range. If some solder joint shape is out of the permissible range, then the corresponding solder joint quality is not acceptable, and there must be fault during the soldering. Through different solder joint shapes, the causes of the corresponding solder joint quality faults can be found out [3]. That is SMT solder joint shape theory meaning the relations between solder joint shape and its quality the solder joint faults.

2.3 Assembly quality control theory for SMT product

The SMT assembly quality control, with the basis for virtual evolving technology of SMT solder joint based on older shape theory, the analyzing method of the solder joint shape image treatment technology based on fuzzy theory, and the theory and method of image digital signal processing and fuzzy mathematical morphology, analyzes the solder joint image signal obtained by optical methods, then through comparing the real solder joint shape parameters with the logical solder joint shape parameters based on the virtual evolving technology of SMT solder joint and with the fuzzy diagnosis technology, we can check up the solder joint and its defects intelligently and low the rate of fault, then improve the solder joint assembly quality and its reliability, as shown in figure 1.

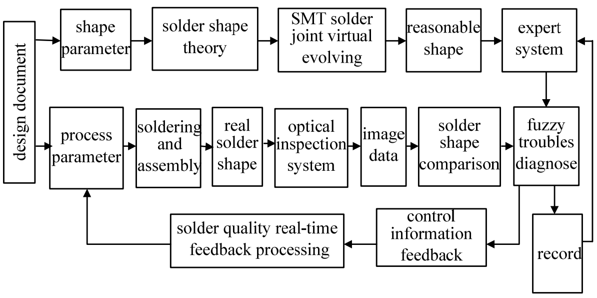

Fig.1. Theory of the SMT product quality control

3 Chip Components Assembly Quality Fuzzy Fault Diagnosis System

3.1 Framework

The chip component is one important type of SMT products. It has the characteristic of multi-fingers and fine space. Figure 2 illustrates the whole framework for chip components assembly quality fuzzy fault Diagnosis. The fuzzy input vector can be obtained by comparing the real solder joint geometric shape with the logical solder joint geometric shape. The fuzzy output vector is the possibility of the solder joint fault. Then the fuzzy solder joint quality fault Diagnosis result will be obtained by ratiocination with fuzzy rules and positive and negative fuzzy ratiocination [4].

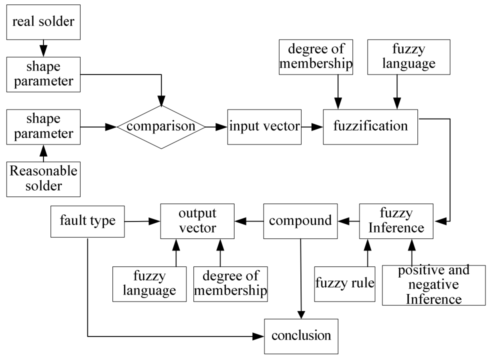

Fig.2. Framework of chip components assembly quality fuzzy fault diagnosis system

3.2 Chip components solder joint geometric shape parameter

The chip components solder joint geometric shape parameters directly relates to the components pins, the solder joint shape, the geometric dimensions and shape of the plate, i.e. meanwhile, the solder joint geometric shape parameters directly relates to solder joint quality. So we have to pay attention to the all-sided solder joint quality parameters and give attention to the main parameters.Figure 3 illustrates several parameters expressing the chip components solder joint shape[5]:

θ_1: Angle of contact which soldering material concreted between the soldering places.θ_2: Angle of contact which soldering material concreted between the pads.X_1, $Y1$: the warps at X axis and Y axis separately between the center of components pins and pad image.θ_3: the angle of the axis of component pin and pad pin. L, B, H: the length, width and high of the solder joint. W: the solder joint maximum right direction angle between the pad plane and pin.

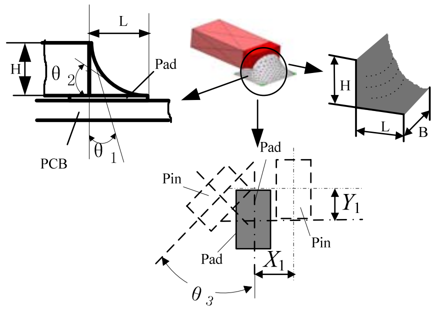

Fig.3. Chip components 3D geometrical shape

3.3 Reasonable solder joint shape of chip components based on solder shape theory

Reasonable solder joint shape is the basal condition for solder joint fault diagnosis. Based on building shape protection models of solder joints, reasonable shape of solder joints were determined through solder joint thermal stress and strain finite element analysis, as shown in Figure 4.

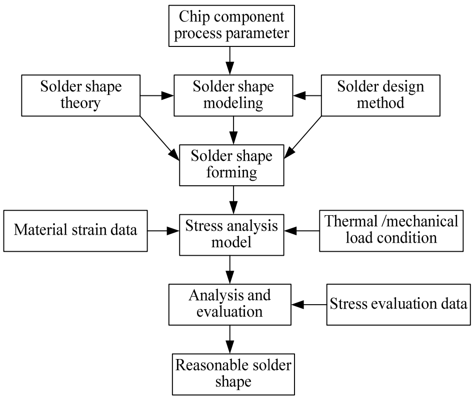

Fig.4. Design of reasonable solder joint shape of chip components

3.3.1 Solder joint shape prediction model of chip components

After definition of initial geometrical conditions, energy form and related constraint conditions of chip component, the shape prediction model is built. Solder joint shape parameters can be computed with Surface Evolver[6] operation when the system energy is minimal, such as coordinate of each solder joint on surface, etc. When melting solder joint material spreading on the metal surface, system energy E of solder joint is sum of surface potential energy E_S, gravitational potential energy E_G and potential energy induced by external force E_f, namely[7]

$$E = E_S + E_G + E_f \quad (1)$$

Related energy control equations are as follows.

Surface potential energy E_S:

The surface potential energy consists of potential energy of free surface and solid and liquid's surface. According to equations, equivalent interfacial tension is defined as:

T_z = -TENS×COS (Zangle×pi/180)

T_x = -TENS×COS (Xangle×pi/180)

In above equations:

TENS: surface potential energy of melting soldering material, here TENS=43000 erg/mm^2.

T_z: equivalent interfacial tensions between melting soldering material and terminal pad.

Zangle: Wetting angle of melting soldering material on the pad.

T_x: equivalent interfacial tensions between melting soldering material and mental surface.

Xangle: wetting angle of melting soldering material on metallic surface with lead wire.

The Surface potential energy between pad (Z=0) and cross-section of liquid soldering material can be described as:

$$Es = \iint T\_z(-\vec{k}) \cdot d\vec{A} = \oint \vec{w} \cdot d\vec{s} \quad (2)$$

$$\nabla \times \vec{w} = T\_z \cdot \vec{k}$$

∇ is Laplace operator. then

$$Es = \oint T\_z(-y)\vec{i} \cdot d\vec{s} \quad (3)$$

The Surface potential energy between the vertical plane(x=0) of soldering component and cross-section of liquid soldering material can be described as:

$$Es = \iint -T\_x(-\vec{i}) \cdot d\vec{A} = \oint \vec{w} \cdot d\vec{s} \quad (4)$$

then

$$Es = \oint T\_x(-y)\vec{j} \cdot d\vec{s} \quad (5)$$

The energy between metallic surface of component bottom (Z=s_h) and cross-section of liquid soldering material can be ignored.

Gravitational potential energy E_G:

The Gravitational potential energy can be inverted equivalent value of corresponding interface or line integral by vector integral.

$$Eg = \iiint_V \rho gz dV = \oint\!\!\oint_{\partial V} \vec{F} \cdot d\vec{A} \quad (6)$$

In the equation,

$$\nabla \cdot \vec{F} = \rho gz, \quad \vec{F} = \rho gzx\vec{i},$$

then

$$Eg = \oint\!\!\oint_{\partial V} pgzx\vec{i} \cdot d\vec{A} \quad (7)$$

Volume constraint:

The volume of soldering material is constant. Its vector form is defined as follows.

$$V = \iiint_V dV = \oint\!\!\oint_{\partial S} (x\vec{i} + y\vec{j} + z\vec{k}) \cdot d\vec{s} / 3 \quad (8)$$

The equivalent volume of PCB pad(z=0) and vertical plane of component(x=0) is zero. Equivalent volume of component metallic surface(Z=s_h) is represented as:

$$V = \iint z\vec{k} \cdot d\vec{A} / 3 = -z\oint y\vec{i} \cdot d\vec{s} / 3 \quad (9)$$

According to above energy control equations and considering geometrical constraint conditions, solder joint shape prediction model of chip components can be built. It is shown in figure 5.

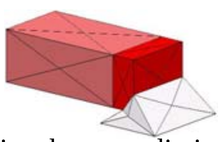

Fig.5. Solder joint shape prediction model

3.3.2 Finite element analysis (FEA) model of chip component solder joint

For solder joint of chip component under thermal cycle loading, its fatigue and failure are induced by mismatching of thermal expansion coefficient among ceramic carrier, solder joint and PCB. Thermal stress and strain of chip component is analyzed to determine range of plastic strain inside solder joint using finite element analysis method.

FEA model and **t**hermal cycle loading curve f chip component solder joint is shown in figure 6. The temperature range is 180℃ (-55℃~+125℃), temperature rise and drop rate is 36℃/min. High and low temperature holds on 10 minutes. Performance parameters of material adopted in finite element analysis are shown in table 1.

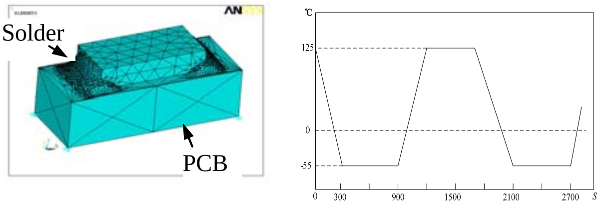

Fig.6. FEA model and **t**hermal cycle loading curve of chip component solder joint

Material name	Flexibility modulus(Mpa)	Poisson's ration	Thermal expansion coefficient (10^{-6}/℃)
Ceramic carrier	3.79×10^5	0.21	6.7
FR4	1.1×10	0.28	15
63Sn/37Pb	1.0×10^4	0.4	21

Table 1. Chip component material parameter

3.3.3 Thermal fatigue life of chip component solder joints

Mansan-coffin revise experience equation given by Engelmaier is adopted to calculate thermal fatigue life of solder joint [8][9].

$$N_f = \frac{1}{2}\left(\frac{\Delta\gamma}{2\varepsilon_f}\right)^{(1/C)} \qquad (10)$$

In the equation, N_f is average life of thermal fatigue and failure,$\Delta\Upsilon$ is shear strain range, $\Delta\Upsilon=\sqrt{3}\Delta\varepsilon$, $\Delta\varepsilon$ is equivalent plastic strain range.

3.4 Input/Output variable of fuzzy diagnosis

3.4.1 Choosing the input vector

The input vector is the corresponding geometric shape parameters that expresses solder joint faults. The fault Diagnosis precision of solder joint joints directly relates to the choice vector. The more parameters expressing the solder joint, precision of fault diagnosis can be higher.

But at the same time the computation is more complicated.

The input vectors for fuzzy diagnosis are the values of comparing the real solder joint geometric shape and logical solder joint geometric shape.

If:

$A=\{x_1,x_2,\ldots\ldots x_n\}$

A: the geometric parameters of the logical solder joint.

x_n: the No. n geometric parameter of the logical solder joint.

$B=\{x'_1,x'_2,\ldots\ldots x'_n\}$

B: the geometric parameters of the real solder joint.

x'_n: the No. n geometric parameter of the real solder joint.

$\Delta x_i=|x_i-x'_i|$, $i=1\ldots\ldots n$

Then,

$I=\{\Delta x_1, \Delta x_2\ldots\ldots\Delta x_n\}$

I: the warp of solder joint geometric shape, i.e. the input vector of fuzzy controller.

Δx_n: the No. n geometric parameter variable, the No. n input variable.

For chip components solder joint, set:

$A=\{\theta_1,\theta_2,\theta_3,X_1,Y_1,L,B,H,W\}$

A: the geometric shape parameter of the logical solder joint.

$B=\{\theta_1',\theta_2',\theta_3',X_1',Y_1',L',B',H',W'\}$

B: the geometric shape parameter of the real solder joint.

Comparing the geometric shape of the real and logical solder joint, we have:

$C=\{\Delta\theta_1,\Delta\theta_2,\Delta\theta_3,\Delta X_1,\Delta Y_1,\Delta L,\Delta B,\Delta H,\Delta W\}$

C: the warp of solder joint geometric shape, i.e. the input vector of fuzzy controller.

3.4.2 Input vector fuzzy process

To process fuzzy consequence, we have to fuzzificate the input and output vectors [10][11].Based on the value domain of the input variable, we take the absolute value of the residual value limit value as the variable range, and set the variable range at $[c, d]$.Mamdani method was used to fuzzificate the variables and its range of the domain is [-6,6].Regarding each input variable has the individual characteristic, this paper use many kind of domains. Set the domain at $[a,b]$, the mapping relation is as follows:

$$k_n=\Delta x_n\times(a-b)/(c-d) \qquad (11)$$

k_n: the domain mapping relation value of the No. n variable.

For chip components, take three kinds of domains: [0,12], [-6,+6], [-12, 0].

The membership function changes the input variables into fuzzy sets, and defines the input variables as disperse multilevel. Then the number of level will determine the determine resolution of the fuzzification. We use the triangle membership curve and seven linguist values (*NL,NM,NS,O,PS,PM,PL*) in turn to express the domain. Figure 7 illustrates triangle membership functions of three kinds of domains.

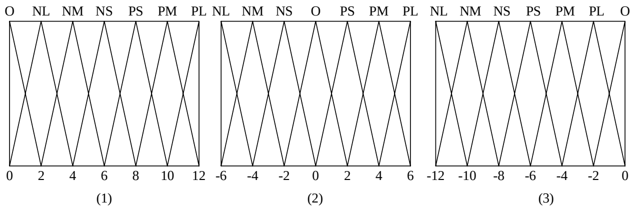

Fig. 7. Membership function for input variable

Table 2 expresses the fuzzification rules of chip components input variable, and *N* represents the residual value of real value and logical value.

Variable	Change Range	Fuzzification Formula	Range After Conversion
$\Delta\theta_1$	(0º,180º)	*N*/15	(0,12)
$\Delta\theta_2$	(0º,180º)	*N*/15	(0,12)
$\Delta\theta_3$	(0º,90º)	2**N*/15	(0,12)
ΔX	(0*mm*,0.3*mm*)	40* *N*	(0,12)
ΔY	(0*mm*,0.5 *m*)	24* *N*	(0,12)
ΔL	(-0.5*mm*,0 *m*)	24* *N*	(-12,0)
ΔB	(-0.3*mm*,0.15*mm*)	26.7* *N* +2	(-6,6)
ΔH	(-0.18*mm*,0.05)	52.2* *N* +3.4	(-6,6)
W	(-0.3*mm*,0.15 *mm*)	26.7* *N* +2	(-6,6)

Table 2. Fuzzification rules of input variable

3.4.3 Choice and design of the output vector

The output vector can value the chip components assembly quality. Set:

$O=\{o_1,o_2,o_3,o_4,o_5,o_6\}$

O: The real solder joint defects possibility degree, i.e. output vector. Where:

o_1: the possibility degree of bridge.

o_2: the possibility degree of pseudo soldering.

o_3: the possibility degree of tomb stoning.

o_4: the possibility degree of excursion.

o_5: the possibility degree of excess solder.

o_6: the possibility degree of solder balls.

domains: {0, 2, 4, 6, 8}

Five fuzzy semantics (*Largest*, *Large*, *Middle*, *Little*, *Littlest*) represent(*maximum*, *big*, *medium*, *small*, *minimum*)separately.

3.4.4 Fuzzy rules

The chip components assembly quality Diagnosis is a multi input/output matching and reasoning process. The following rules are used to express the diagnosis process.

<rule-number > IF <the first precondition> and < the second precondition > and … and < the No. n precondition > THEN <the first rule conclusion> and < the second rule conclusion >and…and < the No. m rule conclusion >, (the degree of rule trust),

where:

< rule-number>= integer

<the first precondition >=< expression >

< rule conclusion >=< expression >

(the degree of rule trust)=real∈[0, 1]

If the precondition of rule is matched, the rule is activated. At the same time, the rule conclusion is processed by the rule trust degree, and trust degree of the rule is brought forward by the expert.

3.4.5 Fuzzy reasoning strategy

Figure 8 is the fuzzy reasoning logical graph. The fuzzy reasoning is the process combined the forward and backward chaining. By the synthesizing chaining rule, the exact chaining conclusions are obtained [12].By traverse matching arithmetic, carrying out the matching analysis of each rule among the rule database from the precondition to the conclusion.After the backward chaining, by the Diagnosis accuracy valueλ, determining the fact from the conclusion to the precondition. The fuzzy output is obtained by Mamdani method combining ratiocination rules.Setting λ as the domain value, then the output variable that is less than the domain valueλ is the solder joint defect.

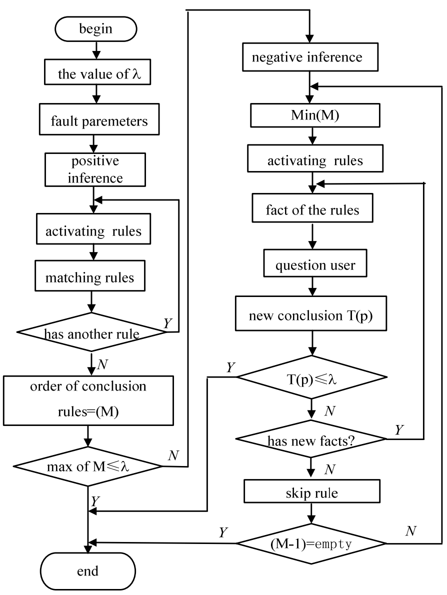

Fig. 8. Principle of fuzzy ratiocination

4 System Implement

According to above Theory, assembly quality fuzzy fault diagnosis system is built based on windows platform. The system can be used in ball grid array (BGA) solder joint, plastic quad flat package (PQFP) solder and so on. Partial interface of system is shown in figure 9.

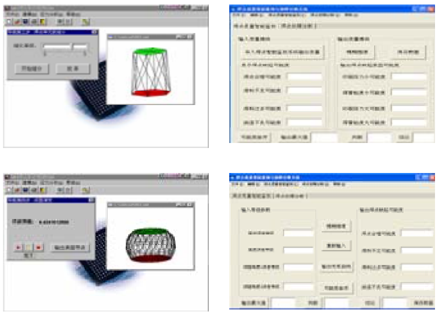

Fig.9. Interface of fuzzy fault diagnosis system

5 Example

Table 3 is the 3D geometric parameters of some real solder joint. Then comparing the real solder joint parameters with the reasonable solder joint parameters, the possibility degree of real solder joint defects (*di*) is obtained. And the range of *di* is [0, 1]. Table 4 is fault possibility degree.

θ_1(°)	θ_2(°)	θ_3(°)	X_1(mm)	Y_1 (mm)
0	0	0	0	0
H(*mm*)	*L*(*mm*)	*B*(*mm*)	*W*(*mm*)	
0.2	0.4	0.4	0.4	

Table 3. Real solder joint geometric parameters

	Bridge	Solder skips	Tombstoning	Excursion	Overmuch
di	0.4124	0.5207	0.9161	0.9200	0.6994

Table 4. Fault possibility degree of real solder joint

Set the value λ=0.45. If $di<\lambda$, the possibility degree of real solder joint defects .The defects of the real solder joint are bridge. The conclusion accords with the fact.

6 Conclusion

SMT solder shape theory based on the characteristic of SMT solder joint quality relating to its 3D geometrical configuration was advanced in the paper. With the solder joint shape theory, the solder shape prediction model is built, and then finite element analysis of thermal stress and life prediction were done with chip components solder. Based on the fuzzy fault diagnosis technology, comparison the actual solder joint shape with logical solder joint shape of chip components was done and it was taken as input vector, simultaneously the possibility degree of solder joint faults were taken as fuzzy output vectors, the possibility degree of solder joint fault is obtained. From the example as above, it proves that the method studied in paper has practical engineering value.

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