Technique for Efficiently Selecting Metal Film with Strong Adhesion to Resin with the Combination of Orthogonal Array and Response-Surface Method

by

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A technique for efficiently selecting a metal film with strong adhesion to a resin with the combination of an orthogonal array and a response-surface method was developed to select appropriate materials for electronics devices. In this technique, at the first step, important factors that significantly influence the adhesion strength were selected from various factors that characterize metal films by use of an orthogonal array with molecular simulations. As a result, the short-side and long-side lattice constants \( a \) and \( b \) were selected from four metal-film factors \( (a, b, \text{the electronegativity}, E, \text{and the surface energy density}, S) \). At the second step, the adhesion strength was described as a function of the selected important factors by using a response-surface method. From this function, the most appropriate values for \( a \) and \( b \) that made the adhesion strength maximum were obtained. The values for \( a \) and \( b \) were obtained as 0.244 nm and 0.423 nm, respectively. At the third step, the most appropriate metal film whose lattice constants were close to \( a=0.244 \) nm and \( b=0.423 \) nm was selected by use of the data base of lattice constants. As a result, a copper/manganese/nickel-laminated film whose lattice constants were \( a=0.242 \) nm and \( b=0.419 \) nm was selected as the most appropriate metal film with the strongest adhesion to a resin.

Key words: Adhesion strength, Metal film, Resin, Response-surface method, Molecular simulation, Orthogonal array

1 Introduction

Following the trend toward increased integration density in multifunctional electronics devices such as biomechanics devices, semiconductor packages, magnetic recording media, and optical disks, nano-scale thin films made up of various functional materials are used in the devices. Because the devices are expected to be used at places of high temperatures and high humidity in the upcoming IoT (Internet of Things) era, the interface adhesion between different materials needs to be strong to realize the efficient device reliability. When the interface between the different materials is not stable, adhesive fractures occur at the interface at high temperatures or in high humidity. Selecting appropriate materials is one of the keys to preventing these adhesive fractures. In semiconductor packages, for example, it is well known that the adhesion of electro-plated nickel-interconnection films to chromium underlayers is very strong. Generally speaking, however, it is difficult to select an appropriate material that has strong adhesion to another material by using a conventional trial-and-error approach. So, recently many researchers have paid attention to materials-informatics\(^ {1)}\) techniques, which can select an appropriate material by using information science with computer simulation and experimental data. However, they sometimes need a long time to obtain results because they usually use a lot of data.

So, the author has developed a technology for efficiently selecting a metal film with strong adhesion to a resin by combining an orthogonal array\(^ {2)}\) with a response-surface method\(^ {3)}\) and by using molecular simulations\(^ {6)}\).

In this technology, at the first step, the important factors that significantly influence the adhesion strength are selected from metal-film factors such as lattice constants and surface energy density that characterize metal films by using an orthogonal array\(^ {2)}\) and molecular simulations\(^ {6)}\). At the second step, by using a response-surface method\(^ {3)}\), the adhesion strength is described as a function of the selected important factors, and the most appropriate values of the factors that make the adhesion strength maximum are obtained. At the third (final) step, appropriate metal films whose factors are close to the most appropriate values are selected.

In this study, the author used a naphthalene-ring-based resin as an example resin because the resin is often used in electronics devices for the reason that it has the strong mechanical strength and the heat resistance. Then, the best metal film with strong adhesion to this resin was selected.

2 Material-Selection Technique

2.1 Material-Selection Technique Made of Three Steps

The basic idea of material selection in this technique is to select a material whose factors \( A, B, C, \cdots \) are close to the most appropriate values \( A_0, B_0, C_0, \cdots \) that optimize an objective material property, \( F \) by describing the property as a function of material factors, that is, \( F(A, B, C, \cdots) \). In this study, the objective material property, \( F \) that the author wants to optimize is the adhesion to a resin, and the factors \( A, B, C, \cdots \) that the author focuses on are the lattice constants, the electronegativity, and the surface energy density of a metal film. To describe the material property \( F \) as a function of material factors \( A, B, C, \cdots \), a number of data of experiments or simulations to interpolate are needed. If the number of factors are too large, many data are needed for interpolation and it takes too much time to obtain the function...
appropriate values are selected. The overview of the material-selection technique is shown in Fig. 1. This figure shows that the method consists of three steps. At the first step, by using the orthogonal-array sensitivity analysis\(^2\) with molecular simulations\(^4\)-\(^9\), the important material factors that significantly influence an objective material property are selected from material factors (the lattice constants, the electronegativity, and the surface energy density) that characterize metal films. In the sensitivity analysis, the results of molecular simulations of the objective material property that is paid attention to are used as input data. At the second step, the objective material property, which is the adhesion in this paper, is described as a function of the selected important factors by using a response-surface method\(^1\) with the molecular-simulation results that are also used at the second step. By using this function, the most appropriate values of the factors that optimize the objective material property, which is adhesion strength in this paper, are determined. At the third (final) step, the materials (metal films) whose factors are close to the most appropriate values are selected.

![Diagram of material-selection technique](image)

**Fig. 1** Overview of material-selection technique.

![Schematic structure of a naphthalene-based resin](image)

**Fig. 2** Schematic structure of a naphthalene-based resin.

### 2.2 Simulations Used at the First and the Second Steps

As shown in Fig. 1, molecular simulations are used in the first and second steps. So the method of the simulations is explained in this section. In this paper, an example resin that contains naphthalene rings is used because this resin is often used in electronics devices for the reason that this has strong mechanical strength and heat resistance. The simulation model of this example resin is shown in Figs. 2 and 3. Figure 2 shows a two-dimensional schematic structure of the resin, which is not a stabilized structure. Figure 3 shows the stabilized structure of the resin, in which two benzene rings are in the direction vertical to two naphthalene rings. The simulation model that author used in this study is an interface between the resin (Fig. 3) and a metal film, as shown in Fig. 4. This simulation model was made by using “Materials Studio®” software from Dassault Systemes BIOVIA. Sixteen resin molecules (four layers of four molecules), one of which is shown in Fig 3, were used as the resin film model. There are 2,272 atoms in the resin molecules.

Next, the size of the metal-film model shown in Fig. 4 is explained in this paragraph. Because the past molecular-dynamics simulations\(^4\)-\(^9\) have found that the adhesion strength between the resin and the metal film was almost independent of the total number of metal layers when that number was more than seven, the number was set at eight in the z direction. The sizes of the metals in the x and y directions are set at 15a and 15b, where the short-side lattice constant, a, and the long-side lattice constant, b, are shown in Fig. 5. So, the number of atoms in the metal film is 3,600. In this study, the atoms were kept free to move.

In this study, the adhesion strength was evaluated by calculating the adhesive fracture energy\(^4\)-\(^9\) which was defined as the difference between the area density of potential energy of the resin/metal-attached state (Fig. 4) and that of
the resin/metal detached state (Fig. 6). This fracture energy was calculated by using molecular-dynamics simulations with the universal force field\(^\text{10,11}\). In the simulations, the temperature was kept at 20°C by using the velocity-scaling method\(^\text{12}\). As described in Refs. 10 and 11, this force field is determined based on the element, its hybridization, and its connectivity.

### 2.3 Material Factors Used at the First Step

In this section, the material factors of the metal film are explained. The author focused on four factors (the short-side and long-side lattice constants, \(a\) and \(b\), the electronegativity, \(E\), and the surface energy density, \(S\)) of the metal film, and then investigated which factors significantly influence the adhesion strength. The lattice constants, \(a\) and \(b\) are defined at the surface of the metal film, as shown in Fig. 5. In this study, the \(xy\)-plane in Figs. 4 and 5 is set parallel to the crystal planes of the highest atomic density, which are the (111), (0001), and (110) planes for the face-centered-cubic (fcc), hexagonal-close-packed (hcp), and body-centered-cubic (bcc) structure metals, respectively. These crystal planes are energetically stable and are experimentally found to be most likely to appear at the surfaces when metal films are deposited by using physical vapor deposition (PVD). So, the short-side and long-side lattice constants \(a\) and \(b\) are defined at the crystal planes of the highest atomic density of the metal film.

The electronegativity, \(E\), that describes the tendency of an atom to attract electrons, is defined in Ref. 13.

The surface energy density of the metal film, \(S\), which is the energy density required to create a surface from bulk, was defined as half of the difference between the area density of potential energy of the surface-connected state (Fig. 7) and that of the surface-separated state (Fig. 8). The surface energy density, \(S\) was calculated by using molecular-dynamics simulations with a universal force field\(^\text{10,11}\). As explained in Refs. 10 and 11), the potential energy of this force field is expressed as a sum of valence or bonded interactions and nonbonded interactions in the following equation.

\[
P = P_b + P_a + P_d + P_{vdw} + P_{el}
\]

Here, bond stretching \((P_b)\), bond angle bending \((P_a)\), dihedral angle torsion \((P_d)\), and inversion terms \((P_{vdw})\) are valence interactions. On the other hand, van der Waals \((P_{vdw})\) terms and electrostatic \((P_{el})\) terms are nonbonded interactions.
2.4 Orthogonal Array Used at the First Step

At the first step of the material-selection technique (Fig. 1), the important material factors (metal-film factors) that significantly influence the objective material property (adhesion strength) are selected by clarifying the dependence of the adhesion strength on the four metal-film factors. When we investigate the dependence, we usually change the value of one factor with the other three factors fixed. However, it is time-consuming to clarify the dependence by using this method. Consequently, the author used the orthogonal-array design methodology\(^1\), which is known to be effective for efficiently designing macro-scale structures such as propeller fans and diaphragms. In this methodology, when there are four material factors, only nine simulations or experiments shown in an L9 orthogonal array (see Table 1) are needed to clarify the important factors on which the adhesion strength strongly depends\(^2\). Here the author set Level 1 (small values), Level 2 (middle values), and Level 3 (large values) of the four factors at the regions shown in Table 1. By looking into the data of the four factors corresponding to 31 metals, the author was able to find nine metals that correspond to the nine sets of factors shown in Table 1. These nine metals are shown in Table 3. When it is impossible to set three levels for each factor, the orthogonal array cannot be used. In such case, the first stage in Fig. 1 has to be skipped, and all the factors have to be dealt with at the second stage, where more data than those of orthogonal array are needed for interpolation\(^4\).

By using the nine metals shown in Table 1, the sensitivity\(^3\) for the adhesive fracture energy\(^5\) between the metal film and the resin was calculated. By applying sensitivity-analysis\(^6\) based on orthogonal arrays to the fracture-energy data calculated for the nine metals, the sensitivity of Level \(j\) of the \(i\)-th factor, \(W_j\) is given by

\[
W_j = 10 \log ([P_{ij} - Q_{ij}] / n),
\]

(2)

where

\[
P_{ij} = (D_{ij} + D_{ij}^2 + \cdots + D_{ij}^7) / n
\]

(3)

and

\[
Q_{ij} = (D_{ij}^2 + D_{ij}^3 + \cdots + D_{ij}^8 - P_{ij}) / (n - 1).
\]

(4)

Here, \(D_{ij}\) is the \(k\)-th fracture-energy datum that belongs to Level \(j\) of the \(i\)-th factor, and \(n\) is the number of the data that belongs to Level \(j\) of the \(i\)-th factor.

According to the sensitivity-analysis method\(^3\) based on orthogonal arrays, the factors whose increase from Level 1 to Level 3 significantly influences the sensitivity \(W_j\) are important in optimizing the adhesion strength, and they are selected as important factors at the first step of the material-selection technique (Fig. 1). At the second step in Fig. 1, the adhesion strength is described as a function of the selected factors by interpolating the nine fracture-energy data corresponding to the L9 orthogonal array in Tables 1 and 3 by use of a response-surface method.

### 2.5 Response-Surface Method

At the second step of the material-selection technique (Fig. 1), a response-surface method is used to describe the objective material property (adhesion strength) as a function of the important factors selected by use of the orthogonal-array analysis explained in Section 2.4. In this study, the author employed a response-surface method, so called Kriging method\(^7\), which is often used in geostatistics and mechanical structure design. The schematic view of one-dimensional data interpolation by use of the Kriging method is shown in Fig. 9. In this method, the function curve is made so that all the data points used for interpolation are

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**Table 1** L9 orthogonal array corresponding to four factors.

| Condition | 1st factor: Short-side lattice constant \(a\) | 2nd factor: Long-side lattice constant \(b\) | 3rd factor: Electro-negativity \(E\) | 4th factor: Surface energy density \(S\) |
|-----------|--------------------------------|-----------------|-----------------|-----------------|
| 1 Level 1 | Level 1 | Level 1 | Level 1 | Level 1 |
| 2 Level 1 | Level 2 | Level 2 | Level 2 | Level 2 |
| 3 Level 1 | Level 3 | Level 3 | Level 3 | Level 3 |
| 4 Level 2 | Level 1 | Level 2 | Level 2 | Level 3 |
| 5 Level 2 | Level 2 | Level 2 | Level 3 | Level 1 |
| 6 Level 2 | Level 3 | Level 1 | Level 2 | Level 2 |
| 7 Level 3 | Level 1 | Level 3 | Level 3 | Level 2 |
| 8 Level 3 | Level 2 | Level 1 | Level 3 | Level 2 |
| 9 Level 3 | Level 3 | Level 2 | Level 1 | Level 2 |

**Table 2** Factors and levels for metal films.

| Metal | 1st factor: Short-side lattice constant \(a\) (nm) | 2nd factor: Long-side lattice constant \(b\) (nm) | 3rd factor: Electro-negativity \(E\) | 4th factor: Surface energy density \(S\) (J/m\(^2\)) |
|-------|---------------------------------|-----------------|-----------------|-----------------|
| Mn    | Level 1 (0.224) | Level 1 (0.388) | Level 1 (1.55) | Level 1 (0.459) |
| Zn    | Level 1 (0.266) | Level 2 (0.461) | Level 2 (1.65) | Level 2 (0.508) |
| Pt    | Level 1 (0.277) | Level 3 (0.480) | Level 3 (2.28) | Level 3 (2.47) |
| V     | Level 2 (0.281) | Level 2 (0.459) | Level 3 (1.96) | Level 3 (2.57) |
| Sn    | Level 2 (0.295) | Level 2 (0.511) | Level 3 (1.54) | Level 2 (1.89) |
| Ti    | Level 3 (0.315) | Level 3 (0.445) | Level 3 (2.16) | Level 2 (1.99) |
| Mo    | Level 3 (0.335) | Level 2 (0.467) | Level 2 (1.50) | Level 1 (3.06) |
| Nb    | Level 3 (0.330) | Level 2 (0.467) | Level 1 (1.78) | Level 2 (0.442) |
| In    | Level 3 (0.325) | Level 3 (0.563) | Level 2 (1.78) | Level 1 (0.442) |
significantly influence the objective material property time-consuming to clarify the dependence by using this of one factor with the other three factors fixed. However, it is of the adhesion strength on the four metal-film factors. When Levels 1, 2, and 3 are shown in Table 2.

Table 3 Nine metal films corresponding to Table 1 (L9), 1), the important material factors (metal-film factors) that design methodology 2), which is known to be effective for Table 2 Factors and levels for metal films.

At the first step of the material-selection technique (Fig. 1). At the second step in shown in an L9 orthogonal array (see Table 1) are needed to by interpolating the data of the four factors corresponding to 31 metals, the

Table 4 Calculated adhesive fracture energy data corresponding to Table 1 (L9).

| Metal | 1st factor: | 2nd factor: | 3rd factor: | 4th factor: | Adhesive fracture energy D (J/m²) |
|-------|-------------|-------------|-------------|-------------|----------------------------------|
| Mn    | Level 1     | Level 1     | Level 1     | Level 1     | 0.209                            |
| Zn    | Level 1     | Level 2     | Level 2     | Level 2     | 0.223                            |
| Pt    | Level 1     | Level 3     | Level 3     | Level 3     | 0.174                            |
| V     | Level 2     | Level 1     | Level 2     | Level 3     | 0.185                            |
| Sn    | Level 2     | Level 2     | Level 1     | Level 1     | 0.186                            |
| Ti    | Level 2     | Level 3     | Level 1     | Level 2     | 0.127                            |
| Mo    | Level 3     | Level 1     | Level 3     | Level 2     | 0.148                            |
| Nb    | Level 3     | Level 2     | Level 1     | Level 3     | 0.112                            |
| In    | Level 3     | Level 3     | Level 2     | Level 1     | 0.0821                           |

Fig. 9 Schematic view of interpolation with Kriging method and comparison with liner- and quadratic-function approximations.

on the curve. The basic idea of the Kriging method is to predict the value of a function at a given point by computing a weighted average of the known values of the function in the neighborhood of the point. The theory derives a best linear unbiased estimator, based on assumptions on covariances, and is mathematically related to regression analysis. By using the Kriging method, the adhesion strength is described as a function of the important material factors (metal-film factors). By using this function, the most appropriate values of material factors that maximize the adhesion strength can be determined. At the third (final) step, appropriate materials

3 Material-Selection Results and Discussions

The calculated adhesive fracture energy data corresponding to the L9 orthogonal array (Table 3) are shown in Table 4. Figure 10 shows the sensitivity, \( W_{ij} \), calculated by using the fracture energy data (Table 4) and Eqs. (2), (3), and (4). From Fig. 10 it is found that the adhesive fracture energy (adhesion strength) strongly depends on the 1st and 2nd factors (the short-side and long-side lattice constants), while the fracture energy does not strongly depend on the 3rd and 4th factors (the electronegativity and the surface energy density). Thus, the short-side and long-side lattice constants, \( a \) and \( b \), were selected as important factors at the first step of the material-selection technique shown in Fig. 1.

At the second step of Fig. 1, the author described the adhesive fracture energy as a function by interpolating the nine data in Table 4 with the Kriging method. The obtained function is shown in Fig. 11. The most appropriate values of the important factors (the short-side and long-side lattice constants, \( a \) and \( b \)) are obtained as \( a = 0.244 \text{ nm} \) and \( b = 0.423 \text{ nm} \) by using the gradient of the obtained function. Because these values are the same values of resin’s lattice constants shown in Fig. 3, it is found that the lattice matching between the metal film and the resin is the most important in increasing the adhesion strength between them.

At the third (final) stage of Fig. 1, the appropriate materials (metal films) whose factors are close to the most appropriate values are selected.

4 Conclusion

The adhesion strength and its factors of nine metal films that are used for the fabrication of fans and diaphragms are calculated by using the response-surface method. At the second step of the material-selection technique (Fig. 1), the sensitivity of Level 1 (small values), Level 2 (middle values), and Level 3 (large values) of the four material factors, on ly nine simulations or experiments are needed for interpolation. In this methodology, when there are nine sets of factors shown in Table 1. These nine metals are selected as important factors at the first step of the material-selection technique shown in Fig. 1.

The calculated adhesive fracture energy data corresponding to the L9 orthogonal array in Tables 1 and 3 by use of a response-surface method is made so that all the data points used for interpolation are unbiased estimator, based on assumptions on covariances, and are calculated by calculating the adhesive fracture energy defined in Section 2.2, the values for nickel (Ni) and cobalt (Co) are obtained as 0.235 J/m² and 0.232 J/m², both of which are larger than any...
The obtained function (Fig. 11) has some prediction errors because it is obtained from only nine data and because 3rd and 4th factors ($E$ and $S$) are neglected. The author will report in the next paper, which focuses on the methodology and accuracy rather than materials-selection application. To clarify the reason that nickel has strong adhesion to the resin, the author visualized the atomic configuration of the interface between the resin and the nickel film, as shown in Fig. 12. Because Fig. 12 shows that nickel atoms can be seen through near the centers of the naphthalene rings and that the configuration of the nickel atoms are in harmony with naphthalene rings, the integration of atomic interactions caused by this harmony is considered to lead to the strong adhesion. Although the figures are not shown in this paper, the atomic configurations of the interface between the resin and cobalt (Co), copper (Cu), and zinc (Zn) are similar to those of the resin/nickel interface shown in Fig. 12.

The atomic configurations of the resin/vanadium interface whose adhesive fracture energy (0.185 J/m²) is smaller than that of the resin/zinc interface are shown in Fig. 13. This figure shows that vanadium atoms can be seen through at the edge of the naphthalene rings (not at the center of the rings). So the integration of atomic interaction at the resin/vanadium interface is smaller than that at the resin/nickel interface shown in Fig. 12.

The atomic configurations of the resin/platinum interface whose adhesive fracture energy (0.174 J/m²) is smaller than that of the resin/vanadium interface are shown in Fig. 14. This figure shows that platinum atoms can not be seen through the naphthalene rings. So the integration of atomic interaction at the resin/platinum interface is smaller than that at the resin/vanadium interface shown in Fig. 13. Thus, the integration of atomic interactions caused by the lattice matching is confirmed to lead to the strong adhesion.

4 Further Improvement by Use of Atomic Multilayer

To further improve the adhesion strength, the author tried to control the lattice constants by using multilayer metal films made up of atomic-scale thin films shown in Fig. 15, instead of using a single metal. Because the thicknesses of Metals 1, 2 and 3 in Fig. 15 are only two, three, and three atomic layers, respectively, misfit dislocations are not formed in the metal films. As a result, by using a copper/manganese/nickel-laminated multilayer film, the higher adhesive fracture energy (0.243 J/m²) was realized.
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5 Comparison between Simulations and Experiments

To confirm the effectiveness of the molecular-dynamics simulation technique described in Chapters 2 and 3, the author conducted a scratch test on the film-laminated structure (scratch tester: CSR-02 made by Rhesca Co., Ltd.) and compared the test results with the simulation results. Recently, more advanced methods for measuring adhesion strength have been proposed in a number of research papers (15–17). However, these advanced methods were very difficult to apply to fairly strong interfaces such as the naphthalene-based-resin/nickel interface. Accordingly, a simple scratch-testing method that was applicable to the naphthalene-based-resin/nickel interface was employed. A schematic view of the scratch testing apparatus is shown in Fig. 17. A diamond indenter with a tip radius of 5 µm makes the dynamic indentations. During the measurement, load is gradually increased and when it reaches a critical load, adhesive fracture occurs at the interface. The adhesion strength is determined by measuring the critical load, \( L \), at which the adhesive fracture occurs.

The author used 0.01-mm-thick naphthalene-based resin films deposited on the metal films for the scratch test. The molecular structure of the resin films is the same as that in Fig 3. For the metal films, the author used the six metal films (Ni, V, Pt, Mo, Nb, and Cu/Mn/Ni), five of which are listed in Table 4. These films were deposited on silicon substrates by using physical vapor deposition (PVD), and the thickness of each film was set at the same as that used in the simulations by controlling the deposition time so that misfit dislocations were not formed. By using the 0-20 scheme of the X-ray diffraction (XRD) analysis, the author selected the specimens that have significant diffraction peaks corresponding only to the planes of the highest atomic density.

The adhesive fracture energy, \( D \), obtained from molecular simulations and the critical load, \( L \), obtained from the scratch test of the interfaces between resin films and metal films are compared in Fig. 18. The ordered molecular orientation of the resin caused by naphthalene and benzene rings is considered to be one of the reasons for the small deviation and the good agreement between the simulations and experiments. Because the linear relationship can be seen between simulations and experiments, the adhesion-calculation method is found to be effective for determining the adhesion strength. Furthermore, from the results shown in Fig. 18, it is experimentally confirmed that the copper/manganese/nickel-laminated film and the nickel film, which were selected by using our material-selection technique (Fig. 1), have strong adhesion to the resin. Thus, our technique for selecting appropriate materials with the combination of an orthogonal array and a response-surface method is considered to be effective for selecting a metal film that has strong adhesion to the resin.
6 Summary

A technology for efficiently selecting a metal film with strong adhesion to a resin with the combination of an orthogonal array with a response-surface method was developed to select appropriate materials for electronics devices. In this technique, at the first step, important factors that significantly influence the adhesion strength to the resin were selected from various factors that characterize metal films by use of an orthogonal array with molecular simulations. At the second step, the adhesion strength was described as a function of the selected important factors by using a response-surface method (Kriging method). From this function, the most appropriate values of the important factors that made the adhesion strength maximum were obtained. At the third step, the most appropriate metal film whose important factors were close to the most appropriate values was selected. By carrying out these procedures, the following results were obtained.

(1) By using the sensitivity analysis based on an orthogonal array, the short-side and long-side lattice constants, and electronegativity values, the most appropriate factors from four metal-film factors (the lattice constants, electronegativity, and the surface energy density) were selected.

(2) By describing the adhesive fracture energy as a function of the important factors (the short-side and long-side lattice constants and electronegativity), the most appropriate values for a and b that made the adhesion strength maximum were obtained as 0.244 nm and 0.423 nm, respectively.

(3) The most appropriate metal film whose lattice constants were close to a =0.244 nm and b=0.423 nm was selected. As a result, a copper/manganese/nickel-laminated film whose lattice constants were a =0.242 nm and b=0.419 nm was selected as the most appropriate metal film with the strongest adhesion to an example resin (naphthalene-based resin).

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