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Unipolar and bipolar pulsed current electrodeposition for PCB production

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This paper is concerned with the study of square-wave unipolar pulse and bipolar pulse reverse electroplating and, particularly, the determination of pulse parameters to optimise through-hole plating rates and uniformity in the production of printed circuit boards (PCBs). The Wagner number, derived from cathode polarization behaviour in electroplating solutions, with and without plating additives, and under pulse plating conditions, was used to rationalize the data obtained. Fundamental predictions were found to compare favourably with results obtained from practical plating tests.

Glossary

a	anodic
b	Tafel coefficient
c	cathodic
$d\eta/di$	slope of the polarization curve, calculated at an average current density ($\mathrm{V\,A^{-1}\,cm^2}$)
L	characteristic length of the deposition process (cm)
i	current density ($\mathrm{A\,dm^{-2}}$)
i_L	limiting current density ($\mathrm{A\,dm^{-2}}$)
i_m	mean current density ($\mathrm{A\,dm^{-2}}$)
i_P	peak current density ($\mathrm{A\,dm^{-2}}$)
P	pulse
PR	pulse reverse
$\mathcal{R}_{Wa}$	Wagner number enhancement ratio [$= Wa_p/Wa_{d.c.}$]
S/H	surface to hole thickness ratio
t_{off}	off-time (ms)
t_{on}	on-time (ms)
Wa	Wagner number [$= \kappa/L(d\eta/di)$] (also see equations 3 and 7)

Greek letters

ϕ	duty cycle (%)
κ	electrolyte conductivity ($\mathrm{S\,cm^{-1}}$)
η	overpotential (V)

1. Introduction

Examination of the effects of applying pulsed currents to an electroplating process dates back to the early 1950s. Since that time there have been many papers and articles on the subject; the most extensive publication on pulse plating being that of Puippe *et al.* [1]. The method has been applied to virtually all metals which it is possible to electrodeposit, including aqueous, non-aqueous and molten salt electrolytes.

From the earlier studies, it has become usual to think of a pulse as approximately < 1 s in duration. Larger polarity changes, up to 20 s duration, are often referred to as periodic reverse changes and have been used successfully to improve levelling in electrowinning processes.

The general definition of a pulse supply is such that a constant current should be capable of being switched from one level to another on a regular basis. The simplest case is that of alternately switching on and off a d.c. supply; this represents the common square wave pulse. Other pulse waveforms include sine wave and triangular wave.

Pulse plating allows for the following improvements:

(i) making the deposit finer, purer, less porous and smoother;

(ii) raising the limiting current density, hence increasing the plating speed;

(iii) providing better adhesion of deposit to substrate; and

(iv) achieving better plating distribution.

The main difference between d.c. and pulsed current is that with d.c. plating only voltage or current can be controlled whilst with pulse plating three parameters – on-time, off-time and the peak current density – can be independently varied (Fig. 1). Such pulses may create changes in mass transport, changes in electrocrystallization conditions and adsorption–desorption phenomena which are not otherwise possible [1, 2].

The object of pulsing is to provide an enhanced plating rate and performance without loss of properties which might be caused by the otherwise excessive

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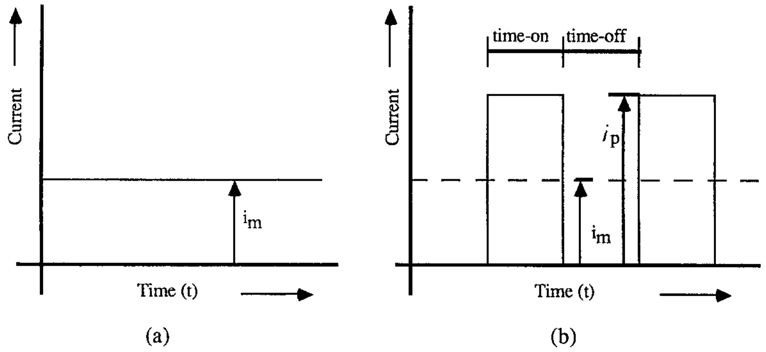

Fig. 1. Typical waveforms under (a) d.c. and (b) unipolar pulse plating conditions.

current employed. Thus, a high forward (cathodic) current can be interrupted by reverse pulses (either anodic or low cathodic) which may cause levelling, anodic polishing or relaxing of the diffusion layers. Consequently, the average or nett forward current must be employed to define overall rates and the pulse character to define any effects achieved.

In practice, the use of pulse plating is restricted mainly by lack of fundamental knowledge of its effects on the properties of the deposit concerned. More variables are involved in pulse plating than with direct current and consequently it is easier to produce an adverse effect rather than the beneficial one sought! Nevertheless, Pearson and Dennis [3] have presented recent work on pulse electroplating of copper on printed circuit boards including the pulse plating effects on additives usage. Similarly, work in the USA by Alkire *et al.* [4] and Chin *et al.* [5] has been specifically directed at the through-hole problem.

During the last ten years pulse plating has been recognized and reported [6, 7] as being useful in certain specific applications, particularly where activation polarization and solution conductivity may be the controlling factors. This is especially true for through-holes in printed circuit boards (PCBs). The use of a dimensionless group to define current distribution in a recess region such as a through-hole was originally proposed by Wagner [8] and has subsequently been termed the Wagner number (*Wa*). This recognizes that the distribution of current is substantially attributable to: (i) the geometry of the recess; (ii) the conductivity of the electrolyte; and (iii) the kinetics (or polarization) prevailing during electrodeposition.

The definition of the Wagner number takes these factors into account. Assuming a 100% cathode efficiency, it is given as

$$Wa = \frac{\kappa}{L}\left(\frac{d\eta}{di}\right) \qquad (1)$$

where κ is the electrolyte conductivity ($\Omega^{-1}\,cm^{-1}$ or $S\,cm^{-1}$), L is the characteristic length (cm), and $d\eta/di$ is the slope of the polarization curve, calculated at an average current density ($V\,A^{-1}\,cm^2$).

In the absence of concentration gradients and with Tafel kinetics, we may write

$$\frac{d\eta}{di} = \frac{b}{i_m} \qquad (2)$$

where b is the Tafel coefficient in the equation $\eta = a \pm b \ln i_m$. Thus, Equation 1 can be rewritten as

$$Wa = \frac{\kappa}{L}\frac{b}{i_m} \qquad (3)$$

The larger the value of *Wa* the more uniform is the current distribution and, subsequently, the deposit distribution. When $Wa \rightarrow 0$ primary current conditions prevail; to raise the value of *Wa*, the solution conductivity should be as high as possible and $d\eta/di$ must also be high.

It is as a consequence of this behaviour that solutions for use in these applications are formulated to maximize conductivity, i.e. high acidity or support electrolyte concentration and relatively low metal ion concentration, but not so low as to reduce plating rates to non-commercial levels. The Wagner number may be derived from the Tafel theory of activation polarization [9, 10] and it is widely believed that increased throwing power can be associated with an increase in Wagner number or Tafel slope [11].

Such an approach has been employed in this research which has been concerned with developing a copper electrolyte and special pulse conditions for plating PCBs having through-hole diameters as low as 0.3 mm and aspect ratios (board thickness : hole diameter) of $\leqslant 8:1$. The quality product criterion is a surface : hole thickness ratio of 1 : 1.

The model electrolyte solution employed was a highly conductive acid copper sulphate with some proprietary additives. The reason for using such electrolytes lies, first, with the fact that it is simple to understand its behaviour; secondly, it is used commercially in plating industries for PCBs; and thirdly, with the current technology in the surface mount industry, holes are becoming smaller and the coating thickness distribution and also the deposit continuity becomes important for commercial purposes. Furthermore, different agitation techniques were also explored in combination with the pulse techniques in order to increase the transport of metal ions in the through-hole PCBs.

2. Experimental details

The experimental arrangement, shown in Fig. 2, employs a current pulse unit having a microprocessor

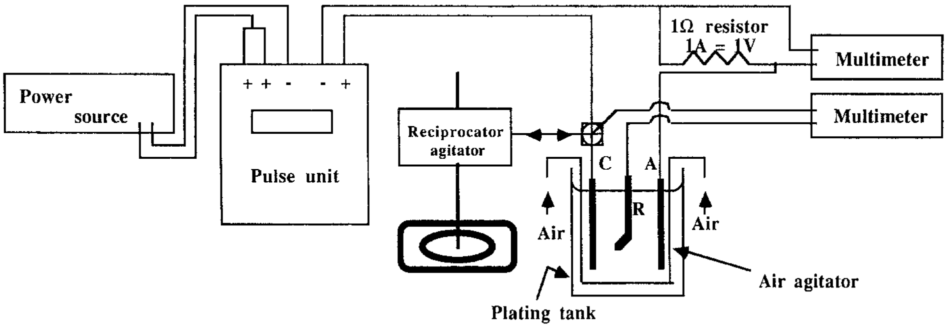

Fig. 2. Experimental arrangement used for polarization studies and also PCB plating under d.c., unipolar and bipolar pulse reverse conditions. (N.B. two power supplies were used in the latter condition.)

controlled electronic switch which allows programming of up to 9 channels and also allows various parameters such as frequency, duty cycle and the pulse direction, either forward or reverse, to be stored.

The work reported here used unipolar pulse and bipolar pulse reverse currents. The electrolyte solutions consisted of a standard acid copper solution (I), $CuSO_4 \cdot 5H_2O$ (0.3 M), H_2SO_4 (2.25 M) and Cl^- (50 p.p.m.), and solution (II) containing LeaRonal proprietary additives of a mixture of polyethylene glycol, mercaptopropyl sulphonic acid and aromatic sulphonic acid. A comparison with d.c. performance was used as the criterion of behaviour.

Initially, the effects of unipolar pulses were examined using a cathode size of 1 dm^2 and electrolyte II. The measurements were carried out by setting the input current to 1 A under direct current and then by examining the effect of mean current density and its relative potential for different duty cycles (Fig. 3). Further measurements were also undertaken at a constant input current of 1 A to examine the effect of peak current density and its relative potential for different duty cycles (Fig. 4). The measurements were obtained at a unipolar pulse frequency of 100 Hz. The potentials were measured 15 s after each duty cycle setting which was found to be sufficient for the potential to stabilize. It can be seen that the mean current density values increase linearly as the duty cycles increase, but the cell potentials decrease linearly with peak current density values decreasing exponentially. The results obtained, as might be expected, follow the formulation for average current density:

$$i_m = i_p \phi \quad (4)$$

where i_m is the mean current density ($A\,dm^{-2}$), i_p the peak current density ($A\,dm^{-2}$), and ϕ the duty cycle (%). The duty cycle is defined as

$$\phi = \frac{\mathrm{time}_{(on)}}{\mathrm{time}_{(on)} + \mathrm{time}_{(off)}} \times 100\% \quad (5)$$

This trend further indicates that the power supply was compatible with the pulse unit [9, 10]. Furthermore, the profile remains the same for different input currents and cathode size. (The peak current density values were obtained using an Advanced Bryan storage oscilloscope.)

Polarization studies were carried out using a Farnell power supply and a JCT pulse unit (Fig. 2). The polarization curves were obtained cathodically by a step-current technique using a copper cathode with an exposed area of 30 cm^2 and two phosphorized deoxidized copper anodes with an exposed area of 60 cm^2 each. The reference electrode was mercury/mercury sulphate.

Agitation was provided by two techniques: (i) air sparging, which greatly enhances the replenishment of metal ions around the cathode [12, 13]; and (ii) reciprocating cathode movements, which enhances the replenishment of metal ion in and around the holes [13] to a lesser extent but is used widely in industrial processes as a consequence of its simplity in installation.

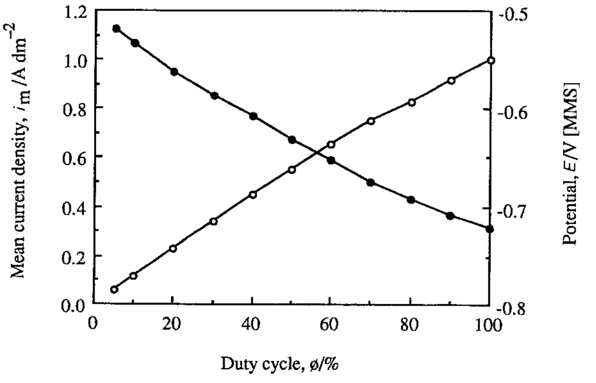

Fig. 3. Mean current density and potential against duty cycle at an input current equivalent to direct current of 1 A at a fixed frequency of 100 Hz using electrolyte II with air and reciprocating agitations combined. (○—○) i_m, (●—●) E.

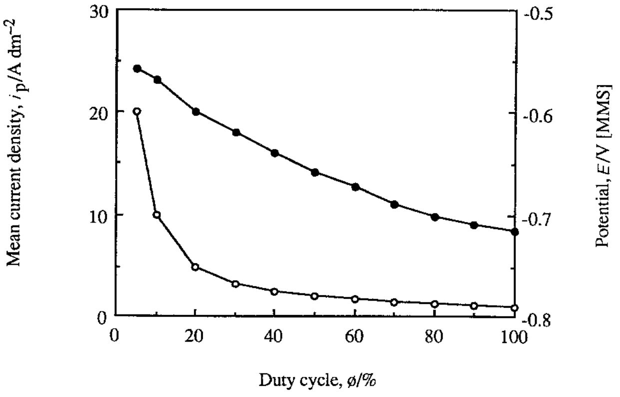

Fig. 4. Mean current density and potential versus duty cycle at a constant input current of 1 A at a fixed frequency of 100 Hz using electrolyte II with air and reciprocating agitations combined. (○—○) i_p, (●—●) E.

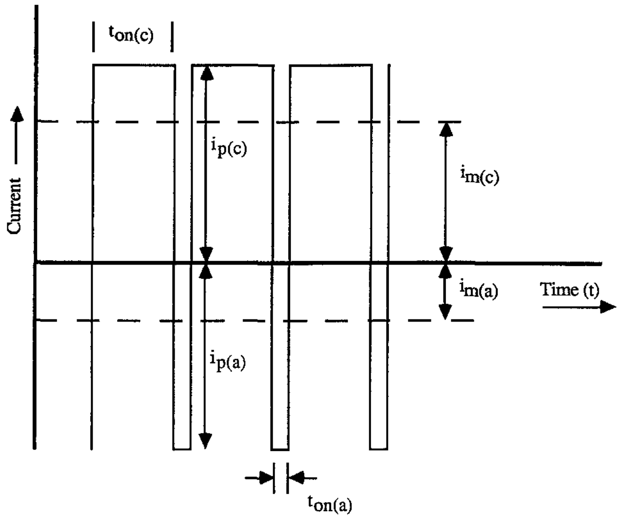

Fig. 5. Typical bipolar pulse reverse waveform.

Other parameters which should be noted are that frequency and duty cycle values were 20, 500, 1000, 2000 and 5000 Hz and 25, 50, 75 and 100%, respectively. The term frequency relates to the pulsation in cycles/second (Hz) and duty cycle was defined in Equation 5.

In experiments using bipolar pulse reverse currents the parameters studied were cathodic/anodic on-time ratio ($t_{\mathrm{on(c)}}/t_{\mathrm{on(a)}}$) and peak current density of cathodic/anodic ratio ($i_{\mathrm{p(c)}}/i_{\mathrm{p(a)}}$). The duty cycles were fixed at 100% (Fig. 5). The bipolar pulse reverse conditions used were varied systematically as indicated in Table 1. The limit on the bipolar pulse reverse conditions chosen were dependent on two factors: (i) the capability of the power sources; and (ii) the cost effectiveness of producing pulses for large-scale industrial uses. These are important as the smaller the on-time the higher the input voltage required and, hence, the greater the expense; thus the cost effectiveness of using pulse to that of d.c. would be low.

The mean current density, i_{m}, for bipolar pulse reverse plating is given by:

$$i_{\mathrm{m}} = \frac{i_{\mathrm{p(c)}} \times t_{\mathrm{on(c)}} + i_{\mathrm{p(a)}} \times t_{\mathrm{on(a)}}}{t_{\mathrm{on(c)}} + t_{\mathrm{on(a)}}} \tag{6}$$

where $i_{\mathrm{p(c)}}$ is the cathodic peak current density ($\mathrm{A\,dm^{-2}}$), $i_{\mathrm{p(a)}}$ the anodic peak current density ($\mathrm{A\,dm^{-2}}$), $t_{\mathrm{on(c)}}$ the cathodic on-time (ms), and $t_{\mathrm{on(a)}}$ the anodic on-time (ms).

The agitation used for both unipolar pulse and bipolar pulse reverse was cathode reciprocation combined with air agitation. The cathode reciprocation was set at 60 cm min^{-1} and a constant air flow rate of 4.5 dm^3 min^{-1}, typical of those used on printed circuit board production plating lines.

Table 1. Experimental conditions for bipolar pulse reverse plating

$i_{\mathrm{p(c)}}/i_{\mathrm{p(a)}}$†	$t_{\mathrm{on(c)}}/t_{\mathrm{on(a)}}$*					
	10/0.2	10/0.5	10/1	10/2	20/1	20/0.5
1/1	√	√	√	√	√	√
1/2	√	√	√	√	√	
1/3	√	√	√	√		
1/4	√	√				

* t_{on} is in ms.
† i_{p} is in $\mathrm{A\,dm^{-2}}$.

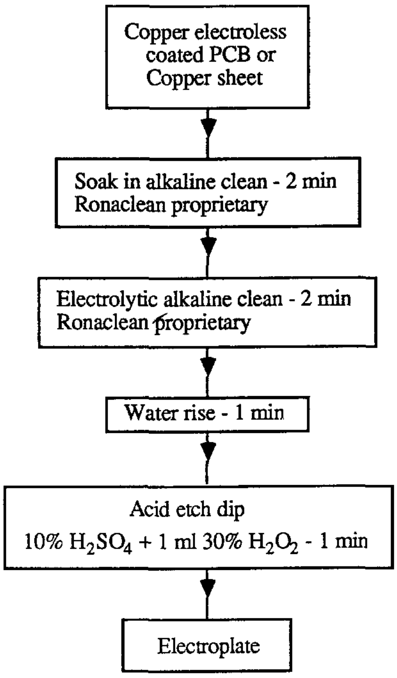

Fig. 6. Flow chart showing the pretreatment stages used in the polarization studies and printed circuit board plating.

Finally, a combination of good, bad and also a middle range of conditions (defined by the Wagner number and appropriate electrolytes) were used to electroplate PCBs under pulsing conditions. The electroplating was carried out at a mean current density of 3.0 A dm^{-2}. The PCB diameters were 0.8 and 0.3 mm with a board thickness of 2.4 mm and the pretreatment of all the samples was carried out as shown in Fig. 6.

The plated samples were mounted and then ground using 1200 grit and finally polished using 1 μm diamond paste and the coating thickness distributions were measured at ten points around the cross-section of the plated PCB holes. Comparative studies were made on the surface (S) to hole (H) thickness ratios obtained, that is, the closer the S/H ratio to 1, the better the coating distribution for printed circuit board manufacture.

3. Results and discussion

In PCB production the transport of metal ions to the hole is a particularly important factor, other than current density, in obtaining a uniform deposit. Ion replenishment is enhanced by agitation which therefore affects the deposition rate. Depletion of ions inevitably leads to non-uniformity, especially in recesses; the use of pulse-type techniques is primarily important in affecting uniformity and any change in deposition rate is of secondary importance.

Figure 7 shows a typical polarization curve obtained using electrolyte containing no additive (I).

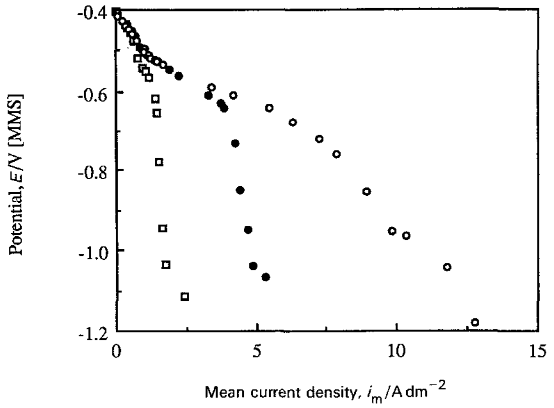

Fig. 7. Polarization curves obtained using electrolyte I for different agitation modes; (□) S-still, (●) R-reciprocating and (○) A-air.

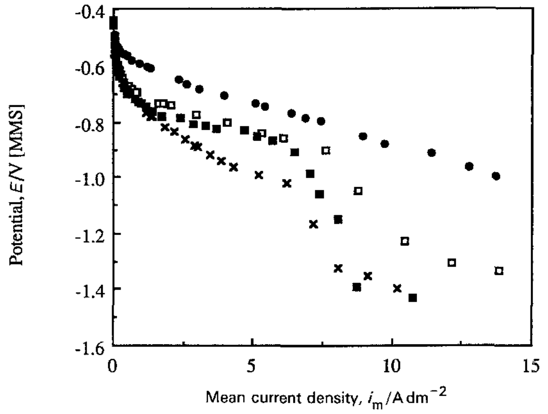

Fig. 9. Polarization curves obtained under d.c. and also unipolar pulse conditions using electrolyte II and air and reciprocating agitations combined. (□) d.c.; (●) 20 Hz, 25% ϕ, (x) 1000 Hz, 75% ϕ; (■) 5000 Hz, 25% ϕ.

It was found that at a constant potential of typically -0.8 V the limiting current densities for the solution with no agitation, reciprocating agitation, and air and reciprocating agitations combined are about 1.5, 4.3 and 8.3 A dm^{-2}, respectively, for electrolyte I and 1.5, 4.5 and 8.3 A dm^{-2}, respectively, for electrolyte II. This shows that with an increase in agitation the current density region of levelled deposition has also increased irrespective of additives being employed.

Polarization curves obtained under different unipolar pulse conditions for electrolytes I and II can be seen in Figs 8 and 9, respectively, both using combined air and reciprocating agitation. It should be noted that only some of the conditions used are described in this paper and a full detailed account of the other conditions can be found elsewhere [9]. In comparison, the limiting current density has usually increased under unipolar pulses over that of d.c. conditions.

Figures 10 and 11 show typical polarization curves obtained for electrolytes I and II respectively under bipolar pulse reverse conditions. It was found that at a constant potential of typically -0.8 V for electrolyte I the limiting current density values are higher than for the d.c. condition but for the electrolyte II it depends on the specific pulse reverse conditions. This indicates that electrolyte II containing additives behaves differently to electrolyte I under bipolar pulse reverse conditions. Thus, the nature of the additives employed must be an important factor to consider; this will be discussed later.

The main part of this work has been concerned with the effect of throwing power (i.e. the ability of a solution to deposit on an uneven surface typically 'through-hole' PCBs) under different pulse conditions and electrolyte solutions, the object being to optimize throwing power for through-holes. The idealized polarization curve of Fig. 12 clearly shows three regions: (a) linear polarization which is the first 30 mV, (b) a region of Tafel behaviour which is assumed to be from 30–200 mV overpotential, and (c) a region of concentration polarization leading to the limiting current condition.

As described previously [10], the Tafel slope can be calculated in two ways: the first is from the slope of a E-log i graph where it is obtained directly from the polarization curve. The second is by a E-log i_C plot, where i_C is a modified or converted current density which eliminates the mass transfer component [11, 14] (NB the Tafel slope has units of mV decade^{-1}). A typical E-log i_C can be seen in Fig. 13 for unipolar pulse conditions in electrolyte I. The E-log i_C curves for bipolar pulse reverse conditions were found to be

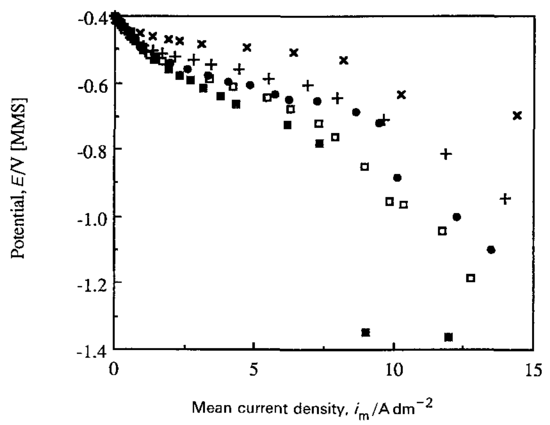

Fig. 8. Polarization curves obtained under d.c. and unipolar pulse conditions using electrolyte I and air and reciprocating agitations combined. (□) d.c.; (x) 20 Hz, 25% ϕ, (●) 500 Hz, 75% ϕ, (+) 500 Hz, 25% ϕ; (■) 500 Hz, 50% ϕ.

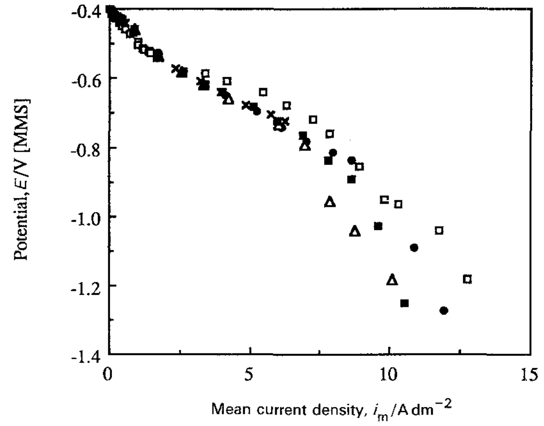

Fig. 10. Bipolar pulse reverse polarization curves for different $t_{on(c)}/t_{on(a)}$ ratios and various $i_{p(c)}/i_{p(a)}$ ratios using electrolyte I. t_{on} is in ms; i_p is in A dm^{-2}. (□) d.c.; (x) 10/0.2, 1/3; (●) 20/0.5, 1/1; (△) 10/0.2, 1/2; (■) 10/0.2, 1/1.

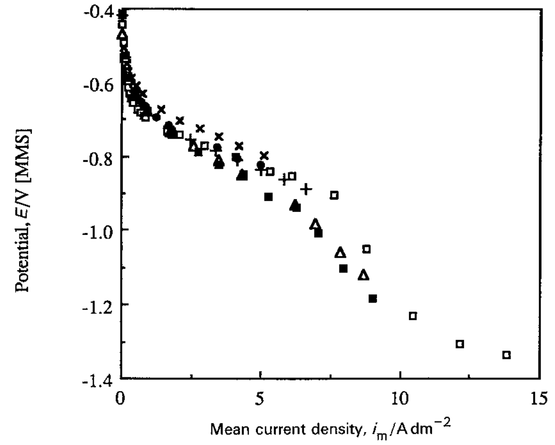

Fig. 11. Bipolar pulse reverse polarization curves for different $t_{on(c)}/t_{on(a)}$ ratios and various $i_{p(c)}/i_{p(a)}$ ratios using electrolyte II. t_{on} is in ms; i_p is in A dm^{-2}. (□) d.c.; (x) 10/0.5, 1/3; (●) 10/0.4, 1/4; (+) 10/0.2, 1/3; (△) 10/0.2, 1/2; (■) 10/0.2, 1/1.

similar to those for d.c.; it should be noted that for clarity only some of the conditions have been plotted. The calculated Tafel slopes showed that the variations under pulsed current with or without additives are significant; in fact, the Tafel slope variations were in the range of 41.7–277.4 mV decade^{-1} under the conditions studied but no particular trend could be established.

In related circumstances Ibl [15] devised a method to describe qualitatively the solution characteristics using primary and secondary current distribution. The parameter employed was the dimensionless Wagner number (*Wa*) which can relate to the uniformity of the electrodeposit and thus the throwing power of the solution. As shown in Equation 1, the Wagner number is calculated by taking into account the solution conductivity, the characteristic length and the Tafel slope of the polarization curve based on average current density. An alternative method of calculating the Wagner number in pulse plating is by taking into account the peak current density rather than the mean current density values, neglecting double layer effects. The practicality of the use of peak current density is mainly under unipolar pulsing conditions, as in this research work, where no deposition occurs during the pulse off-time. Thus, the Equation 1 can be rewritten as

$$Wa = \frac{\kappa}{L}\frac{b}{i_p} \qquad (7)$$

This will show the best and worst pulsing conditions, the best being at high duty cycles and the worst at low duty cycles. The main practical parameter will be pulse frequency. Table 2 shows some of the results obtained from best to worst pulsing conditions using the mean and peak current density values. In this research work, the mean current density has been used.

The relevance of the Wagner number in through-hole plating studies has been established by Yung *et al.* [4, 16, 17] who used this approach to model current distribution and thus theoretical plating uniformity in the hole. In a subsequent study, Goodenough [11] reported an excellent correlation between the Wagner numbers and practical plating performance, and postulated that the major factor influencing deposit uniformity is the solution conductivity and the current density, the object being to obtain a 1 : 1 surface to

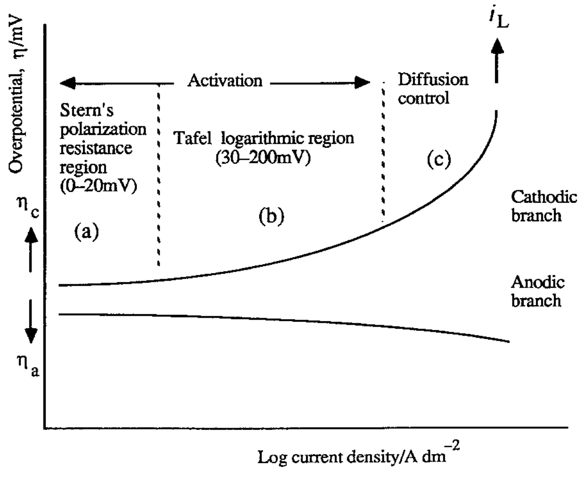

Fig. 12. Illustration of a typical polarization curve showing the simplified regions of behaviour.

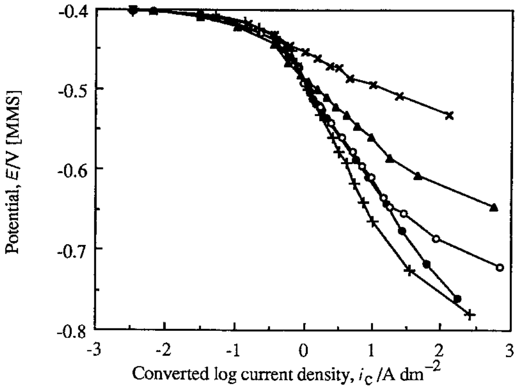

Fig. 13. Relationship between potential and logarithmic converted current density, showing the extrapolated Tafel lines under d.c. and different unipolar pulse conditions using electrolyte I. (●) d.c.; (x) 20 Hz, 25% ϕ; (○) 500 Hz, 75% ϕ; (▲) 500 Hz, 25% ϕ; (+) 5000 Hz, 50% ϕ.

Table 2. Best to worst unipolar pulsing conditions obtained by calculating the Wagner number using Equations 3 and 7 for electrolytes I and II

$Wa = \frac{\kappa}{L}\frac{b}{i_m}$		$Wa = \frac{\kappa}{L}\frac{b}{i_p}$		
I* Hz, % ϕ	II† Hz, % ϕ	I* Hz, % ϕ	II† Hz, % ϕ	
5000, 50	1000, 75	5000, 75	1000, 75	Best
5000, 75	20, 75	1000, 75	20, 75	↓
1000, 75	2000, 75	2000, 75	2000, 75	
5000, 25	1000, 50	500, 75	5000, 75	
2000, 75	5000, 75	20, 75	500, 75	
2000, 50	5000, 25	5000, 50	1000, 50	
500, 75	2000, 50			
20, 75	500, 75			Worst

* I – 0.3 M $CuSO_4$, 2.25 M H_2SO_4, 50 p.p.m. Cl^-.

† II – 0.3 M $CuSO_4$, 2.25 M H_2SO_4, 50 p.p.m. Cl^- and a mixture of polyethylene glycol, mercaptopropyl sulphonic acid and aromatic sulphonic acid additives.

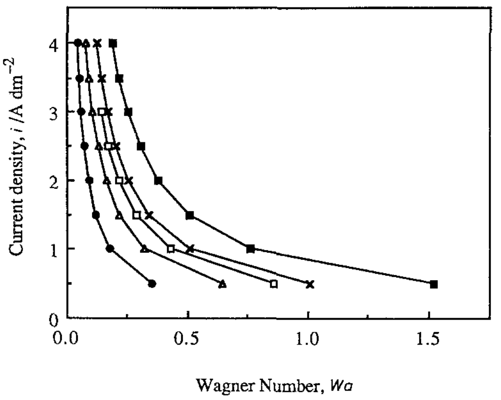

Fig. 14. Relationship between current density and Wagner number under d.c. and unipolar pulse conditions using electrolyte I. (□) d.c.; (●) 20 Hz, 25% ϕ; (x) 500 Hz, 75% ϕ; (△) 500 Hz, 25% ϕ; (■) 5000 Hz, 50% ϕ.

hole thickness ratio. Other investigators have also reported the use of pulsed current in connection with through-hole plating of PCBs [3, 18, 19]. It has been claimed that pulse plating or pulse reverse plating decreases the effect of the mass transfer diffusion layer thickness and thus allows higher instantaneous plating current densities as well as better copper distribution without inducing burning of copper deposits at high current density points [19, 20].

Parameters affecting the Wagner number may be listed as follows:

(i) electrolyte concentration or conductivity of the electrolyte,
(ii) additives and their concentrations,
(iii) current density,
(iv) metal ion depletion tendencies,
(v) duty cycle,
(vi) frequency,
(vii) temperature, and
(viii) geometry of the recess or hole.

Tafel slope values obtained experimentally were used to calculate the Wagner numbers at different current densities. A typical current density–Wagner number (i–Wa) relationship can be seen in Fig. 14 under unipolar pulse reverse current for electrolyte I. The results of both unipolar pulse and bipolar pulse reverse show that there is no particular trend but it was found that different pulse conditions give a clearly different Wagner number. Similar behaviour was also obtained when using bipolar pulse reverse conditions for both electrolytes I and II. The combination of pulsing and additives thus provides a more favourable throwing power option especially from metallurgical view point for the plating process when deposit uniformity is a major requirement.

To differentiate and also to characterize changes in the Wagner number, an enhancement ratio ($\mathscr{R}_{Wa}$) can be defined such that

$$\mathscr{R}_{Wa} = \frac{\text{pulse Wagner number } (Wa_{\mathrm{p}})}{\text{d.c. Wagner number } (Wa_{\mathrm{d.c.}})} \qquad (8)$$

Basically, $\mathscr{R}_{Wa}$ gives an indication of improvement for different pulse conditions in comparison to d.c. conditions. Table 3 shows the $\mathscr{R}_{Wa}$ values calculated at 2.0 A dm^{-2} using combined air and reciprocating agitations for electrolytes I and II under both unipolar pulse and bipolar pulse reverse conditions, assuming $\mathscr{R}_{Wa_{\mathrm{d.c.}}} = 1$. It can be seen that for the two electrolytes used different optimum pulse frequencies and duty cycles may be identified under unipolar conditions, and for bipolar pulse reverse different $t_{\mathrm{on(c)}}/t_{\mathrm{on(a)}}$ and $i_{\mathrm{p(c)}}/i_{\mathrm{p(a)}}$ ratios have been achieved. The results indicate that constituents of the electrolytes play an important role in pulse plating, as reported by Pearson and Dennis [3], hence the choice of electrolyte is crucial for electroplating PCBs. It is also apparent that a good $\mathscr{R}_{Wa}$ under certain pulsing conditions for one electrolyte is not necessarily equally good for another electrolyte. Furthermore, it can also be seen from Table 3 that $\mathscr{R}_{Wa}$ can be as high as three-fold depending on the type of electrolyte and the current density employed. Again, depending on the particular current density, the Wagner number can be increased yet further (Table 4), i.e. with 0.5 A dm^{-2} the $\mathscr{R}_{Wa}$ increases to be as high as ten fold.

Figures 15 and 16 show the microscopical cross-sections of the plated PCBs under d.c., unipolar pulse and bipolar pulse reverse conditions for the electrolytes I and II, respectively. For electrolyte I, it was observed that at 5000 Hz and 50% ϕ, the best unipolar pulse condition, the S/H ratio is somewhat similar or better than d.c. depending upon the board's aspect ratio. For the worst unipolar pulse condition, 20 Hz, 25% ϕ, the S/H ratio is best at lower aspect ratios. However, the results of bipolar pulse reverse conditions have shown that the S/H ratio can become much better than for d.c. and unipolar pulse conditions, Fig. 15.

For example, at $t_{\mathrm{on(c)}}/t_{\mathrm{on(a)}}$ of 10/0.2 and $i_{\mathrm{p(c)}}/i_{\mathrm{p(a)}}$ of 1/3 for board thickness of 2.4 mm, the S/H ratio for hole diameters of 0.8 and 0.3 mm are 1.03 : 1 and 1.09 : 1, respectively, compared to 1.31 : 1 and 1.35 : 1, respectively, for d.c. conditions. The explanation lies with the fact that during the negative cycle the coating at the edges will dissolve in the electrolyte and allow metal ion replenishment in and around the hole to take place; this concept has been recognized theoretically [1] and also practically [3, 6].

For electrolyte II it was found that under unipolar pulse conditions the S/H ratio does not improve greatly compared to d.c. conditions, Fig. 16. This could be due to the additives in the solution acting with the pulsing and it could indicate an adverse effect of pulsing. However, under bipolar pulse reverse conditions it was observed that the S/H ratio has improved substantially compared to that of d.c. or even unipolar pulse conditions. The best bipolar pulse reverse conditions compared to d.c. among the plated PCBs having good to best S/H ratios for $t_{\mathrm{on(c)}}/t_{\mathrm{on(a)}}$ and $i_{\mathrm{p(c)}}/i_{\mathrm{p(a)}}$ are: 10/0.5 and 1/3; 10/0.2 and 1/2; 10/0.2 and 1/3; 10/0.2 and 1/4; 10/0.2 and 1/8. It should be noted that improvements were also observed relative to the surface appearances since it is often preferable that deposits should have a bright finish. The study has shown that:

Table 3. Frequencies and duty cycles under unipolar pulse and bipolar pulse reverse with $\mathscr{R}_{Wa}$ values for electrolytes I and II. Wa_P values were calculated at 2.0 A dm^{-2}

Unipolar pulse		*Bipolar pulse reverse*					
I*	II†	I*	II†				
Hz, % ϕ ($\mathscr{R}_{Wa_P}$)	Hz, % ϕ ($\mathscr{R}_{Wa_P}$)	$t_{on(c)}/t_{on(a)}$,‡	$i_{p(c)}/i_{p(a)}$§	($\mathscr{R}_{Wa_{PR}}$)	$t_{on(c)}/t_{on(a)}$,‡	$i_{p(c)}/i_{p(a)}$§	($\mathscr{R}_{Wa_{PR}}$)
20, 25 (0.41)°	20, 25 (0.69)°	10/2,	1/3	(1.05)°	10/2,	1/3	(0.47)°
2000, 25 (1.02)	5000, 25 (1.02)°	10/0.5,	1/3	(1.81)	10/0.5,	1/3	(1.11)°
20, 75 (1.05)	5000, 75 (1.07)	10/1,	1/2	(2.00)	10/0.2,	1/4	(1.13)°
500, 75 (1.18)	1000, 50 (1.09)	10/0.2,	1/3	(2.33)°	10/0.2,	1/3	(1.17)°
2000, 50 (1.30)	2000, 75 (1.10)	20/0.5,	1/1	(2.47)	10/0.2,	1/2	(1.49)°
5000, 25 (1.42)	20, 75 (1.19)	10/0.2,	1/2	(2.59)	10/0.2,	1/1	(1.50)°
5000, 75 (1.43)	1000, 75 (1.34)°	10/0.2,	1/1	(2.83)°			
5000, 50 (1.76)°		° conditions used for plating PCBs					

* I 0.3 M $CuSO_4$, 2.25 M H_2SO_4, 50 p.p.m. Cl^-.

† II 0.3 M $CuSO_4$, 2.25 M H_2SO_4, 50 p.p.m. Cl^- and a mixture of polyethylene glycol, mercaptopropyl sulphonic acid and aromatic sulphonic acid additives.

‡ t_{on} is in ms.

§ i_p is in A dm^{-2}.

(i) a low duration of anodic cycle can be used to obtain a better S/H ratio compared to d.c., i.e. cathodic/anodic on-time ratio of 10/0.2 was the best;

(ii) as $i_{p(a)}$ increased, the coating thickness distribution for a particular on-time ratio improved; and

(iii) a bright finish can be obtained only under certain bipolar pulse reverse conditions.

In other words, it was found that PCBs plated using bipolar pulse reverse for cathodic/anodic on-time ratio of 10/0.2 were bright and S/H ratio were better than d.c. At higher $i_{p(c)}/i_{p(a)}$ of 1/8, the S/H ratio was the best with semi-bright surface appearance. However, under the worst bipolar pulse reverse conditions for electrolyte II, the S/H ratio was extremely poor as expected, Fig. 16.

By comparison, Pearson and Dennis [2] have found that at $t_{on(c)}/t_{on(a)}$ of 10/0.5 and $i_{p(c)}/i_{p(a)}$ of 1/3, the S/H ratio obtained was 1 : 1 with a matt deposit using 6boards with 8 : 1 aspect ratio but no evidence of a S/H ratio of 1 : 1 was observed in the present work. This clearly indicates that the pulsing conditions obtained for one additive system will not necessarily be suitable for another. Nevertheless, it was found that the S/H ratio at $t_{on(c)}/t_{on(a)}$ of 10/0.5 and $i_{p(c)}/i_{p(a)}$ of 1/3 was better than d.c. in this research programme. Furthermore, the results are also in agreement with those obtained by a production unit [21]. That is,

(i) high aspect ratio boards could be plated at a normal plating rate without any loss of quality, i.e. 25 μm achieved in 45 min with improved distribution;

(ii) small holes 0.3 mm could be plated to a much higher quality, which is beneficial for surface mount production; and

(iii) an improvement in copper covering power is possible.

It may be noted that a marked improvement in coating distribution under pulse conditions, in terms of surface to hole thickness ratio, can be obtained. In terms of choice of the electrolyte, microstructural studies showed that electrolyte II produces a finer deposit to that of electrolyte I which tends to produce long columnar grains. For this reason electrolyte II is preferred despite the fact that the $\mathscr{R}_{Wa}$ is lower since the grain refinement is an important factor in producing a good electrical contact surface.

Table 4. $\mathscr{R}_{Wa}$ values under unipolar and pulse reverse conditions for electrolytes I and II; $Wa_{d.c.}$ value was obtained at 2.0 A dm^{-2}

i/A dm^{-2}	*Unipolar pulse*		*Bipolar pulse reverse*	
	I* 5000 Hz, 50% ϕ $Wa_{d.c.}$ = 0.215	II† 1000 Hz, 75% ϕ $Wa_{d.c.}$ = 0.253	I* 10/0.2, 1/3‡ $Wa_{d.c.}$ = 0.215	II† 10/0.2, 1/3‡ $Wa_{d.c.}$ = 0.253
0.5	7.07	5.38	9.32	4.68
1.0	3.53	2.68	4.66	2.34
1.5	2.35	1.79	3.10	1.56
2.0	1.76	1.34	2.33	1.17
2.5	1.41	1.08	1.86	0.936
3.0	1.18	0.897	1.55	0.780

* I – 0.3 M $CuSO_4$, 2.25 M H_2SO_4, 50 p.p.m. Cl^-.

† II – 0.3 M $CuSO_4$, 2.25 M H_2SO_4, 50 p.p.m. Cl^- and a mixture of polyethylene glycol, mercaptopropyl sulphonic acid and aromatic sulphonic acid additives.

‡ $t_{on(c)}/t_{on(a)}$, $i_{p(c)}/i_{p(a)}$ = 10/0.2, 1/3.

t_{on} is in ms; i_p is in A dm^{-2}.

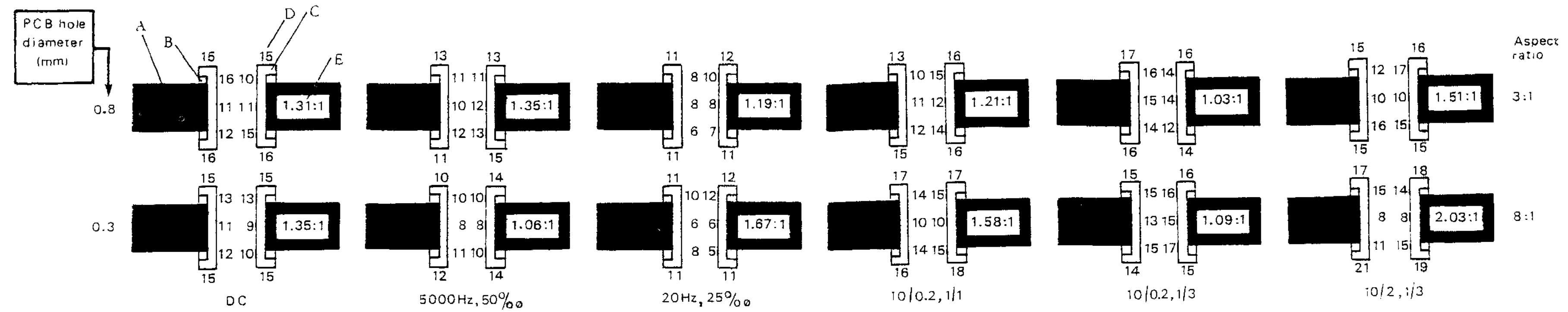

Fig. 15. Representation of PCBs in cross-section, for different hole diameters and a board thickness of 2.4 mm, plated at a mean current density of 3.0 A dm^{-2} using electrolyte I. The plating conditions are d.c., unipolar pulse (Hz, % ϕ) and bipolar pulse reverse ($t_{on(c)}/t_{on(a)}$, $i_{p(c)}/i_{p(a)}$); surface : hole thickness ratio values are also stated. (N.B. t_{on} is in ms; i_p is in A dm^{-2}; coating thicknesses are in μm.) Key: (A) PCB; (B) copper clad; (C) plated coating; (D) coating thickness (μm); (E) S/H thickness ratio.

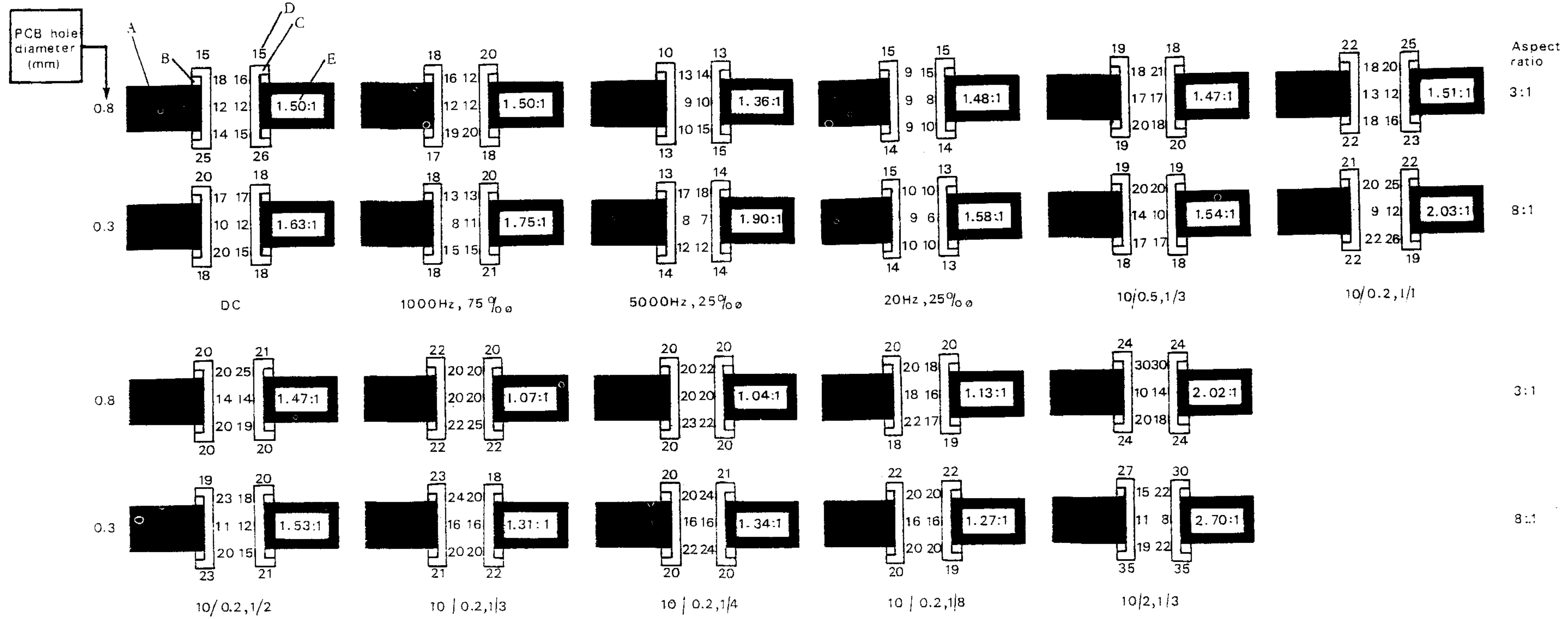

Fig. 16. Representation of PCBs in cross-section, for different hole diameters and a board thickness of 2.4 mm, plated at a mean current density of 3.0 A dm^{-2} using electrolyte II. The plating conditions are d.c., unipolar pulse (Hz, % ϕ) and bipolar pulse reverse ($t_{on(c)}/t_{on(a)}$, $i_{p(c)}/i_{p(a)}$); surface : hole thickness ratio values are also stated. (N.B. t_{on} is in ms; i_p is in A dm^{-2}; coating thicknesses are in μm.) Key: (A) PCB; (B) copper clad; (C) plated coating; (D) coating thickness (μm); (E) S/H thickness ratio.

4. Conclusions

- Applying pulsed current does not increase the Faradaic efficiency but can raise the limiting current density and thus the practical plating current affects the structure and grain size as well as surface levelling.
- It has been shown that the Wagner enhancement ratio, $\mathscr{R}_{Wa}$, is a useful criterion for assessing the effect of pulsed current conditions.
- Electrolytes containing additives improved thickness distribution and produced a fine grain deposit, which is required for good electrical continuity and physical properties, although the improvement was not necessarily as large as $\mathscr{R}_{Wa}$ values might suggest.
- Low duration of an anodic cycle can be used to obtain a better S/H ratio compared to d.c., i.e. cathodic/anodic on-time ratio of 10/0.2 was the best.
- As $i_{\mathrm{p(a)}}$ increased, the coating thickness distribution for a particular on-time ratio improved.
- Bright finishes can be obtained under bipolar pulse reverse.

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