Influence of surface asperities on interfacial extension during solid state pressure welding

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Abstract. The interfacial contact and extension of two joining surfaces are numerically studied using a finite element method. The joining surface is assumed to have two-dimensional triangular asperities. Surface-asperity-induced voids are formed at the initial contact. The interfacial extension of the initial contact area is very different from that of void surface area. The initial void surface area shrank once before full contact was attained. The large asperity angle facilitates interfacial extension and void-surface shrinkage, resulting in the formation of numerous metallic bonds. The pressure-welding-induced interfacial extension and metallic bond formation are largely influenced by the asperity angle, whose effects are experimentally confirmed.

1. Introduction

The solid-state bonding of metals has many advantages, which cannot be obtained using fusion welding [1-3]. Because the bonding temperature, T, is lower than the melting points, the best use of the material properties can be obtained through solid-state bonding. From the view of energy saving and environmental conscious processing, it is necessary to decrease the bonding temperature. As the bonding temperature decreases, the surface oxide film becomes to prevent a good bondability [4]. Plastic-deformation-induced interfacial extension is very important for strongly bonding new clean metallic surfaces. The probability of the metallic contact area, $M_a$, after full void-free contact is given by

$$M_a = \left( \frac{S - S_0}{S} \right)^2 = Y^2,$$

where $s_i$ represents the length of the initial segment (i.e. local length) at the faying surface at time $t = 0$, $s$ represents the length of the pressure-welded segment, and $Y = (s-s_0)/s$ represents the surface exposure [5], which is expressed by $Y = e_i/(e_i+1)$, where $e_i = (s-s_0)/s$ represents the interfacial extension (i.e. strain). The power of 2 in equation (1) means the probability that intimate contact is produced between clean surfaces of similar metals because oxide films on two faying surfaces are not necessarily broken at the same places [5], and $(1-M_a)$ expresses the probability of the area where the oxide film exists. If the ductility, $G_d$, of the surface oxide film or contamination (i.e. cover) layer on the faying surfaces is taken into account [5], equation (1) is modified to $M_a' = \{(1-G_d)Y\}^2$, and $G_d$ ranges from 0.1 to 0.32 [5]. If the oxide film is scrubbed by being stirred around the bond interface during friction welding or...
ultrasonic bonding [6] then $G_d$ is apparently negative. The parameters $M_a$ (or $M'_a$), $Y$, and $\varepsilon_i$ are useful for discussing the oxide film behaviour during frictionless solid-state pressure welding.

Surface asperities largely influence interfacial contacting [7-10]. The surface asperity angle $\alpha_0$ (figure 1), therefore, largely affects the metallic bond ratio. Because the extension behaviour of the void surface has not previously been reported, it must be investigated by increasing the bulk strain, $\varepsilon_{gb}$. Hence, we numerically analysed the effects of $\varepsilon_{gb}$ and $\alpha_0$ on interfacial extension. The breaking behaviour of the surface oxide film was also experimentally surveyed to better understand the distribution of superficial- and interfacial-extension-induced broken oxide films.

2. Calculation procedure

Figure 1 illustrates the cross-sections of two faying surfaces with long triangular ridges. Figure 1 (a) is the pre-joining profile. The initial contact is determined by the instantaneous plastic flow, as illustrated in figure 1 (b) [7]. Half the initial contact width, $X_o$, is given by

$$X_o = \frac{L_{oo} \cdot P}{(1 + \varphi) \cdot \sigma_y (T)},$$

from the slip line analysis, as shown in figure 1 (c), where $L_{oo}$ represents half the interval of the surface asperity; $P$, the bonding pressure; $\varphi$, the angle defined in figure 1 (c); and $\sigma_y (T)$, the yield stress for the instantaneous plastic deformation at $T$ (measured in Kelvin). $L_o$ is supposed to be equal to $L_{oo}$ at time $t = +0$ (i.e. immediately after the initial contact).

The post-initial contact between faying surfaces is assumed to be dominated by viscoplastic deformation under plane strain. Non-linear 8-node isoparametric finite elements were used for the numerical simulation. The calculation procedure is detailed elsewhere in the literature [7].

![Figure 1](image_url)

**Figure 1.** Model of contact between two faying surfaces during solid-state bonding: (a) surface asperity model, (b) instantaneous-plastic-flow-induced post-initial-contact bond interface profile, and (c) slip line field method used to calculate half initial contact width, $X_o$. 

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The equivalent strain rate, $\dot{\varepsilon}$, is given by

$$
\dot{\varepsilon} = A_o \left( \frac{D_o b G}{kT} \right) \left( \frac{\bar{\sigma}}{G} \right)^n \exp \left( \frac{Q_c}{RT} \right),
$$

(3)

where $A_o$ is a dimensionless constant; $D_o$, the frequency factor; $k$, Boltzmann’s constant; $\bar{\sigma}$, the equivalent stress; $b$, a Burgers vector; $G$, the shear modulus; $n$, the stress exponent; $Q_c$, the activation energy; and $R$, the gas constant. Table 1 shows the material constants for pure copper, which can be used for $T/T_m = 0.35–0.5$, where $T_m$ represents the melting point (measured in Kelvin) [7, 11].

Figure 2 illustrates the mesh pattern for area OABCD in figure 1 (b) at $t = +0$ for $\alpha_o = 15^\circ$. $L$ represents half the post-initial-contact asperity width. The height of calculation region $H_o$ is given by $H_o = 1.3 \, L_o$. The stress in the y-direction on the DC plane, $\sigma_y$, is given by the bulk stress $\sigma_y = -L_o \, P / L$, where $P$ represents a nominal bonding pressure at $t = 0$. The BC plane is assumed to have been displaced at $\hat{u}_x$, as shown in figure 2. The bulk strain rate in the x-direction, $\dot{\varepsilon}_x = \dot{\varepsilon} \left( \frac{3}{2} \right)$, can be obtained by substituting $\bar{\sigma} = \left( \frac{3}{2} \right)$ $\sigma_y$ into equation (3). Two horizontal meshes (i.e. 8 elements) were added in the range AB when calculating the contact for $\alpha_o = 60^\circ$.

| Table 1. Material constants for annealed oxygen-free copper. |
|-------------------------------------------------------------|
| **Symbols** | **Values** | **Unit** |
| $A_o$ | $7.24 \times 10^{12}$ | |
| $D_o$ | $0.1 \times 10^{-4}$ | m$^2$s$^{-1}$ |
| $b$ | $2.56 \times 10^{-10}$ | m |
| $n$ | $7.72$ | |
| $Q_c$ | $146.7$ | kJ mol$^{-1}$ |
| $T_m$ | $1356$ | K |
| $G(T)$ | $a_G (T/T_m)^2 + b_G (T/T_m) + c_G$, | Nm$^{-2}$ |
| where | $a_G = -4.7 \times 10^{10}$, $b_G = 1.3 \times 10^{10}$, $c_G = 4.6 \times 10^{10}$. | |
| $\sigma_y$ | $[G(T)/G(T_o)] \Gamma(T) \sigma_{y_o}$, | Nm$^{-2}$ |
| where | $\sigma_{y_o} = 380$ MPa at $T_o = 300$ K [17] | |
| $\Gamma(T)$ | $a_o (T/T_m)^2 + b_o (T/T_m) + c_o$, | |
| where | $a_o = -8.8 \times 10^{-1}$, $b_o = 3.47 \times 10^{-1}$, $c_o = 9.6 \times 10^{-1}$. | |

The bonding conditions were $T = 673$ K and $P = 100$ MPa. Half the asperity width, $L_{oo}$, was $10$ µm, and the surface asperity angle, $\alpha_o$, was changed from 15 to 60$^\circ$. The interfacial extension, $\varepsilon$, was calculated from the extension strain of each segment of finite elements along the faying surface (in line OAB in figure 2). During that stage, the initial-contact-induced extension was ignored although the initial contact ratio, $S_o (= X_o/L_o)$, was in the range 13–21% for $\alpha_o = 15–60^\circ$; that is, $\varepsilon$, as defined here, means the post-initial-contact expansion strain of the void surface or contact interface.
Figure 2. Mesh pattern of finite elements used to simulate interfacial contact ($L = L_0$ at $t = +0$).

Figure 3. Definition of segment number along interface and void surface (at $t = +0$).
Figure 3 illustrates the segment number, \( N_s \), and the nodal points of finite elements along the contact interface, OA, and the void surface, AB. As the mother material (i.e. bulk) deforms, the void shrinks and disappears and then full contact is achieved. The contact ratio, \( S \), is then 100%. The contact process was simulated up to the bulk strain \( \varepsilon_B = (L-L_0)/L_0 = 2.0 \).

Figure 4 illustrates interfacial extension and void crushing. The change in the positions of points O, A, B, A’, and O’ is illustrated. Points A and B are called the ‘void tip point’ and ‘void top point’, respectively.

3. Results and discussion

When surface asperities exist on the joining surfaces, the contact is classified as either Type I or Type II interfacial deformation, as shown in Figure 5 [9]. In Type I, the contact is dominated by void tip folding, as shown in figures 5 (a-1–3), when \( \alpha_o < 30^\circ \). Element \( E_A \) touches the bond line (x-axis). However, the contact is mainly produced by the extension of the initial contact area when \( \alpha_o \) is large enough. Element \( E_B \) in figure 5 (b-1) extends to that in figure 5 (b-2). In Type II, void top folding occurs at the void surface adjacent to the top point. Type I and Type II interfacial deformation largely affect the local \( H_i \).

Figures 6, 7, and 8 show the results calculated for the change in the interfacial extension under \( \varepsilon_B \) (i.e. elongation in the x-direction) for \( \alpha_o = 15, 45, \) and \( 60^\circ \), respectively. Each segment number corresponds to that in figure 3. The red marks represent \( \varepsilon_i \) at \( \varepsilon_B \approx 0.01 \). The blue marks represent \( \varepsilon_B \approx 0.03 \). The outline marks represent the points on the void surface. The solid marks, on the other hand, represent the points on the contact interface. The stars represent \( S = 100\% \). Segments \( N_s = 1–4 \) are on the initial contact interface. The extensions at \( N_s = 4 \) are very high in figures 6 and 7. The original void surface shrinks once, despite \( \varepsilon_B > 0 \). The fine dotted lines mean that the extension is negative. In figure 8, for \( \alpha_o = 60^\circ \), segments \( N_s > 6 \) are not shown because they are compressed to -0.4 at \( S = 100\% \) (i.e. \( \varepsilon_B \approx 0.09 \)) and are crushed to about -0.7 at \( \varepsilon_B = 1 \). In other words, the void surface ABA’ in figure 4 is squashed and concentrated for \( \alpha_o = 60^\circ \). Figure 8, on the other hand, shows segments \( N_s = 1–4 \) exhibit very high extension (\( \varepsilon_i \approx 9 \) at \( \varepsilon_B = 1 \)).

Figure 9 shows the fractional metallic contact area, \( M_d \), at \( \varepsilon_B = 2 \) for \( \alpha_o = 15–60^\circ \). Points O, A, B, A’, and O’ correspond to those in figure 4. \( M_d \) is calculated from \( Y \) in equation (1). \( Y = 2/3 \) and \( M_d = 0.44 \) are obtained at \( \varepsilon_B = 2 \) when \( \alpha_o = 0^\circ \) and \( G_d = 0 \). Figure 9 (a) shows that \( M_d \approx 0.45 \) when \( \alpha_o = 15^\circ \), which is nearly equal to that of a flat surface, although points A and A’ show the peak of \( M_d = 0.54 \). Figure 9 (b) shows that even when \( \alpha_o = 45^\circ \), \( M_d \) is rather low around the void top point, B, i.e. the metallic bond is not always facilitated around B, even when the surface asperities become coarse.
**Figure 5.** Change in mesh patterns and Types I and II interfacial contact. Bonding conditions were $T = 973$ K and $P = 30$ MPa. (a-1) Initial mesh pattern for $\alpha_o = 15^\circ$, (a-2) deformed mesh pattern for $\alpha_o = 15^\circ$, (a-3) schematic illustrating Type I (folding mechanism), (b-1) initial mesh pattern for $\alpha_o = 60^\circ$, (b-2) deformed mesh pattern for $\alpha_o = 60^\circ$, and (b-3) schematic illustrating Type II (extension mechanism).

**Figure 6.** Bulk-strain-dependent interfacial extension calculated for $\alpha_o = 15^\circ$. 
Figure 7. Bulk-strain-dependent interfacial extension calculated for $\alpha_o = 45^\circ$.

Figure 8. Bulk-strain-dependent interfacial extension calculated for $\alpha_o = 60^\circ$. 
However, as $\alpha_0$ increases to 60° (figure 9 (c)), $M_a$ becomes very high (> 0.8). The interfacial extension at $\varepsilon_B = 2$ for $\alpha_0 = 60°$ is much greater than that at $\varepsilon_B = 4$ for the flat surface (i.e. $\alpha_0 = 0°$). When the $\alpha_0 = 60°$ faying surface is pressed, the surface oxide film is squashed by interfacial extension and concentrated to B, as shown in figure 9 (c) (i.e. $M_a = 0$). Reiterating, the Type I folding mechanism becomes dominant as the surface asperities become small, inhibiting large local extension and keeping $M_a$ low. The Type II contact mechanism, on the other hand, facilitates metallic bond formation, resulting in high $M_a$. A large asperity angle is effective for breaking surface oxide films because large asperities produce the Type II mechanism.

4. Experimental study

We used 5-ppm-oxygen copper produced from a cold-drawn rod. The diameter and height of the bonding specimen were 10 and 12 mm, respectively. The faying surfaces were machined using a precision lathe to produce triangular ridges arranged at regular intervals. The asperity angle was changed by regulating the tip angle of bit; that is, three asperity angles were produced: $\alpha_0 = 10–15°$, $40–45°$, and $55–60°$ corresponding to $L_{oo} \approx 140 \mu m$, surface roughness (i.e. height, $h_{oo}$) $\approx 32 \mu m$; $L_{oo} \approx 90 \mu m$, $h_{oo} \approx 85 \mu m$; and $L_{oo} \approx 600 \mu m$, $h_{oo} \approx 950 \mu m$, respectively, although $h_{oo}$ was different because of the precision of the lathe machine. The specimen was preheated in dry air at 473 K for 1200 s before pressure bonding, producing a few-hundred-nm-thick surface oxide film on the faying surface [4]. Similar specimens were then pressure welded. Specimens were also subjected to bondless contacting, during which the specimen was set between a die and a pressing tool to observe the oxide film distribution (i.e. the surface exposure), and 20-μm-thick molybdenum (Mo) foil was inserted between the bonding tool and the specimen [10]. The mean surface roughness of the Mo foil was <0.1 μm. The specimen was pressed under a 10^-3 Pa vacuum at designated temperatures in the range 273–673 K.

The reduction in $\varepsilon_H$ (i.e. the compression ratio) of the specimen along the z-axis (i.e. vertical direction) was defined by $\varepsilon_H = \Delta H/H_0 = (H-H_0)/H_0$, where $H_0$ and $H$ represent the heights of the initial and pressed specimens, respectively. The specimen was pressed at $\Delta H/H_0 = -0.5$ under axisymmetric deformation although the results were calculated based on plane strain. Hence, the specimen should be pressed such that $Y$ is the same under axisymmetric and plane strain for a flat faying surface.
The specimens were bonded such that the area expansion, $H_A = (A - A_o)/A_o$, was comparable with that shown under plane strain, where $A_o = \pi R_o^2$ represents the initial bonding area, and $R_o$ represents the initial radius of the specimen. $A$ is obtained from $A = \pi R^2$, where $R$ represents the radius of the pressed specimen, as measured at the joining surface; $\varepsilon_t = 1.0$ is equivalent to $\varepsilon_{lt} = 1.0$ when $\varepsilon_{lt} = -0.5$. If the faying surface is flat and the surface oxide film is brittle enough ($G_d = 0$), $Y = (\pi R^2 - \pi R_o^2)/(\pi R^2) = 0.5$ when $\varepsilon_t = 1.0$. The experiment was performed to determine whether the effects of the asperity angle on the interfacial extension and the distribution of the oxide area in the pressed specimens were consistent with the numerically predicted effects. Hence, the experimental and calculated data were compared for the same $H_A = 1.0$ ($H_{lt} = -0.5$).

Figure 10 shows optical micrographs of the copper side of the contact interfaces between the copper specimen and Mo foil when the foil was removed from the copper specimen. The black (brown) area shows broken oxide film, and the bright (yellow-white) area shows the interface-extension-produced metallic area. The micrographs were obtained during the pressing tests conducted at room temperature because the broken oxide films partially stuck to the Mo foil with increasing pressing temperature. Pressing temperatures in the range 273–473 K did not significantly affect the distribution morphology of the broken oxide film when the bulk strain (or compression ratio) and the asperity angle were kept constant. In figure 10, $\varepsilon_{lt} = -0.5$ but $\varepsilon_t = \varepsilon_{lt} = 1$ under plane strain. The place marked by ‘B’ in each micrograph corresponds to the void top point, B. Further, figure 10 shows that $\alpha_o$ largely affects the distribution of the broken oxide film. In figure 10 (a), the black-brown oxide area is wholly distributed, as suggested by the calculated result shown in figure 9 (a), although a bright

![Figure 10](image-url)
A metallic area is observed in places because the surface roughness is irregular. Figure 10 (b), on the other hand, shows a periodic black stripe whose period length $= \sim 2L$. Figure 10 (c) shows that the black stripe becomes very sharp when $\alpha = 55–60^\circ$. Traces of the interface-expansion-torn-up oxide film are observed in places. Interfacial extension breaks up the oxide film and gathers it at the void top point.

Suppose that the oxide film is only broken by diffusionless plastic deformation. The fractional oxide film area $(1-M_a)$ at the interface of solid-state pressure-welded bonds is larger than the black area in the micrographs in figure 10 because the micrographs correspond to only one side of the bond interface. If the oxide film is brittle enough (i.e. $G_d = 0$), $(1-M_a) = (1-Y)$ on one side and $(1-M_a) = (1-0.7Y)$ if $G_d = 0.3$ [5]. If $A_{ox}$ and $A_M$ represent the black-brown and white-yellow areas in figure 10, respectively, then $(1-M_a) = 1-(A_M/A)^2 = 2(A_{ox}A_M/A)-(A_{ox}/A)^2$, where $A$, $A_{ox}$, and $A_M$ represent the total, oxide, and metallic areas, respectively, and $A = A_{ox}+A_M$.

$A_{ox}$ and $A_M$ were separated using image processing. The 0–255 binary representations were used to convert the original color images into grayscale ones. The black area was obtained as a threshold less than $\theta^* = 60$, i.e., it was binarized using $\theta^* = 60$. For example, the $A_M/A$ was about 0.85–0.90 for $\alpha = 55–60^\circ$. Although exactly quantifying $(1-M_a)$ was difficult as $A_M/A$ naturally decreased with increasing $\alpha$, the tendency of the change in $(1-M_a)$ could be taken into account. Figure 11 shows $(1-M_a)$ and $(1-Y)$, as estimated from the image processing. The red marks represent $(1-Y)$. For the flat surface (i.e. $\alpha = 0^\circ$), $(1-M_a) = 0.75$ at the bond interface and $(1-Y) = 0.5$ at one side surface. The calculated results shown in figure 11 and the experimental results are consistent, suggesting that $G_d$ is nearly zero for a thick copper oxide film, although the experimental error bars are wider than the circles representing the calculated results. The roughness of surfaces showing large asperity angles breaks oxide films and reduces $(1-M_a)$ from 0.75 to 0.2 when $\alpha = -0.5$.

![Figure 11. Influence of asperity angle on fractional oxide area.](image)
5. Conclusion

The interfacial contact of a joining surface containing surface asperities has been discussed. The contact is controlled by void surface folding and interfacial extension. If surface asperities exist on the faying surface, the interfacial extension is not uniform and can be much greater than the bulk extension. Interfacial expansion is facilitated and the oxide film can be easily broken when $\alpha_c > 50^\circ$. The initial void surface exhibits negative extension before full contact. The surface oxide film is gathered to original void top points. Consequently, surface asperities can produce clean metallic surface area much better than flat surface extension can.

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