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# Analytical approach for describing the collapse of surface asperities under compressive stress during rapid solid state bonding

Gaoqiang Chen [a,b], Zhili Feng [b], Jian Chen [b], Lei Liu [a], Han Li [a], Qu Liu [a], Shuai Zhang [a], Xiong Cao [a], Gong Zhang [a], Qingyu Shi [a,*]

[a] State Key Laboratory of Tribology and Key Laboratory for Advanced Materials Processing Technology, Department of Mechanical Engineering, Tsinghua University, Beijing 100084, PR China
[b] Materials Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

## ARTICLE INFO

## ABSTRACT

Many material manufacturing technologies, such as friction stir welding, rely on rapid solid state bonding to join metal surfaces. In this letter, a differential equation is developed to formulate the growing of the interfacial bonded area owing to the collapse of surface asperities under compressive stress during rapid solid state bonding of metal surfaces. The effect of pressure, temperature and bonding time on the growing of bonded area is discussed. The proposed approach is verified by experimental data.

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Different from the conventional solid state diffusion bonding [1,2], many recent material manufacturing technologies [3–12] rely on rapid solid state bonding (SSB) to join metal surfaces, which occurs in much shorter time ranging from several seconds to several hundreds of seconds. These rapid SSB technologies, such as Friction Stir Welding (FSW), Linear Friction Welding (LFW), Accumulative Roll Bonding (ARB) and Porthole Die Extrusion (PDE), have been successfully applied in joining of metal in many structural components [3,5,7], wafer level sealing in microelectromechanical systems (MEMS) devices [6,13] and additive manufacturing [10]. However, low bonded fraction at the bonding interface, as one of the typical defects, has detrimental effects on bonding quality [14,15], such as the mechanical strength and the fatigue life. In order to avoid these defects, the material bonding behaviors at the bonding interface is considered as an important issue in the fundamental understanding of the rapid SSB process.

For the rapid SSB of large variety of metals [6,11,15–19], it was found that high pressure, high temperature and long bonding time are favorable to increase the bonded fraction. Plata and Piwnik [20] proposed a phenomenological criterion to represent the necessary processing conditions to produce sound SSB between metal surfaces. In the subsequent work [21–24], although several improved phenomenological criteria were proposed for the application in different technologies, much less

is known on the interfacial material bonding behavior during the rapid SSB unfortunately.

In this letter, we propose an analytical approach to describe collapse of surface asperities during the rapid SSB of metal surfaces. A differential equation is developed to formulate the growing of the bonded area based on a simplified geometry and the viscoplasticity theory. As an example, the rapid SSB of aluminum alloy 6061 is discussed. Furthermore, the bonding condition in friction stir welding is analyzed by using the proposed approach.

The simplified geometry of the bonding interface is presented first. The cross-sectional view of the geometry model is illustrated in Fig. 1, which illustrates a metal-metal interface that is under-going SSB process. Because of the existence of the surface asperities due to roughness of the original metal surfaces, the interfacial bonded fraction could be very low at the beginning of bonding. In our model, the bonded fraction is noted as the ratio between the real bonded area and the nominal area,

$$f = \frac{S_{bonded}}{S_{nominal}} \tag{1}$$

where $S_{bonded}$ and $S_{nominal}$ denotes the bonded area and the nominal area at the interface respectively.

The model is subjected to a far field compressive stress field, $p_{nominal}$. This compressive stress results in the collapse of surface asperities. The height of the asperities is reduced and the bonded area increases. Note that the volume of the surface asperities is conserved in the plastic
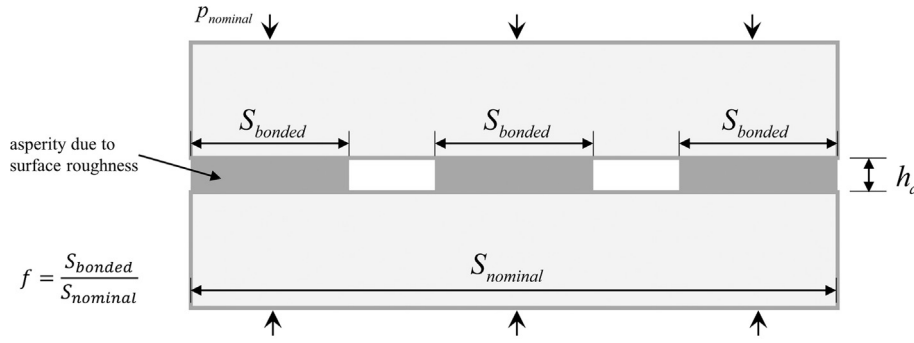
**Fig. 1.** Illustration of bonding interface in the rapid solid state bonding between metal surfaces.

deformation of the surface asperity, we have

$$S_{bonded} \cdot h_a = V_a = \text{constant} \tag{2}$$

where $S_{bonded}$ is the bonded area at the interface and $h_a$ is the height of the asperity.

The height reduction rate of the surface asperities is given by,

$$\frac{dh_a}{dt} = -h_a \cdot \dot{\varepsilon}_a \tag{3}$$

where $h_a$ is the height of the surface asperities and $\dot{\varepsilon}_a$ is the compressive strain rate of the surface asperities due to the applied compressive stress.

By combining Eqs. (1)–(3), the growing rate of the bonded fraction could be obtained as,

$$\frac{df}{dt} = \frac{1}{S_{nominal}} \frac{d}{dt} S_{bonded} = \frac{1}{S_{nominal}} \frac{d}{dt} \left( \frac{V_a}{h_a} \right) = -\frac{V_a}{S_{nominal} h_a^2} \frac{dh_a}{dt} = f\dot{\varepsilon}_a \tag{4}$$

It is interesting to note from Eq. (4) that a simple mathematical equation is established where the growing rate of the bonded fraction is determined by the bonded fraction and the compressive strain rate of the surface asperities.

By the viscoplasticity theory [25], the compressive strain rate of the surface asperities, $\dot{\varepsilon}_a$, could be expressed as a function of the temperature and applied stress on the surface asperities,

$$\dot{\varepsilon}_a = \dot{\varepsilon}_0 \cdot \left( \frac{p_a}{\sigma_R} \right)^{\frac{1}{m}} \cdot \exp\left( -\frac{Q}{RT} \right) \tag{5}$$

where $T$ is the temperature, $p_a$ is the compressive stress on the surface asperities, $\sigma_R$ is a constant, $\dot{\varepsilon}_0$ is a reference strain rate, $R$ is the ideal gas constant, $Q$ is the activation energy of plastic deformation, $m$ is a generally-used factor for the rate sensitivity of plastic deformation [26], given by,

$$m = \frac{d \ln \sigma}{d \ln \dot{\varepsilon}} \tag{6}$$

where $\sigma$ is the stress on material and $\dot{\varepsilon}$ is the resulted strain rate.

In the proposed model, the compressive stress on the surface asperities could be calculated by,

$$p_a = \alpha p_{nominal} / f \tag{7}$$

where $p_{nominal}$ is the nominal pressure on the bonding interface as shown in Fig. 1, $f$ is the bonded fraction defined in Eq. (1), $\alpha$ is a factor accounting for the persistency of the surface asperities [27]. By combining Eqs. (4), (5) and (7), the relation between the bonded fraction and the bonding condition is obtained in form of a differential equation,

given as,

$$\frac{df}{dt} = f \cdot \dot{\varepsilon}_0 \cdot \left( \frac{\alpha p_{nominal}}{f \sigma_R} \right)^{\frac{1}{m}} \cdot \exp\left( -\frac{Q}{RT} \right) \tag{8}$$

By solving the above differential equation under constant temperature and pressure, we get,

$$f = \frac{\alpha p_{nominal} \dot{\varepsilon}_0{}^m t^m}{\sigma_R m^m} \exp\left( -\frac{mQ}{RT} \right) \tag{9}$$

and,

$$\frac{df}{dt} = \frac{\alpha p_{nominal} \dot{\varepsilon}_0{}^m t^{m-1}}{\sigma_R m^{m-1}} \exp\left( -\frac{mQ}{RT} \right) \tag{10}$$

From Eqs. (9) and (10), it could be found that, during rapid SSB, (a) the bonded fraction and its growing rate are both proportional to the nominal pressure on the bonding interface, (b) the growing of the bonded area is a thermal-activation process, the activation energy of which is $mQ$, where $m$ is the rate sensitivity of plastic deformation and $Q$ is the activation energy of the plastic deformation, and that (c) the growing of the bonded area is time dependent and the dependency on bonding time could be described by a power function.

As an example, the rapid SSB of aluminum alloy 6061 at high temperature and high pressure is studied by using the proposed approach. The material constants in Eq. (5) are fitted from the flow stress data of aluminum alloy 6061 ref. [28], which are shown in Table 1.

By using Eq. (9), the bonded fraction at different bonding condition is obtained, as shown in Fig. 2. Fig. 2(a) shows the effect of pressure on the bonded fraction in rapid SSB of aluminum alloy 6061. The bonded fraction increases linearly with the pressure, because higher pressure produces more compressive plastic deformation on the surface asperities, which leads to larger bonded fraction. There is a critical pressure at which full bonding ($f = 1$) is achieved. The critical pressure decreases with temperature. Fig. 2(b) shows the bonded fraction as a function of temperature. At certain interfacial pressure and bonding time, the bonded fraction increases with the temperature owing to its thermal-activation nature. Generally, at constant pressure condition, higher temperature is required for full bonding if the bonding time is shortened. Fig. 2(c) shows the effect of bonding time on the bonded fraction. It is clear that the growing of the bonded fraction is non-linearly related to the bonding time owing to the rate sensitivity factor, $m$. As the value of $m$ is much less than 1, the bonded fraction increases with bonding time while the growing rate of the bonded fraction decreases. For the purpose of verifying the model, the model results are compared to the experimentally obtained values in the literature [29] in Fig. 2(c). It could be found that the present model is able to accurately predict the material bonding behavior within wide range of pressure, temperature and bonding time.

**Table 1**
Material constants for AA6061.

| Parameters | Values |
|---|---|
| $m$ | 0.175 |
| $Q$ | 175.1 kJ/mol |
| $\sigma_R$ | 0.83 MPa |
| $\dot{\varepsilon}_0$ | $0.001 s^{-1}$ |
| $R$ | 8.3145 kJ/(mol K) |
| $\alpha$ | 0.45 |

This analytical investigation provides a straight-forward mathematical approach for understanding and design of the rapid SSB process. However, very limited published experimental data could be used for directly verification of the analytical approach. Here, we use the bonding conditions in FSW to provide some support for the proposed analytical approach. FSW [3,12] is a newly developed rapid SSB-based manufacturing technology. In FSW, solid state materials experience high pressure and high temperature under the welding tool whose diameter is denoted as $D$. The time for SSB could be determined by $t_{welding} = D/v_w$, where $v_w$ is the welding speed in FSW. The average welding pressure in FSW is generally estimated by $p_{welding} = F/A_{shoulder} = 4F/(\pi D^2)$ where $F$ is the axial compressive force by the welding tool [30–32]. The bonding conditions in the FSW of AA6061 by Khandkar et al. [33], Assidi et al. [34] and Elangovan et al. [35] are determined and plotted in Fig. 3. The temperature in Khandkar et al. [33]'s work is estimated from another experimental study [36].

By letting $f = 1$ in Eq. (9), the minimum required bonding time for the formation of the SSB in FSW could be given as,

$$t_{bonding, min} = \left(\frac{\sigma_R}{\alpha p_{welding}}\right)^{\frac{1}{m}} \frac{m}{\dot{\varepsilon}_0} \exp\left(\frac{Q}{RT}\right) \tag{11}$$

where the constants are taken as the same as the above values in Table 1. The predicted bonding conditions at temperatures of 430 °C, 487 °C and 539 °C are shown by the colored lines in Fig. 3. By comparing the predicted and experimental bonding conditions, it is found that the experimental bonding time in FSW is close to or above the predicted
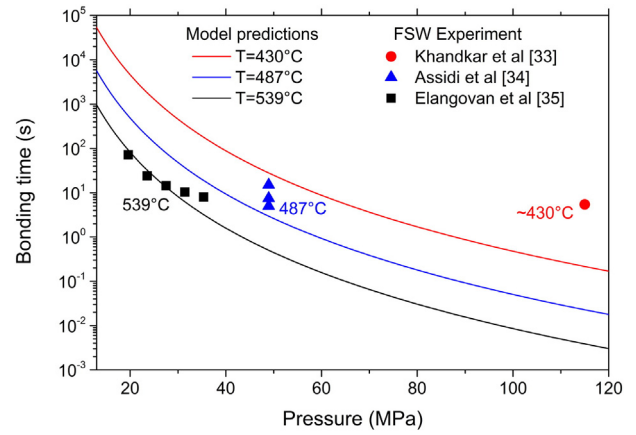
**Fig. 3.** Comparison of modeled and experimental bonding condition for solid state bonding in friction stir welding. The experimental data for friction stir welding was reported by the literatures [33–35].

minimum required bonding time. This indicates that the predictions and the experiments are consistent. It could be also found that, with certain bonding time, i.e. welding speed, the increase of welding pressure allows FSW at lower temperature, which is important for many structural materials, such as carbon steel [37]. However, if the welding temperature is over reduced when the pressure is not high enough, welding defects would be generated [38]. These comparisons and discussions further convince that the proposed approach is able to predict the material bonding behavior in the rapid SSB process.

It is worth noting that the application of the proposed approach in FSW can be further improved in future studies. The calculation of pressure in FSW in the above discussion was simplified based on the assumption [30–32] that the pressure is uniformly distributed under the welding tool. In the calculation, the pressure in the processing zone is determined by the vertical compressive force divided by the shoulder area during FSW, while the influence of other factors such as material flow, is ignored. By using this method, the calculated average pressure value in this study is reasonable in comparison to the normal stresses by in situ neutron diffraction measurements [39]. Owing to the
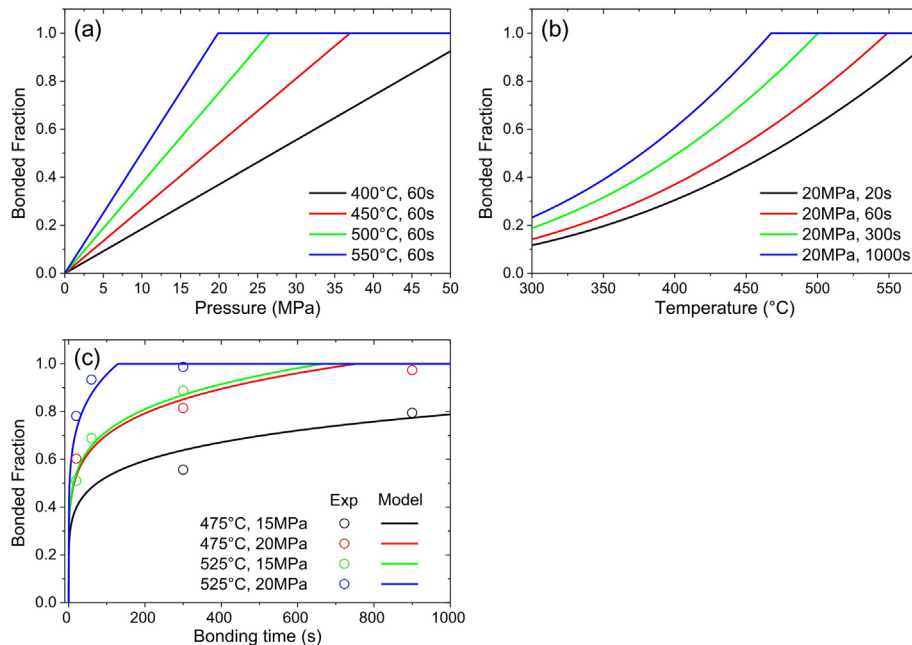
**Fig. 2.** Effect of pressure (a), temperature (b) and bonding time (c) on the bonded fraction. The experimental data is obtained from literature on solid state bonding of 6061 aluminum alloy at various conditions [29].

important role of pressure in controlling the SSB in FSW and the related defects such as kissing bond, it is still very necessary to further develop approaches such as numerical simulation in Buffa et al.'s studies [40,41], in order to characterize the pressure distribution during the FSW process. With the improved pressure calculation, the application of the proposed approach in analyzing the FSW process should be improved greatly.

In conclusion, we have presented an analytical approach to formulate the material bonding behavior in rapid solid state bonding between metal surfaces. A differential equation is proposed to formulate the growing of the bonded area at different bonding conditions. It has been shown that the bonded fraction and its growing rate are both proportional to the nominal pressure at the interface. The growing of bonded area is a thermal-activated process, the activation energy of which is determined by rate sensitivity and activation energy of plastic deformation. The growing of the bonded area is time dependent and the dependency on bonding time could be described by a power function. The comparison between the model and literature data shows that the proposed analytical approach is capable of accurately describing the collapse of surface asperities in the rapid SSB between metal surfaces. This analytical investigation provides a straight-forward mathematical approach for understanding and design of the rapid SSB process.

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