The Influence of the Solid-State Bonding Process on the Mechanical Integrity of Longitudinal Weld Seams∗

Simon-Peter EDWARDS∗∗, Andrew J. Den BAKKER∗∗∗, Jan L. NEIJENHUIS∗∗∗, Wilhelmus H. KOOL∗∗∗∗ and Laurens KATGERMAN∗∗∗∗

For production of complex hollow 6xxx series aluminium extrusions, porthole dies are the predominant tooling set up. In porthole dies, the billet is divided into multiple metal streams, which are rejoined in the weld chamber to form ‘longitudinal weld seams’. Fundamental understanding of the solid state bonding process, as well as the ability to detect a well bonded (or a defective) weld seam are important for the production of high quality structural hollow extrusions. A study is being conducted to investigate the solid state bonding and weld seam formation processes during extrusion. The method chosen was to use a thermomechanical simulator (Gleeble 3500), thereby having the ability to vary process parameters such as strain, strain rate and temperature. The alloy investigated was primary and remelt AA6082. It was determined that the key parameter for bonding is surface stretching (creation of new surface at the interface) and bonding time.

Key Words: AA 6082, Solid-State Bonding, Extrusion, Weld Seam

1. Introduction

During extrusion through a porthole die solid-state bonding takes place as the metal streams join under the mandrel suspensions and so form a ‘longitudinal weld seam’(1). Previously, in the literature there has been great interest studying weld seam formation using FEM calculations(2). However, there is a scarcity of work dealing with the subject of how process parameters affect the formation of the weld seams. Previous work concentrated rather on die design and parameters, material properties and flow through the die. This work aims to give insight into fundamental aspects of the solid state bonding process occurring in weld seam formation.

2. Experimental

The strategy adopted was to investigate weld seam formation by pressing (or ‘bonding’) two Al surfaces under specific pre-defined experimental conditions. A schematic diagram of the experimental set-up is shown in Fig. 1. The experiments were performed using a thermomechanical simulator (Gleeble 3500). The alloy chosen was homogenised AA6082 with both primary (commercially pure) and remelt (containing approximately 75% scrap and 25% primary ingot) billet sources studied. The strain (ε) and strain rate (dε/dt) are controlled by changing the length of L₀ and the deformation time, respectively. ΔL is the displacement (in these experiments value is negative) and L₀ is the length of the deformed region known as the ‘barrelled’ region. The samples were spark eroded from a 123 mm thick billet slab. The sample dimensions were 10 mm in diameter and 123 mm in length. For no more than one day prior to testing the samples are cut in half, with no grinding or polishing, and immersed in ethanol to minimise oxide growth. The experiments are carried
out in a vacuum ($< 10^{-1}$ Torr). The test consisted of the following sequence; the halves of the samples were axially aligned with the cut faces in contact. A pre-force was applied to ensure electrical contact for resistance heating to the set temperature. The temperature was allowed to stabilise throughout the sample for 30 seconds, before deformation with the pre-defined parameters ($T, \varepsilon, \dot{\varepsilon}$). After deformation, an air quench using compressed air was applied for 2 minutes, allowing the temperature to drop below $50^\circ$C. Experiments were performed characterised by four ‘deformation’ strains, with each deformation strain using three temperatures ($480^\circ$C, $520^\circ$C and $560^\circ$C) and three deformation rates (1, 10 and 100 s$^{-1}$). A thermocouple was placed as close as possible to the interface of the sample to monitor the temperature during deformation. The different deformation strains and strain rates during the Gleeble experiments resulted in different barrel diameters centred on the interface. After the experiments, the diameter change $\Delta D$ is measured at multiple locations around the interface. Since it is expected that the creation of new surface is advantageous for bond formation, a value $\omega$ representing the amount of surface stretching at the interface is defined in Eq. (1):

$$\omega = \left(\frac{D_o + \Delta D}{D_o}\right)^2 - 1$$

(1)

Where $D_o$ is the original diameter. The surface stretching rate ($\dot{\omega}$) can be obtained by dividing the stretching parameter by the deformation time:

$$\dot{\omega} = \frac{\omega}{t_B}$$

(2)

The stress ($\sigma$) is the force applied during deformation per unit of interface and is calculated in-situ by the Gleeble 3500 thermo-mechanical simulator using the equation:

$$\sigma = \frac{\text{Force}}{\pi(D_o)^2\frac{L_o}{4}}$$

$$= \frac{4}{L_o + \Delta L}$$

(3)

After deformation a certain bending load was applied to the samples under similar but not well defined conditions. If a sample did not fracture, a bond was considered to have formed.

3. Results

3.1 The physical characteristics of the deformed region

During deformation the samples formed a deformed region that was characterised by a ‘barrel’ centred on the interface. The most obvious difference between the two billet sources is seen in the appearance of a much rougher surface over the barrel in the samples from the remelt billet source, shown in Fig. 2. This surface difference is observed at all deformation strains and deformation rates. The relationship between the barrelling length ($L_B$) and surface stretching parameter ($\omega$) is shown in Fig. 3. The figure does not differentiate between the different strain rates or temperatures ($T$) and suggests that $L_B$ is independent of $\dot{\omega}$ and $T$.

The figure exhibits little variation in the $L_B$ values over a wide range of $\omega$ values, which means that except for the first stage of deformation it is mainly the diameter that changes. Therefore, the shape of the barreled region does not remain constant during deformation. The dashed line in Fig. 3 (a) is a fit through the data points. For
comparison’s sake, the line in Fig. 3 (b) is identical so any differences are highlighted. The most obvious difference between the billet sources is that for \( \omega \leq 0.72 \), lower \( L_B \) values are seen in the remelt billet source.

### 3.2 Conditions for bonding: effect of surface stretching

Figure 4 plots the surface stretching parameter in terms of whether a bond was formed or not. The figure is independent of \( T \) and \( \dot{\omega} \).

It is evident from Fig. 4 that there are three regions present: for \( \omega \leq 0.4 \) bonds do not form; this will be referred to as the ‘non-bonding region’ (region 1). Conversely, for \( \omega \geq 0.72 \) bonds are readily formed, this will be referred to as the ‘bonding region’ (region 3). Between the \( \omega \) values (0.4 \( \leq \omega \leq 0.72 \)) there is a region, referred to as ‘intermediate’ region (region 2), where there is a mixture of samples that bonded and did not bond. In region 2 it is thought that other parameters such as surface stretching rate (\( \dot{\omega} \)) and temperature become more important in determining whether a bond is formed or not. Since a large amount of the data points overlap each other in Fig. 4, Tables 1 and 2 give a breakdown of how many samples bonded and how many did not bond.

The results show that there is no significant difference between the two billet sources in terms of bonding behaviour. Therefore, for the remainder of the paper the results from only one billet source will be presented.

### 3.3 Conditions for bonding: effect of surface stretching rate, temperature, bonding time and stress

In this section, it is investigated whether the introduction of a new criterion, for the intermediate region, will result in a discrimination between non-bonding/bonding.

#### 3.3.1 Effect of surface stretching rate (\( \dot{\omega} \))

Figure 5 introduces a ‘second’ criterion based on the \( \dot{\omega} \) data. This means that the intermediate region disappears so that there are only two regions i.e. region 1, that describes the non-bonding condition and region 2, that describes the bonding condition. Generally it can be seen from the ‘intermediate region’ in Fig. 5 that the lower the surface stretching rate the more likelihood there is that a bond will be formed. The dotted line shows the bonding/non-bonding boundary based on this second criterion.

Table 1 The amount of bonded and non-bonded samples for each region, for the primary billet source. Total samples studied were 104 samples

<table>
<thead>
<tr>
<th>Region</th>
<th>Non–bond: Number (%)</th>
<th>Bond: Number (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Non–bond)</td>
<td>27 (97%)</td>
<td>1 (3%)</td>
</tr>
<tr>
<td>2 (Intermediate)</td>
<td>6 (38%)</td>
<td>10 (62%)</td>
</tr>
<tr>
<td>3 (Bond)</td>
<td>0 (0%)</td>
<td>60 (100%)</td>
</tr>
</tbody>
</table>

Table 2 The amount of bonded and non-bonded samples for each region, for the remelt billet source. Total samples studied were 100 samples

<table>
<thead>
<tr>
<th>Region</th>
<th>Non–bond: Number (%)</th>
<th>Bond: Number (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Non–bond)</td>
<td>30 (94%)</td>
<td>2 (6%)</td>
</tr>
<tr>
<td>2 (Intermediate)</td>
<td>4 (22%)</td>
<td>14 (78%)</td>
</tr>
<tr>
<td>3 (Bond)</td>
<td>1 (2%)</td>
<td>49 (98%)</td>
</tr>
</tbody>
</table>

Fig. 4 Bonding data as a function of surface stretching parameter for (a) primary and (b) remelt. (1) designates the non-bonding region, (2) the ‘intermediate’ region and (3) the bonding region. \( \bullet \) = bond, \( + \) = non-bond

Fig. 5 Bonding condition for various surface stretching rates and surface stretching parameters. (1) designates the non-bonding region and (2) the bonding region. \( + \) = non-bond, \( \bullet \) = bond
Fig. 6 Bonding condition for various bonding times and surface stretching parameters. (1) designates the non-bonding region and (2) the bonding region. + = non-bond, • = bond

Region 1 (non-bonding): Region 2 (bonding):
For $\omega \leq 0.4$ all $t_B$; For $\omega \geq 0.72$ all $t_B$;
For $0.4 \leq \omega \leq 0.72; \hat{\omega} \geq 20\,s^{-1}$ For $0.4 \leq \omega \leq 0.72; \hat{\omega} \geq 20\,s^{-1}$

3.3.2 Effect of bonding time ($t_B$) Figure 6 introduces a ‘second’ criterion based on the $t_B$ data. The intermediate region disappears so that there are only two regions i.e. region 1, that describes the non-bonding condition and region 2, that describes the bonding condition. Bonding time ($t_B$) (i.e. deformation time) is closely related to $\omega$ by Eq. (2). The non-bonding/bonding criteria is defined below:

Region 1 (non-bonding): Region 2 (bonding):
For $\omega \leq 0.4$ all $t_B$; For $\omega \geq 0.72$ all $t_B$;
For $0.4 \leq \omega \leq 0.72; t_B \leq 0.03\,s$ For $0.4 \leq \omega \leq 0.72; t_B > 0.03\,s$

Generally it can be seen from the ‘intermediate region’ in Fig. 6 that the longer the bonding time the more likely a bond will be formed. The dotted line shows the bonding/non-bonding boundary based on this second criterion.

3.3.3 Effect of temperature ($T$) Figure 7 introduces a ‘second’ criterion based on the temperature data. The intermediate region disappears so that there are only two regions i.e. region 1, that describes the non-bonding condition and region 2, that describes the bonding condition. The non-bond/bond regions have been defined as

Region 1 (non-bonding): Region 2 (bonding):
For $\omega \leq 0.4$ all $T$; For $\omega \geq 0.72$ all $T$;
For $0.4 \leq \omega \leq 0.72; T \leq 505^\circ C$ For $0.4 \leq \omega \leq 0.72; T \geq 505^\circ C$

3.3.4 Effect of stress ($\sigma$) Figure 8 introduces a ‘second’ criterion based on the $\sigma$. The intermediate region disappears so that there are only two regions i.e. region 1, that describes the non-bonding condition and region 2, that describes the bonding condition. The non-bonding/bonding criteria for $\sigma$ can be defined as follows as:

Region 1 (non-bonding): Region 2 (bonding):
For $\omega \leq 0.4$ all $\sigma$ For $\omega \geq 0.72$ all $\sigma$
For $0.4 \leq \omega \leq 0.72; \sigma \geq 65\,MPa$ For $0.4 \leq \omega \leq 0.72; \sigma \leq 65\,MPa$

The figure shows that bonds are formed very readily at stress levels as low as 15 MPa. However, there is no logic in the criterion since for certain $\omega$ values, bonding is promoted by low stresses and vice versa. This issue will be addressed accordingly in section 4.1

3.3.5 Summary of the effect of these parameters The criteria applied to the ‘intermediate region’ are based on surface stretching rate, bonding time, temperature or stress and led to an excellent discrimination between non-bonding and bonding.

However, since the same data set is used in all cases, the surface stretching rate, bonding time, and stress are not independent parameters. This means that the result of the discrimination for these cases is identical. The results are given in Table 3.
4. Discussion

4.1 The assessment of criteria

Figure 9 displays bonding times, stresses, and temperatures arranged into fields containing similar values. It can be seen that not all experimental conditions are independent. For instance, high values of the stress involve also high values of the strain rate or short bonding times. This explains the illogical observation in section 3.3.4 that in the intermediate region bonding was observed for the low stresses and non-bonding for the high stresses. With this set of experimental conditions a determining factor in bonding or non-bonding is therefore not the stress. Apparently the stresses applied are sufficient for obtaining a good bond and a critical stress below which bonding is not obtained should be lower than 15 MPa. The message that should be taken from Fig. 9 is that it is not possible to have all parameter combinations independent of each other using the present experimental approach.

An attempt to relate the concept of diffusion to bonding/non-bonding was introduced by calculating a diffusion length (x) from the bonding time data, using the equation $x = \sqrt{D_{Al} t_b}$. The aluminium diffusion coefficients were taken from Ref. (3) and are given in Table 4.

It was seen that with a diffusion length of 100 nm (~ 300 atomic distances) both bonding (high strains) and non-bonding (low strains) are observed, which means that a criterion only based on diffusion (length) was rejected. Using the criteria given in section 3.3, it can be seen that all the criteria give the same discrimination between bonding/non-bonding (Table 3). In spite of this, stress and temperature are considered to be above a critical (low) value for this set of experiments and are not considered as realistic parameters for the discrimination of bond/non-bonding. Surface stretching rate and bonding time (Eq. (3)) are closely linked, and regarding these two parameters bonding time is considered as the more relevant parameter. It is therefore concluded that the main parameters which determine bonding/non-bonding are firstly the surface stretching parameter $\omega$ and secondly bonding time. The surface stretching parameter is closely linked to the creation of new, non-oxidized interface surface (1).

4.2 Uncertainties and limitations of the criteria

Figure 4 has been used as the basis for a first criterion for bonding that relates the amount of surface stretching at the interface during deformation to whether a bond is formed or not. Due to lack in the experimental data near the boundaries of the intermediate zone (region 2), at $0.4 \leq \omega \leq 0.72$ this area requires some further research. Since the quality of bonding was not considered (only bonding or not bonding) and the testing method used was simple, controlled and more elaborate testing methods should be applied in future for determining the joint strength. However, the determination of bond quality is not yet well established and should in fact be dependent on the load conditions during service. It is thought that a static tensile test is not adequate enough to define bond quality and therefore the use of dynamic testing methods will be necessary.

In defining the criteria, as is done in Fig. 6, the distinction is taken as simple as possible and therefore based on fixed, constant parameter values. A different shape of the transition boundary (such as for instance line (b) in Fig. 10) might yield similar or even better results. How-

---

Table 3 The amount of bonded and non-bonded samples for each region, for the primary billet source

<table>
<thead>
<tr>
<th>Region</th>
<th>Non-bond: Number (%)</th>
<th>Bond: Number (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Non-bond)</td>
<td>29 (97%)</td>
<td>1 (3%)</td>
</tr>
<tr>
<td>2 (Bond)</td>
<td>3 (4%)</td>
<td>71 (96%)</td>
</tr>
</tbody>
</table>

Table 4 Diffusion coefficients, taken from Ref. (3)

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>$D_{Al}$ ($10^{-11}$ m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>480</td>
<td>0.7</td>
</tr>
<tr>
<td>520</td>
<td>4</td>
</tr>
<tr>
<td>560</td>
<td>7</td>
</tr>
</tbody>
</table>

Fig. 9 Process parameters, grouped together. The non-bond/bonding transition is indicated by the dotted line.

Fig. 10 Examples of possible non-bond/bond criteria.
ever, lack of sufficient data does not justify at this stage of the research the use of a more sophisticated transition boundary. A limitation in this work is that the temperature or local stress appears to be of less importance, but certainly by using low temperatures or stresses bonding will not be achieved. Critical temperatures or stresses below which bonding will not occur were outside the parameter range studied in this work. Therefore, the boundaries of the criteria depend on more parameters than only the two assumed in this work. A further limitation is that certain parameters could not be chosen independently, for instance low stresses always combined with long bonding times. In these compression tests shear deformation along the interface is not expected to play a role, due to the symmetrical set-up. During extrusion, shear deformation is possible and shear deformation is expected to promote bonding. As such, this type of experiment without shear deformation at the interface should provide the most critical data when applied to extrusion practice.

5. Conclusions

The most influential parameter on bonding is the surface stretching parameter, $\omega$. This parameter accounts for the amount of new interfacial surface created during deformation. Furthermore, a long bonding time, $t_B$ is also useful in promoting bonding. A simple criterion involving these process parameters gives excellent discrimination between bonding/non-bonding with only a few errors. In these experiments not all process parameters could be adjusted independently. Stress and temperature were sufficiently high not to influence bonding. An influence in the bonding behaviour of different billet sources was not found.

Acknowledgements

This research was carried out under the research program of the Netherlands Institute for Metals Research (Project No. MC4.00083). The authors would like to thank Thim Zuidwijk for his assistance during the Gleeble thermo-mechanical simulator experiments.

References