Influence of contact pressure on the thermal contact conductance of layered AA3003 aluminium

TAISHI MATSUSHITA¹, ILIA BELOV¹, ANDERS JOHANSSON² and ANDERS E. W. JARFORS¹

¹School of Engineering
Jönköping University
Gjuterigatan 5, Jönköping
SWEDEN
²Gränges Sweden AB
SWEDEN
taishi.matsushita@ju.se

Abstract: For the optimization of the annealing process of aluminium coils, simulation of the process is often performed. To simulate the process with higher accuracy, reliable input parameters are required and the thermal conductivity (thermal contact conductance) is one of them. In the present study, the thermal conductivity and thermal contact conductance of AA3003 alloy sheets were measured by a steady state comparative longitudinal heat flow method at different contact pressure. To evaluate the thermal conductance at the interface, thermal resistance network model was applied. In addition, the surface roughness of the sheets was also investigated. Based on the measurement results, the semi-empirical equation for the relationship between thermal contact conductance and contact pressure was obtained.

Key-Words: - Thermal conductivity; Thermal contact conductance; Pressure; Surface profile; Aluminium; AA3003; Coil;


1 Introduction
To optimise the annealing process for industrial Al coils, it is required to simulate the temperature change against time, local temperature change, heating rate, etc. For the simulation, radial thermal conductivity and thermal contact conductance are required. It is known that they vary with the contact condition between coil strips. Possible factors which may affect the contact condition are i) contact pressure (winding force of the coil), ii) surface roughness of the coil strip and iii) macroscopic waviness of the surface. It is expected that the contact conductance increases with the contact pressure [1]. This fact can be understood by considering the increase of actual contact area at the interface due to the elastic or plastic deformation with increasing the contact pressure. The actual contact area will be also influenced by the surface roughness and macroscopic waviness of the surface as well. Hence, it is important to measure the effective thermal conductivity of the layered structure and thermal contact conductance (resistance) under the contact conditions similar to the actual coil. In the present study, a lab-scale apparatus was built to mimic the coil strip layers in terms of contact pressure, surface condition and thickness of the strips. Next, the influence of the contact pressure between the AA3003 aluminium alloy sheets on the thermal conductivity and thermal contact conductance was investigated. To evaluate the thermal conductance at the interface, thermal resistance network model [2] was applied. In addition, the surface roughness of the sheets was measured and the influence on the aforementioned factors was discussed. Apart from the academic interests, the results of this work should be of interest for process engineers to estimate the effective radial thermal conductivity of Al coils as part of the annealing process design.

2 Experimental
2.1. Materials
AA3003 aluminium alloy (Gränges Sweden AB) was chosen for the present study. Square samples (27 mm×27 mm) were cut out from the rolled AA3003 aluminium alloy sheets of different thickness. The samples had a thickness 0.1, 0.4 and 0.8 mm. The nominal composition of AA3003 aluminium alloy is shown in Table 1.
Table 1 Nominal composition of AA3003 aluminium alloy (mass %)

<table>
<thead>
<tr>
<th></th>
<th>Mn</th>
<th>Fe</th>
<th>Si</th>
<th>Zn</th>
<th>Cu</th>
<th>Others</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.0–1.5</td>
<td>Max. 0.7</td>
<td>Max. 0.6</td>
<td>Max. 0.1</td>
<td>0.05–0.20</td>
<td>Max. 0.15</td>
<td>Balance</td>
</tr>
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2.2. Apparatus

The thermal conductivity and thermal contact conductance were measured by a steady state comparative longitudinal heat flow method. A photo and a schematic illustration of the experimental set up are shown in Figure 1 and Figure 2. The apparatus consists of a testing machine for tensile and compression tests (Zwick/Roell Z100) which can apply pressure up to 100 kN, control unit of the testing machine, IR-camera (FLIR T640) to measure the temperature and an in-house made heater which can be heated up to 400 °C. The side surface of the pushrod and samples were coated by graphite using a graphite spray (Svenska Tanso AB) and the emissivity value for the IR camera was decided by referring the temperature measured by a K-type thermocouple.

2.3. Procedure

The AA3003 sheets were piled up and sandwiched by pushrods made of aluminium which thermal conductivity is known (Figure 2). The number of layers was 40 layers for 0.1 mm sheets, 14 layers for 0.4 mm sheets and 10 layers for 0.8 mm sheets. The top surface of the pushrod was heated to 300 °C and the force was applied to the test sample. The applied forces were 1, 5, 10 and 30 kN which corresponded to pressure P equal to 1.3, 6.4, 12.8 and 38.3 MPa, respectively. After 15 min, when the system reached the steady state, the temperatures $T_1$, $T_2$, $T_3$ and $T_4$ were measured by IR-camera, Figure 2. The experiments were carried out in the air atmosphere. The heat flux through pushrod 1, $q_1$, was calculated from the temperature difference $T_1$ and $T_2$. The heat flux through pushrod 2, $q_3$, was calculated from the temperatures $T_3$ and $T_4$, and the average of $q_1$ and $q_3$ was taken as the heat flux through the test sample, $q_2$. The temperature of the sample part was between 246.8–283.7 °C depending on the pressure and the sample composition. Thermal contact conductance at each interface was evaluated using the measured temperatures $T_2$ and $T_3$ and AA3003 thermal conductivity. To estimate the thermal conductivity of AA3003 at the experimental temperature, firstly, the thermal diffusivity of AA3003 at 25°C was calculated using the thermal conductivity of AA3003 at 25°C (155 W·m$^{-1}$·K$^{-1}$) [3], density and specific heat capacity at constant pressure at 25°C calculated by Thermo-Calc software (TCAL6 database). Then, by considering temperature dependency of the thermal diffusivity of Al alloys (Eq. 1) [4], density and specific heat capacity at constant pressure at the experimental temperature were calculated using Thermo-Calc software.
Finally, the thermal conductivity of the AA3003 alloy at the experimental temperature was estimated as 180 W·m⁻¹·K⁻¹.

\[ \alpha_T = \alpha_{298} \cdot \left\{ 1 + 2 \cdot \left( \frac{T-298}{275} \right) \cdot 10^{-2} \right\} \]  

where \( \alpha_T \) is the thermal diffusivity at temperature \( T \), \( \alpha_{298} \) is the thermal diffusivity at 298 K.

According to the Thermo-Calc calculation, the temperature coefficient of the specific heat capacity at constant pressure is \( 5.4 \times 10^{-4} \) and the temperature coefficient of the density is \( -1.8 \times 10^{-4} \), and thus the change in thermal conductivity within the sample temperature gradient (246.8–283.7 °C) can be neglected.

It was assumed that the temperature drop \( \Delta T \) is the same at each interface including the interface between the pushrod and the sample (Figure 3). It was assumed that the temperature drop between the pushrod and the sample is the same as that between sample sheets. However, the measurement error caused by this assumption can be neglected due to the large number of layers in the test sample. The heat transfer by conduction was dominant in the setup, therefore, the heat transfer by radiation and convection is neglected in the further analysis.

3. Results and Discussion
3.1 Thermal contact conductance and thermal contact resistance

The thermal contact conductance, \( h \), of each interface at different pressures is shown in Figure 4, Figure 5 and Figure 6. The thermal contact resistance, \( R(=1/h) \), is also plotted in the same graphs for the convenience.

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Figure 2 A schematic illustration of the temperature drop.

Figure 3. Thermal contact conductance and thermal contact resistance (0.1 mm sample)

Figure 4. Thermal contact conductance and thermal contact resistance (0.4 mm sample)
Figure 5. Thermal contact conductance and thermal contact resistance (0.8 mm sample)

As can be seen from the above figures, the thermal contact resistance decreases drastically with pressure at lower pressure range followed by the moderate change, and then become constant (approximately $3 \times 10^{-6}$ m$^2$K/W). The significant influence of the thickness on the thermal contact resistance was not found.

3.2. Uncertainty of the measurement

The uncertainty of the measurement was assessed using GUM based analysis [5]. The thermal contact conductance, $h$, can be expressed as follows using directly measured values, i.e. $T_1$, $T_2$, $T_3$, $T_4$, the total thickness of the sample layer $L$, distance $x$ between measurement points for $T_1$, $T_2$, $T_3$ and $T_4$, thermal conductivity of the push-rod $k_{rod}$, thermal conductivity of the metal sheet, $k_M$, and number of layers $N$.

$$h = \frac{(N+1)(A+B)}{2(T_2-T_3-(A+B)L/k_M)}$$

(2)

where $A = -\frac{k_{rod}(T_2-T_1)}{x}$ and $B = -\frac{k_{rod}(T_4-T_3)}{x}$.

The combined uncertainty was calculated using the following equation:

$$u_h = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial h}{\partial z_i}\right)^2 u^2(z_i)}$$

(3)

where $z_i$ is the factors used in the equation for $h$ (Eq. 2).

According to the analysis, the influence of the uncertainties in $T_2$ and $T_3$ is dominant and the influence is $10 – 100$ times higher than that of the other parameters.

3.3. Curve fitting for thermal contact conductance

Theoretically, the contact thermal conductance should not depend on the thickness of the sheets, provided that the surface roughness is similar. Therefore, the results from different thickness samples can be treated as a set. It is known that the actual contact area at the interface is proportional to $P^{2/3}$ for the elastic deformation [6]. Therefore, it is expected that the thermal contact conductance, which is proportional to the actual contact area, follows the same relation. A curve fitting was made for the thermal conductance against pressure using the experimental results under the pressure 1.3 and 6.4 MPa since, presumably, the influence of the elastic deformation is still dominant, and the result, $h = 478 \times 10^2 P^{2/3} + 841 \times 10^2$, is shown with the dotted line in Figure 7. The above-mentioned experimental uncertainty is shown as error bars in the graph.

Figure 6. Thermal contact conductance (0.1, 0.4 and 0.8 mm samples)

As can be seen in Figure 7, the deviation of the thermal contact conductance values from the fitting curve becomes larger with pressure as it exceeds the elastic deformation range. For the comparison, the empirical curve which is fitted using all data points is shown with the dashed line. The empirical equation for the fitting is $h = -210P^2 + 155 \times 10^2 P + 1.33 \times 10^5$. 
3.4. Actual contact area fraction and actual contact area ratio

It is known that the increase of the thermal contact conductance with contact pressure is due to the increase of the actual contact area. The metal-to-metal contact area fraction, $f_c$, i.e. the fraction of actual contact area between the sheets, was estimated from the measured thermal contact resistance by means of the commonly used thermal resistance network model. (Figure 8).

\[ \frac{1}{R} = \frac{1}{R_M} + \frac{1}{R_G} \]  

\[ R = \frac{b}{k_M f_c + k_G (1 - f_c)} \]

where $b$ is the thickness of the interface i.e. air gap (based on the surface profile measurements mentioned in the next section (Section 3.5, $b$ is estimated as 6 μm), $k_M$ is the thermal conductivity of metal (AA3003), $k_G$ is the thermal conductivity of the gas phase (air), $f_c$ is the contact area fraction.

By using the above equation, $f_c$ and the actual contact ratio, $\Phi$ ($= f_c / (1 - f_c)$) were calculated and the results are shown in Figure 9 and Figure 10. The actual contact area ratio, $\Phi$, in the present study, approximately $5 \times 10^{-3} - 2 \times 10^{-2}$, reasonably agrees with the literature values [7]. Note that $\Phi \approx f_c$ as can be seen from Figure 9 and Figure 10 since the value of $f_c$ is small.

3.5. Surface profile of the sheets

It is known that thermal contact conductance depends on the surface condition and one of the factors is surface roughness. To investigate the influence of the pressure on the contact surface profile (interfacial contact), the samples were pressed at the desired pressure (0, 1.3, 6.4, 12.8 or 38.3 MPa) and after the releasing of pressure, the surface profile was measured. The surface profile measurements were carried out using the Taylor WSEAS TRANSACTIONS on HEAT and MASS TRANSFER DOI: 10.37394/232012.2020.15.10

Taishi Matsushita, Ilia Belov, Anders Johansson, Anders E. W. Jarfors

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Hobson, Surtronic 3+. A typical result of the surface profile measurement is shown in Figure 11 (0.8mm sheet, before pressing). The significant influence of the pressure or thickness of the sheet on the surface profile (maximum height) was not observed (cf. Figure 12, 0.8mm sheet, after 38.3 MPa applied pressure).

Figure 10. Surface profile (0.8mm sheet, before pressure applied)

The height of the gap (thickness of the interface), \( b \), in the thermal resistance network model (Figure 8) which is mentioned in the previous section (Section 3.4) was estimated from the surface profile measurement. The maximum height difference of the surface of one side was ca. 3 \( \mu \text{m} \) (±1.5 \( \mu \text{m} \) as can be seen in Figure 11 and Figure 12) for all samples and pressures.

Figure 11. Surface profile (0.8mm sheet, after pressing at 38.3 MPa)

The height of the gap under a pressurized condition, \( b_p \), can be expressed as follows.

\[
b_p = b - b \times \epsilon \quad (6)
\]

where \( \epsilon \) is the strain.

According to the definition of Young’s modulus,

\[
\epsilon = \frac{P}{E} \quad (7)
\]

where \( P \) is the pressure and \( E \) is Young’s modulus (75 GPa for AA3003).

Hence,

\[
b_p = b - b \times \frac{P}{E} \quad (8)
\]

For example, the actual contact area fraction, \( f_c \), for the 0.8mm sample under 10 kN (corresponding to the apparent pressure, 12.8 MPa) is \( 1.11 \times 10^{-2} \). Therefore, the pressure at the contact part becomes \( 38.3 \times 1.11 \times 10^2 \) MPa.

Hence, under the pressure condition, the height of the gap will become

\[
\frac{b_p}{b} = 1 - \frac{P}{E} = 1 - \frac{38.3 \times 1.11 \times 10^2}{75 \times 10^3} = 0.985 \quad (9)
\]

i.e. 98.5% of the initial height when the apparent pressure is 12.8 MPa (next highest pressure in the present study). This is obviously out of the elastic deformation range and the plastic deformation occurs. If a plastic deformation occurs under pressure, the plateau will be found in the surface profile after pressing, i.e. in Figure 12. However, such a clear indication was not observed according to Figure 11 and Figure 12.

To visualize the small degree of plastic deformation, a parameter to assess the surface, Material Ratio \( \text{Rmr}(c) \), which is often used to assess the wear performance, was evaluated. Material Ratio, \( \text{Rmr}(c) \), is the length of bearing surface (expressed as a percentage of the evaluation length, \( l_n \)) at a depth of \( c \) below the highest peak, i.e.

\[
\text{Rmr}(c) = \frac{\sum_{i=1}^{n} b_i}{l_n} \times 100 \quad (10)
\]
The material ratio curve, \( \text{Rmr}(c) \), for the initial surface and for the surface after 30 kN (38.3 MPa) exposure are shown in Figure 13.

Figure 12. Material ratio curve

For the simple case, the surface before and after a plastic deformation might be drawn as shown in Figure 14. In this case, the schematic illustration of the material ratio curve would become as shown in Figure 15. As can be seen in Figure 15, at a higher position, the material ratio after plastic deformation becomes lower than that of the initial surface. This rather weak trend can be seen in Figure 13, i.e. at a higher position, the material ratio after 30 kN exposure is lower than that of 0 kN (initial surface) and the curves are overlapped at the lower position range.

![Figure 13. A schematic illustration of the surface (a) before and (b) after a plastic deformation](image)

Figure 14. A schematic illustration of the material ratio curve for Figure 14

It might be necessary to consider the size effects to discuss the deformation of the surface, i.e. mechanical behaviour, in more detail since the thickness of the sheets used in the present study is relatively thin. It is known that the mechanical behaviour of metals which have fcc structure depends on the dimensions (thickness). In the case of aluminium, when the ratio of the thickness, \( t \), and the grain size, \( d \), \((t/d) \) becomes less than 5 [8–10], it does not show polycrystal mechanical behaviour anymore and it shows multicrystal mechanical behaviour. A discrete multicrystal behaviour implies that grain orientation becomes important and thus there may be a texture effect with either harder or softer behaviour than a polycrystal or continuum behaviour depending of overall sheet texture.

The grain size of the samples used in the present study is approximately 50 μm and the thickness of the sheets is 0.1 mm, 0.4 mm and 0.8mm. It implies that the \( t/d \) ratio is less than 5 for the 0.1 mm thickness sheet and it shows multicrystal mechanical behaviour. On the other hand, for the 0.8 mm thickness sheet it shows polycrystal mechanical behaviour. The \( t/d \) ratio for the 0.4 mm thickness sheet is close to the critical value, 5, and thus it can be considered as the transition state between polycrystal and multicrystal mechanical behaviours. These mechanical behaviour difference may lead the different surface profile after the pressing and as a consequence, it may lead the thickness dependence of the thermal contact conductance (Figure 7) and real contact area (Figure 9), especially at the higher pressure range.
3.6. Effective thermal conductivity and influence of the atmosphere

The effective conductivity, i.e. the thermal conductivity of one sheet and one interface, $k$, which is calculated using the thermal resistance network model, is shown in Figure 16.

![Figure 15. Effective thermal conductivity (0.1, 0.4 and 0.8 mm samples)](image)

In the present study, the measurements were done only under air atmosphere. The influence of the atmosphere on the effective thermal conductivity can be estimated using the thermal resistance network model, i.e. by replacing the thermal conductivity of air in the model by the thermal conductivity of another gas.

The thermal contact resistance at the interface, $R$, can be expressed as Eq. (5).

Thus, for example, the difference between air and nitrogen is negligible since the thermal conductivity of nitrogen at 250 °C is 0.0413 W·m⁻¹·K⁻¹ and 0.0418 W·m⁻¹·K⁻¹ for air. In the case of vacuum ($k_G \approx 0$ W·m⁻¹·K⁻¹) condition, the thermal contact resistance at the interface, $R$, will be increased ca. 1–5% in the range of present experiments.

4. Conclusion

By measuring the thermal contact conductance by a steady state comparative longitudinal heat flow method and by measuring the surface profile of the sheet samples representing the industrial AA3003 coil strips, the following conclusion is obtained.

1. In the lower pressure range (up to approximately 10 MPa), the change in the thermal contact conductance/resistance was drastic. However, in the higher pressure range the change becomes moderate, and at high pressure levels the thermal contact conductance/resistance becomes almost constant.

2. Through the GUM based uncertainty assessment, it was found that the temperature in the vicinity of sample surfaces ($T_2$ and $T_3$) was 10–100 times more sensitive to the uncertainty than the other parameters.

3. The fitting curve for the thermal contact conductance in the elastic (low-pressure) region deviates from the empirical fitting curve in the higher-pressure range, i.e. the plastic deformation region. However, even at the highest tested pressure (38.3 MPa), the conductance value fitted under the assumption of the elastic material behaviour is still within the experimental uncertainty.

4. The parameter, Material Ratio, $R_{mr(c)}$, was assessed using the measured surface profile. It was found through the analysis that $R_{mr(c)}$ can be utilized to assess a small plastic deformation.

5. By calculating the effective thermal conductivity, it was found that the influence of the atmosphere on the effective thermal conductivity of the layered structure is negligible for the studied cases.

References


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