EFFECTS OF DIFFUSION BRAZING PARAMETERS ON DIMENSIONAL VARIATION OF NICKEL ALUMINIDE MICROCHANNELS

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Abstract

Nickel aluminide (NiAl) foil is a novel structural material for high-temperature micro-scale fluidic devices. NiAl foils can be used to fabricate micro-scale fluidic devices through a microlamination process. For the micro-scale fluidic devices, dimensional variation of flow conduits is very critical to fluid flow behavior and heat transfer performance. It is found that the variation usually occurs during the joining stage of the microlamination process. In this study, diffusion brazing was used as the joining technique of NiAl foils. However, information on the relationship between brazing parameters and dimensional variation of flow passages is not available. An investigation of brazing parameter effects on the dimensional variation of flow conduits was performed in this study. Analysis of variance technique was employed to analyze the effects of each brazing parameter. The results showed that the minimum deviation would appear to obtained when the temperature and the time are at the high level and the pressure is at the low level.

Key words: Diffusion brazing, Nickel aluminide foil, Micro-scale fluidic devices, Analysis of variance

Introduction

Microtechnology-based Energy and Chemical Systems (MECS) have been under development with the goal to decentralize and make portable micro- and meso-scale fluidic systems such as heat pumps, chemical reactors, and bio-sensors. The miniaturization of MECS devices is made possible by the use of microchannel arrays to increase the ratio of surface area to volume of the conduits within the devices resulting in an improvement in the heat and mass transfer performance of the flow conduits in the devices (Wang et al., 1991; Peng et al., 1995; Brooks et al., 1999). In building MECS devices, conventional materials that have been used are stainless steel, copper, and brass. However, the devices made by these conventional materials are not functional at high temperatures, which are required of many applications such as steam reforming, flue gas desulphurization, and mobile engine heat recovery (Jovanovic, 2001; Paul et al., 2002). New material systems for high-temperature microchannel array devices are required to fulfill these applications.

Nickel aluminide (NiAl) possesses high potential to be used as structural material for high-temperature microchannel array devices. This intermetallic compound is attractive to high-temperature applications because of its high melting temperature and good high-temperature corrosion resistance. This is because of the inherent property of the aluminum (Al) contained in the aluminides to form protective oxide layers (Al₂O₃).

NiAl foils can be used to fabricate MECS devices by microlamination techniques. These techniques have been used to produce MECS devices that typically possess complex arrays of internal micro-scale features. Three steps are involved in microlamination: lamina patterning, laminae registration, and laminae bonding. With the development of micromachining methods, many techniques can be used for lamina patterning including micromilling, laser micromachining, photochemical etching, and electrochemical machining (Wegeng et al., 1996; Martin et al., 1999; Paul et al., 1999). For intermetallic materials, electro discharge machining (EDM) has been widely used for patterning purposes (Nakao et al., 1991; Lutfullin et al., 1995; Glatz and Clemens, 1997). After the lamina patterning step, laminae are registered and then consolidated into a solid block of material by a joining process.

Joining of intermetallic compounds has been studied by many researchers. Joining techniques, such as diffusion bonding, diffusion brazing, and transient liquid phase bonding, were found promising for bonding intermetallic compounds (Nakao et al., 1991; Glatz and Clemens, 1997; Uenishi et al., 1995; Moore and Kalinowski, 1993; Strum and Henshall, 1994; Wu and Huang, 2001). It is found from these reports that joining intermetallic compounds is successful when performed under high temperatures and/or high pressures. However, results from the literature cannot be applied directly to the case of joining intermetallic microchannels because the previous research efforts were performed on simple bulk specimens, but microchannel devices are complex structure. Applications of
heat and pressure affect not only joining the foils, but also causing dimensional variation of the devices. In the case of fabricating the microchannel devices, dimensional variation (warpage) of microchannels or fins is very critical to the fluid flow behavior and heat transfer performance of the devices as reported in research of Alman et al. (2001) and Paul et al. (2001; 2002). Joining under high temperature and pressure can lead to warpage of microchannel fins in the devices. In this study, NiAl foils were laminated by a diffusion brazing process, and effects of the brazing parameters on warpage of the foils were investigated.

**Experimental Approach**

The foil used in this study was NiAl foil with nominal thickness of 127 µm. Diffusion brazing was employed as the joining technique. Commercially pure (99.99%) Ni foil with nominal thickness of 7.5 µm was used as the filler metal to promote joining of the NiAl foils. Test article was intentionally designed to emulate the fin of microchannel devices. Geometry and cross section of the patterned foils and filler metal are shown in Figure 1. The dimensions of the bridge structure are 5.08 mm wide and 10.16 mm long.

![Cross section of NiAl foils and filler metal](image)

**Figure 1. Test sample configuration and cross section**

The laminae were then registered to the designed sequence. In this experiment, a graphite fixture with edge alignment was employed to register all specimens during bonding. Finally, the foils were diffusion brazed at various conditions in a vacuum environment. For every bonding cycle, the specimens were heated up from and cooled down to room temperature. Deflection of the fin structure was measured by a profiler. The profiler’s stylus was traced along the length of the bridge to measure magnitude of the warpage. The measurement was performed at three different locations on the bridge, near the left and right edges and at the center line of the bridge, to obtain an average value of the warpage.

Process parameters investigated in this study were bonding temperature, pressure, and time. The process response was the magnitude of the fin warpage. Each process parameter was run at two levels. A 2 x 2^3 full factorial design was created to study brazing parameter effects on warpage of the foils. There were totally 16 runs performed in this experiment. The experiments were run in a random order to average out the effects of confounding factors that may be present. It is assumed that three-way interaction has negligible effect on the warpage. The experimental conditions are shown Table 1.

<table>
<thead>
<tr>
<th>Table 1. Experimental Factors Levels</th>
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<tr>
<td>Factor</td>
</tr>
<tr>
<td>A Pressure</td>
</tr>
<tr>
<td>B Temperature</td>
</tr>
<tr>
<td>C Time</td>
</tr>
</tbody>
</table>

**Results and Discussion**

Analysis of variance was performed on the data sets as shown in Table 2. Based on the analysis, brazing temperature had significant effect on warpage of the fin ($p$-value $< 0.05$). From Figure 3, the magnitude of warpage increases with the increase of brazing temperature. It was suggestive, but inconclusive, that the brazing pressure also had effect on the warpage ($0.05 < p$-value $< 0.10$). The warpage of the fin seems to increase as the brazing
pressure increases as shown in Figure 2. From the analysis, the brazing time did not show influence to the deformation of the fins. Note from the AB interaction as shown in Figure 4 that the pressure (A) has a large positive effect when the temperature (B) is at the high level, but the pressure has fairly large negative effect at low temperature, with the best results obtained with either the pressure is at the low level and the temperature is at the high level, or the pressure is at the high level and the temperature is at the low level. From Figure 5, the AC interaction indicates that the pressure effect is very small when the time (C) is at the low level and very large when the time is at the high level, with the best results obtained with the low level of the pressure and the high level of the time. Therefore, the minimum warpage would appear to obtained when the temperature and the time are at the high level and the pressure is at the low level.

Table 2. Analysis of Variance Table

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>Df</th>
<th>Mean Square</th>
<th>F-Ratio</th>
<th>P-Value</th>
</tr>
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<tr>
<td>MAIN EFFECTS</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>A:ExpPressure</td>
<td>271.083</td>
<td>1</td>
<td>271.083</td>
<td>4.78</td>
<td>0.0566</td>
</tr>
<tr>
<td>B:Temp</td>
<td>370.685</td>
<td>1</td>
<td>370.685</td>
<td>6.54</td>
<td>0.0308</td>
</tr>
<tr>
<td>C:Time</td>
<td>29.941</td>
<td>1</td>
<td>29.941</td>
<td>0.53</td>
<td>0.4859</td>
</tr>
<tr>
<td>INTERACTIONS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AB</td>
<td>1034.44</td>
<td>1</td>
<td>1034.44</td>
<td>18.24</td>
<td>0.0021</td>
</tr>
<tr>
<td>AC</td>
<td>247.112</td>
<td>1</td>
<td>247.112</td>
<td>4.36</td>
<td>0.0664</td>
</tr>
<tr>
<td>BC</td>
<td>157.506</td>
<td>1</td>
<td>157.506</td>
<td>2.78</td>
<td>0.1299</td>
</tr>
<tr>
<td>RESIDUAL</td>
<td>510.319</td>
<td>9</td>
<td>56.7021</td>
<td></td>
<td></td>
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<tr>
<td>TOTAL (CORRECTED)</td>
<td>4238.38</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2. Plot of pressure and deviation  
Figure 3. Plot of temperature and deviation

Figure 4. Interaction of pressure-temperature  
Figure 5. Interaction of pressure-time

Conclusions

This study investigated effects of brazing parameters on warpage of nickel aluminide foils. The results showed that brazing temperature had significant effect on warpage of the fin. The warpage of the fin increased with the increase of brazing temperature. It was suggestive, but inconclusive, that the brazing pressure also had significant effect on the warpage. After considering interactions of brazing parameters, nickel aluminide foils
should be brazed at the high level of temperature and time and low level of pressure to obtain minimum warpage. Future research could be performed on optimization of these brazing parameters.

References


