1. Introduction

Application of light materials, such as aluminum alloy, is effective in weight reduction for fuel efficient future vehicle\(^1\). On the other hand, main frame of the automobile body still need to be constructed of carbon steel due to its higher strength and low cost. Thus, spot welding between aluminum alloy and carbon steel is needed for construction of an ideal light weight fuel efficient car. Conventional resistance spot welding between Al alloy and carbon steel is fairly difficult. It is because thick intermetallic compound (IMC) layer is formed at the weld interface. Intermetallic compound is essentially fragile and deteriorates the mechanical strength of the weld joint. Recently, solid phase welding between dissimilar metals by friction stirring was newly developed by authors\(^2\)\(^-\)\(^6\). We succeeded in spot welding between Al alloy and mild steel by friction stirring\(^7\),\(^8\). Typical steel materials for automobile manufacturing were mild steel (270MPa of yield strength), high tensile strength steel (HTS steel, 980MPa of yield strength). The variation of cross tensile and tensile shear strengths of weld joints has the similar tendency. After shown the maximum strength, both tensile strengths decrease with increasing plunge depth. Torque, vertical load and temperature measured during welding between AA5052 and HTS steel indicate a high value more comparatively in any measurements than another one measured during welding between AA5052 and mild steel. The plastic flow like a tornado in AA5052 is caused by combining some plastic flows that had different directions.

Key Words: friction stirring, dissimilar metal welding, spot welding

2. Experimental procedure

Figure 1 shows the schematic view of the spot welding...
between aluminum alloy and steel by friction stirring. Weld materials were fixed on the backing plate by the upper plate. Aluminum alloy was on the top, and steel plate was its underneath. The rotating tool had a shoulder with $\phi 10$mm in diameter with a small conical center probe of 0.3mm height. Tool material was WC-Co cemented carbide. The rotating tool was plunged into aluminum alloy, and generated a frictional heat by the relative motion between the tool and aluminum alloy. The heat made the temperature of aluminum alloy higher, and the lower deformation resistance of aluminum alloy caused the plastic flowing of the material. At the setting plunge depth, the tool was held for a setting period. After that, tool was pulled out from the weld materials. The welding conditions, such as rotating speed, plunging speed, plunge depth and hold time were controlled by machining center (ENSHU S400). Table 1 shows the welding conditions. The influence of steel property on the welding between aluminum alloy and steel was investigated by changing the plunge depth. Dimensions of weld materials were $W30 \times L120 \times Th1$mm for aluminum alloy AA5052, and $W30 \times L120 \times Th1.6$mm for mild steel and HTS steel. Torque acted on rotating tool, vertical load acted on weld materials, and temperature of weld interface were measured.

Also, zinc coated mild steel with dimensions $W30 \times L120 \times Th1.6$ mm was used for observation of plastic flow of aluminum alloy. The mechanical properties of the weld joints were evaluated with cross tensile strength and tensile shear strength by tensile tester (SHIMADZU AGS-J). The microstructure of weld interface was observed by OM (Optical Microscope) and SEM (Scanning Electron Microscope).

### 3. Result and discussion

Figure 2 shows result of cross tensile strength test of weld joints, and figure 3 shows result of tensile shear strength test on weld joints. As a result, similar transition tendency of strength test was found in mild steel and HTS steel. The maximum cross tensile strength achieved at 0.6mm of the plunge depth and the maximum tensile shear strength achieved at 0.3 or 0.4mm of the plunge depth. Besides, each result didn't have large difference between mild steel and HTS steel in the numerical value. Thus, the kind of steel did not influence on the characteristic of tensile strength of weld joint.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Welding conditions</th>
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<tbody>
<tr>
<td>Tool Rotation $N$ (rpm)</td>
<td>3000</td>
</tr>
<tr>
<td>Tool Plunge Speed $v$ (mm/min)</td>
<td>50</td>
</tr>
<tr>
<td>Tool Plunge Depth $d$ (mm)</td>
<td>0.1~0.7</td>
</tr>
<tr>
<td>Hold Time of Tool $t$ (s)</td>
<td>5</td>
</tr>
</tbody>
</table>

To investigate the behavior of both steels during welding, torque, vertical load and temperature were measured. Figure 4 shows measurement result of the torque, vertical load acted on the weld materials and temperature at the weld interface during welding. Both of torque showed the maximum value at the same time that was the end of plunging. After that, it decreased rapidly during tool holding. The reason was that tool finished plunging and aluminum alloy softened at the step of tool holding, although aluminum alloy had never been softening during tool plunging. This tendency was showed measurement result of vertical load. On the other hand, the temperature was almost constant during tool holding unlike the torque and vertical load. It is because the heat radiation and the heat input were balanced. Comparing two results of temperature, the temperature of HTS steel was totally higher than the one of mild steel, and difference of the temperature was about from 20K to 80K during welding. The difference of temperatures was caused by the difference of vertical loads. If vertical load increases, the contact area of rotating tool and aluminum alloy also increases. Thereby, the frictional heat increases, and the temperature rises.

This tendency originated in the characteristic of the steel. But strength of welding point didn’t have large difference. Then, weld interface that had brought weld strength was observed.

To investigate the difference of welding state between high
tensile strength steel and mild steel, cross section of weld joints were observed. Figure 5 and figure 6 shows the cross section microstructure of weld interface between AA5052 and mild steel or HTS steel. From these figures, both weld interfaces had reaction layer on the weld interfaces. These layers were thick at weld center, and thin at 4mm from the center. The weld interface was smooth for mild steel and rough for high tensile strength steel. From the EDX analysis, these layers were composed by aluminum and iron.

According to these results, the difference of welding state between mild steel case and HTS steel case wasn’t seen. Then, the plastic flow of aluminum alloy generated by torque, vertical load and temperature was important, because it physically influenced weld interface.

Therefore, plastic flow in AA5052 was observed. Figure 7 shows vertical cross-section of weld joint between AA5052 and zinc coated mild steel. Figure 7 (a), (b), (c) and (d) were taken after etched by 0.5wt% fluorinated acid (HF). The zinc coated mild steel was given because of the coated layer had the effect as the tracer to clarify the plastic flow in AA5052. It could be seen clearly by etched by HF. From figure 7 (a), (b), (c) and (d), the curved lines from weld interface to the surface of AA5052 has been confirmed. It was zinc because it expanded from weld interface and its contrast was different from AA5052. On the other hand, zinc piles up in the surrounding area that doesn’t weld, from figure 7 (e). It was caused by the plastic flow to the outer in AA5052. In these observations at the cross section, two forms of plastic flow were confirmed. One was from weld center to AA5052 surface, the other extends to surroundings.

Figure 8 shows vertical cross-section and horizontal cross-sections of weld joint between AA5052 and zinc coated mild steel. Figure 8 (a) shows position and direction of observation.
Figure 8 (b) shows horizontal cross-section at 0.3mm from weld interface before and after etching by 0.5wt% HF. Rotating direction of tool at welding was counter clockwise in the view of observed direction. Before etching, the area of 1–2.5mm from weld center had different contrast. After etching, the plastic flow in AA5052 was shown clearly. Plastic flow seemed to be like swirl at concentric circle. Figure 8 (c) shows horizontal cross-section at weld interface before and after etching by 0.5wt% HF figure 8 (b). Before etching, the area showed a contrast different from other areas like 0.3mm from weld center. After etching, the plastic flow at this observed position shows a concentric circle. But it was more complex than it observed in figure 8 (b). Zinc existed at weld center. Therefore, weld center had not cause the plastic flow. In these observations at horizontal cross-sections, the plastic flow of the concentric circle was confirmed.

Following these results of observation, the plastic flow that directions are to outside, to upside and circumference in AA5052 is composed. The flow in AA5052 is like a tornado that caused by combined those flows. As a result, the plastic flow influenced the weld joint.

4. Conclusions

In this study, following results were obtained in the spot welding by friction stirring between Al alloys and steel plates.

(1) The variation of cross tensile and tensile shear strengths of weld joints had the similar tendency. After shown the maximum strength, both tensile strengths decreased along with the rise of plunge depth increased.

(2) Torque, vertical load and temperature measured during welding between AA5052 and HTS steel indicate a high value more comparatively in any measurements than another one

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References

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