Effect of Tool Materials on Frictional Properties of Galvannealed Steel Sheets

Katsuya Hoshino¹,²*, Yuji Yamasaki¹, Wataru Tanimoto², Masayasu Nagoshi³, Shoichiro Taira¹ and Naoto Yoshimi⁴

¹Steel Research Laboratory, JFE Steel Corporation, Fukuyama 721–8510, Japan
²Solution Office (West Japan), JFE Techno-Research Corporation, Fukuyama 721–8510, Japan
³Steel Research Laboratory, JFE Steel Corporation, Kawasaki 210–0855, Japan
⁴Steel Research Laboratory, JFE Steel Corporation, Chiba 260–0835, Japan

The frictional behavior of galvannealed steel sheets (GA) depending on tool materials was investigated. GA having different ζ/δ₁ phase intensity ratios was prepared as specimens. In addition, lubrication-treated GA was also prepared using these specimens as the base material. Four kinds of tools composed of zinc alloy die casting (ZAS), ductile cast iron (FCD), alloy tool steel (SKD) and Cr-coated FCD (CR) were used as sliding tools in order to simulate actual press tools used in trials and mass production. When the tool material was harder than the test specimens, the friction coefficient of the GA increased as the amount of the ζ phase increased, and the effect of the lubrication treatment was clearly observed. However when the tool material was softer than the test specimens, the friction coefficient was constant and independent of the existence of the ζ phase and lubrication treatment. The change in the frictional behavior was discussed from the viewpoint of the change in the friction mechanism depending on the relative hardness of the surfaces of the specimens to the tool materials.

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1. Introduction

Galvannealed steel sheets (GA) are commonly used as automotive body materials due to their excellent corrosion resistance. Frictional properties between sheets and dies are important for automotive materials, as these materials are generally used after press forming, and the improper frictional properties can cause wrinkles and cracks in automotive panels during press forming. The frictional properties between GA and dies have been studied and their behavior has been reported in many works. It is well known that the friction coefficient of GA decreases with increasing Fe content in the GA coating and increases with decreasing Fe content in the GA coating[1–3]. This is because a decrease of the Fe content causes an increase of the ζ phase, which has higher adhesion force to the tool. On the contrary, an increase in the Fe content results in a decrease of the ζ phase, and in this case, the GA coating mainly consists of the δ₁ phase, which has lower adhesion force to the tool. In order to decrease and stabilize the friction coefficient of GA more efficiently, various kinds of lubrication treatment have been developed and used commercially[2–6].

Many kinds of press tools are also employed in mass press production. In press forming of mild steel, ductile iron (FCD) is generally used as the tool material, while in press forming of high strength steel, tool steel (SKD) is generally used. Cr, VC and TiC coatings on these materials are also used to protect the tools from wear and so on. In addition, soft Zn-Al alloy (ZAS) is often used as a tool material in press trials before mass production. It is well known that the friction coefficient depends not only on the test specimen but also on the tool material[2–14]. Therefore, in industry, these changes in the friction coefficient depending on the tool material cause defects such as cracks, wrinkles and surface distortion, which were not observed in press trials, because the tool materials in mass production are different from these in the press trials. However the mechanisms responsible for the changes in the friction coefficient depending on the tool materials were not clarified.

In this paper, in order to clarify these mechanisms, the changes in the frictional behavior depending on the combination of GA and tool materials were investigated. As test specimens, both GA with different Fe contents in the GA coating layer and lubrication-treated GA were used. The tool materials used here were ZAS, FCD, SKD, and Cr-coated FCD (CR), which are typical tool materials used in press trials and mass production.

2. Experimental Procedure

The test specimens, flat sliding test method, tool materials and surface analytical method used in this paper will be explained in this chapter.

2.1 Test specimens

Three kinds of GA with different Fe contents: GA1, GA2 and GA3 were used as test specimens. Their properties are shown in Table 1. The ζ/δ₁ phase peak ratio, which was calculated from the ζ and δ₁ phase peak intensities obtained by

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Thickness /mm</th>
<th>Coating weight /g · m⁻²</th>
<th>Fe content/%</th>
<th>Phase structure (ζ/δ₁ phase intensity ratio)</th>
<th>Roughness (Ra)/μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>GA 1</td>
<td>1.2</td>
<td>40</td>
<td>11.4</td>
<td>10</td>
<td>0.57</td>
</tr>
<tr>
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<td>1.2</td>
<td>43</td>
<td>10.6</td>
<td>40</td>
<td>0.68</td>
</tr>
<tr>
<td>GA 3</td>
<td>1.2</td>
<td>40</td>
<td>10.0</td>
<td>66</td>
<td>0.63</td>
</tr>
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</table>

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*2Corresponding author, E-mail: k-hoshino@jfe-steel.co.jp
X-ray diffraction (XRD) using CuKα as the X-ray source, was defined as shown in eq. (1)\(^{15}\). The calculated values of the \(\xi/\delta_1\) phase peak ratio of each specimen are also shown in Table 1.

\[
\frac{\xi}{\delta_1} \text{ phase peak ratio} = \left( \frac{\xi \text{ phase peak intensity}}{\delta_1 \text{ phase peak intensity}} \right) \times 100
\]

where, \(\xi\) phase peak intensity is the net intensity of the peak observed at 45.5° and \(\delta_1\) phase peak intensity is the net intensity of the peak observed at 47.8° of the diffraction angle of 2θ. These peaks are caused by the \(\xi\) and \(\delta_1\) phase structures, respectively. The \(\xi\) and \(\delta_1\) phases were also distinguished by cross-sectional SEM observation of the GA coating layer as shown in Fig. 1. The \(\xi\) phase is not observed clearly on GA1, meaning the GA coating layer of GA1 mainly consists of the \(\delta_1\) phase. In contrast, the \(\xi\) phase is observed on GA2 and GA3, and their thickness were approximately 1 \(\mu\)m and 3 \(\mu\)m, respectively. The thickness of the \(\xi\) phase, which was obtained from the cross-sectional SEM images, tends to increase with increasing in the \(\xi/\delta_1\) phase peak ratio obtained by XRD.

In addition to the above-mentioned GA specimens, lubrication-treated GA1, GA2 and GA3 were also prepared in order to compare the frictional behavior of the lubrication-treated sheets. As a base materials of the lubrication-treatment, the above-mentioned GA1, GA2 and GA3 were used respectively. A surface modification technology which modifies several 10 nm of the thickness of GA surface was applied as the lubrication-treatment in this study\(^{16–18}\). This technology utilized a commercial product with viscosity of 17.4 cSt at 40°C.

### 2.2 Flat sliding test

The friction coefficient was measured by a flat sliding test. A tool with a contact area 10 mm\(\times\)50 mm and 4.5-mm-corr.

#### 2.3 Tool materials and coatings

Four kinds of tool materials, ZAS, FCD, SKD and CR were used, as shown in Table 2. Before the test, the tools were polished with #2000 polishing paper in the orthogonal direction to the sliding direction. The surface roughness after finishing was measured in the sliding direction; these results are also shown in Table 2. The chemical compositions of the ZAS, FCD and SKD used as tool materials are shown in Table 3.

#### 2.4 Surface analysis

After the sliding test, these test specimens and tools were ultrasonically degreased in alcohol. The surfaces of both the test specimens and the tool materials after the sliding test were observed with a laser microscope (VK-X100, KEYENCE) and 3-dimensional optical profiler (NewView 7300, Zygo). In addition, the specimens and tools were also observed and analyzed by SEM-EDX (Ultra Plus, Carl Zeiss). The SEM observation was carried out at an accelerating voltage of 1 kV, and the EDX analysis was carried out at 5 kV. The observed and analyzed area was the center of the test specimens and tools after the sliding test.

### 3. Results

The results of measurements of the friction coefficient and surface observation of both the test specimens and tools before and after the sliding test will be described in this chapter.

#### Table 2. Tool materials.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Material</th>
<th>Quench</th>
<th>Coating</th>
<th>Hardness/HV</th>
<th>Roughness (Ra)</th>
<th>(\mu)m</th>
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<tr>
<td>ZAS</td>
<td>ZAS</td>
<td>-</td>
<td>-</td>
<td>89</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td>FCD540</td>
<td>FCD540</td>
<td>-</td>
<td>-</td>
<td>284</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>SKD11</td>
<td>SKD</td>
<td>-</td>
<td>Quenched</td>
<td>728</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>CR</td>
<td>FCD540</td>
<td>-</td>
<td>Cr coating 2 (\mu)m</td>
<td>981</td>
<td>0.08</td>
<td></td>
</tr>
</tbody>
</table>

#### Table 3. Chemical compositions of tool materials.

<table>
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<tr>
<th>Tool material</th>
<th>Fe</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Mg</th>
<th>Zn</th>
<th>Al</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZAS</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>FCD540</td>
<td>Bal</td>
<td>3.53</td>
<td>2.64</td>
<td>0.42</td>
<td>0.019</td>
<td>0.008</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SKD11</td>
<td>Bal</td>
<td>1.44</td>
<td>0.30</td>
<td>0.38</td>
<td>0.023</td>
<td>0.000</td>
<td>11.19</td>
<td>0.80</td>
<td>0.21</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
3.1 Friction coefficient

Figure 2, Fig. 3, Fig. 4 and Fig. 5 show the relationship between the friction coefficient and \( \zeta/\delta_1 \) phase intensity ratio when using the SKD, CR, ZAS and FCD tools, respectively. The tendency of the relationship between the friction coefficient and the \( \zeta/\delta_1 \) phase intensity ratio can be divided into the following three groups.

Group 1 is the case when SKD and CR were used as tool materials, as shown in Fig. 2 and Fig. 3. In this case, the friction coefficient of GA increases as the \( \zeta/\delta_1 \) phase intensity ratio increases. Because GA1 mainly consists of the \( \delta_1 \) phase and the top surfaces of both GA2 and GA3 are covered with the \( \zeta \) phase as mentioned previously, this tendency can be explained by the fact that the friction coefficient increases as the amount of the \( \zeta \) phase increases, and the friction coefficient becomes saturated over a certain amount of the \( \zeta \) phase. The friction coefficient of GA3 was slightly lower than that of GA2. This can be explained by the fact that the surface roughness of GA3 is slightly lower than that of GA2. On the contrary, all the lubrication-treated GA samples show lower friction coefficients than the non-treated ones, independent of the \( \zeta/\delta_1 \) phase intensity ratio. The tendency of the friction coefficients obtained in this group is in good agreement with that of prior works which investigated the friction coefficients of GA and lubrication-treated GA by using SKD as the tool material\(^2,3,16–18\). In a comparison between the SKD and CR tools, they show similar tendencies.

Group 2 is the case when ZAS was used as the tool material, as shown in Fig. 4. The friction coefficient of GA is independent of the \( \zeta/\delta_1 \) phase intensity ratio, and the non-lubrication-treated GA and lubrication-treated GA show similar values. The tendency of the friction coefficients obtained in this group is different from that of prior works which investigated the friction coefficients of GA and lubrication-treated GA by using SKD as the tool material\(^2,3,16–18\).

Group 3 is the case when FCD was used as the tool material, as shown in Fig. 5. The friction coefficient of GA increases as the \( \zeta/\delta_1 \) phase intensity ratio increases and the relationship between the friction coefficient and \( \zeta/\delta_1 \) phase intensity ratio is linear. Although the friction coefficients of the lubrication-treated GA are smaller than those of the non-treated ones, the difference between friction coefficient of GA1, which mainly consists of the \( \delta_1 \) phase, and lubrication-treated GA1 is small.

3.2 Surface observation of test specimens and tool materials before and after sliding test

The geometry of the tool surface was measured by using the 3-dimensional optical profiler. The results are shown in Fig. 6. The tools after sliding on four kinds of test specimens (GA1, GA2, GA3 and lubrication-treated GA3) were chosen in order to understand the behavior of the friction coefficient depending on the combination of test specimens and tool materials. Because the frictional behaviors of the SKD and CR tools were similar, the results for CR were omitted here.

Before sliding, micro-grooves are observed on the surfaces...
of the tools. These micro-grooves are grinding marks introduced by polishing using #2000 polishing paper in the orthogonal direction to the sliding direction.

When ZAS was used as the tool material, the grinding marks introduced before the test are not observed after the test. Instead, new scratch marks in the parallel direction to the sliding direction are observed. These new scratch marks are observed on the tools independent of the test specimen.

When FCD was used as the tool material, the surface of the tool after sliding depend on the test specimen. In the combination with GA1, which mainly consists of the $\delta_1$ phase, and GA2, which contains the $\zeta$ phase, new scratch marks with a depth of about 1 $\mu$m are observed in the parallel direction to the sliding direction. These are similar to the case of ZAS described above. Regarding the scratch marks observed after sliding, the damage on GA2 is minor to that on GA1. However, in the combination with GA3, which has a large amount of $\zeta$ phase, and the lubrication-treated GA3, of which the base material is GA3, the grinding marks before sliding are observed and new scratch marks in the parallel direction to the sliding direction are almost not observed.

When SKD was used as the tool material, the surface of the tool shows almost no change after sliding, independent of the test specimen.

The surface of the test specimen after sliding was observed with the laser microscope. The results are shown in Fig. 7.

![Fig. 6 3-dimensional optical profiler observation images of tool surfaces after sliding on GA1, GA2, GA3 and lubrication-treated GA3.](image1)

![Fig. 7 Laser observation images of specimen surfaces after sliding by ZAS, FCD and SKD sliding tools.](image2)
Four kinds of test specimens were chosen for the same reason as mentioned above. The bright contrast areas on the test specimens before sliding are plateaus formed by contact with the temper roll in the manufacturing process of GA. In the cases of sliding with FCD and SKD, the bright plateau areas increase as a result of the sliding test. The increase of the bright plateau areas tend to be independent of the tool material and depend on the kind of test specimen.

In contrast, when ZAS was used as the tool material, the surface of test specimen do not show any large changes after sliding.

4. Discussion

The reason why the friction coefficient depended on the combination of the test specimen and the tool material will be discussed from two viewpoints in this chapter. One is the difference of the adhesion force between the GA coating layer and the tool material. The other is the difference of the mechanism of generation of frictional force deriving from the relative hardness of the test specimen to the tool material.

4.1 Relationship between friction coefficient and real contact area

In order to clarify the mechanism of the increasing trends of the friction coefficient as the $\xi/\delta_1$ phase intensity ratio increases and the decreasing tendencies of the friction coefficient with lubrication treatment shown in Figs. 2, 3 and 5, the surface flattened area ratio on the test specimens after sliding was calculated by thresholding the images in Fig. 7. Figure 8 shows the relationship between the friction coefficient and the surface flattened area.

When SKD was used as the tool material, the friction coefficient increases linearly as the surface flattened area increases. It is known that scratch marks caused by sliding are observed in the real contact area on the test specimen by microscopic observation at 10,000x magnification. However, in low magnification observation at 100x, the real contact area is observed as a flattened area because GA initially has comparatively higher roughness than the scratch marks. Therefore, the surface flattened areas shown in Fig. 7 are thought to be the real contact areas because they were observed at 10x low magnification. It has also been reported that the real contact area occurs as a result of the shear force caused by shearing the adhesion between theasperities of the test specimen and the tool material. The increase of the real contact areas of the test specimens is determined by the adhesion force at the interface as well as the shear strength of the surface of the test specimen. In this study, it is assumed that the shear strengths of the surfaces of GA2 and GA3 are the same because the top surfaces of them are covered with the same $\zeta$ phase. Although GA1 mainly consists of $\delta_1$ phase, the shear strength of the surface of GA1 is also assumed to be similar to that of GA2 and GA3 because, in the case of SKD, a good correlation is observed between the friction coefficient of GA and the surface flattened area as shown in Fig. 8. This means the $\zeta$ phase could exist on the top surface of GA1 slightly and it could affect the shear strengths of the surface, or the shear strengths of $\delta_1$ phase could be similar to that of $\zeta$ phase. In addition, the lubrication treated layer is considered not to affect the shear strengths of the surface of the test specimen because it is too thin. This suggests that the surface flattened area of the test specimen increases with increasing adhesion force between the test specimens and the tool material because the shear strengths of the surface of the test specimen are almost the same as mentioned above. Therefore, GA2 and GA3 had larger surface flattened areas than GA1 because GA2 and GA3 had larger amounts of the $\zeta$ phase, which has higher adhesion force to the tool, and the lubrication-treated GA3 shows a smaller surface flattened area than the non-treated GA3 because the lubrication treatment layer prevents adhesion between the test specimen and the tool. Consequently, adhesion force increases in the order lubrication-treated GA3 < GA1 < GA2 ≈ GA3, and the friction coefficient increases in the same order.

The relationship between the friction coefficient and the surface flattened area also shows a good correlation in the case when CR was used as the tool material as well as in the case of the combination of the FCD tool and both GA3 and lubrication-treated GA3. These tendencies strongly agree with the case in which SKD was used as the tool material. Therefore, as in the case of SKD, it is thought that the friction coefficient also increases with increasing adhesion force between the test specimens and tool materials in these cases.

In contrast, in the case when ZAS was used as the tool material as well as in the case of the combination of the FCD tool and both GA1 and GA2, the relationship between the friction coefficient and the surface flattened area shows a different trend from the case of SKD. In these cases, it is in common that the new scratch marks in the parallel direction to the sliding direction are observed on the tool surface after sliding, as shown in Fig. 6.

4.2 Effect of relative hardness of test specimens to tool materials on friction models

In order to clarify the reason why the new scratch marks in the parallel direction to the sliding direction occurred on the tool surface after sliding, the surfaces of both the test specimens and the tool materials were investigated in detail by using SEM and EDX. Both the tool materials and the test spec-
imens were observed after sliding on GA1 by using ultra-low voltage SEM. The results are shown in Fig. 9. The analytical results of the areas indicated by white boxes numbered from 1 to 11 in Fig. 9, which were obtained by using EDX, are summarized in Table 4.

When ZAS was used as the tool material, as shown in Fig. 9(a), the scratch marks in the parallel direction to the sliding direction are observed, but adhered materials are not observed on the tool surface. On the surface of the test specimen after sliding, as shown in Fig. 9(d), the area indicated by number 3, which is considered to be the area of contact with the tool, is observed. The chemical composition of this area 3 is different from that of area 2, which is on the GA coating, and is close to the composition of area 1, which is on the tool. Therefore, in this case, the new scratch marks in the parallel direction to the sliding direction shown in Fig. 6 can be explained by the fact that the tool was plowed by the asperities of the test specimen.

It is thought that the tool was plowed by the test specimen because the hardness of the tool was smaller than that of the surface of the test specimen. It is well known that the hardness of the GA coating depends on its phase structure, and it has been reported that the hardness of the $\zeta$ phase is 200 HV and that of the $\delta_1$ phase ranges from 284 to 300 HV\(^2\)). The tool materials also have different hardness, as shown in Table 2.

When using a tool with a smaller hardness than the test specimen, such as ZAS (89 HV), as shown in the schematic model of the friction mechanism in Fig. 10(a), the tool was plowed by the asperities of test specimen, and this force controls the total frictional resistance. Consequently, as shown in Fig. 4, the effect of the $\zeta/\delta_1$ phase intensity ratio and lubrication treatment on the friction coefficient was smaller and, as shown in Fig. 8, the relationship between the friction coefficient and the surface flattened area ratio was different from that in the case of the SKD tool.

Conversely, when SKD was used as the tool material, as shown in Fig. 9(c), both the initial grinding marks, which were introduced by polishing in the orthogonal direction to the sliding direction, and adhered materials, which consist of the GA coating material (area 9), are observed on the tool surface. The surface flattened area (area 11) of the GA coating is observed on the test specimens, as shown in Fig. 9(f).

When using a tool with a larger hardness than the test specimen, such as SKD (728 HV) and CR (981 HV), the test specimen was plowed by the tool surface, and the plowed GA coating layer adhered to the tool. Thus, as shown in the schematic model of the friction mechanism in Fig. 10(b), the test specimen was flattened by the tool, and the adhesion force between the GA coating and the tool surface occupies the total frictional resistance. Consequently, as shown in Figs. 2 and 3, since the adhesion force between the test specimens and the tool materials depends on the $\zeta/\delta_1$ phase intensity ratio and lubrication treatment layer, these two factors affected the friction coefficient. Moreover, the relationship between the friction coefficient and the surface flattened area ratio showed a good correlation, as discussed in section 4.1.

### Table 4

<table>
<thead>
<tr>
<th>Point</th>
<th>Zn %</th>
<th>Fe %</th>
<th>Al %</th>
<th>Si %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>2.3</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>85.0</td>
<td>14.0</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>98.5</td>
<td>0.0</td>
<td>1.5</td>
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</tr>
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</tr>
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</tr>
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<td>6</td>
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<td>0.0</td>
</tr>
<tr>
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</tr>
<tr>
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</tr>
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<td>86.2</td>
<td>13.3</td>
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</table>

Fig. 9  SEM images of tool surfaces and specimen surfaces after sliding. Tool materials of (a) ZAS, (b) FCD and (c) SKD after sliding on GA1, and GA1 surface after sliding by tools (d) ZAS, (e) FCD and (f) SKD.

Fig. 10  Schematic models of friction mechanism depending on relative hardness of tool to specimen. (a) Tool hardness is smaller and (b) Tool hardness is larger.
When FCD was used as the tool material, as shown in Fig. 9(b), both the initial grinding marks in the orthogonal direction to the sliding direction and new scratch marks in the parallel direction to the sliding direction are observed on the tool surface, and in addition, adhered materials (area 5) consisting of the GA coating material are also observed. As shown in Fig. 9(e), a surface flattened area (area 7) is observed on the test specimen after sliding.

The hardness of FCD (284 HV) is close to that of the GA coating layer. In other words, it is larger than that of the ζ phase (200 HV) and is similar to that of the δ₁ phase (284–300 HV). Therefore, the friction model of this case can be described by a combination of Fig. 10(a) and (b). In this case, the relative hardness changes depending on the phase structure of the GA coating, for example, whether the coating mainly consists of δ₁ phase or also includes the ζ phase. When the test specimen was GA1 with the coating layer mainly consisting of the δ₁ phase, which has similar hardness to that of FCD, the plowing force of the tool strongly affects frictional resistance. As a result, the difference between the friction coefficient of GA1 and that of lubrication-treated GA1 is small, as in the case of the ZAS tool. However, when the test specimen was GA3 with a coating layer with a high content of the ζ phase, which is softer than FCD, the effect of the adhesion between the test specimen and the tool material becomes remarkable. As a result, the difference between the friction coefficient of GA3 and that of lubrication-treated GA3 is large, as in the cases of the CR and SKD tools. Therefore, the relationship between the friction coefficient and the surface flattened areas of GA3 and lubrication-treated GA3 approached the tendency of the CR and SKD tools, as shown in Fig. 8. In addition, with the FCD tool, the new scratch marks observed on the FCD tool after sliding tended to be reduced with an increasing ζ/δ₁ phase intensity ratio, which means decreasing plowing of the tool material and an increasing effect of adhesion. Thus, in this case, the friction coefficient of GA increases as the ζ/δ₁ phase intensity ratio increases as shown in Fig. 5 because it is necessary to consider the plowing effect of the tool depending on the GA phase structure. As a result, the trend of the relationship between the friction coefficients of GA and the ζ/δ₁ phase intensity ratio seemingly appears linear.

However, as with ZAS, adhered materials of tool elements were not observed on the test specimen after sliding of the observed area, even though the tool was plowed by the test specimen in this case (Fig. 9(e)). It seems that the amount of tool elements was small because the hardness of the FCD and that of the δ₁ phase of the GA coating are similar.

5. Conclusions

The frictional behavior of galvannealed steel sheets (GA) and lubrication-treated GA, which are used as automotive materials, was investigated with typical press tool materials used in mass press production or press trials. In this study, Zn-Al alloy (ZAS), ductile iron (FCD), tool steel (SKD) and Cr-coated FCD (CR) were used as the sliding tool materials. The following conclusions were obtained.

(1) When the tool material was softer than the surface of the test specimen, the tool was plowed by the test specimen during sliding. In this case, the effect of both the ζ/δ₁ phase intensity ratio and lubrication treatment on the friction coefficient was smaller because the main frictional resistance was the force that caused the test specimens to plow the tool.

(2) When the tool material was harder than the surface of the test specimen, the surface of the test specimen was flattened by the tool during sliding. It is suggested that the friction coefficient increases with increasing adhesion force between the GA coating layer (ζ and δ₁ phases, lubrication treatment) and tool materials (FCD, SKD, Cr coating) because the friction coefficient increases as the real contact area on the test specimen increases.

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