Effects of the Die Condition and Billet Composition on the Surface Characteristics of the Extruded 6063 Aluminum Alloy

By Mitsugu Tokizawa* and Norio Takatsuji*

The surface of extruded material and the corresponding bearing surface in extrusion were directly observed by using the split-type die whose bearing can be easily replaced. The mechanism of surface-roughness formation was schematized and examined, taking the effects of composition and finishing conditions of the bearing surface into consideration. As for the usual Al-Mg-Si-type 6063 alloys, the effects of the precipitates including Mg₂Si and Al-Si-Fe compounds on the surface roughness were also investigated. Thus, the following conclusions were obtained.

(1) As the bearing area increases, the extrusion pressure increases and the extruded-material surface becomes coarser. If the bearing is edge-like and its length is zero, however, the chain-line adhesion appeared on the bearing surface and therefore the state of the product surface becomes worse.

(2) When the extrusion temperature is high, the adhesion on the bearing surface shows plastic flow in the extruding direction and forms extremely rough stripes, and the product surface becomes rough.

(3) On the bearing surface ground vertically to the extruding direction, the ground grooves are filled with the adhesion material and the bearing surface becomes smooth, giving rise to a better surface condition of the extruded material. On the contrary, the ridged stripe of adhesion grows on the bearing surface which was ground in parallel with the extruding direction, and the resulting product surface becomes rough. The buffed bearing surface shows the spot-like poor adhesion which makes the product surface rough.

(4) When the nitrided SKD61 or WC-type sintered alloy (G₂), which have a weak affinity for the extruded material, is employed for the bearing surface, it is covered with a thin film consisting mainly of Al-Mg or of Al-Fe-Mg compounds and the extruded material with an improved surface can be produced.

(5) If the buffed SKD or buffed-and-salt-coaked VC, which have a strong affinity for the extruded material, is adopted for the bearing surface, the stripe of adhesion consisting mainly of Al, Fe and Si spread in parallel with the extruding direction, and the Al-Fe-Si compounds segregate in a high concentration from the die-surface corner to the bearing surface. In this case, the product surface becomes rough.

(6) As for the 6063 alloy for the general-purpose aluminum sashes, it is essential that Mg₂Si particles should not precipitate but disperse uniformly. When both Fe and Si are added, the product surface is rough.

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I. Introduction

The increase of productivity is attracting considerable attention in hot extrusion of shapes of aluminum alloy, but its attainment is very difficult because of the quality of products. The quality of product surfaces is affected by such extrusion factors as the tool surface in working, billet composition, state of precipitate distribution in the billet, and friction between the tool and the billet, in addition to the extrusion ratio, speed and temperature. A large number of studies have been concerned with the friction mechanism during cold extrusion. However, because of the experimental difficulty, only a few papers¹⁻³ have dealt with the surface observations of shape products in hot extrusion.

In this study, a 6063 alloy was hot-extruded using a split die, in which the surfaces of both the extruded material and the corresponding bearing were directly examined, and a model...
of the mechanism of surface-roughness formation in the extruded material was constructed. In addition, the effects of finishing conditions for the bearing surface on the surface roughness of the extruded material were investigated, together with the general relation between the surface roughness of the extruded material and the state of adhesion on the bearing surface when the composition of the bearing surface was changed. The interfacial phenomenon between the surface of the bearing and the billet due to adhesion were analysed by using a X-ray micro-analyzer (EPMA), and the effects of constituent transfer on the surface roughness of the extruded material were also investigated.

II. Experimental Methods

Since the composition of the bearing surface should be changed, the experimental apparatus was designed so that the bearing could be replaced readily after extrusion as shown in Fig. 1. Both the bearing surface and the die surface correspond to 5, which was incorporated into the die as shown in the right detailed figure. The billet 3 was first inserted into the die-integrated split container 4 and assembled. The apparatus was heated in an electric furnace up to 20 K, higher than a given working temperature, while the temperature was measured by a thermocouple. Then the billet was extruded by using 0.3 MN Amsler universal testing machine at a ram speed of \(1.4 \text{ mm} \cdot \text{s}^{-1}\). After extrusion, 3 and 4 were simultaneously pushed out of 6 and disassembled to observe the surfaces of both the extruded material and the bearing. Further, the bearing 5 and the extruded material were taken out, with the two fixed together, to observe their contacting surfaces continuously. The surfaces of the extruded material and the bearing were examined by using an optical microscope, whereas the surface roughness was measured with the Talysurf Model 4. For the measurement of the migration and distribution of chemical elements on the contacting surfaces of the bearing and extruded material, we used Shimadzu's EMS-SM-type X-ray microanalyzer which is capable of performing the linear analysis.

The test billet was made of the 6063 alloy which had been subjected to homogenization treatment at 833 K for 10.8 ks after casting, and machined to 20 mm × 30 mm × 100 mm with an accuracy of 0.1 µm. The extrusion ratio was 12 (2 mm-thick, 26 mm-wide plate), while the extrusion temperatures were 723 and 773 K.

Table 1 shows the finishing conditions for the bearing surface and its composition. The bearing surface was finished by buffing and by grinding perpendicular to and in parallel with the extruding direction. With regard to the bearing compositions, we selected nitriding-treated SKD61 which is widely used in extrusion plants together with heat- and wear-resistant materials which are used in ordinary metal working plants.

III. Results and Discussions

1. Effects of bearing-surface shapes on surface properties of extruded materials

Figure 2 shows the relationship between the extrusion pressure and the bearing shapes and areas, when the extruded materials reach a
length of 500 mm. The extrusion pressure increases linearly with increasing bearing area, regardless of the bearing shape. This is clearly attributable to the increased frictional force between the bearing and the extruded material surfaces because of the increased adhesion area of the billet material on the bearing surface. When the bearing surface areas are equal, the extrusion pressures are nearly constant irrespective of the bearing shapes. This is because the total frictional forces at the outlet of a die are equal, although the distribution of frictional forces varies with the bearing shape.

Figure 3 depicts the effect of the bearing length on the surface roughness of the extruded material and extrusion pressure when a rectangular bearing is used. The extrusion pressure, as shown in Fig. 2, increases nearly linearly with increasing bearing length, whereas the surface roughness of the extruded material tends to become slightly coarse in the range of the bearing length from 1 to 5 mm. This may result from the temperature rise due to the conversion of working energy to heat energy on the bearing surface. In the case of the edge-type bearing with a smaller friction, the surface roughness of the extruded material unexpectedly becomes coarser. To find out the causes for this, the bearing surfaces to which billet materials adhere are observed, and the

| Surface properties     | Symbol | Surface roughness/µm | Treatment                |
|------------------------|--------|-----------------------|-------------------------|
| Tool steel             | SKD  | 0.50 – 1.75           | Quenching, HRC 52       |
| Nitriding              | N     | 0.80                  | Gas nitriding           |
| TiC coating            | TiC   | 1.20                  | Chemical                |
| VC coating             | VC    | 1.10                  |                         |
| CrC coating            | CrC   | 2.50                  | Salt soaking            |
| NbC coating            | NbC   | 1.70                  |                         |
| Sintered alloy         | G2    | 1.70                  | WC-type                 |

Table 1 Finishing conditions for bearing surface and its composition.

Fig. 2 Effects of bearing shapes and its area on extrusion pressure.

Fig. 3 Effects of the bearing length on surface roughness of extruded materials and extrusion pressure.
results are shown in Fig. 4. In the edge-type bearing, unlike other types of bearing, the billet materials adhere in the form of an unstable chain line at the boundary of the run-off of the bearing, thereby resulting in the rough surface of the extruded materials. On the bearing surface 5 mm long, the adhesion of the billet materials spreads greatly in the extruding direction because of the heat generated by the rise of the extrusion pressure.

2. Effects of finishing conditions for bearing surfaces on surface properties of extruded materials

Figure 5 shows the change in the surface roughness of the extruded material measured perpendicular to the extruding direction at an arbitrary length from the front end of the extruded material. On all the bearing surfaces finished under any conditions, the surface roughnesses of the extruded materials become constant when their lengths from the front end exceed 400 mm. We used two types of bearings subjected to parallel grinding or buffing. For these two types of bearing, the surfaces of the extruded materials become coarse in the range of 100 to 200 mm from their front ends. Beyond it the surface roughness produced by parallel grinding bearing immediately reaches its saturation point while the roughness produced by the buffed bearing saturates after being smoothed a little. On the other hand, the surface roughness of the extruded material obtained by using the vertically ground die bearing is extremely smooth and reaches the saturation point, compared with the ones obtained by other die bearings. The investigation on the effects of extrusion temperatures by using the buffed die bearing reveals that the surface of the extruded material at 723 K is much smoother than that of the extruded material at 773 K.

Figures 6 and 7 show the bearing surfaces corresponding to the surfaces of the extruded materials whose surface roughnesses become constant in the process of extrusion. Figure 6 shows a comparison of the microphotographs of the adhered zones at 723 K and 773 K by using the buffed die bearing. Numerous white spot-like adhesion are seen near the run-off (outlet) of the bearing surface in the 723 K extrusion, while white stripe-like adhesion in the extruding direction along with a black matrix of the bearing surface to which no billet material adheres can be observed in the 773 K extrusion. Therefore, the state of the billet materials adhering to the bearing surfaces may
be considered as follows. In the higher temperature range, the extruded material decreases in deformation resistance and tends to adhere to the bearing surface, and then the adhesion material in the inlet of the bearing surface spreads in the extruding direction and forms a projection. In the lower temperature range, however, the adhesion material is distributed homogeneously over the bearing surface and forms smooth roughness. The results on the ground bearing surfaces shown in Fig. 7. On the vertically ground surface, numerous white spots of the adhesion material are found in the extruding direction. On the bearing surface ground in parallel, the stripe-shaped adhesion materials spread in the extruding direction and project in the form of a saw blade, while grooves are formed in the other parts of the bearing surface to which no materials adhere. As a whole the bearing surface becomes very rough.

From all the results mentioned above, the mechanism of the surface-roughness formation of the extruded materials is indicated in Fig. 8. The billet material adheres to the bearing surface along the boundary of the bearing surface and the billet material. If the adhesion material on the bearing surface is thin and uniform, the resultant surface of the extruded material is smooth, but, on the other hand, if the adhesion material is not uniform but shows a stripe-like shape spreading in the extruding direction, the resultant surface of the extruded material is rough. To obtain fine extruded materials, the billet material is required to adhere tightly to the bearing surface in the form of a thin smooth film, and for this purpose, the vertically ground surface is preferable because this can uniformly fix the adhesion material. The interfacial phenomenon of this kind in which adhesion takes place between the bearing surface and materials resembles working-surface properties formed with built-up edges in machining. But in hot extrusion, the firmly covering thin adhering film which does not fall off easily can produce the extruded material with the most smooth surface. Since on the smooth bearing
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surface finished by buffing the adhesion material tends to fall off and cannot be fixed, the resultant surface of the extruded material is coarser than that produced by the vertically ground bearing surface.

3. Effects of bearing surface properties on surface properties of extruded materials

The surface roughnesses of the extruded materials are compared with each other by varying of the finishing method and the composition of the bearing surface. The results are shown in Fig. 9. The desirable bearing surfaces which can produce the extruded-material surfaces to be 0.5 \( \mu \)m or less in arithmetical average roughness (Ra) are the buffed and vertically ground nitrided, G2, and NbC surfaces, and the vertically ground SKD surface. However, all the surface roughnesses of the extruded materials produced through any bearing surface prepared by parallel grinding are two to three times as coarse as those through the vertically ground bearing surfaces. A comparison of the results obtained by the buffed bearing surface with those by the vertically ground ones clearly shows that the latter is better than the former in every bearing-surface property.

Figure 10 gives the results of observation of the bearing surfaces corresponding to the surfaces of extruded material shown in Fig. 9. The adhering films on the nitrided, G2, and NbC bearing surfaces which provide smooth surfaces of the extruded material are flat and thin, whereas those over the buffed TiC, VC and SKD bearing surfaces which provide rough extruded-material surfaces become wide white strips as indicated by the arrows. On the vertically ground bearing surface, every groove portion is completely filled with the adhesion materials and forms the tight, difficult-to-fall-off thin films, whereby the surface of the extruded material is much smoother than those produced by the buffed bearing surface.

Fig. 7 Effect of grinding direction on the state of adhering to the bearing surface.

(a) Grinding vertically against extruded direction

(b) Grinding parallel to extruded direction

B: Bearing, C: Container, F: Releaf
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4. Movement of alloying elements on friction surfaces and surface properties of extruded materials

To clarify the friction behavior between the bearing surfaces and billet materials, the component elements of the adhesion materials on the bearing surface and of the surface of the extruded materials have been continuously observed by using an X-ray microanalyzer.

Figures 11-13 show the results of continuous EPMA analysis for the boundary between the bearing surface and extruded materials.

Fig. 8 Asperity models of adhesion on the bearing surface.

Fig. 9 Effects of bearing surface properties on surface roughness of extruded materials.

Fig. 10 Effects of bearing surface properties on the state of adhering to the bearing surface.
material after they are carefully taken out without separating, air-cooled and cut transversely. On the buffed SKD surface shown in Fig. 11, Fe contained in the bearing surface and Si in the billet tend to fuse together by their strong affinity, so that the concentrations of Fe and Si on the surface of the extruded material surfaces become higher and that of Mg approaches zero. The characteristic X-ray photographs reveal that Fe and Si segregate at high concentrations from the corner of the die surface to the bearing surface. Accordingly, the adhesion materials on the bearing surface in this case is a hard compound consisting mainly of Al, Fe and Si and tends to fall off during extrusion, resulting in rough extruded surfaces. On the buffed nitrided surface shown in Fig. 12, the Fe and Mg concentrations become higher as in the case of the O₂ concentration, while the Si concentration decreases conversely. Although the figure is omitted, the behavior of this kind can be seen in the vertically ground bearing surfaces, and smooth extruded surfaces can be produced in both cases. On the buffed G₂ surface in which Fe is not contained as shown in Fig. 13, the Fe and Si concentrations are nearly constant with no segregation, but the Mg concentration on the surface of the extruded material becomes higher. On the G₂ and nitrided surfaces where the affinity be-

![Fig. 11 Results of continuous EPMA analysis for the boundary between the bearing surface and extruded material. (Bearing surface: The buffed SKD61)](image)
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5. Effects of billet compositions on surface properties of extruded materials

Further, the effects of the chemical compositions of the billets made of the usual Al–Mg–Si-type 6063 alloys on the surface properties of the product are investigated. Figure 14 indicates the effects of Mg$_2$Si particles on the surface roughnesses of the extruded materials. As clearly shown in the figure, the surface roughness of the extruded material tends to become coarser with the increasing Mg$_2$Si content.
centration, irrespective of heat-treatment conditions. As for the conditions of the homogenization-treatment, the method of water quench after casting enables the resultant extruded material to become smoothest. Consequently, it is essential to make the cooling rate on billet homogenization faster, to prevent Mg$_2$Si from precipitating and to have Mg$_2$Si particles dispersed homogeneously, if precipitated. Figure 15 shows the effects of excess additive elements on the surface properties of the Al–0.8Mg$_2$Si alloy. Excessive addition of Mg and Si have no remarkable influence on the surface roughness of the extruded material, but those of Fe and Si make the surface of the extruded material rough. Together with the results in Fig. 11, it is clear that the precipitation of Al–Fe–Si compounds greatly affects the surface roughness.

IV. Conclusions

In this paper, the surface of extruded material and the corresponding bearing surface in extrusion were directly observed by using the split-type die whose bearing can be easily changed. The mechanism of surface-roughness formation was schematized and examined, taking the effects of composition and finishing conditions of the bearing surface into consideration. As for the usual Al–Mg–Si-type 6063 alloys, the effects of the precipitates including Mg$_2$Si and Al–Si–Fe compounds on the surface roughness were also investigated. Thus, the following conclusions are obtained:

1. Since the frictional force between the bearing and billet surface increases with the increase in bearing area, the extrusion pressure increases and the surface of the extruded material become coarser. If the bearing is edge-like and its length is zero, however, the chain-line adhesion appeared on the bearing surface and therefore the state of the product surface becomes worse.

2. When the extrusion temperature is high, the adhesion on the bearing surface shows plastic flow in the extruding direction and forms extremely rough stripes, and the product surface becomes rough.

3. The surface roughness of the extruded material depends greatly on the finishing conditions, composition of the bearing surface, and the affinity of metal elements contained in the bearing and the surface of the extruded material. To obtain well finished extruded materials, the bearing surface must be tightly covered with the thin, smooth adhesion film.

4. The state of the adhesion material on the bearing surface varies greatly with the finishing conditions for the bearing surface. On the bearing surface ground vertically to the extruding direction, the ground grooves are filled with the adhesion material and the surface becomes smooth, and subsequently the better surface of the extruded material results. On the contrary, the ridged stripe of adhesion grows on the bearing surface which was ground in parallel with the extruding direction, and the resulting product surface becomes rough.

5. When the nitried SKD61 or WC-type
sintered alloy \((G_2)\) which have lower affinity for the extruded material is employed for the bearing surface, the surface is covered with a thin film consisting mainly of \(\text{Al-Mg}\) or \(\text{Al-Fe-Mg}\) compounds and the extruded material with better surface conditions can be produced.  
(6) If the buffed SKD or buffed-and-salt-soaked VC which have greater affinity for the extruded material is adopted for the bearing surface, the stripe of adhesion consisting mainly of \(\text{Al, Fe and Si}\) spread in parallel with the extruding direction and the \(\text{Al-Fe-Si}\) compounds segregate in a high concentration from the die-surface corner to bearing surface. In this case, the product surface becomes rough.  
(7) As for the 6063 aluminum alloy for the general-purpose aluminum sashes, it is essential that \(\text{Mg}_2\text{Si}\) particles should not precipitate but disperse uniformly. When both \(\text{Fe}\) and \(\text{Si}\) are added, the product surface is rough.

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