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RESEARCH ARTICLE

Effect of die coating on surface crack depth of hot extruded 7075 aluminum alloy

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Abstract: The aluminum alloys belonging to the 7000 series are high-strength alloys used in a wide variety of products for weight reduction. They are primarily used in the field of transportation and aerospace. Among these, the A7075 alloy has the highest strength and is expected to be applicable in a wide range of fields, such as aircraft components and sports equipment. However, it has high deformation resistance and is prone to surface defects, which is called tearing. Tearing typically occurs at high temperatures and high ram speeds, and adversely affects productivity. The localized melting of Zn and additive compounds, due to the heat generated during the process, is considered to cause tearing. In this study, the effect of friction, heat, and tearing at the tool–metal interface was mitigated by improving the die surface quality. The reduced friction eliminated recrystallization by preventing the temperature from increasing to recrystallization temperature. In addition, an AlCrN coating was adopted instead of nitriding to improve the die surface quality. The tearing size and heat generated when using the AlCrN coating were found to be limited. Moreover, the grain size observed in the tearing region on the extruded surface was small. The simulations using the shear friction coefficient *m* observed from friction tests indicate that the use of the AlCrN coating improved the material flow. Thus, the AlCrN coating is considered effective for reducing friction at the interface and preventing the recrystallization of the extruded surface. From the aforementioned results, it can be inferred that a die coating can reduce the tearing sensitivity and increase the productivity of the A7075 alloy.

Keywords: hot extrusion; 7075 aluminum alloy; die coating; tearing

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1 Introduction

The 7000 series aluminum alloys are high-strength alloys used primarily in transportation equipment and aerospace applications for weight reduction. They possess high strength, excellent corrosion resistance, and good electrical and thermal conductivity. Moreover, their strength can be increased by heat treatment [1]. In this series, A7075 alloy extrusion is the most suitable for a wide range of lightweight applications, such as aircraft parts, automobile parts, and sporting goods. The production of aluminum alloys by hot extrusion involves forcing the billet through an opening die to obtain a predetermined shape. The requisite cross-sectional shape with adequate surface finish can be obtained in a single deformation. The hot extrusion process is widely used in the production of aluminum alloys because of its high productivity and extrusion rate [2]. ASTM H13 is commonly used as die steel in hot extrusion of aluminum alloys.

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Nomenclature

h_{f}	Forward extrusion length (mm)	m	Shear friction coefficient
h_{b}	Backward extrusion length (mm)		

The extrusion productivity of the A7075 alloy is the lowest among the alloys in the series owing to the cracking that occurs on the surface of the extrudate during the process, especially under high-speed and high-temperature conditions. This cracking defect is known as a tearing. In addition, the A7075 alloy is one of the most difficult aluminum alloys to deform and has high flow stress, which considerably limits the extrusion speed to approximately 0.8–2.0 m/min [3].

The extrudability of alloys used for hot extrusion is evaluated by the extrusion limit diagram, and the extrusion limit at which tearing occurs is largely related to the billet temperature and extrusion speed. Arif et al. [4] reported that tearing is more likely to occur under conditions of high extrusion speed and high billet temperature. Saha [5] reported that during hot extrusion, frictional heat causes localized melting at the billet–tool interface as the initial melting temperature of the billet is reached. Rappaz et al. [6] reported that molten intermetallic compounds are deposited on grain boundaries at high temperatures, and tensile stresses are generated during shear deformation, resulting in tearing at the grain boundaries. It has also been reported that micro-solid bridges, which are compounds deposited on grain boundaries, are generated and subsequently initiate grain boundary cracking. In addition, it has been reported that alloying elements such as zinc (Zn), magnesium (Mg), copper (Cu), and iron (Fe) migrate to the grain boundaries of A7075 alloy at high temperatures, especially when the Zn concentration is the highest [7].

Our previous studies showed that tearing is more likely to occur under high-temperature and high-velocity conditions [8]. We have reported that tearing is caused by the segregation and localized melting of soluble intermetallic compounds containing Zn and Mg in the crystalline structure. This, in turn, occurs due to the expansion of the recrystallization layer caused by the heat generated during the process and the strong tensile stress in the extrusion molding area. In this study, we focused on improving the surface properties of the die to suppress the heat generation during forming. The lubrication has not been considered in the extrusion process because it is sealed in the forming section and container, and no lubricants are available for use in the hot process. With regard to the application of coatings to hot extrusion of aluminum alloys, Jerina and Kalin [9–11] conducted a series of friction tests on hot extruded aluminum alloys using a two-cylinder crossed friction tester wherein two rods were slid at high temperature. The AW6060 material was used as the work material and H13 as die steel material. CrN and TiAlN alloys were tested. The friction coefficient was measured over a temperature range of 300–500 °C. The results showed that the tools coated with TiAlN exhibited less adhesion, indicating that TiAlN has excellent resistance to hot aluminum (Al) adhesion. Birol [12] also conducted sliding wear tests on AISI H13 tools coated with AA6063, CrN, AlTiN, and AlCrN, and found that the friction coefficient and amount of wear were lower for tools coated with AlCrN and TiAlN compared to tools coated with CrN. The AlTiN coating particularly showed superior performance. These studies indicate that the application of coatings on Al improves the frictional properties of tools, such as wear resistance. In the case of extrusion and in other processes that involve high pressure loads and high surface area expansion, it is difficult to measure the friction coefficient during the process, and only a few friction test methods can simulate these processes. In addition, the coating itself cannot withstand high temperature and high loading conditions; thus, evaluating the peeling life is difficult. In addition, when complexshaped molds with deep holes or constrictions are targeted, the physical vapor deposition (PVD) methods such as ion plating and sputtering cannot be used to form the coating; consequently, these methods cannot be used. In our previous studies [13, 14], the forming section was divided to ensure that the coating could be applied evenly to the die bearing section, and the PVD coatings were applied to suppress blistering defects in hot extruded A6063 alloys. AlTiN and AlCrN were used to suppress oxidation on the die surface. The results of this study showed that AlCrN and TiAlN can effectively remove plucking defects compared to nitriding, which is typically used as a surface treatment.

The coating was applied to the tool surface to suppress the tearing that occurs during the hot extrusion of 7000 series aluminum alloys. Three types of coatings, viz., AlCrN, TiAlN, and diamond-like carbon (DLC), were applied to the die. AlCrN and TiAlN coatings were selected because of their small friction coefficient at 500 °C. Hu et al. [15] devised a forward–backward friction testing machine for cold plastic working to measure the friction coefficient of stainless steels. It has been reported that this method has a large surface area expansion ratio and is effective for measuring shear friction coefficients in cold forging and other applications. The purpose of this study is to investigate the effect of coatings on tearing in tools with various surface properties during the hot extrusion process. This was achieved by measuring the friction coefficient during hot extrusion using the hot forward–backward extrusion friction tests.

2 Experimental method

In this experiment, hot extrusion and hot friction tests were conducted using the A7075 alloy. Table 1 lists the alloy compositions. The billets were fabricated from commercial billet-cast alloys. Figure 1 shows the 20,000 kN horizontal hydraulic press machine (YKK Corporation) that was used for the hot extrusion experiments. Cartridge heaters and thermocouples were installed in the container, and the temperature and ram speed were controlled using an operation board. A pressure sensor was attached to the hydraulic controller to measure the extrusion load during hot extrusion. The ram stroke was measured using a laser-displacement meter.

Figure 2 shows the shape and appearance of the two-part plate die used in the hot extrusion experiment. The bearing length of the die is 3 mm. The die orifice width *W* is 18.6 mm and the thickness *t* is 1.5 mm. The material of the two-part plate die in this experiment was AISI H13 (HRC48). Four different coatings (nitriding, AlCrN, TiAlN, and DLC) were applied to each die in successive experimental runs. As experimental conditions, billet temperatures of 425, 450, 475, and 500 °C and ram speeds of 0.5–11.5 mm/s were used. The billet for the hot extrusion process had dimensions of Ø41.5×120 mm. The billet and die were heated prior to extrusion and maintained at the extrusion-setting temperature for 2.5 h. The hot-extrusion conditions used in this experiment are listed in Table 2. The results obtained from this extrusion experiment were used to evaluate the extrusion limit diagram. Table 3 lists the thickness,

Table 1 Chemical composition of A7075 (wt%).

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Zr	Ti	Al
A7075	0.08	0.21	1.78	0.05	2.46	0.19	5.61	—	0.01	Balance

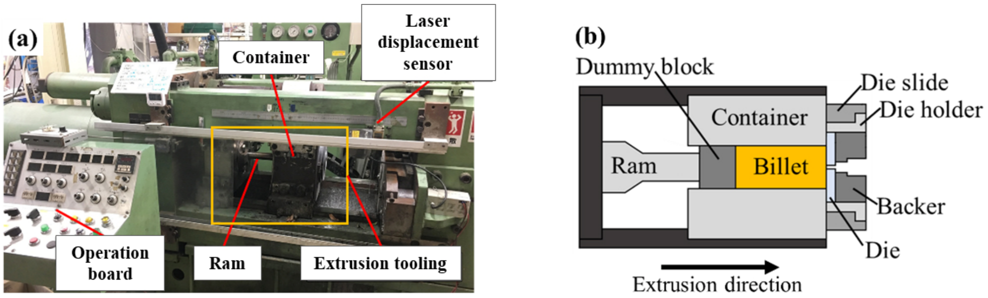


Fig. 1 (a) 20,000 kN (200 ton) horizontal hydraulic oil press machine; (b) extrusion tooling.

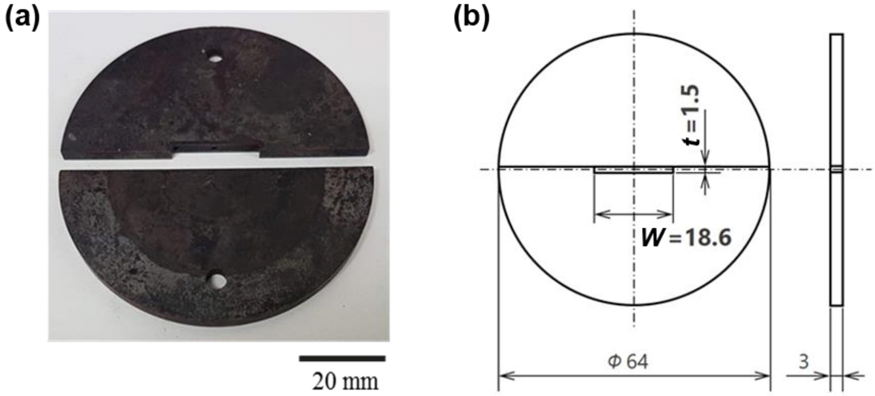


Fig. 2 Shape of segmented die ((a) picture and (b) design).

hardness, and surface roughness *Ra* of the dies with four different die coatings: nitriding, AlCrN, TiAlN, and DLC. Radical nitriding was used. AlCrN and TiAlN were coated by PVD, and DLC was coated by chemical vapor deposition (CVD). Four sets of coated tools were prepared, and each was used under the same temperature. A sodium hydroxide solution was used to wash Al adhered to the die so that the experiments could be repeated.

In this study, a friction test was conducted using a hot forward–backward extrusion friction test for an A7075 alloy specimen to evaluate the shear friction coefficients of dies with different coatings in hot extrusion. The obtained results were analyzed using a numerical or finite element method (FEM) to determine their correlation with shear friction coefficient *m*. Figure 3 shows an external view of the 10,000 kN vertical hydraulic press used for the hot forward–backward extrusion friction test.

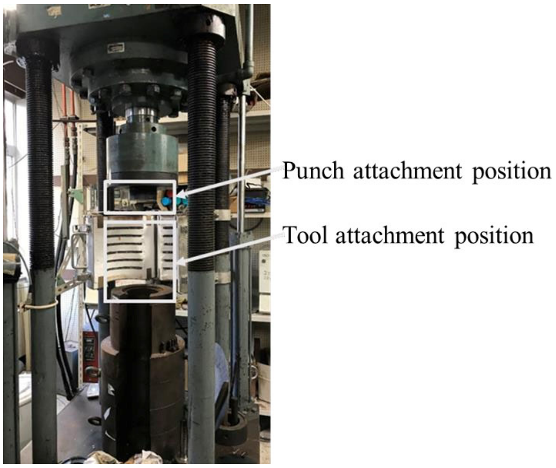


Fig. 3 10,000 kN (100 ton) vertical hydraulic press machine.

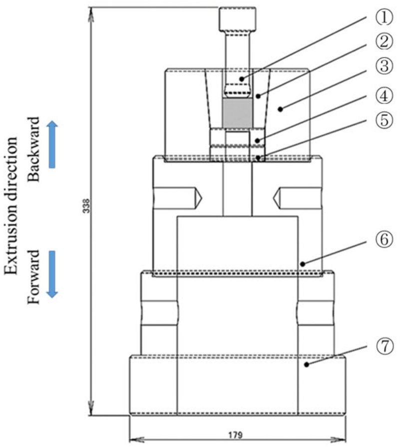
Table 2 Hot extrusion condition.

Billet size (mm)	Ø41.5×120
Billet temperature (°C)	425, 450, 475, and 500
Ram speed (mm/s)	0.5–11.5
Ram stroke (mm)	80
Extrusion ratio	49
Die Coating	Nitriding, TiAlN, AlCrN, and DLC

Table 3 Coating condition.

Coating type	Coating method	Coating thickness (μm)	Hardness (GPa)	*Ra* (μm)
Nitriding	Radical Nitriding	—	—	0.008
AlCrN	PVD	3.8	31	0.036
TiAlN	PVD	5.0	30	0.046
DLC	CVD	1.0	29	0.018

A punch and an extrusion die were installed in the frame, and the die was heated to the test temperature in a furnace. Hu et al. [15] developed the forward–backward extrusion friction test as a friction test for cold forging. This test is characterized by a higher surface area expansion ratio and contact normal stress compared to conventional friction tests such as the ring compression test. It can be applied as a friction test for complex forging and extrusion processes. A schematic of the extrusion tools used in this study is shown in Fig. 4. The tools consisted of a punch, container, container holder, die, backer, Assist. tool 1, and Assist. tool 2. The tools are made of AISI H13 (HRC48). The container was coated with nitriding, AlCrN, TiAlN and DLC, and the punch and die surface were also treated in the same way. One set of

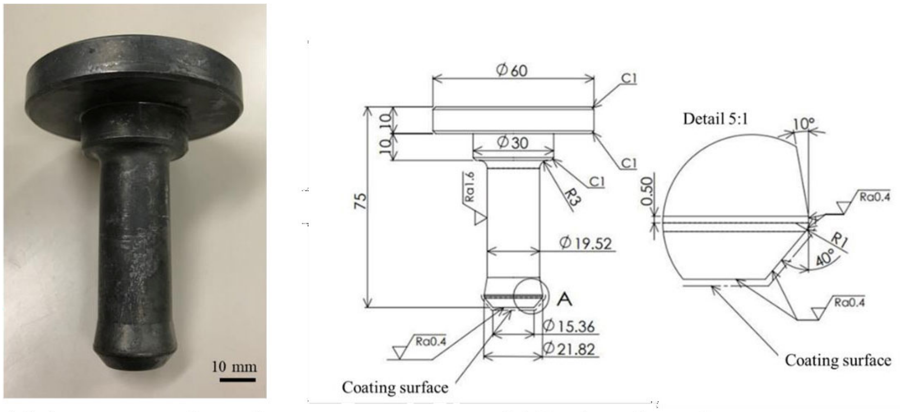


①	Punch
②	Container
③	Container holder
④	Die
⑤	Backer
⑥	Asisst. tool 1
⑦	Asisst. tool 2

Fig. 4 Assembly drawing of hot forward–backward extrusion friction test tool.

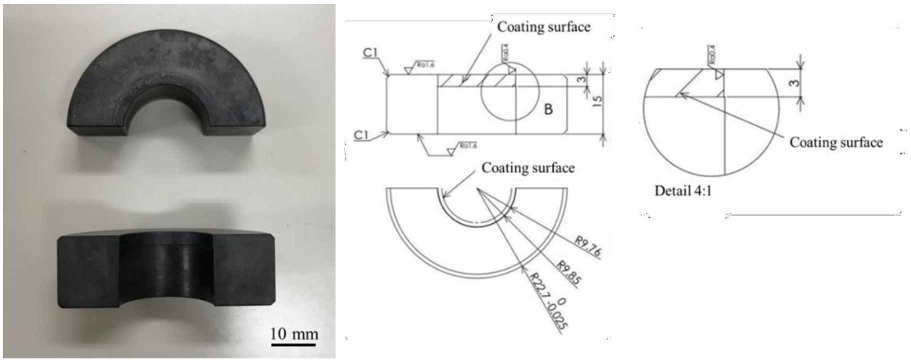
coating tools were prepared for each hot forward–backward extrusion friction test. Because the extrusion is performed in the forward–backward direction, bearing loads are concentrated on the surfaces of the die and punch, i.e., the surfaces in contact with the billet. The punch, die, and container were modeled based on the cold forward–backward extrusion friction test machine designed by Hu et al. [15].

Figure 4 shows a schematic of the hot forward–backward extrusion friction test used in this study. Figure 5(a) shows the punch used for the hot forward–backward extrusion friction test, and Fig. 5(b) shows the punch dimensions. A 40° tapered punch with a bearing length of 0.5 mm was used, and a hollow material with a diameter of 25.2 mm and a wall thickness of 1.19 mm was extruded in the backward part. The die appearance is shown in Fig. 6(a), and the die dimensions are shown in Fig. 6(b). The bearing length was set to 3 mm, and a round bar with a diameter of 19.52 mm was extruded in the forward part. Figures 7(a) and 7(b) show the appearance and shapes of the container, respectively. The punch and die in the experiment were made from AISI H13 (HRC48) with surface treatments of nitriding, AlCrN, TiAlN, and DLC. The dimensions of the billet were



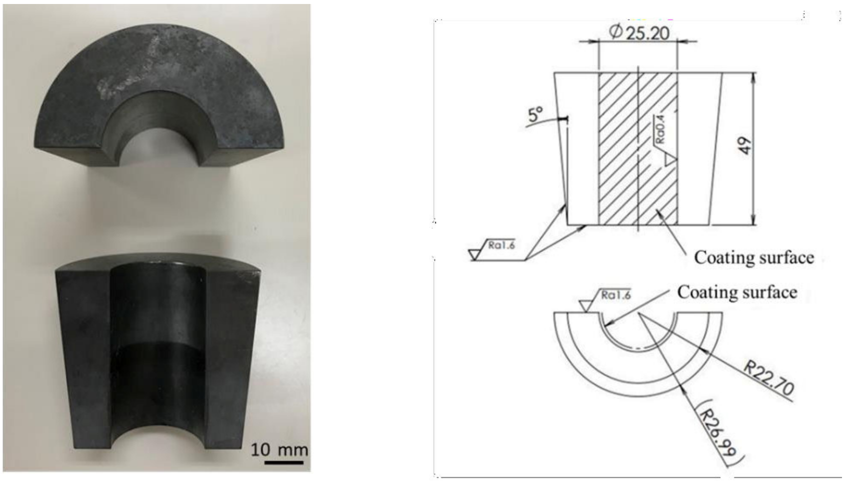
(a) Appearance of punch (b) Design of punch

Fig. 5 Punch for forward–backward extrusion test.



(a) Appearance of die (b) Design of die

Fig. 6 Segmented die for forward–backward extrusion test.



(a) Appearance of container (b) Design of container

Fig. 7 Segmented container for forward–backward extrusion test.

Ø25×25 mm. The friction test was conducted at a test temperature of 500 °C and a punching speed of 0.5 mm/s. However, the forward extrusion length h_f and the backward extrusion length h_b are different owing to the difference in friction between the forward and backward extrusions. Thus, the friction was evaluated based on the extrusion length ratio $h_\mathrm{b}/h_\mathrm{f}$.

The software (DEFORM-3D, YAMANAKA GOKIN Co. Ltd.) was used to generate the calibration curves for the hot forward–backward extrusion friction test, and the Lagrange method was used for analysis. The analysis conditions are listed in Table 4. The value of m was varied from 0.1 to 1.0 in the increment step of 0.1, and the heat transfer coefficient was set at 11 (N/(°C·s·mm^2)). During the test, the material flowed forward and backward along the same extrusion direction. The extrusion lengths h_f and h_b were measured to calculate the extrusion length ratios $h_\mathrm{b}/h_\mathrm{f}$ for different shear friction coefficients and used for the calibration curves. The m at each surface was measured from the calibration curve by simulation, and the extrusion length ratio $h_\mathrm{b}/h_\mathrm{f}$ was measured in the friction test.

Table 4 Simulation conditions of hot forward–backward extrusion test.

Simulation software	DEFORM-3D ver. 11.0
Simulation method	Lagrange
Material	A7075
Shape of billet (mm)	Ø 25×25
Punch speed (mm/s)	0.5
m	0.1, 0.2, … , 1.0
Billet temperature (°C)	500
Heat transfer coefficient (N/(°C·s·mm^2))	11
Number of element	100,000

A digital microscope was used to observe the tearing of the extrudate surface. In addition, the optical microscopy (OM), scanning electron microscopy (SEM), and electron backscatter diffraction (EBSD) were used to observe the microstructures of the extrudate and residual material.

3 Results and discussion

3.1 Evaluation of friction properties of coatings by hot forward–backward extrusion friction testing

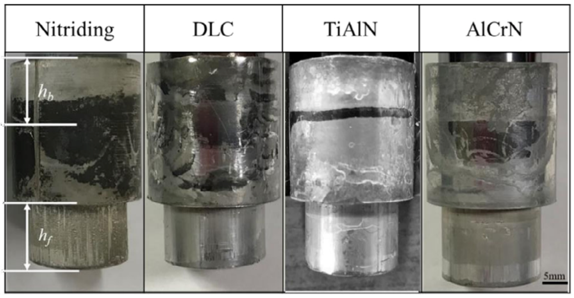
Figure 8 shows the appearance of the specimens after the hot forward and backward extrusion friction test for the different coatings of nitriding, AlCrN, TiAlN, and DLC at a test temperature of 500 °C and a punch speed of 0.5 mm/s, and their corresponding measurement results. A comparative study of the forward and backward extrusion lengths for different coatings revealed the following: The descending order of the forward extrusion lengths was AlCrN > TiAlN > nitriding > DLC. The descending order of the backward extrusion lengths was DLC > nitriding > TiAlN > AlCrN. Furthermore, the extrusion length ratios for nitriding, AlCrN, TiAlN, and DLC were 0.94, 0.68, 0.77, and 0.97, respectively. Finally, surface defects, such as protrusions on the grain, were observed at the bottom of the forward extrusion length for tool with the nitriding.

Figure 9 shows the cross-section of the specimens, the measured results of the forward and backward extrusion lengths, and the extrusion length ratios at a temperature of 500 °C and punch speed of 0.5 mm/s, for shear friction coefficients from 0.1 to 1.0. In addition, the calibration curve and extrusion length ratio were shown to be related to the shear friction coefficients between 0.1 and 1.0. The forward extrusion length was the longest for *m* = 0.1, and decreased as *m* increased. It was the shortest for *m* = 1.0. Conversely, the backward extrusion length was the shortest for *m* = 0.1, and the longest for *m* = 1.0. For each *m*, the forward extrusion length was longer than the backward extrusion length for all the conditions, and the extrusion length ratio approached 1 as *m* increased.

In conclusion, the experimental results for the nitriding and DLC coated tools at 500 °C agreed with the analytical results for *m* = 1.0. Similarly, the experimental results for the TiAlN-coated and AlCrN-coated tools agreed with the analytical results for *m* = 0.5 and 0.2, respectively. Similar to the results of the hot sliding friction tests by Jerina and Kalin [9–11] and Birol [12], AlCrN and TiAlN showed lower shear friction coefficients, with AlCrN possessing the lowest value.

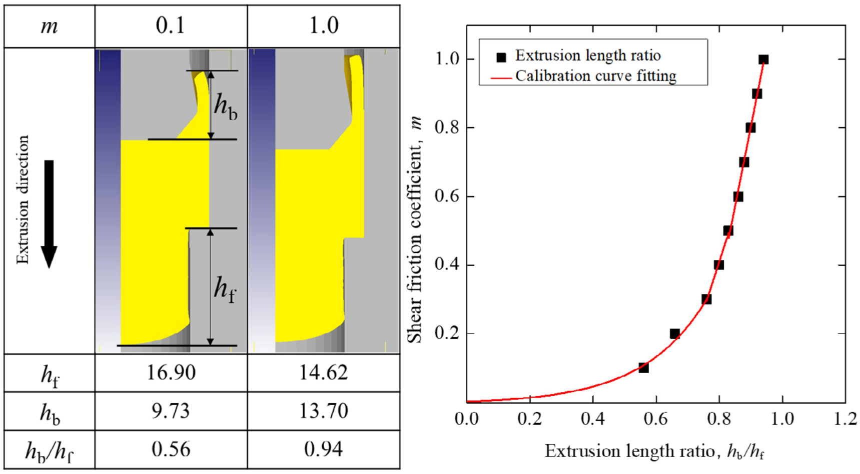
3.2 Effect of die coating on tearing of A7075 during hot extrusion

Figure 10 shows the surface appearance of the material extruded at a ram speed of 1.0 mm/s and a billet temperature of 450 °C. The total length of the



Coating condition	Nitriding	DLC	TiAlN	AlCrN
Forward extrusion length h_f (mm)	14.58	14.26	15.05	16.35
Backward extrusion length h_b (mm)	13.75	13.89	12.61	11.07
Extrusion length ratio h_b/h_f	0.94	0.97	0.83	0.68

Fig. 8 Hot forward–backward extrusion test in each coating (billet temperature: 500 °C; punch speed: 0.5 mm/s).



m	0.1	1.0
h_f	16.90	14.62
h_b	9.73	13.70
h_b/h_f	0.56	0.94

Fig. 9 Hot forward–backward extrusion simulation results and calibration curve (billet temperature: 500 °C; punch speed: 0.5 mm/s).

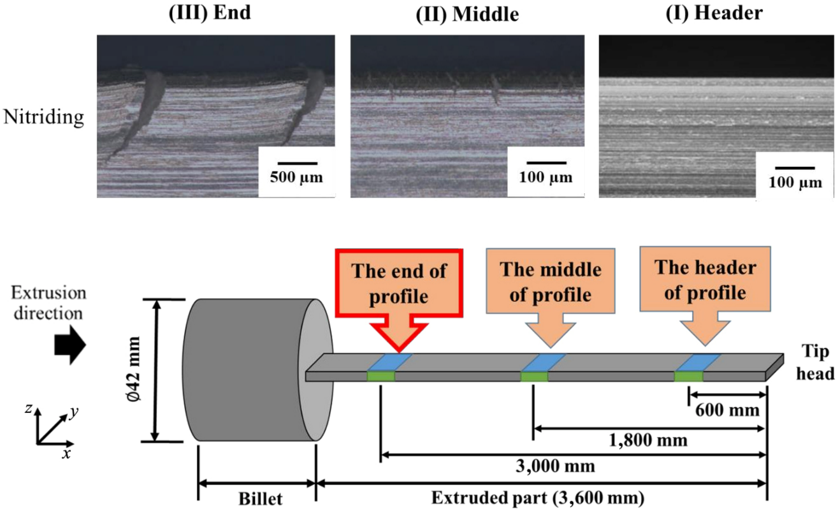


Fig. 10 Surface appearance of extruded material at difference distances from the tip head by *z*-axis view: (I) 600 mm, (II) 1,800 mm, and (III) 3,000 mm, extruded at the temperature of 450 °C with the extrusion speed of 1.0 mm/s. The die was coated using nitriding.

extruded material after hot extrusion was 3,600 mm. The surface of the extrudate was observed at different positions in terms of the distance from the extrudate tip: 600 mm (Symbol I), 1,800 mm (Symbol II), and 3,000 mm (Symbol III) in Fig. 10. No cracks were observed on the surface of the extrudate at a length of 600 mm. However, at 1,800 mm, small cracks were observed, and large cracks were clearly observed at 3,000 mm. Thus, in this experiment, the extrudability of the A7075 alloy was evaluated by observing the surface condition of the extrudate at 3,000 mm, classifying the cracks and creating an extrusion limit diagram.

An extrusion limit diagram of the A7075 alloy used in this experiment is shown in Fig. 11. In this experiment, tearing was classified into two types: no tearing and macro-tearing. A surface without tearing is represented by Symbol ●. Surfaces with a crack depth of 50 μm or greater are represented by Symbol ×. From Fig. 11, it is seen that tearing is more likely to occur under high-temperature and high-speed conditions. The relationship between processing conditions and extrudability in hot extrusion of the A7075 alloy can be evaluated using the extrusion limit curve.

Figure 12 shows a comparison of the extrusion limit curves of A7075 alloy using different die coatings. The extrusion limit curves with the nitriding die and the AlCrN die were almost identical. However, the

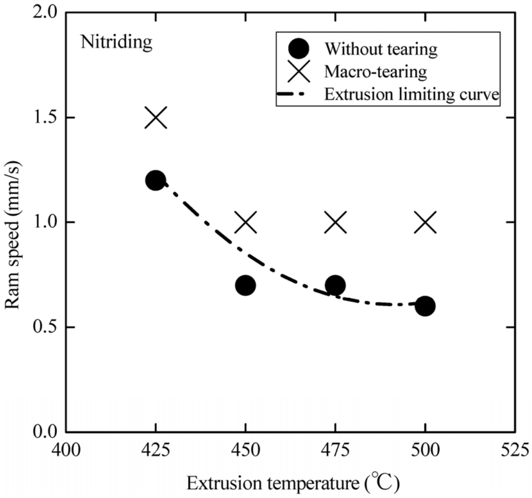


Fig. 11 Extrusion limit diagram for tearing of A7075 alloy. The die was coated using nitriding

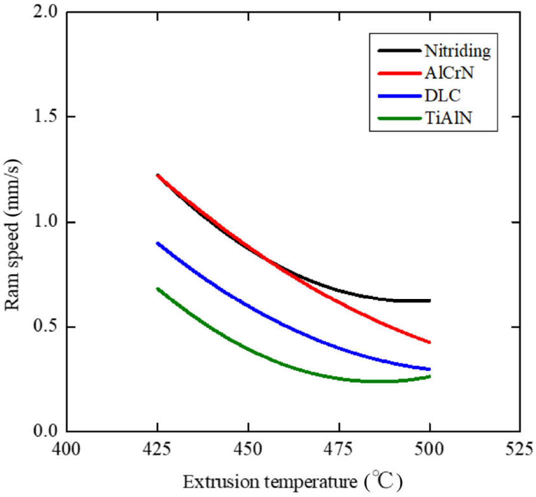


Fig. 12 Extrusion limit diagram for tearing of A7075 alloy using the dies with different coatings.

extrusion limit curves of the AA7075 alloy with TiAlN and DLC dies are lower than those with the nitriding and AlCrN dies.

Figure 13 shows the tearing size–stroke diagram for various die coatings. In the previous study [8], it was shown that tearing increased with the stroke, which is consistent with the obtained result. Furthermore, the tearing depth increases with the stroke for all extrusion conditions, but the tearing depth of the AlCrN die is smaller than those of the nitriding, TiAlN, and DLC dies.

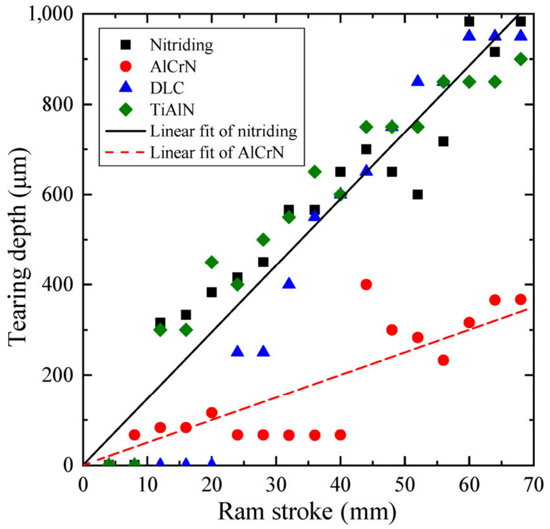


Fig. 13 Tearing size–stroke diagram of each die with different coatings (billet temperature: 450 °C, ram speed: 1.0 mm/s)

Figure 14 shows the crystal orientation of the extruded material surface for the AlCrN and nitriding dies, which were observed using the EBSD up to a depth of 3,000 mm. The extrudate was a sample with a billet temperature of 450 °C and a ram speed of 1.0 mm/s. According to the EBSD observations, the grain structure at the edge is large, equiaxed, and has a fibrous crystal structure at its center. Comparing the areas where tearing occurred, it is seen that tearing occurred at the coarse structure area, which indicates that cracks occurred along the grain boundaries. At a high magnification, the microstructure of the extruded material of the AlCrN die was smaller than that of the nitriding die. From the above results, it can be concluded that tension generated on the bearing surface at the AlCrN die is the lowest among the different dies. Thus, it can be inferred that AlCrN was more effective than the other coatings in reducing the friction generated during hot metal forming.

The tearing depth of the extruded material surface for each coating die was similar for the nitriding, TiAlN, and DLC dies; however, the tearing depth for AlCrN

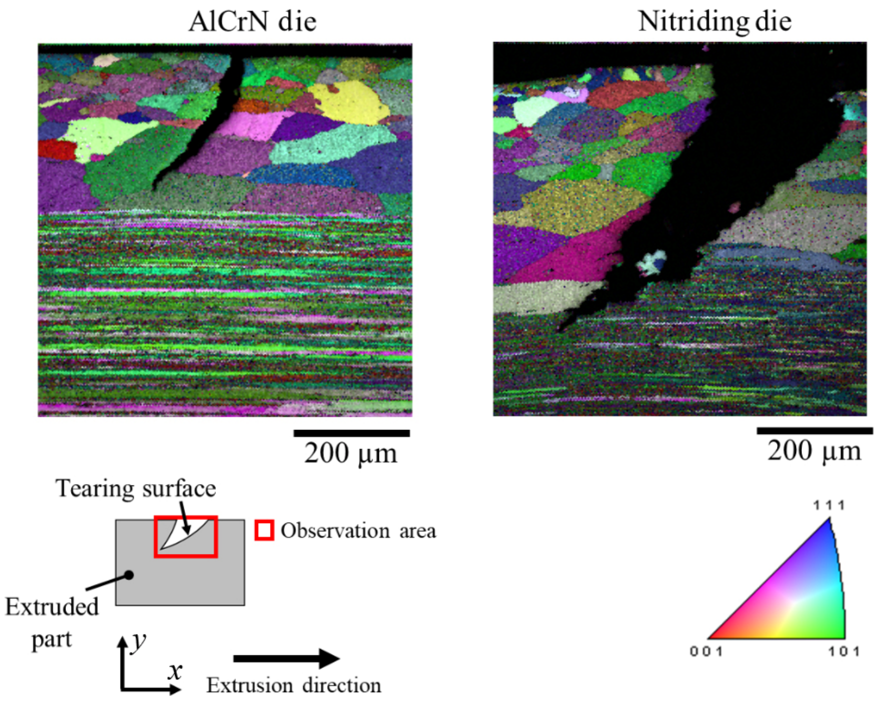


Fig. 14 Microstructure observation of the crystal orientation of the extruded material surface for AlCrN and nitriding dies by the EBSD (billet temperature: 450 °C, ram speed: 1.0 mm/s)

die was the smallest. The shear friction coefficients during hot plastic working at 500 °C were 1.0 for the nitriding and DLC dies, 0.5 for the TiAlN die, and 0.2 for the AlCrN die. The finite element simulations of the hot extrusion process were performed based on the results of friction tests. The simulation conditions are shown in Table 5. The main simulation conditions were the same as those in Table 4. The billet had the dimension of Ø41.5×120 mm, which is the same as that of the billet used in the hot extrusion experiment. From the hot forward–backward friction test, the shear friction coefficients were determined as $m = 0.2$ and 1.0 for AlCrN and nitriding, respectively. The temperature and stress distributions of the hot extrusion for the nitriding and AlCrN dies are shown in Fig. 15. For $m = 1.0$ (nitriding die), the temperature near the die bearing area is approximately 516–520 °C, and for $m = 0.2$ (AlCrN die), the corresponding temperature is approximately 513–516 °C. In the red region of the extrudate temperature (516–520 °C), the AlCrN die had a small amount of extrudate, whereas the nitriding die had a large extrudate overall. This indicates that the temperature distribution at $m = 0.2$ (AlCrN die) is lower than that at $m = 1.0$ (nitriding die). Thus, it can be inferred that a smaller shear friction coefficient is more effective in lowering the temperature of work heating during hot extrusion and reducing the work heating region at 516–520 °C.

From the stress distribution obtained by the hot extrusion analysis of nitriding and AlCrN dies, $m = 1.0$ (nitriding die) exhibits a wide range of non-uniform principal stresses near the die bearing area. The range of principal stresses at the edge of the extrudate increases as it passes through the corner of the die bearer, owing to the high degree of workability at the inside corner of the container. The effect of friction on the billet as it passes through the die bearing section should be considered, which results in a decrease in material flowability. For $m = 0.2$ (AlCrN), the stresses

Table 5 Simulation conditions of hot extrusion test.

Simulation software	DEFORM-3D ver. 11.0
Simulation method	Lagrange
Material	AA7075
Shape of billet (mm)	Ø41.5×120 mm
Punch speed (mm/s)	0.5
m	0.2 and 1.0
Billet temperature (°C)	500
Heat transfer coefficient (N/(°C·s·mm^2))	11
Number of elements	100,000

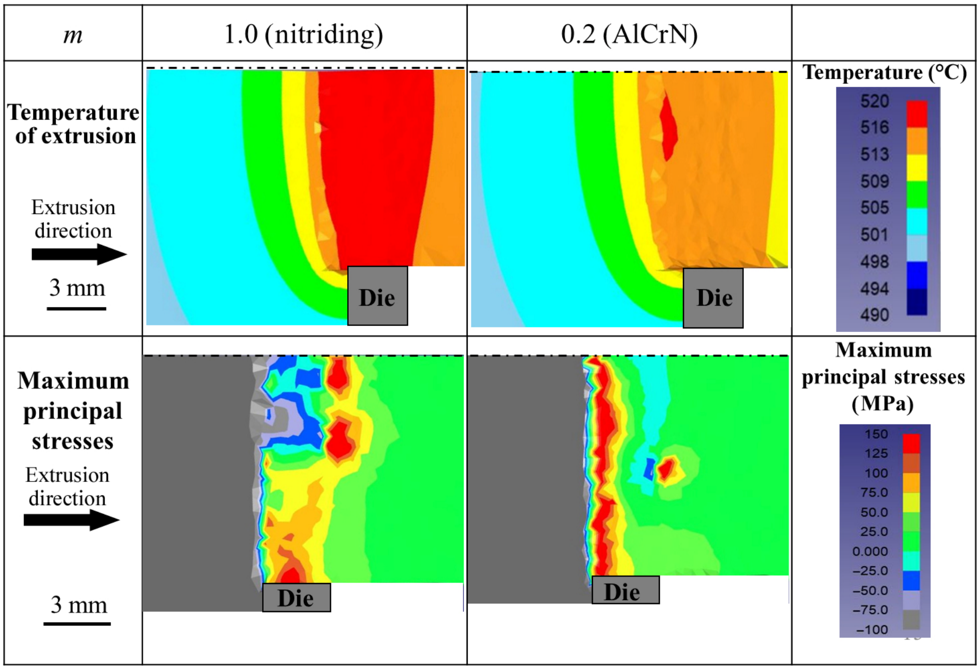


Fig. 15 Temperature distribution and principal stress distribution by hot extrusion analysis (billet temperature: 500 °C, ram speed: 0.5 mm/s)

near the die bearing area act uniformly only on the die bearing area. The effect of friction is reduced when the billet passes through the die bearing, which improves the material flowability.

In summary, the shear friction coefficient is closely related to tearing. For instance, m = 0.2 for the AlCrN die was due to the effect of friction on the work heating temperature and area during hot extrusion. It is worth noting that the work heating can be reduced. In addition, the tearing depth can be reduced owing to material flowability improvement. However, the results did not lead to the suppression of the tearing defect itself. The tearing defect was significantly affected by the processing temperature, and control of the product temperature and microstructure is more effective than the suppression of heat produced during forming.

4 Conclusions

In the hot extrusion process of A7075 alloy, the effects of die coating on die bearing and tearing were investigated. The following results were obtained.

1) The shear friction coefficient of AlCrN was found to be the lowest in the hot forward–backward extrusion friction test, which is very useful in reducing friction.

2) The average of the tearing depths of the extrudate from the nitriding, TiAlN, and DLC dies was 963 μm from the tip to the end of the extrudate, while that of the extrudate from the AlCrN die was 367 μm from the tip to the end of the extrudate.

3) The EBSD observation of the crystalline structure of extrusions obtained from hot extrusion experiments showed that the crystalline structure near the tearing of AlCrN die was smaller than that of nitriding die, and the depth of the recrystallized layer was also smaller.

4) Comparing the FEM results of the hot extrusion of AA7075, using nitriding and AlCrN dies, it was found that the temperature increased due to the heat generated during the process. It was more in nitriding die than the AlCrN die. The stress in the extrudate was non-uniform in nitriding die, whereas the AlCrN die showed limited and uniformly distributed stress.

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