Phenomena of tool adhesion at elevated temperature in V-groove friction test of AA7075

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Abstract. 7000 series aluminum alloys are high-strength alloys used in various lightweight products in the transportation equipment and aerospace industries. AA7075 extrusions are expected to find further applications in multiple fields, including aircraft parts, automotive parts, and sporting goods. However, the high deformation resistance and surface cracking defects caused by tool galling and adhesion have resulted in extremely low productivity. In this study, the V-groove compression test was proposed as a method to determine the coefficient of friction in hot metal forming. Using AA7075 as the experimental material, what did the V-groove compression test at various temperatures to compare the results with calibration curves created from the numerical analysis and observe the growth of adhesion.

Introduction

The advantages of 7000 series aluminum alloys are high strength, excellent corrosion resistance, and good electrical and thermal conductivity. Thus, these are used in various products to reduce weight in transportation equipment and aerospace applications [1]. In producing aluminum alloys by hot extrusion, the billet is passed through an opening die and pressed to shape. A cross-sectional shape with a surface finish can be obtained in a single deformation. Hot extrusion is widely used in the production of aluminum alloys because of its high productivity and extrusion yield [2]. However, AA7075 has the lowest extrusion productivity due to cracks that develop on the extrudate surface during hot extrusion, especially under high speed and high-temperature conditions, and due to adhesion to the tool. This cracking defect is known as tearing. In addition, AA7075 is one of the least deformable aluminum alloys and has high flow stress, which significantly limits the extrusion speed from 0.8 to 2.0 m/min. In our previous research, we reported that tearing was caused by low-melting intermetallic compounds containing magnesium (Mg) and zinc (Zn) [3]. It reported that the intermetallic compound with a low melting point locally melted due to the heat generated by the forming process.

The crack propagates due to the strong tensile stress applied to the product at the forming part during extrusion. As a method to suppress tearing defects that occur during the hot extrusion of 7000-series aluminum alloys, a coating on the die bearing section is proposed to reduce friction between the billet and tool interface [4]. Three coatings, AlCrN, TiAlN, and Diamond-like Carbon (DLC), were applied. The hot forward-backward extrusion friction test measured their friction coefficients, a friction test simulating plastic working at high temperatures. The friction coefficients from the friction tests and the occurrence of tearing when various die coatings were used showed that tearing was reduced for the low-friction AlCrN at high temperatures. It reported

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that this was due to the improvement of material flowability, and homogenization of tensile stress imparted to the product by low friction in the forming section. Therefore, it is necessary to investigate the extrusion tribology that contributes to tool adhesion and material fluidity to suppress tearing.

Friction tests for plastic forming can be classified into three types: basic friction tests such as pin-on-disk tests, friction tests simulating plastic forming, and friction tests using actual workpieces. The basic friction test is a simple way to obtain the coefficient of friction. Still, it does not apply to plastic forming because it does not involve a deformation process involving an increase in surface area. In particular, the surface area expansion ratio becomes extremely large when extrusion or forging is assumed. Friction tests using actual machines are only possible on those machines, making it challenging to obtain general-purpose results. Therefore, conducting friction tests that simulate extrusion and forging is necessary. The most common friction test that simulates extrusion and forging is the ring compression test. However, the compression ratio of this test is only about 50 percent and a friction test that allows a larger surface area expansion ratio is needed. In addition, reports of friction tests simulating hot extrusion and hot forging include the two-cylinder crossed friction test by Kalin et al. [5-7] and the Warm and Hot Upsetting Sliding Test (WHUST) by Dubar et al. [8-10] as examples of hot friction tests. Although these have been reported, there are few examples of friction tests simulating hot extrusion and hot forging. The hot forward-backward extrusion friction test conducted by the authors is also a friction test that simulates plastic forming. Still, it can only identify the friction coefficient for the entire process and is not suitable for measuring friction phenomena that change in complex ways during forming [4].

Zhang et al. proposed the T-shape compression test (TSCT), which can evaluate friction in complex extrusion and compression deformations and achieve a high surface area enlargement of more than 50% [11]. From the stimulation of the TSCT, Fereshteh-Saniee et al. conducted friction tests on AZ31 and AZ80 alloys in this test for hot plastic working of magnesium alloys. They reported that the experimental and simulation results agreed [12]. In addition, TSCT and ring compression tests were conducted to evaluate the friction of Dry, MoS2, and CASP during hot working. And it was reported that the experimental and simulation results agreed and that MoS2 was highly influential in lubricating the alloy during hot working based on the calibration curve created from the simulation. In addition, the friction coefficient of TSCT is higher than that of the ring compression test due to the difference in surface area expansion. These reports indicate that TSCT is effective as a basic friction test for micro- to macro-scale, cold- and hot-forging.

In this study, a hot V-groove friction test is proposed as a friction test that simulates hot extrusion and forging regarding the TSCT. In the hot V-groove friction test, a cylindrical test piece is compressed using a V-groove tool. The friction coefficient is identified from the aspect ratio of the compressed product since either longitudinal extrusion or transverse compression is the preferred deformation because of friction. The characteristics of this test are that it combines both extrusion and compression deformation, has a high surface area expansion ratio of more than 50 percent, and is a two-dimensional deformation in which the circle is collapsed. The dimensions and compression ratio can be easily changed. In this research, tool dimensions and the mechanism of adhesion under different temperatures and compaction amounts are investigated as part of the development of the V-groove friction test. By using AA7075 as the test material and varying the temperature and stroke amount, this study aims to examine the effect of working temperature on the process of adhesion growth during hot forming.

Experimental Method

The AA7075 shown in Table 1 was used in this study. The test pieces were turned to a diameter of 7.0 mm and a length of 70 mm. These dimensions were chosen because the size should be at least 10 times larger than the diameter so that deformation in the depth direction can be ignored.

Fig. 1 shows the 100-ton vertical hydraulic press used in this experiment. The press has a furnace in the forming section to provide a hot test environment. A data logger from the hydraulic system and a displacement transducer read the test force and stroke rate.

Table 1. Chemical composition of AA7075 (mass%).

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Zr	Ti	Al
AA7075	0.08	0.21	1.78	0.05	2.46	0.19	5.61	-	0.01	Bal.

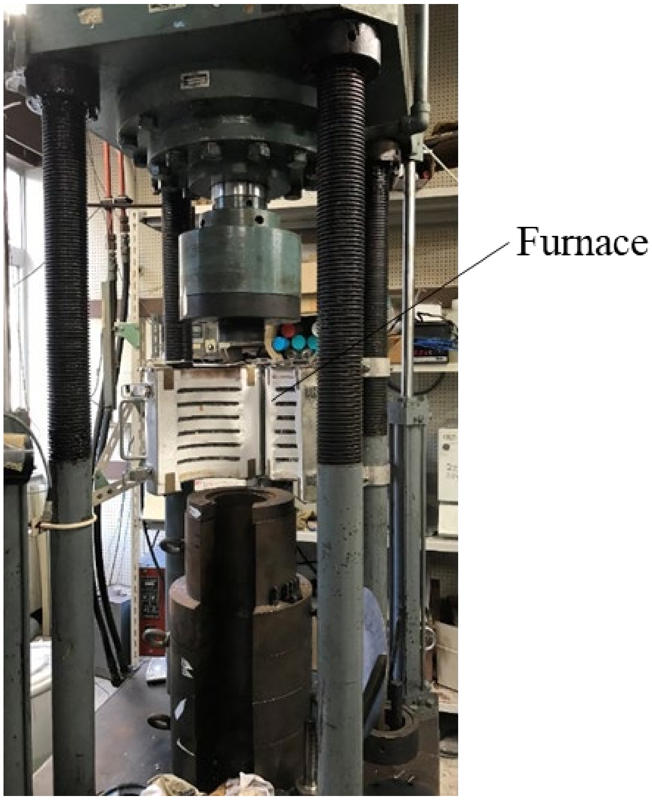

Fig. 1. 100-ton vertical hydraulic press machine.

Table 2 shows the conditions of the hot V-groove friction test and the numerical analysis conditions. Fig. 2 shows a schematic diagram of the V-groove friction test AISI H13 (HRC48) nitrided tool used as the tool material. The numerical analysis software used was DEFORM-3D by Yamanaka Eng Co., Ltd. The groove angles were 15° and 30°, and the groove corner radius R was 1.0 mm and 3.0 mm, referring to the study by Zhang et al. to examine the tool geometry for the hot V-groove friction test [11]. The groove depth was set to 10 mm. The punch stroke is set to 0.1 mm/s with a stroke volume of 4.5 mm. The temperatures of the billet and testing machine were 400°C and 500°C.

The Hot V-groove friction test numerical analysis was performed for shear friction coefficients $m = 0.1, 0.2, ..., 1.0$. The shear friction model was used as the friction model. The material data was used from previous authors' AA7075 research [4]. Friction changes the height (H) and width (W) of the test piece after the V-groove friction test. When friction is low, extrusion becomes dominant, and the height of the test piece increases.

On the other hand, when friction is high, compression becomes dominant, and the width of the test piece grows. Calibration curves were created from the sample's aspect ratio (H/W) after forming at each friction coefficient. The friction coefficients were identified by comparison with the aspect ratio of the model after the experiment. Experiments were conducted three times each for reproducibility.

The amount of elemental deposition on the V-groove tool surface was measured by Electron Probe Micro Analyzer (EPMA, JEOL) to confirm the deposition growth process. Fig. 3 shows the schematic diagram of the measurement points.

Table 2. V-groove friction test and numerical analysis conditions.

Testing conditions		
Billet material		AA7075
Tool material		AISI H13
Billet shape	[mm]	φ7.0×70
Punch speed *V*	[mm/s]	0.1
Punch stroke	[mm]	4.5
Billet temperature *T*	[℃]	400, 500
Groove depth	[mm]	10
Groove angle	[°]	15, 30
Corner radius R	[mm]	1.0, 3.0
Lubrication		No-lubricant
Tool surface treatment		Nitriding
Numerical analysis conditions		
Simulation soft		DEFORM-3D
Numerical analysis method		Lagrangian method
Billet material		AA7075
Tool material		AISI H13
Number of elements		100,000
Heat transfer coefficient	[Nmm/sec℃]	11
Friction model		Share friction model
Share friction coefficient *m*	[-]	0.1, 0.2, . . . 1.0

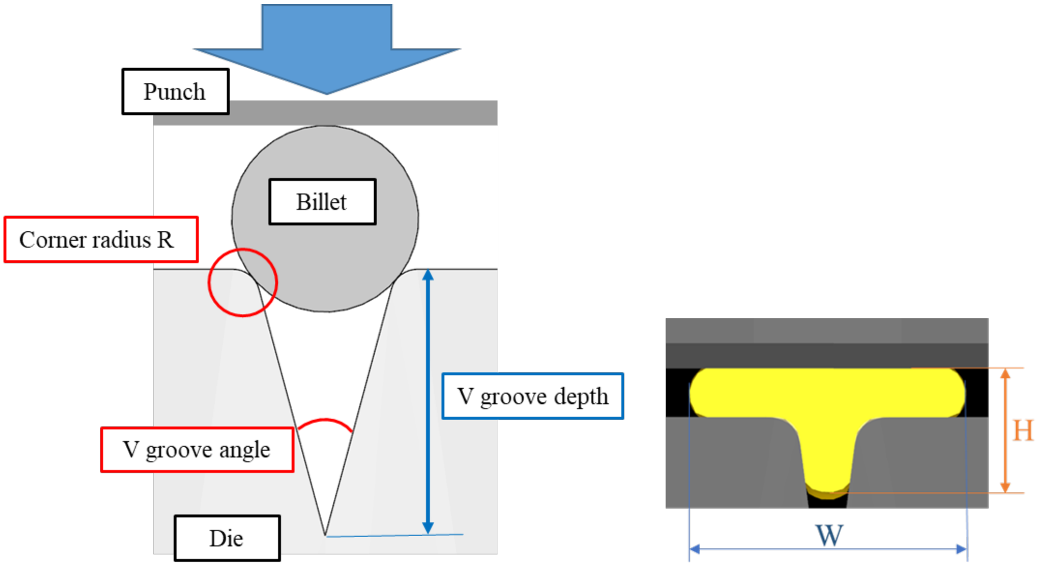

Fig. 2. Schematic view of V groove compression test (left) and shape of the test piece after the test (right (H: hight, W: width)).

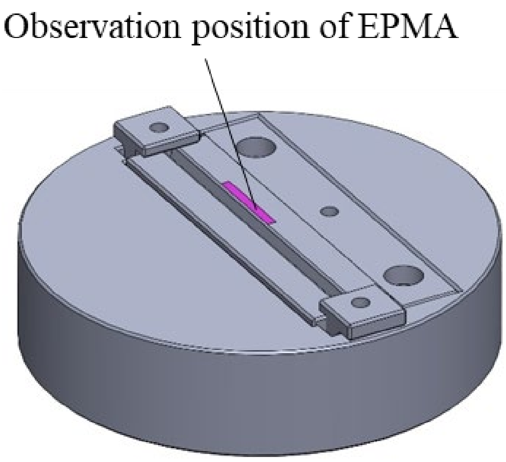

Fig. 3. Schematic of tool for V-groove compression test and EPMA observation position.

Experimental Results

Fig. 4 shows the calibration curves for each tool condition generated from the numerical analysis. The friction coefficient cannot be determined for the R1, 15° condition because the shear friction coefficient does not determine the magnitude of the aspect ratio. Under the R3, 15° condition, a right ascending calibration curve was observed, but the aspect ratio increased and decreased under low friction, indicating that an accurate friction coefficient may not be obtained. In the R3, 30° condition, the shear friction coefficients of m = 0.9 and 1.0 could not analyze, and a calibration curve could not be generated. Based on these results, the basic V-groove shape of the die for the V-groove compression test was determined to have an R radius of 1 mm and a V-groove angle of 30°.

Fig. 5 shows the V-groove compression test conducted at a test temperature of 400°C. As a result, H/W was 0.526, and the coefficient of friction was m = 0.9.

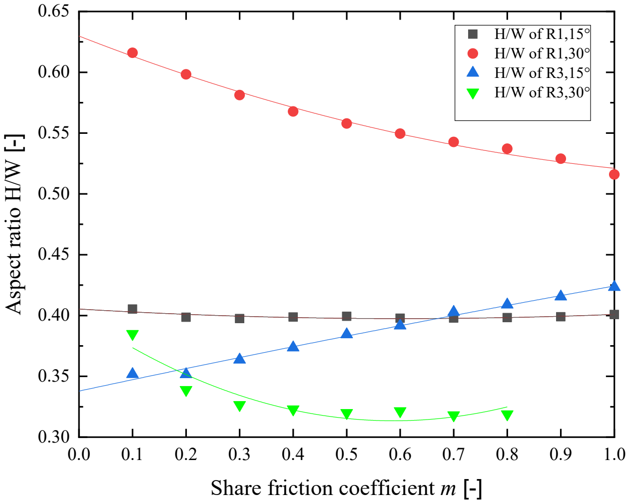

Fig. 4. V-groove compression test calibration curves for each tool condition (Simulation soft: DEFORM-3D, Temperature: 400°C, punch speed: 0.1 mm/s).

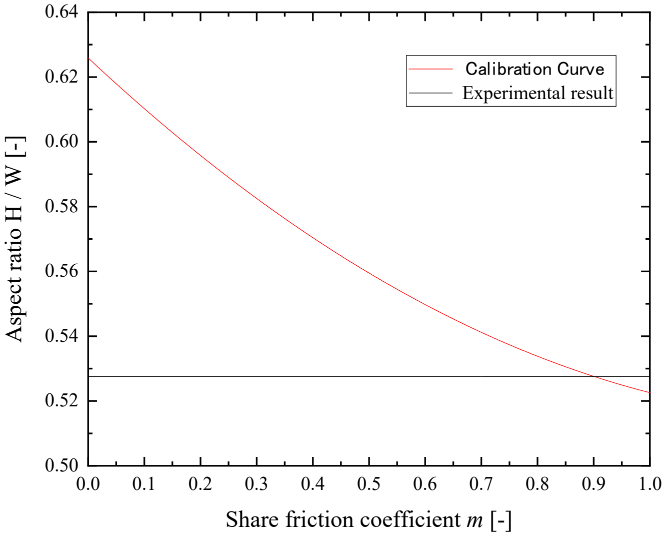

Fig. 5. Calibration curves and experimental aspect ratios (test temperature: 400°C, punch speed: 0.1 mm/s).

Fig. 6 shows an numerical analysis (m=0.9) and experimental force-punch stroke diagram for the V-groove friction test at a test temperature of 400°C. The experimental and numerical force curves were similar. The maximum force was 176.0 kN in the numerical analysis and 176.9 kN in the experiment. Fig. 7 compares the material flow between the experimental and numerical results. At the corner radius R, the material flow is divided into extrusion in the direction of punch travel and compression in the vertical movement of the extrusion. From the sample dimensions after the test shown in Fig. 7 and the calibration curve shown in Fig. 4, it can assume that material flow in the direction of extrusion is dominant when friction is low, and material flow in the direction of compression is dominant when friction is high.

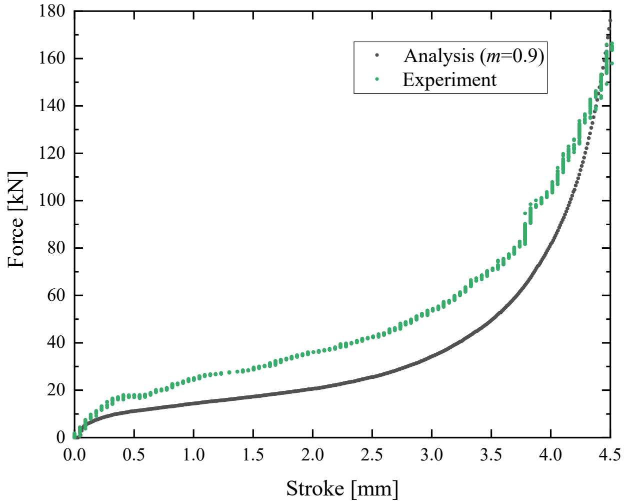

Fig. 6. Force-stroke curves for V-groove compression test and numerical analysis (test temperature: 400°C, punch speed: 0.1 mm/s).

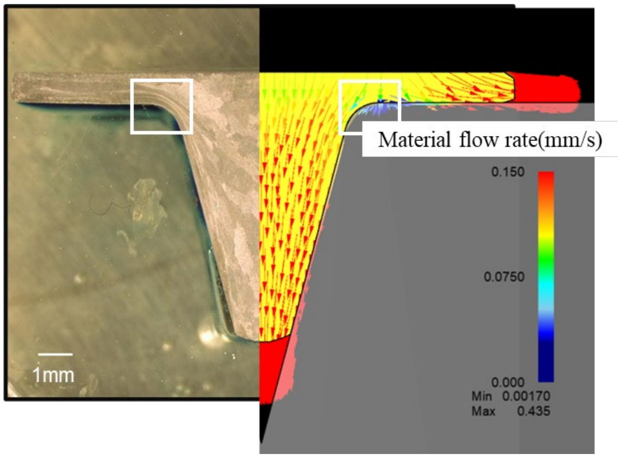

Fig. 7. Comparison of experimental and numerical material flow (test temperature: 400°C, punch speed: 0.1 mm/s).

Based on the experimental and numerical results of the V-groove compression test at 400°C, this test was validated as a friction test simulating hot extrusion and forging. Friction and adhesion between the die and aluminum on the tool surface are assumed to be significant causes of tearing defects on the product surface and burning on the tool at high temperatures and high forging speeds, which is a friction problem in extrusion and forging. Therefore, we conducted a V-groove compression test at 500°C and compared the results with those at 400°C to evaluate friction and adhesion to the tool as a function of temperature.

Fig. 8 shows the experimental results of the V-groove compression test at 500°C and the calibration curve. H/W from the experiment was 0.538, and the coefficient of friction was $m = 1.0$. The results of a previous hot forward-backward extrusion friction test at 500°C between a nitrided tool and AA7075 conducted by the authors also showed m=1.0, which is the same result as in the present study [4].

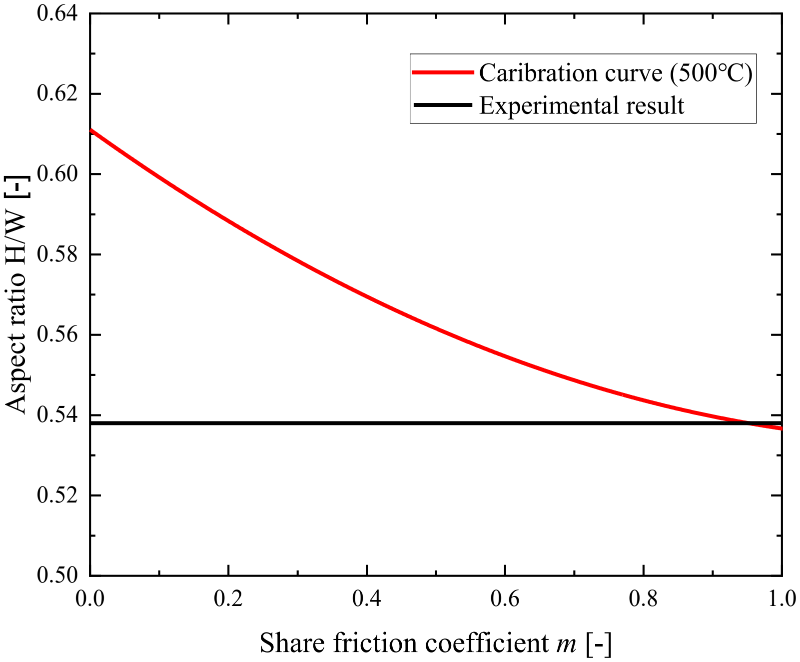

Fig. 8. Calibration curves and experimental aspect ratios (test temperature: 500°C, punch speed: 0.1 mm/s).

Fig. 9 shows the adsorption of alloying elements and oxygen (O) on the tool in the V-groove compression test at 400°C and 500°C. Before the test, aluminum (Al) was removed with sodium hydroxide solution and then analyzed by EPMA. The results of the EPMA analysis show that the adsorption of the alloying elements increased with increasing temperature in the Mg case. The strong O reaction on the entire tool surface at 500°C indicates that the tool surface is strongly oxidized, while the responses of Cu and Zn are small at 400°C and strong at 500°C, respectively. Previous studies by the authors have confirmed that magnesium oxide (MgO) is deposited by O on the tool surface and oxidized at high temperatures during the hot extrusion of AA6063 and Mg contained in the alloying elements [13]. At 400°C, the reaction of O is also vital in the Mg range, suggesting that MgO is formed.

On the other hand, at 500°C, the entire tool is uniformly oxidized, and the extent of Mg deposition is considered to have increased. The V-groove friction test also showed the same tendency, with Mg firmly adhering at the R part where the high surface pressure is applied, and from the quaternary state diagram of the Al-Zn-Mg-Cu alloy, Al+ $Al_2Mg_3Zn_3$+ $Al_5Cu_2Mg_2$ at 400°C or higher [14]. Since the composition of AA7075 in this study contains 1.6% Cu, $Al_2Mg_3Zn_3$ melts at temperatures above 480°C, and $Al_5Cu_2Mg_2$ melts at temperatures above 500°C. The Cu and Zn have not adhered at 400°C on the tool.

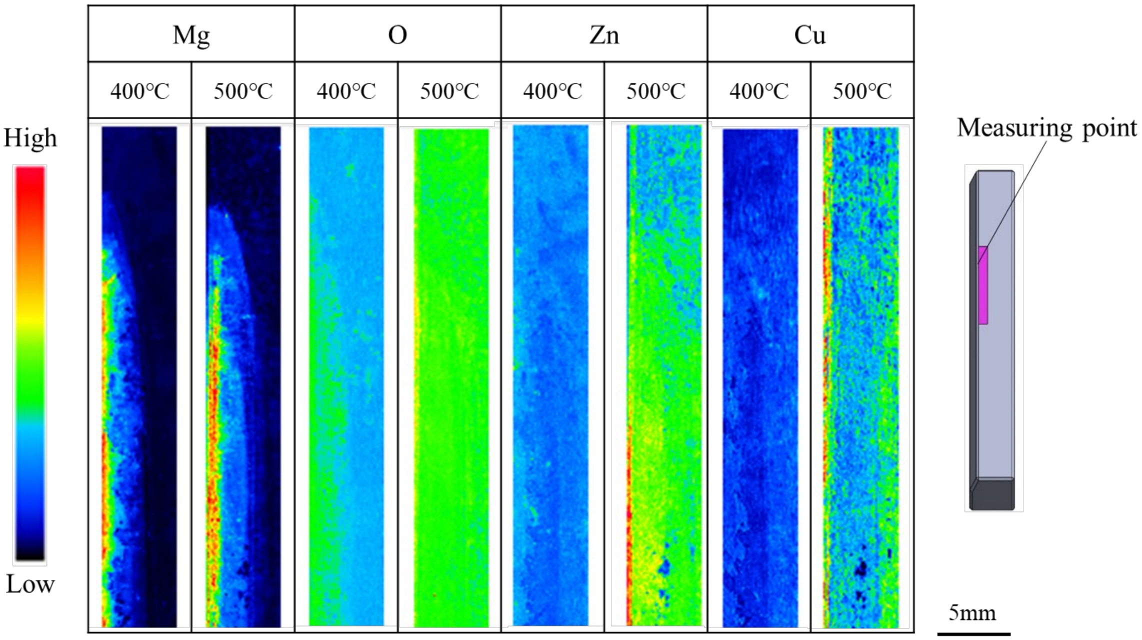

Fig. 9. Elemental analysis of tool surface after V-groove compression test (test temperature: 400, 500°C, punch speed: 0.1 mm/s).

Summary

In this study, the hot V-groove friction test is proposed as a friction test simulating extrusion and forging, measuring the coefficient of friction at various temperatures, and evaluating the adhesion to the tool surface. The hot V-groove friction test is practical as a friction test that simulates plastic forming at high temperatures because it achieves a high surface area expansion ratio. In addition, it was possible to reproduce the adhesion process of the tool surface during extrusion. The results obtained are listed below.

- The tool geometry was optimally affected by friction when the corner radius of the groove R was 1.0 mm, and the groove angle was 30°.
- From the calibration curve obtained from the numerical analysis, the shear friction coefficient m of AA7075 at 400°C was 0.9, and at 500°C, the shear friction coefficient m was 1.0.
- The EPMA evaluation of tool surface adhesion at 400°C and 500°C showed that the extent of Mg adhesion increased with increasing temperature, and the oxidation of the tool surface became stronger; Cu and Zn adhesion became more active at 500°C due to melting of intermetallic compounds.

Future research will include investigating the effects of surface pressure, heat generation, and tool surface adhesion using analysis and investigating the impact of tool surface treatment on tribological properties by applying die coating, tool surface texturing, and V-groove compression testing.

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