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Tribo-Characteristics in Hot AA7xxx via V-Groove Friction Test

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Abstract

High-strength AA7075 aluminum alloys are essential for lightweight design in the aerospace and automotive sectors. However, their hot extrusion process is limited by severe adhesive wear and surface tearing under high-temperature conditions. This study systematically investigates the hot tribological behavior of AA7xxx series alloys with varying Zinc (Zn) contents (0Zn, AA7075, and 8Zn) against conventional nitrided SKD61 dies. A hot V-groove friction test simulating severe plastic deformation was combined with Finite Element Method (FEM) simulations conducted at 400°C, 450°C, and 500°C to establish calibration curves correlating the shear friction coefficient (m) with specimen deformation. The developed calibration curves successfully determined the actual friction coefficients from physical experiments. The adhesion behavior of alloying elements was subsequently quantified using Electron Probe Micro Analysis (EPMA). Results indicated that while macroscopic deformation resistance and friction levels remained high and largely independent of Zn content, elemental adhesion was highly sensitive to chemical composition. Crucially, high Zn content promoted severe tool adhesion and surface tearing at 500°C due to the localized melting of low-melting-point intermetallic phases. These findings provide critical guidance for optimizing alloy compositions and tool-die conditions in hot processing, facilitating improved productivity and extending the overall service lifespan of forming tools.

1 Introduction

High-strength 7000 series aluminum alloys (Al-Zn-Mg-Cu) are increasingly essential for lightweight design in critical industries such as aerospace, automotive, and sporting goods due to their high specific strength and excellent mechanical properties (Misiolek, ASM Handbook, 2005). Despite these advantages, the productivity of hot extrusion for alloys like AA7075 is significantly restricted by their poor extrudability. Specifically, the high deformation resistance and susceptibility to defects limit the extrusion speed to approximately 2.0 m/min (Misiolek, ASM Handbook, 2005). A critical limitation is the occurrence of surface defects known as "tearing," especially under high-speed and high-temperature conditions. These defects, combined with severe adhesive wear (galling) on the die bearing, drastically reduce die service life and compromise product integrity (Saha, Aluminum Extrusion Technology, 2000), (Ngernbamrung, J. Jpn. Inst. Light. Met., 2018).

Previous research has indicated that tearing is closely related to the tribological interaction between the workpiece and the tool. Specifically, low-melting-point intermetallic compounds containing Zinc (Zn) can melt locally due to the heat generated during deformation, leading to adhesion and subsequent crack propagation under tensile stress (Ngernbamrung, J. Jpn. Inst. Light. Met., 2018), (Funazuka, Friction, 2022). To mitigate these issues, understanding the friction and adhesion phenomena at the tool-workpiece interface is paramount. While various die coatings have been proposed to reduce friction (Funazuka, Friction, 2022), a fundamental understanding of how specific Zinc levels contribute to adhesion and surface integrity is still required.

Evaluating these tribological characteristics requires robust testing methods. Basic friction tests, such as pin-on-disk, often fail to replicate the severe deformation conditions of bulk metal forming. Conventional methods like the ring compression test are limited by a relatively low surface expansion ratio (~50%) (Zhang, J. Mater. Process. Technol., 2009). To address this, simulative tests that combine extrusion and compression modes with high surface expansion are necessary. The T-shape compression test (TSCT) has been shown to effectively simulate hot forging conditions (Zhang, J. Mater. Process. Technol., 2009), (Fereshteh-Saniee, Mater. Des., 2011).

Building on this concept, Funazuka et al. proposed the "hot V-groove friction test," which induces a two-dimensional deformation combining longitudinal extrusion and transverse compression, achieving high surface expansion ratios suitable for simulating hot extrusion (Funazuka, Materials Research Proceedings, 2023). A primary advantage of the V-groove technique is its ability to accurately evaluate interfacial friction using small-scale specimens at elevated temperatures. This efficiency is crucial for high-temperature investigations as it ensures uniform heating throughout the specimen while reducing the mechanical load required from experimental equipment. Furthermore, the technique provides a sensitive correlation between material flow and friction, making it an effective tool for assessing the complex tribological interactions found in high-pressure metal forming processes.

In this study, the hot V-groove friction test is utilized to evaluate the tribological behavior of AA7xxx series alloys. Unlike previous studies that focused on standard AA7075, this research investigates the specific influence of varying Zinc (Zn) contents (0Zn, AA7075, and 8Zn) on tool adhesion and surface integrity. By employing Finite Element Method (FEM) simulations to establish calibration curves and utilizing Electron Probe Micro Analysis (EPMA) for surface characterization, this study aims to clarify the mechanism of elemental adhesion on nitrided SKD61 dies. The findings provide critical data for optimizing alloy compositions and developing strategies to extend die life in hot processing.

2 Methodology

2.1 True Stress-Strain Characteristics of Specimens via Hot Compression Test

To accurately model the deformation behavior in hot processing, hot compression tests were conducted following the ASTM E209 standard to identify critical material parameters, specifically the true stress-strain relationships. Since the mechanical properties of aluminum alloys vary significantly with temperature, it is essential to characterize the material at each specific processing temperature used in extrusion.

The investigation focused on three variations of AA7xxx series aluminum alloys with systematically adjusted Zinc (Zn) content to isolate its effect on tribological characteristics. These included a low-zinc variant (0ZN), a standard AA7075 variant, and a high-zinc variant (8ZN). The chemical compositions of these test billets are detailed in Table 1.

Table 1: Chemical composition of test billets (mass %)

Alloys	Mg	Si	Fe	Cu	Mn	Cr	Zn	Ti	Al
0ZN	2.47	0.09	0.21	1.82	0.05	0.17	<0.01	0.01	Bal.
A7075	2.54	0.09	0.21	1.82	0.05	0.19	5.80	0.01	Bal.
8ZN	2.48	0.09	0.21	1.87	0.05	0.19	8.13	0.01	Bal.

The compression tests utilized cylindrical specimens with a diameter of 10 mm and a height of 15 mm to minimize frictional effects at the tool interface and to prevent buckling during the 90% reduction process. Testing was performed under lubricant-free conditions at temperatures of 400°C, 450°C, and 500°C. Initial strain rates were set at 0.06, 1.0, and 3 s^{-1} to evaluate the strain rate sensitivity of the alloys. The data obtained from these tests served as the fundamental material model for the FEM simulations described in Section 2.3.

2.2 Hot V-Groove Friction Test

The hot V-groove friction test was performed to evaluate interface characteristics under severe deformation. The experiments used a 100-ton vertical hydraulic press, as shown in Fig. 1. The V-groove die geometry, illustrated in Fig. 2, featured a groove angle β of 30°, a corner radius (R) of 1.0 mm, and a groove depth of 10 mm. Tests were performed on AA7xxx billets with a diameter of 7.0 mm and a length of 70 mm under lubricant-free conditions at 400°C, 450°C, and 500°C with a punch speed of 0.1 mm/s.

During the test, the cylindrical billet undergoes a complex two-dimensional deformation mechanism. As the punch compresses the specimen, a portion of the material is forced to flow downward into the V-shaped groove, closely simulating the severe longitudinal material flow and high contact pressures typical of an extrusion process. Simultaneously, the remaining material is compressed between the flat tool surfaces, causing it to expand laterally (transverse expansion). The balance between this longitudinal extrusion into the groove and the transverse expansion is highly sensitive to the frictional conditions at the tool-workpiece interface. After compression, the geometrical changes were analyzed by measuring the height of the extruded part (h) and the width of the laterally deformed specimen (w). The final aspect ratio (h/w) was calculated and compared with simulation results to derive the shear friction coefficient (m). To isolate the effect of Zn, three alloy variations were used as described in Table 1.

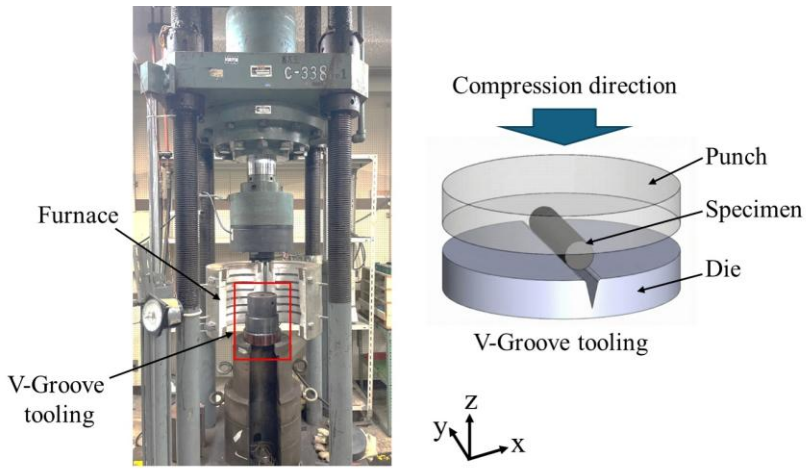

Figure 1: The 100-ton vertical hydraulic press machine and V-groove tooling used for hot friction testing.

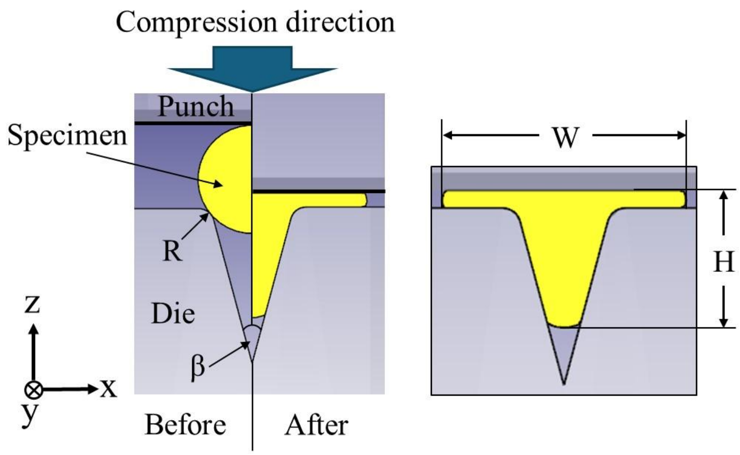

Figure 2: Schematic illustration of the hot V-groove friction test showing the longitudinal extrusion and transverse compression modes.

2.3 Finite Element Method (FEM) Simulation

Numerical simulations were performed using the DEFORM-3D software to establish friction calibration curves. A one-quarter (1/4) symmetric model was utilized, as shown in Fig. 3, to optimize computational efficiency while leveraging the geometric symmetry of both the workpiece and tooling. The material properties derived from the hot compression tests (Section 2.1) for the AA7xxx alloys (0Zn, AA7075, and 8Zn) were integrated into the simulation as a plastic body model, while the tool was modeled as rigid AISI H13 steel.

The simulation setup strictly replicated the physical testing conditions and V-groove geometry (R = 1.0 mm, depth = 10 mm). Thermal and mechanical boundary conditions matched the experimental environment, comprising billet temperatures of 400°C, 450°C, and 500°C, a punch speed of 0.1 mm/s, and a target punch stroke of 4.5 mm. To ensure numerical accuracy, the workpiece was meshed with approximately 100,000 elements, and a heat transfer coefficient of 11 N/mm/sec°C was applied at the tool-workpiece interface. Calibration curves were generated using a shear friction model by systematically varying the shear friction coefficient (m) from 0.1 to 1.0. This allowed for the empirical derivation of the actual friction coefficients observed in the physical tests.

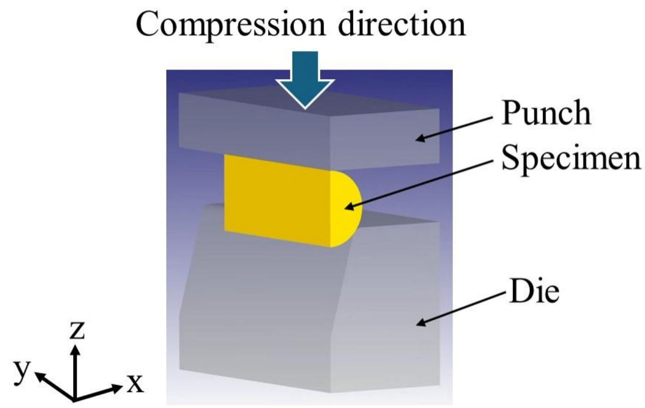

Figure 3: The one-quarter (1/4) symmetric simulation model used for Finite Element Method analysis of the hot V-groove friction test.

2.4 Surface Analysis

Surface characterization was performed using an Electron Probe Micro Analyzer (EPMA) to evaluate the adhesion behavior. The analysis focused on two primary regions, the flat top surface and the inner groove surfaces (V-groove area), as illustrated in Fig. 4, where the most significant material flow and pressure were concentrated. Wavelength Dispersive Spectroscopy (WDS) mapping was conducted for Mg, Zn, Cu, and O to quantify elemental distribution and adhesion intensity across these specific functional zones.

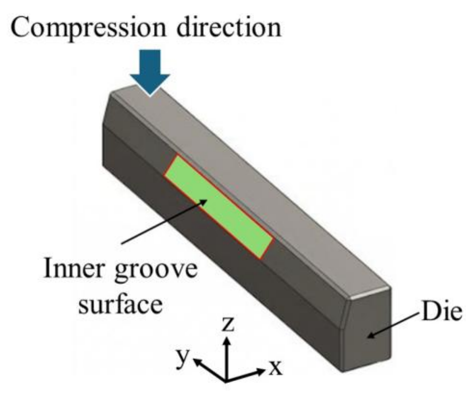

Figure 4: Schematic representation of the analyzed tool regions, identifying the inner groove surfaces for element adhesion evaluation.

3 Results and Discussion

3.1 True Stress-Strain Characteristics

The true stress-strain curves obtained from the hot compression tests for the 0Zn, AA7075, and 8Zn alloys are presented in Fig. 5. The results clearly indicate that the flow stress of these AA7xxx series alloys is highly sensitive to both deformation temperature and strain rate. Across all alloy compositions, an increase in temperature significantly reduced the flow stress due to the thermal activation of dislocation motion and dynamic recovery. For example, at a strain rate of 0.06 s^{-1} (Fig. 5a), the steady-state flow stress of the AA7075 alloy decreased from approximately 49.3 MPa at 400°C to 20.5 MPa at 500°C. Conversely, increasing the strain rate resulted in a pronounced elevation of the flow stress. Taking the AA7075 alloy at 400°C as an example, the flow stress escalated from 49.3 MPa at 0.06 s^{-1} to 67.5 MPa at 1.0 s^{-1}, and further to 73.8 MPa at the highest strain rate of 3 s^{-1} (Fig. 5c). This positive strain-rate sensitivity combined with temperature dependence is a characteristic rheological feature of high-strength aluminum alloys during hot working.

Regarding the influence of Zinc (Zn) content on deformation resistance, the experimental data revealed minor variations among the alloys, particularly at the lowest testing temperature. At 400°C and a strain rate of 0.06 s^{-1}, the flow stress was highest for the 0Zn alloy (approximately 56.0 MPa) compared to AA7075 (49.3 MPa) and 8Zn (47.7 MPa), suggesting that a lower Zinc content slightly increases deformation resistance under these specific conditions. A similar trend was observed at a higher strain rate of 3 s^{-1}, where 0Zn exhibited a flow stress of 87.5 MPa versus 73.8 MPa and 75.0 MPa for AA7075 and 8Zn, respectively. However, as the deformation temperature increased to 500°C, the flow stress differences between the three alloys diminished significantly, converging to a narrow range of 17.5 to 20.5 MPa at 0.06 s^{-1}. These comprehensively determined experimental flow stress curves provided the accurate plasticity data required for the subsequent FEM simulations, ensuring high reliability in evaluating the frictional boundary conditions during the simulative V-groove friction tests.

3.2 Frictional Characteristics and Calibration Curves

The simulated friction calibration curves derived from the FEM analysis for the AA7xxx compositions with varying Zn at 400°C, 450°C, and 500°C are presented in Fig. 6. Across all investigated alloys (0Zn, AA7075, and 8Zn), the simulated aspect ratio (h/w) continuously decreases as the shear friction coefficient (m) increases from 0.1 to 1.0. This behavior occurs because higher interfacial friction makes it increasingly difficult for the material to flow longitudinally downward into the V-groove, resulting in a decrease in the extruded height (h). Consequently, the material is forced to flow outward laterally in the top flat region, which promotes transverse expansion and increases the specimen's width (w).

A detailed analysis of each alloy composition reveals the specific influence of temperature on this deformation mechanism. In the simulation results for the 0Zn alloy (Fig. 6(a)), the calibration curves at 400°C, 450°C, and 500°C show that at lower friction conditions ($m < 0.5$), the higher temperature of 500°C results in a slightly lower aspect ratio compared to 400°C. This is primarily due to the thermal softening of the material at high temperatures, which facilitates lateral expansion on the flat surface over longitudinal flow into the groove. However, as the friction condition approaches the sticking limit ($m \geq 0.8$), the curves for all three temperatures converge to a similar aspect ratio of approximately 0.51. This temperature-independent behavior at high friction is consistently observed in the simulations for the standard AA7075 alloy shown in Fig. 6(b) and the high-zinc 8Zn alloy shown in Fig. 6(c). For both AA7075 and 8Zn, the calibration curves across 400°C, 450°C, and 500°C almost entirely overlap at high m values. This indicates that under severe frictional conditions, the geometric deformation in the

V-groove test is dominated heavily by the friction at the die-workpiece interface rather than the temperature-dependent flow stress of the material.

The experimental forming load recorded during the physical tests remained highly consistent across the different Zinc contents, measuring approximately 17.6 tons at 400°C for the 0Zn, AA7075, and 8Zn alloys. Following the physical hot V-groove friction tests, the actual extruded height (h) and the laterally deformed width (w) of the test specimens were physically measured. By calculating the experimental aspect ratio (h/w) and directly matching these values with the corresponding FEM calibration curves in Fig. 6, the actual shear friction coefficients (m) could be accurately estimated. Based on this comparative approach, the actual friction coefficients at 400°C were determined to be, 0Zn (m = 1.0), AA7075 (m = 0.94), and 8Zn (m = 0.93). These high values empirically verify that severe sticking friction occurs on the nitrided SKD61 dies across all Zn compositions during hot processing.

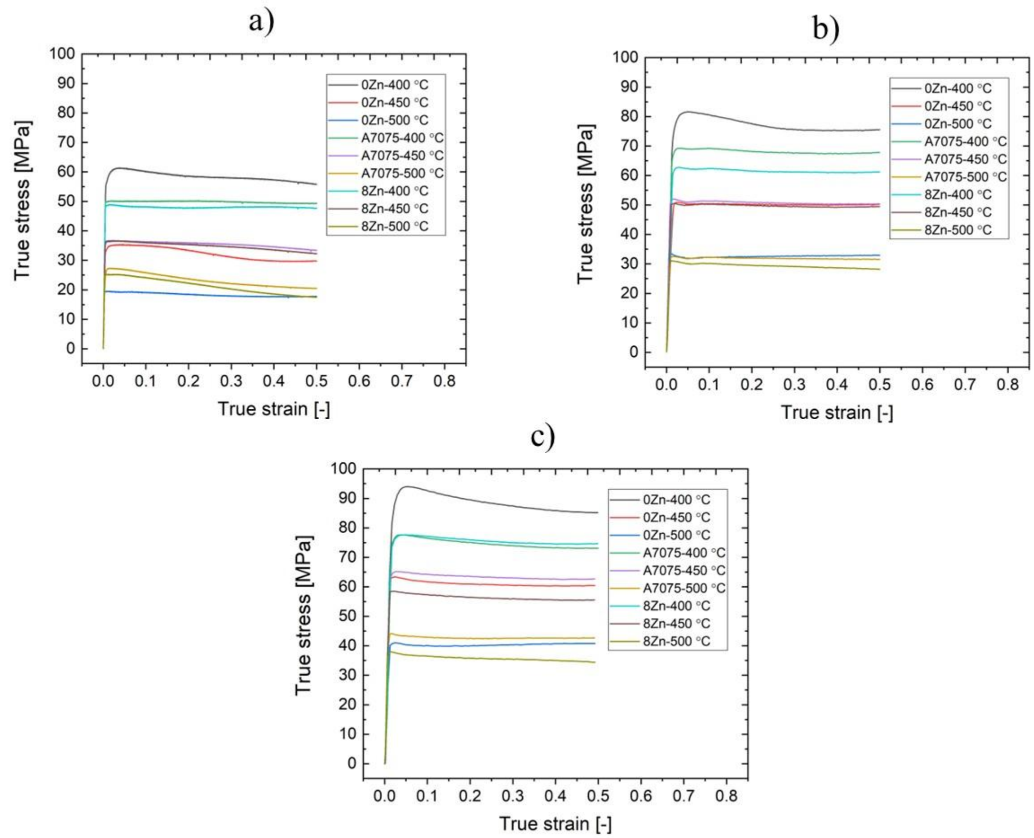

Figure 5: Experimental true stress-strain curves of AA7xxx alloys (0Zn, AA7075, 8Zn) at temperatures of 400 °C, 450 °C, and 500 °C for strain rates of: (a) 0.06 s^{-1}, (b) 1.0 s^{-1}, and (c) 3.0 s^{-1}.

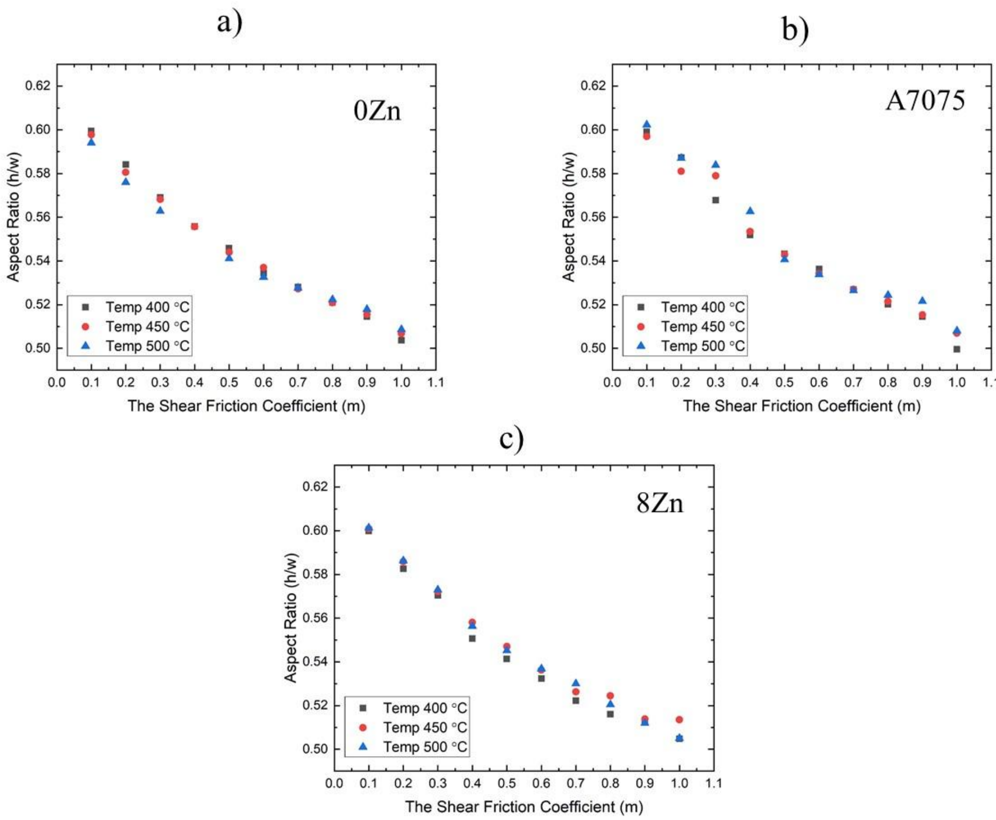

Figure 6: Friction calibration curves showing aspect ratio (h/w) as a function of shear friction coefficient (m) for A7000 alloys with varying Zinc content: (a) 0Zn, (b) A7075, and (c) 8Zn.

3.3 Elemental Adhesion Analysis

Since this research primarily focuses on the effect of varying the Zinc content in AA7xxx series alloys, the elemental adhesion analysis predominantly presents the investigation of Zinc transfer. Accordingly, Fig. 7 displays the EPMA mapping results specifically analyzing the amount of Zinc (Zn) elemental adhesion on both the top flat surface and the inner V-groove surfaces of the specimens after the hot friction testing.

The EPMA mapping demonstrated that the adhesion intensity was significantly higher on the inner groove surfaces compared to the flat top surface due to the increased contact pressure within the V-groove. From Fig. 7, it is evident that Zn adhesion to the die had already occurred at 400°C. The intensity of this elemental transfer correlated directly with the initial Zinc content in the test billets (0Zn < AA7075 < 8Zn). Furthermore, when the testing temperature reached 500°C, the amount of Zn adhesion increased substantially.

This temperature-dependent increase in adhesion behavior can be explained by the thermal characteristics of the Al-Zn-Mg-Cu alloy system. Localized melting of low-melting-point constituents begins to occur at temperatures above 480°C and becomes more pronounced at 500°C (Ngernbamrung, J. Jpn. Inst. Light. Met., 2018). Therefore, it is considered that the significant increase in Zn adhesion observed at 500°C is directly driven by this localized melting phenomenon, which subsequently exacerbates adhesive wear on the tool surface.

Regarding other alloying elements analyzed during the tests (not explicitly shown in Fig. 7), Magnesium (Mg) exhibited consistent adhesion across all samples starting from 400°C, indicating an active chemical reaction with the nitrided die. Copper (Cu) adhesion became prominent only at an elevated temperature of 500°C, coinciding with the onset of the localized melting. Interestingly, for the 8Zn alloy tested at 500°C, the Cu adhesion intensity was notably lower compared to the standard AA7075 alloy. This reduction is likely because the abundant liquid Zn-rich phase dominated the interface and acted as a physical barrier, thereby inhibiting direct contact between Copper and the die surface.

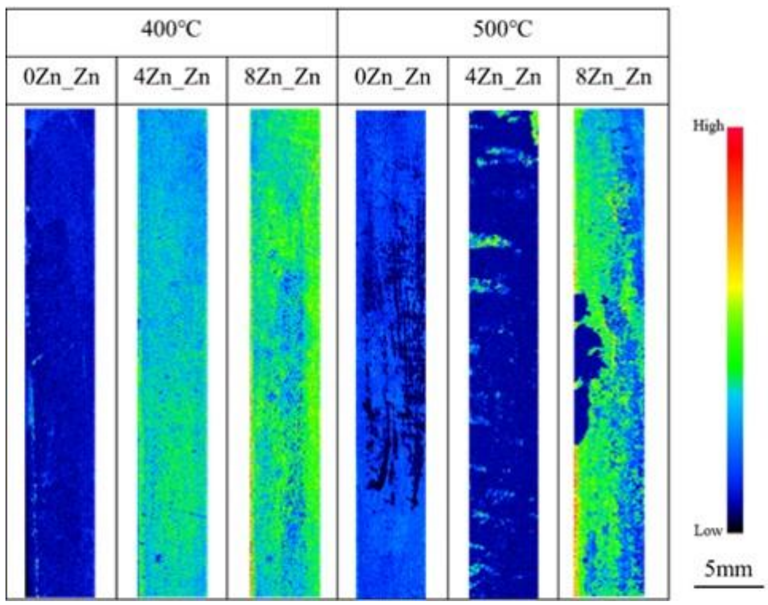

Figure 7: EPMA element mapping of the die surface showing the distribution and intensity of Zinc (Zn) adhesion after hot friction testing.

4 Conclusion

This study systematically investigated the hot tribological characteristics and deformation behavior of AA7xxx series aluminum alloys with varying Zinc contents (0Zn, AA7075, and 8Zn). By utilizing the hot V-groove friction test and Finite Element Method (FEM) simulations, the interface friction and elemental adhesion on nitrided SKD61 dies were rigorously evaluated at elevated temperatures. The integration of true stress-strain data from hot compression tests ensured high accuracy in the numerical modeling of the macroscopic deformation. Furthermore, surface analysis via EPMA provided critical insights into the micro-scale mechanisms of tool-die reactions. Based on the comprehensive experimental and analytical results, the following key conclusions can be drawn:

1. The flow stress is highly sensitive to deformation temperature and strain rate, whereas varying the Zinc content from 0% to 8% exerts only a minor influence on the macroscopic deformation resistance, particularly at higher temperatures.

2. The change of zinc exerts no significant effect on observable friction values (about 0.93–1.0), which remain high on nitrided SKD61 dies. This is mainly due to the extreme sticking conditions and elevated contact pressures within the V-groove, which affect the interface behavior without regard to alloy composition.
3. Zinc adhesion on the die is relatively constant at the lower processing temperature of 400°C and rises in direct proportion to the concentration of zinc in the billet. Conversely, at a temperature of 500°C, zinc transfer increases significantly due to the localized melting of low-melting-point components, with the highest level of heat continuously observed on the inner groove surfaces.

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