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COMPARATIVE STUDY OF DIE MATERIALS FOR HOT ALUMINIUM FORMING USING AN AUTONOMOUS TRIBOLOGICAL TESTING SYSTEM

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This study examines the tribological characteristics of different die materials for hot aluminium forming processes using an autonomous testing system. Four die materials – P20, CR7V, UH1, and RPU – were tested against AA6111 aluminium alloy blanks at elevated temperatures of 300 °C and 350 °C, with lubricant applied to the blank surface prior to each sliding cycle. The investigation incorporates both single-cycle friction behaviour and multi-cycle analysis to simulate industrial forming conditions, using an advanced robotic testing system for consistent and repeatable measurements. A comprehensive analysis of the coefficient of friction evolution during continuous sliding and across multiple cycles was conducted to understand the tribological behaviour under various temperature conditions. The study aims to establish quantitative relationships between die materials, temperature, and friction characteristics for hot forming applications, providing reference data for industrial die material selection.

Keywords: robotic arm; aluminium hot stamping; tribological analysis.

1. Introduction

The hot stamping of aluminium alloys has become increasingly important in the automotive industry due to its ability to form complex components while achieving high strength (Anyasodor & Koroschetz, 2017). The process offers significant advantages including weight reduction and enhanced mechanical properties (Atxaga *et al.*, 2022), making it particularly attractive for manufacturing lightweight vehicle components in automotive and aerospace industries.

The examination of tool-workpiece interfacial interactions in these processes is crucial as it directly influences material flow behaviour and surface quality of the formed components (Pujante *et al.*, 2015). These interactions become particularly complex at elevated temperatures, affecting both the forming process stability and final part quality (Venema *et al.*, 2018).

Various tribological testing methods have been developed and investigated to understand tool-workpiece interactions under different conditions. For general wear and friction studies, pin-on-disc and ball-on-disc tests have been widely employed due to their ability to maintain consistent contact conditions and continuous measurement capability (Ghiotti *et al.*, 2011; Hardell & Prakash, 2008). For sheet metal forming applications, researchers have developed more specialised testing methods. Strip drawing tests simulate the blank holder and die radius regions

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(Decrozant-Triquenaux *et al.*, 2021; Schwingenschlögl & Merklein, 2020), while twist compression tests evaluate friction under high contact pressures (Kim *et al.*, 2008).

However, these conventional testing methods predominantly focus on lab-scale constant contact conditions, which cannot adequately represent industrial hot stamping processes. In actual forming operations, the interfacial conditions undergo complex evolution due to varying temperature distributions, changing contact pressures, and diverse sliding velocities (Pereira *et al.*, 2010). Die materials experience repeated contact with fresh workpiece surfaces at elevated temperatures. These interactions occur at temperatures typically ranging from 300 °C to 500 °C (Ma *et al.*, 2021), leading to dynamic changes in friction characteristics and potential wear mechanisms. Furthermore, the cyclic nature of mass production introduces additional complexities that are not captured in standard tribological tests, such as cumulative thermal effects and progressive changes in surface conditions.

To address these limitations, Yang et al. (2021; 2022) developed the TriboMate system, an advanced friction testing apparatus capable of evaluating various tool-workpiece combinations under hot forming conditions. Building upon this platform, our study incorporates enhanced control measures and data processing techniques to enable a comprehensive multi-cycle analysis, better representing industrial forming conditions.

This study employs this autonomous testing system to evaluate four different die materials – P20, CR7V, UH1, and RPU – against AA6111 aluminium alloy blanks at elevated temperatures of 300 °C and 350 °C. The investigation encompasses both single-cycle friction measurements for detailed friction evolution during continuous sliding and multi-cycle analysis to examine tribological stability under repeated contact conditions. Through this systematic approach, we aim to establish quantitative relationships between die materials and workpiece interactions under conditions representative of industrial hot forming processes.

2. Methodology

An autonomous tribological testing system TriboMate (Yang *et al.*, 2021; 2022) (as shown in Fig. 1) was developed to evaluate die materials under conditions representative of hot aluminium forming processes. The system centres on a UR10 robotic manipulator integrated with a custom-designed pin holder for precise control of the die material samples. A real-time data exchange (RTDE) interface enables a synchronous recording of force and position data throughout testing.

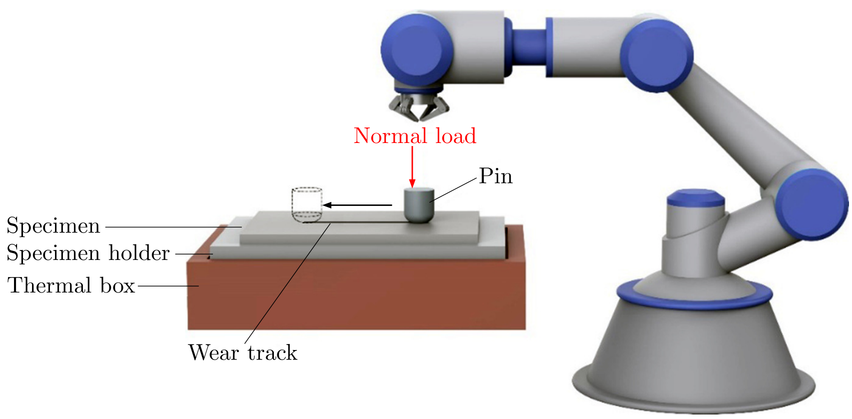

Fig. 1. Schematic diagram of the experimental setup (Yang *et al.*, 2021; 2022).

The test specimens comprised pins made from four die materials: P20, CR7V, UH1, and RPU, all without heat treatment. These materials were tested against AA6111 aluminium alloy blanks in T4 condition. Testing was conducted at two elevated temperatures: 300 °C and 350 °C, chosen to represent typical hot forming conditions. A direct contact heating system was used to heat the aluminium blanks. To compensate for heat losses and maintain stable blank temperatures of

300 °C and 350 °C, the heating system was set to 330 °C and 385 °C, respectively. Temperature was monitored using K-type thermocouples attached to the blank surface, and preliminary testing verified uniform temperature distribution across the blank. A pneumatic spraying system applied lubricant to the blank surface immediately prior to the sliding, with volumes of 35 g/m^2 at 300 °C and 55 g/m^2 at 350 °C to maintain consistent lubrication conditions.

The testing sequence began with heating the aluminium blank to the target temperature. Once the desired temperature was reached, lubricant was applied to the blank surface. The spherical die material pin then engaged with the blank under a constant normal load of 6 N, sliding at a speed of 30 mm/s over a distance of 75 mm. This sliding action represents a single cycle of contact between die and workpiece material (Yang *et al.*, 2024a; 2024b).

To simulate industrial stamping operations where tools repeatedly contact fresh blank surfaces, each test comprised 18 consecutive cycles on different tracks (as shown in Fig. 2). The robotic system maintained a 2 mm spacing between adjacent tracks to prevent overlap. This testing strategy reflects the actual working conditions of die materials in mass production, where tools contact new blank surfaces while experiencing cumulative wear effects. The system maintained consistent testing parameters throughout all the cycles, including temperature, contact load, and sliding speed.

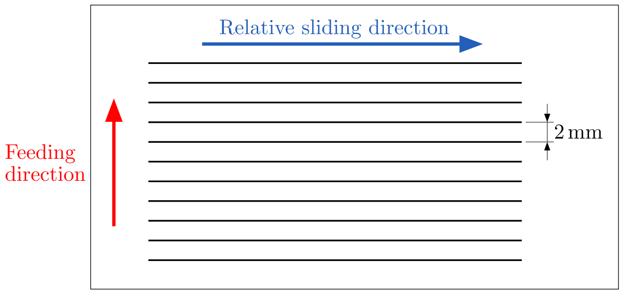

Fig. 2. Schematic of tribological test setup showing sliding and feeding directions.

Data processing occurred in two stages. During testing, the system collected real-time measurements of normal and friction forces along with position data. These measurements enabled the calculation of the instantaneous coefficient of friction values throughout each sliding cycle. The second stage involved the statistical analysis of the collected data to examine both detailed friction evolution within individual cycles and broader trends across multiple cycles.

For a single-cycle analysis, the system tracked the coefficient of friction evolution throughout the entire 75 mm sliding distance, capturing initial contact behaviour, running-in characteristics, and steady-state friction conditions. A multi-cycle analysis examined the evolution of average friction coefficients across all 18 cycles, measuring the tribological behaviour under repeated contact with fresh blank surfaces.

The testing system incorporated several control measures to ensure measurement reliability. Temperature monitoring maintained consistent heating conditions throughout testing. The pneumatic spraying system provided uniform lubricant coverage across all the tests. Position sensors in the robotic manipulator ensured precise control of sliding speed and distance, while the external force sensor attached on the end effector maintained consistent normal load application.

3. Results and discussion

3.1. Effect of a die material on the coefficient of friction evolution at 300 °C

The coefficient of friction (CoF) measurements at 300 °C revealed distinct characteristics for each die material in both single-cycle and multi-cycle analyses. The initial temperature significantly influenced the tribological interaction patterns between the die materials and the aluminium blank.

In the single-cycle sliding tests, P20 recorded the highest average CoF values with notable fluctuations. High-amplitude oscillations persisted throughout most of the sliding distance, indicating continuous variations in the tribological interface. After 60 mm of sliding, P20 exhibited a decreasing trend in CoF, suggesting potential changes in contact conditions during extended sliding. CR7V demonstrated a characteristic U-shaped CoF evolution pattern, with an initial decrease in friction followed by a gradual increase in the latter portion of sliding. In contrast, both UH1 and RPU maintained relatively steady CoF values throughout the sliding distance, with RPU recording the lowest average values. This stability in friction behaviour suggests more consistent tribological interactions at the interface (Fig. 3).

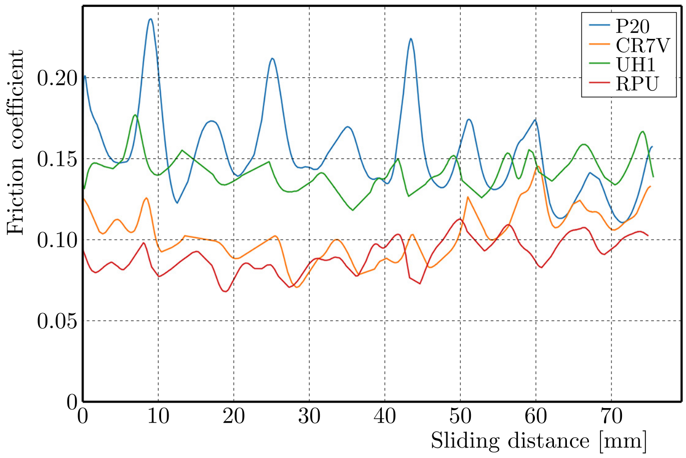

Fig. 3. Comparison of the coefficient of friction evolution on different die materials at 300 °C.

The multi-cycle analysis at 300 °C provided insights into the evolution of tribological characteristics across repeated sliding events. Throughout the 18 test cycles, all the materials maintained CoF values below 0.5, indicating stable tribological conditions. P20 consistently recorded the highest CoF values, ranging from 0.165 to 0.285 across all the cycles, with notable cycle-to-cycle variations. CR7V showed a distinctive behaviour pattern, exhibiting a gradual increase in average CoF until the sixth cycle, with values ranging from 0.104 to 0.217, after which the values stabilised. RPU maintained the lowest and most consistent CoF range (0.081–0.180) throughout the cycles, though its standard deviation increased with a cycle number. For all the materials, the progressive increase in standard deviation with a cycle number suggests growing variability in tribological interactions over repeated sliding events (Fig. 4).

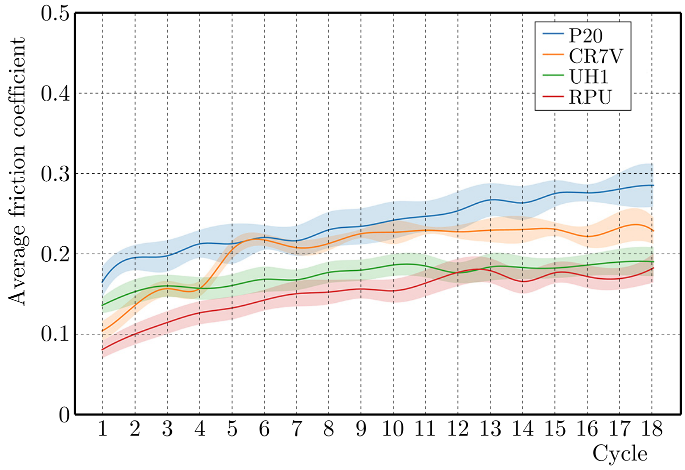

Fig. 4. Comparison of average CoF evolution for a multi-cycle analysis on different die materials at 300 °C, with SD envelopes.

3.2. Effect of a die material on the coefficient of friction evolution at 350 °C

At the elevated temperature of 350 °C, the friction characteristics demonstrated marked differences from the lower temperature tests, revealing temperature-dependent changes in the tribological behaviour of all the die materials.

In a single-cycle analysis, a distinctive feature emerged: all the materials exhibited a pronounced running-in stage within the first 3 mm of sliding. This stage was characterized by high initial CoF values followed by rapid stabilisation, a phenomenon not observed at 300 °C. P20 recorded the highest CoF values during this initial running-in stage. After the running-in period, all four die materials showed similar CoF values, fluctuating within a narrow range between 0.15 and 0.2, with CR7V maintaining its characteristic U-shaped evolution pattern (Fig. 5).

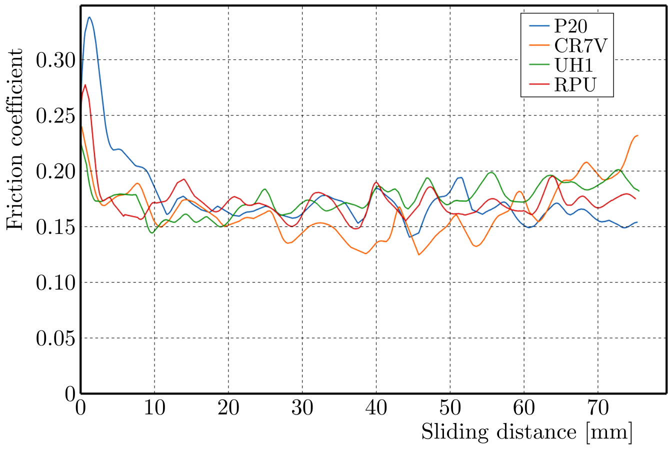

Fig. 5. Comparison of the coefficient of friction evolution on different die materials at 350 °C.

The multi-cycle behaviour at 350 °C revealed distinctive patterns in friction evolution. All the materials exhibited a gradual increase in average CoF across the successive cycles, accompanied by progressively increasing standard deviations. During the initial and middle stages (cycles 1–14), the materials showed similar CoF ranges, varying from 0.18 ±0.02 to 0.3 ±0.01, indicating more uniform tribological behaviour at elevated temperatures. The later stages (cycles 15–18) revealed differentiation in material behaviour, with CR7V and RPU recording notably lower average CoFs, reaching values of 0.273 and 0.312, respectively, at cycle 18. This divergence in late-cycle behaviour suggests the emergence of material-specific tribological mechanisms at extended sliding durations (Fig. 6).

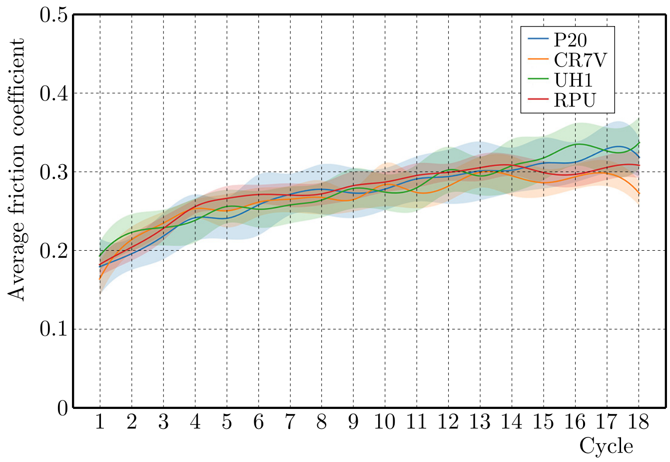

Fig. 6. Comparison of average CoF evolution for a multi-cycle analysis on different die materials at 350 °C, with SD envelopes.

3.3. Effect of lubricant volume on the coefficient of friction evolution at 350 °C

Due to the elevated temperature of 350 °C, a higher lubricant volume was required to compensate for potential evaporation and maintain optimal lubrication performance. To investigate this effect, the UH1 die material was selected for further evaluation, as it exhibited relatively stable tribological behaviour in the previous tests.

Figure 7 presents the single-cycle CoF evolution for UH1 at 350 °C under three different lubricant volumes: 35 g/m^2, 55 g/m^2, and 70 g/m^2. At the lower volume of 35 g/m^2, which was used for the tests at 300 °C, the CoF values were higher, indicating inadequate lubrication at the elevated temperature.

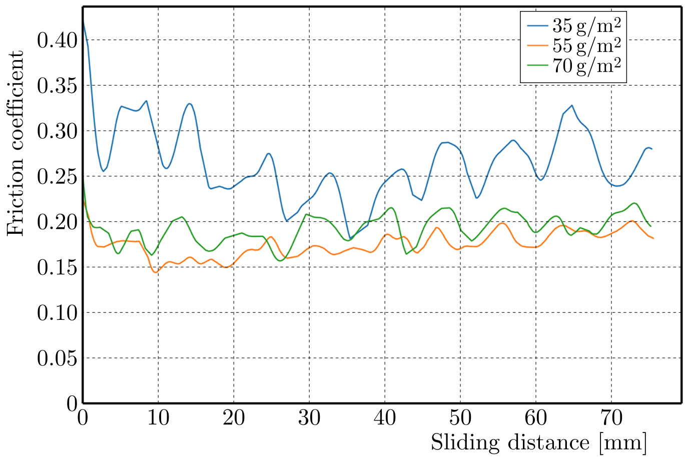

Fig. 7. Comparison of the coefficient of friction evolution on a different lubricant volume at 350 °C.

When the lubricant volume was increased to 55 g/m^2, a significant reduction in CoF was observed, demonstrating the beneficial effect of enhanced lubrication at higher temperatures. The volume of 55 g/m^2 was considered saturated, as a further increase in the lubricant volume to 70 g/m^2 did not lead to a further decrease in CoF. In fact, the CoF values for the 70 g/m^2 condition were slightly higher than those for 55 g/m^2, potentially due to excess lubricant affecting the tribological interactions.

4. Conclusions

In this study, tribological characteristics of various die materials for hot aluminium forming were investigated using an autonomous testing system. The comprehensive evaluation encompassed both single-cycle friction evolution and a multi-cycle stability analysis at elevated temperatures of 300 °C and 350 °C. The autonomous system enabled consistent measurement conditions throughout testing, incorporating real-time data acquisition and advanced processing routines. A systematic comparison between P20, CR7V, UH1, and RPU die materials revealed distinct temperature-dependent friction behaviours and long-term stability characteristics. The following conclusions can be drawn from this investigation:

- at 300 °C, die materials exhibited distinct friction patterns, with P20 recording the highest CoF values (0.165–0.285) and RPU showing the lowest range (0.081–0.180) across 18 cycles. The CoF values increased initially before stabilizing in the middle and late cycles, while standard deviation showed a progressive increase with a cycle number;
- temperature elevation to 350 °C introduced a pronounced running-in stage within the first 3 mm of sliding for all the materials. After this stage, the materials showed uniform friction behaviour with CoF values between 0.15–0.2. A multi-cycle analysis revealed similar CoF ranges (0.18 ±0.02 to 0.3 ±0.01) during the early cycles, with CR7V and RPU recording lower values of 0.273 and 0.312, respectively, in the final cycles;

– the transition from 300 °C to 350 °C demonstrated significant changes in friction characteristics, most notably the emergence of the running-in stage and reduction in friction coefficient differences between the materials. These temperature-dependent changes provide essential insights for die material selection in different temperature ranges;
– lubricant volume optimisation proved critical at elevated temperatures, as evidenced by UH1's reduced friction coefficients when increasing lubricant volume from 35 g/m^2 to 55 g/m^2 at 350 °C, while a further increase to 70 g/m^2 showed no additional benefits.

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