

# Selection and Investigation of Thermoplastic Materials as Forming Tools for Warm Dry Forming of Magnesium and High-Strength Aluminum Sheets

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**Abstract.** The growing demand for lightweight components has highlighted the potential of sheet metal parts made from high-strength aluminum and magnesium alloys. However, the forming of these materials is often limited by complex manufacturing processes that typically require lubricants, raising environmental and economic concerns. This study investigates the feasibility of using thermoplastic polymers as tooling materials for dry forming of aluminum alloy 7075-T6 and magnesium alloy AZ31B at temperatures up to 300 °C. A number of high-performance thermoplastic polymers were selected based on their superior mechanical and thermal properties and evaluated through compression and tensile tests, dilatometry, pin-on-disk and draw-bend tests. In addition, the influence of coatings on the tribological performance of the polymers was systematically investigated. The results showed that thermoplastic tools have the potential for efficient dry forming of AA 7075-T6 and AZ31B parts at temperatures up to 300 °C, achieving good tool stability, wear resistance and part quality. TECAPEEK PVX with original tribological optimization proved to be the most promising candidate and was validated in challenging cross cup forming experiments. This lubricant-free approach offers significant environmental and economic benefits, providing a sustainable solution for prototyping and small-scale production of lightweight metal components.

## Introduction

The global push for more fuel-efficient transportation systems, coupled with increasingly stringent environmental regulations, has driven demand for high-strength yet lightweight structural components. Aluminum and magnesium alloys in particular offer an excellent balance of low density and high specific strength, making them prime candidates for aerospace, automotive, and consumer electronics applications [1, 2]. However, their room temperature formability is still limited by low ductility and an increased tendency to springback. In addition, because these alloys tend to adhere strongly to conventional tool steels-especially at elevated temperatures-lubricants are often used during forming [3]. While lubricants reduce friction and wear, they also pose significant environmental and economic challenges [4]. Increased sustainability goals, driven by both regulations and consumer expectations, are driving research into lubricant-free or "dry" forming processes [5]. Realizing such processes requires innovative tool materials, coatings, and process configurations to effectively manage friction and wear under challenging thermo-mechanical conditions.

Plastics as alternative tool materials have attracted considerable interest since the early 2000s [6, 7]. Various plastics have been successfully used in deep drawing [8], bending [9], stamping [10], hydroforming [11], and incremental sheet metal forming, demonstrating advantages for prototyping and small-scale production. These advantages include low cost, rapid tool manufacturing (particularly through additive manufacturing [12]), ease of machining, and ease of maintenance-all while

achieving acceptable dimensional accuracy in formed parts [9]. However, most studies using polymer-based tools address room-temperature forming; research focusing on plastic tool materials for warm or tempered forming of magnesium and high-strength aluminum alloys remains limited.

High-performance thermoplastic polymers hold promise for tempered forming of these alloys. Their low density, chemical resistance, and ability to maintain sufficient mechanical integrity up to 260 °C for long-term exposure - and up to 300 °C for short-term exposure - make them suitable for small scale production [13]. In addition, their properties can be tailored to meet specific process requirements by incorporating reinforcing fillers (e.g., carbon (CF) or glass (GF) fibers) or by using coatings and additives (e.g., polytetrafluoroethylene).

The present study investigates the feasibility and performance of thermoplastic materials as forming tools for the tempered dry forming of magnesium and high-strength aluminum sheet. By evaluating different thermoplastics in terms of their suitability for thermo-mechanical and tribological properties, we aim to gain a comprehensive understanding of the possibilities and limitations of this innovative approach to sheet metal forming.

## Material Characterization and Experimental Methods

### Sheet materials and their characterization.

Two sheet materials were selected for this study: aluminum alloy AA 7075-T6 (2 mm thick) and magnesium alloy AZ31B (1 mm thick), which were provided by industrial partners and reflect standard industry stocks and manufacturing practices. To investigate their mechanical properties such as yield ( $R_{p0.2}$ ) and ultimate ( $R_m$ ) strength and elongation ( $A$ ), uniaxial tensile tests were performed on Zwick/Roell universal testing machines at four temperatures (room temperature (20 °C), 150 °C, 200 °C, 250 °C) using a constant strain rate of 0.005 s<sup>-1</sup>. Test specimens, prepared according to standard guidelines, were extracted from the rolled sheets in two orientations (0°, 90°) to capture the anisotropic behavior. Formability limits under varying conditions were determined by temperature-controlled Forming Limit Curve (FLC) tests performed according to the Nakajima test method (DIN EN ISO 12004-2 [14]). These tests used specimens of four different widths ( $w = 50$  mm, 90 mm, 130 mm, 200 mm) and were conducted at the same temperatures as the tensile tests at a controlled punch speed of 3.5 mm/s. Strain measurements and analysis were performed using GOM's ARAMIS 3D optical measurement system. All tests were repeated three times and the results of the tests at 250 °C are summarized in Table 1.

**Table 1.** Properties of the sheet material at 250 °C.

		AA 7075-T6		AZ31B	
		0°	90°	0°	90°
Tensile test	$R_{p0.2}$ [MPa]	177	181	25	30
	$R_m$ [MPa]	182	181	26	31
	$A$ [%]	25	11.2	53	58
		$\phi 1$	$\phi 2$	$\phi 1$	$\phi 2$
FLC test	$w = 50$ mm	-0.16	0.38	-0.19	0.69
	$w = 90$ mm	0.01	0.26	-0.05	0.50
	$w = 130$ mm	0.10	0.28	0.03	0.39
	$w = 200$ mm	0.19	0.31	0.13	0.42

### Plastic materials and their characterization.

A comprehensive evaluation was conducted to assess the feasibility of using plastic as tool materials for the target process. Based on manufacturer data and suggestions of the involved polymer manufacturers nine candidate polymers were selected. These include four low-cost polyurethane-based (PUR1-4) plastics - which, although not thermoplastics, perform adequately up to 100 °C - and thermoplastics based on polyamide 66 (TECAMID 66/X GF50 black), polyetheretherketone (TECAPEEK natural, TECAPEEK PVX black and TECAPEEK CF30 black) and

polyphenylsulfide (TECATRON GF40 black). Some of these materials are reinforced with CF or GF or enhanced with additives. Table 2 summarizes the selected plastic materials.

The temperature-dependent properties of these materials were systematically characterized. Tensile tests were performed according to DIN EN ISO 527 [15] at a constant strain rate of  $0.005 \text{ s}^{-1}$  to determine the ultimate tensile strength ( $R_m$ ) at 20 °C, 75 °C, 100 °C, 150 °C, while compression tests were performed according to DIN EN ISO 604 [16] at a displacement rate of 2 mm/min to determine the compressive yield stress ( $\sigma_c$ ) at 20 °C, 75 °C, 100 °C, 150 °C, 200 °C, 250 °C. In addition, the thermal expansion ( $\alpha$ ) behavior was investigated using dilatometry at a heating rate of approximately 2 °C/min from ambient to 150 °C. Samples were prepared according to established standards, with a minimum of three samples per material to ensure statistically robust data. Results are summarized in Table 2.

**Table 2.** Selected plastics and characterization results.

Plastic	Filling	$R_m$ [MPa]		$\sigma_c$ [MPa]		$\alpha$ [ $10^{-5}/\text{K}$ ]	
		20 [°C]	150 [°C]	20 [°C]	150 [°C]	20 [°C]	150 [°C]
PUR1	n.a.	54	28*	108	12*	3.4	5.7*
PUR2	n.a.	73	-	93	-	3.5	5.6*
PUR3	n.a.	75	-	107	-	6.9	-
PUR4	n.a.	41	-	106	-	5.4	-
NAT	-	116	43	128	13	2.7	4
PVX	10% PTFE, 10% Gr, 10% CF	84	45	113	17	2.1	3
CF30	30% CF	83	42	141	30	3.2	4.9
TRON	40% GF	112	60	148	13	2.1	2.7
66/X	50% GF	115	37	124	34*	2.7	6.3

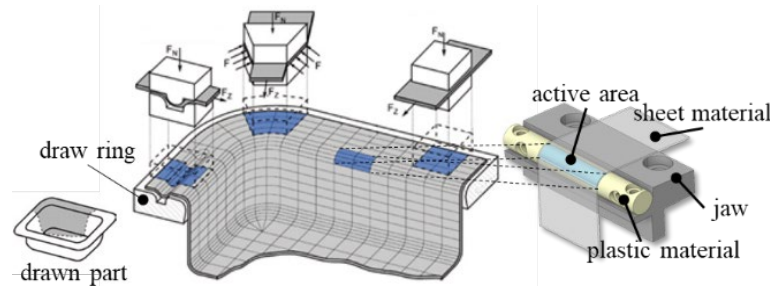
\* - up to 100 °C

### Coating and tribological tests.

Pre-screen tribological pin-on-disk (PoD) tests were performed on all candidate polymers using a CETR UMT-3 universal tribometer in oscillating mode. Test parameters were set at 1 Hz oscillating frequency, 10 N normal load, and 10 mm amplitude, with each test lasting 30 min (thus performing 1800 strokes). In order not to soften up the PUR-materials too much the temperature was controlled to 100 °C. The tests were performed on sheet metal blanks, and the pins were machined from extruded bars with a rounded contact tip of 10 mm radius.

The average coefficient of friction and extent of the wear marks on both sheet metals and pins were measured. All beforementioned polymers were tested untreated and plasma treated in a  $\text{CF}_4$ -atmosphere in normal and parallel orientation towards the direction of rolling. All tests were repeated to check the reproducibility, and the average value was calculated. Due to its rapid screening method allowing for quick estimation of wear and friction behaviour of the investigated polymers, PoD was used for the preliminary selection of candidates to rank polymer/sheet pairs under challenging kinematics.

To simulate the realistic friction conditions encountered in sheet metal forming, a draw-bend test was conducted as part of ongoing tribological research on plastics. The test used a draw-bend system equipped with a deflection mechanism and a furnace to replicate the drawing and bending edge - the most demanding part of the tool (Fig. 1). The best-performing plastic candidates were selected based on their experimentally superior heat resistance, strength, frictional behavior, and machinability.

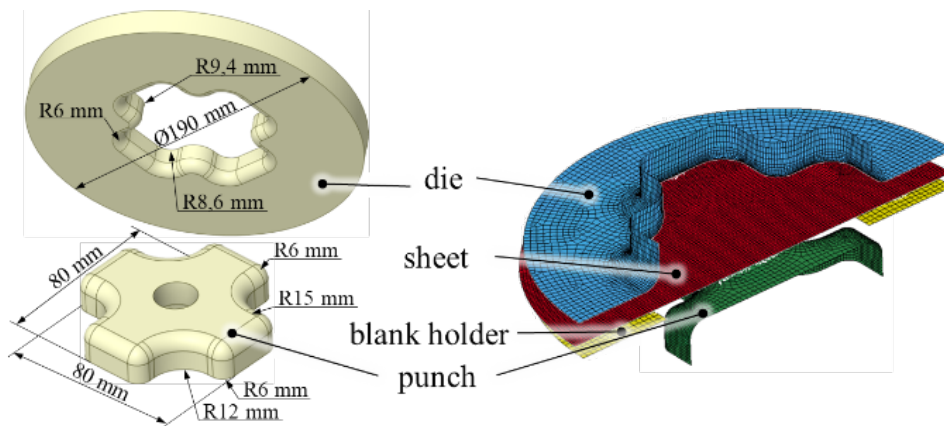


**Fig. 1.** Variants of the draw-bend test [17].

In the experiment, test sheets were heated to 250 °C and 300 °C and then pulled through a fixed tool made from candidate plastics. The tool surfaces were prepared in three different conditions: uncoated and CF<sub>4</sub>-treated. This method allowed a quantitative evaluation of the frictional performance of the thermoplastic tools under realistic forming conditions. Each test combination was repeated three times.

### Finite element simulation.

Finite element (FE) simulations were employed to initially evaluate the structural integrity of plastic tools under combined thermal and mechanical loads. A complex cross-cup geometry (Fig. 2) was chosen for its inherent variations in stress and strain, which lead to non-uniform material distribution and localized stress concentrations during forming. Despite the increased load, a successful outcome would demonstrate the potential of plastics for use in a variety of geometries.



**Fig. 2.** Active components of the cross-cup tool (left); surface shells of the tool parts for FE simulation (right).

The simulation approach builds on the methodology described in [18]. Specifically, the deep drawing process for two sheet materials was simulated at temperatures up to 300 °C using 3D shell models in LS-DYNA®. The resulting contact forces and temperature distributions, obtained at the punch surface, were subsequently applied as boundary conditions in a coupled thermo-mechanical analysis of a 3D elastic solid punch using ANSYS Workbench. Material maps derived from the characterization tests of the sheet metal and plastic materials were incorporated to accurately capture material behavior. The primary objectives of the FE simulations were to quantify the key loads encountered during tempered forming - namely, the distribution of contact pressure at the tool-sheet interface, temperature variations, tool deformation, and stress distributions under combined thermal and mechanical loading. This allowed an initial assessment of the material stability.

### Experimental setup

Pre-industrial-scale tests were conducted to evaluate the feasibility of using plastics for forming high-strength aluminum and magnesium alloys at temperatures up to 300 °C without lubricants. A pillar-guided cross-cup tool was installed in a C-frame hydraulic press (model CLDZ 250), and the

active tool components (punch and die) were fabricated from the selected plastic using conventional milling techniques.

AA 7075-T6 was selected for the forming tests because it requires significantly higher forming loads than AZ31B. AA 7075-T6 blanks 127 mm in diameter were preheated to 400 °C in an adjacent furnace, resulting in a sheet temperature of approximately 300 °C at the time of forming. To determine the forming limits, the blanks were drawn to their maximum depth before cracking, which was 15 mm. To minimize friction - and thus reduce the risk of premature material failure or tool overload - the blank holder was held at a constant distance from the sheet thickness during the test.

After a specified number of strokes, the punch was evaluated for wear and stability. Gravimetric measurements were taken using an Acculab ALC-210.4, and optical inspections were performed using a Keyence VR 6200 3D laser scanning microscope.

## Result and Discussion

### Sheet materials and their characterization.

Experimental tensile and FLC test results for AA 7075-T6 and AZ31B were used to develop accurate material maps to define temperature-dependent mechanical properties for FE sheet metal forming simulations. The material maps were implemented using LS-DYNA®'s \*MAT\_BARLAT\_YLD2000 model in combination with \*MAT\_ADD\_EROSION. YLD2000 integrates experimentally obtained temperature-dependent flow curves to model anisotropic plasticity using tabulated data. In addition, \*MAT\_ADD\_EROSION integrates FLCs with the LCFLD option to predict strain-based fracture.

### Thermoplastics and their characterization.

Compression tests showed that most thermoplastics remained dimensionally stable up to 250 °C (see Table 2). In contrast, polyurethane-based materials performed poorly: PUR1 was only stable up to 100 °C, PUR2 up to 75 °C. While PUR3 and PUR4 were only effective at room temperature. Carbon fiber-reinforced CF30 showed the best  $\sigma_c$  over the entire temperature range, while 66/X and TRON (glass fiber-reinforced) showed comparable strength up to 200 °C but showed a significant decrease above 100 °C compared to another thermoplastic. PVX and NAT, maintained similar compressive performance up to 250 °C. In compression tests, specimens reached temperatures as high as 250 °C. This is because polymers generally retain their structural integrity better under compressive loads due to the confinement effect [19], allowing them to withstand higher temperatures without significant loss of load-carrying capacity. This is a critical requirement for tools associated with predominantly compressive loads in sheet metal forming. Determining the  $R_m$  of plastics in tensile tests is challenging because of the inherently arc-shaped stress-strain curves observed, a behavior that results from viscoelasticity, melting effects, softening, and other temperature-dependent phenomena [20]. Consequently, tensile test results are presented in terms of temperature-dependent  $R_m$  values. Tensile tests showed similar trends: PUR1 was limited to 75 °C, and PUR2, PUR3 and PUR4 did not meet performance criteria below this threshold. CF30 showed the least reduction in tensile strength with increasing temperature, while the other thermoplastics maintained dimensional stability and comparable  $R_m$  up to 150 °C.

Thermal expansion analysis showed that all materials exhibited an increasing linear coefficient of thermal expansion with increasing temperature. TRON, CF30, PVX and NAT showed modest changes, while 66/X showed the greatest dimensional change between RT and 150 °C. The polyurethane-based materials PUR1 and PUR2 were only suitable up to 100 °C. All thermoplastics except 66/X performed similarly in three tests.

### Coating and tribological tests.

Due to the low thermal stability of the PUR polymers and the high wear of the GF-filled polymers, only the PEEK-based materials NAT, PVX and CF30 are regarded in the following PoD tests.

The average coefficients of friction ( $\mu$ ) for AA 7075-T6 versus tool steel 1.2379 reference was 0.4 in both sliding directions. Regarding the polymers there is no clear evidence for a distinct influence

of plasma treatment on the  $\mu$ . The smallest  $\mu$  were observed for NAT and PVX, in a range from 0.22 to 0.25.

The  $\mu$  for AZ31B again shows no distinct influence of the plasma treatment. The reference value of 1.2379 was 0.32. The candidate with the lowest  $\mu$  is PVX CF<sub>4</sub>-treated at the value of 0.25.

Fig. 3 (left) shows the cross-sectional area of the wear marks (average of 5 measurements) on the blank surfaces for AA 7075-T6 and AZ31B (both untreated and CF<sub>4</sub> plasma-treated). The pin wear is displayed in terms of area of the spherical wear mark on the pin dome.

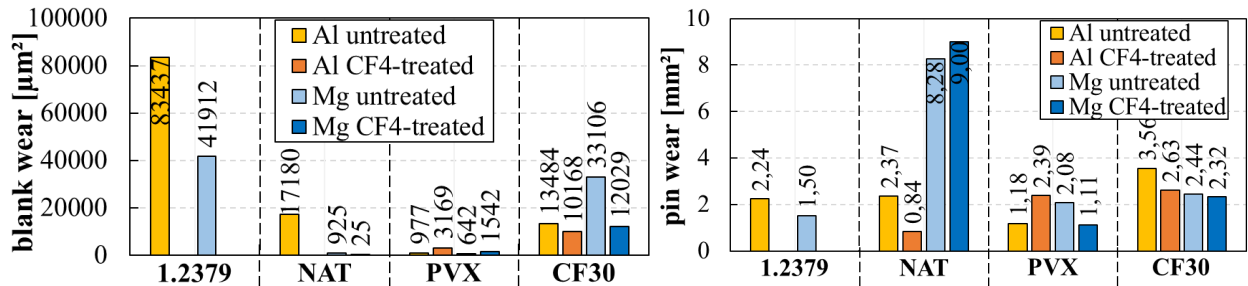


Fig. 3. Blank (left) and pin (right) wear mark comparison.

In terms of wear, NAT and PVX produced minimal wear tracks compared to tool steel, while CF30 reaches higher levels, probably caused by the highly abrasive CF filling. For both sheet metal materials, there is no visible significant effect of plasma treatment.

On the tool side, the lowest pin wear was observed for NAT and PVX on AA 7075-T6 and for PVX on AZ31B (Fig. 3, right). There was no significant effect of plasma treatment. There is extremely high wear on NAT for the test versus AZ31B with a value up to 9 mm<sup>2</sup>.

Summarizing the tribological PoD tests, NAT and PVX seem to be interesting for further investigations in untreated and CF<sub>4</sub>-treated state. These two PEEK-based polymers show relatively low  $\mu$  combined with low wear values on the blank and the pin side.

Based on the criteria mentioned in Section 2.3, the two best candidates (NAT and PVX) were selected for further evaluation using the draw-bend test. The coefficients of friction for AA 7075-T6 and AZ31B sheets were measured at 250 °C and 300 °C on samples with three surface conditions: uncoated and CF<sub>4</sub>-treated. The result is shown in Fig. 4.

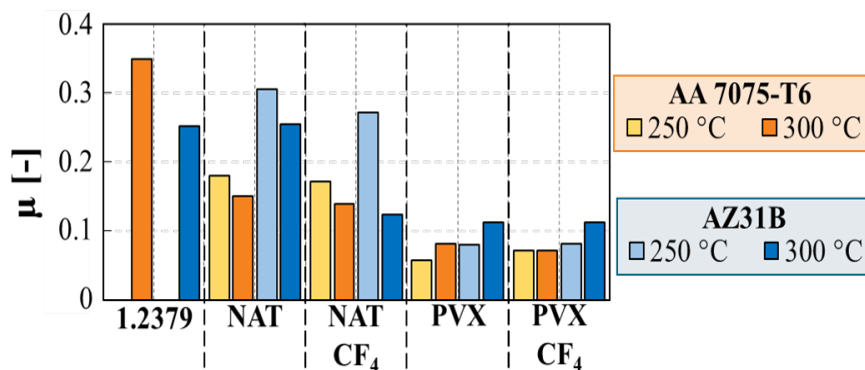
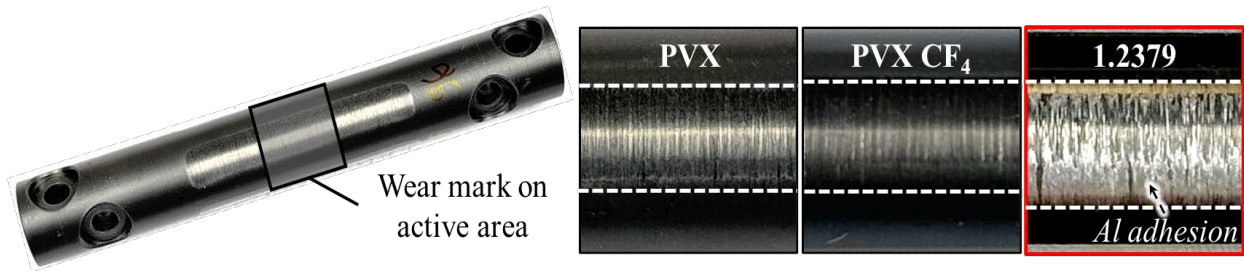


Fig. 4. Comparison of coefficients of friction measured by draw-bend test for PVX and NAT vs. both sheet materials.

For AA 7075-T6, both tested plastics showed lower  $\mu$  than the 1.2379 steel reference ( $\mu = 0.35$ ). In particular, the PVX exhibited superior sliding properties compared to the NAT. The  $\mu$  of the CF<sub>4</sub>-treated and uncoated PVX was similar. Analysis of wear marks on 1.2379 against AA 7075-T6 (Fig. 5) revealed strong adhesion of the sheet material, resulting in noticeable scratches on the sheet – an effect also observed for 1.2379 in the case of AZ31B sheets. Additionally, uncoated and CF<sub>4</sub>-treated plastics exhibited minimal optical alterations due to surface smoothing, as verified by supplementary tactile measurements conducted with the Zeiss Prismo coordinate measuring machine.



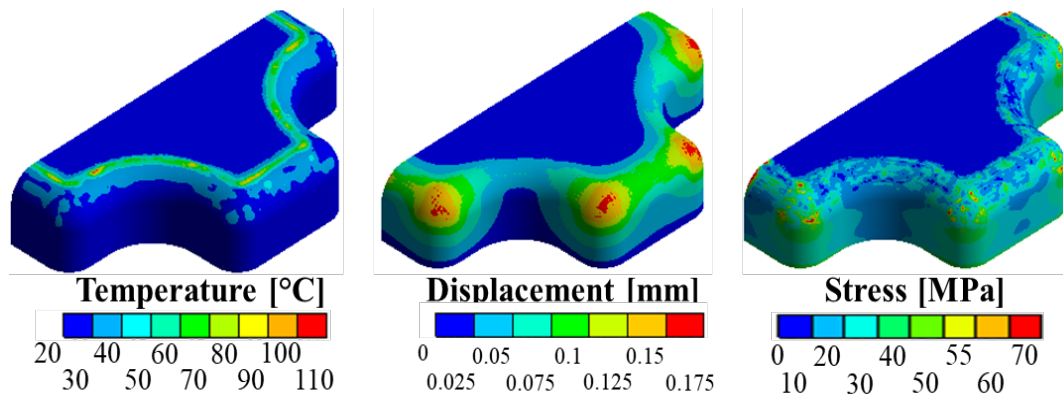
**Fig. 5.** Comparison of wear marks on draw-bend tools from PVX vs. AA 7075-T6.

For AZ31 sheets,  $\text{CF}_4$ -treatment improved the performance of NAT, and PVX showed consistently lower  $\mu$ . In both cases, uncoated and  $\text{CF}_4$ -treated PVX achieved friction values approximately half that of the steel reference. These results confirm that PVX offers the best sliding properties for applications involving both AA 7075-T6 ( $\mu = 0.06 - 0.08$ ) and AZ31B ( $\mu = 0.08 - 0.11$ ) sheets.

### Finite element simulation.

FE simulations were used to preliminarily evaluate the feasibility of using plastics as tool materials for sheet metal forming up to 300 °C. The maximum thermo-mechanical loads on the punch, just before the onset of thinning in the cross-cup geometry, were extracted from LS-DYNA®. The simulation results were in good agreement with experimental observations and showed sheet thinning at the cup corners at constant drawing depths.

Nodal forces and temperature distributions from LS-DYNA® were applied as boundary conditions in ANSYS Workbench to simulate the punch behavior. The thermo-mechanical properties of the characterized plastics were integrated into the ANSYS material library. Evaluation based on the von Mises stress criterion, displacement and temperature distribution (Fig. 6) showed that in AA 7075-T6 forming, where tool stresses are higher, the stresses (up to 70 MPa) in all thermoplastics remained within elastic limits. In case of PVX, it was shown that short-term surface temperatures of up to 110 °C were acceptable and that the low thermal conductivity of the plastic ensured gradual temperature penetration into the punch. This was confirmed by experimental data showing that after 10 cycles of contact with a 300 °C AA 7075-T6 sheet, the temperature 2.5 mm from the surface did not exceed 140 °C. Although local stress concentrations were observed near the cross-cup radii, the overall elastic deformation of the tool was up to 160  $\mu\text{m}$ .



**Fig. 6.** Results of the PVX-punch's behavior under forming loads of AA 7075-T6 under 300 °C.

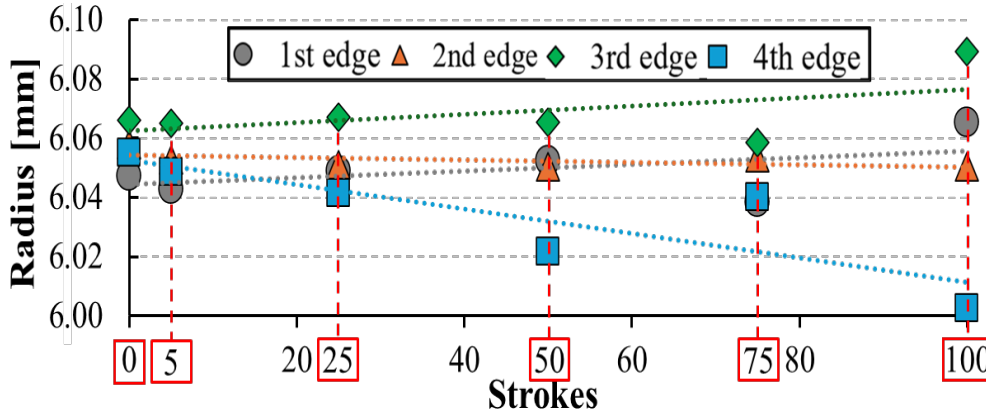
As with PVX, FE analysis showed that all thermoplastics exhibited the theoretical ability to form sheet metal at temperatures up to 300 °C, whereas PUR materials did not maintain stability under production loads.

### Experimental results.

For laboratory testing, the active tool components (die and punch) were manufactured from PVX, a material that has shown the best tribological properties and stability at temperatures up to 300 °C, similar to other thermoplastics. One set of punch and die was used to produce 100 cups, with the

punch evaluated after 0, 5, 25, 50, 75 and 100 strokes according to the procedures described in experimental setup section.

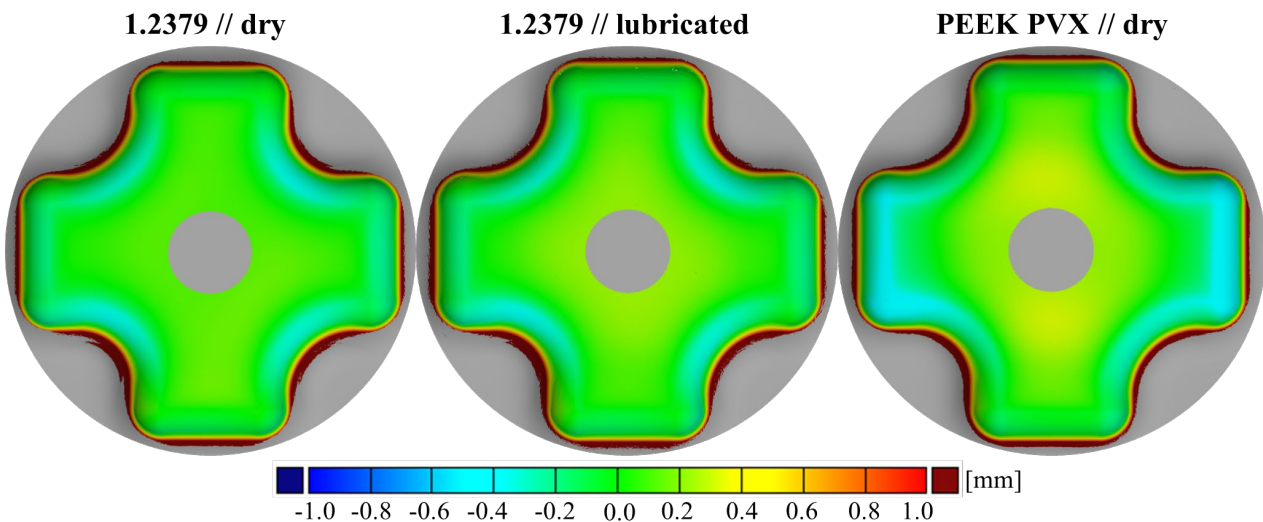
No weight loss was observed after 100 strokes ( $< 0.01\%$ ), indicating that no material was removed. Digital length gauge measurements confirmed that there was no significant deviation or compression of the punch ( $< 0.01\%$ ). Optical profiling of the punch edge was performed at specified intervals using a digital Keyence microscope (Fig. 7). Three lines of measurement were taken for each of the four edges, and an additional ten lines from adjacent areas were used to calculate the average radius and evaluate deviations.



**Fig. 7.** Evaluation of PVX punch edge radius after forming AA 7075-T6 at different stroke numbers.

Although there is no universal standard for acceptable wear in deep drawing tools, the general tolerance standard DIN ISO 2768-1 [21] (classes f and m,  $\pm 0.2$  mm total tolerance) has been used. The maximum punch radius deviation (4th edge) of 6.055 mm to 6.005 mm ( $-0.05$  mm) falls within this tolerance.

Dimensional accuracy was evaluated by comparing the formed cross-cups optically to the CAD model. Five parts, each drawn to 10.5 mm at 300 °C, were scanned using a GOM ATOS system for each tool variant (1.2379 dry, 1.2379 + lubricant Multidraw SHF 431, and PVX) and compared to the nominal punch CAD geometry (Fig. 8). The steel tools exhibited local inner-surface deviations of approximately  $-0.4$  to  $+0.25$  mm, while the PVX parts showed similar deviations of about  $-0.5$  to  $+0.3$  mm. These deviations are primarily due to sheet springback and slight variations in punch radii (steel: 5.98 mm; PVX: 6.05 mm), as well as minor thermal and handling variations. These results suggest that polymer tooling does not result in a loss of dimensional precision.



**Fig. 8.** CAD-to-part deviation maps of the inner surface of AA 7075-T6 cross-cups for three tool variants referenced to the nominal punch CAD geometry.

The PVX tool increases the forming window by about 45 % at 300 °C compared with dry steel (from 11 mm to 16 mm) and by about 23 % compared with lubricated steel (up to 13 mm). The cross-cup parts were fully formed with a high-quality surface on the plastic tool sides, though adhesion of the sheet materials was observed on the steel holder side.

## Conclusion

This study demonstrated the feasibility of using thermoplastics as tool materials for dry forming of high-strength aluminum AA 7075-T6 and magnesium AZ31B alloys at temperatures up to 300 °C. Extensive experimental investigations complemented by a primary FE-based assessment provided a robust evaluation of the candidate polymers. These results indicate that thermoplastic tools offer a promising, cost-effective, and environmentally friendly alternative to conventional steel tools for tempered dry forming of magnesium and high-strength aluminum sheets, particularly in prototyping and small-scale production (> 100 parts). Among the materials tested, original tribologically optimized TECAPEEK PVX exhibited superior performance, maintaining dimensional stability and low friction under thermo-mechanical loading. Punch wear analysis revealed minimal degradation after 100 parts, with residual edge radius deviations of up to 50 µm.

Cross-cup forming trials at ~ 300 °C on a PVX tool confirmed the process benefits at the component level. For AA 7075-T6, the maximum crack-free draw depth increased by  $\approx + 45$  % vs. the 1.2379 tool and by  $\approx + 23$  % vs. the 1.2379 tool with lubricant. Comparisons of the CAD model and the part at a constant draw depth showed comparable dimensional deviations for the cross cups formed by the tool and the PVX tool, which were mainly attributed to sheet springback, small differences in punch radii, and minor thermal and handling variations. The cross-cup parts formed on the plastic tool remained fully formed with high surface quality compared to parts formed on the steel tool.

Future work should further optimize thermoplastic tools for dry tempered sheet metal forming. Statistical robustness should be improved by testing a broader parameter set and increasing repeat measurements during material characterization, thereby reducing uncertainty and strengthening FE model calibration. Surface treatments also require refinement, particularly regarding coating adhesion and the development of alternative or multilayer systems with improved tribological performance. Long-term cyclic tests under realistic thermo-mechanical loading are needed to quantify tool life and fatigue resistance and to assess feasibility for medium-scale production. Experimental repeatability should be enhanced by tightening control of sheet/tool temperatures, closing rates, and part handling. Finally, validation on industrially relevant geometries with defined tolerances is required. Together, these steps will support wider industrial adoption as a cost-effective and environmentally preferable alternative to steel tooling for small - and potentially medium - series production.

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