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Warm forming of thermoplastic fibre metal laminates

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Abstract. In this paper, the forming behaviour of sheet-like metal/polymer/metal (MPM) and thermoplastic fibre metal laminates (TFMLs) is introduced. TFMLs are based on thin metallic cover sheets and fibre-reinforced thermoplastic matrix (here polyamide 6). With this material combination, the specific mechanical, structural, thermal and acoustic properties can be improved and designed compared to the monomaterials and laminates without fibre reinforcements. However, the restricted formability of TFMLs at room temperature is a strong limitation. Therefore, the approach of this study is concerned with the fundamental description of the influence of warm forming on the degree of the forming improvement of pre-bonded TFMLs sheets experimentally via the investigation of the deep drawability and determining the forming limit curves compared to the formability of steel and MPM sheets. Two elevated test temperatures (200 and 235 °C) besides the room temperature are considered. The results of this approach revealed that warm forming could lead to over 300 % improvement of the forming limit curve (FLC) level of TFML; however, an ignorable difference between 200 and 235 °C is found. For steel and MPM sheets, increasing the temperature showed a slight improvement. Regarding deep drawing, similar results like for FLC were found, where the drawing depth of TFML could be increased from approx. 15 mm up to at least 40 mm before cracking. However, other failure types arose like wrinkling and core squeezing-out. Therefore, a one-step deep drawing approach for TFMLs is foreseen, where the adhesion and forming processes take place simultaneously.

Introduction

Thermoplastic fibre-metal-laminates (TFMLs) are composed of metallic cover sheets (or even interlayers) and layer(s) of fibre reinforced thermoplastic polymers [1]. With such a set-up several advantages can be gained, e.g. improved mechanical properties at lower density [2]. This materials group is developed to overcome the formability drawbacks of the thermoset-based FML such as glass-reinforced aluminium laminate (GLARE) or aramid-reinforced aluminium laminates (ARALL) [3]. Moreover, the potential TFMLs application is increasing due to their recyclability in relation to the thermoset-based FMLs. TFMLs were considered in some projects, e.g. the LEIKA project, where several steel/fibre reinforced polyamide (PA) components can be applied as crash absorbers or as battery carriers in e-vehicles [4]. Besides, lab-scale TFMLs like carbon fibre-reinforced polyamide/aluminium laminate (CAPAAL) and carbon-fibre-reinforced polyetheretherketone/titanium foil laminate (CAPET) showed improved behaviour under bending conditions [5]. Based on this, TFMLs proved their suitability for automated series production in semi-finished products or even directly to finished components starting from single layers. For lightweight applications, metal/polymer/metal (MPM) sandwich laminates, with nonreinforced polymer core, were also developed such as Litecor [6] and Hylite [7].The deep-drawability of MPM materials is reduced directly with increasing the core layer thickness due to the tensile stresses exerted by the soft polymer core on the outer metal cover near the edge of the punch and the corresponding increased void volume fraction within the metal [8]. Regarding TFMLs, the mobility of the brittle fibre-reinforcement in the core layer is restricted together with the limited plastic deformation of the core layer can lead directly to a sharp increase in tensile stress on the outer steel sheet and premature cracking. Therefore, it is necessary to study the deep-drawability of TFMLs under controlled thermal conditions for identifying and defining the processing conditions of TFMLs with a polymer matrix close to or even above its melting point. In a previous study, the deep drawing of 190 mm diameter TFML (steel/GF-PA6)/steel) blanks utilizing a 100 mm diameter punch was studied, where cracking-free samples could only be obtained utilizing high holding forces of 200-300 kN (i.e. 10-15 MPa holding pressure) for drawing depths of less than 17 mm, where severe wrinkling and thickness irregularities took place [9]. In another study on Al/GF-PA6/Al laminates, forming at a temperature of 270 °C (significant higher than the melting point of PA6, i.e. 220 °C) leading to a significant polymer squeeze-out during deep drawing and thermal degradation of the PA6 matrix [10]. On this basis, there is still a need to understand and identify the forming behaviour of such TFMLs aiming to maximise their limits at reduced processing conditions (temperatures and holding pressures). This can be a further source of energy saving during processing TFMLs.

The current paper is concerned with the warm forming of MPMs and TFMLs. For this purpose, the forming behaviour is characterized via standard methods (tensile testing, deep drawing and FLC determination) at room temperature and two elevated temperatures, which are selected in relation to the melting temperature (T_m) of the polyamide matrix, which is approx. 220 °C. In this regard, the warm forming behaviour of MPMs and TFMLS was characterized at 200 °C (below T_m) and 235 °C (slightly higher than T_m) in order to define the forming temperature at which less defects can be reached. The investigations of this paper focus on the different testing methods on one combination of MPM and TFML, however other combinations are studied previously [11].

Materials and experimental work

The used TFMLs are three-layered ones containing steel cover sheets together with non-reinforced or fibre-reinforced PA6 core layers. The steel sheet grade TS290 is electrolytically-galvanized and has a thickness of 0.3 mm. The fibre-reinforced core used is a roving glass fibre-reinforced PA6 consolidated composite organosheets (Tepex® dynalite 102-RG600(2)/47%, LANXESS Germany GmbH) with a fibre content of 47 vol-% in thicknesses of 0.5 and 1.0 mm, where its weaving style is twill 2/2 [12]. With this, two laminates are investigated: a) metal/PA 6/metal with a core thickness of 1.0 mm, abbreviated as MPM-1.0 and b) metal/Tepex®/metal with the same core thickness of 1.0 mm, abbreviated as TFML-1.0. The steel/core adhesion for the semi-finished laminates is achieved via hot-pressing at 245 °C, 0.3 N/mm² and 5 min holding time. Prior to hot-pressing, the materials were prepared following the scenario described in [13], where the steel sheets are grinded, tempered (at 440 °C for 1 min), cleaned with acetone, applying a co-polyamide-based adhesive agent, and finally activated at 250 °C for 3 min. With this, an adhesion strength in terms of the single lap shear strength for MPM and TFML of about 23 and 15 MPa could be obtained, respectively [13].

To achieve good warm forming conditions, the tools being in contact with the blank were designed. A schematic representation of the FLC determination and deep drawing tools is shown in Fig. 1. The forming die and punch parts are warmed-up before the test in a separate furnace, however the blank holder is in-situ heated via implemented heating cartridges. Insulating ceramic discs are utilized to minimize the heat loss and protect the forming machine from overheating. The testing temperatures (200 and 235 °C) could be successfully controlled with a tolerance of ±5 K [14]. The testing conditions are summarized in Table 1.

Lubrication is a dominant factor affecting the forming limits. For FLC determination, a combination of Teflon and additional thermoplastic films with inlayers of grease were utilized at RT with a total thickness of 2 mm, however only Teflon foils were used at the elevated forming temperatures with a total thickness of 2 mm. For deep drawing, a 0.05 mm thermoplastic film was used at RT, however a combination of Teflon (0.05 mm) and Molycote® spray are utilized for the elevated temperature testing condition. For determining the limiting strains, a digital image correlation system was used, where heat-resistant sprays for the stochastic pattern were applied for a successful strain evaluation.

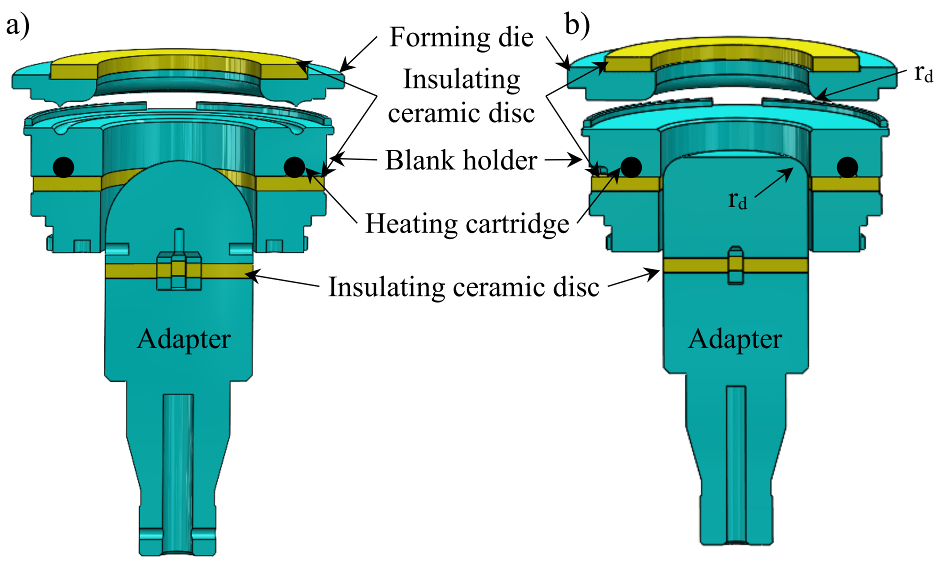

Fig. 1: Schematic representation of: a) the 100 mm^{Ø} semi-spherical punch for FLC determination, and b) the 100 mm^{Ø} flat cylindrical deep drawing punch.

The FLC curves were determined based on the line-fit method, where the thinning rate is considered for determining the localisation and therewith the major and minor strains for the FLC can be obtained [15]. Four test samples geometries with different widths are utilized for different stress states, namely 200, 150, 100, and 50 mm for equi-biaxial, in-between, plane strain and uniaxial strain conditions, respectively.

Table 1: Test conditions for the FLC and deep drawing experiments.

Test	D_0 [mm]	d_0 [mm]	r_p [mm]	r_d [mm]	v [mm/s]	F_h [kN]	T [°C]
FLC	200	100	-	10	1.5	100	RT, 200, 235
Deep drawing	180	100	15	15	0.5	15	RT, 200, 235

D_0: blank diameter, d_0: punch diameter, r_p: punch corner radius, r_d: die radius, v: test speed, F_h: holding force, T: test temperature

Results and discussion

Firstly, the influence of the temperature on the tensile properties of the steel sheet TS290 is determined and the corresponding results are summarized in Table 2. It can be clearly observed that the strength-related properties (yield strength (YS), ultimate tensile strength (UTS) and elastic modulus (E)) are reduced with increasing the testing temperature up to 235 °C with a slight increase in the strain at failure (A_{80}). This result is expected to have an impact on reducing the forming forces at the elevated test temperatures and improving the fracture displacement, too.

Table 2: Temperature-dependent mechanical properties of the TS290 steel sheet.

Steel grade	T [°C]	E [GPa]	UTS [MPa]	YS [MPa]	A_{80} [%]
TS290	RT	178 ± 2	410 ± 1	283 ± 2	19.5 ± 0.5
	235	168 ± 5	379 ± 1	257 ± 1	20.8 ± 0.9

Forming limits curves (FLC): FLCs for the monolithic steel sheet and the different laminates (MPM and TFML) at different temperatures are presented in Fig. 2. To indicate the forming forces and displacements at failure, Fig. 2a) depicts the force-displacement curves for the samples for the equi-biaxial strain path, i.e. the 200 mm diameter samples. Similar to the behaviour of the tensile properties, the maximum forming force of the steel is reduced from 30 kN down to 24 kN with an increase of the displacement from 33 to 35 mm. As a result, the FLC level of the steel at 235 °C (Fig. 2b)) is slightly higher than at RT in the equi-biaxial straining range (right-side of the diagram).

The same tendency was found for the MPM sheets; however, the level of the forming forces is unsurprisingly higher than those for only one steel sheet. The punch displacement of MPM is less than the ones of the steel sheets indicating a possible reduction of the FLC level.

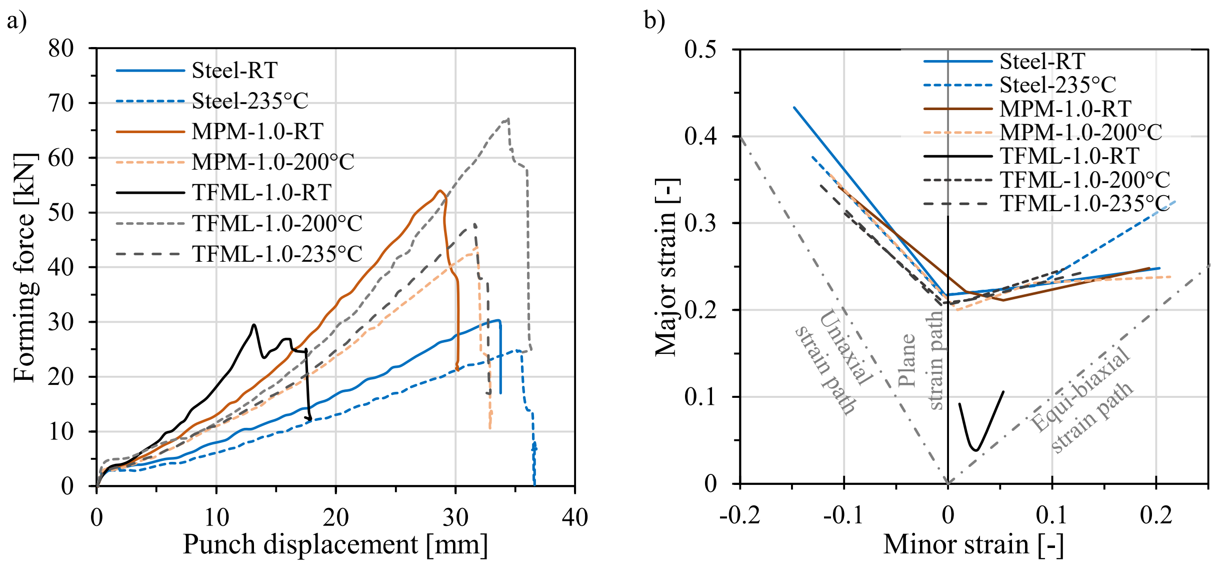

Fig. 2: a) Force-displacement curves for the samples with the 200 mm diameter (i.e. equi-biaxial strain) and b) the obtained FLCs for different materials and testing temperatures.

This is in accordance with the literature, where MPMs have slightly lower forming limits in relation to their monolithic metallic cover sheets [16], where the non-reinforced polymer core can be plastically-uniformly matching the formability of the cover steel sheets. Only for thicker cores (at core volume fraction > 60 %), the FLC level of such thick-cored MPM can be reduced in the right-side of the FLC, as found recently for MPMs with polypropylene core [17], too. Like the steel sheets, there is no significant difference between the FLC of MPM at RT and 200 °C (Fig. 2b)).

Regarding the FLC levels for the TFMLs, as can be seen from Fig. 2b), the FLC level at RT is extremely low and the main failure strains are located in the plane strain regions. This can be attributed to the restricted and localised formability of the organosheets (2/2 twill fabric) at RT and its influence on the plastic deformation of the outer steel sheet, instead of the uniform straining for the steel and MPM sheets, leading to earlier failure; this is in accordance with the results stated in [18]. This can be clearly observed through the displacement value in Fig. 2a), where only a depth of 13 mm before cracking can be reached compared to approx. 35 mm at the elevated forming temperature. The FLC level of TFMLs increases remarkably with increasing the temperature to 200 °C or 235 °C, reaching the level of the MPMs or even the monolithic steel sheet, which is the maximum FLC level achievable. The difference between the FLC levels determined at 200 and 235 °C is negligible. Therefore, forming at 200 °C is sufficient extending the forming limits of TFML together with less squeezing-out of the polymer matrix, which took place in the melted matrix at 235 °C. It can be stated that at RT the forming/draping limit of the organosheet dominates the FLC level of its TFMLs; however, at the elevated temperatures, the cover sheet dominates the FLC level.

Deep drawing results: the deep drawing results in terms of force-displacement curves and the forming strains are depicted in Fig. 3. A criterion was defined indicating a satisfactory forming which is a forming depth of 40 mm. This limit was reached by the steel sheets at 235 °C as well as at RT (see Fig. 3a). This criterion was fulfilled by the MPM sheet at RT, too. This is in accordance with the FLC results, where MPM with the non-reinforced core show a FLC level next to that one of the steel sheet. Specific deep-drawn cups are presented in Fig. 4.

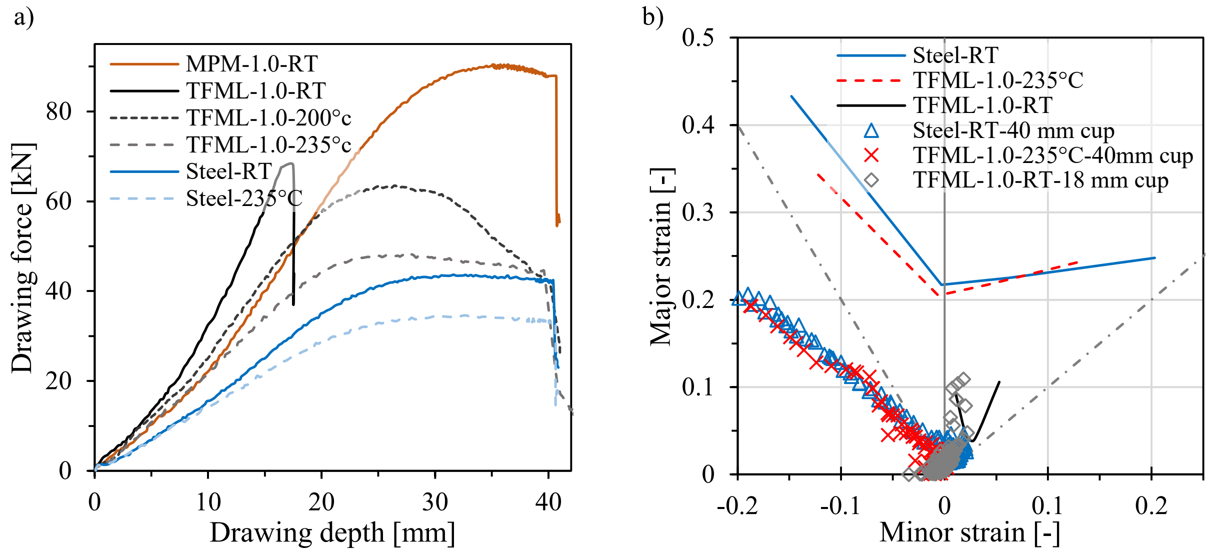

Fig. 3: Deep drawing behaviour of the steel, MPM and TFML sheets at different temperatures in terms of: a) deep drawing force-displacement and b) forming strains compared to the FLC.

With deep drawing of TFML at temperatures above the melting point of PA6, i.e. at 235 °C as shown in Fig. 4e), severe wrinkling on the inner cover sheet and waviness on the outer side took place. The reason is that the molten polymer matrix does not provide the stability of the cover against the circumferential compressive stresses of the blank in the flange and cup wall regions. A geometrical factor could play a role in wrinkling which is the larger gap size (3.3 mm) and the die radius (r_d = 15 mm), where a large gap to sheet thickness ratio often leads to waviness during drawing of the sheet [19]. As shown in Fig. 3a), the drawing force of TFML is reduced at 200 °C and 235 °C compared to RT, which is due to the softening of the core material and, consequently, the increase in fibre mobility/drapability in the PA6 matrix. The maximum drawing depth of the TFML at RT was about 15 mm. It should be mentioned that the drawing depth of the monolithic organosheet (Tepex) core is the same like in the TFMLs at room temperature [14]. This limit was increased to > 40 mm drawing depth at 235 °C, which could be attributed to fibre fracture in the flange area [14]. This highlights the dominancy of the organosheet core determining the forming limit.

A comparison of the strain distribution on the drawn samples with the previously obtained FLCs is shown in Fig. 3b) in order to examine the crack probability as well as to examine the validity of the FLC itself. The minor-major strain points of the failed TFML at RT are overlapped in the diagram. The results show that these strain values are beyond the FLC level indicating cracking and confirming the applicability of the obtained FLC. For the MPM and TFML at elevated temperature, no failure by cracking is expected, where most of the strain values are below the uniaxial tensile strains in the direction of the compressive and shear regions confirming the wrinkles formed.

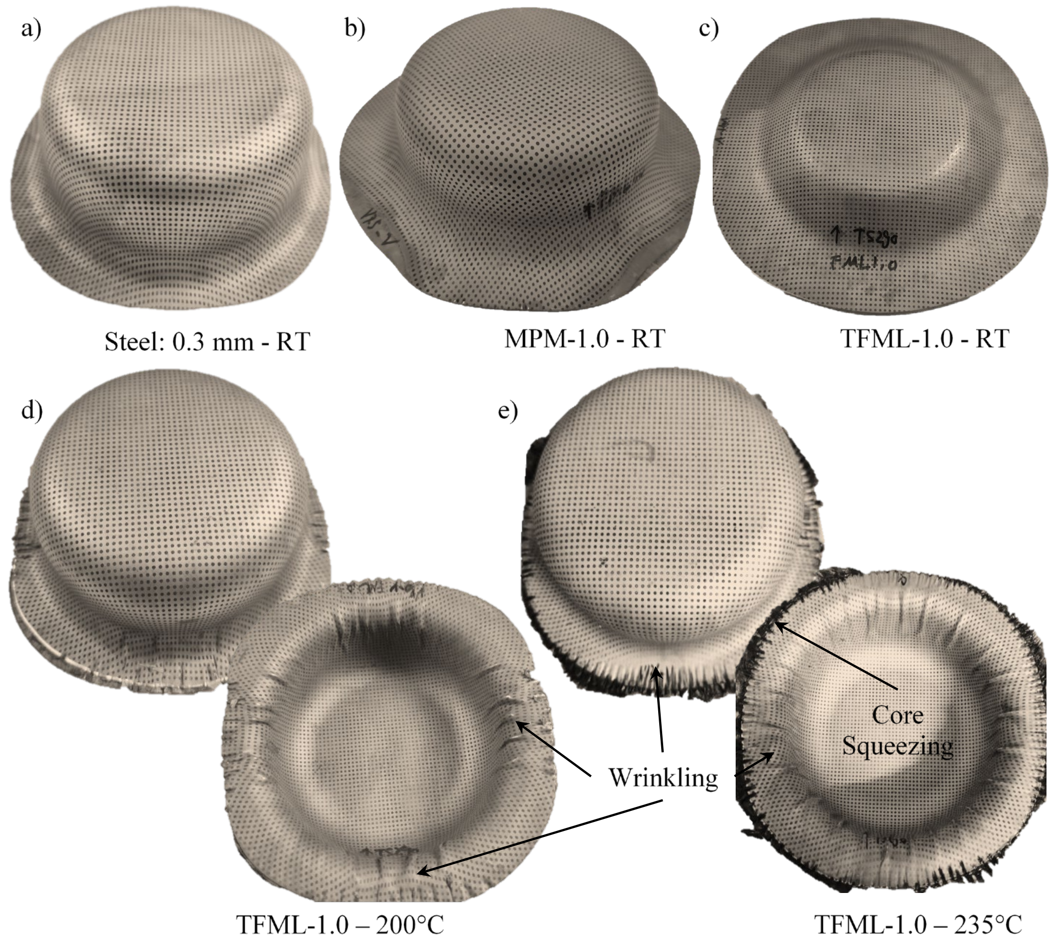

Fig. 4: Drawn cups at RT of: a) the steel sheet, b) MPM-1.0 and c) TFML-1.0, in addition to the TFML drawn cups at: d) 200 °C and e) 235 °C showing wrinkling and squeezing-out.

In order to examine the critical drawing depth, at which wrinkling starts forming, two-step drawing operation was carried out up: 1st drawing: up to 25 mm, and 2nd step: up to 40 mm [14]; it was found that no wrinkling was observed at the 25-mm step at the elevated temperatures.

Summary and conclusions

The influence of the forming temperature on the forming limits of monolithic steel, MPM and TFML sheets was determined in terms of forming limit curves and deep drawing. The following conclusions can be drawn:

- The FLC of the MPMs is comparable to the one of the monolithic steel cover sheets, regardless the testing temperature.
- The FLC of TFML is remarkably improved compared to forming at RT at elevated temperatures near the melting point of the polymer matrix. Forming close below and above the melting point (200 °C and 235 °C) doesn't show significant differences. Therefore, forming at 200°C can be favoured, where less defects like core squeezing-out and thickness irregularities are expected. The organosheets dominate the FLC-level at RT and the steel cover sheets are dominant at the elevated temperatures.

- Under deep drawing conditions, TFML at RT is subjected to localized tensile stresses exerted by the fibre-reinforced core on the outer cover of TFML, leading to early failure. The strain distribution of the drawn parts at RT are dominated by the fibre-reinforced core. At the elevated temperatures of TFML and MPM, the cover sheets dominate the failure conditions. Drawing at 235 °C leads to unavoidable thickness irregularities. Therefore, deep drawing of pre-bonded TFML is favoured at 200 °C. Wrinkling is more susceptible by forming above the melting temperature of the polyamide matrix (i.e. at 235 °C).

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