Forming limit curves for quasi-static and dynamic working-media-based forming processes

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Abstract

The production of complex, multi-functional, high-strength components is becoming increasingly important in the sheet metal industry. Especially with small batch sizes, quasi-static working-media-based forming processes (WMF), such as hydromechanical deep drawing (HMD) or high-pressure sheet metal forming (HPF), can be advantageous. If shorter process times or higher forming speeds are necessary, working-media-based high-speed forming processes (WMHSF) are best used. These permit the production of sharp edged parts with less tooling than for quasi-static WMF. The successful use of WMB processes requires knowledge of the significant process parameters and the material characteristics under process-specific conditions. This paper describes the new approach of a modified hydraulic bulge test, which permits the flexible determination of forming limit curves (FLC) under true quasi-static and dynamic WMF process conditions. Results for the formability of steel DC04 and aluminium (A5754, A1050) alloys in the WMF process are shown. Here, the dynamic conditions are analysed through the use of pneumo-mechanical (PMF) testing equipment. The application of quasi-static forming conditions is analysed in high-pressure sheet metal forming (HPF) processes. A comparison of the maximum strains of parts formed by HPF and PMF shows that quasi-static and dynamic working-media-based forming processes lead to different forming limits.

Keywords

Pneumomechanical Forming, Electro Hydraulic Forming, High Speed Hydroforming

1 Introduction

The protection of the environment and resource saving are becoming increasingly important in manufacturing industry, and especially in the automobile and aerospace industries. Several recent research projects have thus been aimed at implementing lightweight concepts in production, using innovative materials and complex part designs with an enhanced functionality (Neugebauer, 2005, Vovk, 2005). Here, it is necessary to develop new, innovative production processes which are able to meet the requirements for shaping new materials like high strength steels or hybrid materials into highly complex geometries.

In this context, working-media-based forming processes (WMB) and especially high-speed-forming processes have a high potential for meeting these requirements. This makes it possible to create very sharp-edged and complex geometries (Kleiner, 1999, Homberg, 2012).

The successful use of quasi-static and dynamic WMB processes requires knowledge about material conditions and material behaviour under process-specific conditions. This paper presents new variant of the hydraulic bulge test pursued at the Chair of Forming and Machining Technology (LUF), permitting the flexible determination of material behavior under true quasi-static and dynamic process conditions. Furthermore, the formability of steel DC04 and aluminium alloys (A5754) measured with the new testing variant are shown. Different materials were examined to this end under quasi-static and dynamic stresses so as to examine the forming limits in both cases. The results represent the basis for further systematical analytical or numerical consideration of WMBF processes.

2 Experimental setups and working principles

For the experimental investigations, a special combined pneumo-mechanical (HPF-PMF) setup was used (see Figure 1). The HPF-PMF setup includes options for single and combined quasi-static or dynamic forming operations.

The combined experimental HPF-PMF setup used at the LUF for the determination of forming limit curves consists of a pneumatically accelerated plunger, a pressure generation unit (1), a vertically arranged acceleration tube (3) and a two-part forming tool. The forming tool consists of a conical pressure chamber with an opening angle of α = 45° and a die with the base plates. Here, the two halves of the forming tool are clamped during the forming process with the help of two locking rings (9). At the lower end of the tube is a device for measuring the plunger speed in order to determine the plunger energy. Below the measuring device is a ventilation system for limiting the proportion of compressed air in front of the plunger during the downward movement; for more details see also (Djakow, 2016).

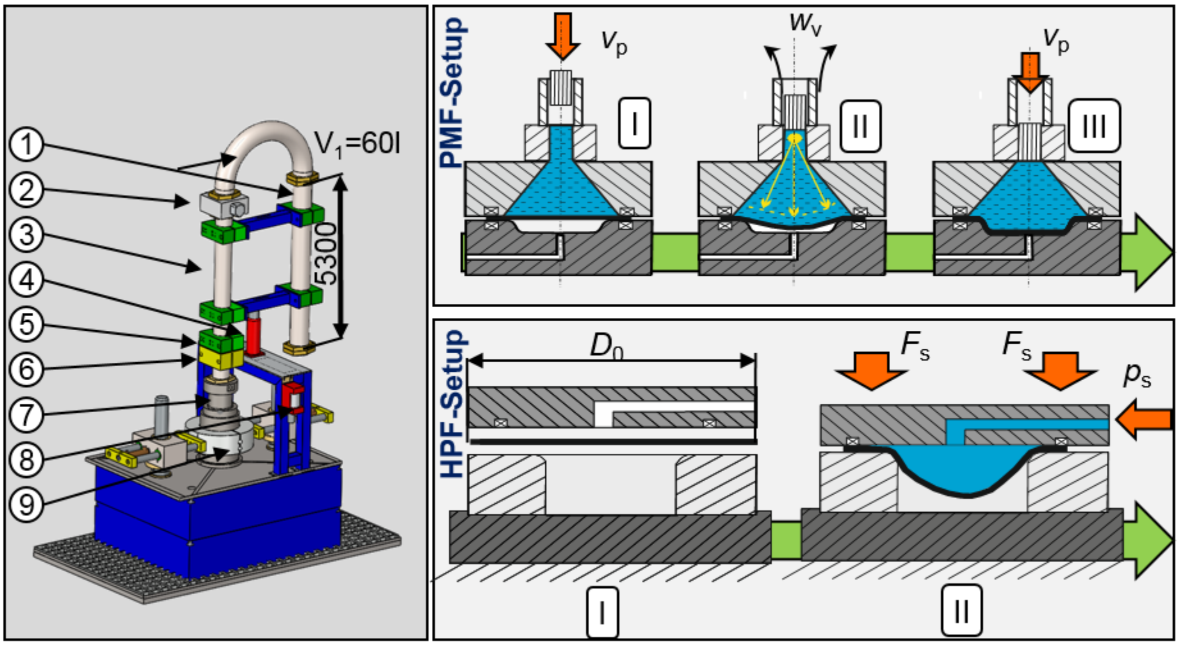

Figure 1: *Combined HPF-PMF-setup: 1 – pressure generation; 2 –release mechanism; 3 – acceleration tube; 4– lifting device; 5 – light barrier; 6 – venting system; 7 – tube adapter; 8 – high-pressure pump; 9 – ring pliers.*

In the case of the PMF process, an accelerated plunger generates the pneumo-mechanical working-media pressures. Here, the accelerated plunger dives into the water-filled cavity of the die, reaching the desired speed at the end of the accelerating tube. Due to the kinetic movement of the plunger and the incompressible properties of the working medium, very short and high-pressure pulses of up to several dozen MPa can be generated. To accelerate the plunger in the PMF machine, compressed air pressure is necessary.
In addition to the pneumo-mechanical setup, quasi-static hydroforming setup was used as a reference for comparing conventional and high-speed forming processes with the combined HPF-PMF setup. Here, the same sheet tool setup consisting of a two-part forming die, a high-pressure adapter and a pressure intensifier was used; for more details see also (Djakow, 2016).

3 Measuring procedure

In this work, a modified bulge test method was developed for the simple determination of both quasi-static and dynamic strain changes directly in working-media-based forming machines. As shown in Figure 2, the method employed is analogous to DIN EN ISO 12004-2 and in line with the procedure of Hasek, Nakajima and Marciniak (Hasek, 1973, DIN12004-2, 2008). In principle, during the modified bulge test the material undergoes different strain states in the forming limit diagram and thus portrays different characteristics of different process areas. In order to set the same possible load conditions and comparable tribological properties during the forming operation, the material flow from the flange is not suppressed.

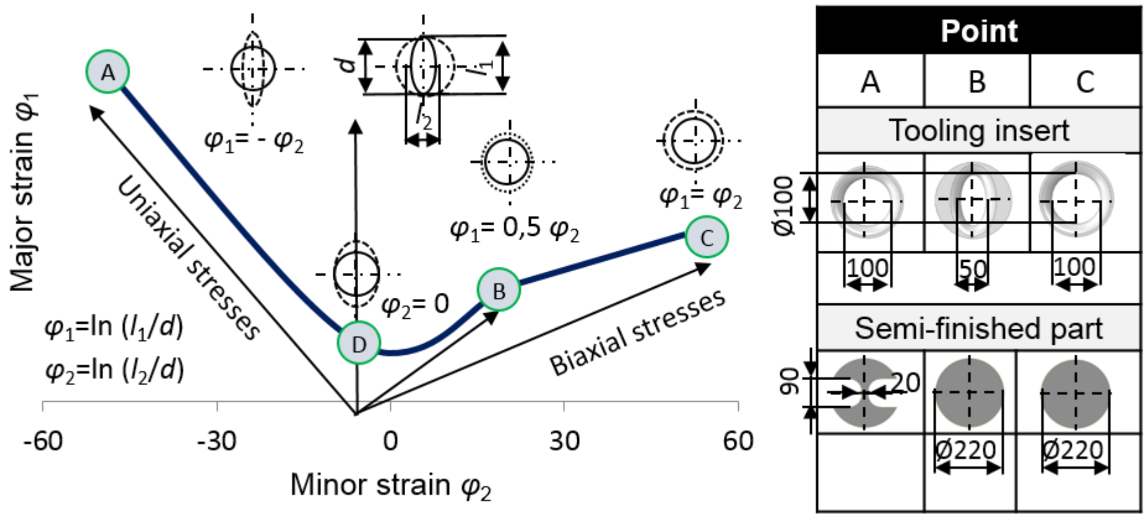

Figure 2: *Determination system of the modified bulge test*

Figure 2 shows that, during the WMBF process, it is mainly tensile / tensile or tensile / compressive stress states that occur. Hence, only the first and the second quadrants in the forming limit diagram were considered. The forming limit curve is generated using one point in the second quadrant (A) and two points in the first quadrant (B, C) of the forming limit diagram. The fourth point (D) results from the highest data points at A, B and C that are laid on the major strain axis representing the plane strain status. By contrast to the three points (A, B, C), the superimposed point (D) does not represent the maximum forming limit, but rather shows the maximum true forming limit in the plane during uniaxial and biaxial forming.

The modified method of strain analysis is based on a qualitative comparison of local strain before and after forming. For this purpose, the sample is captured in the first step in its original state by an optical measuring system. Here an optical 3D forming analysis system (GOM Argus©) is used to investigate and visualize the attained forming limits. In the second step, the sample is formed either quasi-statically or dynamically, or pre-formed quasi-statically followed by a dynamic calibration. After forming, the strains are captured by the optical measurement system again. The resulting forming limits are then generated on the basis of the qualitative comparison of the forming stages. The identification of the crack area is performed manually. The forming limits were generated from material data that has not been damaged and does not include cracks. In addition, the crack propagation (primary and secondary cracks) is analysed and evaluated. Figure 3 shows, from left to right, the characteristic crack initiation and crack propagation during quasi-static and dynamic loading with increasing forming speeds.

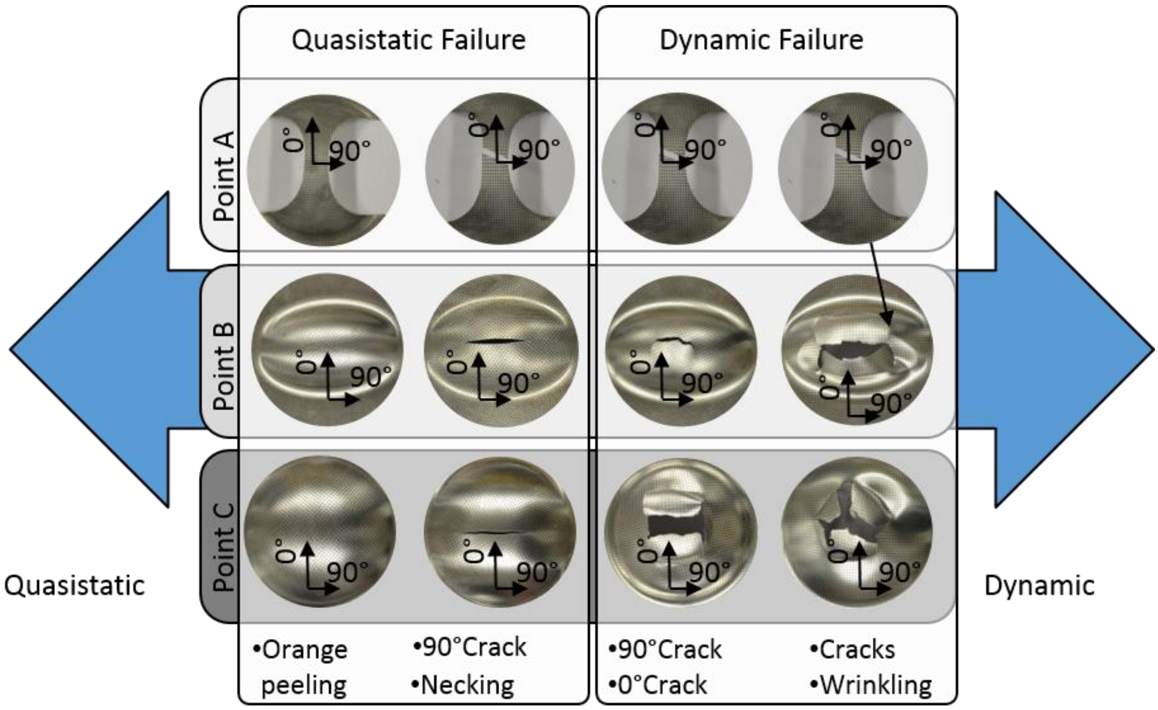

***Figure 3**: Failure during quasi-static and dynamic forming*

When considering the formation of cracks, crack initiation always occurs at the deepest point (apex), regardless of the type of load and the forming speed. Due to the higher possible tension in the rolling direction, the primary crack propagation occurs at 90 ° to the rolling direction. In quasi-static stress, crack propagation usually remains only in the 90 ° direction. Dynamic load, by contrast, also leads to the initiation of secondary cracks, due to the inertial forces acting or higher load conditions. Secondary cracks are a result of primary crack propagations and are usually orthogonal to the primary cracks.

4 Results and discussion

The focus of this work is on analysing the limitations and potential of quasi-static and dynamic forming in terms of the maximum forming limit, with the aim of increasing process efficiency and comparing pneumo-mechanical high speed forming with conventional forming processes. To describe the limitations and potentials of the forming limit, three different materials were examined under quasi-static and dynamic stresses. The steel DC04 and two aluminum alloy (EN AW 5754, EN AW 1050) with two different material states (H111, H22) were tested. The forming velocity were less than 30 ms^{-1} for steel DC04, 20 ms^{-1} for EN AW 5754 and 15 ms^{-1} for EN AW 1050.

4.1 Deep Drawing Steel DIN EN 10130 (DC04)

The experimental investigations on deep drawing steel have shown that the quasi-static and dynamic forming limit characteristics differ mainly in the maximum attainable major and minor strains. The experimentally-generated curves show that the DC04-steel has a similar trend in the uniaxial and biaxial strain region in quasi-static working-media-based forming process as for the standardized bulge tests. By comparison to the PMF process, quasi-static forming leads to 30% higher forming limits in the uniaxial area and 15% higher limits in the stretch-drawing area than for the PMF process. In addition, the deep drawing steel DC04 exhibits the highest forming limit changes in the uniaxial strain range (second quadrant) under quasi-static and dynamic stresses. Figure 4 shows the forming limit curves of deep drawing steel DC04 under quasi-static and dynamic loading by comparison to the standardized forming limit curve.

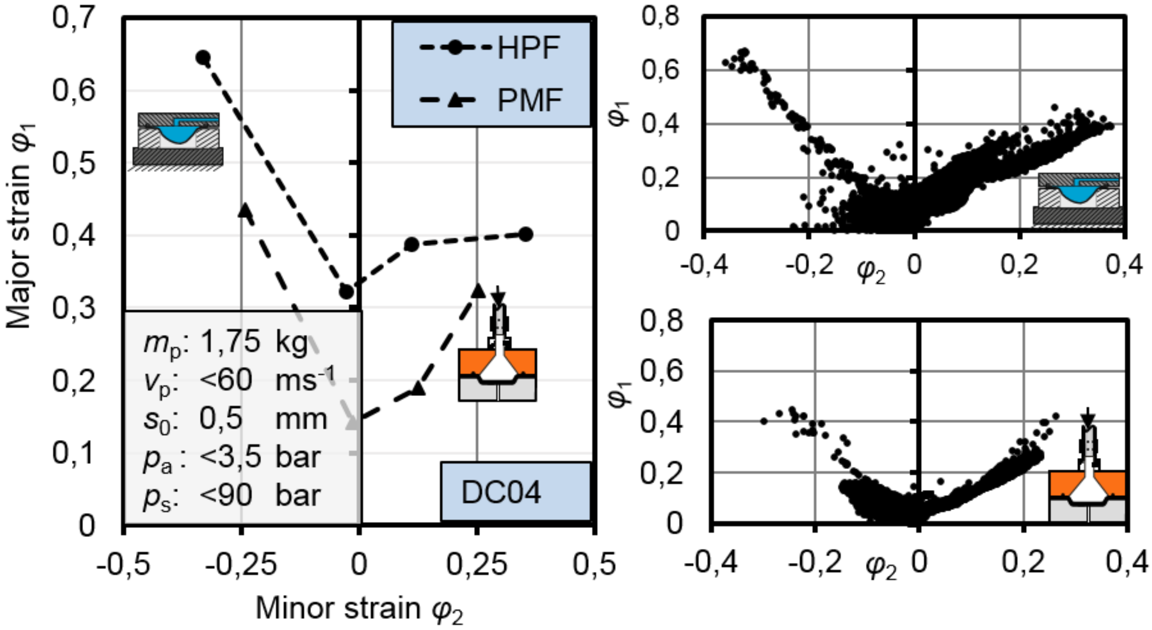

Figure 4: *Forming limit curves for deep drawing steel DC04*

In the case of a quasi-static working-media-based forming process, the DC04 steel achieves a major strain φ_1 of 0.65 with a minor strain φ_2 of -0.35. In the plane strain range, the φ_1 value is 0.27. In the pure stretch-drawing range, quasi-static forming attains a major strain φ_1 of 0.41 and a minor strain of 0.38.

4.2 Aluminum EN AW 5754 (H111/H22) and EN AW 1050 (H111/H14)

In the case of dynamic forming of the aluminum alloy EN AW 5754 in the H22 state, the experimental investigation with aluminum EN AW 5754 shows 7 - 9% higher major strains and 3 - 7% higher minor strains by comparison to quasi-static forming. Here, the values of the major strains achieved in both quadrants are almost the same as the φ_1 values in quasi-static and dynamic forming. Figure 6 presents the forming limits determined for aluminum EN AW 5754 in the states H22/H111.

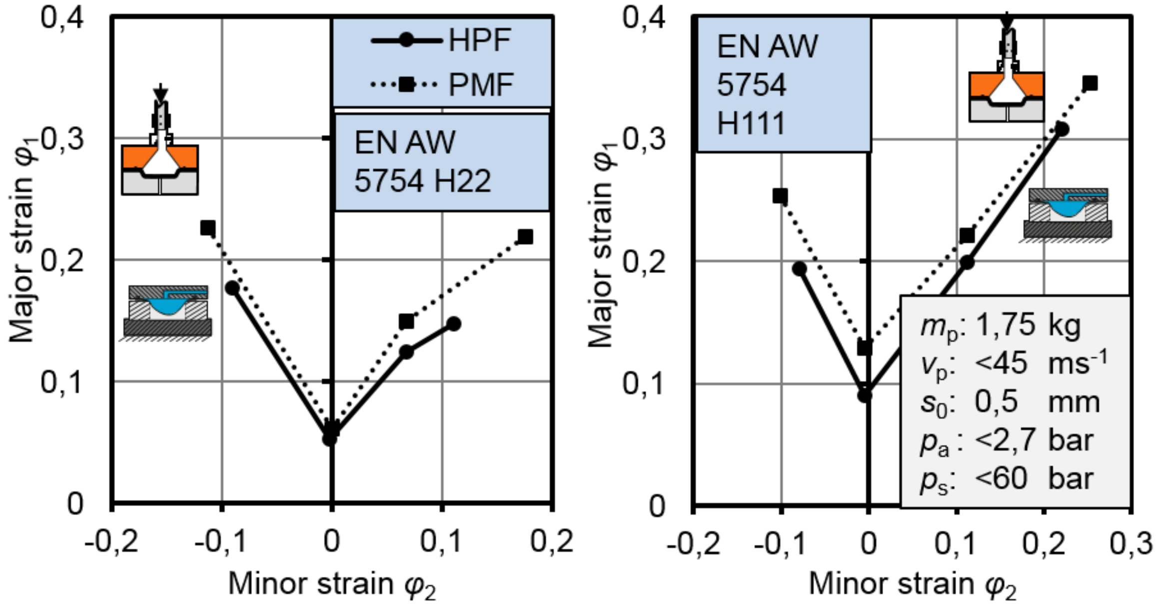

Figure 5: *Forming limit curves for aluminium EN AW 5754(H22/H111)*

For aluminum alloy EN AW 5754 in the H111 state, it can be seen that the results of quasi-static and dynamic tests are nearly identical. In the same way as for the H22 state, the dynamic forming shows 3-5% higher forming limits here than for quasi-static forming. In addition, the forming limits in state H111 are 3-10% higher than for the hard material state (H22). Unlike other aluminum materials, this condition shows that the limit for stretch forming is significantly higher than for pure uniaxial tension.

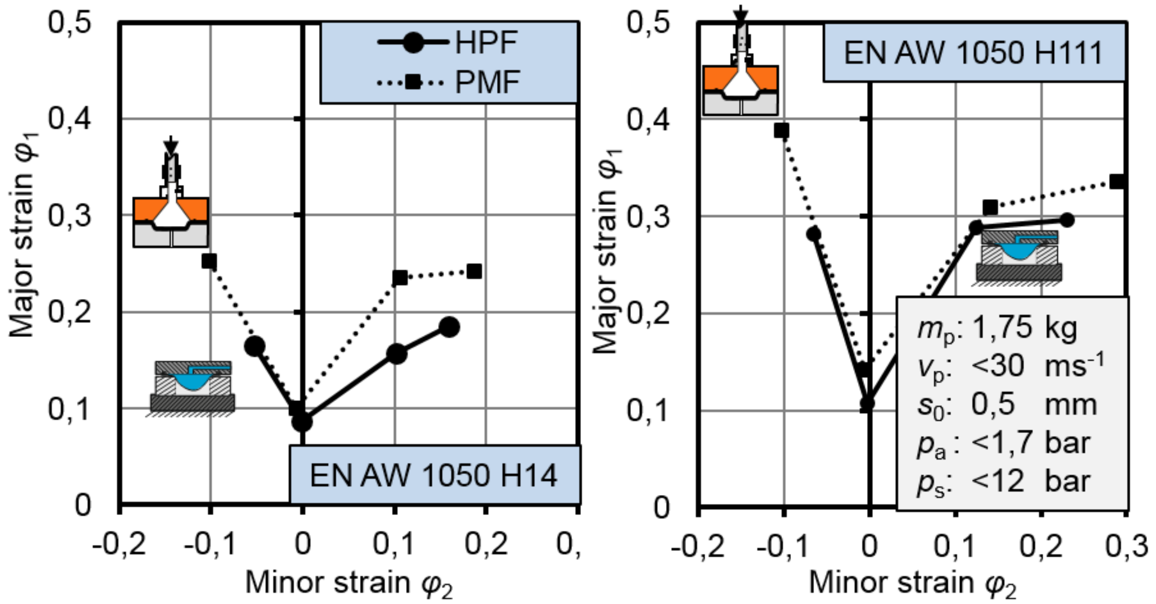

Figure 6: *Forming limit curves for aluminium EN AW 1050 (H14/H111)*

The same behavior as for EN AW 5754 was also found in the alloy EN AW 1050 in state (H111/H14). Here, the achievable forming limits are about 8 -12% higher for dynamic forming than for a quasi-static working-media-based forming process.

5 Conclusion

In this this work an alternative method is presented for generating the FLC under actual quasi-static and dynamic process conditions. Here, the investigations have shown that three characteristic strain points are already sufficient for approximating a forming limit curve. Investigations into the forming limits of four mostly industrially used materials have shown that:

- steel DC04 shows 3-15% lower forming limits under dynamic stresses than quasi-static stresses. It was seen that the differences between the forming processes decrease with the increasing strength of a material.
- in contrast to steel, the aluminum alloys of the 1050 and 5754 series in both the hard and the soft state show a 10% higher limit strain response when employing dynamic forming processes.

Furthermore, the results showed that varying the working-media pressures (quasi-static/ dynamic) can effectively increase the forming limits. The increase in the forming limit depends on the material group and the material alloy. To conclude, the WMBF processes are a highly innovative and efficient forming technique which provides an opportunity to expand the forming limits.

6 Acknowledgement

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