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Investigation of the surface integrity of mechano-chemically finished powder metallurgy gears

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Abstract

Automotive gears are facing stringent requirements regarding weight and functional surfaces, especially in view of the electric powertrain. To achieve these demands, powder metallurgy gears need to be finished using grinding, and in certain cases, mechano-chemical treatments. With regards to the latter, five different triboconditioning strategies based on vibratory tub finishing and/or centrifugal barrel finishing were considered and their effects on the surface integrity and friction behavior were investigated. Triboconditioning improved the surface roughness after grinding and resulted in higher compressive residual stresses. Additionally, microscopic observations of the surface topography were carried out. The lowest friction coefficients were observed for triboconditioning with a doped material (tribofilm) on the finished surface.

Keywords: Finishing; Triboconditioning; Abrasive; Grinding; Powder metallurgy; Gear; Surface integrity; Surface modification; Tribology; Friction

1. Introduction

Powder metallurgy (PM) is a precision material-conversion process used to produce near net shape components with lower manufacturing costs, particularly for mass production. Recent advancements in densification techniques have improved the process quality and capability and expanded the utilization of PM gears in automotive gearboxes of both passenger cars and heavy-duty trucks [1]. This is because the densification enhances the mechanical properties of lightweight PM gears equivalent to conventionally manufactured gears. Additionally, a higher damping capacity of PM materials leads to a quieter transmission, which is a key advantage for electric powertrains. On the other hand, the performance of gears, such as efficiency, pitting resistance and noise vibrations and harshness (NVH) strongly relies on the finishing [2,3] which is the final step in the manufacture of gears that requires the highest quality in terms of form, accuracy, and surface integrity. Many studies have emphasized the influence of surface asperities on the performance of gears and reported that the smoother surface enhances the micropitting resistance [4,5] yields a higher mesh efficiency [6] and minimizes the NVH behavior [2]. Finishing of gears employs a multitude of readily available industrial solutions from skiving [7], grinding, to abrasive fine finishing (such as grind-finishing, honing, mass finishing) [8]. While these technologies primarily improve the surface integrity by a mechanical action, it is well known that the addition of a

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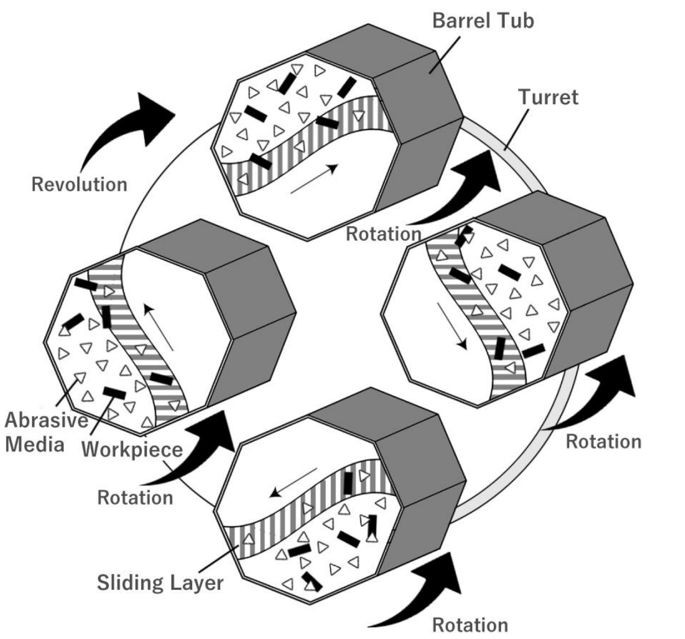

Fig.1. Schematic illustration of centrifugal barrel finishing (Copyright(c)2019 Tipton Corp., Japan)

chemical agent to the process can improve material removal due to a mechano-chemical effect, resulting in an isotropic surface texture and a high material-ratio curve, such as in chemically enhanced vibratory finishing [9]. In this study, the latest advancement of mechano-chemical finishing called Triboconditioning® is presented, designed to fine finish PM gears. As a first step, however, a proof-of-concept study/application is carried out on cylindrical workpiece specimens made of PM gear material with the intention to understand the process capabilities and the resulting surface integrity characteristics.

2. Triboconditioning

Triboconditioning® is a mechano-chemical finishing process for improving the tribological properties of precision components trademarked and commercialized by Tribonex AB in Sweden. The technology combines the elements of mechanical machining with abrasives (e.g., mass finishing) with a chemical deposition of a solid lubricant tribofilm [10]. This technology proved capable of finishing a variety of precision components and resulting in a consistently robust plateaued surface texture with reduced gradient roughness and increasingly negative skewness, next to the presence of doping elements from the process fluid [11]. Triboconditioning® is not limited to specific abrasive fine finishing, as it can be implemented by several different technologies, such as vibratory finishing (using bowl or tub) or centrifugal barrel finishing. In vibratory finishing, the dominant force in the contact between the abrasive media and the workpiece occurs in a normal direction and depends on the hydrostatic pressure (vibration), whereas the cutting speed predominantly depends on the impact velocity of the media [12]. The understanding of pressure and kinematics in vibratory finishing is important, as the Triboconditioning® requires a certain minimum pressure and velocity to cause plastic deformation and to generate sufficient frictional energy to trigger the tribo reaction. In centrifugal barrel finishing, several individual barrels are mounted on a turret. The turret is rotated in one direction, while the barrels rotate in the opposite direction. Such a kinematics (see Fig. 1) creates a relatively high hydrostatic pressure needed for material removal [13]. As mentioned above, Triboconditioning® is not limited to vibratory finishing or centrifugal barrel finishing. The technology could be implemented in other mass finishing operations, such as drag (spindle) finishing [14], where the components are clamped to a workpiece holder. The holder is then dragged in a circular motion through a bowl containing a stationary abrasive media. Here the workpiece is given a translatory (drag) and optionally a rotary (spindle) motion and has hence a more controlled kinematics. In the case of a vibrating bowl, the abrasive media would move in the opposite direction of the dragged workpiece, which is characteristic of stream finishing [15].

3. Materials and experimental work

Powder metallurgy (PM) cylindrical specimens with dimensions of 9.5 mm in diameter and 55 mm in length and made of Astaloy® CrA (Fe-1.8% Cr) were used as test specimens.

Table 1. Sample specification and mass-finishing technologies

S. No	Treatment platform	Media type	Test Designation
1	Vibratory tub finishing	Non-abrasive 1	V-NA1
2	Vibratory tub finishing	Abrasive 1	V-A1
3	Centrifugal barrel finishing (single step)	Abrasive 2	C-A2
4	Centrifugal barrel finishing (two steps)	Abrasive 2 + Non-abrasive 2	CC-A2NA2
5	Centrifugal barrel + Vibratory finishing	Abrasive 2 + Non-abrasive 2	CV-A2NA2

The specimens were compacted to 7.2 g/cm^3 and sintered at 1120°C for 30 min in an atmosphere of 90% N_2 and 10% H_2. These specimens were then case-hardened through a low pressure carburization (LPC) process at 965 °C under 10 mbar of vacuum using ECM-Fulgra Duo furnace. During LPC process, C_2H_2/N_2 and N_2 gas is used for the boost and the diffusion step, respectively. This is followed by high pressure gas quenching (HPGQ) using 20 bar of N_2. After LPC a subsequent tempering was performed at 200°C for 60 min in air. A case depth of about 1 mm and surface micro hardness of 760 $HV_{0.1}$ was obtained with the applied hardening treatment. After casehardening, the specimens were ground using cylindrical OD grinding machine, a conventional wheel and non-aggressive [16] grinding and dressing conditions, such as standard parameters for gear grinding. After grinding, the specimens were triboconditioned using two different mass finishing processes: (i) vibratory tub finishing and (ii) centrifugal barrel finishing using diverse abrasive media types and chemical compounds. The details of the mass-finishing processes along with their designation used in this study are listed in Table 1. Noteworthy that from here on every sample is referred to by the specific test designation as presented in Table 1.

Unfortunately, due to proprietary concerns, the specification of the abrasive media or chemical compounds used cannot be fully specified in the study. The triboconditioned samples have been evaluated by two different crossed-cylinder friction tests where the sample is rotated against a cylindrical steel probe (made of 100Cr6 bearing steel) to obtain a sliding contact, see experimental set-up in Fig. 2. The applied contact force was 3 N, resulting in the initial Hertzian pressure of 1.2 GPa. Here, a polyalphaolefin-2 (PAO2) oil was delivered to the contact area at the start of the test. Both the applied normal force and the frictional force were measured by using load cells that are attached to the friction probe holder. All tests were performed at room temperature. The first test was performed at a constant rotational speed of 165 rpm (82 mm/s) for 1 h. In the second friction test, the speed was accelerated from zero to 275 rpm (137 mm/s) and then decelerated back to zero, which was done two times over 960 s.

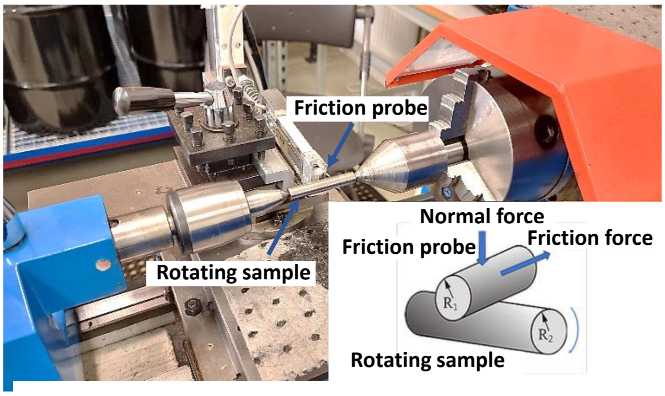

Fig. 2. Crossed cylinder tribocouple configuration used for friction testing.

4. Characterization methods

Surface roughness measurements were performed using a Sensofar S Neox optical interferometry measurement system. Two profile areas were measured for each condition from which the average value of the roughness parameters was obtained. The measured surfaces were around 2 mm x 7 mm and measurements were taken at 10x magnification. The cylindrical form was removed by the software prior to the filtering of the waviness from the roughness. All the data processing, filtering and evaluation were performed according to ISO 25178 standard. The following areal (3D) parameters S_a, S_v, and S_{10z} were considered for the surface analysis.

The microstructure and topographical characteristics were characterized by a LEO Gemini 1550 high-resolution scanning electron microscope (SEM) equipped with a field emission gun. The imaging was done at an acceleration voltage of 5 kV.

The residual stresses were measured using the Xstress 3000G2R instrument using Cr-Kα source. A collimator with a diameter of 1.5 mm was used for irradiating X-rays. The lattice deformation for the {211} α-Fe peak was measured, and the stresses were determined by using the standard $\sin^2(\psi)$ technique with five equi-$\sin^2(\psi)$ tilts ranging from -40/+40°.

5. Results and discussions

The surface roughness values of ground and triboconditioned samples are presented in Fig. 3. It is evident from the graph that the S_a (average height of the selected area) which is the most common roughness parameter used for base line comparison is approximately 0.2 µm for all finished surfaces irrespective of the process applied. This is nearly a 50% drop in comparison to the initial S_a roughness of the ground surface which was about 0.5 µm. Although it is not a significant difference, CC-A2NA2 yielded the lowest S_a value (0.17 µm) among the applied finishing treatments. Interestingly, the maximum valley depth, i.e., the S_V parameter of finished surfaces, remains similar to the ground surface emphasizing that some of the valleys are still present and are not completely removed by the finishing processes. However, the S_{10Z} parameter, which represents the summation of the average of the heights of the five peaks and valleys also decreased after finishing. Overall, the mechano-chemical finishing was able to remove the peaks of the ground surface, while some valleys still exist.

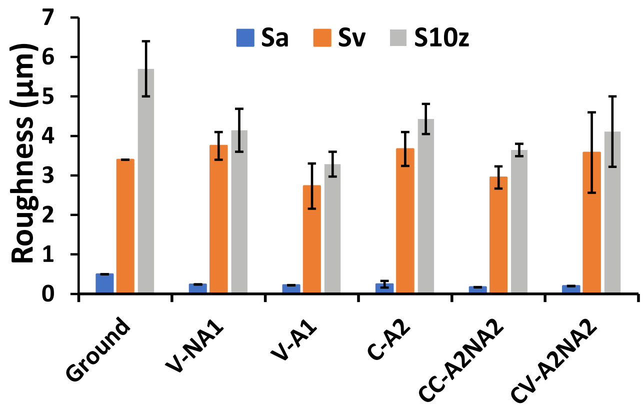

Fig. 3. Surface roughness values of the ground surface and after different mechano-chemical finishing processes.

In addition to the surface roughness measurements, the topographical characteristics were also observed at high magnification for a better understanding of the microscopic surface features. This is important because micro-topographical features generated by finishing processes determine the real contact area and, hence, dictate the tribological conditions and contact fatigue. Surface topographies of specimens from selected finishing processes are presented in Fig. 4. Here, the roughness lay of the ground surface (see Fig. 4a) is oriented parallel to the circumferential direction and is uniform all over the surface. It consists of adjacent peaks and valleys with irregular surface asperities. The deformation of these asperities and associated the microstructural changes are known to be associated with micropitting phenomena in ground gears [17]. Hence, eliminating these asperities has become a prime motive of the post-grinding, abrasive fine-finishing processes. The surfaces appeared similar for both the V-NA1 and V-A1 treatments. As seen in Fig. 4b, the V-A1 process plastically deformed the surface peaks by ploughing and rubbing of the abrasive media which resulted in covering most of the adjacent valleys. However, some valleys still exist and are visible. Additionally, randomly oriented abrasion marks were also present in the surface along with a small percentage of surface asperities (observation based on several micrographs).

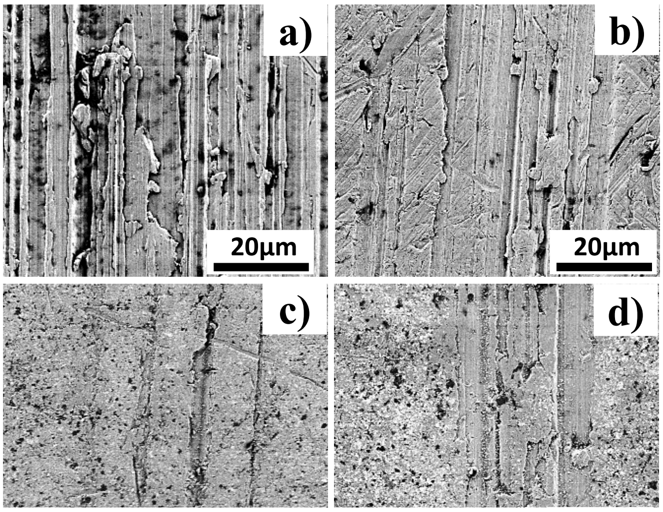

Fig. 4. Surface topography after (a) grinding (b) V-A1 (c) CC-A2NA2 and (d) CV-A2NA2 triboconditioning.

The surface appearance of C-A2, CC-A2NA2, and CV-A2NA2 is similar, which is expected because these specimens were first finished by centrifugal-barrel finishing which produces a base surface. No surface asperities or lay related to abrasive processing were observed for these finishing treatments. However, some valleys are still visible but not to the extent observed when using the other two treatments (V-NA1 and V-A1). The most distinctive feature, however, is the presence of doping materials on the surface. Both the dark and bright contrast doping materials can be observed on CC-A2NA2 and CV-A2NA2 triboconditioned surfaces. For the sake of comparison, a higher fraction of elements is present on the CV-A2NA2 surface. Meanwhile, in the case of C-A2, only dark particles are visible. Chemical analysis of these surfaces is not yet available.

The microstructure of the case-hardened layer typically consists of martensite and a small percentage of retained austenite. The cross-section analysis revealed no surface deformation for any of the finished specimens. Residual stresses play an influential role in enhancing the fatigue life of gears. Hence, it is important to understand the stress levels obtained after different finishing processes. The surface stress levels in the as-ground specimen and after different finishing treatments are presented in Fig. 5. It is evident from the graph that the stresses in both directions were compressive for all the conditions. However, the compressive surface stresses induced by grinding in the axial direction were more than double those in the circumferential direction. This is because in OD cylindrical grinding, the material is cut by shearing in a circumferential direction. This is typical of a grinding process, which commonly generates unequal biaxial stresses particularly in case-carburized (steels) gears [18]. After grinding, the compressive stresses increased for all mechano-chemical treatments applied. However, the increase was higher for centrifugal barrel finishing processes in comparison to vibratory tub finishing methods. Moreover, for all the applied finishing treatments after grinding, a biaxial stress state was achieved, meaning that the difference in stress levels between the directions was eliminated.

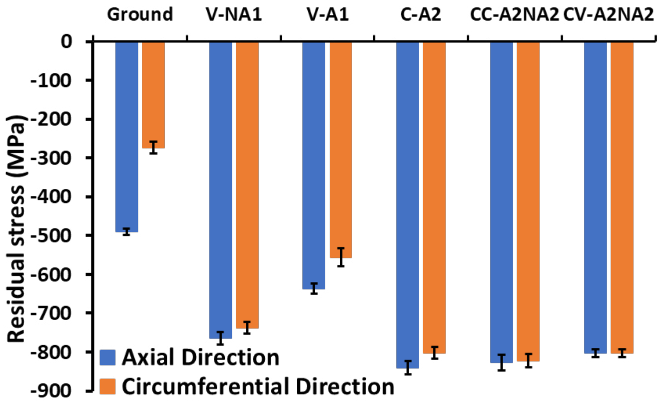

Fig. 5. Surface residual stresses of ground and triboconditioned samples in both circumferential and axial directions.

These results are consistent with the study of Mallipeddi et al. [19] that investigated the effects of manufacturing methods on the surface integrity of carburized gears. An increase in compressive residual stresses and equal stress levels between directions were observed for honed and isotropic (mass) finished gears. The investigation further revealed a decrease in the content of retained austenite due to higher compressive stresses, which typically develop because of the volume expansion that takes place during the transformation of retained austenite to deformation-induced martensite. It is noteworthy that the transformation of retained austenite is confined to the outermost layers of approximately 5 µm. Similarly, in the present study, mechanical load/hydrostatic pressure applied on surfaces might reduce the retained austenite content and therefore compressive stresses were increased after triboconditioning. However, a detailed characterization of the retained austenite content needs to be performed to validate the above hypothesis.

Another critical feature is that the effect of grinding and abrasive fine finishing on induced residual stresses is confined to the outer most layers [19,20]. Therefore, it is reasonable to assume that the applied triboconditioning in this study possesses similar characteristics and is limited to the workpiece surface. Due to the limitation of the size of the cylindrical samples, residual stress depth profiles were not characterized and this needs to be clarified in future studies.

The surface topography is not a static indicator of the functional performance of a component and evolves during its life cycle, especially during the initial cycles (usually referred to as the running-in period). Running-in significantly influences the friction coefficient and, therefore, the efficiency.

Importantly, the change in the friction coefficient also varies depending upon the finishing method applied. For example, Andersson et al. [21] studied and compared the film thickness (λ) and friction coefficient (μ) of ground and isotropic finished gears during the running-in process. They reported higher λ values and lower μ values for isotropic finished gears compared to the ground gears. Overall, a higher mesh efficiency was recorded for isotropic finished gears compared to ground gears. Also, here in this study, the tribological performance of mechano-chemical processes with respect to ground specimens was evaluated using the crossed-cylinder friction test. Friction data resulting from this test is presented in Fig. 6.

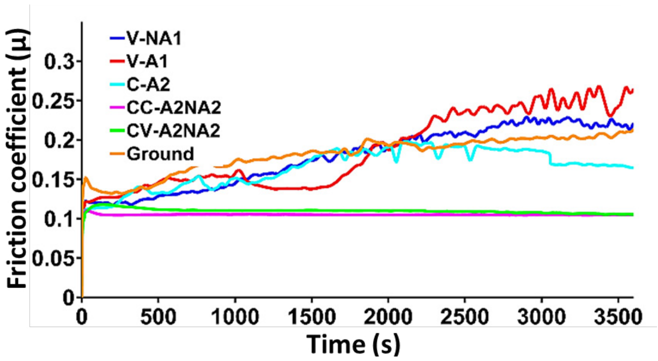

Fig. 6. Friction coefficient as a function of time for constant speed friction test.

It is evident from the graph that specimens treated with CC-A2NA2 and CV-A2NA2 processes produced a lower and constant coefficient of friction (μ) throughout the test period, while for the rest of the treated specimens, the μ value increased along with the test period. A similar behaviour can be observed for the reference ground sample. The increase of the μ value over time for all the specimens except CC-A2NA2 and CV-A2NA2, and the transition in friction coefficient of V-A1 at around 1750 s, can be explained by accumulation of wear particles in the contact zone during the test. This also indicate a very limited wear of CC-A2NA2 and CV-A2NA2 processed specimens. Furthermore, during the initial period the μ value was higher for ground specimens compared to any triboconditioned specimens. This behaviour can be attributed to the high incidence of asperity contacts between the mating surfaces. Interestingly, even though the surface roughness (in particular the S_a values) is similar, there is a large variation in the frictional behaviour between the triboconditioned samples. The reason for the lower μ values for the CC-A2NA2 and CV-A2NA2 specimens can be attributed to the presence of doping materials and the associated tribofilm, see Fig. 4c and 4d.

The results of the acceleration friction test are presented in Fig. 7. The first ramp cycle of the test is not useful due to the development of the mating spot – starting with a highly loaded point contact in the beginning, rapidly expanding to a normal wear ellipsoid in the end. In the second ramp cycle, the contact pressure remains reasonably constant. The reference ground specimen along with the triboconditioned samples V-NA1, V-A1 and C-A2 demonstrate a much higher friction close to the zero speed. This indicates an early lubricant film breakdown in the high load/low speed limit (referring to the boundary lubrication regime on the Stribeck curve). This suggests that the one-step process fails to provide the optimal surface with enhanced tribo-layer properties needed to minimize the friction. A two-step process combining abrasive and non-abrasive media types i.e., samples CC-A2NA2 and CV-A2NA2 offers greater flexibility and has allowed us to produce the desired surface roughness. Moreover, the presence of doping materials and the associated tribofilm managed to keep the lubricant film intact in the high load/low speed limit. Overall, irrespective of the friction test performed, samples CC-A2NA2 and CV-A2NA2 produced lower coefficient of friction which indicates the possibility of yielding higher efficiency.

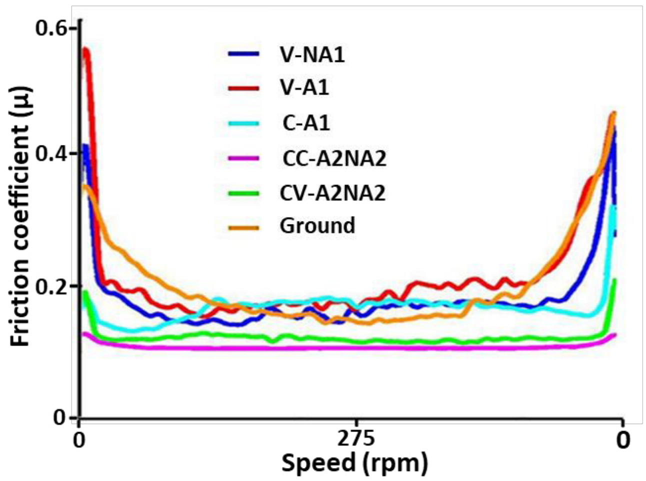

Fig. 7. Friction coefficient as a function of speed for speed acceleration friction test.

6. Conclusions

The effects of mechano-chemical finishing after grinding on the surface integrity are often not systematically studied. Therefore, an investigation into the effects of grinding and triboconditioning on the surface roughness, microstructure, and residual stresses was carried out. The concerned triboconditioning featured vibratory tub finishing and centrifugal barrel finishing operations. The specific knowledge gained from the results is as follows:

- The triboconditioning treatment reduced the roughness S_a of ground specimens up to 50%. This was the case for all the five different mechano-chemical strategies applied.
- All mass finishing operations are capable of reducing the surface roughness after grinding. However, only a specific triboconditioning strategy (CC-A2NA2 and CV-A2NA2) results in doping of the material onto the surface resulting in the reduced friction.
- Similarly, mass finishing increases the level of compressive residual stresses on the triboconditioned surfaces. The highest compressive stresses (-827 MPa) were achieved with centrifugal barrel finishing.
- The lowest and constant coefficient of friction (~0.1) was obtained for CC-A2NA2 and CV-A2NA2 finishing operations.

The results of the presented proof of concept study demonstrate the potential and feasibility of triboconditioning for real powder metallurgy gear applications.

Acknowledgements

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