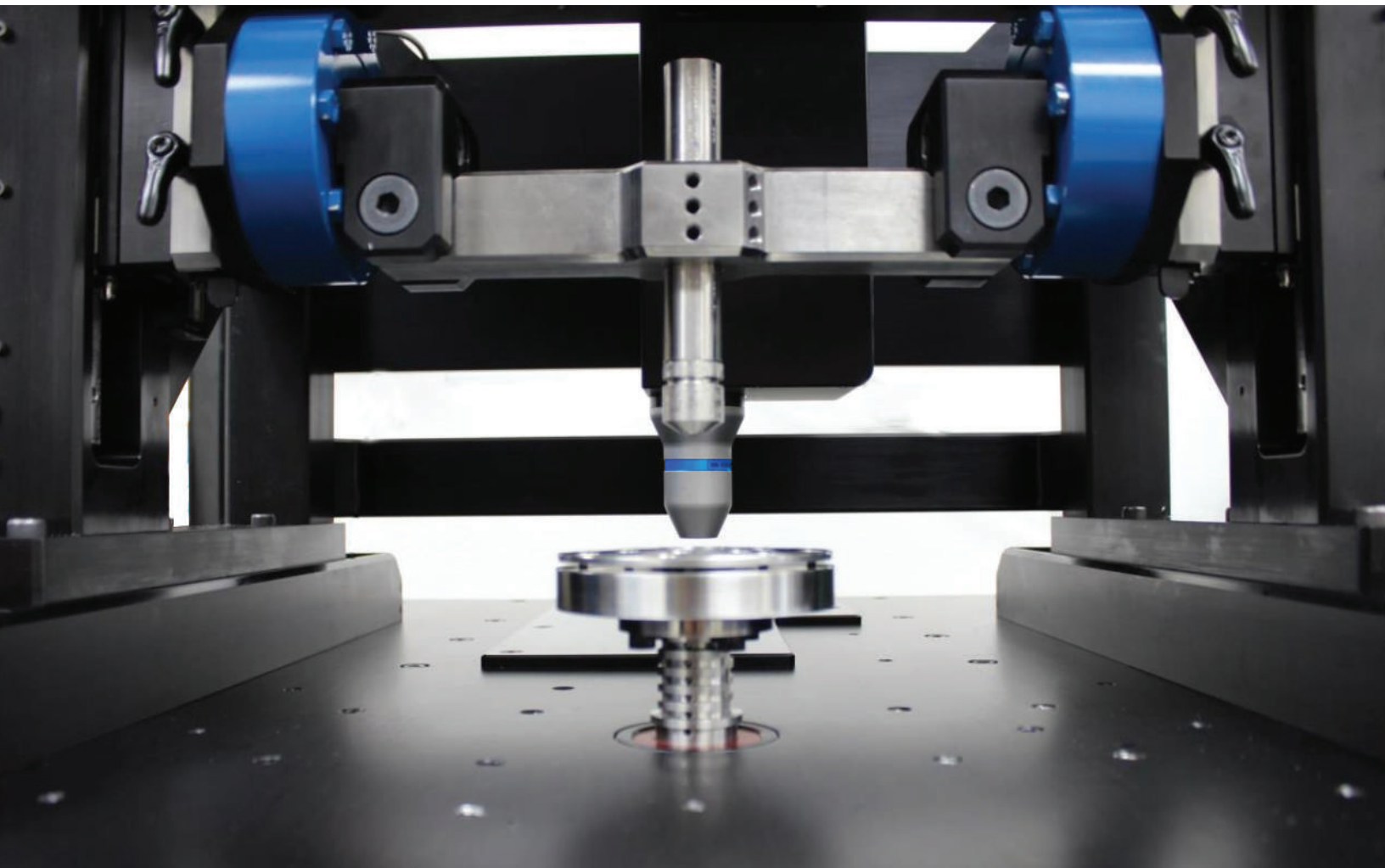


DYNAMIC LOAD TRIBOLOGY



Prepared by

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Introduction

Wear takes place in virtually every industrial sector and imposes costs of ~0.75% of the GDP¹. Tribology research is vital in improving production efficiency, application performance, as well as conservation of material, energy, and the environment. Vibration and oscillation inevitably occur in a wide range of tribological applications. Excessive external vibration accelerates the wear process and reduces service performance which leads to catastrophic failures to the mechanical parts.

Conventional dead load tribometers apply normal loads by mass weights. Such a loading technique not only limits the loading options to a constant load, but it also creates intense uncontrolled vibrations at high loads and speeds leading to limited and inconsistent wear behavior assessments. A reliable evaluation of the effect of controlled oscillation on the wear behavior of materials is desirable for R&D and QC in different industrial applications.

Nanovea's groundbreaking high load tribometer has a maximum load capacity of 2000 N with a dynamic load tribology system. The advanced pneumatic compressed air loading system enables users to evaluate the tribological behavior of a material under high normal loads with the advantage of damping undesired vibration created during the wear process. Therefore, the load is measured directly with no need for buffer springs used in older designs. A parallel electromagnet oscillating loading module applies well-controlled oscillation of desired amplitude up to 20 N and frequency up to 150 Hz.

Friction is measured with high accuracy directly from the side force applied to the upper holder. The displacement is monitored in situ, providing insight into the evolution of the wear behavior of the test samples. The wear test under controlled oscillation loading can also be performed in corrosion, high temperature, humidity, and lubrication environments to simulate the real work conditions for the tribological applications. An integrated high-speed non-contact profilometer automatically measures the wear track morphology and wear volume in a few seconds.

MEASUREMENT OBJECTIVE

In this study, we showcase the capacity of the Nanovea T2000 Dynamic Load Tribometer in studying the tribological behavior of different coating and metal samples under controlled oscillation loading conditions.

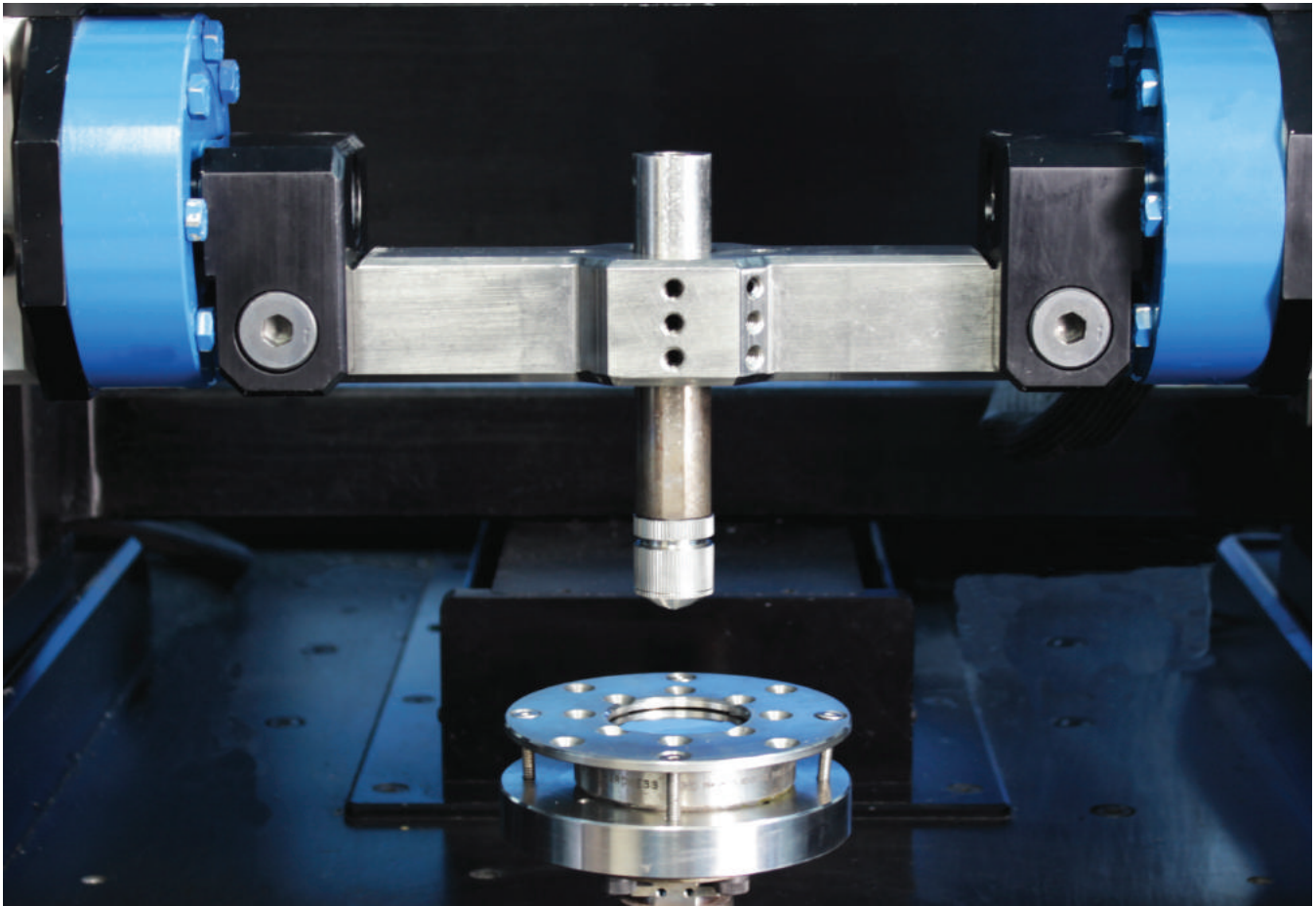


Figure 1: Close-up view of the Dynamic Load Tribometer.

TEST PROCEDURE

The tribological behavior, e.g. coefficient of friction, COF, and wear resistance of a 300 µm thick wear-resistant coating was assessed and compared by the Nanovea T2000 Tribometer with a conventional dead load tribometer using a pin on disk setup following ASTM G99².

Separate Cu and TiN coated samples against a 6 mm Al₂O₃ ball under controlled oscillation were evaluated by Dynamic Load Mode of the Nanovea T2000 Tribometer.

The test parameters are summarized in Table 1.

The integrated 3D profilometer equipped with a line sensor automatically scans the wear track after the tests, providing the most accurate wear volume measurement in seconds.

Test parameters	Value
Height Parameters	
Normal force	100N
Rotational speed	100RPM
Duration of test	3000 cycles
Radius	10mm
Counter material	10mm Al ₂ O ₃ ball
On Cu:	
Normal force	50N
Oscillation amplitude	0N, 5N
Oscillation frequency	100Hz
Rotational speed	500RPM
Duration of test	500 cycles
Radius	3mm
Counter Material	6mm Al ₂ O ₃ ball
On TiN Coating:	
Normal force	60N
Oscillation amplitude	0N, 5N, and 10N
Oscillation frequency	100Hz
Rotational speed	500RPM
Duration of test	500 cycles
Radius	3 mm
Counter material	6mm Al ₂ O ₃ ball

Table 1: Test parameters of the wear measurements.

RESULTS AND DISCUSSION

Pneumatic loading system vs. Dead load system

The tribological behavior of a wear-resistant coating using Nanovea T2000 Tribometer is compared to a conventional dead load (DL) tribometer. The evolution of the COF of the coating are shown in Fig. 2. We observe the coating exhibits a comparable COF value of ~ 0.6 during the wear test. However, the 20 cross-section profiles at different locations of the wear track in Fig. 3 indicate that the coating experienced much more severe wear under the dead load system.

Intense vibrations were generated by the wear process of the dead load system at high load and speed. The massive concentrated pressure at the contact face combined with a high sliding speed creates substantial weight and structure vibration leading to accelerated wear. The conventional dead load tribometer applies load using mass weights. This method is reliable at lower contact loads under mild wear conditions; however, under aggressive wear conditions at higher loads and speeds, the significant vibration causes the weights to bounce repeatedly, resulting in an uneven wear track causing unreliable tribological evaluation. The calculated wear rate is $8.0 \pm 2.4 \times 10^{-4} \text{ mm}^3/\text{N m}$, showing a high wear rate and large standard deviation.

The Nanovea T2000 tribometer is designed with a dynamic control loading system to dampen the oscillations. It applies the normal load with compressed air which minimizes undesired vibration created during the wear process. In addition, active closed loop loading control ensures a constant load is applied throughout the wear test and the stylus follows the depth change of the wear track. A significantly more consistent wear track profile is measured as shown in Fig. 3a, resulting in a low wear rate of $3.4 \pm 0.5 \times 10^{-4} \text{ mm}^3/\text{N m}$.

The wear track analysis shown in Fig. 4 confirms the wear test performed by the pneumatic compressed air loading system of the Nanovea T2000 Tribometer creates a smoother and more consistent wear track compared to the conventional dead load tribometer. In addition, the Nanovea T2000 tribometer measures stylus displacement during the wear process providing further insight into the progress of the wear behavior in situ.

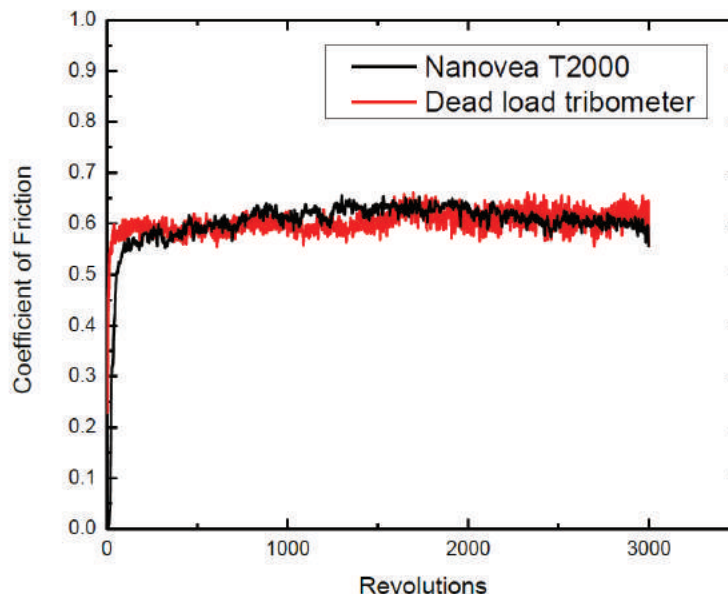
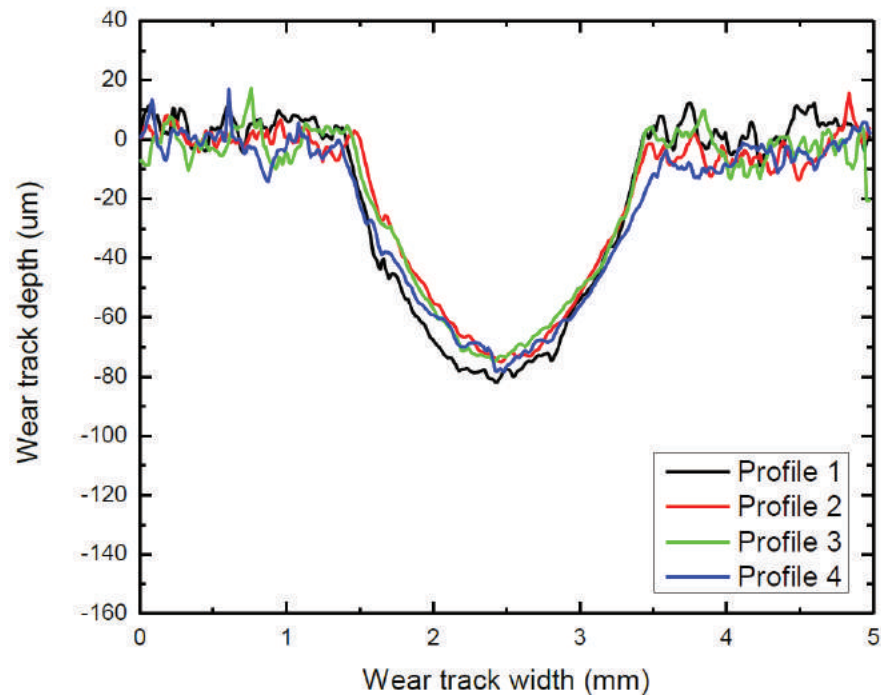


Figure 2: The COF of the coating tested by Nanovea T2000 and dead load tribometer.

(a) Cross-section wear track profiles by Nanovea T2000



(b) Cross-section wear track profiles by conventional dead load tribometers

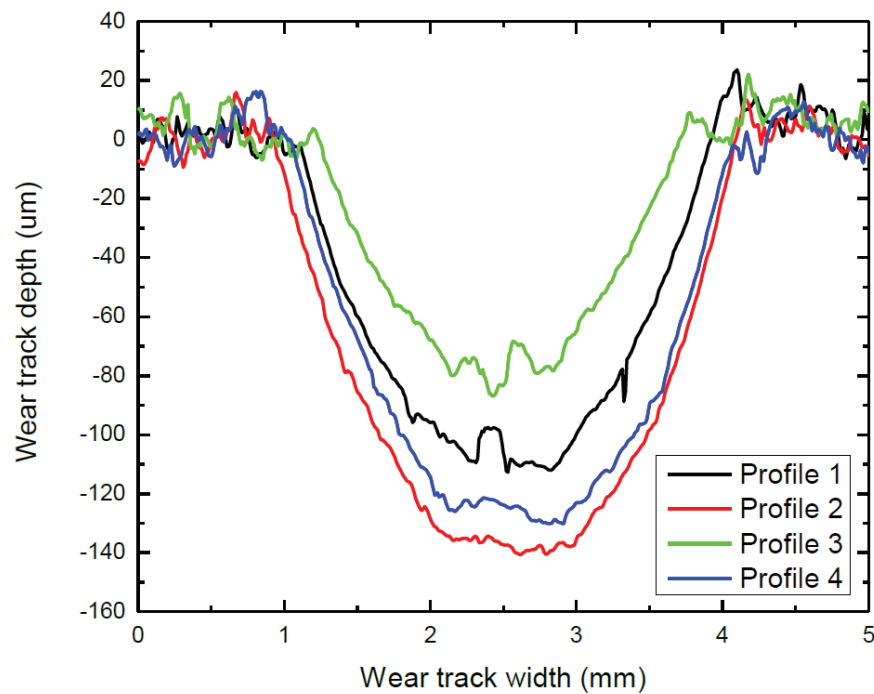
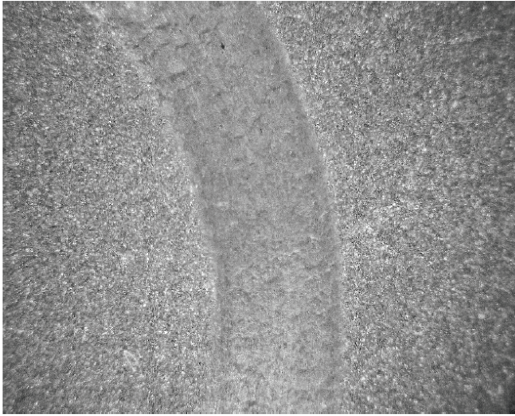


Figure 3: Cross-section wear track profiles by (a) Nanovea T2000 and (b) conventional dead load tribometer.

(a) Wear track by Nanovea T2000-Location 1:



(b) Wear track by Nanovea T2000-Location 2:



(c) Wear track by DL tribometer-Location 1:



(d) Wear track by DL tribometer-Location 2:

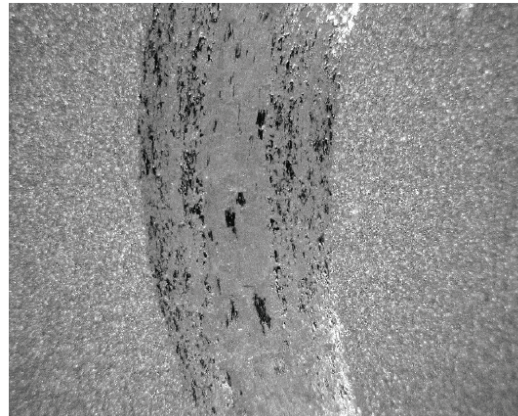


Figure 4: Wear tracks under the optical microscope.

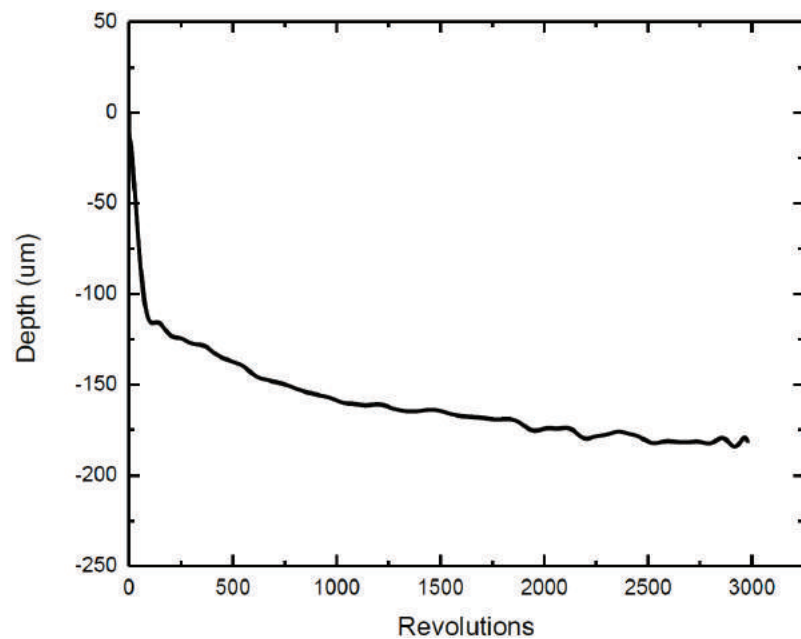


Figure 5: T2000, Evolution of the depth during the wear test.

Controlled Oscillation on Wear of the Cu sample

The parallel oscillating loading electromagnet module of the Nanovea T2000 Tribometer enables users to investigate the effect of controlled amplitude and frequency oscillations on the wear behavior of materials. The COF of the Cu samples is recorded in situ as shown in Fig. 6. The Cu sample exhibits a constant COF of ~ 0.3 during the first 330-revolution measurement, signifying the formation of a stable contact at the interface and relatively smooth wear track. As the wear test continues, the variation of the COF indicates a change in the wear mechanism. In comparison, the wear tests under a 5 N amplitude-controlled oscillation at 50 N exhibits a different wear behavior: the COF increases promptly at the beginning of the wear process, and shows significant variation throughout the wear test. Such behavior of COF indicates that the imposed oscillation in the normal load plays a role in the unstable sliding state at the contact.

Fig. 7 compares the wear track morphology measured by the integrated non-contact optical profilometer. It can be observed that the Cu sample under a controlled oscillation amplitude of 5 N exhibits a much larger wear track with a volume of $1.35 \times 10^9 \mu\text{m}^3$, compared to $5.03 \times 10^8 \mu\text{m}^3$ under no imposed oscillation. The controlled oscillation significantly accelerates the wear rate by a factor of ~ 2.7 , showing the critical effect of oscillation on wear behavior.

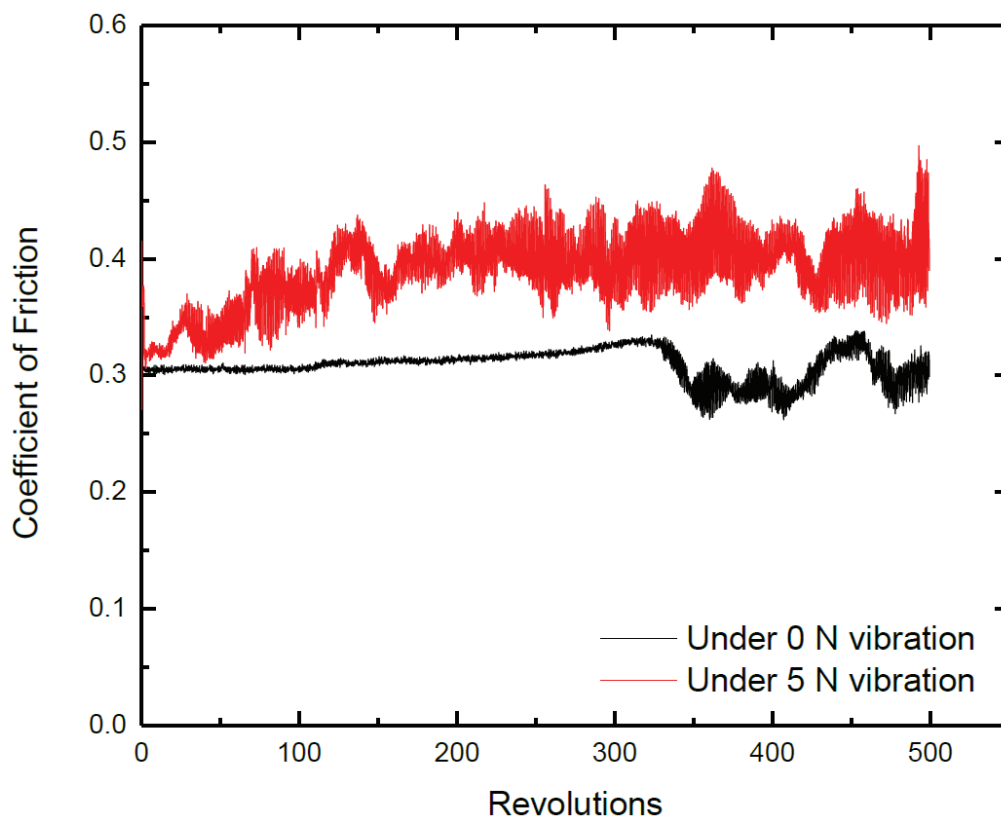


Figure 6: Coefficient of friction of Cu sample during pin-on-disk tests under the oscillation of 0 and 5 N amplitude.

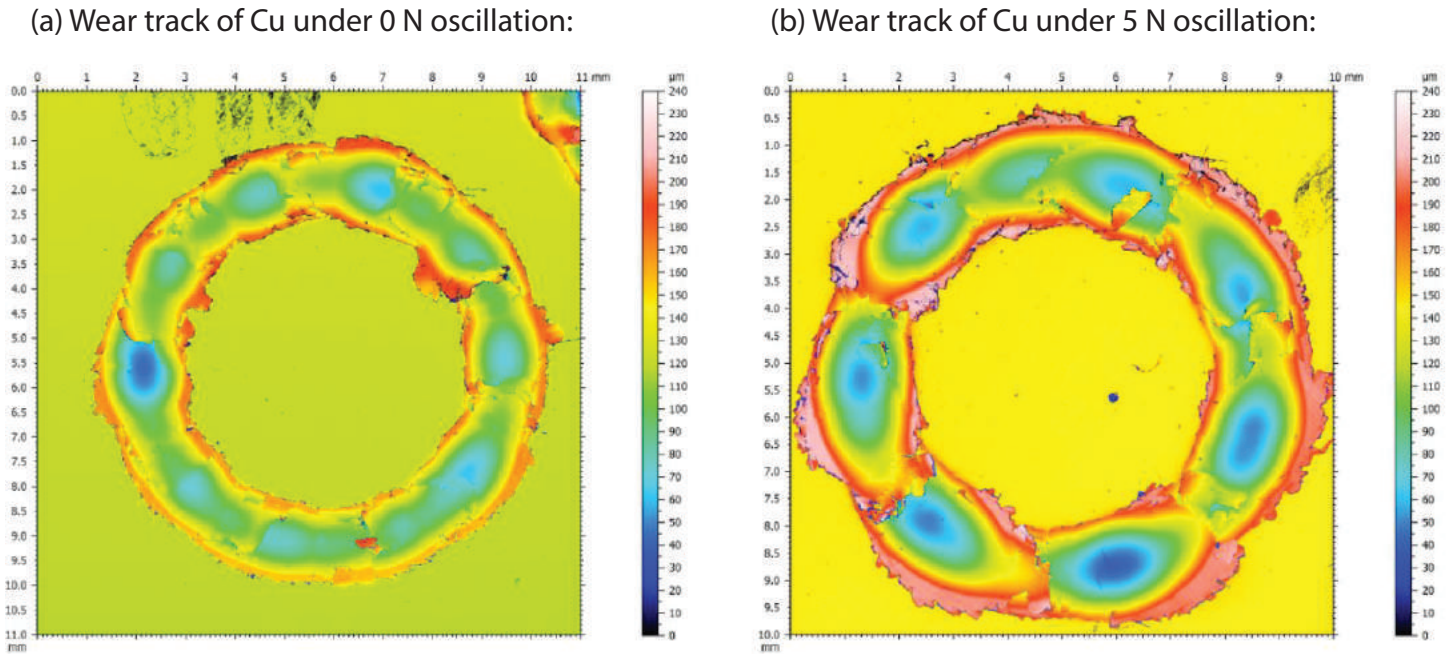


Figure 7: Wear track of Cu sample after the pin-on-disk tests under the oscillation of 0 and 5 N amplitude.

Controlled Oscillation on Wear of the TiN Coating

The COF and wear tracks of the TiN coating sample are shown in Fig. 8. The TiN coating exhibits significantly different wear behaviors under oscillation as indicated by the evolution of COF during the tests. The TiN coating shows a constant COF of ~ 0.3 following the run-in period at the beginning of the wear test, due to the stable sliding contact at the interface between the TiN coating and the Al_2O_3 ball. However, when the TiN coating starts to fail, the Al_2O_3 ball penetrates through the coating and slides against the fresh steel substrate underneath. A significant amount of hard TiN coating debris is generated in the wear track at the same time, turning a stable two-body sliding wear into three-body abrasion wear. Such a change of the material couple characteristics leads to the increased variations in the evolution of COF. The imposed 5 N and 10 N oscillation accelerates the TiN coating failure from ~ 400 revolutions to below 100 revolutions. The larger wear tracks on the TiN coating samples after the wear tests under the controlled oscillation is in agreement with such a change in COF.

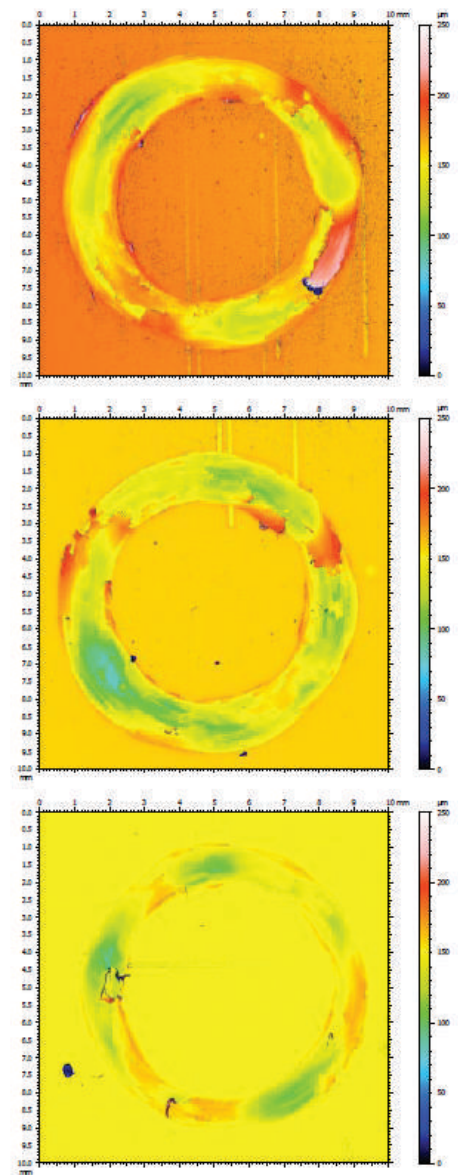
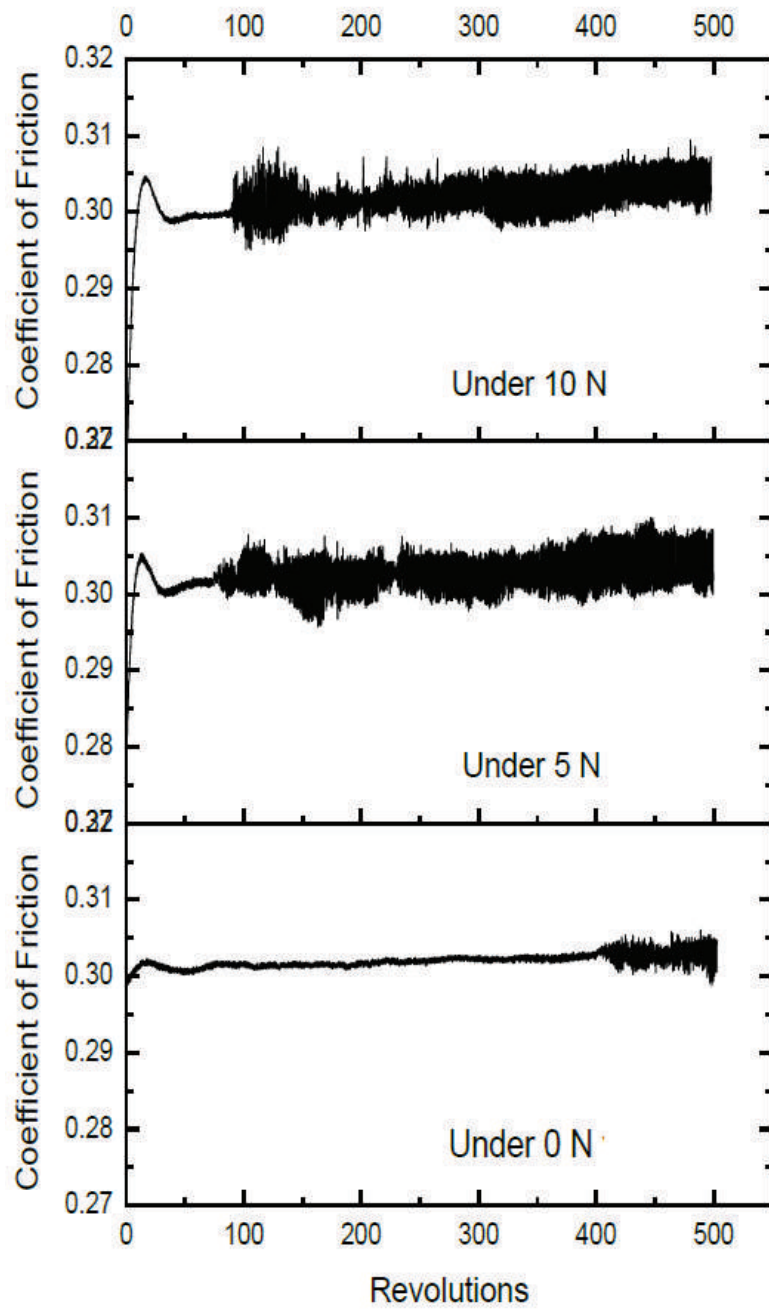
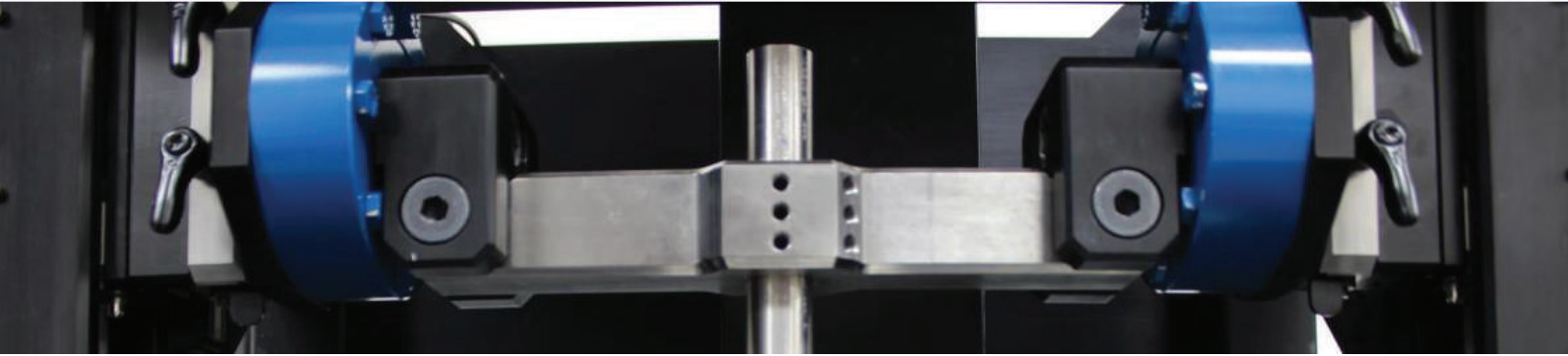


Figure 8: Coefficient of Friction and wear tracks of the TiN coating under the oscillation of 0, 5 and 10 N amplitude



Conclusion

The advanced pneumatic loading system of the Nanovea T2000 Tribometer possesses an intrinsic advantage as a naturally quick vibration damper compared to traditional dead load systems. This technological advantage of pneumatic systems is true compared to load-controlled systems that use a combination of servo motors and springs to apply the load. The technology ensures reliable and better-controlled wear evaluation at high loads as demonstrated in this study. In addition, the active closed loop loading system can change the normal load to a desired value during wear tests to simulate real-life applications seen in brake systems.

Instead of having influence from uncontrolled vibration conditions during tests, we have shown the Nanovea T2000 Dynamic Load Tribometer enables users to quantitatively assess the tribological behaviors of materials under different controlled oscillation conditions. Vibrations play a significant role in the wear behavior of metal and ceramic coating samples.

The parallel electromagnet oscillating loading module provides precisely controlled oscillations at set amplitudes and frequencies, allowing users to simulate the wear process under real-life conditions when environmental vibrations are often an important factor. In the presence of imposed oscillations during wear, both the Cu and the TiN coating samples exhibit substantially increased wear rate. The evolution of the coefficient of friction and stylus displacement measured in situ are important indicators for the performance of the material during the tribological applications. The integrated 3D non-contact profilometer offers a tool to precisely measure the wear volume and analyze the detailed morphology of the wear tracks in seconds, providing more insight into the fundamental understanding of wear mechanism.

The T2000 is equipped with a self-tuned, high-quality, and high torque motor with a 20-bit internal speed and a 16-bit external position encoder. It enables the tribometer to provide an unmatched range of rotational speeds from 0.01 to 5000 rpm that can change in stepwise jumps or at continuous rates. Contrary to systems that use a bottom located torque sensor, the Nanovea Tribometer uses a top located high-precision load cell to accurately and separately measure friction forces.

Nanovea Tribometers offers precise and repeatable wear and friction testing using ISO and ASTM compliant rotative and linear modes (including 4ball, thrust washer, and block on ring tests), with optional high-temperature wear, lubrication and tribo-corrosion modules available in one pre-integrated system. Nanovea T2000's unmatched range is an ideal solution for determining the full range of tribological properties of thin or thick, soft or hard coatings, films, and substrates.

1 JR Davis, Surface Engineering for Corrosion and Wear Resistance, ASM International, 2001.

2 <https://www.astm.org/Standards/G99>

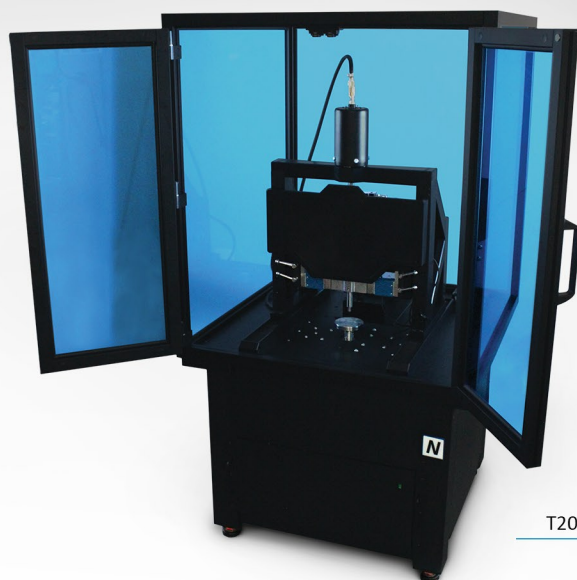
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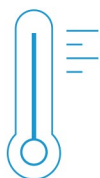


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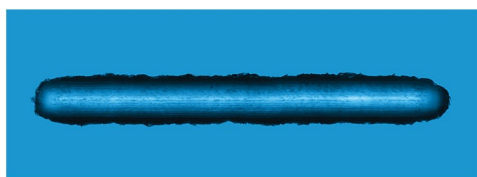
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