Innovative Approaches to Sustainable Materials and Surface Treatments for Household Appliances

POLYMERS AND COMPOSITES LAB
UNIVERSITÀ DEGLI STUDI DI TRENTO

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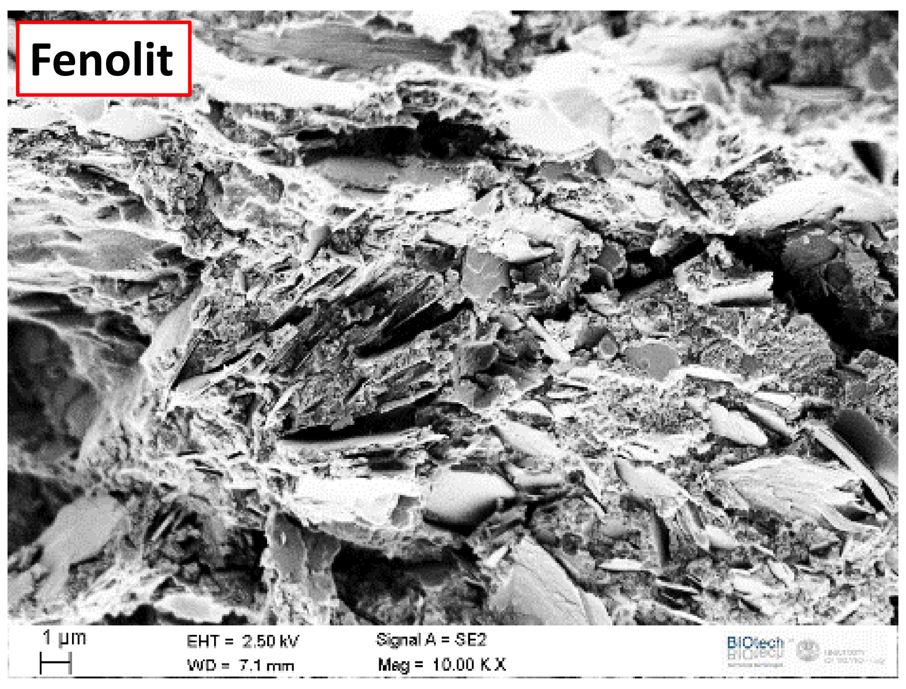
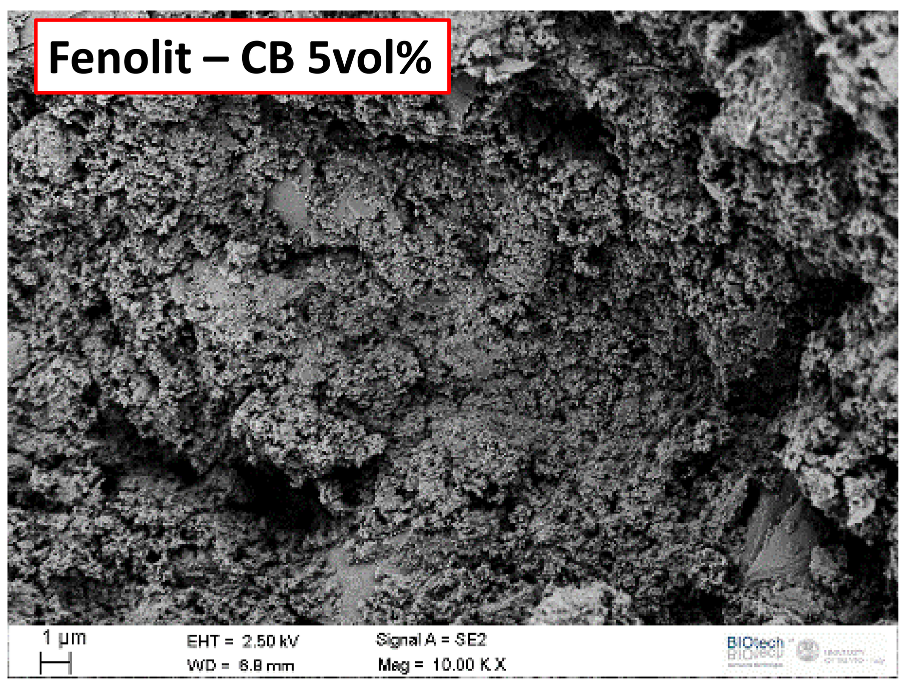
Thermoset plastics, commonly used in household appliance components, are experiencing an annual growth rate exceeding 4% due to their exceptional heat and solvent resistance. These materials, such as epoxy resins and phenol formaldehyde, offer advantages like good mechanical strength and chemical resistance. However, their inherent properties also lead to significant environmental challenges, as thermosets are difficult to recycle due to their irreversible rigidity and strong covalent bonds formed during cross-linking, necessitating the exploration of effective recycling methods. Recycling thermosets presents significant challenges due to their cross-linked structures, which traditionally hinder reprocessing and reintegration into production cycles. However, recent advancements have shown promising pathways to overcome these limitations, thereby supporting circular economy models.

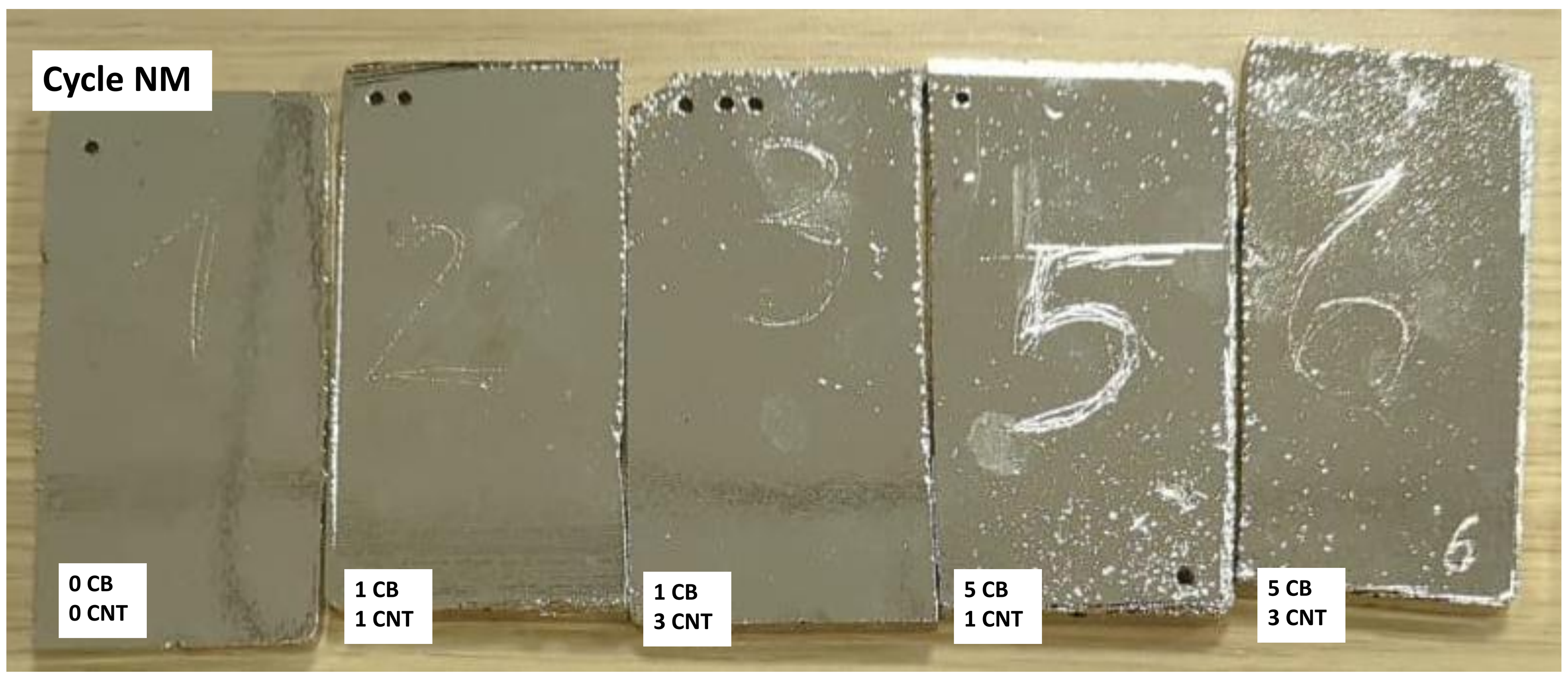
Addressing this, this project aims to redefine the production processes of the industrial partner through a circular economy lens. The project investigates innovative methods for recycling production and post-consumer waste, replacing current thermoset polymers with recyclable thermoplastics, including biopolymers. Furthermore, it explores advanced surface finishing technologies with reduced environmental impact. As part of this initiative, this study focuses on developing a chromium-free surface treatment for phenolic resins, offering an environmentally friendly alternative to traditional plating methods. Conventional electroplating of thermoset polymers typically requires harsh chemical pre-treatments, such as acid etching and electroless nickel deposition, which pose sustainability and safety concerns. In contrast, this work explores a chromium-free, non-electroless approach by incorporating conductive fillers—carbon black, graphene, and carbon nanotubes—directly into the resin matrix.

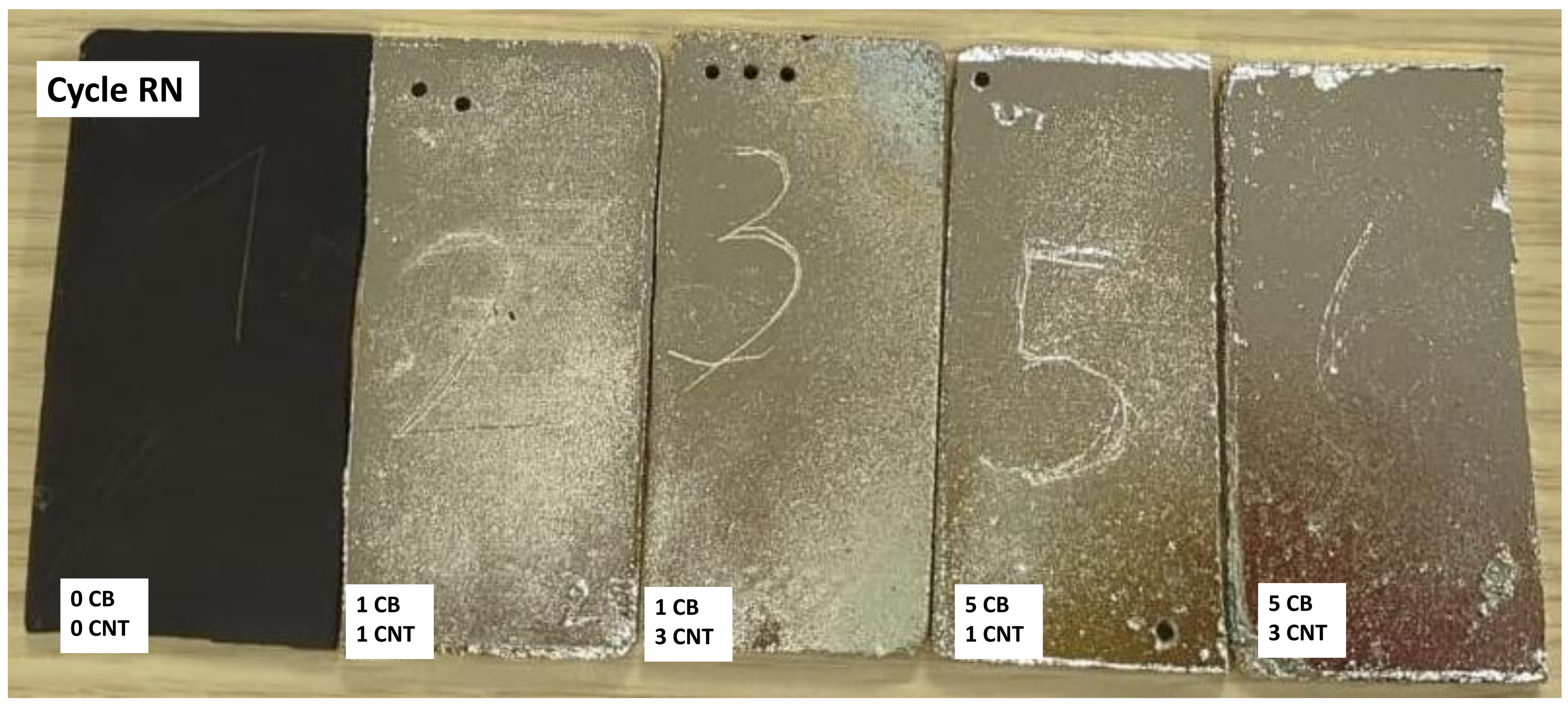


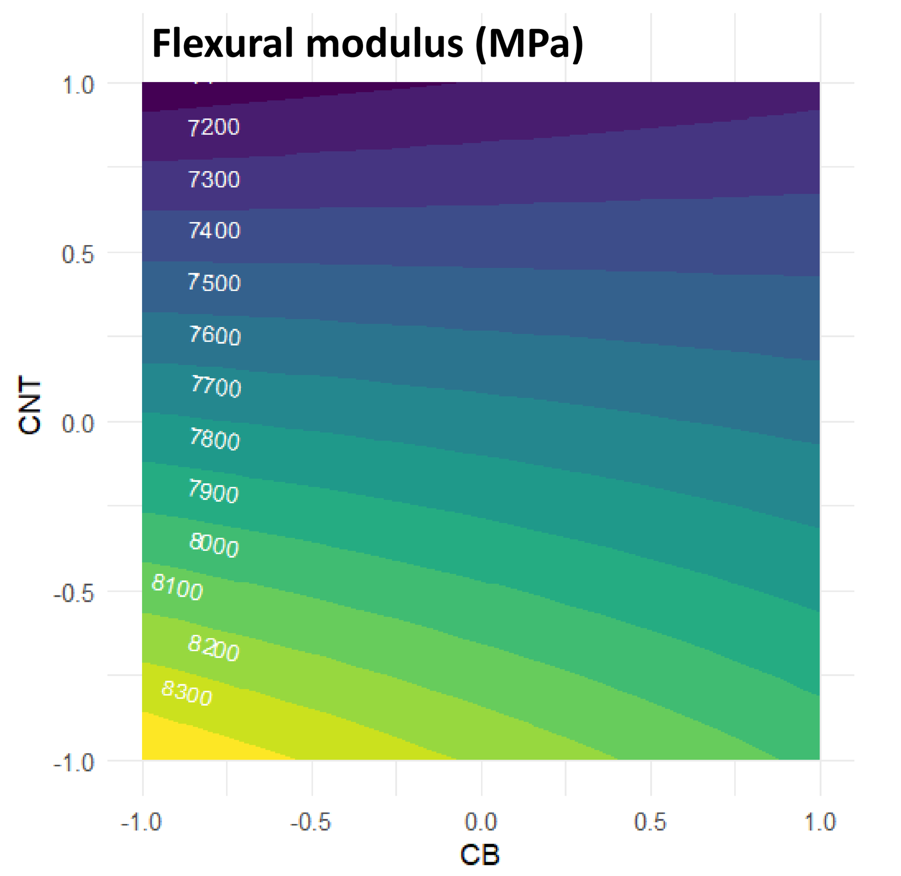


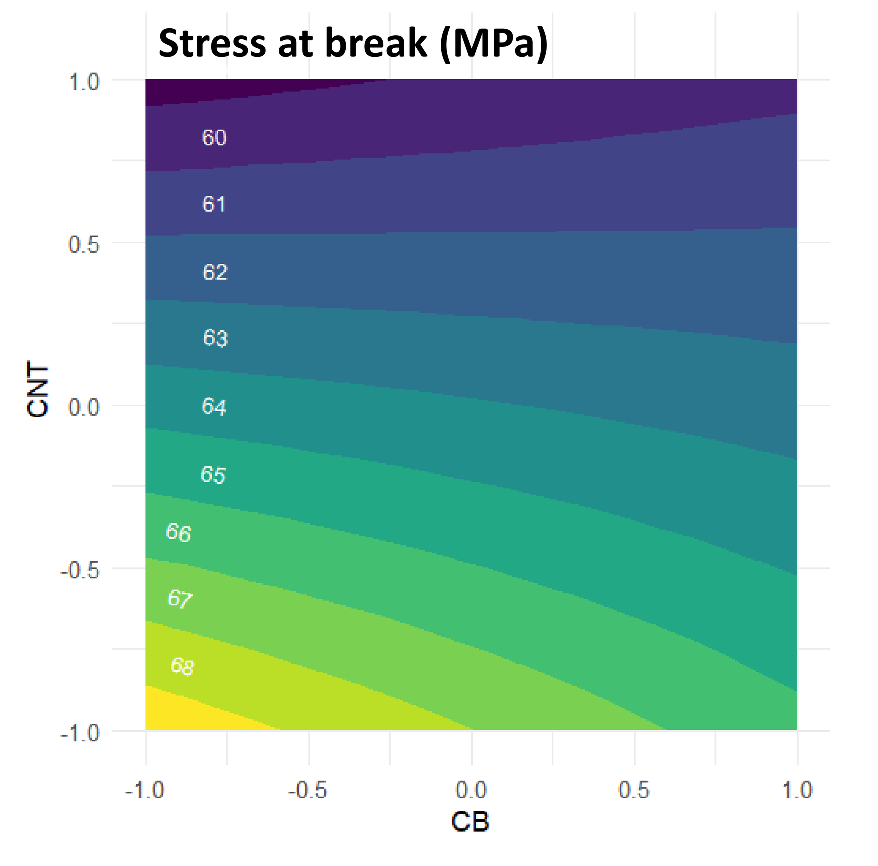
Phenolic resin-based composites were developed by incorporating carbon black (CB) and carbon nanotubes (CNT) as conductive fillers, aiming to enhance the electrical and thermal properties of the base material for sustainable surface treatment applications. Scanning Electron Microscopy (SEM) analysis confirmed a good dispersion of both types of fillers within the polymer matrix, indicating effective integration without significant agglomeration at the investigated concentrations. Based on the experimental results analyzed through Response Surface Methodology (RSM), a nuanced understanding of the composite behavior emerged. The analysis was conducted across filler volume fractions normalized between 0% and 5%. Although the primary objective was to enhance electrical and thermal performance, the mechanical response revealed an inverse trend with increasing filler content. At low to moderate filler contents (up to approximately 3–4% vol.), the composites retained acceptable mechanical integrity while still achieving substantial gains in conductivity. However, beyond 5% vol., not only did the structural cohesion deteriorate, but the material also exhibited insufficient filler aggregation and matrix continuity, preventing the formation of stable parts. These observations emphasize the necessity of a carefully balanced formulation strategy, where conductive enhancement must be weighed against the mechanical performance essential for practical applications in chromium-free surface treatments.
The conventional coating process typically involves multiple chemical steps, including an initial acid bath cleaning, chromium VI-based etching (mordanting), electroless nickel deposition, followed by electroplating with copper and nickel layers. In this study, two alternative and more sustainable coating cycles were investigated, aiming to reduce the environmental impact by eliminating the most critical chemical treatments. These simplified cycles were evaluated for their effectiveness in achieving high-quality metal coatings while significantly reducing the use of hazardous chemicals.

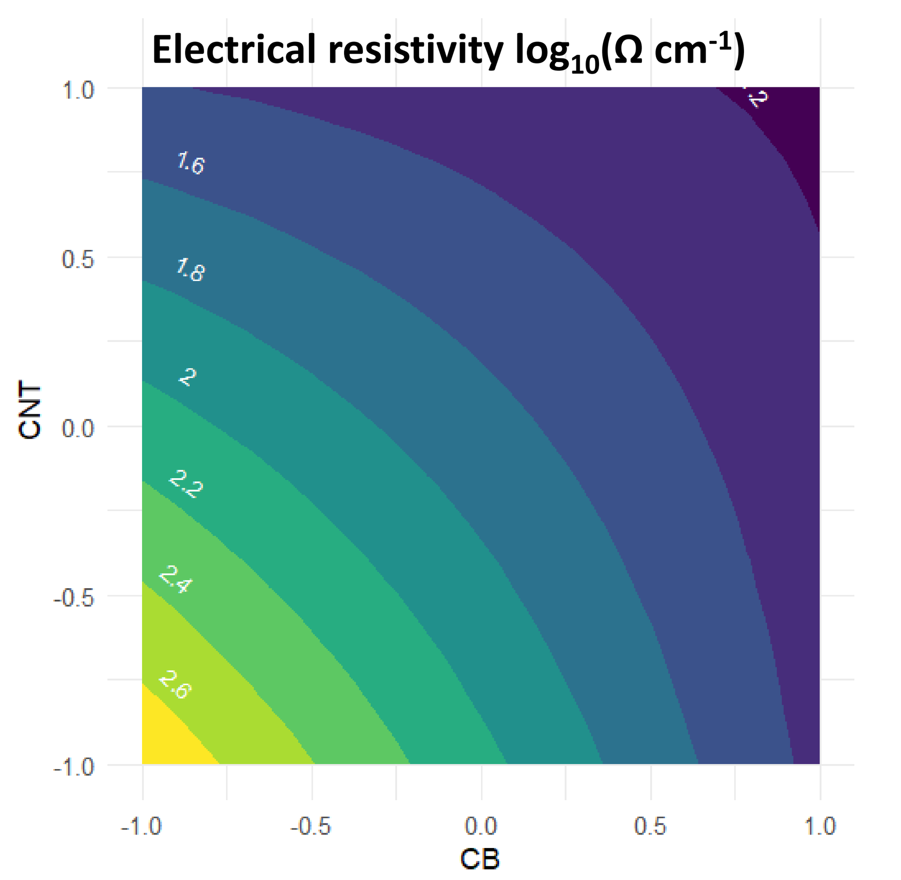
Conventional Coating Process	Modified NM Cycle	Modified RN Cycle
Acid cleaning bath	Acid cleaning bath	~~Acid cleaning bath~~
Chromium VI-based etching	~~Chromium VI-based etching~~	~~Chromium VI-based etching~~
Electroless nickel plating	Electroless nickel plating	~~Electroless nickel plating~~
Electroplating with copper	Electroplating with copper	Electroplating with copper
Electroplating with nickel	Electroplating with nickel	Electroplating with nickel

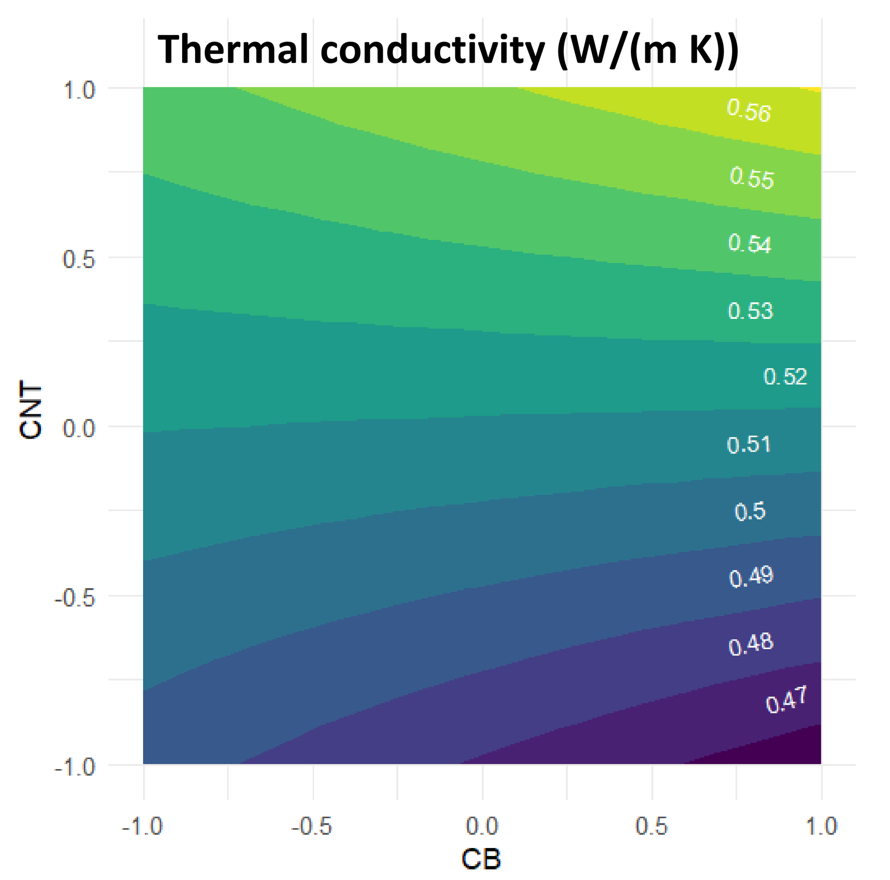




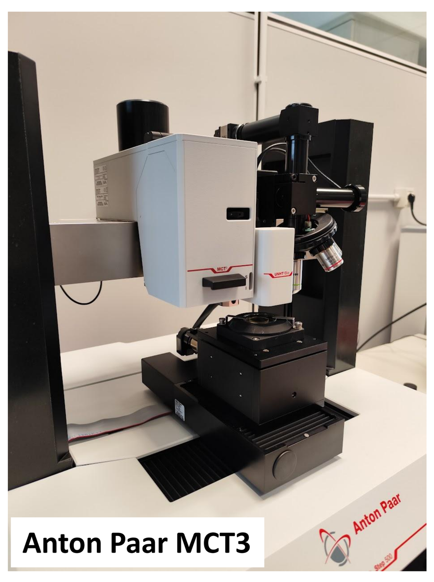


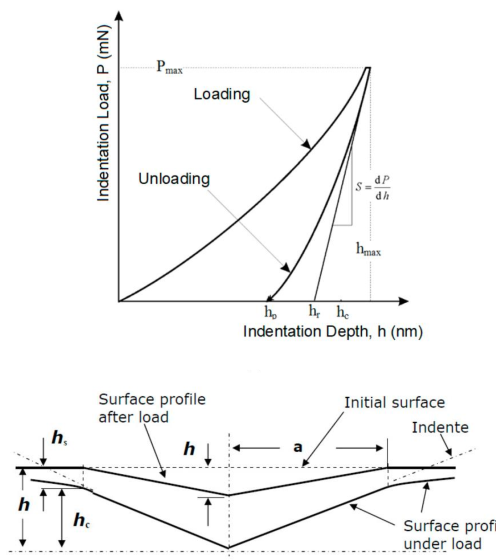


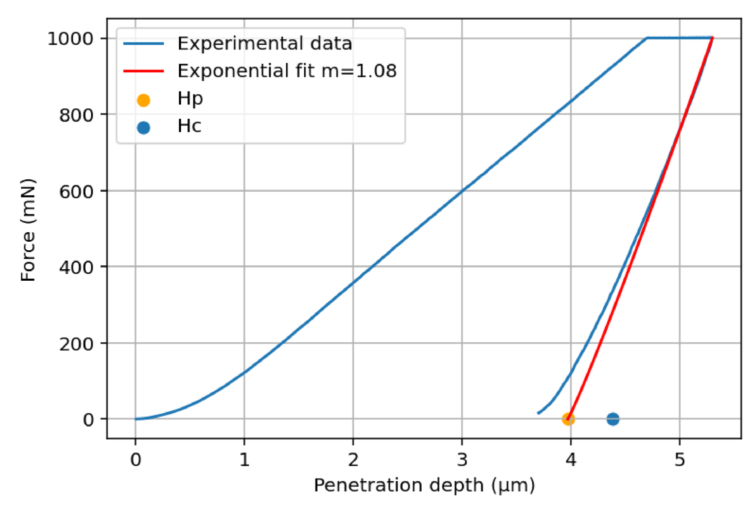


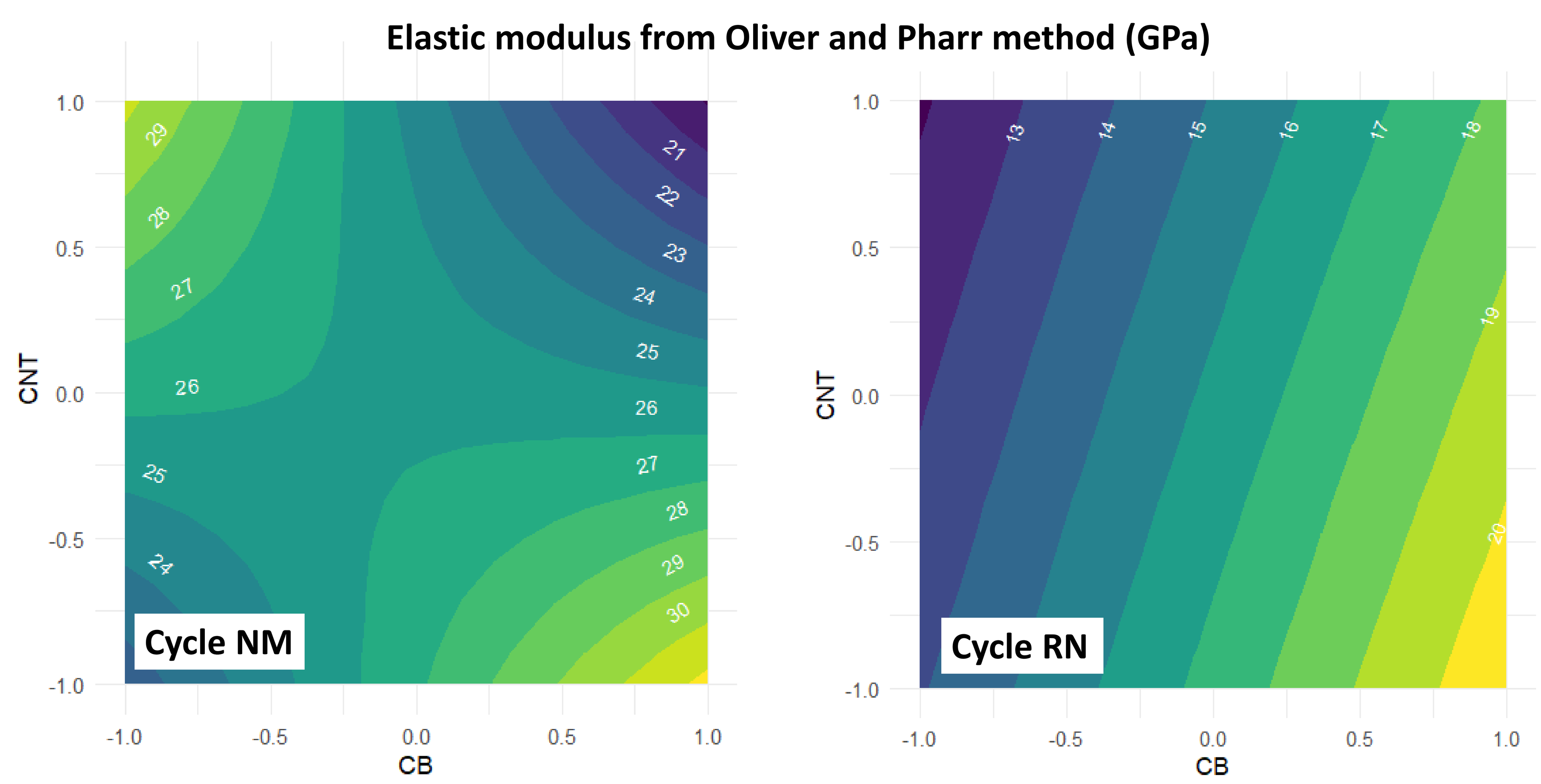


The coating was characterized using an Anton Paar microindenter, applying the Oliver and Pharr method to extract mechanical properties such as hardness and elastic modulus from the load–displacement curves. This approach enabled precise evaluation of the surface mechanical response of the plated layers.









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