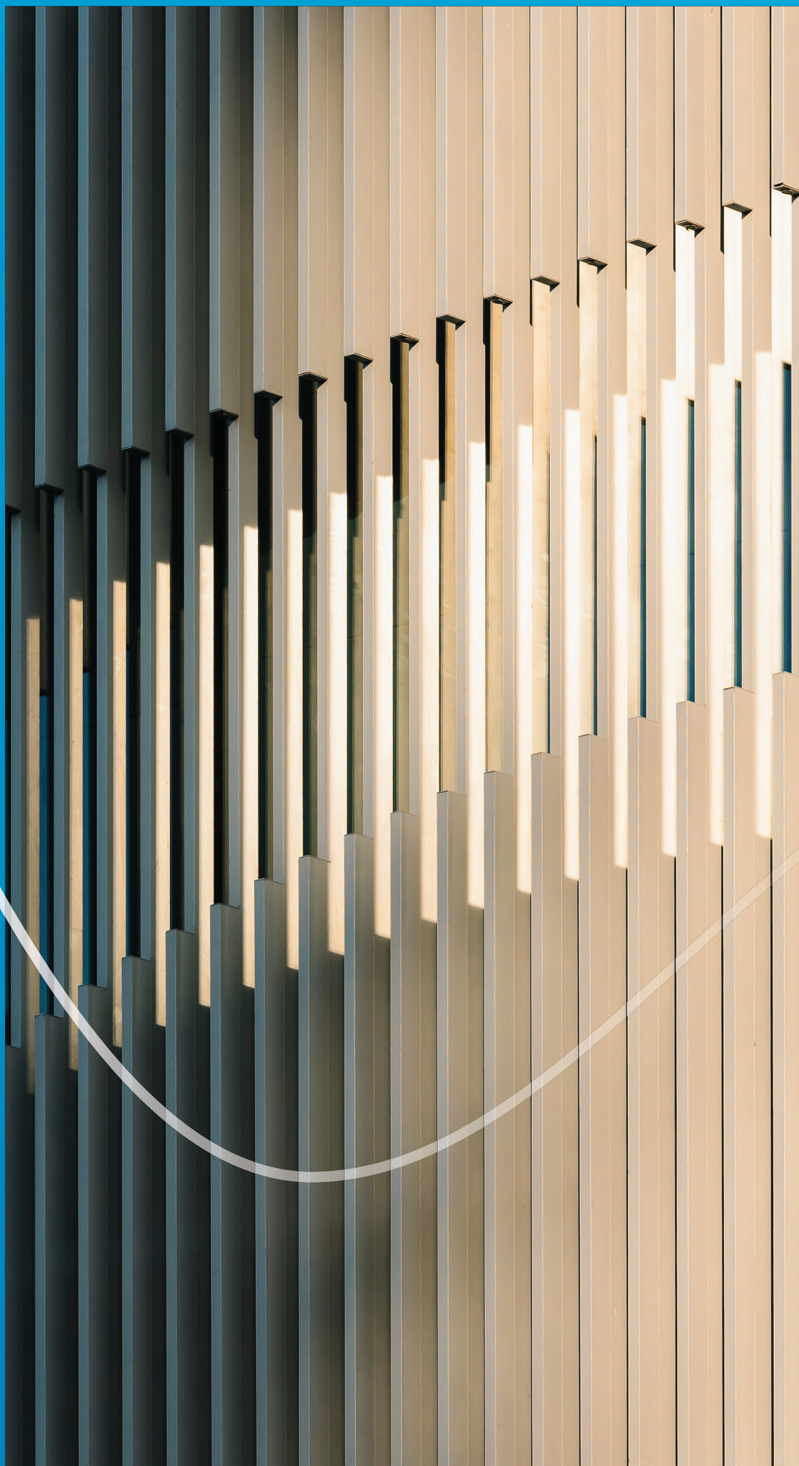
A laser focus on materials: *innovative benefits* for key industries



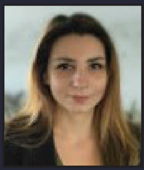
Capgemini engineering

Accelerating the discovery of new materials is crucial for addressing pressing energy and sustainability challenges across various industries. The future of materials discovery is poised for a radical transformation, driven by groundbreaking advancements in automation, robotics, rapid fabrication and characterization techniques, and artificial intelligence (AI). These technologies have the potential to usher in an era of autonomous, closed-loop material discovery.

Laser processing emerges as a powerful tool capable of inducing subtle modifications to the macro-nanostructure of material surfaces, thereby unlocking entirely new properties within common materials. When coupled with rapid characterization techniques, this approach enables the fabrication, testing, and optimization of diverse surface properties. Furthermore, integration with machine learning (ML) and AI allows for the training of models that can predict optimal parameters for testing, accelerating the discovery of materials tailored to specific properties.

The convergence of these technological capabilities brings us closer than ever to realizing the autonomous discovery of new materials for energy and sustainability applications. Fostering collaboration between industry and academia is essential to further accelerate this transformative process.

Vassilia Zorba

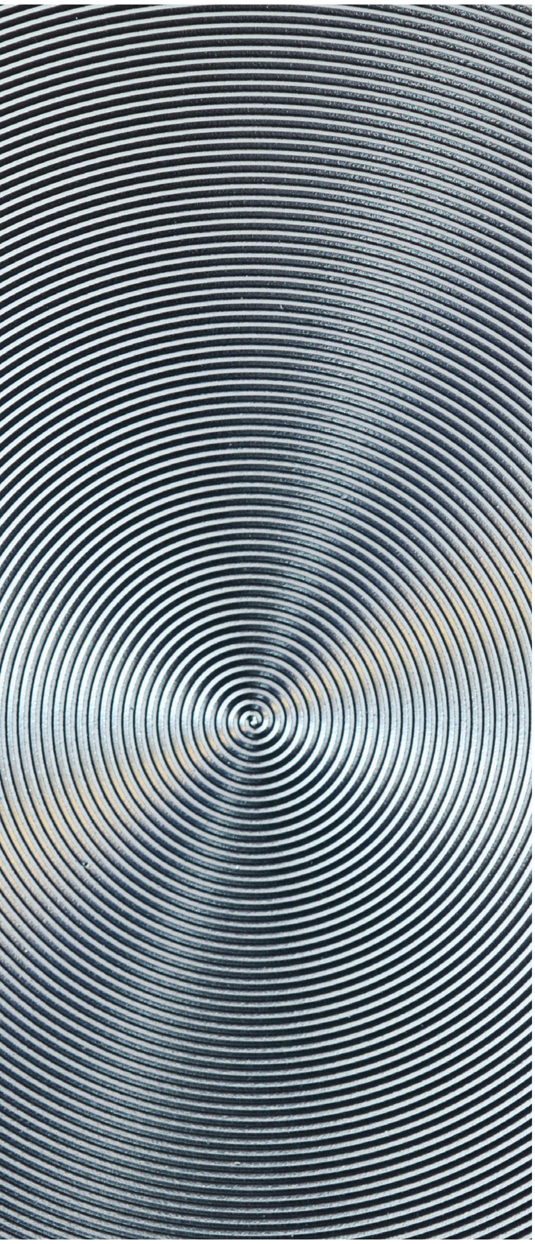


Engineered materials are rapidly gaining prominence as we seek to develop novel properties for emerging applications. The engineered surface properties of materials, in particular, offer immense potential to revolutionize existing materials. By optimizing characteristics like wettability, light absorption, and corrosion resistance, we can unlock new possibilities and expand the horizons of material utilization.

In parallel, artificial intelligence (AI) is emerging as a powerful tool that is reshaping the landscape of engineering and research. By accelerating the design and evaluation of experiments, AI significantly reduces time-to-market, propelling innovation forward.

Ramon Antelo

Executive summary



An exciting field of research in metals with improved surface properties is emerging in the world of innovative manufacturing technologies to increase the performance of products, open new applications, and contribute to meeting sustainability goals. This study explores the intersection of materials science and surface morphology, materials chemistry, deriving practical applications from theoretical knowledge and charting a revolutionary path to advanced materials that will be of value to a wide range of professionals, from engineers and researchers to marketing and sales professionals.

Metals such as aluminum, steel and titanium are key elements in sectors such as aerospace, energy and transportation. This article examines the complex relationship between material type, properties, and surface morphology and how these influence the specific properties of different metals. New laser texturing processes such as nanosecond, picosecond and femtosecond laser processing are opening up a new era of precision manufacturing that can redefine all these industries and much more.

The focus is on surface properties and on the major impact they may have on metal characteristics, ranging from nanoscale modifications to macroscopic transformations. Improved wettability, biofouling prevention, optical property manipulation, defrosting, self-cleaning, and corrosion and wear resistance are just a few of the possibilities, with the potential to deliver tailored and improved performance across a variety of applications.

Collaboration is key. The part of Capgemini Engineering's work with the University of California (UC) Berkeley presented in this paper, sits within the framework of its Strategic University Research Partnership Program with world-class universities, which addresses the question: 'What are the key challenges of a more intelligent industry in our society?'

https://www.capgemini.com/news/press-releases/Capgemini-collaborates-with-the-university-of-California-Berkeley-to-accelerate-time-to-market-of-new-materials/

The Capgemini-Berkeley collaboration focuses on building new methodologies and tools to accelerate the design of new surface properties by combining cutting-edge laser technologies, automation and AI, and reducing the time to market of new materials.

Introduction

Materials science and technology have constantly evolved, driven by the search for advanced materials with customized properties and innovative functions. Among various materials, metals such as aluminum, steel and titanium play a crucial role in key sectors such as aerospace, energy, and environmentally friendly transport. In this paper we consider the interplay between material type, properties, and surface morphology, and how making changes can lead to innovative applications in different key sectors and contribute to meeting sustainability goals.

For instance, the energy industry is driven by the need to generate and store energy efficiently and relies heavily on metals with tailored surface properties. Understanding the relationship between material type and surface morphology enables the development of advanced materials that withstand harsh environmental conditions, improve energy conversion efficiency, and contribute to sustainable energy development.

In aerospace, safety and performance are paramount. Adjusting the surface morphology of metals can result in increased corrosion resistance, reduced friction, improved wear resistance, reduced drag, and improved aerodynamics, ultimately helping to make aircrafts safer, more cost-effective, and more fuel-efficient.

In the medical field, the surface morphology of medical devices can be optimized to improve their biocompatibility and prevent infections, while in the construction sector, the surface morphology of building materials can be tailor-made to increase their durability and resistance to atmospheric agents.

Additionally, as global sustainability efforts increase, metals with improved surface properties are becoming key components of green technologies. Reducing biofouling can help protect marine ecosystems. Moreover, biofouling prevention can add up to 10% of production costs for many industrial applications. Specifically for naval transport, the accumulation of biofouling accounts for 35-50% higher fuel consumption, which impacts both cost and environmental aspects [1]. Also, metals with customized surface properties can pave the way to a greener future, by recovering solar energy, reducing fuel consumption, and more.

Metal corrosion is not simply a maintenance issue. Corrosion can have several negative effects, such as reduced product yield, product contamination, damage to expensive instruments, and reduced productivity. In extreme cases, corrosion can become a real drain on profitability. According to US government studies, corrosion costs the US more than $276 billion a year, so there is a huge market for corrosion protection [2]. Several national studies conducted in different countries over the last 50 years have consistently estimated the cost of corrosion at around 3% to 4% of each country's gross domestic product (GDP). With a global GDP of $100 trillion (as of 2022), the worldwide cost of corrosion is estimated to be a staggering $3.5 trillion [3]. According to the EU-funded project MULTIPROTECT, corrosion is an important cause of decreased capital value, with over €100 billion lost in Europe annually [4].

Laser technologies for surface texturing

In the past few decades, laser technologies have revolutionized various fields, enabling extraordinary precision and control in the processing and production of materials. In terms of material types, properties, and surface morphology, nanosecond, picosecond, and femtosecond laser processing techniques are breakthrough innovations. These laser technologies offer unique opportunities for precise material modification, surface engineering and micro-fabrication, revealing new opportunities for advances in key industries [5].

Nanosecond laser processing, with pulses lasting a few to several hundred nanoseconds, delivers controlled energy to materials, resulting in rapid heating and vaporization. The technique is used in a variety of industries such as automotive, aerospace, and electronics, enabling rapid cutting, welding, annealing, and surface texturing. Nanosecond lasers have become powerful and important tools for industrial applications due to their suitability for processing a wide range of materials [6].

Picosecond laser technology takes accuracy to a new level, with picosecond (billionths of a second) pulses. This ultra-fast laser treatment ensures minimal heat-affected zones and offers excellent control over material removal and surface modification. Medicine uses picosecond lasers in ophthalmology, tattoo removal and dermatology, while the electronics and semiconductor industries utilize them for micromachining with extreme precision [7].

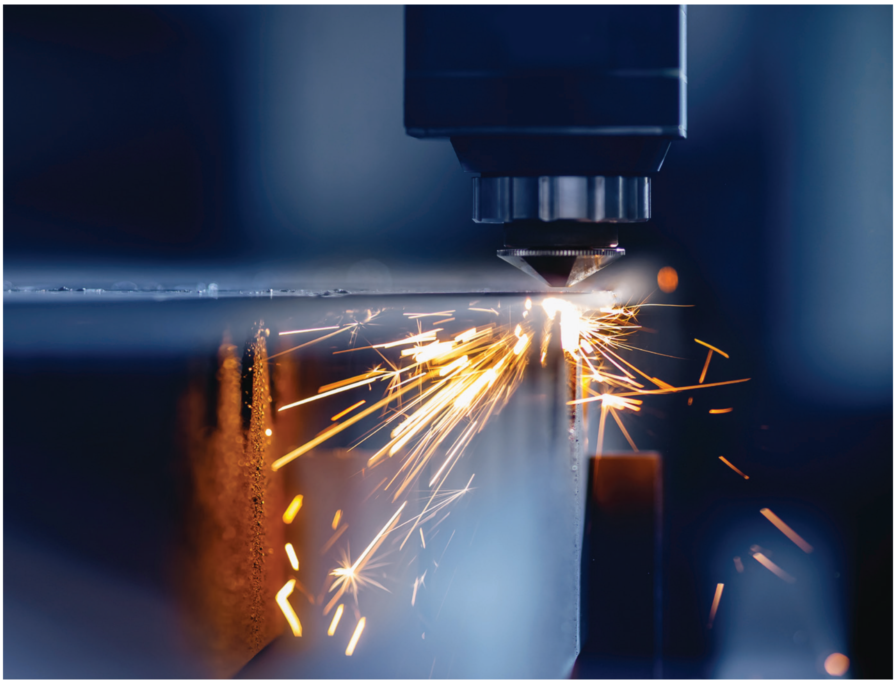
At the forefront of laser processing is **femtosecond technology**, where the pulses are very short, on the order of tens of femtosecond (a quadrillionth of a second). The extremely high peak power of femtosecond lasers enables non-linear interactions with materials, making it possible to process transparent materials and produce complex but very fine and precise microstructures. Therefore, femtosecond lasers play a key role in microelectronics, optoelectronics, and medical research, pushing the boundaries of what is feasible in terms of precision and material processing [8].

All these types of laser treatments can be used to tailor surface properties, and the choice of laser treatment depends on the specific application. For instance, femtosecond laser processing can be used to create surfaces that are more hydrophobic, i.e. water-repellent. Picosecond laser processing can produce more corrosion-resistant surfaces, while nanosecond laser processing can change the reflectivity of the surfaces [7] [8].

It is important to bear in mind that corrosion resistant surfaces and surfaces with tailored reflectivity can be fabricated with either nanoseconds, fentosecond or picosecond lasers.

The type of structure or micro/nanoscale feature that is created will depend on the specific combination of the laser processing parameters being used. The most critical parameters include:

- the laser power, which defines the amount of energy that is delivered to the surface of the material per time unit.
- the pulse duration, which defines the time over which the laser interacts with the material
- the scanning speed, which determines the number of laser pulses per location,
- the spot size, which is the size of the point at which the beam is most concentrated.
- the wavelength of the laser system, which determines its absorption and interaction with the material [5].

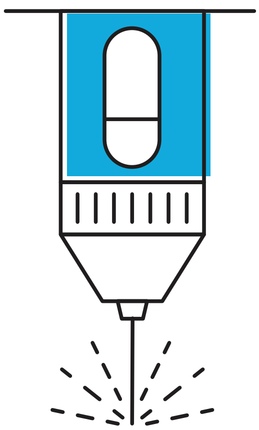


The choice of parameters will result in different surface textures, providing a material with performance tailored to a selected application. Thus, customized solutions can be realized for bottleneck problems in various real-life applications [5].

The following table shows how the different laser processing parameters can affect the surface structure.

Table 1: Process parameters vs. surface structure

Laser processing parameter	Effect on surface structure
Laser power	Higher laser power causes more ablation, rougher surface
Pulse duration	Shorter pulse duration leads to more precise surface features
Scanning speed	Faster scanning speed causes less ablation, less rough surface
Spot size	Smaller spot sizes allow the beam to be focused on smaller dimension on the sample
Wavelength	Different wavelengths are absorbed by materials differently, leading to different surface features



Surface morphology: the key to improve material performance

The surface morphology of metals is key to unlocking advanced material properties, and can be characterized by several parameters, including roughness, shape of surface features, and distribution of surface features.

Surface roughness can affect friction, wear resistance and adhesion. Surface texturing can increase or decrease wettability, reduce icing, and promote self-cleaning. Understanding and controlling surface morphology is critical to tailoring materials for specific applications, from reducing drag in airplane wings to improving biocompatibility in medical implants [9].

- Hydrophobic surfaces are achieved by producing a surface with a high water-surface contact angle. This means that for highly hydrophobic surfaces the water drop may form a perfect sphere, which may eventually roll off the surface, instead of wetting it.

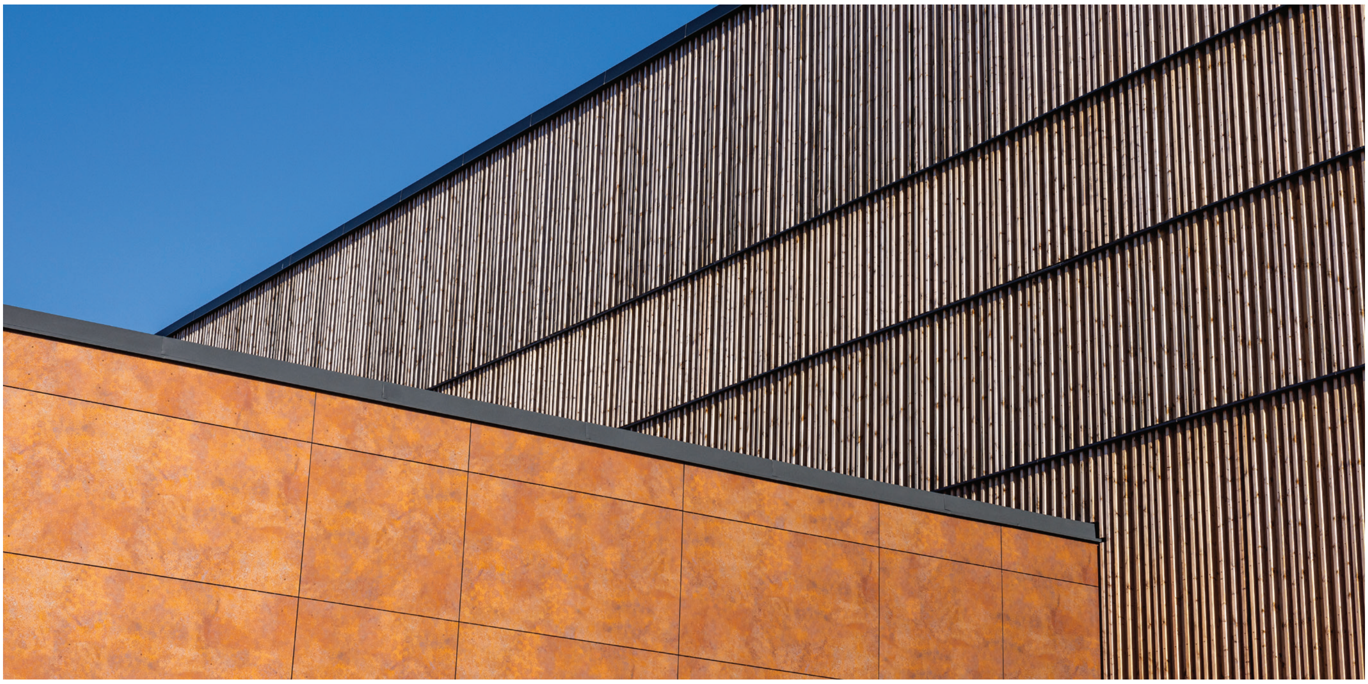
One way to produce hydrophobic surfaces is to apply a laser treatment to obtain specific structures in the micro- and nanometer range.

These structures can trap air molecules, creating a barrier that prevents water from wetting the surface. In other words, the surface is so modified that the direct contact of the water to the metallic substrate is reduced.

Adjusting surface roughness and adding hydrophobic or hydrophilic coatings can have a significant impact on wetting ability.

In aviation, hydrophobic coatings on aircraft surfaces reduce water build-up and improve aerodynamic efficiency, which leads to lower fuel-consumption, cost reduction and lower environmental impact.

In medical devices, hydrophilic coatings facilitate fluid flow and prevent the formation of unwanted blood clots, while in the electronics industry they facilitate ink penetration into electronic prints [10]. A special case is the so-called superamphiphobic surface, which defines a special wettability surface that repels liquids with lower surface tensions than water, such as organic fluids. Thanks to this special feature, superamphiphobic surfaces can be used in various applications such as self-cleaning, anticorrosion, flame retarding, flexible sensors, electrical conductivity, super-fast bubble bursting and droplet control [11].



Superhydrophilic surfaces can also act as anti-gravity wicking and as an efficient solar desalination evaporator for interfacial solar steam generation, an eco-friendly way to desalinate water [12].

- Corrosion-resistant surfaces can be achieved by creating a textured surface with a protective metal oxide layer. This oxide layer is corrosion- resistant because it is an insulating barrier (i.e. it is not electrically conducting) that prevents water and other chemicals from reacting with the underlying metal. Moreover, controlled surface textures can create hydrophobic surfaces that prevent moisture accumulation and thereby protect surfaces from corrosion [13]. Inspired by examples from nature, superhydrophobic coatings were initially produced for corrosion-resistant surfaces analogous to natural superhydrophobic surfaces such as butterfly wings or lotus leaves. Nevertheless, surface texture is often not enough, and additional mechanisms are required for high protective properties, such as the type of interface or its chemical features composition [14]. This complex relationship necessitates more systematic and pragmatic research to be carried out in this field. Whereas high corrosion resistance was observed on superhydrophobic AISI 316 steel square grid microtextured surfaces with nanosecond laser processing [15] and on ultrahydrophobic hollow pillar structured aluminum surfaces [16], superhydrophilic aluminum surfaces treated with a femtosecond laser process obtaining micro-scale protrusions and holes possessed much better corrosion resistance compared to their superhydrophobic counterparts, since superhydrophobic samples led to an increased salt retention capability and pitting corrosion [17].

- Surface morphology also affects the optical properties of metals, such as reflectivity, scattering and absorption coefficients. Nanostructured surfaces can be engineered to manipulate light at the nanoscale, improving light absorption in solar cells and light extraction in light-emitting devices. By tailoring surface morphology, metals can be used to achieve specific optical effects, promoting applications in sensing, imaging, and communications. The laser- textured nanostructures support surface plasmon resonances, enhancing light-matter interactions, while the periodic nanostructures can control light propagation and enable optical filtering [18]. A study conducted by S. Wang and others prepared hierarchical micro/nano-conical structures by femtosecond laser processing on titanium with very high light absorption, reflecting light several times within the textured structure arrays to achieve light trapping. The nanoparticles on the conical structures increased the absorption because of their quantum interactions with the incident light [19]. Similarly, micro-conical surface structures provided high light absorption for different aluminum alloys [20].
- In marine environments, surface morphology influences biofouling – in other words, the undesirable accumulation of marine organisms on submerged surfaces. Surface engineering can produce antifouling coatings that help prevent biofouling on ship hulls and underwater structures, which can reduce maintenance costs and environmental impact. Under certain conditions, a rough surface is less likely to accumulate microorganisms than a smooth one, since microorganisms find rough surfaces more difficult. In industries such as transportation and renewable energy, anti-fouling surfaces are critical to operational efficiency

50%

decrease in average microbe attachments was observed on superhydrophobic stainless steel surfaces

and durability [21, 22]. S. Vanithakumari and colleagues [23] achieved a four- order reduction in bacterial adhesion on laser-patterned titanium surfaces, which can be very critical for titanium parts used as condenser material in seawater-cooled nuclear power plants. Moreover, in several other publications it was reported that using different laser processing biofouling behaviour could be achieved in different steel, copper, and titanium alloys [23]. Although titanium has a very high corrosion resistance, its high biocompatibility facilitates the biofouling problem in comparison to other structural materials. D. Yue, X. Jiang, H. Yu and D. Sun demonstrated hierarchical nanostructures in titanium alloys could form highly stable and durable super-lubricated surfaces for anti-biofouling in marine engineering [24]. In another study, a 50% decrease in average microbe attachments was observed on superhydrophobic stainless steel surfaces with controllable micro groove and pit structures [25].

- The de-icing properties of a material can also be influenced by its surface morphology. Surface textures can create anti-icing surfaces with micro/nanostructures that postpone or suppress ice formation, reducing the need for de-icing chemicals and energy-intensive defrosting methods while ensuring the safety of critical infrastructure, transportation, and aerospace systems [26]. Considering that de-icing is a maintenance measure for aircrafts, any reduction of de-icing procedures may have a positive impact on cost reduction of commercial aircraft operations in airports worldwide. A research team [27] created superhydrophobic hierarchical micro-nano structures on aluminum via picosecond laser processing, exhibiting low-temperature-adaptive water repellency, which delays frozen time and reduce the freezing point with enhanced stability and lifespan without any post-treatments. Similarly, superhydrophobic aluminum surfaces with increased roughness through micro/nano-scale hierarchical structures created by a hydrothermal method demonstrated good ice-phobic characteristics and good mechanical properties, in which the starting icing time of the water droplet was effectively delayed [28].
- By designing superhydrophobic or superamphiphobic surfaces, metals can exhibit self-cleaning behavior, easily removing water and contaminants. Thanks to its repellency, any liquid dropping onto the surface collects contaminants as it rolls off [29]. Multiple hierarchical surface patterns minimize the contact area between surfaces and contaminants, enabling the effortless removal of dirt and pollutants. Self-cleaning properties on solar panels, building exteriors and various automobile surfaces minimize maintenance expenses and environmental impact [30]. Depending on whether the surface is superhydrophobic or superamphiphobic, self-cleaning can be achieved by using water or different organic fluids [29]. It has been demonstrated [29] that the micro/nano-texturing of an aluminum surface with a nanosecond laser and post-treatments can help tune the repelling properties and achieve self-cleaning with different liquids such as water and ethylene glycol. Similarly, Wang and others prepared hierarchical micro/nano-conical structures with femtosecond laser processing on titanium, which possessed excellent self-cleaning performance thanks to their superhydrophobic nature [19].

Potential applications in key industries and key challenges

Aviation

Improving safety and performance via surface morphology

The ideal combination of material type, property and surface morphology is vital to enhance **aircraft performance** and **safety** in the aviation industry. Significant improvements in fuel efficiency can be achieved by optimizing surface morphology to reduce drag and enhance aerodynamics. Anti-icing and anti-corrosion surface treatments also improve the durability and **reliability** of aircraft components, ensuring safe operation even in challenging conditions [31].

Precise laser processing of metallic surfaces enhances the safety and performance of aviation equipment. Superhydrophobic coatings with micro/nanostructured patterns reduce ice buildup on aircraft wings, thus improving aerodynamic efficiency and reducing fuel consumption. Furthermore, aircraft components critical for safe and reliable operation are protected by laser-textured surfaces with corrosion-resistant coatings. Using anti-fouling surfaces to aircraft exteriors can reduce the biofouling of aircraft parts including fuel tanks, pipes, and filters, which is crucial for preventing operational issues, fires, and explosions, while also ensuring optimal aircraft performance [31, 32].

Energy

Increasing efficiency and durability in power generation

Tailoring the surface morphology of metallic materials through laser processing is crucial in the energy industry for enhancing the efficiency of energy conversion processes. Micro and nanostructured patterns on solar panels may change light absorption, thus improving the efficiency of solar energy conversion. Furthermore, laser-textured surfaces on wind turbine blades heighten aerodynamics and decrease fouling, resulting in increased energy production and minimized maintenance downtime. The lifespan of components in nuclear power plants is extended through the utilization of corrosion-resistant surfaces, which contribute to safe and reliable energy generation.

Sustainability

Eco-friendly materials for a greener future

Surface engineering enhances material performance and reduces environmental impact, contributing to sustainability efforts. The use of cleaning chemicals can be reduced by hydrophobic and self-cleaning surfaces, and anti-fouling surfaces prevent harmful biofouling in marine environments. Extending the lifespan of materials by optimizing their surface morphology to reduce corrosion and wear leads to reduced waste and resource consumption.

Eco-friendly metallic materials with tailor-made properties can be developed using laser processing. In transportation, micro/nanostructured anti-corrosion surfaces reduce maintenance needs and extend the lifespan of critical components, adding to the sustainability of infrastructure. In water treatment systems, laser-textured surfaces with antibacterial coatings prevent biofouling and ensure a clean and safe water supply. Metals with optimized surface morphology in energy-efficient lighting devices not only reduce reflection but also enhance light absorption, promoting energy conservation with lower environmental footprint [33, 34, 35, 36].

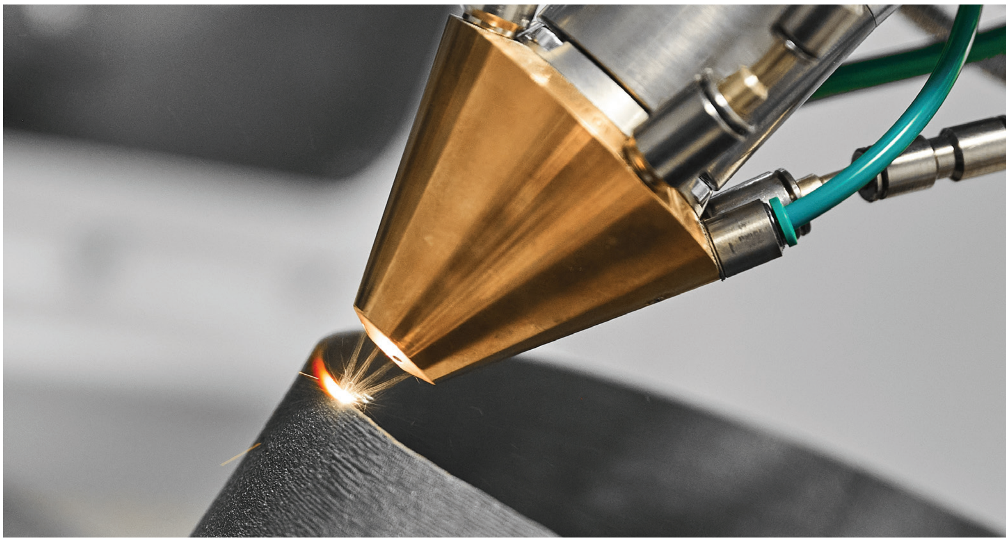
Future directions

Research and innovation on the interrelated triangle of material type, property and surface morphology will continue. Researchers are pursuing novel techniques and materials for surface engineering to achieve desired functionalities across a broad range of applications. Recent progress in laser technologies, including higher power and shorter pulse durations, have created new prospects for precise material processing and surface engineering. The opportunities for potential advances can be summarized as follows:

- **Advanced surface texturing techniques:** Developing innovative laser processing techniques to create complex and intricate surface structures with precise control over micro/nano components.
- **Tunable surface properties:** Exploring new materials and laser parameters to achieve customizable and flexible surface functionalities that adapt to changing environments.
- **Bio-inspired (biomimetic) surface engineering:** The use of surface structures in nature as a source of inspiration for the design of unique surface patterns that have superior properties for specific applications.

Moreover, the integration of laser processing technologies with artificial intelligence and machine learning shows great potential for adaptive and automated manufacturing processes. Additive manufacturing and 3D printing have enabled the creation of complex structures and micro-patterns on metal surfaces in precision surface engineering. Integrating laser processing with additive manufacturing techniques enables the creation of complex structures with customized surface properties in fewer manufacturing steps. In-situ process monitoring ensures quality control and enables adaptive surface engineering.

In addition, hybrid surface engineering, which combines laser processing with other surface modification techniques such as chemical treatments or mechanical finishing, can produce synergistic effects and thus create multifunctional surfaces.



Outlook: surface tailoring processes are technology multipliers!

Advanced materials with customized functions and properties have driven the advancement of materials science. Metals such as aluminum, steel and titanium have emerged as essential components for key sectors such as aerospace and energy. The complex interrelationship between unique material types, properties and surface morphology can significantly affect the characteristics of individual metals.

Innovations in laser texturing techniques, such as utilizing nanosecond, picosecond, and femtosecond laser processing outperform conventional methods, thereby can revolutionize precision manufacturing in various industries. The manipulation of surface offers significant opportunities to enhance and alter various material characteristics and properties, such as wettability, biofouling, optical properties, and wear resistance, from the nanoscale to the macroscopic level. These capabilities mark the beginning of a new era of possibilities by providing a pathway towards custom-made materials with enhanced performance for various applications and helping achieving sustainability goals.

This exploration of materials research and surface morphology offers a pathway to a future characterized by advanced materials that blend theory and practicality seamlessly.

By utilizing collaborative efforts and interdisciplinary approaches such as that demonstrated in the partnership between Capgemini Engineering and UC Berkeley, the complex relationship between material type, properties and surface morphology provides opportunities for innovation and discovery that bring us closer to a brighter future, where the attributes of metals and their surfaces are instrumental in shaping progress, sustainability, and a better world for all.

References

1. M. J. Romeu und F. Mergulhao, „Development of Antifouling Strategies for Marine Applications," Microorganisms, Bd. 11, Nr. 6, p. 1568, 2023.
2. SilcoTek, „The True Cost of Corrosion Resistant Coatings for Stainless Steel," SilcoTek, 18 6 2018. [Online]. Available: https://www.silcotek.com/blog/calculating-the-true-cost-of-corrosion-resistance. [Zugriff am 2024].
3. Industry Europe, „The Impact of Corrosion on Heavy Equipment," Industry Europe, 7 11 2023. [Online]. Available: https://industryeurope.com/sectors/construction-engineering/the-impact-of-corrosion-on-heavy-equipment/#:~:text=Various%20national%20studies%20conducted%20in,Gross%20Domestic%20Product%20(GDP). [Zugriff am 2024].
4. M. Veith, M. Wittmar und C. Hahn, „Final Report Summary - MULTIPROTECT (Advanced environmentally friendly multifunctional corrosion protection by nanotechnology)," 2011.
5. J. Lawrence und J. Dowden, Laser Surface Engineering: Processes and Applications, Woodhead Publishing, 2015.
6. . A. G. Grigor'yants, M. A. Kazaryan und . N. A. Lyabin, Laser Precision Microprocessing of Materials, CRC Press, 2022.
7. K. Sugioka und Y. Cheng, Ultrafast Laser Processing: From Micro- to Nanoscale, Jenny Stanford Publishing, 2013.
8. E. G. Gamaly, Femtosecond Laser-Matter Interaction: Theory, Experiments, and Applications, Jenny Stanford Publishing, 2011.
9. T. Burakowski, Surface Engineering of Metals: Principles, Equipment, Technologies, CRC Press, 2015.
10. G. A. Somorjai und Y. Li, Introduction to Surface Chemistry and Catalysis, Wiley, 2010.
11. W. SI und Z. Guo, „Enhancing the lifespan and durability of superamphiphobic surfaces for potential industrial applications: A review," Advances in Colloid and Interface Science, p. 102797, 2022.
12. Z. Chen, Y. Lin, Q. Qian, P. SU, Y. Ding, P. Tuan, L. Chen und D. Feng, „Picosecond laser treated aluminium surface for photothermal seawater desalination," Desalination, p. 115561, 2022.
13. S. Caraguay, T. Pereira, R. Giacomelli, A. Cunha, M. Pereira und F. Xavier, „The effect of laser surface textures on the corrosion resistance of epoxy coated steel exposed to aggressive environments for offshore applications," Surface and Coatings Technology, p. 128371, 2022.
14. K. A. Emelyanenko, A. M. Emelyanenko und L. B. Boinovich, „Laser Obtained Superhydrophobic State for Stainless Steel Corrosion Protection, a Review," Coatings, p. 194, 2023.
15. U. Trdan, M. Hocevar und P. Gregorcic, „Transition from Superhydrophilic to Superhydrophobic State of Laser Textured Stainless Steel Surface and Its Effect on Corrosion Resistance," Corrosion Science, pp. 21-26, 2017.
16. L. Ruiz de Lara, R. Jagdheesh und J. Ocana, „Corrosion Resistance of Laser Patterned Ultrahydrophobic Aluminium Surface," Materials Letters, pp. 100-103, 2016.
17. J. Ley, Y. Kwon, C. Park und S. Menon, „Corrosion of femtosecond laser surface textured aluminium alloy," Corrosion Engineering, Science and Technology, p. 1348090, 2017.
18. B. D. Bartolo und J. Collins, Nano-Optics: Principles Enabling Basic Research and Applications, Springer, 2017.
19. S. Wang, S. Dong, X. Liu und S. Yan, „Multifunctional surface of titanium alloy with dual-scale hierarchical micro/nanostructures fabricated by femtosecond laser processing," Optics and Laser Technology, p. 109423, 2023.
20. K. Wöbbeking, M. Li, W. Scahde und E. Hübner, „Microconical surface structuring of aluminium tubes by femtosecond laser processing," Journal of Physics Communications, p. 111001, 2020.
21. R. K. Gupta, T. A. Nguyen, M. Bilal, A. K. Nadda und S. Sharma, Advances in Nanotechnology for Marine Antifouling, Elsevier, 2023.

22. F. Zhou, Antifouling Surfaces and Materials - From Land to Marine Environment, Springer, 2015.

23. S. Vanithakumari, A. Choubey, C. Thinaharan, R. Gupta, R. George, R. Kaul, K. Bindra und J. Philip, „Laser patterned titanium surfaces with superior antibiofouling, superhydrophobicity, self-cleaning and durability: Role of line spacing," Surface & Coatings Technology, p. 127257, 2021.

24. D. Yue, X. Jiang, H. Yu und D. Sun, „In-situ fabricated hierarchical nanostructure on titanium alloy as highly stable and durable super-lubricated surface for anti-biofouling in marine engineering," Chemical Engineering Journal, p. 142389, 2023.

25. K. Sun, H. Yang, W. Xue, A. He, D. Zhu, W. Liu, K. Adeyemi und Y. Cao, „Anti-biofouling superhydrophobic surface fabricated by picosecond laser texturing of stainless steel," Applied Surface Science, pp. 263-267, 2018.

26. M. Grizen, T. Maitra und M. Tiwari, „Nanotextured surfaces for anti-icing," in Proceedings of the 16th International Heat Transfer Conference, 2018.

27. W. Xing, Z. Li, H. Yang, X. Li, X. Wang und N. Li, „Anti-icing aluminum alloy surface with multi-level micro-nano textures constructed by picosecond laser," Materials and Design, p. 108156, 2019.

28. X. Tan, M. Wang, Y. Tu, T. Xiao, S. Alzuabi, P. Xiang, R. Guo und X. Chen, „Icephobicity studies of superhydrophobic coating on aluminium," Surface Engineering, p. 1853002, 2020.

29. D. M. N. Menon, M. Giardino und D. Janner, „Tunable pulsewidth nanosecond laser texturing: From environment friendly superhydrophobic to superamphiphobic surfaces," Applied Surface Science, p. 155356, 2023.

30. T. Heckenthaler, S. Sadhujan, Y. Morgenstern, P. Natarajan, M. Bashouti und Y. Kaufman, „Self-Cleaning Mechanism: Why Nanotexture and Hydrophobicity Matter," Langmuir, p. 15526–15534, 2019.

31. J. M. Vazquez-Martinez, I. D. S. Illana, E. U. Arrien, M. Batista und J. Salguero, „Chapter 18 - Laser surface texturing as a finishing process for aerospace alloys," in Advanced Machining and Finishing, Elsevier, 2021, pp. 643-666.

32. V. Shyam, M. Eggermont und A. F. Hepp, Biomimicry for Aerospace Technologies and Applications, Elsevier, 2022.

33. J. M. Vazquez-Martinez, I. D. S. Illana, E. U. Arrien, M. Batista und J. Salguero, „Chapter 18 - Laser surface texturing as a finishing process for aerospace alloys," in Advanced Machining and Finishing, Elsevier, 2021, pp. 643-666.

34. T. Soga, Nanostructured Materials for Solar Energy Conversion, Elsevier, 2006.

35. Q. Li, Nanomaterials for Sustainable Energy, Springer, 2016.

36. R. Yeo, W. Wu, N. Tomczak, R. JJi, S. Wang, X. Wang, J. Kong, H. Liu, K. Goh, J. Xu, X. Loh und Q. Zhu, „Tailoring surface reflectance through nanostructured materials design for energy-efficient applications," Materials Today Chemistry, p. 101593, 2023.

37. M. Alston und T. N. Lambert, Energy-Sustainable Advanced Materials, Springer, 2021.

About the authors

Ramon Antelo

Vice President – CTO Manufacturing & Operations – Head of Digital Engineering Portfolio – Capgemini Engineering

ramon.antelo @capgemini.com

Ramon started his career back in 1990 as a fresher in an industrial company, and ever since he has been involved in improving the performance of manufacturing operations, including the technological, organizational and human perspective. He deeply understands the interactions of the three perspectives, and firmly believes that transformations will succeed if companies consider all of them.

Dr. Anne-Laure Cadène

Vice President – Head of University Strategic R&D Partnerships – Capgemini Engineering

anne-laure.cadene@capgemini.com

Dr. Anne-Laure Cadène has been with Capgemini since 2019 and has over 20 years of experience in R&D and innovation. She has held various roles as consultant, business manager, scientific director and research and innovation director in aerospace, automotive, life science and systems domains. She's currently VP Head of University partnerships, working closely with CTOs, industry leaders, research & innovation ecosystem and academics to build research collaborations to contribute to the advancement of engineering at 3-5 years research horizon, and also leads the Ventures engineering business relations with Capgemini ventures.

Dr. Selim Coskun

Materials Science & Nanotechnology Senior Expert – Capgemini Engineering

selim.coskun@capgemini.com

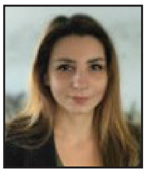
Dr. Selim Coskun is a senior expert in materials science & nanotechnology with a very broad experience in composite materials, nanomaterials, powder metallurgy and different characterization methods. Prior to joining Capgemini, he worked as Head of department and assistant professor at the Turkish-German University, and as Co-Founder at Nanokomp Advanced Materials. He holds a PhD in Materials Science and Engineering from Istanbul Technical University, Turkey. Selim also worked as researcher at the University of Cambridge, UK.

Dr. Luis Prado

Materials Science & Nanotechnology Expert, Research & Innovation – Capgemini Engineering

luis.prado@capgemini.com

Dr. Luis Prado has 25+ years of experience as a researcher in Chemistry, Organometallic Chemistry, Polymers and Composites, Polymer Nanocomposites, Materials Science and Nanotechnology. In his role, Luis creates new opportunities and ideas in three main sectors: sustainable aircraft development, technological developments for the generation of renewable energy and hydrogen-based technologies for a carbon-neutral industry. Combining chemistry, materials science, and his 10- year experience in the aviation industry, he drives the development of unconventional ideas for Capgemini Engineering's partners.



Vassilia Zorba

Associate Adjunct Professor – University of California, Berkeley

zorba@berkeley.edu

Vassilia Zorba is an Associate Adjunct Professor in the Department of Mechanical Engineering of the University of California, Berkeley. She is also the Leader of the Laser Technologies Group at the Lawrence Berkeley National Laboratory (LBNL) in Berkeley CA, as well as the Deputy Director of Operations for the Energy Storage & Distributed Resources Division at LBNL.

Vassilia is an editor for several peer-reviewed scientific journals in physics, chemistry and engineering. She is a Fellow of Optica and a Fellow of the Royal Society of Chemistry, with 95 publications in peer-reviewed journals, 65 invited talks and a 2011 R&D 100 Technology Award.

About Capgemini Engineering

World leader in engineering and R&D services, Capgemini Engineering combines its broad industry knowledge and cutting-edge technologies in digital and software to support the convergence of the physical and digital worlds. Coupled with the capabilities of the rest of the Group, it helps clients to accelerate their journey towards Intelligent Industry. Capgemini Engineering has 65,000 engineer and scientist team members in over 30 countries across sectors including Aeronautics, Space, Defense, Naval, Automotive, Rail, Infrastructure & Transportation, Energy, Utilities & Chemicals, Life Sciences, Communications, Semiconductor & Electronics, Industrial & Consumer, Software & Internet.

Capgemini Engineering is an integral part of the Capgemini Group, a global business and technology transformation partner, helping organizations to accelerate their dual transition to a digital and sustainable world, while creating tangible impact for enterprises and society. It is a responsible and diverse group of 340,000 team members in more than 50 countries. With its strong over 55-year heritage, Capgemini is trusted by its clients to unlock the value of technology to address the entire breadth of their business needs. It delivers end-to-end services and solutions leveraging strengths from strategy and design to engineering, all fueled by its market leading capabilities in AI, cloud and data, combined with its deep industry expertise and partner ecosystem. The Group reported 2023 global revenues of €22.5 billion.

Get the future you want | www.capgemini.com