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# Smart Surface Design for Efficient Ice Protection and Control

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# Smart Surface Design for Efficient Ice Protection and Control

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# Foreword

Back in 2017, when we started our first brainstorming on the topics of icing and ice protection technologies, Carlo Antonini, Iliia Roisman and I did not anticipate that a Marie Skłodowska-Curie project would follow and that a very dedicated and skilled team of PhD students would advance several aspects in this research area so considerably. As sometimes happens, it came differently, and now you have in front of you the latest findings in the form of this book.

As an Airbus expert who has worked for many years in this research field, I am truly amazed how effective a team of young and passionate researchers guided by some very dedicated academic supervisors could be in addressing the icing challenge and in delivering results that are scientifically relevant and industrially valuable. Indeed, icing and ice protection are very interdisciplinary topics. Atmospheric physics, thermodynamics, mechanical engineering, chemistry and materials science must come together, willing to learn each other's languages and to contribute experimentally and through theoretical and numerical models and tools. That such disciplines would find common ground and ways of interfacing and collaborating was not clear in the beginning, but it is exactly what happened within the SURFICE consortium.

Most supervisors had previous experience in one or more aspects of icing, such as physical modeling of ice formation, mechanical modeling of ice adhesion, the design and development of icephobic coatings, the design and prototyping of mechanical devices, or icing wind tunnel testing. However, as you will realize reading this book, these separate disciplines have successfully 'fused' and proposed next-generation technological solutions. These are achievements of which the young researchers who contributed this breadth of new knowledge should be especially proud!

The common thread connecting the chapters of this book addresses three critical aspects of icing: (i) understanding the physics of ice formation in most diverse atmospheric conditions and understanding what chemistry can do to control ice formation and ice removal from surfaces; (ii) understanding the physico-chemical mechanisms controlling ice adhesion and designing functional coatings and electro-mechanical technologies to efficiently crack ice off surfaces; and (iii) making use of the knowledge gained in (i) and (ii) for designing and developing novel icephobic coatings that are not only effective, but also durable enough to be adopted in industrial applications.

Indeed, the surfaces of aircraft wings, wind turbine rotor blades, high-voltage line cables, or antennas for telecommunications must resist unaffected most atmospheric weather conditions, from heavy rain to sand storms to UV radiation to snow and ice storms. You will find the latest scientific outcomes and technological solutions addressed in this book—so enjoy the read!

Munich, 31 January 2025  
Elmar Bonaccorso  
Airbus Central R&T

# Preface

*The context*—Icing is a natural phenomenon affecting our daily life and safe operations in diverse areas, such as aeronautics and ground transportation, operations in critical environment, power systems (such as power lines, wind turbines or solar panels), communication systems and infrastructures. In particular, human activities at high latitudes or at high altitudes require energy-efficient and environmentally sustainable ice protection solutions.

*The challenge(s)*—The existing solutions for prevention or delay of icing, for reduction of the icing rate and for ice removal facilitation include both active and passive systems. Active systems are sophisticated mechanical or energy-demanding thermal systems, whereas passive systems include specialized materials or morphological modifications of surfaces or coatings. The passive systems are often based on the use of hydrophilic polymers and utilization of colligative properties of solutions for lowering of the freezing point. Also, superhydrophobic and lubricant-infused surfaces may reduce the time of water contact with the surface or reduce adhesion strength. However, at present, technological problems are associated with the design of coating-based anti-icing systems: as examples, substrate erosion and corrosion, liquid impalement and consequent increase in ice adhesion to the solid surface due to high-speed drop impact. These factors have so far represented a bottleneck for the transition of coating-based technologies to industrial applications.

*The book's genesis*—In November 2017, an initial core team of three scientists (Carlo Antonini, Ilia Roisman, Elmar Bonaccorso) initiated the discussion on how to tackle the above challenges and conceived a project within the framework of Marie Skłodowska-Curie European Training Networks, a unique scheme to train a cohort of interdisciplinary scientists. The core team gathered a consortium comprising universities, research institutions, enterprises and partner organizations in eight European countries (Italy, Germany, France, the UK, the Netherlands, Belgium, Austria, Switzerland). A few years down the line came this book, as a result of that initial vision.

*The scientific objectives: why read the book?*—The project SURFICE (smart surface design for efficient ice protection and control), that gives the title to the book, has the goal to formulate a rational framework for the design, fabrication and testing of icephobic surfaces for industrially relevant applications. The three major research objectives of SURFICE, tackling the existing knowledge gaps, have been: (i) the investigation of the physics of icing of morphologically complex microstructured surfaces; (ii) the rational design of new icephobic materials and coatings; and (iii) the development of new technologies and systems for efficient ice prevention and control. Consequently, the objective of this book is to integrate information about the modeling, coating and material preparation, characterization and applications of icephobic surfaces in one volume. By combining the discussion of all aspects together, our hope is that the reader will benefit from a single reference book to understand the fundamentals of coating strategies based on icephobicity and the possible implementation into industrial systems.

*The book's audience*—This book has been designed as useful reading for materials scientists, physicists, chemists and engineers, interested in any aspect of surface, colloid and polymer science and thermodynamics relevant to icing phenomena and related coating strategies.

*How to read the book*—The book is structured in two sections. The first part covers the fundamentals, including the theory of physics of icing (chapter 1) and the state-of-the-art on existing surface-based strategies for icephobicity (chapter 2). This first part should help readers familiarize themselves with the terminology, the relevant physical mechanisms and surface chemistry concepts, especially to guide those who approach the topic for the first time or are looking for a comprehensive systematic overview of the research field. The second part of the book discusses the most recent significant scientific advances, spanning from the understanding of ice adhesion and fracture mechanisms (chapters 3–5) to strategies for effective icephobic coatings (chapters 6–10).

Milan, 31 January 2025  
Carlo Antonini, Irene Tagliaro

# Acknowledgements

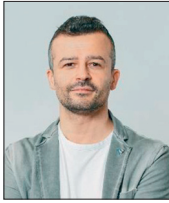
All the book authors and contributors acknowledge funding through SURFICE (smart surface design for efficient ice protection and control) ([www.surfice-itn.eu](http://www.surfice-itn.eu)), a European Training Network funded by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 956703. The project started in January 2021 and was completed in January 2025.

A personal acknowledgment from Carlo Antonini: I am particularly grateful to Ilia Roisman and Elmar Bonaccorso, the other two members of the initial core team, for kindly nudging me, giving me the opportunity to take the lead as a project coordinator, despite my initial self-doubt about being fit for the role. I hope I will be able to pay it forward.

# Editor biographies

## Carlo Antonini

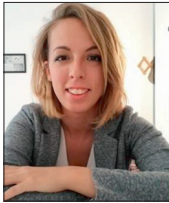
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Carlo Antonini received a BSc in Aerospace Engineering (2004) and MSc in Aeronautical Engineering (2007) from Politecnico di Milano, and a PhD from University of Bergamo (2011), Italy. From 2012 to 2018 he worked in Zurich, first at ETH as a Marie Sklodowska-Curie post-doc, then at EMPA as a scientist. In September 2018 he joined the Department of Materials Science at the University of Milano-Bicocca (Italy) as assistant professor, where he created and currently leads the ‘Surface Engineering and Fluid Interfaces Laboratory’ (SEFI Lab, [sefilab.mater.unimib.it](http://sefilab.mater.unimib.it)). In 2021 he received tenure as associate professor. From 2021 to 2025 Antonini has been the coordinator of SURFICE, an MSCA-ITN project supported by the EU, focusing on surface based-strategies to contrast icing.

## Irene Tagliaro

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Irene Tagliaro completed her MSc in chemistry science and technology at the University Milano-Bicocca (2015), Italy, where she also obtained a PhD in materials science in 2019. Later, she worked as consultant for small and medium enterprises (SMEs), until she returned as a post-doc to the University Milano-Bicocca at the ‘Surface Engineering and Fluid Interfaces Laboratory’ (SEFI Lab, [sefilab.mater.unimib.it](http://sefilab.mater.unimib.it)), led by Professor Antonini, working as project manager of SURFICE (smart surface design for efficient ice protection and control) an ITN-MSc project, where she coordinated the work of 13 PhD students located in different European countries and a Consortium of 10 institutes and several partners. In 2025, she became an assistant professor, developing her research interests in the fields of coatings, biopolymers and sustainable materials.

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