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Multiscale analyses and characterizations of surface topographies

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ABSTRACT

This work studies multiscale analyses and characterizations of surface topographies from the engineering and scientific literature with an emphasis on production engineering research and design. It highlights methods that provide strong correlations between topographies and performance or topographies and processes, and methods that can confidently discriminate topographies that were processed or that perform differently. These methods have commonalities in geometric characterizations at certain scales, which are observable with statistics and measurements. It also develops a semantic and theoretical framework and proposes a new system for organizing and designating multiscale analyses. Finally, future possibilities for multiscale analyses are discussed.

1. Introduction

Surfaces cover everything. Heat, mass, loads, and charge transfer across surfaces. Contact, wear and adhesion occur between surfaces. Cracks and degradation start at surfaces. Surfaces scatter, reflect, and absorb radiation. Wetting occurs on surfaces. These and other topographically related phenomena are considered.

Surface topographies influence many things, and almost all manufacturing processes influence surface topographies. Physical features of different sizes comprise topographies. These will often appear to be different when observed at different scales of observation, hence the need for multiscale considerations. An impressively comprehensive overview of surface generation, surface characterization, and surface function can be found in Whitehouse [189].

The study of surfaces has a long tradition within CIRP. The Scientific Technical Committee — Surfaces deals with research into the geometrical, physical, and chemical properties of the workpiece surface in relation to the production process. A number of excellent keynote papers have been produced throughout the years on the characterization of surfaces. In 2000 De Chiffre et al. gave an overview of characterization methods for surfaces, including 3D roughness parameters [64]. Three years later surface technologies related to micro and nanotechnology were presented, including discussions on characterization [63]. In 2008, Bruzzone et al. presented relationships between surface characteristics and their functional performance [48].

However, these excellent studies predate much of the work on multiscale analyses. Despite all the work on topographies, there is still a lack of experimental evidence of correlations or discrimination for many situations in which surface topographies are suspected of being involved. This is despite the multitudes of parameters available for characterization [4,60,83]. Traditional parameters appear to lack systemization [60,188] and can seem

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disconnected from each other and from design and manufacturing applications. It is also often unclear which parameters might be useful for a given situation [60]. Publications that suggest parameters for specific applications should cite experimental evidence with functional correlations for validation.

Here, the term multiscale analysis describes the process of studying topographies at multiple scales of observation, and comparing, merging, or associating the findings, acquired from observations or calculations at different scales. Conventionally, measured topographies are decomposed into a small number of scale ranges, e.g., roughness, waviness, and form [4], which are not sufficient to solve many of the problems addressed here. To be included in the discussions in this work multiscale analyses and characterizations must be applied intentionally, systematically, and in detail over a significant range of scales.

The results of multiscale analyses have the potential to add value and reduce costs in the design of products and processes. Multiscale analyses facilitate the understanding of relations between processing or performance and topographies. Multiscale analyses also can elucidate certain fundamental scales for surface interactions in physics, chemistry, and biology, and advance the understanding of many topographically related phenomena. Scale ranges from atomic to cosmic can be interesting.

1.1. Objectives

The objective of this work is to review multiscale analyses and characterizations of surface topographies, to discuss future possibilities and to synthesize a system for the organization and designation of multiscale analyses. Methods, applications, and associated insights are included, for a wide range of applications. Analyses and characterizations with potential that help solve manufacturing, tooling, quality assurance and process design problems are of particular interest. However, multiscale analyses and characterizations are also valuable for addressing scientific questions involving topographies in other fields, such as, geography, paleontology, and archaeology. In addition, the multiscale characterizations and analyses developed by researchers in these fields can be valuable when applied to industrial problems. Thus, a review of multiscale analyses and characterizations in the scientific literature is also included where appropriate.

Section 2 provides definitions of terms and concepts. Sections 3 and 4 review engineering and other multiscale applications. Section 5 provides a systematic synopsis of the methods. Section 6 includes syntheses and concluding remarks. Table 1 defines less common abbreviations that appear here in multiple, non-sequential paragraphs.

Table 1
Abbreviations particular to this study.

SI	Sampling interval — the spacing between measured heights reported in a measurement
SZ	Sampling width — the region over which a measured height is determined by the instrument
FD	Fractal dimension
CP	Characterization parameter — a metric that describes the topography
MC	Multiscale characterization — CPs that describe an aspect of the topography as a function of scale
MCSS	MC statistical summary — a characterization that summarizes the MCs that vary with position
MAC	Multiscale analysis for characterization — analysis done in order to calculate the values of MCs
MSA	Multiscale statistical analysis — analysis completed for correlation and discrimination based on MCs

2. Definitions and concepts

This section begins with basic terminology to build a semantic and theoretical framework for studying multiscale phenomena and advancing surface metrology as a scientific discipline.

Surfaces are thin, continuous regions that define a boundary in composition or phase. Abrupt physical and chemical gradients, that are normal to surfaces, define the boundaries of these regions. Topographies are collections of locations of surfaces.

2.1. Scales

The term "scale" has had many meanings in metrological studies. Scale can refer to the ratio of lengths on measurement renderings to the actual lengths on the actual surface. In this paper, and in much of the literature, scale refers to a segment of wavelengths or spatial frequencies. This segment, range or window, can be narrow when compared to the full size of a measurement. When scale is used without a modifier or with a single value, this segment is intended to be as small as the sensitivity in the measurement, be it linear, areal, or volumetric.

The concept of scale is often enmeshed with size. Topographic features of a given size will be best discernible when observed at certain scales. Thus, scale and size are often used interchangeably.

Scales are important. Topographically dependent behavior can be controlled by physical interactions taking place at multiple scales. Topographic modifications during fabrication or use (e.g., wear) can occur at multiple scales. The ability to understand the relationships between surface topographies and the phenomena that influence them, during manufacturing and use, depends on how topographies are measured, analyzed, and characterized at multiple scales. The scales that are useful for understanding interactions with topographies are generally not known a priori.

Strong functional correlations and confident discriminations are important for understanding how topographies should be specified to optimize products and manufacturing processes. These understandings can lead to better product and process designs and improved quality assurance and quality control.

Knowing the scales of interactions for topographically related phenomena is important. Many engineering surfaces must fulfil multiple functions that can require different kinds of topographies.

In certain situations, different functions can be adjusted by different topographic characteristics on the same surface. The different characteristics that control these functions can coexist on the same surface, at different scales. For example, road surfaces should be smooth at larger scales for a comfortable ride, and rough at finer scales, to provide friction for turning and stopping.

A systematic approach to solving these kinds of topographic design problems would involve determining the scales of the different interactions controlling the functions. The scales of these interactions could be determined by using multiscale analyses and characterizations appropriately.

2.2. Roughness and irregularity

Mandelbrot [117] titled the introduction to his autobiography 'Beauty and Roughness.' He noted that common patterns in nature are nearly all rough, having exquisitely irregular and fragmented aspects to them. The omnipresence of irregular roughness, its multiscale nature, and its complex influence on functionality are not always adequately considered, even in supposedly sophisticated experimental work.

Real, manufactured surface topographies tend to be irregularly rough at sufficiently fine scales. Many developments in manufacturing can be seen as efforts to push irregular roughness, and its inherent geometric uncertainty, to finer and finer scales. This irregularity can make the characterization of topographies particularly challenging. The values of geometric topographic characterization parameters (CPs) depend on the scales of the measurements and of the calculations in their computations. It could be that only a few of these scales are useful for understanding a particular topographically related phenomenon.

On irregularly rough surfaces, fundamental geometric properties, like area and curvature, change with scale. The appropriate scales for analyzing areas for heat or mass transfer, or for analyzing