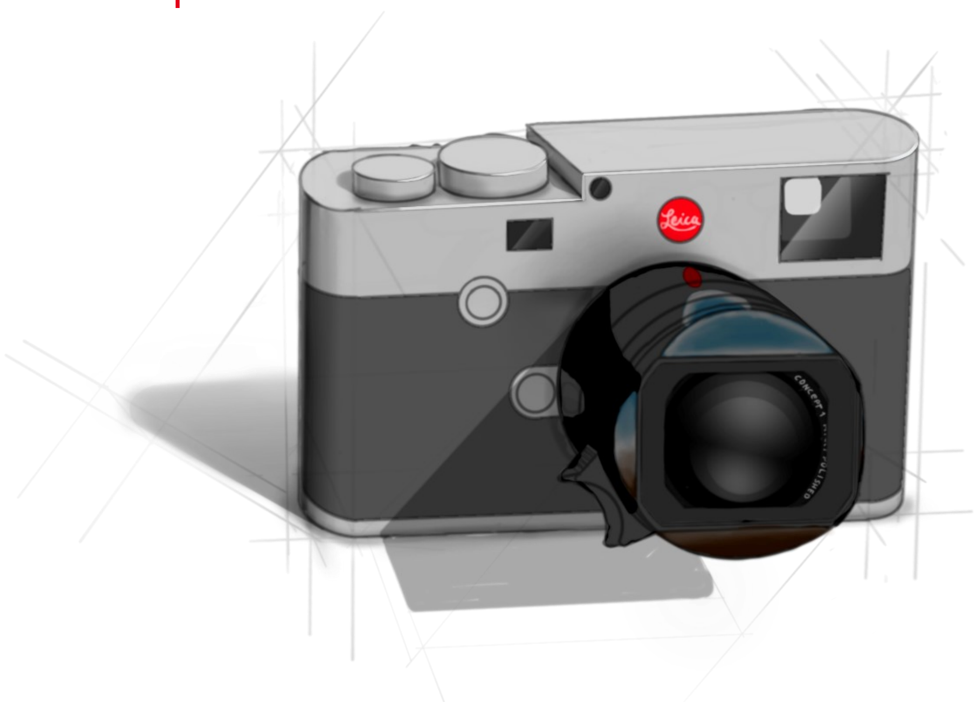
Industrial Design Engineering | University of Twente

Ceramic Surfaces as a Source of Luxury in Handheld Devices

A Study on the Physical Attributes that Predict Luxury and how to apply these in technical ceramics manufacturing



Michel D. Schmale

20.2.2024

ABSTRACT

This thesis investigates the potential of technical ceramics as a material for creating premium handheld products, with a specific focus on luxury camera components. Through a series of user studies, this work explores the relationship between surface attributes and the perception of luxury and premiumness. These insights, coupled with a comprehensive analysis of manufacturing processes, offer a valuable framework for understanding the feasibility of producing ceramic products that meet high-end consumer expectations.

The research revealed that material choice plays a significant role in consumer perception, with zirconia oxide ranking favourably across metrics for luxury and premiumness. Findings highlight the importance of surface smoothness and its positive correlation with perceived value. Additionally, attribute combinations (such as smooth and glossy) were also identified as having a significant impact on user perception. Manufacturing limitations and opportunities were a key focus. Injection moulding and green machining emerged as ideal methods for achieving the desired surface qualities. While challenges in sourcing ceramic samples were encountered, this thesis adapted its approach, incorporating a design case study focused on a special edition camera lens. This exploration emphasized the advantages of technical ceramics for innovative product design.

This work offers Leica insights into consumer perceptions and the practical considerations for integrating technical ceramics into their offerings. Future research directions include refining the attribute-perception relationship across various product categories, exploring novel ceramic manufacturing techniques, and investigating the potential for technical ceramics in diverse applications.

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to those who have supported me throughout this thesis project.

To my parents and siblings, thank you for your constant love and encouragement. Your belief in me has been a driving force.

I am grateful to my supervisors at the University of Twente, Emile, and Dave, for their guidance and valuable feedback. Your insights have been essential to the development of this work.

Thank you to Sam at Leica for his mentorship and support. Your knowledge and expertise have significantly contributed to my learning experience.

I appreciate the help and guidance I've received from all of you. Thank you for your role in this journey.

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

1 INTRODUCTION

1.1 CONTEXT

Figure 1 Leica M-A "Titan"

This master's thesis explores the potential of ceramics as a luxurious material within the context of high-end camera design. The investigation stems from the desire to create a special edition Leica camera lens featuring a material uncommon in their product line and will also consider the ways in which ceramics can embody the qualities of luxury.

Leica Camera, a leading manufacturer of premium cameras and optical devices, has a rich history dating back to 1869. Founded by Ernst Leitz as an optical institute, the company revolutionized photography in 1925 with the Leica I, the first commercially successful 35mm film camera. Leica's commitment to quality and innovation is reflected in their range of products, including rangefinder, mirrorless, and SLR cameras tailored to varying market segments.

The company's strategy of producing limited edition cameras serves multiple purposes. These exclusive releases reinforce Leica's luxury brand image while providing a platform for exploring new manufacturing techniques, materials, and surface finishes. Limited editions often boast distinctive aesthetics, premium materials, and collaborations with renowned artists—exemplified by the titanium Leica M-A "Titan," (see Figure 1), the Leica Q2 Daniel Craig x Greg Williams, and the Leica M10-P "Reporter." These special models underscore the inherent link between material choice and the perception of luxury.

Ceramics, known for their hardness, heat resistance, chemical stability, and diverse properties, remain relatively unexplored in the realm of consumer camera products. Their unique aesthetics, potential for exceptional finishes, and implied durability make ceramics a compelling material for potential Leica limited editions. This thesis will delve into how ceramics might embody luxurious qualities, alongside the manufacturing complexities and potential impacts on camera weight, feel, and functionality.

1.2 RESEARCH OBJECTIVES

This project has three primary objectives designed to provide Leica with both a theoretical foundation and actionable design concepts.

The first goal focuses on exploring the feasibility, processes, and design guidelines essential for integrating ceramic and ceramic-like components into handheld devices. This investigation will delve into how the unique properties of ceramics (hardness, friction, heat resistance, and diverse finishing potential) could translate into tangible benefits for device durability, longevity, and overall user experience. The aim is to uncover not only the manufacturing methodologies suited to this material but also the critical design considerations and potential limitations Leica must address when incorporating ceramics into their product line.

The second goal seeks to deepen the understanding of how consumers define "luxury" and "premium" specifically within the context of handheld devices. This involves conducting a thorough analysis of both market trends and direct consumer feedback, exploring the complex interplay between physical surface attributes (texture, colour, finish, etc.) and the intangible perceptions of luxury. The aim is to develop a comprehensive framework that designers can employ to intentionally infuse handheld devices with qualities that resonate with consumers' desires for exclusivity and high value.

The third goal is to synthesize insights gained from the first two objectives, ultimately creating innovative, ceramic-inspired lens designs that embody Leica's established brand identity. These designs will place a strong emphasis on design for manufacturability, ensuring their aesthetic appeal is matched by practical feasibility. Beyond the designs themselves, this goal will provide Leica with valuable insights and future directions, offering a robust starting point for the potential development of a ceramic special edition lens that would redefine handheld camera luxury.

While the initial project envisioned direct experimentation with ceramic components, challenges in securing suppliers and materials within the project's budget constraints led to a pivot in focus. This adaptability, rather than hindering the project, opened new and valuable research avenues. It allowed for an in-depth exploration of real-world manufacturing limitations and the identification of alternative solutions, offering Leica expanded possibilities for considering ceramic inclusion. Additionally, by researching ceramic-like surface coatings, the project investigates cost-effective paths for achieving the luxurious textures and finishes associated with ceramics, further broadening Leica's design toolkit. This adaptability underscores the commitment to generating knowledge that is both theoretically sound and practically applicable for Leica. Constraints were strategically navigated, leading to a deeper dive into the potential applications of ceramic technologies and associated design thinking.

2 LITERATURE REVIEW

2.1 INTRODUCTION

This literature review delves into the academic literature that explores the perception of luxury and premium as it relates to product surfaces. The motivation behind this review is to investigate the potential of new materials, such as ceramics, in the creation of luxurious products.

To do this, first it the defining characteristics of luxury need to be understood. Additionally, how different surface types are perceived by various demographics, and the range of surface types achievable through ceramic manufacturing. This aligns with the first goal of the project, which is to explore the feasibility, processes, and design guidelines needed to create premium/luxury ceramic parts and ceramic-like parts in handheld devices.

The ultimate objective of this review is to identify gaps in the existing literature, particularly in the area of luxurious surface perception. By understanding these components and designing a study to address these gaps, I aim to achieve the goals of this project.

The review will be structured in three parts:

1. A review of literature on surface perception,
2. An exploration of how luxury is defined, and
3. A review of ceramic manufacturing literature, focusing on potential manufacturing processes.

Through this comprehensive review, I hope to lay a solid foundation for this thesis and contribute to the understanding of luxury perception in relation to product surfaces. This will also provide valuable insights into the feasibility and processes of creating ceramic parts, contributing to the achievement of the first goal of this project.

2.2 METHODOLOGY

The methodology for this literature review follows a common approach often seen in academic papers and graduate theses. This approach involves synthesizing the existing literature on the topic and identifying gaps in knowledge that the thesis aims to address. The process begins with a comprehensive search of the existing literature on the three key topics: the perception of product surfaces, the nuances distinguishing 'luxury' and 'premium' in consumer hardware, and the manufacturing processes of technical ceramics parts for consumer hardware. The sources include academic journals, industry reports, and other relevant publications.

The selected literature is then thoroughly reviewed and synthesized. This synthesis involves drawing together findings from different sources, comparing theories, and identifying patterns and trends in the research. This process helps to provide a theoretical foundation for the thesis and validates the presence of the research problem.

The review also aims to justify the research as one that contributes something new to the cumulated knowledge. It does this by highlighting gaps in the current literature and suggesting areas for future research. The methods and approaches used in the review are validated through this process. The methodology used in this review is designed to ensure a thorough and rigorous analysis of the literature on the chosen topics. It aims to provide a comprehensive understanding of the current state of knowledge and identify areas where further research is needed.

This methodology is based on established practices in literature review conduct, as described by [1], [2], [3]

2.3 PERCEPTION OF SURFACES

2.3.1 Surface Attributes

Understanding Product Surface Attributes

Product surfaces hold crucial importance in how users perceive and interact with products. They significantly contribute to a product's aesthetic value, perceived quality, and functionality. Exploring the specific attributes used to describe product surfaces sheds light on how to achieve both user satisfaction and communicate design intent.

Key Product Surface Attributes

Researchers have identified two main categories of attributes influencing the user experience with product surfaces:

- Sensory Attributes: These directly relate to our senses – how a surface looks, feels, sounds, and even potentially smells or tastes.
- Symbolic Attributes: These convey meaning and associations beyond the immediate physical experience. A surface may feel "aggressive," look "Expensive" or project a sense of "Masculinity”.

Johnson et al. [4] provide a valuable framework for understanding surface attributes and how designers can apply them. Their study, which involved compiling a vocabulary of sensory and symbolic attributes from design reviews and descriptions, tested and refined this vocabulary through an experiment with design students. It underscores the importance of a shared vocabulary to express the aesthetic and perceptual qualities of products. The research revealed a degree of consensus on how these attributes are applied, and significantly, highlights the strong influence of material choices on aesthetic perception. Johnson et al. [4] also note that form and context can reshape the symbolic meanings associated with a material.

Building upon this foundation, Vihma et al. [5] investigate the use of sensory and symbolic attribute lists among design students. This study refines the existing vocabulary (see Figure 2) and suggests areas for further development. Crucially, their work reinforces the notion that product context plays a significant role in how specific attributes are understood by users.

Aesthetic (sensory) attributes (**bold face** = significantly selected in previous experiment)		Perceived (symbolic) attributes (**bold face** = significantly selected in previous experiment, parenthesis = close to being significant)	
Feel: **Soft**, **hard**, warm **cold**, light, heavy, flexible, stiff Texture: Smooth, rough, rubbery, slippery Form: **Organic**, **angular**, **aerodynamic**, flat, squared, rounded Smell: Fresh, stale, natural, **artificial**	Optics: Transparent, translucent, **opaque**, **reflective** Colour: Clear, white, muted colours, bright colours, grey/black, metallic, natural Taste: Sweet, sour, salty, bitter Sound: **Muffled**, ringing	**Aggressive** – Passive **Cheap - Expensive** Classic - **Trendy** Clinical- Cosy **(clever) - (silly)** **(Common) – Exclusive** Decorated – Minimal Delicate – Rugged Anonymous – Inviting Elegant - Clumsy **Masculine – feminine**	Formal – Informal Fragile – Robust Friendly - Frightening **Functional** - ornamental **(Futuristic)** - historic Handmade - **Mass-produced** High-tech – Simple Humorous - Serious Mature - **Youthful** Restrained – Extravagant Temporary – Permanent
Words deleted from the initial list: **Industrial**		Words deleted from the initial list: **Clean, (Dull), Strong**	

Table 1. The revised vocabulary from the previous experiment (Johnson et. al 2003). Words used by a significant number of the participants to describe the 6 products in Figure 1 are shown in boldface.

Figure 2 Grouped surface attributes from [5]

Applications

By understanding and working with these assigned attributes, designers have the tools to:

- Communicate Design Intent: A shared vocabulary around product surface attributes bridges the gap between a designer's concept and the user's understanding.
- Shape User Perception: Designers can carefully select materials, textures, and finishes to evoke desired user responses and contribute to the perceived luxury of a product.
- Evaluate Design Outcomes: Attributes provide a measurable way to assess whether a design successfully meets its aesthetic and functional goals.

Implications for this thesis

While there is valuable exploration in this area, it's important to remember that the meaning of product surfaces is never fixed. Cultural perspectives, individual preferences, and changing trends demand an adaptable vocabulary and continued research. During the preparation of a user study, select attributes from this framework will be used to fit the context of handheld premium devices.

2.3.2 PERCEPTION OF PRODUCT SURFACES

Product surfaces act as gateways to our initial product encounters, shaping early impressions of quality, functionality, and aesthetic appeal. To design effectively for positive experiences, we must delve into the senses involved in this perception and how those processes shift based on context and individual traits.

The Multisensory Nature of Perception

Surface perception is rarely confined to a single sense. Studies demonstrate a complex interplay between vision, touch, smell, and even taste that influences how we respond to an object [6], [7]. Klatzky and colleagues highlight that, while touch alone draws focus to texture and hardness, combined with vision, attention expands to include shape and other broader attributes. Interestingly, taste itself can be heavily influenced by touch when surface patterns alter perceptions of a drink's sweetness or intensity [7].

Contextual Influences

External factors profoundly impact how we process surface cues. Peck and Childers [8], [9] show that whether buying online or in person, factors like the availability of haptic interaction change how an individual uses, values, and trusts touch-based product information. For instance, an inability to touch might reduce reliance on this sense while heightening reliance on visual cues or written descriptions when evaluating objects. Ranaweera and colleagues [10] point to another contextual influence—that our expectations around an object's weight and texture significantly impacts how we perceive personality traits like sophistication or playfulness.

Individual Differences & the Need for Touch

No two individuals perceive surfaces identically. Our sensitivities to tactile input, along with other personal preferences, shape our interaction with products. The concept of Need for Touch (NFT), formulated by Peck and Childers [8], [9], emphasizes individual differences in the desire to acquire product information through physical touch. People high in "autotelic" NFT enjoy the sensory pleasure of touching, while those high in "instrumental" NFT focus on touch as a functional information-gathering tool. NFT level has strong implications for how consumers respond to haptic marketing elements [11].

Implications & Opportunities

- These insights reveal key takeaways for design practice:
- Surfaces are multisensory communicators. Strategic sensory design must account for how attributes from touch, sight, and even taste might come together.
- Context changes everything. Designers must anticipate situational variables, both restrictions (a display case) and how product context informs perceptions of surface features.
- "One size fits all" can rarely apply. Knowing the target audience, including their sensory sensitivities and their need for touch, helps curate effective surface experiences.

Building on this established knowledge, this thesis aims to explore surface perception within the high-stakes realm of luxury goods. It specifically seeks to:

- Identify Key Attributes: Establish which combinations of sensory attributes (texture, weight, pattern, etc.) most strongly align with consumer definitions of luxury.
- Inform Design Recommendations: Provide data-driven recommendations for creating surfaces that effectively elicit feelings of luxury, tailored to diverse consumer segments.
- Contextual Considerations: Since context influences perception, consider how variations in the experimental setup (e.g., physical product interaction vs. visual representations) might impact data collection.

2.3.3 CONCLUSION

This part of the literature review underscores the vital role of product surface attributes in shaping consumer experiences. Materials, textures, and patterns convey much more than aesthetic qualities; they impact how a product feels, what it symbolizes, and ultimately, how it's perceived. Moreover, perception is revealed as a multi-layered process. Multiple senses intertwine, while individual preferences, like the need for tactile information, along with contextual factors, all influence how surface features are interpreted.

2.4 LUXURY AND PREMIUM

The concepts of "luxury" and "premium" hold significant sway in marketing, branding, and consumer behaviour. Yet, a universal definition for either term remains elusive. Their subjective nature, shaped by individual preferences, cultural contexts, and product categories, contributes to this complexity.

While premium products typically embody superior quality and above-average pricing [12], the meaning "'premiumness' takes on many different forms for different people and is dependent on the mood and experience of the consumer" [13]. The challenge of definitively classifying "luxury" is noted by Kapferer [14], who highlights that many definitions neglect to specify the essential characteristics that categorically define a product as luxurious.

Some definitions adhere more rigorously to definitional standards. Dubois et al. [15] propose six facets of luxury: high price, superior quality, scarcity, refined aesthetics, heritage/personal history, and superfluousness. Kapferer notes potential contention around "superfluousness," as some individuals might classify luxuries as necessities instead. De Barnier et al. [16] offer a multidimensional approach, identifying seven factors (elitism, creativity, uniqueness, distinction, refinement, quality, and power) that distinguish levels of luxury – with elitism holding primary importance.

Cultural perceptions of luxury can also differ. Kapferer's work [17] reveals "high quality" as a common cross-cultural association (see Figure 3). However, in China, "expensive" is the dominant attribute. This underscores the need for marketers to understand these nuanced variations. Kapferer et al. [18] further illuminate strategic distinctions with a positioning triangle that delineates different business models for luxury, premium, and fashion (see Figure 4).

TABLE 1.1 Meaning evoked by the word 'luxury' for consumers in six countries (n = 3,085)

	France	United States	China	Brazil	Germany	Japan
1	high quality	high quality	expensive	high quality	high quality	high quality
2	prestige	expensive	high quality	pleasure	expensive	prestige
3	expensive	prestige	fashion	dream	fashion	expensive
4	pleasure	pleasure	minority	expensive	dream	intemporal

Figure 3 Meaning evoked by the word 'luxury' for consumers. From [17]

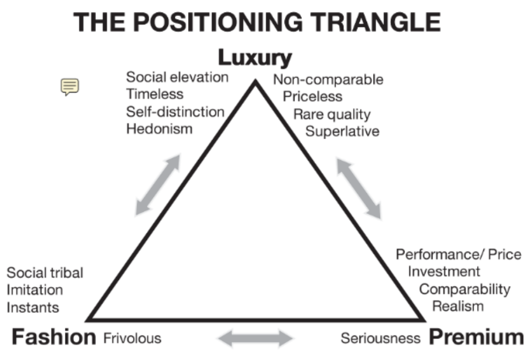


Figure 32.2 Positioning of three business models

Source: Adapted from Kapferer and Bastien, *The luxury strategy* (2012: 32), with permission.

Figure 4 Positioning triangle from [18]

In the Australian context, a study [19] found that premium price, an authentic/reliable brand, and positive brand reputation/status constitute primary luxury attributes. Interestingly, premium pricing becomes an expected rather than a defining element once other luxury indicators are present.

Synthesis, Implications, and Thesis Connection

Luxury and premium are dynamic concepts shaped by a confluence of individual perception, culture, product type, and evolving trends. Marketers face the vital task of grasping this complexity to tailor strategies effectively. A deep understanding of consumer-specific preferences for defining luxury and premiumness enables precise segmentation, targeting, and product offerings that harmonize with expectations.

The thesis probes a knowledge gap – the definitive link between surface attributes and their perception as premium or luxurious. Specifically, it will explore:

- Innovative Ceramic Surfaces: Can newly developed technical ceramic surfaces satisfy consumer expectations for the luxurious and premium qualities of materials?
- The Aesthetic Dimension of Premiumness: How do product aesthetics (shape, symmetry, etc.) influence both luxury and premium perceptions?

Conclusion

The thesis will further explore how the differences of luxury and premium manifest in the context of handheld devices. With focus on the role of surface attributes (form, finish, texture, etc.), the study will examine consumer perceptions of both terms and how they influence evaluations of a technical ceramic device. To assess potential nuances in meaning, both the terms "luxury" and "premium" will be employed throughout the different studies. The subsequent chapters will delve deeper into the research fields that underpin this exploration of material perceptions and their relationship to luxury and premium experiences.

2.5 TECHNICAL CERAMICS MANUFACTURING

From pots and other vessels made of clay to heat-resistant and durable tools for metalworking, ceramics have been essential for making various products that we use every day. Ceramics have also played a key role in enabling the progress of metallurgy by facilitating the production of early metals such as bronze [20]. In contrast to these traditional ceramics, which are mainly based on natural raw materials, technical ceramics are engineered from synthetic compounds to achieve better properties and functions. Technical ceramics are known for their high strength, hardness, and resistance to wear and corrosion [20], [21], [22]. They are also non-conductive and can withstand high temperatures, making them ideal for use in harsh environments. However, ceramics also pose some challenges for manufacturing, such as high costs, complex processes, and limited design options. Therefore, it is important to explore the current research into ceramic materials and production methods for general ceramic manufacturing, with a focus on their application to low volume luxury consumer products. In accordance with the first two goals of the thesis the main research questions that this literature review aims to answer are:

How to design and produce ceramic parts for luxury consumer products in small batch sizes?

How are luxurious product surfaces perceived?

To answer this question, this literature review will examine scholarly sources from various disciplines, such as materials science, engineering, design, and marketing. The sources will be selected based on their relevance, currency, authority, accuracy, and purpose. The sources will be divided into four main themes that correspond to the sub questions of the main research question:

- What are the different types of ceramic materials used in manufacturing and what are their properties?
- What are the different manufacturing methods used to produce ceramic parts and what are their advantages and disadvantages?
- What are the design considerations for ceramic parts and how can they be optimized for efficient production?
- What are the consumer preferences and market trends related to ceramic products?

Within each theme, the sources will be analysed and synthesized to identify the key findings, debates, gaps, and implications for future research.

The structure of this literature review is as follows: The first section will discuss the different types of ceramic materials used in manufacturing and their properties. The second section will review the different manufacturing methods used to produce ceramic parts and their pros and cons. The third section will explore the design considerations for ceramic parts and how they can be designed for efficient production. The fourth section will examine the consumer perspective and market trends related to ceramic products. The final section will summarize the main points of the literature review and suggest directions for future research.

2.5.1 CERAMIC MATERIAL REVIEW

Ceramic materials are a diverse and complex group of materials that are difficult to define based on a single property or characteristic. As [23] and [24] point out, most definitions of ceramic materials simply state what they are not, rather than what they are. A common definition is that ceramic materials are non-metallic, inorganic solids that have a wide range of applications and properties. Ceramic materials can be classified into two main categories: traditional ceramics and advanced ceramics. Traditional ceramics are those that have been used by ancient civilizations for pottery, bricks, tiles, and other products. Technical ceramics [20] are those that have been developed in recent decades for high-tech applications such as electronics, aerospace, biomedical, and energy.

One of the potential applications of ceramic materials is in luxury consumer products such as watches, jewellery, and tableware. These products require ceramic materials that have high aesthetic appeal, durability, and biocompatibility. However, not all ceramic materials are suitable for this application, as some of them have drawbacks such as brittleness, low fracture toughness, and difficulty in machining. Therefore, it is important to select the ceramic materials that have the right properties for the desired product.

Some of the properties that are relevant for luxury consumer products are mechanical, thermal, optical, and chemical properties. Mechanical properties include hardness, strength, fracture toughness, and wear resistance. These properties determine how well the ceramic material can resist deformation, fracture, and abrasion. Thermal properties include thermal conductivity, thermal expansion, and thermal shock resistance. These properties determine how well the ceramic material can conduct heat, expand or contract with temperature changes, and withstand rapid temperature changes. Optical properties include colour, transparency, reflectivity, and refractivity. These properties determine how the ceramic material interacts with light and affects the appearance of the product. Chemical properties include corrosion resistance, biocompatibility, and environmental impact. These properties determine how the ceramic material reacts with other substances and affects the health and safety of the user and the environment.

Based on these properties, some of the ceramic materials that are suitable for luxury consumer products are ceramic oxides, such as zirconium oxide (ZrO_2/zirconia) and aluminium oxide

(Al_2O_3/alumina). These materials have high hardness, strength, fracture toughness, and wear resistance, which make them durable and scratch resistant. They also have moderate thermal conductivity, low thermal expansion, and high thermal shock resistance, which make them stable and resistant to cracking. They have various colours, transparencies, and reflectivities, which make them attractive and versatile. They have high corrosion resistance, biocompatibility, and environmental friendliness, which make them safe and sustainable.

However, zirconia and alumina have some differences in their properties, which may affect their suitability for different products. Zirconia has higher fracture toughness and strength than alumina, which make it more resistant to breaking. However, zirconia also has lower thermal conductivity and higher thermal expansion than alumina, which make it more prone to thermal stress and distortion. Zirconia also has higher refractivity than alumina, which make it more reflective and less transparent. Alumina has higher hardness and thermal conductivity than zirconia, which make it more resistant to scratching and heat transfer. However, alumina also has lower fracture toughness and strength than zirconia, which make it more brittle and prone to cracking (see Figure 5). [21]

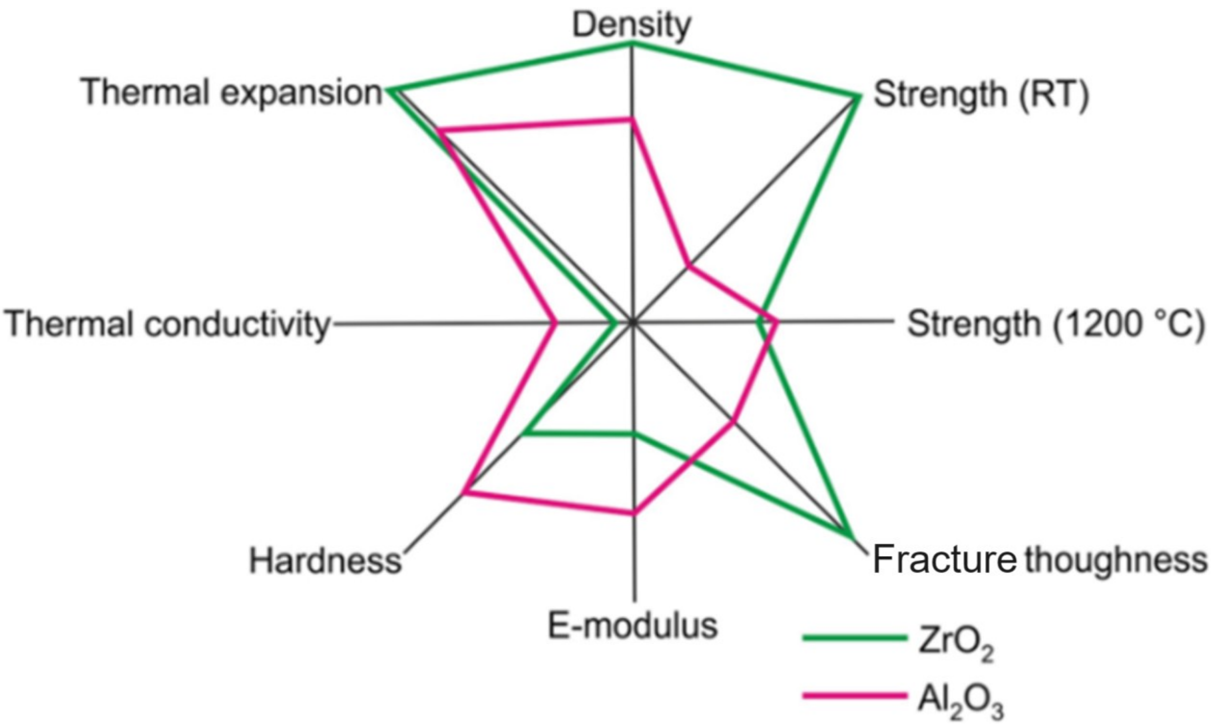


Figure 5 Image taken from [21]

Therefore, the choice between zirconia and alumina depends on the specific product and the trade-off between the properties. For example, for a watch case, zirconia may be preferred over alumina because of its higher fracture toughness and strength, which make it more durable and shock resistant.

In conclusion, ceramic materials are a promising option for luxury consumer products because of their high performance and aesthetic appeal. However, not all ceramic materials are suitable for this application, and the selection of the most appropriate material depends on the product and the properties. Zirconia and alumina are two of the most widely used ceramic oxides for luxury consumer products, but they have different advantages and disadvantages that need to be weighed carefully. Future research and development may focus on improving the properties of ceramic materials, creating new ceramic materials, and optimizing the design and fabrication of ceramic products.

2.5.2 PRODUCTION METHODS

Ceramic materials are widely used in luxury consumer products such as watches, jewellery and tableware because of their aesthetic appeal, durability, and biocompatibility. However, producing ceramic parts for these products is not a trivial task, as it involves several stages of processing, each with its own challenges and requirements. The ceramic production process typically consists of three main stages: shape forming, sintering, and post processing. Each stage affects the properties and quality of the ceramic parts, such as the density, strength, hardness, fracture toughness, wear resistance, colour, and surface finish. Therefore, it is important to understand the different methods and technologies that can be used in each stage and how they influence the final product.

This chapter aims to answer the following research question: What are the different manufacturing methods used to produce ceramic parts and what are their advantages and disadvantages? To answer this question, the chapter is divided into three sub-chapters, each covering one of the main stages of ceramic production. The first sub-chapter will discuss the shape forming stage, where the ceramic powder is compacted into a desired shape by applying pressure or other techniques. The second sub-chapter will discuss the sintering stage, where the compacted powder, also known as the green body, is heated to a high temperature below its melting point to consolidate the powder particles and improve the mechanical properties. The third sub-chapter will discuss the post processing stage, where the sintered body is polished, coated, or decorated to enhance the appearance and performance of the ceramic part.

In addition to the conventional methods and technologies for ceramic production, the chapter will also include emerging methods and technologies that offer new possibilities and opportunities for ceramic parts. These include additive manufacturing (AM), laser processing, and microfabrication. These methods and technologies can create ceramic parts with complex geometries, fine details, and internal structures that are difficult or impossible to achieve by traditional methods. They can also reduce the material waste, energy consumption, and production time and cost compared to traditional methods. However, they also have some limitations and challenges, such as the availability and quality of the ceramic powder, the control and stability of the process parameters, and the compatibility and integration with other stages of ceramic production.

2.5.2.1 SHAPE FORMING

Shape Forming is a key process step in the manufacture of ceramic parts. There are several different shape forming processes that can be used to produce these parts, including pressing, casting, plastic forming and additive manufacturing. In this section of the literature review, there will be an overview of each of these processes and highlight relevant processes that can be used for the application of luxury tech products.

Pressing

Pressing is one of the most widely used methods for shape forming of technical ceramics. It involves compacting ceramic powder into a desired shape by applying pressure in a die. The powder is usually pre-mixed with suitable binders and lubricants to improve its flowability and cohesion. The pressure can be applied in one direction (uniaxial pressing) or in all directions (isostatic pressing). Uniaxial pressing is simpler and cheaper, but it may result in uneven density and shape distortion. Isostatic pressing is more complex and expensive, but it produces more uniform and complex shapes. Pressing can be used to manufacture feedstock for green machining or hard machining, or to produce simple finished green bodies that only require sintering [22], [25].

Casting

Casting is another method for shape forming of technical ceramics. It involves pouring a liquid slurry of ceramic powder and binder into a mould and letting it solidify. The mould can be made of plaster, metal, rubber, or other materials. The most common type of casting is slip casting, where the slurry is poured into a porous mould that absorbs some of the liquid and forms a thin layer of solidified ceramic on the mould surface. The excess slurry is then drained, and the cast is removed from the mould. Casting can produce complex and intricate shapes, but it may also have defects such as cracks, shrinkage, and bubbles. Casting is not very relevant for the topic of this thesis, as it is mainly used for traditional ceramics such as pottery and porcelain [22].

Plastic Forming

Plastic forming is a method for shape forming of technical ceramics that uses a plastic mixture of ceramic powder and additives. The mixture can be shaped by applying pressure or by extruding, rolling, or drawing. The additives can be water, organic materials, or other fluids that provide plasticity and lubrication. Plastic forming can produce flexible and continuous shapes, but it may also have problems such as drying, cracking, and contamination. Plastic forming is not very relevant for the topic of this thesis, as it is mainly used for clay-based ceramics such as earthenware and stoneware [22], [26].

Additive manufacturing

Additive manufacturing (AM) is a promising method for shape forming of technical ceramics. It involves building a part layer by layer from ceramic powder using a computer-controlled process such as laser sintering, binder jetting, or extrusion. AM can produce parts with complex geometries, fine details, and internal structures that are difficult or impossible to achieve by conventional methods. AM also reduces the material waste, energy consumption, and production time and cost compared to traditional methods. AM enables greater product customization and innovation, as it allows the design and fabrication of parts that meet specific customer requirements and preferences. AM is especially relevant for the topic of this thesis, as it can create ceramic products with high aesthetic appeal, functionality, and performance [22], [27].

Green machining

Green machining is a process in which ceramic parts are machined in an unfired state prior to sintering. Green machining can be performed using conventional tools and machines such as milling, drilling, turning, and grinding. Green machining can offer several advantages over hard machining, such as lower cost, greater flexibility, and easier geometry control. Green machining can also reduce material waste and improve the dimensional accuracy and surface finish of sintered parts. However, green machining also has some limitations, such as the need for proper handling and clamping of the fragile green parts, the possible deformation and shrinkage during sintering, and the difficulty of machining some types of ceramics with high binder content or low green strength [22].

2.5.3 SINTERING

Sintering transforms the shaped ceramic 'green body' into a dense, robust material using heat below the ceramic's melting point. During sintering, critical parameters like temperature, time, and atmospheric composition can profoundly affect the resulting properties of the ceramic. For luxury products, sintering choices directly influence a consumer's perception through characteristics such as durability, weight, and most prominently, colour. [22], [28]

The sintering atmosphere plays a pivotal role in determining the final colour of the ceramic. Take zirconium oxide as an example: depending on oxygen levels and gases present during sintering, it can manifest as white, various shades of brown, or even black [29]. Adding specific components, like titanium, to the ceramic mixture provides another avenue for controlling colour during sintering [29]. These colour possibilities impact both aesthetic appeal and product design options. Sintering also affects aspects like porosity and surface texture, potentially altering the consumer's tactile experience with a luxury product.

Understanding and carefully controlling the sintering process is therefore vital to achieving the desired visual and physical qualities required for luxury ceramic products.

2.5.4 POST PROCESSING

After the ceramic parts have been sintered and have reached their full strength and density, they can be further machined in a process called final machining. This process can use ultra-hard tools and machines such as grinding, lapping, polishing, honing and ultrasonic machining to achieve higher precision, better surface finish and more complex geometry than green machining. Final machining can also improve the mechanical properties and performance of ceramic parts by removing surface defects and residual stresses. However, final machining also has some limitations, such as high cost, low material removal rate and possible damage to the ceramic parts due to their brittleness and hardness [22].

For the application of luxury consumer products, such as watches, jewellery and tableware, final machining is an important stage to ensure the quality and attractiveness of the ceramic parts. The processes that are relevant for this application are those that can produce smooth, glossy, and scratch-resistant surfaces, as well as those that can create intricate and detailed patterns, such as engraving. Some of the processes that can achieve these goals are:

Polishing: Polishing is a process that uses abrasive materials, such as diamond, alumina, or silica, to remove the surface roughness and improve the reflectivity and transparency of the ceramic parts. Polishing can be done by hand or by machine, using different techniques such as buffing, tumbling, or vibratory finishing. Polishing can enhance the aesthetic appeal and the wear resistance of the ceramic parts, but it may also introduce micro-cracks and stresses that can reduce the strength and fracture toughness [22].

Engraving: Engraving is a process that uses a tool or a beam to cut or mark the surface of the ceramic parts with a desired design or text. Engraving can be done by mechanical or non-mechanical methods, such as electrical discharge machining (EDM), laser, milling, or etching. EDM uses a high-voltage spark to erode the material, laser uses a high-energy beam to vaporize the material, milling uses a rotating cutter to remove the material, and etching uses a chemical or physical agent to dissolve the material. Engraving can create unique and personalized ceramic parts, but it may also affect the surface integrity and the mechanical properties of the material [30], [31].

Among these engraving methods, EDM, laser, and milling are more suitable for ceramic materials than etching, as they can produce more precise and accurate results, as well as avoid the environmental and safety issues associated with etching. However, these methods also have some drawbacks, such as high cost, low speed, and possible thermal damage to the ceramic parts [30], [31].

Final machining is a necessary and beneficial stage for the production of ceramic parts for luxury consumer products, as it can improve the appearance and the performance of the parts. However, final machining is also a challenging and costly stage, as it requires special tools and machines, as well as careful control and optimization of the process parameters. Therefore, it is desirable to reduce the final machining process as much as possible.

2.6 CONCLUSION

Technical ceramics offer a compelling array of material properties and manufacturing possibilities, opening a realm of design opportunities within the luxury product space. As this literature review has demonstrated, perception is complex: surface elements carry symbolic weight, trigger tactile responses, and are evaluated amidst a web of individual and contextual factors. Therefore, understanding how to shape, sinter, and refine technical ceramics demands a nuanced perspective that marries material knowledge with consumer insights.

The distinction between "luxury" and "premium" further underscores the need to analyse perception at multiple levels. While premiumness emphasizes superior quality and performance, true luxury resides in aspects like exclusivity, heritage, and the ability to evoke a profound emotional experience.

Building on this multi-faceted view of perception, subsequent chapters embark on two interrelated investigations:

- Research into Surface Perception: Experimental research will explore how consumers evaluate different product surfaces, identifying the specific material qualities and finishes that resonate most strongly with the notions of luxury and premium. This understanding will provide direction for manufacturing choices.
- Design for Manufacturing technical ceramics Analysis: Informed by the literature and insights from perceptual studies, the thesis will develop guidelines for luxury ceramic product design and manufacturing. Case studies will apply these principles, balancing small-batch realities, desirable surface attributes, and optimized production techniques.

This research seeks to empower the design and production of technical ceramic products that not only excel in performance but also embody the essence of luxury and premiumness in a contemporary context.

3 RESEARCH INTO SURFACE PERCEPTION

3.1 INTRODUCTION

This chapter embarks on a multi-faceted investigation with two interconnected aims. The first goal is to illuminate the relationship between material surface attributes, their perception by consumers, and feasible manufacturing methods within the domain of luxury technical ceramic handheld devices. A second vital focus aligns with this thesis' broader investigation into how the concepts of "luxury" and "premium" are embodied in handheld products. Here, surface characteristics will be linked to how these prestigious qualities are perceived.

The research strategy unfolds as follows:

- **Study 1: Online Survey - Material Preferences** This initial survey gauges consumer interest in various materials used in luxury tech. Exploration of factors like aesthetics, perceived exclusivity, and linked values reveals which materials intrinsically project these key qualities to a broad audience.
- **Study 2: Online Survey - Surface Attribute Descriptions** Descriptions of desirable surfaces commonly found in luxury objects (watches, cameras, etc.) will be collected from consumers using this second survey. This builds a rich lexicon of sensory and tangible terms crucial for later evaluation of ceramic surface variations.
- **Study 3: Multi-Sensory Material Evaluation** Here, participants directly handle sample objects with varied surface finishes. They'll evaluate these against identified attributes from Study 2, alongside perceived luxuriousness and premiumness. Analysis of these correlations reveals which specific surface qualities most powerfully evoke these highly valued perceptions.

Linking Research to Thesis Goals

These interlinked studies directly bolster the second core goal of this thesis. Studies 1 and 2 inform the analytical lens applied in Study 3 to assess various ceramic surface treatments. Findings from this pivotal study provide a basis for:

Identifying Key Surface Attributes: Understanding how "luxury" and "premium" are reflected in tangible textures, colours, and other material qualities informs selection.

Bridging Perception & Practice: Outcomes from Study 3 will be considered alongside feasible production methods. If, for example, specific surface attributes show strong consumer resonance, ideal manufacturing techniques to achieve them within technical ceramic capabilities under luxury small-batch constraints will be explored.

Fundamentally, this chapter explores the potential of technical ceramics to serve as an expressive medium for premium handheld products. Understanding and translating consumers' expectations driven by perceived surface characteristics is crucial for unlocking this potential.

3.2 CUSTOMER SURVEY HIGH TECH MATERIALS

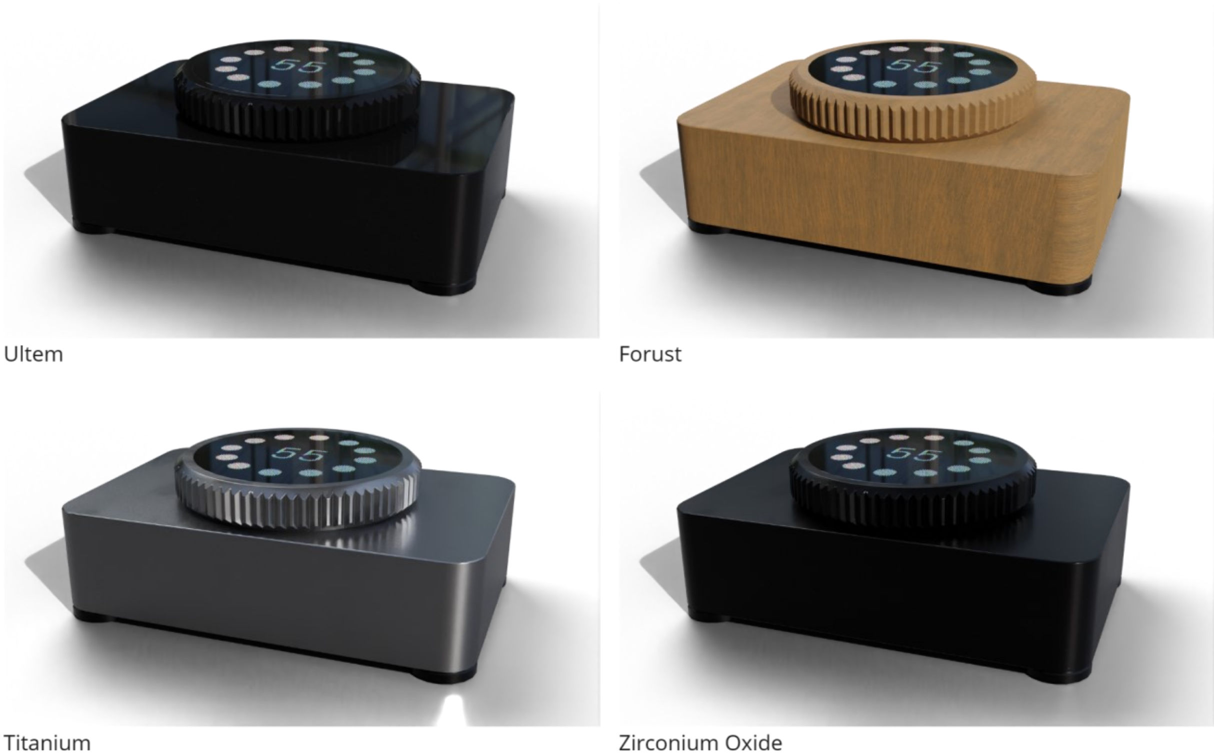


Figure 6 Sample Object Survey

Introduction

This initial exploratory survey examines the potential impact of diverse materials on consumer perceptions of value and attractiveness within the burgeoning world of luxury tech products. Building upon established literature highlighting the critical role of surface attributes, this study specifically probes how broader associations embedded within a material's identity interact with key luxury perceptions. For this, participants evaluate product images paired with material descriptions, expressing their responses across factors like aesthetics, exclusivity, innovativeness, and emotional attachment.

Methodology

This study employed a quantitative online survey designed to gather a range of consumer perceptions linked to different materials utilized in luxury tech products. Due to the exploratory nature of this research, the survey focused on collecting broadly comparable data about initial material impressions without the complexities of direct physical interaction. Participants were recruited through targeted online platforms where individuals express interest in design, technology, and lifestyle products. This was essential to increase the likelihood of reaching an audience aligned with the luxury technology consumer target group.

Survey Design & Structure

The survey featured a randomized structure composed of several key sections:

- Introduction: Participants were presented with a brief overview of luxury tech products, introducing terminology (e.g., "premium materials", "exclusive design") to help guide their understanding of the research concept.
- Material Evaluation: Using visual (see Figure 6) and text-based (descriptor) pairings, this core section explored how different materials align with consumers' perceptions. Each material, like "Zirconium Oxide," was shown with identical product imagery. Participants responded using a 5-point Likert scale to rate aspects like the material's perceived aesthetic appeal, exclusivity, perceived innovation, emotional resonance, and aspirational qualities. These specific metrics were selected to address this thesis' research goals on identifying links between surface attributes, luxury, and perceived value.
- Demographic Questions: Simple demographic questions on age, spending habits on luxury items, and technology usage levels aimed to segment results and identify potential trends across respondent groups.

Data Analysis: Quantitative data obtained was analysed using basic descriptive statistics to gauge trends, while correlations across the evaluation scores and demographic traits were examined for insightful patterns.

Key Limitations & Theoretical Underpinnings

It is imperative to acknowledge the significant limitations imposed by online surveys within a research field such as this, where a tactile dimension heavily influences consumers' luxurious product appraisals. The concept of 'Need for Touch' (NFT), well-researched in prior literature [8], [9] emphasizes the impact of individual variances in sensory preference on product evaluations. An online methodology inherently lacks the direct, haptic experiences consumers typically rely on during such luxury assessments.

Despite these limitations, this study is designed to uncover preliminary insights into consumer associations between various materials and their perceived prestige and desirability in luxury tech products. Future research endeavours involving haptic-rich methodology can expand upon the groundwork established and further nuance understandings within this domain.

3.2.1 RESULTS

Overall, Zirconium Oxide received the highest ratings across most indicators associated with luxurious and premium products, followed by titanium. This strong trend is clearly visualized in Figure 7(Spider Plot), highlighting these materials' favourable perceptions when paired with luxury technology products. Interestingly, Forust's scores indicate potential, particularly in its exclusivity and innovation ratings, hinting at consumer openness to less expected luxury tech materials. While falling behind in several other luxury indicators, these niche high scores raise questions about how factors like market positioning and specific audience targeting might alter perception of this material. In stark contrast, Ultem shows consistently lower rankings across all aspects associated with luxury tech, emphasized visually in Figure 7.

Figure 7 Customer Survey High Tech Materials

This survey demonstrates Zirconium Oxide's strong alignment with consumer perceptions associated with premium and luxury objects. It consistently outperformed other materials on indicators like aesthetics, emotional resonance, and perceived exclusivity. Combined with its known technical advantages, these outcomes strongly suggest Zirconia holds significant promise as a viable material choice within the luxury tech product space. While Ultem falls short on key luxurious traits, further research may uncover whether targeted consumer education regarding these materials' technological strengths could shift such perceptions.

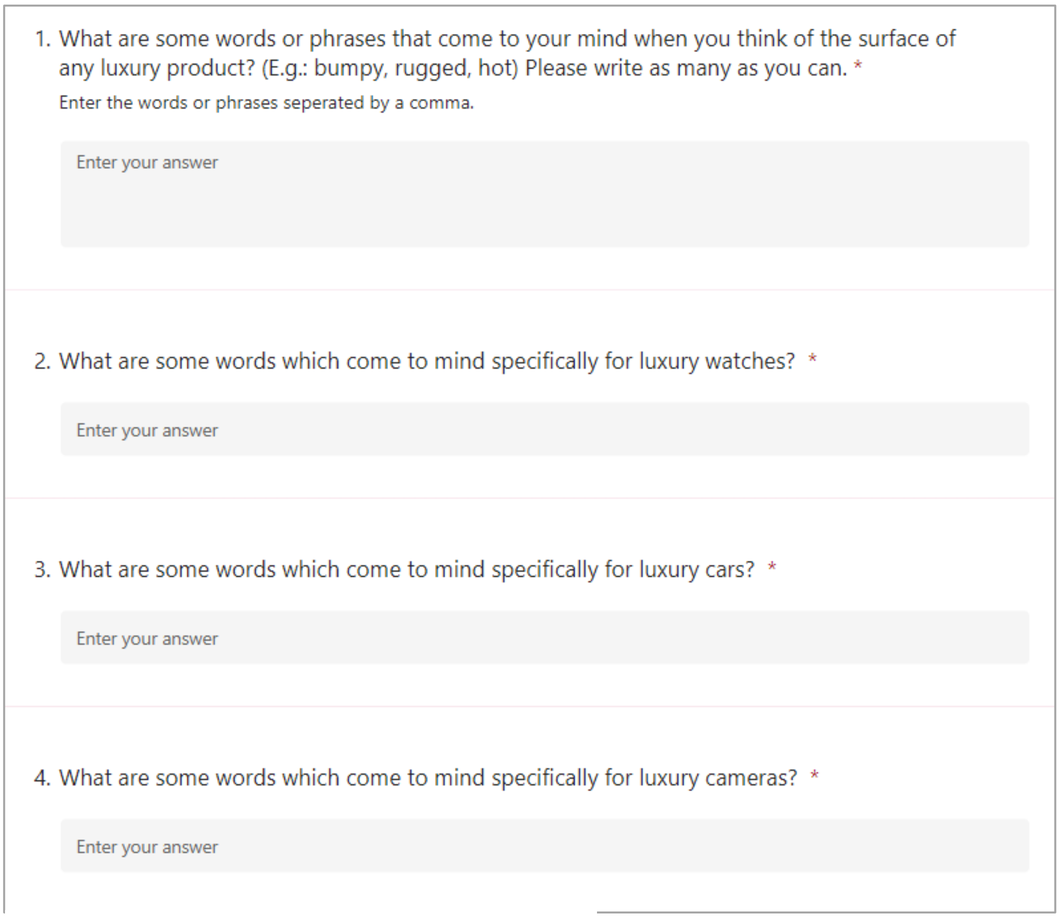
3.3 CUSTOMER SURVEY ATTRIBUTES LUXURY

Introduction

This study aimed to uncover common descriptive language when discussing luxury objects across multiple product categories. Since literature in this area is Consumer-generated word associations were collected to investigate trends with an open-ended online survey. Recognizing the need to account for online survey quality as discussed previously, this initial exploration seeks a wide initial vocabulary pool in a largely unexamined research area.

Methodology

Participants were asked four sequential questions within an online survey format (see Figure 8). One asked broadly about attributes they associate with any luxury item, then followed by three focusing on descriptive words applied to luxury watches, cars, and cameras. An unlimited field was provided for respondents to list whatever adjectives and related terms came to mind, capturing diverse perceptions.


1. What are some words or phrases that come to your mind when you think of the surface of any luxury product? (E.g.: bumpy, rugged, hot) Please write as many as you can. *

Enter the words or phrases seperated by a comma.

Enter your answer

2. What are some words which come to mind specifically for luxury watches? *

Enter your answer

3. What are some words which come to mind specifically for luxury cars? *

Enter your answer

4. What are some words which come to mind specifically for luxury cameras? *

Enter your answer

Figure 8 Survey for surface attributes

Results

A total of 36 participants took part, generating 165 unique, relevant words or phrases across the prompts. After translating German responses into English and combining synonyms or similar phrasings, a cohesive dataset emerged. Below are illustrative findings, with accompanying graph visualization (Figure 9), focusing on top 5 frequent attribute mentions per category:

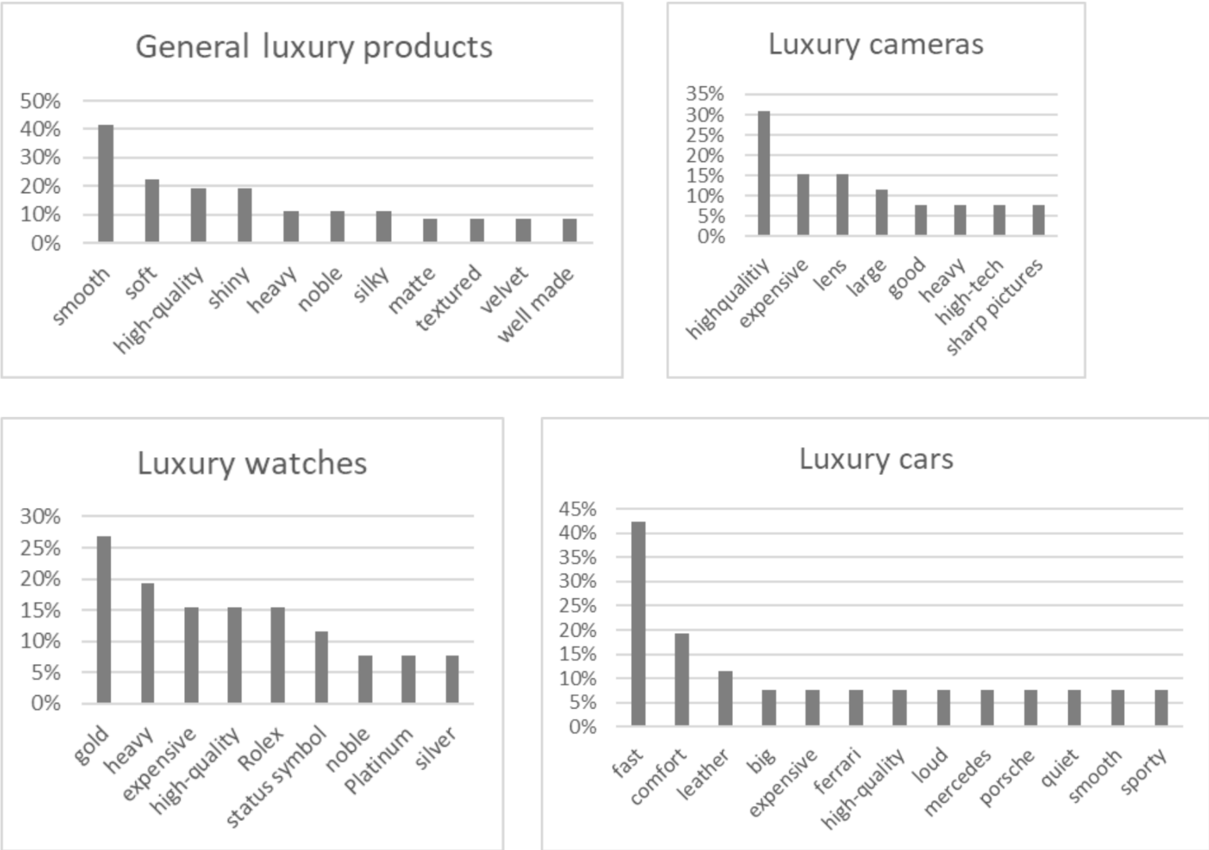


Figure 9 Most used words in different categories

Findings and Implications

Several intriguing findings are illuminated by these results. Firstly, no single word universally defines 'luxury', emphasizing its subjective and complex nature. Nevertheless, themes of "high-quality," "expensive," and visual appeal are consistently associated across multiple product categories.

It is observed that expectations of luxury items vary based on the product in question. Attributes like 'heavy' are emphasized for watches, potentially linked to quality materials and craftsmanship. This contrasts with cameras, where weight seems less of a luxury indicator. These distinctions must be considered when evaluating customer perceptions of luxury across different product types. These insights, along with the assembled lexicon of words, will play a pivotal role in informing Study 3.

Addressing Gaps and Context

Importantly, this study addresses existing research gaps. While some broader attributes of 'luxury' are suggested in literature (e.g.[4], [5]), they might not fully reflect the nuances of luxury perceptions when considering handheld devices. This survey rectifies this, as consumer language about relevant product categories was specifically examined. This establishes a grounded vocabulary based on expectations rather than purely theoretical constructs.

Potential discrepancies between these findings and those of Vihma et al[5]. warrant deeper exploration. While overlaps exist ('expensive,' 'smooth'), the data reveals a greater emphasis on attributes like 'heavy' (particularly for watches) and 'fast' (for cars). This variance could arise from either product-specific expectations or changing consumer attitudes toward 'luxury'.

The lack of universally dominant descriptors highlights the effectiveness of a targeted survey approach. This focused method ensures Study 3 examines factors essential to today's customers when evaluating potential luxury or premium devices. Understanding which materials, colours, and finishes align with contemporary expectations provides insights into how perceptions of luxury and premiumness can be successfully evoked.

Comparison Table

The following table illustrates potential points of comparison between established literature and the specific findings:

Vihma et al. Attributes	This Survey's Findings	Notes
Expensive	Expensive, High-Quality	Strong match
Smooth	Smooth, Shiny	Consistent
Soft, Warm, etc.	Heavy (watches), Fast (cars)	Potential consumer evolution or product-specific expectations to explore further

3.4 PERCEPTION OF SURFACE ATTRIBUTES

This chapter builds upon insights gained from prior surveys aimed at understanding the language consumers use to describe luxury objects and the attributes they prioritize. The overarching goal remains uncovering the tangible surface qualities that most strongly evoke perceptions of premiumness and luxuriousness. These are invaluable to understand how technical ceramics can be leveraged for high-end handheld devices.

Due to planning constraints, this specific study did not include sample objects manufactured from technical ceramics. However, the results remain extremely valuable for several reasons:

Fundamental Attribute Relationship: By mapping consumer perceptions of luxury and premium against a wide range of existing finishes and materials, core surface qualities strongly associated with those concepts can be isolated. This understanding translates to technical ceramics by guiding finish selection and development.

Suitable Manufacturing Paths: Identifying which existing finishes achieve high luxury/premium scores illuminates manufacturing techniques potentially compatible with technical ceramic capabilities. This narrows down the most promising methods for realizing the desired surface outcomes.

Benchmarking: This study establishes a baseline for comparison. Evaluating various ceramic surface treatments developed later against this benchmarked dataset aids in the objective assessment of which finishes most successfully embody the qualities consumers associate with luxury and premiumness.

Crucially, this data indicates whether single attributes or their combinations hold the strongest associations with consumer perceptions. Such insight will be leveraged to guide both technical ceramic manufacturing selection and, in the future, could help research focusing specifically on ceramic samples tailored to meet premium market expectations.

3.4.1 METHODOLOGY

Attribute Selection: Insights from the two earlier surveys formed the basis for attribute selection in this study. The focus narrowed to those surface qualities showing prominence in consumer word associations as well AS ATTRIBUTES described in relevant literature on SURFACE perception [4], [5]. Due to the study's time constraints, only attributes directly connected to physical and aesthetic aspects were prioritized; broader symbolic attributes were reserved for future studies. Table 1 outlines the final set of attributes to be evaluated during the perception survey.

Selected Surface Attributes

Group	Category	Attributes	
Aesthetic (sensory)	Feel	soft	hard
		heavy	light
		cold	warm
	Texture	smooth	
		silky	
		rough	
		slippery	
	Optics	reflective	
		glossy	
		matte	transparent
		opaque	translucent
	Colour	gold	black
		silver	
		clear	
		white	
	Sound	muffled	
		ringing	
Perceived (symbolic)		Luxurious - Essential	
		Premium - Standard	

Table 1 Selected Surface Attributes

Sample Set: A variety of sample objects manufactured with diverse techniques was gathered (Figure 10). This assortment encompassed materials and finishes both existing in Leica's production portfolio and those representing unexplored manufacturing paths. Importantly, all samples maintained identical geometry to isolate the impact of surface qualities alone on aesthetic and quality perception.

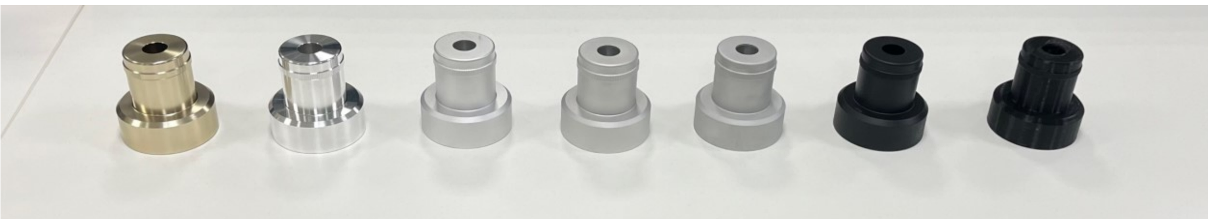


Figure 10 Selection from sample set

Participants: Twenty participants were engaged, drawn from two primary groups. First, Leica Customers. Several individuals who were attending a photography course at the Leica Akademie. As active Leica clients, their perspective provides unique insights into perceptions aligned with the brand's target market. And second, Leica Employees. They represent both internal stakeholders and those with in-depth product knowledge.

Survey Design & Setup: To facilitate in-person evaluation, sample objects were arranged on individual standing tables placed throughout a dedicated room (see Figure 11). This created a gallery-like setting, allowing participants to freely move between samples for convenient comparative analysis. The room maintained comfortable lighting conditions to aid visual judgement.

Figure 11 Study setup at Leica Akademie

Participants were given the choice to examine between 6-10 sample objects during their allotted time. Sample distribution targeted a similar number of responses per object for reliable comparisons. To assess each sample, participants filled out a questionnaire in printed form. The questionnaire evaluated the presence of attributes defined in Table 1, as well as subjective estimations of premiumness and luxuriousness.

3.4.2 RESULTS

The perception study yielded 115 valuable datasets from 20 participants assessing 6-10 surface samples each. These datasets were meticulously digitized for accurate and comprehensive analysis. Correlation analysis was employed to understand the relationships between surface attributes and the key perceptions of luxuriousness and premiumness. Here are the core findings:

Individual Attribute Correlations

Initial analysis examined the correlation of individual surface attributes with perceptions of luxury and premium. While some mild correlations appeared, one particularly noteworthy finding is the positive correlation between surface 'smoothness' and both luxuriousness (r = 0.36, p = 0.00) and premiumness (r =0.33, p = 0.00). This highlights smoothness as a potentially important influencer in achieving perceptions aligned with these desirable qualities.

Furthermore, the study found a strong correlation (r=0.79) between perceived luxuriousness and premiumness. This suggests that individuals participating in the study broadly conceptualize these two terms similarly in the context of surface evaluation. Table 2 provides a complete overview of correlations between attributes and *'luxurious' and 'premium'* and along with their statistical significance. See Table 4 in the Additional Figures chapter for a complete overview of the correlations between each attribute.

Table 2 Individual attribute correlation

Attribute	*Luxurious*	*p-value*	*Premium*	*p-value*
Ringing	0,39	0,00	0,37	0,00
Smooth	0,36	0,00	0,33	0,00
Gold	0,29	0,00	0,32	0,00
Hard	0,25	0,01	0,19	0,04
Silky	0,22	0,02	0,26	0,01
Silver	0,22	0,02	0,21	0,03
Cold	0,16	0,09	0,17	0,07
Heavy	0,15	0,12	0,08	0,38
Glossy	0,10	0,28	0,09	0,34
Reflective	0,07	0,44	0,12	0,19
Opaque	0,07	0,45	0,13	0,16
Translucent	0,05	0,62	-0,01	0,93
Matte	0,04	0,68	0,02	0,82
White	0,02	0,80	-0,08	0,41
Soft	0,02	0,82	0,10	0,29
Light	0,00	0,97	-0,06	0,56
Slippery	-0,06	0,55	0,00	0,97
Warm	-0,09	0,36	-0,06	0,50
Clear	-0,13	0,17	-0,13	0,17
Muffled	-0,36	0,00	-0,34	0,00
Rough	-0,37	0,00	-0,39	0,00
Black	-0,43	0,00	-0,39	0,00

Multiple Attribute Combinations

Following preliminary results, it can be hypothesized that combinations of surface attributes might more strongly correlate with both luxuriousness and premiumness. Secondary correlation analysis simultaneously analysing two attributes within a sample confirmed this.

This combination approach yielded significantly stronger correlations compared to the single-attribute analysis. For example, 'smooth' and 'slippery' together showed a moderate correlation with both luxury (r = 0.56, p = 0.04) and premium (r = 0.64, p = 0.02). Table 3 outlines the ten most statistically significant positive and negative multi-attribute correlations found in the dataset.

Table 3 Multiple Attribute Correlations

Only objects perceived as	*Attribute*	*Luxurious*	*p-value*	*Premium*	*p-value*
Slippery	Smooth	0,56	0,04	0,64	0,02
Light	Ringing	0,55	0,00	0,41	0,00
Black	Matte	0,54	0,00	0,44	0,01
Hard	Ringing	0,53	0,00	0,45	0,00
Rough	Silver	0,53	0,00	0,43	0,01
Glossy	Smooth	0,53	0,00	0,48	0,00
Soft	Smooth	0,46	0,01	0,35	0,04
Rough	Ringing	0,46	0,00	0,33	0,04
Black	Smooth	0,45	0,01	0,42	0,01
Soft	Ringing	0,44	0,01	0,35	0,04
Glossy	Rough	-0,47	0,00	-0,46	0,01
Rough	Black	-0,49	0,00	-0,34	0,04
Silky	Black	-0,52	0,00	-0,50	0,00
Soft	Black	-0,52	0,00	-0,39	0,02
Hard	Muffled	-0,53	0,00	-0,45	0,00
Light	Muffled	-0,54	0,00	-0,41	0,00
Slippery	Black	-0,56	0,05	-0,31	0,31
Soft	Rough	-0,60	0,00	-0,53	0,00
Light	Black	-0,60	0,00	-0,62	0,00
Glossy	Black	-0,68	0,00	-0,67	0,00

3.4.3 DISCUSSION

This study provides valuable insights into the complex relationship between surface attributes and perceptions of luxury/premium quality in handheld devices. Here's an analysis of key findings and their implications for manufacturing selection:

Multi-attribute correlation analysis outperformed single-attribute assessments. This reveals that luxury and premium perceptions are likely driven by an interplay of surface qualities, not simply the presence of any one attribute in isolation. For example, a 'smooth' surface coupled with a sense of 'softness' yielded a stronger association with luxury than either attribute alone.

Smoothness showed a consistent positive correlation with luxuriousness and premiumness, making it a crucial manufacturing target. Achieving this finish on technical ceramics may benefit from processes excelling at uniform surfaces, such as various polishing, lapping, or honing techniques.

Strong correlations found with specific attribute combinations provide potential clues about suitable manufacturing routes. For instance, a surface feeling both 'light' and 'ringing' was associated with luxury; achieving this combination likely requires processes capable of forming precise, thin-walled components.

Participants generally conceptualized 'luxury' and 'premium' similarly in their surface evaluations. This finding has implications for the handheld device segment as it might suggest that the surface attributes tested there alone are not responsible to differentiate between a luxury and a premium product. There might be other attributes which describe the products form, design or surface which is only seen in either luxury or premium products. The differentiation of these two concepts might also lie outside of the perception surface qualities and other related attributes and come more from things like price, brand perception and other factors.

Limitations

It's essential to note limitations as they guide future research:

Materials used in this study (i.e., 3D printed plastic) may have inherently biased results towards lower luxury/premium scores. Exploring a broader material set in future studies will mitigate this influence.

While correlations with certain combinations were stronger, they were still moderate. Expanding on these results (with higher sample sizes and perhaps regression analysis) could unlock a predictive model for crafting highly 'luxurious' surfaces.

A dedicated study evaluating luxury/premium perceptions of various ceramic surface treatments is needed to provide the most conclusive manufacturing guidance.

Overall, this study demonstrates the value of examining the nuances of surface perception to achieve high-end finishes on technical ceramics. The findings, while preliminary, can be used as a foundation for future work as designers and engineers strategize manufacturing paths aimed at embodying the qualities most closely associated with premium and luxurious handheld products.

3.5 CONCLUSION

This chapter provided a multifaceted investigation into the relationship between material surface qualities and perceptions of luxury and premiumness in handheld devices. Utilizing online surveys and a hands-on perception study, it delved into the complexities of associating both individual attributes and their intricate combinations with these key values. Several crucial insights emerged, such as the importance of understanding the descriptive words consumers use to define 'luxury' across multiple product categories which allows the design process to target what resonates with the target market. Addressing gaps between theoretical conceptualizations of luxury and consumer's language was central to this endeavour.

Furthermore, smooth surfaces exhibited consistent positive correlations with luxuriousness and premiumness. Manufacturing guidelines must ensure that surface treatments for technical ceramics achieve this, even in the face of technical constraints.

The Importance of Combinations: It became evident that no single surface attribute definitively conveys a sense of luxury or premiumness. Evaluating attribute combinations proved vital. Manufacturing methods will therefore need flexibility to generate finishes evoking specific sets of perceptions through tactile experience.

These findings serve as the blueprint for the next chapter. Here, a 'Design for Manufacturing' guideline is created to empower a seamless translation of luxuriousness and premiumness into the specific domain of technical ceramics. This guide will provide a comprehensive list of prioritized aesthetic and tactile qualities derived from all conducted studies. These should include individual attributes and their most influential combinations for evoking desirable perceptions. The guideline will identify promising technologies and manufacturing partners to fill the gap.

This multifaceted approach, informed by user perception and grounded in manufacturing realities, sets the stage to elevate technical ceramic materials and their finishes to a level of true luxury and desirability within the field of premium handheld devices.

4 DESIGN FOR MANUFACTURING TECHNICAL CERAMICS ANALYSIS

4.1 INTRODUCTION

This chapter provides a comprehensive analysis of technical ceramic manufacturing for handheld devices, with a specific emphasis on applications suitable for Leica camera lens designs. We'll explore how to leverage the beneficial properties of technical ceramics, such as durability, scratch resistance, and luxurious aesthetics, within the realm of handheld product design. Building upon the insights on luxurious surface attributes identified in the previous chapter, the focus shifts toward understanding the manufacturability of such qualities as they pertain to technical ceramics. In addition to a general overview of relevant processes, this chapter will pinpoint methods with high alignment to Leica's current capabilities and internal guidelines. The goal is to inform the concept designs proposed in the conclusion, where technical ceramic components are seamlessly integrated to enhance Leica lenses.

Key Areas of Exploration:

- Ceramic Landscape: Analysis of the current state of technical ceramics within the handheld product market.
- Manufacturing Methods: Examination of various technical ceramic manufacturing processes and their design implications.
- Cost Assessment: A cost analysis of selected manufacturing methods to aid decision-making.
- Design Guidelines: Creation of a comprehensive design guide to streamline the selection process for utilizing technical ceramics.
- Case Study: Demonstration of the most promising manufacturing methods through a practical design example.

4.2 CURRENT STATE OF CERAMICS IN PRODUCT DESIGN

The use of technical ceramics within product design has experienced significant growth, particularly in the realm of handheld devices. This shift is driven by the unique combination of properties offered by technical ceramics: unmatched durability, exceptional scratch resistance, chemical inertness, and an innate potential for luxurious aesthetics. These qualities hold the key to elevating the user experience for premium handheld products.

This chapter delves into the current landscape of technical ceramics in handheld devices. We'll explore their strategic use in watches, smartphones, and other products, examining how different manufacturers exploit both the functional and aesthetic advantages of various ceramic materials. This analysis will cover:

- Analysis of ceramic handheld products
- Manufacturing Processes: Insights into how different products leverage techniques like machining, sintering, and injection moulding to realize their ceramic components.
- Marketing Strategies: Analysis of how brands like Omega, Apple, Samsung and Swatch emphasize the benefits and the perceived premium value of ceramics in their communication with consumers.
- Design Implications: Examination of how incorporating ceramics often necessitates specific design considerations which will inform later discussions on design for manufacturing.

By understanding the current state of technical ceramics in handheld devices, a foundation was built which helps analyse their potential within the context of Leica camera lens designs. This analysis will consider technical limitations, manufacturing realities, and the opportunity to redefine a luxury handheld product experience through the discerning selection of ceramic materials and processes.

4.2.1 EXSISTING CERAMIC PRODUCTS

Figure 12 Three different ceramic watch models

To gather more insight into the world of ceramic handheld devices the following analysis explores the marketing material of three different models of watches and two phones. First the examples of the Omega Speedmaster, Apple Watch, and Swatch 'Bio Ceramic' watches (see Figure 12) reveal a spectrum of approaches to incorporating ceramics in watch design:

Omega positions its ceramic Speedmaster[32] as a high-end luxury timepiece. Their marketing language emphasizes the material's origin ("keramos"), scientific nature ("inorganic, non-metallic substance"), and technical achievement ("heated to 1400 degrees centigrade"). Omega reinforces a sense of exclusivity through elevated material quality and sophisticated manufacturing processes. The Apple Watch[33] showcases ceramic as a viable option for everyday wear in the context of a smartwatch. Here, the focus remains on durability and luxurious feel ("lustrous") yet balances this with accessibility for a broader market. Swatch's 'Bio Ceramic'[34] introduces a ceramic-polymer hybrid. This innovation offers the appeal of ceramic-like properties at potentially lower costs. Swatch targets environmentally conscious consumers who desire both durability and sustainable choices.

From these three examples multiple themes emerge. First the material as differentiator. Ceramics serve as a key point of differentiation in the watch market. They allow brands to carve out niches based on luxury, accessibility, or innovation. Second aesthetics matter.

Beyond pure functional benefits, ceramic plays a crucial role in visual appeal. The ability to achieve pearlescent finishes, and a range of colours (black, white, etc.) enhances the 'desirability factor' for brands. And lastly manufacturing influences design: The choice of ceramic type and manufacturing process likely shapes design parameters. Machining pure ceramic calls for different geometries than injection-mouldable hybrid polymer-ceramic compositions.

In mobile phones there has been also a use of ceramic materials in the design which can be seen by the integration of ceramics into smartphones like the Samsung Galaxy S10 Plus [35] and Xiaomi Mi 6 [36], which demonstrates a strategic effort to redefine everyday consumer electronics.

Figure 13 Marketing Image for Samsung Galaxy S10+ Ceramic versions

Samsung prominently markets the ceramic back as a "premium" feature. This underscores the power of material choice in signalling exclusivity and superior quality to potential buyers. Like Omega, Samsung invokes references to "traditional ceramicware" while also emphasizing the heat treatment process ("1400 degrees centigrade"). This blend of the traditional and advanced reinforces the notion that a ceramic phone isn't just about material, but about craftsmanship and innovative manufacturing. Limited and sophisticated colour palettes ("Ceramic Black", "Ceramic White") cater to consumers who desire understated elegance, aligning with the overall desire to express the 'premium' feel of the device.

The implications of mass market products utilising ceramics in their design is the mass market potential. It suggests that these materials, while positioned as luxurious, could become more accessible within handheld product design, while still needing to balance cost and luxury, since ceramic production likely adds to the manufacturing cost of a phone. Brands therefore need to masterfully communicate the value proposition to the consumer to drive increased sales prices.

Implications for Leica: The analysis of both watches and smartphones illuminates several pathways for Leica to harness the potential of technical ceramics. The clear emphasis on material exclusivity in Omega's marketing underscores how ceramic components can position select Leica lenses as ultra-premium collector's items. Simultaneously, Apple's focus on functionality within a broader market speaks to the potential for integrating ceramic with a focus on durability and enhanced grip - characteristics highly valued by photographers. As innovation leaders, Leica could even follow Swatch's example, exploring more sustainable or cost-effective ceramic composites without sacrificing visual or tactile appeal. However, just as in smartphone design, Leica must find a delicate balance between cost, technical constraints, and delivering a superior user experience that justifies the integration of ceramic across different lens ranges.

4.3 MANUFACTURING METHODS FOR CERAMICS

Technical ceramics offer exciting possibilities for elevating handheld products. However, to successfully integrate ceramics into Leica lenses, selecting the optimal manufacturing method is crucial. Each method comes with a unique set of design considerations and constraints, directly impacting achievable geometries, tolerances, surface finishes, and costs.

This section will analyse a range of ceramic manufacturing processes, including green machining, hard machining, additive manufacturing, injection moulding, pressing, and various post-processing techniques. The benefits and limitations of each method will be assessed, leading to clear insights for Leica's design guidelines. Specifically, it will be considered how factors like desired batch size, surface quality requirements, and geometric complexity will steer the decision-making process.

4.3.1 GREEN MACHINING

Green machining offers flexibility for smaller production runs of technical ceramic parts. In this process, a 'green' (unsintered) ceramic part – a blend of ceramic particles and organic binder – is CNC machined into the desired shape. After machining, the green part is sintered. During sintering, the binder burns away, and the ceramic particles fuse, resulting in a solid part with the final desired strength. Note that sintering causes substantial shrinkage that must be accounted for during design.

Advantages for Leica:

- Prototyping and Small Batches: No moulds are required, making this ideal for prototype testing and limited production runs of lens components.
- Geometric Flexibility: CNC machining allows for a wider range of geometries compared to some other ceramic production methods.

Key Design Considerations:

- Fragility of Green State: Ceramic in the green state is more fragile. To avoid breakage during machining:
    - Avoid Sharp Edges: Use chamfers and generous fillets.
    - Minimum Wall Thickness: Maintain at least a 3mm wall thickness for structural integrity.
- Shrinkage: Design the green part larger to compensate for the shrinkage during sintering. The ceramic supplier can provide the expected shrinkage rate for the specific material used.

- General CNC Guidelines: Standard CNC machining best practices also apply (draft angles, etc.). See [37] for a resource.

4.3.2 HARD MACHINING

Hard machining involves CNC machining of technical ceramic components after they have been fully sintered. This approach offers several benefits for precision lens components:

Advantages for Leica:

- Tighter Tolerances: Since no shrinkage occurs post-machining, significantly tighter tolerances and more intricate details can be achieved compared to green machining. This can be especially beneficial for lens mounts or other areas where extreme precision is needed.
- Geometric Freedom: Sharp edges and thinner wall thicknesses become feasible as the risk of breakage associated with a 'green' part is eliminated. This gives Leica greater design freedom.
- Surface Finish: Hard machining often leads to a smoother surface finish than green machining due to the higher density of the ceramic material.
- Consistency: As there is no shrinkage variability, hard machining can offer better consistency in part dimensions across different production batches.

Design Considerations:

- Standard CNC Guidelines: As with green machining, general CNC machining best practices apply for optimal outcomes.
- Tool Wear: Machining hard ceramic can induce higher tool wear. Specialized tools may be required, and these can factor into the production cost.

When to Choose Hard Machining:

Hard machining is well-suited for Leica lens components when extremely tight tolerances, precision detailing, and a superior surface finish are paramount. If larger batch sizes justify the investment in specialized tooling, hard machining offers superior control and design freedom compared to green machining.

4.3.3 ADDITIVE MANUFACTURING

Additive Manufacturing (AM) offers unique capabilities for ceramic components, potentially expanding Leica's design and prototyping capabilities. Within AM, a range of processes are available, each with design implications. Let's start with a highly relevant one: Stereolithography (SLA).

4.3.3.1 STEREOLITHOGRAPHY (SLA)

The SLA Process:

In SLA, a UV-curable resin containing ceramic particles is built up layer-by-layer. After printing, the 'green' part undergoes de-binding (removal of binder), and sintering, as with other ceramic methods. SLA enables highly complex geometries that may be impractical or costly with machining.

Advantages for Leica:

- Prototyping Complex Geometries: Ideal for quickly assessing the form and fit of novel lens component designs with internal features that would be difficult to machine.
- Internal Structures: SLA creates structures like internal supports or even integrated grip patterns that may be impossible to achieve with conventional methods.
- Small Batches: Potentially economical for very limited runs compared to tooled processes if surface requirements permit.

Design Considerations

- Surface Finish: Expect courser finishes compared to machined parts. SLA is best for internal components or situations where cosmetic perfection is less critical.
- Shrinkage: As with other methods, parts shrink during sintering; compensation is needed in design.
- Support Structures: Designs may require supports during printing, potentially affecting surface quality where these supports attach.
- SLA-Specific Guidelines: Follow best practices for overhangs, wall thickness, etc. See [38]

4.3.3.2 FUSED DEPOSITION MODELING (FDM)

FDM is a widely accessible form of additive manufacturing. In ceramic FDM, filaments containing a blend of thermoplastic and ceramic powder are used to create 'green' parts. These parts undergo the same de-binding and sintering process as other ceramic methods, leading to substantial shrinkage.

Potential Benefits for Leica:

- Prototyping Accessibility: FDM is often cost-effective for very early conceptual prototypes, as widely available FDM printers may already exist within Leica's design facilities.
- Internal Geometries: FDM still excels at enabling complex internal structures that would be difficult or impossible to prototype traditionally.

Key Limitations:

- Surface Finish: FDM usually results in a significantly coarser surface finish, making it unsuitable for cosmetic or exterior lens components.
- Precision: Due to high shrinkage and FDM's inherent layering limitations, tight tolerances are difficult to achieve. These limits use for end-use parts.
- Material Strength: The blended thermoplastic/ceramic nature often leads to compromised mechanical properties compared to fully dense technical ceramics.

Best Use Cases for Leica:

Ceramic FDM is best suited for strictly internal, early-stage prototype components where visual appearance and strength are secondary considerations. Even for this, rough tolerances must be accounted for during design.

Design Considerations:

- Shrinkage: Design to compensate for significant shrinkage. The material supplier can provide the exact rate.
- FDM Guidelines: General FDM printing best practices must be followed (overhangs, supports, etc.). See [39]

4.3.3.3 BINDER JETTING FOR CERAMICS

Binder jetting offers design freedom and potential cost advantages for unique ceramic parts. In this process, a liquid binder is selectively deposited onto a bed of ceramic powder, layer by layer. Just as with other methods, these 'green' parts then undergo de-binding and sintering. [40]

Advantages for Leica:

- Complex Geometries: Minimal need for support structures during printing, enabling intricate designs that might be impossible to machine.
- No-Tooling Production: Can be cost-effective for small runs where intricate internal features are essential, and surface quality is less crucial.
- Internal Features: Ideal for producing complex internal structures within a lens assembly (e.g., integrated grip patterns or support frameworks).

Design Considerations:

- Surface Finish: Expect a porous, somewhat coarse finish as characteristic of the process. This limits binder jetting to internal or non-cosmetic components.
- Porosity: Parts created are generally more porous than with other ceramic methods, potentially making them unsuitable for demanding mechanical applications.
- Shrinkage: Design must account for the shrinkage during sintering which is likely significant.

Key Takeaway: Binder jetting could be a powerful tool in Leica's design arsenal for specialized internal lens components where geometric complexity takes priority over surface perfection or extreme mechanical strength.

4.3.4 INJECTION MOULDING

Injection moulding holds great potential for larger-scale production of technical ceramic lens components. In this method, a mix of ceramic powder and a polymer binder is injected into a precision-made mould. After de-binding and sintering (which accounts for shrinkage), the resulting parts offer advantages that could dramatically expand Leica's capabilities:

Benefits for Leica:

- Surface Finish: Expect an excellent surface finish out of the mould, often suitable for even cosmetic exterior lens components. This surpasses other ceramic options with rougher textures.
- Scale & Cost: The high upfront tooling cost becomes cost-effective when spread across many units. Ideal for high-volume lens components when ceramic's material properties are essential.
- Reproducibility: Once the process is fine-tuned, injection moulding allows for extremely consistent results across batches, crucial for Leica's high-quality standards.

Design Considerations:

- Tooling Investment: Design must balance manufacturing feasibility against the potentially high mould cost. Simpler geometries may be preferable initially.
- Shrinkage Compensation: The mould itself must be oversized to account for sintering shrinkage. Close collaboration with the supplier is important.
- Injection moulding Guidelines: Standard design rules apply to ensure proper mould fill and easy part ejection. This includes uniform wall thicknesses, avoiding undercuts, draft angles, etc.

Key Takeaway: While requiring significant investment upfront, injection moulding offers Leica a path to achieving truly mass-produced lenses featuring the benefits of technical ceramics in a way that other manufacturing methods could not.

4.3.5 PRESSING

Pressing is a valuable technique for manufacturing uniform ceramic components or preparing 'green' parts for additional processes like green machining. Ceramic powder mixed with a binder is compressed within a mould under high pressure. These 'green' parts then undergo the usual de-binding and sintering process.

Use Cases for Leica

- Simple Geometries: Best for basic lens components with consistent features (rings, spacers, etc.). More complex forms likely require additional machining post-pressing.
- Green Part Creation: Pressing is often the method of choice to produce dense, uniform 'green' blanks for green machining further complex geometries.
- Batch Production: Can be an intermediate step for medium volume runs within certain geometric limitations.

Design Considerations

- Uniformity: Shapes must have consistent thicknesses and features to ensure even material density during pressing, which significantly impacts final part quality.

4.3.6 POST PROCESSING

After sintering, technical ceramic parts often require additional processes to achieve the desired final surface, tolerances, or visual markings. Common methods include:

CNC Grinding

- CNC grinding delivers tight tolerances and an improved surface finish. This could be crucial for Leica lens components where smooth interfaces or close fits are needed.
- Design Considerations: The grinding tool must be able to access all target areas. Design rules mirror those of CNC machining in general.

Vibratory Grinding

- Overall Surface Improvement: Ideal for smoothing sintered ceramic surfaces over a broader area. Rounded edges and a less 'raw' texture is often the outcome.
- Limitations: Vibratory grinding can't achieve precision tolerances; consider it for cosmetic components where minor dimensional variation is acceptable. Small features or cavities might not receive effective finishing.

Laser Engraving

- Lasers can effectively mark sintered ceramic surfaces. Depending on the material and laser specifications, depth and colour contrast can be controlled.

- Applications for Leica: Adding logos, serial numbers, or even decorative embellishments could create unique value-adds for specialized ceramic lens components.

CNC Engraving

- As a form of hard machining CNC engraving can be used to add intricate details, markings, and even decorative textures onto sintered ceramic surfaces. This is an excellent way to add branding, serial numbers, or lens markings to Leica lens components.
- CNC engraving provides superior control over depth compared to laser methods, and seamlessly follows curved surfaces due to multiple axes of machining.
- Design Considerations: General guidelines from hard machining apply for optimal results (avoiding tool breakage in small features, etc.).

4.3.7 CERAMIC COATING

While this thesis focuses on solid technical ceramics, ceramic coatings provide additional design possibilities for select Leica lens components. Coatings like those applied via Physical Vapor Deposition (PVD) impart ceramic-like qualities onto more familiar metals or plastics. This offers improved scratch resistance, durability, and even a distinctive ceramic aesthetic. Coatings offer wider material freedom. Consider using traditional and machinable materials for the structure of certain components, then apply a ceramic surface-layer only where premium properties are necessary. They might also provide a cost-effective way to achieve the look and feel of premium ceramics on select, easily producible parts without having to commit to fully ceramic manufacturing.

Design Considerations for Leica

- Optimal coating results heavily depend on precise surface preparation of the base material. Integrate this pre-finishing into the workflow.
- Visibility: Workpiece mounting during the coating process can leave minor 'shadows'. Designate these regions on hidden or unseen sections of the part.
- Function First: Coatings primarily affect surfaces; don't rely on them as a substitute for true ceramics where material strength or heat resistance are critical.

4.3.8 CONCLUSION

The design for manufacturing in the context of ceramics is profoundly influenced by the chosen manufacturing method, each bringing its own set of design guidelines and constraints. **Green machining** allows for small batch production with specific design rules to accommodate the fragility of green parts, such as avoiding sharp edges and maintaining a minimum wall thickness. **Hard machining** offers better final tolerances and the ability to include sharper edges and thinner walls due to the absence of sintering-induced shrinkage.

Additive manufacturing methods like **SLA** and **FDM** provide unique advantages in design freedom, allowing for complex internal geometries and early prototyping, respectively. However, they also come with their own limitations, such as coarser surface roughness and high shrinkage rates. **Binder jetting** enhances design freedom further by eliminating the need for support structures, though it typically results in parts with lower surface quality and higher porosity. **Injection moulding** is ideal for larger batch sizes, offering high surface finish and mass production capabilities, but requires consideration for the design of the mould to account for shrinkage. **Pressing** is another method that necessitates uniform part geometry for even density in green parts. Post-processing techniques like **CNC grinding** and **vibratory grinding** refine the sintered parts to achieve the desired surface finish and tolerances, with design rules similar to CNC machining. Lastly, **ceramic coatings** such as **PVD** allow for the application of ceramic-like surfaces on less expensive materials, requiring careful design consideration for work holding and pre-finishing of the surface.

In conclusion, each manufacturing method for ceramics demands a tailored approach to design for manufacturing, ensuring that the final product meets both functional and aesthetic requirements while optimizing the potential of the chosen production technique.

4.4 COST ANALYSIS CERAMIC PRODUCTION METHODS

Introduction

While technical ceramics elevate product design, they introduce higher manufacturing costs than traditional materials. Understanding this cost differential is crucial for Leica when exploring ceramics for special edition lenses or product lines. This analysis compares two methods: green machining and injection moulding. It highlights cost factors and explores scenarios where each method gains an economic advantage.

4.4.1 GREEN MACHINING COST ANALYSIS

This cost analysis draws its foundation from a vendor quote obtained for a custom sample part made from technical ceramic. While the specifics of the quote are confidential, we'll use it as a reference point to evaluate the potential cost impact of introducing ceramic components into a Leica lens assembly.

Cost Factors

To estimate the cost factors, The quote to produce a sample part is used as a baseline to use later on to compare to the production of all the parts of the lens casing with the same processes.

Since the individual cost factors, or a breakdown of the costs is not known in enough detail from this quote the breakdown needs to be estimated. The final price of the sample part is known to be X for an order of one, X*0.9 for an order of two and X*0.84 for an order of three. It can be presumed that with increased order amounts the price of the individual sample is going to drop even more but each time at a smaller rebate. From the three values it can be extrapolated that this order price per individual unit to eventually level out at Y=X*0.65 see Figure 14.

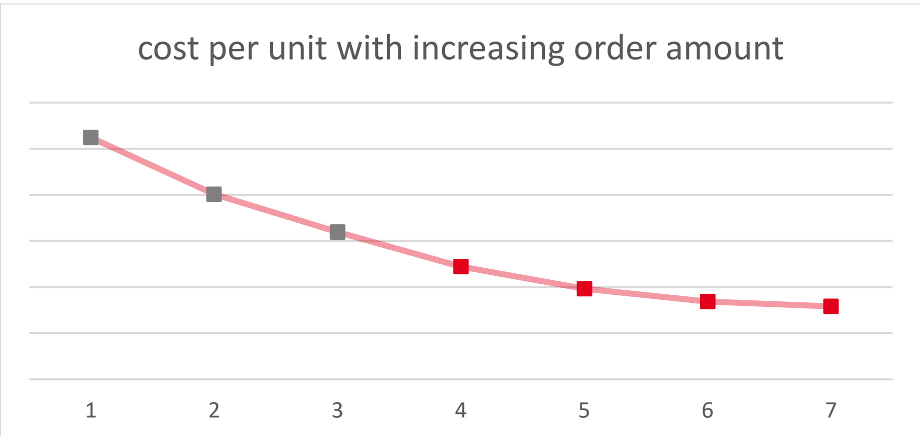


Figure 14 Unit costs are lower when multiple are ordered

This overall cost value of Y is used to calculate the individual costs of material cost, machining cot, sintering cost, grinding cost and labour cost. Material cost can be estimated by using the price per weight from this supplier [41] quotes 246€ for 500g which comes to a per gram price of around 0.5€. This brings the estimate for the material price for the quoted sample part to be Y*0.13 based on the final weight of the part and a factor of two increase for lost material and production of the green part the sample is milled from.

Subtracting the estimated material cost of Y*0.13 from the final part price of Y leaves Z=Y*87 which is labour and production costs. The process chain is machining, sintering and vibratory grinding. The remaining cost between the different processes and the labour cost is split with a ratio of 40% of the cost to machining and 20% to the rest. So, 20% to labour, sintering and vibratory grinding.

This estimated breakdown can now be used to estimate the price for each individual part of the lens housing. This is done in the next section.

Methodology

With the estimated cost breakdown for each cost factor of the sample part the price for each individual part is estimated by comparing the complexity of the individual part to that of the sample part. This is done for each cost factor. So, for example comparing the complexity of machining the index ring to the complexity of machining the sample part a complexity factor is decided on which multiplies with the cost factor of the sample part and therefore gives an estimate of the cost factor of the new part. In this example the complexity factor for machining was chosen to be 0.5 because of the smaller size fewer complex features such as the knurling. This process is done for all parts and with every cost factor. For the material price the weight of each part is calculated and multiplied by the previously mentioned factor which accounts for some material loss in the milling of the part.

Cost Estimation

The previously mentioned methodology was used to evaluate the estimated price of all the housing parts to be made from technical ceramics.

The estimate from the method here shown shows that the cost for all ceramic parts of the lens in question would be around the mark of Y*4. This value as previously mentioned cannot be guaranteed to be very accurate since many factors were estimated, but it gives a good idea of the cost range which could help Leica decide on whether to continue pursuing this project in the future or whether the cost of producing these parts is not worth it with the expected value increase in making a ceramic special edition lens.

Conclusion

Estimating the cost with the described method showed that the cost of the housing parts made from ceramic comes to around Y*4 which compared to the price of the lens with aluminium parts will rise the cost of production of the lens by a factor of 2. This would make the lens one of the most expensive special editions made. This of course is an expensive proposition that needs to be accounted for when deciding to use this production process for producing part. The use in special editions could be justified with a small series production with a large price increase, but for standard editions the cost of ceramic parts for only the housing would be the biggest cost driver in the cost of the production of the lens so it is probably not worth it to consider this option. For small applications where the mechanical properties of technical ceramics are used to an advantage the value proposition could make sense even for standard editions, but most likely other production methods make more sense for this, considering the larger volume of production.

4.4.2 INJECTION MOULDING COST ESTIMATION

Estimating the cost of injection moulding technical ceramics without direct supplier quotes poses challenges. The approach is to use reasoned assumptions regarding materials, tooling, post-processing, and labour.

- Material Costs: Since dedicated ceramic feedstock prices often aren't publicly available, approximate cost is estimated based on that of the raw ceramic[41] with an added factor to account for binder inclusion and the creation of moulding pellets. Note that specialized feedstocks could deviate from this estimation.
- Tooling Costs: Injection mould prices vary greatly depending on complexity. An online tool like [42] was used to obtain baseline mould costs.
- Post-Processing: De-binding and sintering costs introduce some per-part expense. Here, I'll make initial assumptions regarding time and resources needed, understanding that real-world scenarios may vary.
- Labor Costs: Injection moulding generally offers labour savings vs. green machining due to automation. This is factored in, with the caveat that specialized ceramic handling may warrant adjustments.

Results

These estimations project Y for a production run of 100. At larger volumes, like 1000 costs reduce to Y*0.5 - still potentially exceeding conventional lens parts but highlighting the scaling advantage injection moulding offers.

Conclusion

The significant cost difference between injection-moulded ceramic and green machining is apparent, even within estimation margins. Notably, as batch sizes increase, a break-even point emerges where injection moulding becomes advantageous. Here's why this matters for Leica:

- Low Volumes: The initial analysis supports green machining for very small runs or one-offs. But, if a small series becomes successful, costs quickly spiral upward.
- Design Complexity: Highly complex shapes may favour green machining in moderate sizes, as intricate moulds themselves become costly. This trade-off requires evaluation specific to potential Leica parts.

4.5 DESIGN GUIDELINES FOR CREATING CERAMIC PARTS IN HANDHELD DEVICES

The research presented so far offers insights into technical ceramic manufacturing methods, their inherent constraints, cost implications, and the material's potential market appeal. To maximize these assets while avoiding pitfalls, a consolidated set of guidelines will empower Leica's designers.

Decision-Making Flowchart

The core of this chapter is a flow chart for decision making. Key decision points along the chart would include:

- Target Production Volume: (One-offs, limited edition, high-volume) – Immediately guides designers towards methods like green machining vs. injection moulding with its tooling expenses.
- Geometric Complexity: Highlighted with visual examples where intricate, internal-feature-heavy parts lean towards AM methods that would be costly/impossible to machine.
- Performance Needs: Does the ceramic offer purely aesthetic benefits or is crucial scratch resistance required? Guides material selection and whether cheaper ceramic coatings could substitute where true structural advantages are not essential.
- Cost Thresholds: Based on cost research, the chart shows relative costs where early budget checks become vital, as some methods scale dramatically in cost beyond specific batch sizes.

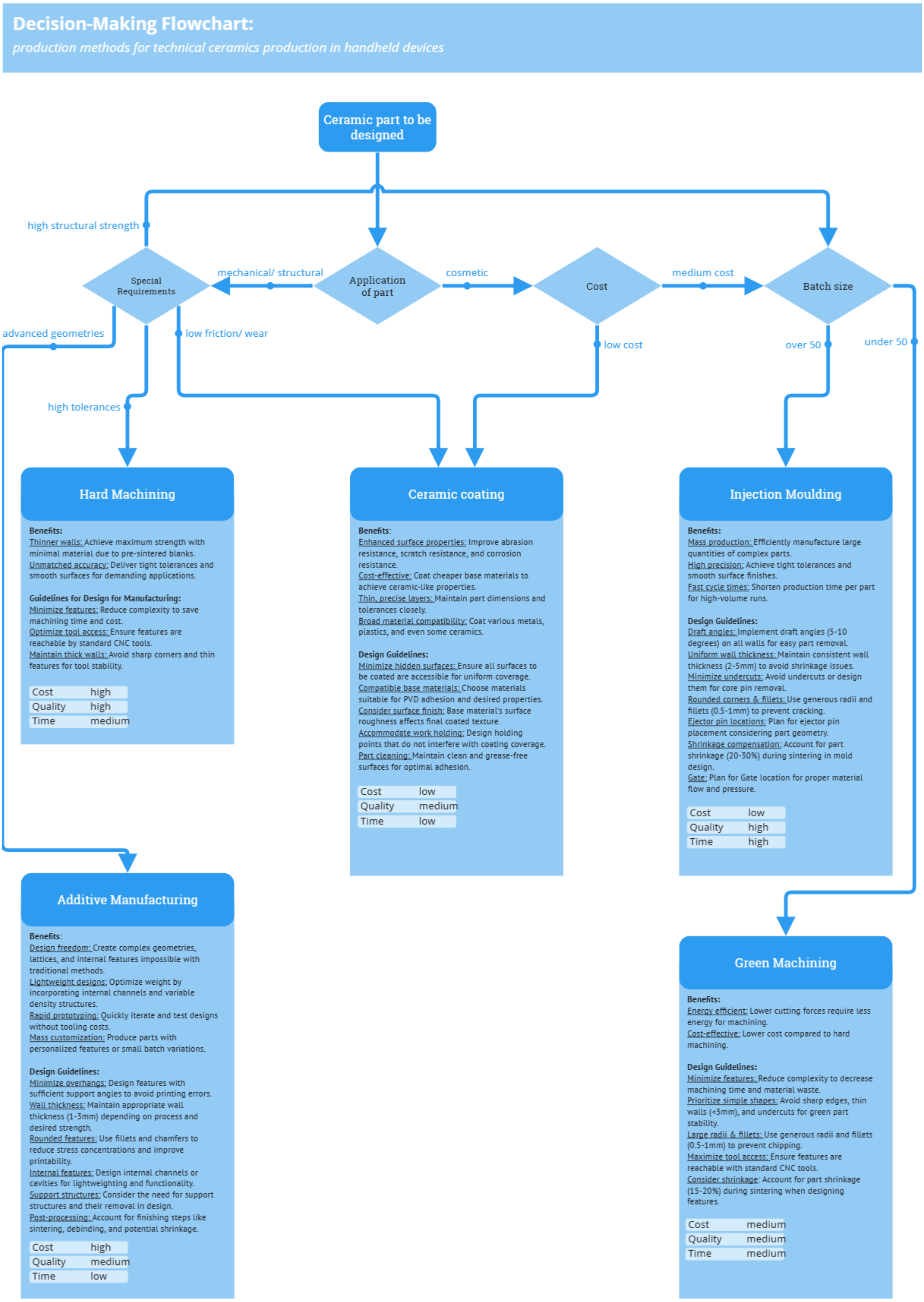


Figure 15 Decision-Making Flowchart

4.6 CASE STUDY

This thesis aims to apply insights gleaned from previous chapters to the design and manufacturing of a special edition camera lens constructed from technical ceramics. Technical ceramics were selected as a compelling material due to their potential to deliver a uniquely premium experience for Leica consumers.

To validate this concept, a user study was conducted. This study analysed user perceptions of luxury and premium qualities as they relate to surface attributes like smoothness, roughness, gloss, and matte finishes. Preferences and expectations of both Leica users and employees were captured to inform optimal surface qualities for a ceramic lens.

Alongside the user study, a technical analysis compared the pros and cons of various technical ceramic production methods (green machining, injection moulding, additive manufacturing). Cost estimations were included, as were the specific challenges and opportunities presented by the technical ceramics industry.

This chapter presents a case study integrating findings from both the user study and the technical analysis into diverse design concepts for a special edition ceramic lens. The study's goal is two-fold:

1. Demonstrate the possibilities and constraints of technical ceramics within the lens manufacturing context.
2. Provide Leica with actionable insights for future development of ceramic lens options.

Each design variation will exemplify the strengths of its chosen manufacturing technique. The variations will also serve as reference points for a decision tree, visually highlighting potential design directions based on the research conducted.

4.6.1 SYNTHESIS OF FINDINGS

This thesis project explored the potential of a special edition Leica camera lens constructed with technical ceramics. This research had two essential components: a technical analysis of ceramic production methods and a user study focused on how luxury and premium qualities are perceived in relation to surface attributes.

Technical Analysis

Various technical ceramic production methods were analysed, including green machining, injection moulding, and additive manufacturing. Key takeaways include:

- Green machining: An expensive approach due to material waste, time-consuming processes, and part complexity. In fact, our cost estimation revealed a tenfold price increase over current aluminium parts production.

- Injection moulding: A highly cost-effective solution, particularly for production runs exceeding 100 parts. The mature injection moulding industry offers competitive pricing.
- Additive manufacturing: Unique advantage in that increased geometric complexity does not equal increased cost. This allows design optimization for assembly, function, or aesthetics. However, surface quality may require costly post-processing to achieve a luxurious visual and tactile experience.

A significant challenge is the limited supplier network for technical ceramics, particularly in green machining. Finding a willing partner for sample part production proved difficult.

User Study

Leica users and employees participated in a survey evaluating surface samples on luxuriousness and attributes like smoothness, roughness, gloss, and matte finish. Key findings:

No single attribute guarantees premiumness: Perception of premiumness seems to stem from specific combinations of attributes, rather than individual qualities. Combinations like smooth/glossy, rough/matte, and smooth/matte ranked highly.

Ceramic Insights: The study generated valuable insights specifically about ceramic materials and their contribution to a luxury experience. [Summarize 2-3 key insights specific to ceramics here]

4.6.2 DESIGN PHASE

Idea behind creating concept designs: understand the benefits and drawbacks of technical ceramics and the production processes, which then can be used to inform future projects at Leica of how to approach the design, manufacturing etc. also find out which of the results of the research study are usable in which production method.

New grip features taking advantage of the increased design freedom with the additive manufacturing method.

4.6.2.1 CONCEPT 1

- Process: Ceramic feedstock (a blend of ceramic powder, binder, and solvent) is injected into a precision metal mould mirroring the lens housing design. The feedstock solidifies, then undergoes heating to remove the binder and fuse the ceramic particles.
- Advantages:
    - Scalability: Ideal for larger production runs (200+ units) with reliable consistency in form and quality.
    - Cost-effectiveness: Most financially viable option among the concepts explored.
- Challenges:
    - Design Adaptation: The original design may need modifications for successful injection moulding.

- Lead Time: Fabricating the mould introduces a longer lead time compared to other methods.

- Cost: Manufacturing the lens housing through injection moulding is estimated to be double the cost of traditional methods.
- Aesthetics: The highly polished ceramic housing offers superior scratch and wear resistance due to the exceptional hardness of zirconium oxide.

Concept Sketch: Illustrate the elegance of the polished housing, suggesting how its refined surface plays with light and offers a luxurious tactile experience.

Figure 16 Concept sketch of an injection moulded mirror finish on a lens

4.6.2.2 CONCEPT 2

- Process: Ceramic powder in contrasting colours (like black and white) is pressed to create the marbled green body. This 'blank' is then precision-machined with careful consideration for its green state fragility. Sintering completes the transformation into a durable lens housing.
- Advantages:
  - Individuality: Each lens boasts a unique, visually striking marbled pattern.
  - Precision: Green machining yields exceptional dimensional accuracy and a high-quality finish.
- Challenges:
  - Design Restrictions: Significant design overhaul is required to ensure the part is safely machinable while 'green'.
  - High Cost: This stands as the most expensive concept due to material waste and specialized labour.
- Cost: Tenfold increase compared to traditional lens housing manufacture.

Figure 17 Concept sketch and rendering of the marbled texture.

4.6.2.3 CONCEPT 3

- Process: Precise, layered deposition of ceramic powder mixture (via nozzle or laser) builds the green body. Sintering then creates a solid lens housing.
- Advantages:
  - Form Freedom: Additive manufacturing facilitates intricate organic shapes and details (like revolutionary grip textures) impossible with traditional methods.
- Challenges:
  - Design for Advantage: To fully capitalize on this method, substantial design rethinking is needed.
  - Moderate Expense: Cost falls between the other two concepts explored.
- Cost: Estimated to be five times more expensive than traditional lens housing creation.

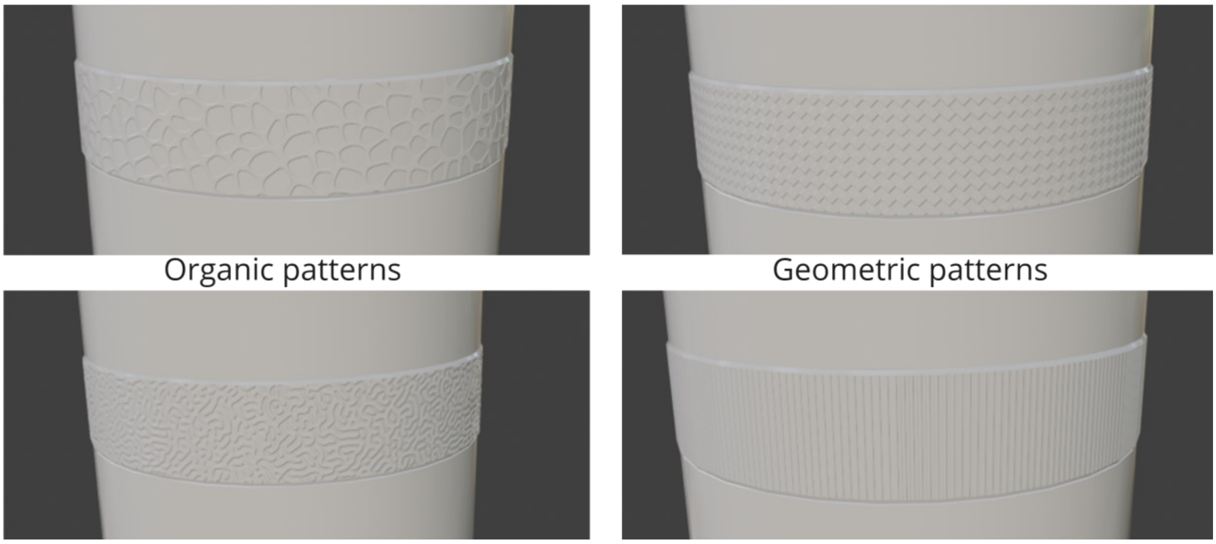


Figure 18 Different grip pattern variations

4.6.2.4 DISCUSSION

The process of designing these three distinct concepts generated invaluable insights about the potential, and the constraints, of utilizing technical ceramics in Leica lens production. Firstly, the need for design adaptation became undeniable. While injection moulding promises affordability and scalability, it necessitates design modifications to ensure successful moulding. Green machining, while capable of stunning bespoke outcomes, demands a complete design overhaul due to the constraints of machining a fragile green body. Additive manufacturing tempts with intricate forms and innovative grip possibilities, but only if the entire design approach embraces the specific freedoms this method offers.

Beyond design constraints, cost implications surfaced as a central consideration. Both green machining and additive manufacturing proved significantly more expensive than traditional Leica lens fabrication. This raises complex questions about balancing material innovation and visual distinction against market realities. Does the luxuriousness of marbled ceramics or the potential for revolutionary ergonomics via additive manufacturing justify the increased price point for the consumer? These concepts reveal the importance of weighing such trade-offs in future Leica projects.

Moreover, the user preference study underlined the significance of surface finishes. This knowledge dovetails nicely with two concepts. Injection moulding can excel in delivering the desired combination of smooth and glossy surfaces, appealing to the tactile aspects of a premium lens experience. On the other hand, green machining's striking marbled effect could infuse smaller accent elements with luxurious individuality. However, additive manufacturing may demand post-processing to overcome rough surface quality without sacrificing cost-effectiveness, posing a design complexity.

This concept phase highlights that incorporating technical ceramics is not a plug-and-play affair. It demands a holistic perspective across design, manufacturing, consumer value, and ultimately, Leica's unique market positioning. Technical feasibility alone isn't enough – success hinges on the thoughtful fusion of material characteristics, production realities, and the nuanced desires expressed by Leica's discerning customer base.

4.7 CONCLUSION

This chapter provided a comprehensive exploration of technical ceramics within the realm of handheld product design. Through close analysis of the current market landscape for ceramic devices, a detailed comparison of manufacturing methods (including green machining, injection moulding, and additive manufacturing), and a thorough cost assessment, a vital set of design guidelines emerged. These guidelines serve as a decision-making framework for designers and manufacturers seeking to implement technical ceramics strategically, balancing material attributes and production realities. To showcase the real-world impact of these guidelines, three distinct design concepts were developed. Each concept highlighted the unique advantages and constraints posed by specific manufacturing methods, emphasizing the design adaptations needed to unlock the full potential of ceramics. Ultimately, this work lays a foundation for Leica and other industry innovators to make informed choices about technical ceramic integration, pushing boundaries while navigating cost, design feasibility, and user expectations for premium handheld products.

5 RESULTS

The three studies conducted in this thesis yielded valuable insights into the relationships between surface attributes, user perceptions of luxury and premiumness, and the feasibility of manufacturing technical ceramic products with these desired attributes.

Study 1: Online Survey - Material Preferences

This survey revealed that zirconia oxide is perceived as possessing several attributes associated with luxury and premium products, including high quality, exclusivity, and a sense of innovation. Interestingly, Ultem, another technical ceramic, ranked lower in these attributes, suggesting that material choice plays a significant role in consumer perceptions of luxury.

Study 2: Online Survey - Surface Attribute Descriptions

The second study generated a rich vocabulary of sensory and tangible terms used to describe luxury objects across multiple product categories. These terms were organized into a comprehensive list of surface attributes, providing a valuable resource for designers and manufacturers seeking to create products that evoke feelings of luxury and premiumness.

Study 3: Multi-Attribute Perception Evaluation

The third study directly investigated the relationships between surface attributes and user perceptions of luxury and premiumness. The results showed a positive correlation between perceived smoothness and both luxury and premiumness, suggesting that this attribute is particularly important in creating high-end products. Additionally, certain combinations of attributes, such as smooth and glossy, were found to have a strong positive impact on perceptions of luxury.

Implications for Manufacturing

The findings from these studies have important implications for the manufacturing of technical ceramic products. To achieve the desired smooth surfaces that are associated with luxury, injection moulding or green machining are the most suitable methods. While additive manufacturing can also produce ceramic parts, the resulting surfaces may be rough and require additional post-processing steps to achieve the desired smoothness.

Case Study: Special Edition Lens

The results of the user studies and the analysis of manufacturing methods were applied to the design of a special edition camera lens constructed from technical ceramics. Injection moulding was selected as the most appropriate manufacturing method for this product, as it offers the best combination of cost-effectiveness, surface smoothness, and design freedom. The final design of the lens incorporates several features that take advantage of the unique properties of technical ceramics, such as its high strength and scratch resistance.

6 DISCUSSION

Benchmark Product

The benchmark product used in this study was a 3D printed plastic sample. While this product was useful for evaluating user perceptions of surface attributes, it is important to note that the results may not generalize to actual technical ceramic products. This is because technical ceramics have unique properties, such as their high strength and scratch resistance, which may influence user perceptions. In future studies, it would be beneficial to use actual technical ceramic products as the benchmark.

Future Research

This study provides a foundation for future research on the use of technical ceramics in premium handheld products. Several areas could be explored in more depth, including:

- **The relationship between surface attributes and user perceptions of luxury and premiumness for different product categories.** This study focused on handheld devices, but it would be interesting to investigate whether the same relationships hold true for other product categories, such as watches or jewellery.
- **The development of new manufacturing methods for technical ceramics.** The manufacturing methods used in this study are well-established, but there may be opportunities to develop new methods that can produce technical ceramic products with even better surface finishes and properties.
- **The use of technical ceramics in other applications.** This study focused on the use of technical ceramics in handheld products, but there may be other applications where technical ceramics could offer unique advantages. For example, technical ceramics could be used in medical devices or automotive components.

What Went Wrong?

As mentioned in the Results chapter, the direction of this project changed several times. This was due to a number of factors, including:

- **The difficulty in obtaining technical ceramic samples.** The project initially aimed to create a prototype of a special edition lens made from technical ceramics. However, it proved to be difficult to obtain technical ceramic samples from suppliers. This was due to a number of factors, including the high cost of technical ceramics and the reluctance of suppliers to provide samples for research purposes.
- **The lack of a clear definition of what the project wanted to achieve.** At the outset of the project, there was no clear definition of what the project wanted to achieve. This led to some confusion and wasted effort.

Perception Study

The perception study revealed that some attributes, such as smoothness, are positively correlated with perceptions of luxury and premiumness. However, other attributes, such as roughness, are negatively correlated with these perceptions. This suggests that material selection is an important factor in creating products that evoke feelings of luxury and premiumness.

Insights for Leica

The results of this Thesis provide Leica with valuable insights into the use of technical ceramics in premium handheld products. These insights can be used to inform future product development decisions. For example, Leica could consider using technical ceramics in products where a smooth surface finish is important, such as lenses or camera bodies.

7 CONCLUSION

This thesis has explored the potential of using technical ceramics to create premium handheld products. Through a series of user studies and an analysis of manufacturing methods, the thesis has identified the key surface attributes that are associated with luxury and premiumness and has investigated the feasibility of manufacturing technical ceramic products with these desired attributes.

The results of the user studies showed that smoothness is a key surface attribute that is associated with luxury and premiumness. Other attributes, such as glossiness and warmth, were also found to be positively correlated with these perceptions. However, attributes such as roughness and coldness were found to be negatively correlated with perceptions of luxury and premiumness.

The analysis of manufacturing methods showed that injection moulding and green machining are the most suitable methods for producing technical ceramic products with smooth surfaces. Additive manufacturing can also be used to produce technical ceramic products, but the resulting surfaces may be rough and require additional post-processing steps to achieve the desired smoothness.

The findings of this thesis have important implications for the design and manufacture of premium handheld products. By understanding the relationships between surface attributes, user perceptions of luxury and premiumness, and the capabilities of different manufacturing methods, designers and manufacturers can create products that meet the expectations of discerning consumers.

Future research could explore the following areas:

- The relationship between surface attributes and user perceptions of luxury and premiumness for different product categories.
- The development of new manufacturing methods for technical ceramics.
- The use of technical ceramics in other applications, such as medical devices or automotive components.

Overall, this thesis provides a valuable foundation for future research on the use of technical ceramics in premium handheld products.

8 REFERENCES

[1] C. Hart, "Hart, Chris, Doing a Literature Review: Releasing the Social Science Research Imagination. London: Sage, 1998.," 1998.

[2] Y. Levy and T. J. Ellis, "A systems approach to conduct an effective literature review in support of information systems research.," *Inf Sci*, vol. 9, 2006.

[3] A. Sylvester, M. Tate, and D. Johnstone, "Beyond synthesis: re-presenting heterogeneous research literature," *Behaviour & Information Technology*, vol. 32, no. 12, pp. 1199–1215, Dec. 2013, doi: 10.1080/0144929X.2011.624633.

[4] K. Johnson, T. Lenau, and M. Ashby, "THE AESTHETIC AND PERCEIVED ATTRIBUTES OF PRODUCTS," in *INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN*, 2003.

[5] S. Vihma, T. Lenau, B. Westerlund, and M. Stokholm, "Semantic & Aesthetic Functions in Design."

[6] R. L. Klatzky, S. Lederman, and C. Reed, "There's More to Touch Than Meets the Eye: The Salience of Object Attributes for Haptics With and Without Vision," *J Exp Psychol Gen*, vol. 116, no. 4, pp. 356–369, 1987, doi: 10.1037/0096-3445.116.4.356.

[7] T. J. L. van Rompay, F. Finger, D. Saakes, and A. Fenko, "'See me, feel me': Effects of 3D-printed surface patterns on beverage evaluation," *Food Qual Prefer*, vol. 62, pp. 332–339, Dec. 2017, doi: 10.1016/J.FOODQUAL.2016.12.002.

[8] J. Peck and T. L. Childers, "Individual Differences in Haptic Information Processing: The 'Need for Touch' Scale," *Journal of Consumer Research*, vol. 30, no. 3, pp. 430–442, Dec. 2003, doi: 10.1086/378619.

[9] J. Peck and T. L. Childers, "To have and to hold: The influence of haptic information on product judgments," *Journal of Marketing*, vol. 67, no. 2. pp. 35–48, Apr. 2003. doi: 10.1509/jmkg.67.2.35.18612.

[10] A. T. Ranaweera, B. A. S. Martin, and H. S. Jin, "What you touch, touches you: The influence of haptic attributes on consumer product impressions," *Psychol Mark*, vol. 38, no. 1, pp. 183–195, Jan. 2021, doi: 10.1002/mar.21433.

[11] J. Peck and J. W. Johnson, "Autotelic need for touch, haptics, and persuasion: The role of involvement," *Psychol Mark*, vol. 28, no. 3, pp. 222–239, Mar. 2011, doi: 10.1002/mar.20389.

[12] J. A. Quelch, "Marketing the Premium Product," *Bus Horiz*, vol. 30, no. 3, pp. 38–45, 1987, doi: https://doi.org/10.1016/0007-6813(87)90035-8.

[13] J. Allsopp, “Additional Practice Papers: Premium pricing: Understanding the value of premium,” *Journal of Revenue and Pricing Management*, vol. 4, no. 2, pp. 185–194, 2005, doi: 10.1057/palgrave.rpm.5170138.

[14] J.-N. Kapferer, “The challenges of luxury branding,” in *The Routledge companion to contemporary brand management*, Routledge, 2016, pp. 473–491.

[15] B. Dubois, G. Laurent, and S. Czellar, “Consumer rapport to luxury: Analyzing complex and ambivalent attitudes,” 2001. [Online]. Available: https://EconPapers.repec.org/RePEc:ebg:heccah:0736

[16] V. De Barnier, S. Falcy, and P. Valette-Florence, “Do consumers perceive three levels of luxury? A comparison of accessible, intermediate and inaccessible luxury brands,” *Journal of Brand Management*, vol. 19, no. 7, pp. 623–636, May 2012, doi: 10.1057/bm.2012.11.

[17] J.-N. Kapferer, *Kapferer on Luxury: How luxury brands can grow yet remain rare*. Kogan Page, 2015.

[18] Kapferer J. and Bastien V., *The Luxury Strategy: Break the Rules of Marketing to Build Luxury Brands*, 2nd ed. Kogan Page Publichers, 2012.

[19] T. Sjostrom, A. M. Corsi, and L. Lockshin, “What characterises luxury products? A study across three product categories,” *International Journal of Wine Business Research*, vol. 28, no. 1, pp. 76–95, Mar. 2016, doi: 10.1108/IJWBR-05-2015-0017.

[20] M. Martinón-Torres and T. Rehren, “Technical ceramics,” *Archaeometallurgy in Global Perspective: Methods and Syntheses*, vol. 9781461490173, pp. 107–131, Aug. 2014, doi: 10.1007/978-1-4614-9017-3_6/FIGURES/23.

[21] B. Arnold, “Zirconium Oxide Versus Aluminium Oxide,” in *Zircon, Zirconium, Zirconia - Similar Names, Different Materials*, B. Arnold, Ed., Berlin, Heidelberg: Springer Berlin Heidelberg, 2022, pp. 67–71. doi: 10.1007/978-3-662-64269-6_15.

[22] D. W. Richerson and W. E. Lee, *Modern Ceramic Engineering Properties, Processing, and Use in Design Fourth Edition.* 2018. [Online]. Available: http://taylorandfrancis.com

[23] W. D. Kingery, H. K. Bowen, and D. R. Uhlmann, “Introduction to ceramics (2nd edition),” *John Wiley & Sons, Inc.*, p. 864, 1976, Accessed: May 15, 2023. [Online]. Available: https://www.wiley.com/en-ie/Introduction+to+Ceramics%2C+2nd+Edition-p-9780471478607

[24] D. W. Richerson, “The status of ceramic turbine component fabrication and quality assurance relevant to automotive turbine needs,” Feb. 2000, doi: 10.2172/757308.

[25] K. P. Constant, “Ceramic Materials,” *Encyclopedia of Condensed Matter Physics*, pp. 165–173, Jan. 2005, doi: 10.1016/B0-12-369401-9/00537-4.

[26] H. Tan, X. Li, M. Liu, B. Ma, B. Gu, and X. Li, "Tolerance of clay minerals by cement: Effect of side-chain density in polyethylene oxide (PEO) superplasticizer additives," *Clays Clay Miner*, vol. 64, no. 6, pp. 732–742, Dec. 2016, doi: 10.1346/CCMN.2016.064037.

[27] J. C. Wang, H. Dommati, and S. J. Hsieh, "Review of additive manufacturing methods for high-performance ceramic materials," *International Journal of Advanced Manufacturing Technology*, vol. 103, no. 5–8. Springer London, pp. 2627–2647, Aug. 19, 2019. doi: 10.1007/s00170-019-03669-3.

[28] C. A. Handwerker, J. E. Blendell, and R. L. Coble, "Sintering of Ceramics," *Science of Sintering*, pp. 3–37, 1989, doi: 10.1007/978-1-4899-0933-6_1.

[29] A. Sinhamahapatra, J. P. Jeon, J. Kang, B. Han, and J. S. Yu, "Oxygen-Deficient Zirconia (ZrO2-x): A New Material for Solar Light Absorption," *Sci Rep*, vol. 6, Jun. 2016, doi: 10.1038/srep27218.

[30] B. Ji, H. Tong, J. Li, Y. Li, and M. Xu, "Scanning process of spark assisted chemical engraving (SACE) on ZrO2 ceramics by constraining discharges to tool electrode end," *Ceram Int*, vol. 46, no. 2, pp. 1433–1441, Feb. 2020, doi: 10.1016/J.CERAMINT.2019.09.107.

[31] J. Peter, B. Bhattacharyya, J. Peter, Á. B. Doloi, Á. B. Bhattacharyya, and B. Doloi, "Nd:YAG Laser Marking on Zirconia Ceramic," 2015, doi: 10.1007/978-81-322-2352-8_16.

[32] "Dark Side of the Moon Speedmaster Schwarze Keramik Chronograph Uhr 311.92.44.51.01.003 | OMEGA DE®." Accessed: May 03, 2023. [Online]. Available: https://www.omegawatches.com/de-de/watch-omega-speedmaster-dark-side-of-the-moon-co-axial-chronometer-chronograph-44-25-mm-31192445101003

[33] Apple, "Apple Watch Series 2." Accessed: Feb. 20, 2024. [Online]. Available: https://www.apple.com/newsroom/2016/09/apple-introduces-apple-watch-series-2/

[34] "BIOCERAMIC by Swatch – Ceramic and biosourced plastic watches | Swatch® [United Kingdom]." Accessed: May 03, 2023. [Online]. Available: https://www.swatch.com/en-gb/bioceramic.html

[35] Samsung, "Samsung Galaxy S10." Accessed: Feb. 20, 2024. [Online]. Available: https://news.samsung.com/us/galaxy-s10s-design-team-created-galaxy-everyone/

[36] cnet.com, "Xiaomi Mi 6." Accessed: Feb. 20, 2024. [Online]. Available: https://www.cnet.com/reviews/xiaomi-mi-6-review/

[37] hubs.com, "CNC machining guide hubs.com." Accessed: Feb. 20, 2024. [Online]. Available: https://www.hubs.com/knowledge-base/how-design-parts-cnc-machining/

[38] hubs.com, “How to design parts for SLA 3D printing.” Accessed: Feb. 20, 2024. [Online]. Available: https://www.hubs.com/knowledge-base/how-design-parts-sla-3d-printing/

[39] hubs.com, “How to design parts for FDM 3D printing.” Accessed: Feb. 20, 2024. [Online]. Available: https://www.hubs.com/knowledge-base/how-design-parts-fdm-3d-printing/#how-do-you-design-for-fdm-printing

[40] matthey.com, “Leading the way in binder jet ceramic 3D printing.” Accessed: Feb. 20, 2024. [Online]. Available: https://matthey.com/science-and-innovation/expert-insights/leading-the-way-in-binder-jet-ceramic-3d-printing

[41] sigmaaldrich.com, “Ceramic Powder Price.” Accessed: Feb. 20, 2024. [Online]. Available: https://www.sigmaaldrich.com/DE/de/search/zirconium-oxide?focus=products&page=1&perpage=30&sort=relevance&term=zirconium%20oxide&type=product_name

[42] IcoMold.com, “Injection Molding Cost Calculator Online Quotes in 30 Seconds.” Accessed: Feb. 20, 2024. [Online]. Available: https://icomold.com/much-injection-molding-cost/

9 APPENDIX

9.1 ADDITIONAL FIGURES

Table 4 Correlation Analysis Complete

	Soft	Hard	Heavy	Light	Cold	Warm	Smooth	Silky	Rough	Slippery	Reflective
Soft	1										
Hard	-0,25898	1									
Heavy	-0,21302	0,167074	1								
Light	-0,2491	-0,28367	-0,39093	1							
Cold	-0,22861	0,007356	-0,05824	-0,10945	1						
Warm	0,051106	0,021449	-0,12857	0,10283	-0,27076	1					
Smooth	-0,09322	0,164656	0,205707	-0,163	0,260273	0,083119	1				
Silky	0,311395	-0,12828	-0,12559	-0,00158	-0,26647	0,175272	-0,39839	1			
Rough	-0,04109	0,046278	-0,11215	0,054646	-0,13552	-0,11231	-0,35087	-0,35087	1		
Slippery	-0,16282	-0,01257	0,039107	0,098736	0,193315	-0,04153	0,005296	-0,26481	-0,18288	1	
Reflective	-0,22861	0,007356	0,083195	0,097286	0,190476	-0,03471	0,154924	-0,16112	-0,13552	0,193315	1
Glossy	-0,2439	0,10124	0,05858	0,048652	0,289579	-0,06222	0,412549	-0,29553	-0,04109	0,335414	0,16003
Matte	0,333914	0,046335	-0,05696	-0,06661	-0,35211	0,201534	-0,32245	0,36997	0,076181	-0,34551	-0,46296
Opaque	-0,05347	0,067911	0,14132	0,09655	-0,03517	0,289694	0,029749	0,029749	0,04741	0,25173	-0,18464
Gold	-0,16282	-0,17289	-0,14221	-0,03378	0,193315	0,109768	0,410461	-0,12976	-0,18288	0,113043	0,193315
Silver	-0,2491	0,195373	0,367556	-0,26708	0,30402	-0,16843	-0,08229	-0,08229	0,054646	-0,03378	0,200653
Black	0,091826	-0,04633	-0,29163	0,321381	-0,31298	-0,10457	-0,11031	0,062793	0,222683	-0,08081	-0,20214
Clear	0,086426	0,07151	0,121312	-0,05911	-0,11573	0,236209	-0,03012	-0,03012	-0,13868	0,197814	-0,11573
Muffled	-0,14985	-0,09205	0,150847	0,208075	-0,21281	0,19325	-0,00158	-0,163	0,240441	-0,03378	-0,00608
Ringing	0,029101	0,174168	-0,0826	-0,14396	0,078801	-0,19089	0,04733	0,127791	-0,24515	0,08548	0,078801
Luxurious - E	-0,13854	-0,18571	-0,00457	-0,00959	0,106172	-0,17622	-0,18196	-0,247	0,118906	0,245696	0,022868
Standard - Pr	0,201292	0,050668	0,06231	-0,01423	-0,0414	0,226557	0,285111	0,221707	-0,21178	-0,05647	0,175141

	Glossy	Matte	Opaque	Gold	Silver	Black	Clear	Muffled	Ringing	urious - Essen	ndard - Premium
Soft											
Hard											
Heavy											
Light											
Cold											
Warm											
Smooth											
Silky											
Rough											
Slippery											
Reflective											
Glossy	1										
Matte	-0,624	1									
Opaque	-0,05347	0,024079	1								
Gold	0,501493	-0,48762	-0,1315	1							
Silver	-0,0506	0,018317	-0,24699	-0,29881	1						
Black	-0,12104	0,092857	0,221523	-0,22291	-0,61279	1					
Clear	-0,12347	0,169031	0,384617	-0,08242	-0,22658	-0,16903	1				
Muffled	-0,0506	0,018317	0,325574	-0,16629	-0,0295	0,066607	0,275839	1			
Ringing	0,029101	-0,03984	-0,26189	0,08548	0,013932	-0,04482	-0,2357	-0,85449	1		
Luxurious - E	-0,00523	-0,19817	0,057302	-0,03909	-0,17979	0,266608	0,177311	0,054228	-0,11602	1	
Standard - Pr	0,149313	0,013517	-0,03234	0,186426	0,172403	-0,32485	-0,1393	0,027243	0,012161	-0,78951	1