INVESTIGATION OF THE PROPERTY & TOPOLOGY GRADIENTS OF SCALED REPTILE SKIN FOR BIO-MIMETIC WEAR RESISTANCE OF MATERIAL SYSTEMS

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

Investigation of the Property & Topology Gradients of Scaled Reptile Skin for Bio-Mimetic Wear Resistance of Material Systems

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The research objective of this project is to investigate the unique combinations of material property and topology gradients exhibited within a class of nature's hierarchical material systems, which are optimized to achieve its intended function(s) by strategically combining aspects of form, structure, and properties. A systematic mapping and analysis of these property and topology distributions will help generate design guidelines for material systems to improve performance while catering to the operating environment. The class of mentor organism features that is selected for study is scaled reptile skin. Scaled reptile skin is typically optimized for excellent abrasive wear resistance through strategies such as the biological coupling of hard surface scale layers with flexible inner regions for shock/vibration absorption, the size/shape/arrangement of topological features, etc. For achieving the objective, specimen will be suitably sectioned and prepared, their property distributions will be mapped through appropriate mechanical characterization testing, chemical distributions through spectroscopy, and topologies through non-contact white light interferometry. These will be combined to create a 3D model of the material with distributed property and topology gradients. Such a model will serve as the input template for finite element studies aimed at attaining material system performance at levels close to the efficiencies found in nature.

ACKNOWLEDGMENTS

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Finally, I would like to thank my parents, Phillip and Christine Hale, whose support (both emotional and financial) made this possible.

CHAPTER I

INTRODUCTION

Biomimicry is a multi-disciplinary field that is dedicated to solving human problems by optimizing synthetic designs through the investigation of naturally occurring models and material systems [1]. The focus of biomimicry is less on what can be taken out of nature and more on what can be learned from millions of years of evolution, and how it can be adapted to synthetic designs. The result of investigating and analyzing the relationship between nature-intended function(s) and material properties of biological material-systems can provide insight on improving various properties of synthetic material-systems utilized in various applications.

Synthetic material systems used in abrasive environments often lack the antithetical combination of abrasive wear resistance on the surface (through high hardness, yield strength and related properties) along with a relatively flexible and tough inner structure that is capable of effective shock and vibration absorption. In nature, however, scaled reptilian skin is an excellent example of optimized wear resistance. The biological coupling of a hard surface layer of scales with flexible inner regions allows shock/vibration absorption and the necessary size, shape, and arrangements of topological features to contribute towards abrasive wear resistance. Further investigating these various properties of scaled reptile skin and analyzing the relationship between these properties and structure of the material will help to understand improved material design guidelines for synthetic materials in abrasive environments.

Previous research concerning the investigation of scaled reptile skin provides insight on the various properties scales possess, the future implications, and possible applications for the findings; however, there is lack of an overall analysis of the relationships between the various mechanical, topological, and structural properties. This research will be dedicated to investigating the various properties of scaled reptilian skin and analyzing the relationships of these properties through 3D mapping of material properties and topology distributions. A conclusive 3D model of all of the properties of the scales can then be used as a foundation for future finite element studies. Such finite element material models that are better representations of the collective material system could potentially lead to the development of synthetic material-system design guidelines, as well as to the improvement of property and topology combinations of materials tailored to the operating environments.

Objectives

The objectives of this research project are to:

- Investigate the material property and topology gradients of a natural hierarchical material-system (scaled reptile skin) through mechanical characterization testing, spectroscopy, and interferometry.
- Map and analyze the gradients in mechanical property distributions, chemical distributions, and topology of specimens.
- Combine the distributions in topology and properties to create 3D models of the material systems that represent the specimens satisfactorily.

Methodology

It is proposed to investigate the relationships between the material properties, structure, and topology of scaled reptile skin through mapping and analyzing the property and topology distributions. First, the specimen will be acquired and prepared for mechanical testing, spectroscopy, and interferometry (task-1). After testing the specimen, the mechanical property distributions will be spatially mapped through mechanical characterization testing, the chemical distributions will be mapped through energy dispersive spectroscopy, and the surface topology of the specimen will be mapped through non-contact scanning white light interferometry (task-2). Finally, once the property and topology distributions are mapped, the results will be combined in order to create a 3D model of the specimen, including distributed property and topology gradients (task-3).

Expected contributions

The expected contribution from this work will be:

- Understand how a specific class of reptilian skin works as a material system to achieve its intended function of abrasive wear resistance effectively
- A better understanding of the spatial distribution of mechanical properties and the topologies of these material systems
- How these distributions and gradients synergistically contribute and achieve the intended function in an effective manner
- A 3D map created from these property and topology gradients/distributions
- Develop biomimetic strategies using these 3D maps of property and topology gradients and distributions for future material-system designs

CHAPTER II

BACKGROUND

Biomimetics

The term "biomimetics," coined by Otto Schmitt, refers to the mechanisms, structures, and systems that are found in nature being imitated to improve synthetic designs. Ideas for synthetic designs can be inspired by the appearance, function, or structure of a biological organism or material [2]. Although the term biomimetics was coined relatively recently, the practice of drawing inspiration for design from nature has been in practice for centuries. Well-known designs that are inspired by nature include Leonardo da Vinci's sketches of flying machines that were inspired by the movements and anatomy of birds, and Georges de Mestral's inspiration for the invention of Velcro through the hooked seeds of the burdock plant [3]. Since organisms have adapted over time to operate in its living environment in a remarkably efficient and sustainable manner, bio-mimicking their structure and function can be very useful in discovering new technologies and ways to improve man-made designs.

The biomimetics of scaled skin

Friction and wear of materials are common challenges to take into consideration while designing man-made systems containing moving parts in different operating environments. Inspirations for improving the designs of these material surfaces in contact can be taken from investigating naturally occurring material-systems, which have evolved to provide excellent wear resistance and reducing friction. There are many such examples of scaled skin providing protection to animals in nature that can inspire man-made designs.

Investigations on non-reptilian scaled skin

In nature, there are many organisms native to sandy desert regions that have evolved the necessary abrasive wear resistant properties to withstand erosive wear due to high speed wind storms or when burrowing in the sand. Desert scorpions, for example, have adapted to the desert environment by evolving and developing a highly abrasive-resistant outer shell, allowing the scorpions to minimize abrasive wear due to high wind speed sandstorms, apart from a few minor surface scratches. As shown in **Figure 1**, a class of scorpions feature a grooved surface along the longitudinal direction of the exoskeleton, which was attributed to contributing towards excellent wear resistant properties [4]. The biological coupling of the surface topologies, material properties, and region-specific flexibility of the back of desert scorpion has inspired fabrication and testing of bio-inspired designs, which exhibited high resistance to abrasive wear [5].

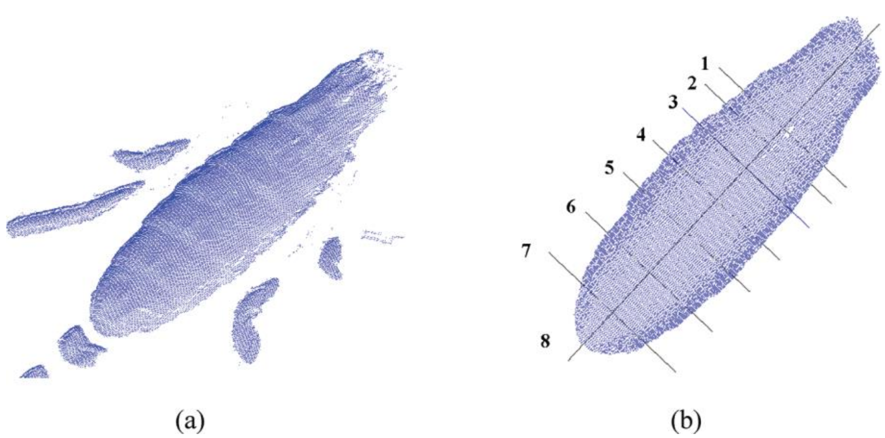


Figure 1: Point cloud map of the exoskeleton of a scorpion back [4]

Other animals, not native to sandy desert regions, also possess protective skin that function to protect the animal. For example, the outer layer of armadillo armor consists of a hard, leathery layer that functions to protect the armadillo from predatory animals. This body armor, or the osteoderm, consists of hexagonal and triangular scales. The outer layer of the osteoderm consists of keratin and the inner layer consists of a material having a composition close to that of bone, as seen in **Figure 2** [6]. The presence of non-mineralized fibers, called Sharpey's fibers, which hold the individual scales together contribute to the overall flexibility of the armor and increase the tensile strength of the armor [7].

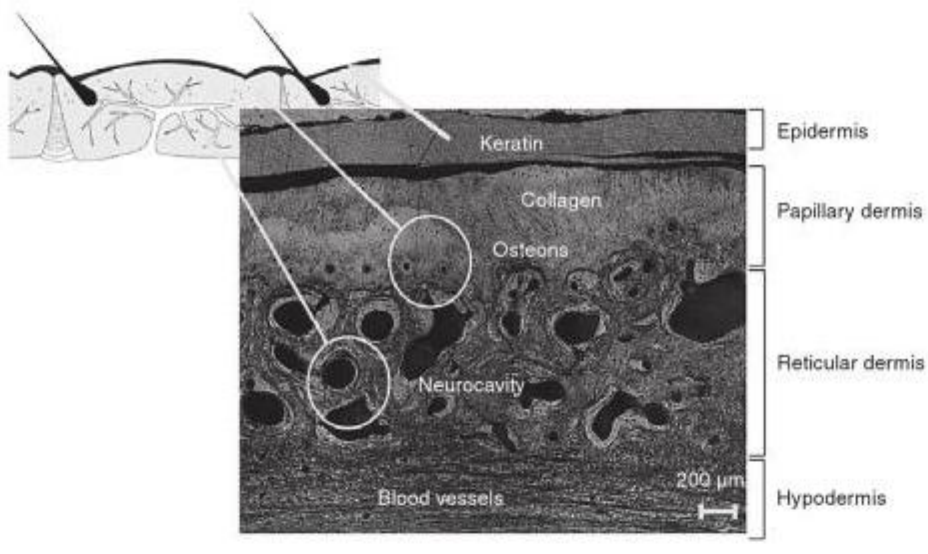


Figure 2: Optical Micrograph of a section of the Armadillo Osteoderm [6]

As shown in **Figure 2**, armadillo skin features several different layers that contribute to the overall function of the armor. The outer epidermis layer, which consists of keratin, has a higher hardness than the inner layer of the dermis, which consists of collagen followed by a porous layer. This porous layer of bone contributes to the compressive and deformation properties of the osteoderm, allowing the osteoderm to experience a large amount of distortion before experiencing failure [7]. The gradients in the mechanical properties combined with the composition of the material of the osteoderm contribute to the overall wear resistance, hardness, and toughness of armadillo armor.

Fish scales also possess similar property distributions that contribute to the flexibility, hardness and toughness. The hardness, toughness, and strength in fish scales are achieved by the different layers of materials in the scales. On a microstructural level, the outer surface of fish scales are mineralized, which contributes to the hardness of the scale, while the inner layers consist of collagen fibers [8, 9]. This layering of a highly mineralized outer layer with a flexible collagen layer in the scales contributes to the strength, hardness, and toughness of the fish scales [10, 11].

Investigations on scaled reptilian skin

Reptiles have also adapted to abrasive environments. Snakes rely primarily on serpentine movement to move across surfaces, since they are limbless organisms. Some species of reptiles also take to burrowing in the dirt and sand to take shelter. For example, sandfish, a species of skink native to the Sahara desert region, have skin that exhibits very low coefficient of friction such that the skink is able to “swim” through the sand without experiencing significant abrasive wear [12]. The biological coupling of a hard surface layer of scales with flexible inner regions allows for shock and vibration absorption, along with the necessary size, shape, and arrangements of topological features to contribute towards abrasive wear resistance [13, 14]. The gradient in material properties from a hard outer surface to a soft, flexible inner layer contributes to abrasive wear resistance through the combination of flexibility and stiffness [15].

Most scaled reptiles generally possess some common features in the construction of their skin. The skin of a scaled reptile consists of an outer layer of skin, or the epidermis, which is the skin that is preparing to shed, and an inner layer of skin, or the dermis, that grows in to eventually replace the shed skin. As shown in **Figure 3**, both the epidermis and the dermis have the same sub-layers [13]. These layers have higher hardness the closer to the surface they are. By the time that the dermis has matured into the epidermis and ready to be shed, the outermost *oberhautchen* layer is the hardest layer consisting of a highly keratinized surface, and the hardness of the skin decreases with each layer, with the inner layer of skin consisting of connective tissue and flexible fibers.

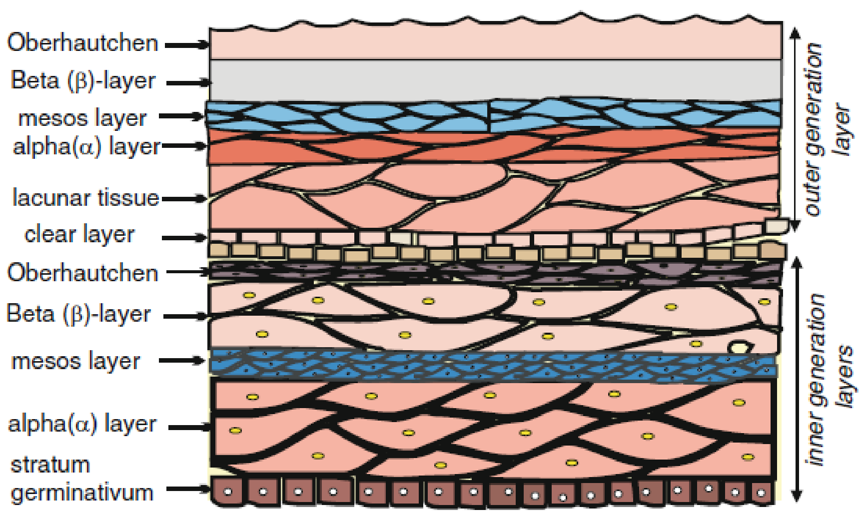


Figure 3: An illustration of the general features of the epidermis of a scaled reptile [13]

Along with the gradient in mechanical properties of the different layers of the skin of scaled reptiles, the topography of the scales also serves a functional purpose. **Figure 4** depicts two separate white light interferometer graphs of scaled snake skin [14]. The left graph depicts a surface map of the topology of a grouping of scales, while the right graph depicts a surface map of the topology of a single scale. The lighter regions of the graphs indicate the highest point of the topography while the darker regions indicate the lower points in the topography. These topography features allow the snakes to modify the surface as animal moves across the ground, changing the coefficient of friction in order to reduce frictional traction [16].

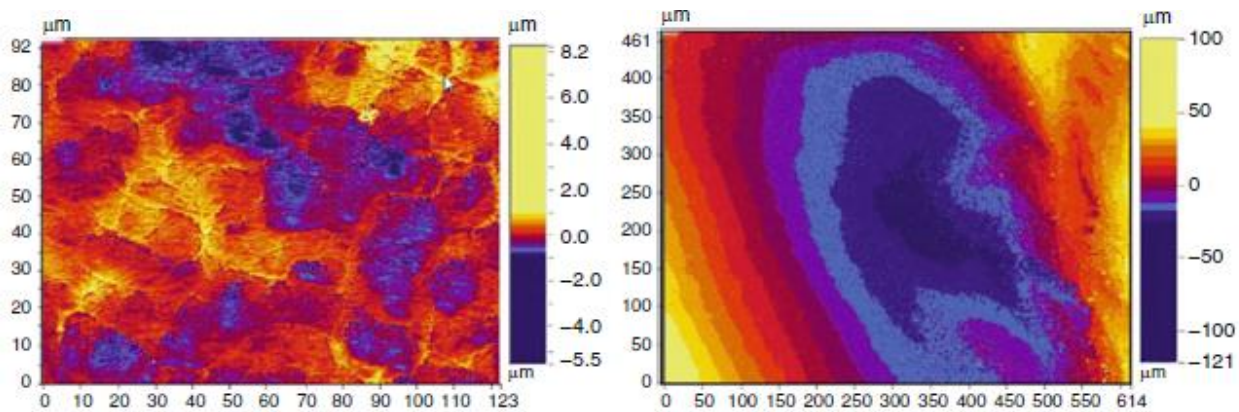


Figure 4: White light interferometer maps of scales [14]

These highly abrasive wear resistant scales have inspired the fabrication and testing of biomimetic designs. Bionic samples inspired by the scale structure of a species of desert lizard were created by Huang *et al*. using aluminum and silicon, with aluminum acting as the outer shell and the silicon as the soft, flexible inner region [17]. It was found that the bionic sample featured improved erosion resistance. Similarly, Greiner *et al.* were inspired by the surface topologies and scale arrangements of sandfish skinks and ball pythons to develop new etching methods to reduce friction and wear on metals [18].

More in-depth investigation on how the relationship between the mechanical, chemical, and topological properties of reptilian skin will lead to a better understanding of how structure and composition affects the wear resistant properties, and how these properties can be imitated in synthetic designs.

CHAPTER III

SPECIMEN PREPARATION FOR PROPERTY TESTING AND METROLOGY (TASK-1)

In this chapter, the specimen selection process and initial imaging of the specimen is included. The specimen preparation and background on the topology, chemical distribution, and mechanical testing of the specimen is also detailed.

Specimen selection

Because the general purpose of this study is to investigate the combination of properties that attribute to the wear-resistance of scaled reptile skin, organisms native to abrasive environments were considered for study. Arid desert regions are the most common natural abrasive environments where there exists a large quantity of native reptile species. These environments are harsh, and contain an abundance of coarse dirt and rocks. In these regions, reptiles have adapted to navigating through the sand, rocks, and coarse dirt without major damage to their skin. Some species of reptiles in these environments burrow in the ground to escape the heat or hunt for prey. The burrowing reptiles in these regions have developed highly wear-resistant skin because of the abrasion of the dirt against the scales as the reptile burrows in the ground. It is from these burrowing species native to arid regions that the specimen for this study was selected, especially due to their wear-resistant scales.

Arizona elegans (glossy snake)

The species chosen for this study is the *Arizona elegans* snake, or the glossy snake. Glossy snakes are native to Mexico and the southwestern United States. These snakes inhabit the semi-arid grasslands and sandy desert regions of these areas. The snake, as pictured in **Figure 5**, is a non-venomous, non-aggressive nocturnal species. Glossy snakes are medium-sized snakes with smooth scales that are a light grey or beige in color with gold or brown scale patterns. The glossy snakes are known for burrowing in the ground during the day to seek shelter from predators, and in the winter to hibernate during the cold weather. The combination of the natural habitat of an arid dry region, and the burrowing behavior of this species were the main factors in the selection of this species for study, along with the conservation status of this species. In the state of Texas, glossy snakes are not a protected or endangered species.

Figure 5: *Arizona elegans* adult snake [19]

Experimental specimen

The samples of skin and scales that are used were acquired from the Biodiversity Research and Teaching Collections (BRTC) at Texas A&M University. The specimen consists of two sections of dorsal scales, which are scales located along the back and sides of the snake. These are stored in 70% ethanol in a glass container at room temperature, at the recommendation of BRTC curators. To avoid drying out the skin, the specimen is removed from the ethanol for short periods and is returned to the ethanol immediately after examination or testing procedures.

Images of specimen

The initial observations of the specimen were performed using a microscope with multiple objectives. To prepare the specimen for microscopy, one of the snakeskin samples was removed from the glass container using metal forceps and placed on a clean surface. A small section of scales was cut from the main piece of snakeskin, and placed on a clean petri dish. **Figure 6** shows the small section of scales below, with a 20x objective.

Figure 6: Section of scales under 20x objective

Figure 7, pictured below, shows the overlapping along the edges of the scales. The scales on the snakes overlap to provide protection to the skin of the snake, while maintaining the necessary flexibility of the skin for movement.

Figure 7: Overlapping of scales (50x)

Under the 200x objective, the grooves on the top of the scales that are faintly visible under the 50x objective become more apparent, as seen in **Figure 8**.

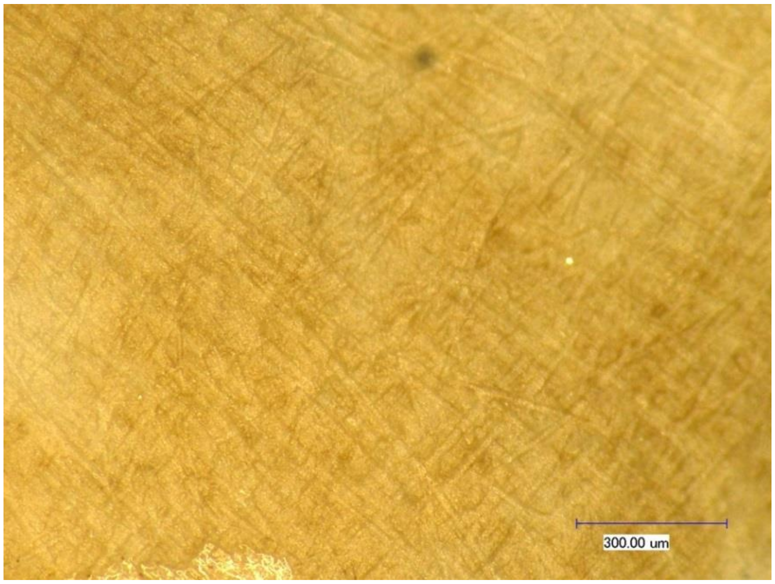


Figure 8: Top of scale (200x)

Specimen preparation for testing and metrology

The first main objective of this study is to investigate the material property and topology gradients of a scaled reptile skin through interferometry, spectroscopy, and mechanical characterization testing.

Capturing topology: white-light interferometry and 3D optical microscopy

White-light interferometry operation principle

The topography of the scales, in combination with the chemical distribution and mechanical properties, contribute to the overall wear-resistance of the scales. One way to obtain the topography, or surface features, of the scales is through white-light interferometry. White-light interferometry uses light as a non-contact method for measuring the topography of the specimen. During operation, a beam of light is emitted and then is split into two beams by a beam splitter. The beam splitter is located between the specimen and the camera, as seen in **Figure 9.** After splitting, one of the beams travels to the specimen's surface while the other beam is reflected in a reference mirror. The beams are then re-combined to create an interference pattern, and travel into to the detector. The detector then uses the interference pattern to measure the light intensities, which is then used to create a 3D image of the specimen's surface features.

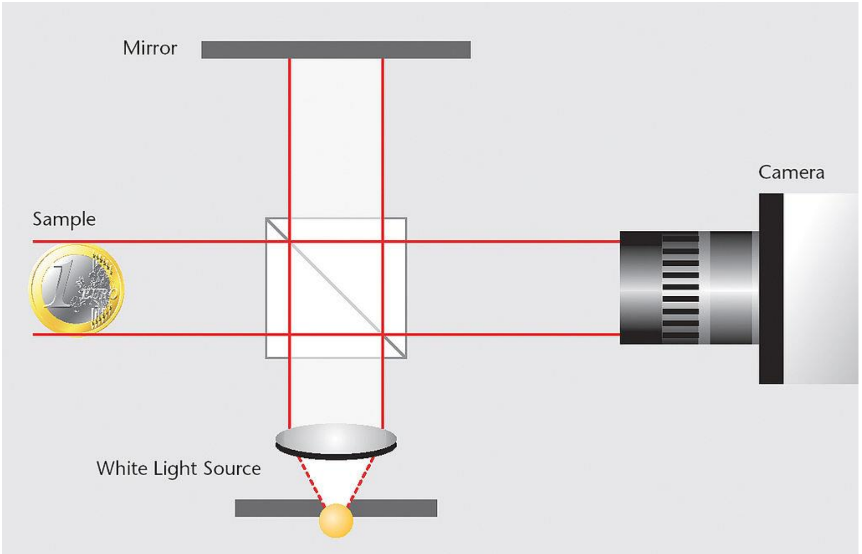


Figure 9: Basic operating principle of a white-light interferometer [20]

White-light interferometry is able to use this method to measure the surface height of features on a specimen in order to create a 3D image of the surface of the specimen. The interferometer used in this study to capture the surface features of the snakeskin is a ZYGO optical profiler, pictured in **Figure 10.**

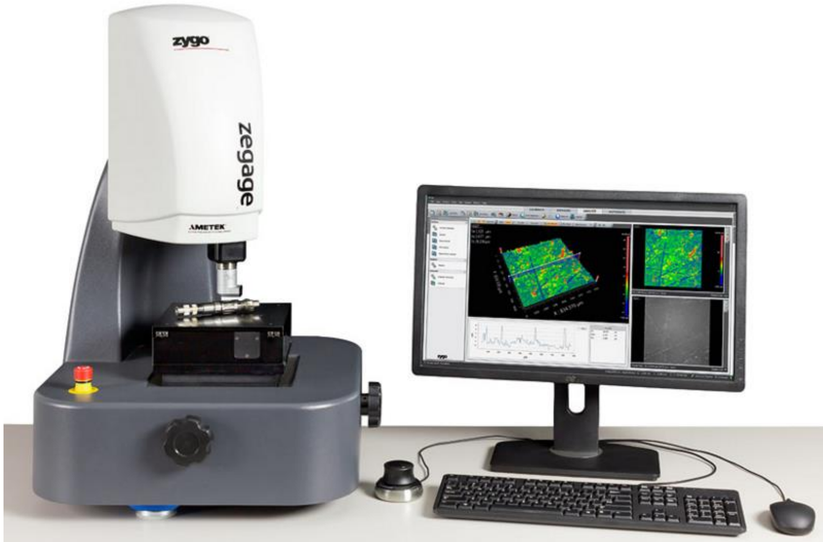


Figure 10: ZYGO optical profiler [21]

3D optical microscopy operation principle

The surface features of the scales were also obtained through 3D optical microscopy. An Alicona InfiniteFocus system (**Figure 11**) was used to obtain data on the surface features of the snakeskin. The system is a combined surface roughness and a 3D micro-coordinate measurement system. Similar to the white-light interferometer, this system also uses light. The beam of light is reflected off the specimen on the stage and projected to a sensor in the optic lens. The image is generated using the focus variation technique. As the optic moves in the vertical direction, images at different focuses are captured. The sharpness of each position is determined, and the variations of the sharpness of these positions are used to create the 3D image. The system is also capable of capturing the surface roughness and area of an entire specimen through movement of the stage in the X and Y directions.

Figure 11: Alicona InfiniteFocus system [22]

For the initial imaging of the surface features, two separate sections of the snakeskin were used. To avoid drying out the specimen, a previously dried out section of the snakeskin was used to focus the system approximately. Then, the wet specimen was placed on a clean petri dish and the excess ethanol was wiped off the surface of the specimen. After the scan was completed, the wet specimen was placed back in the container of ethanol. This initial capture of the surface features (**Figure 12**) shows some variation in height along the scales. Although there is some noise present, the middle areas of the scales are shown to be generally higher than the areas where the scales overlap each other. In the next chapter, Spatial Mapping of Mechanical/Chemical Property Distributions and Surface Topologies, a complete scan of the specimen will be captured and included.

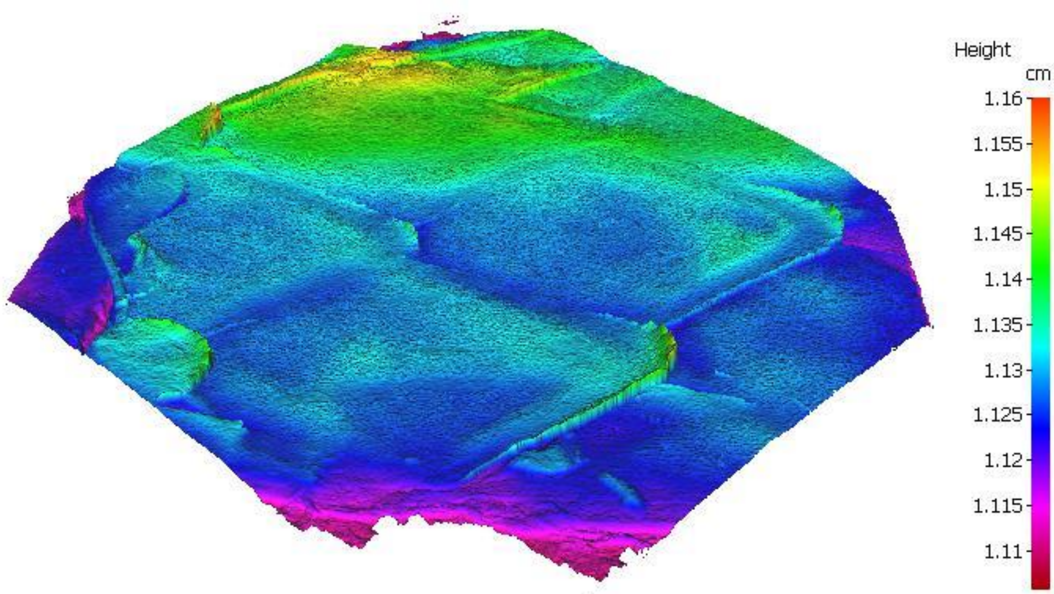


Figure 12: Initial capture of the surface features of a section of scales

Capturing chemical distribution: scanning electron microscopy and energy dispersive x-ray spectroscopy

Scanning electron microscopy (SEM) was used to analyze the chemical distributions in the scales. In SEM, images of the specimen are produced by scanning an electron beam across the specimen's surface. As the electrons strike the surface of the specimen, signals are generated. These signals contain information on the composition and the topology of the specimen. The main signals that provide the most information about the specimen are backscattered electrons, secondary electrons, and X-rays. Energy-dispersive X-ray (EDX) analysis is used primarily for elemental analysis of the specimen. When the electron beam hits the surface of the specimen, the interaction causes a shell transition in the atoms on the surface of the specimen. This shell transition in the surface results in the emission of X-rays. EDX is a technique that analyzes these emitted X-rays. Each emitted X-ray contains unique characteristics of the elements at the surface of the specimen. Using these characteristics, the chemical composition of the specimen can be mapped and analyzed.

SEM/EDX analysis requires specific sample preparation procedures, depending on the sample types. Since the specimen used in this study consists of biological material, the specimen requires a specific type of sample preparation procedure, beginning with a dehydration process. The specimen used for analysis was already stored in 70% ethanol, so the dehydration procedure began with immersing the specimen in 80% ethanol in a centrifuge tube for 20 minutes. This was then repeated for 90% ethanol and 100% ethanol. Once the specimen is completely dehydrated, the next main step in preparing biological samples for the analysis is freeze-drying of the specimen. Freeze-drying is necessary to avoid collapsing or shrinking of the surface features of the specimen for accurate results. The specimen was placed in a lyophilizer for 24 hours for the freeze-drying process. After freeze-drying, the specimen was mounted on copper tape and sputter coated with platinum-palladium layer of a thickness of 10 nm.

Capturing mechanical properties: mechanical testing

Mechanical tests are useful in determining the mechanical properties of materials. Mechanical properties of materials, like hardness, toughness, and fatigue, are generally used to classify materials. These properties are also used to determine how materials will perform under an applied load. There are many different types of tests used to determine these properties of materials, such as tensile, compressive, and hardness tests. Due to the small size and the nature of the material, nanoindentation was considered a sufficient method to analyze the mechanical properties of the scales. Nanoindentation is a type of indentation hardness test that operates on a nanoscale. Indentation hardness testing is used to measure the hardness of a material, which measures the ability of a material to resist permanent indentation. In indentation hardness testing, a predetermined load is applied to the indenter with a known size, which is lowered onto the surface of the material. As the indenter is removed from the material, it leaves an indentation on the surface. This indentation can then be measured to determine the hardness number. Since nanoindentation is on the nanoscale, the deformation of the surface caused by the indenter is measured by the machine as the load is being applied to the specimen. This relationship between the load applied to the indenter and the depth of the deformation, shown in **Figure 13**, can be used to determine the several mechanical properties of the specimen.

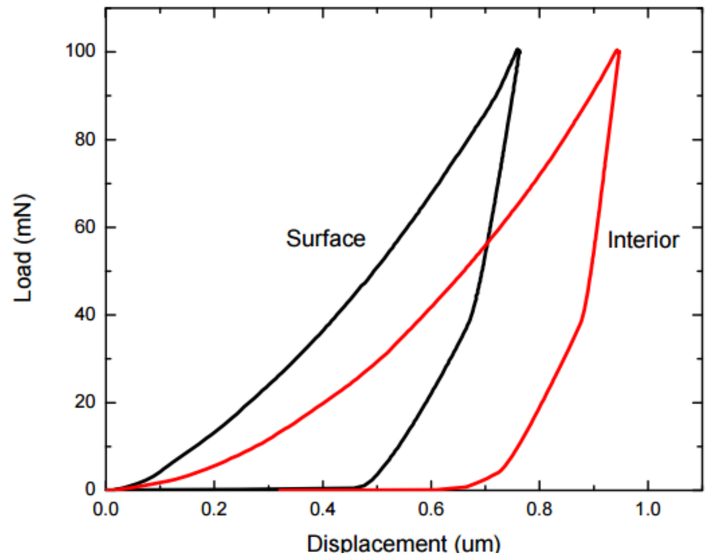


Figure 13: An example graph of the relationship between the load and deformation during deformation [23]

Using the load-displacement curve, the maximum load and the contact area of the indenter can be used to calculate the hardness of the material. The Young's modulus, or modulus of elasticity, can also be calculated using the load and displacement of the indentation. Indentation tests can also be used to determine the creep, stress, strain, and compression strength of a material, among other properties.

In order to determine the change in mechanical properties throughout the scales, the hardness will be evaluated at multiple places on the specimen. Indentations will be done on the top and middle of the scales to determine the hardness at the high points of the scales. These indentations will also be done at different points along the top of the scales. The hardness will also be determined in between the scales, where the scales overlap. This change in mechanical properties can then be analyzed along with the chemical distributions and topology.

This chapter detailed the specimen selection process, and initial images taken of a sample of the *Arizona elegans* snakeskin were included. The general working principles of each machine used for analysis on the specimen were summarized, along with the specimen preparation processes required for each procedure.

CHAPTER IV

SPATIAL MAPPING OF MECHANICAL/CHEMICAL PROPERTY DISTRIBUTIONS AND SURFACE TOPOLOGIES (TASK-2)

The wear resistant properties of snake scales are achieved through the combination of various properties in the scales. The properties analyzed in this study are mechanical and chemical properties, along with the topologies of the scales. Through investigating these properties of scaled reptile skin and analyzing the relationship between the properties and structure of the material, a material design guideline for synthetic materials can be established.

This chapter details the results and analysis of the properties obtained from each procedure performed on the specimen.

Chemical composition

An in-depth investigation of the chemical composition of the snake scales was achieved through SEM/EDX analysis. After the sample was prepared, as detailed in the previous chapter, the SEM/EDX analysis was performed in an environmental scanning electron microscope (ESEM). The initial image of the specimen is shown in **Figure 14**. As seen in the image, the sides of the scales on this specimen are curled up at the edges, and the tip of one of the scales is folded over at the top. This disturbance of the scales had occurred during the prior handling of the specimen, which is also visible in **Figure 6**.

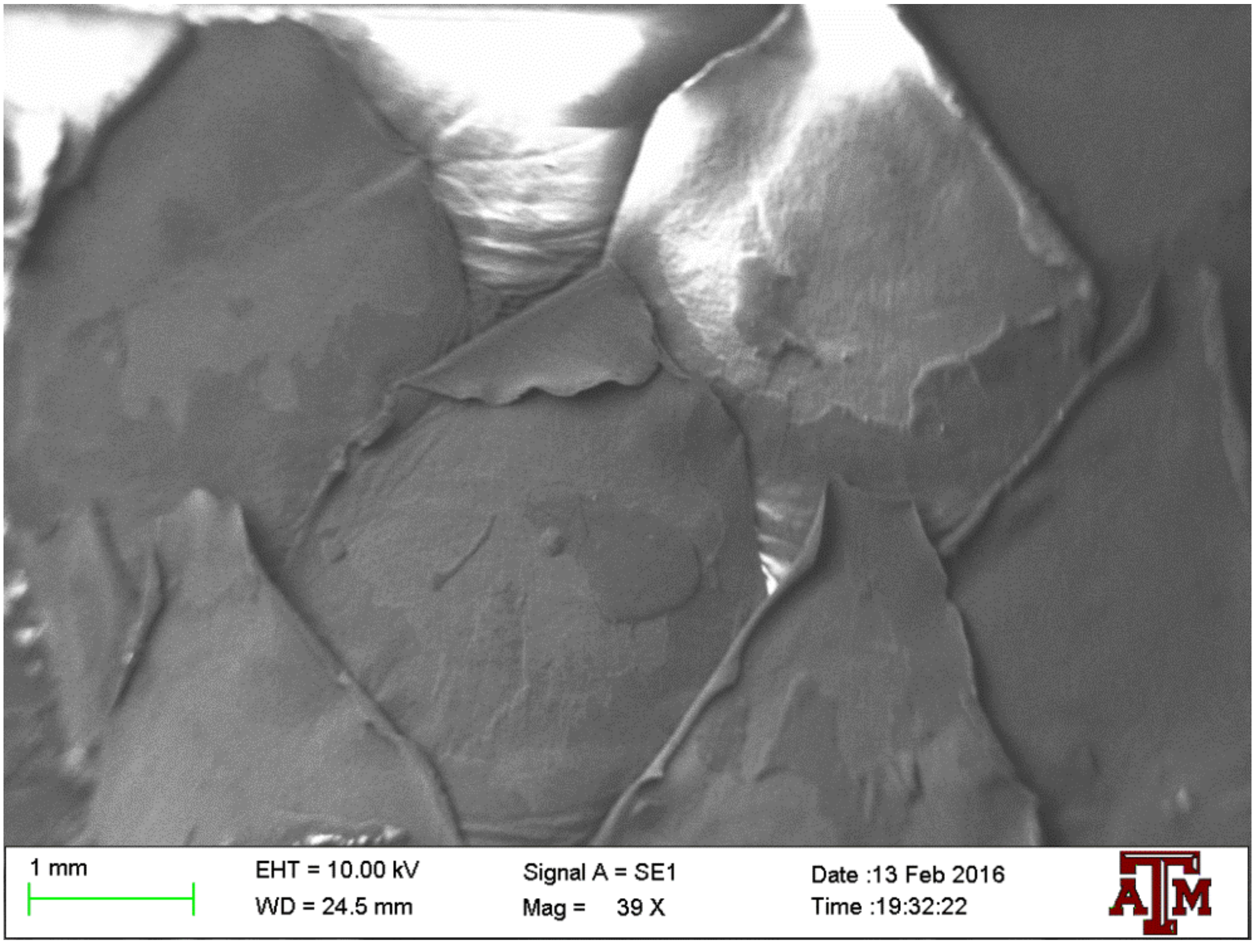


Figure 14: Initial SEM/EDX capture of snake scales

In a more detailed close up image, **Figure 15**, the imperfections on the snake scales are more visible. The tops of each scale clearly have what appear to be ridges or grooves along the length of the scales, which were also visible in **Figure 8**. However, the raised imperfections on the top of the scale were not previously visible.

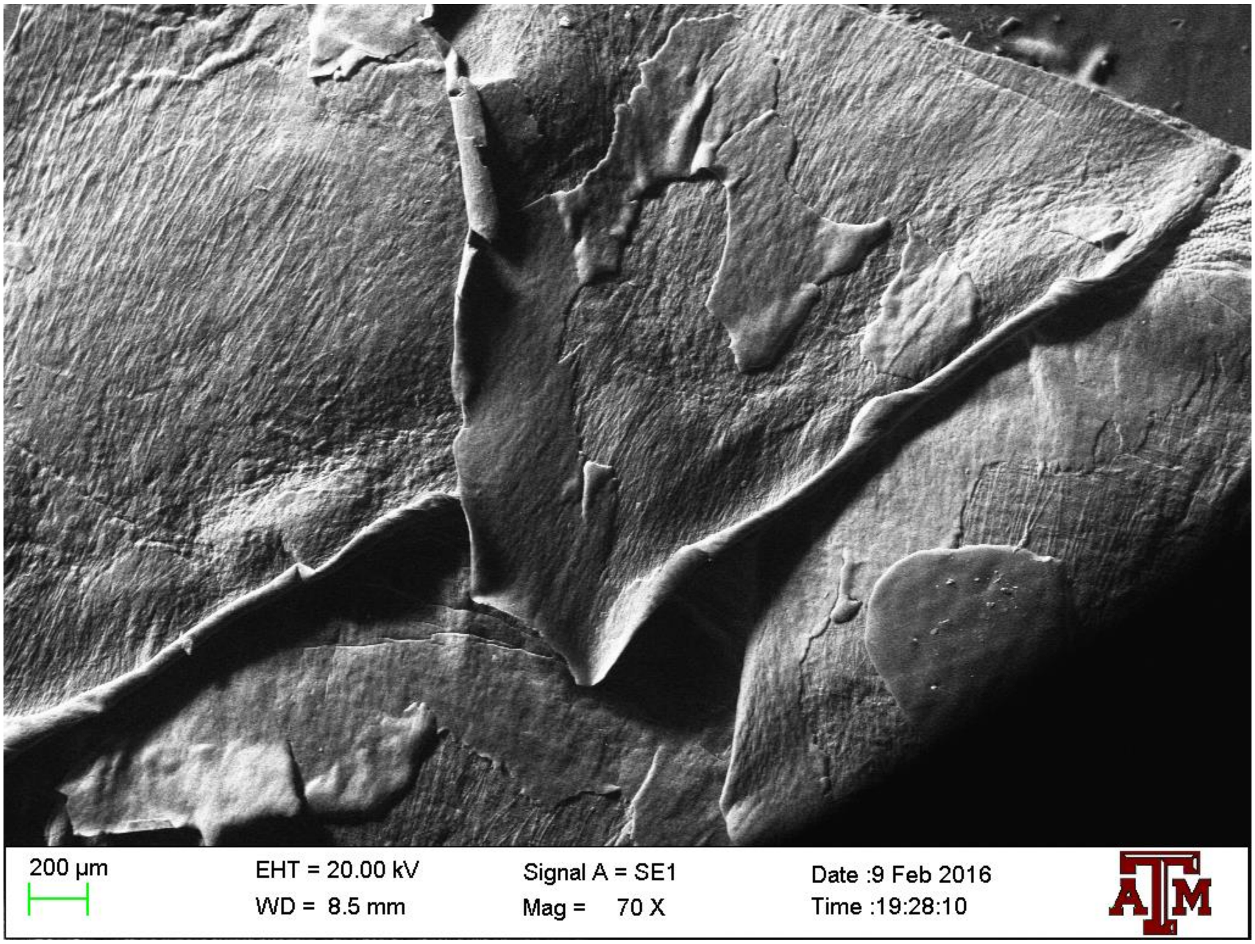


Figure 15: SEM/EDX capture of snake scales

The EDX analysis of the specimen is pictured in **Figure 16**. The analysis shows that the scales primarily consist of carbon, oxygen, and phosphorous. The top right quadrant displays the distribution of carbon on the scales, the bottom left quadrant displays the distribution of oxygen, and the bottom right quadrant displays the distribution of phosphorous. Some areas of the scales that appear black in quadrants, meaning there is an absence of those elements in that area. This appears to occur around the edges of the scales, where one scale overlaps the others. This apparently lack of elements in those areas is due to the blocking of the electron beam by the curled edges of the scales. These raised edges caused the electron beam to cast a “shadow” onto the surrounding areas, making it appear that there was a significant lack of elements in these areas.

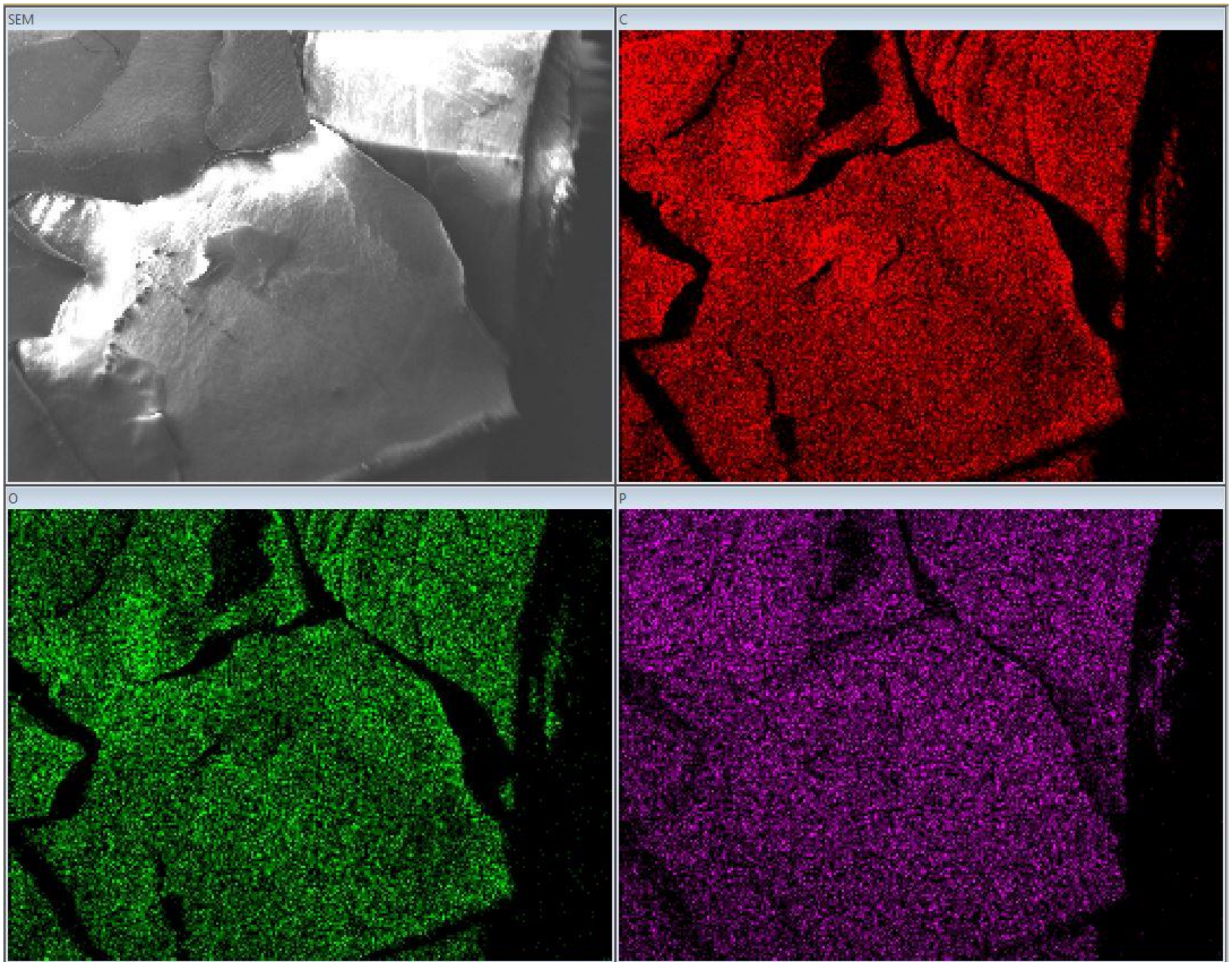


Figure 16: EDX analysis of an area of scales

Further analysis of the EDX analysis showed the similar distributions across all of the elements. Error! Reference source not found. is an EDX analysis on an area of scales that includes a scale that was flipped up during handling, exposing the skin below the scale. **Figure 18** displays the line analysis across several different features of these scales. This line analysis included the top of one scale, an area of skin under a scale, and the bottom area of a flipped scale. The analysis along this line illustrates the overall similarity in intensity of each element, even on different features of the snakeskin.

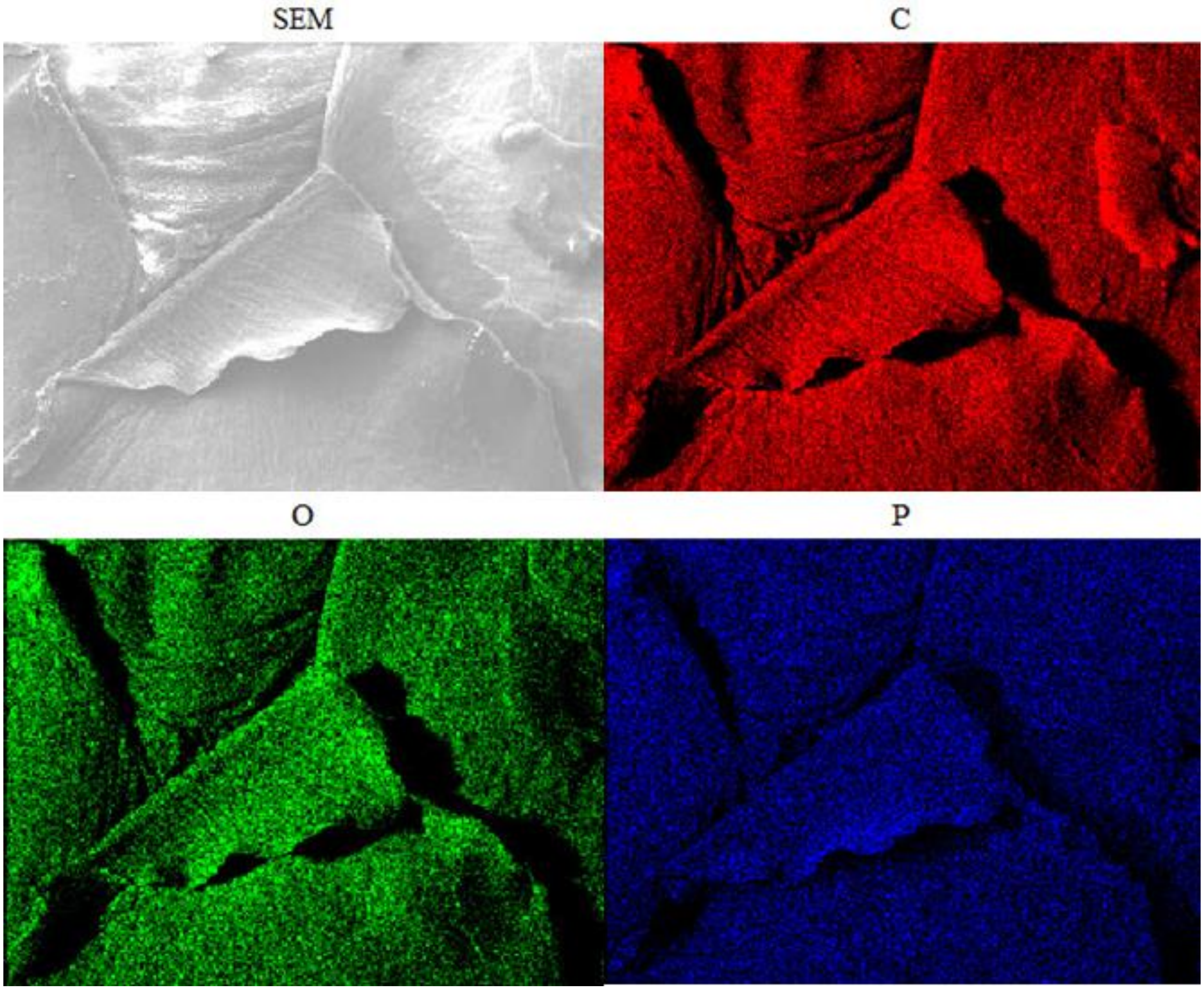


Figure 17: SEM/EDX analysis of specimen containing flipped scale with exposed skin

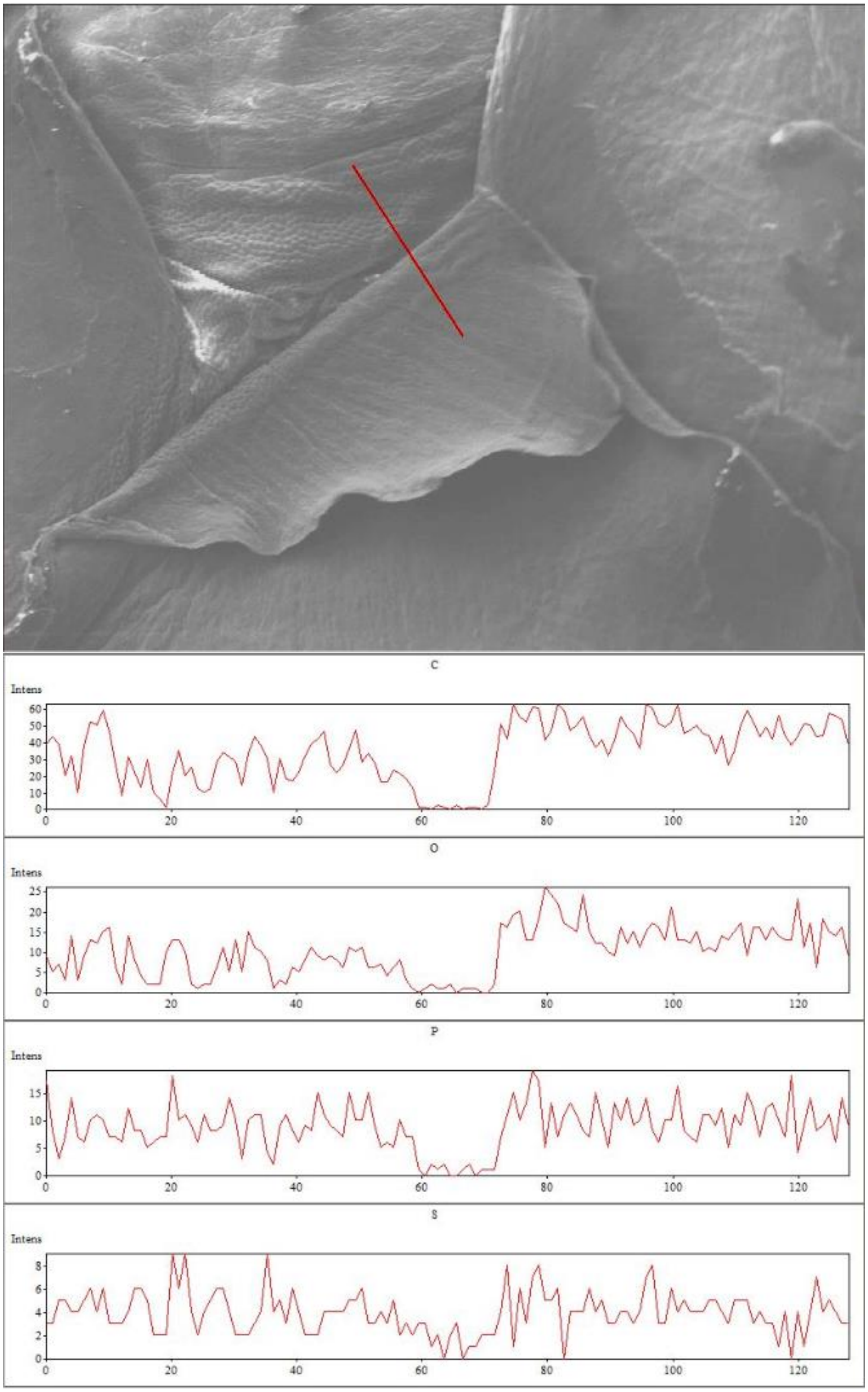


Figure 18: Line analysis across an area of scales

Figure 19 shows approximate points taken to compare the intensity of the elements across these features of the scales. **Table 1** details these approximate intensities, as seen on the graph in **Figure 17**. Carbon remains constant across the line, while there is only a slight increase then decrease in the intensity of oxygen, and a slight decrease in the intensity of phosphorous. The intensity of sulfur remains approximately constant across the line, though the intensity is so low that it should not contribute much to the overall chemical properties of the snakeskin.

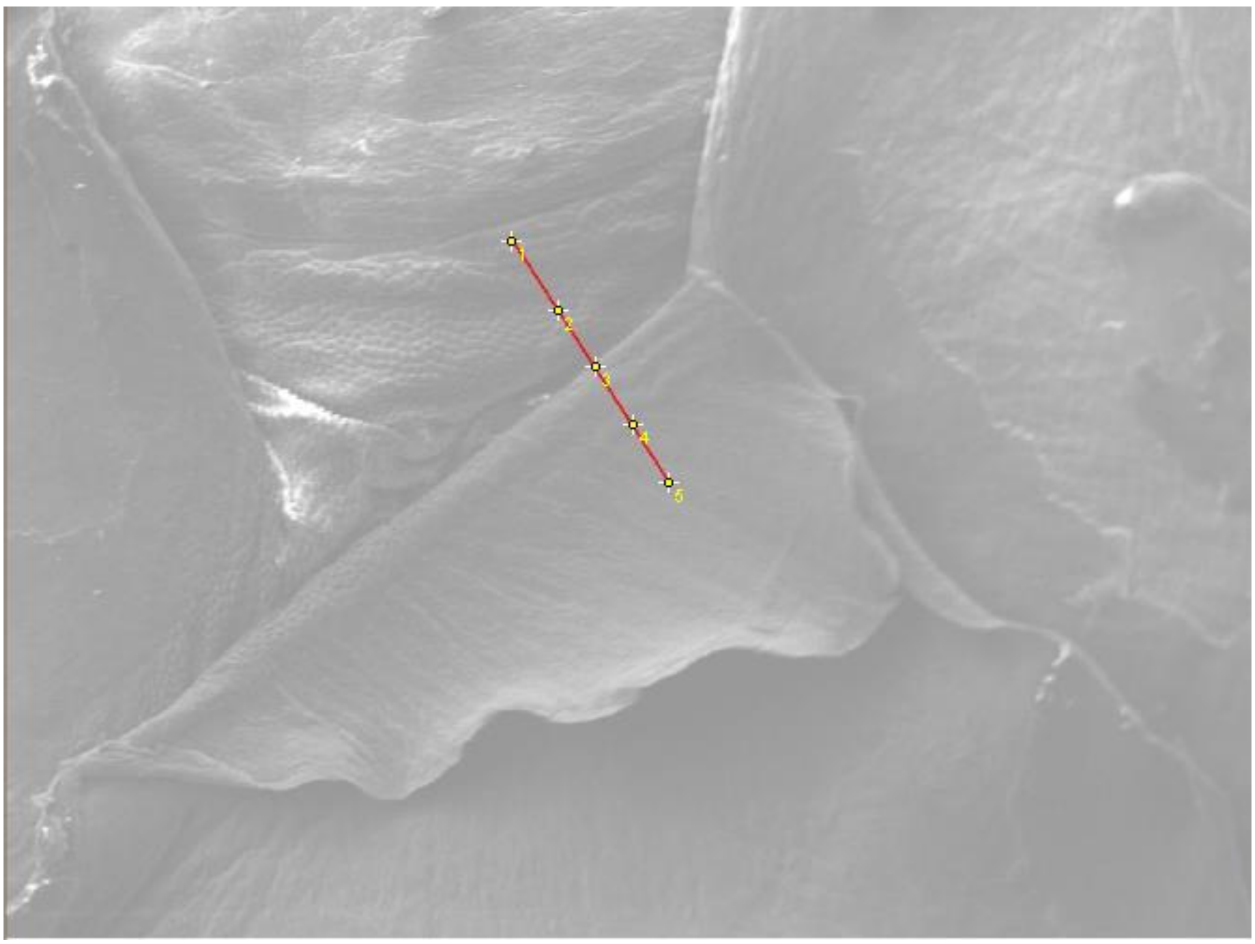


Figure 19: Approximate points for elemental intensity comparison

Table 1: Comparison of elemental intensities across line shown in Figure 18

	Carbon (C)	Oxygen (O)	Phosphorous (P)	Sulfur (S)
1	40	8	16	3
2	30	12	14	2
3	0	0	0	3
4	40	13	6	4
5	40	10	10	4

Surface topologies

The surface features of the skin also contribute to the resistance of abrasive wear on the scales. As previously pictured, **Figure 12** depicts the topography of a section of scales. This section of scales was analyzed straight out of the ethanol the skin is stored in, with no preparation procedure. The specimen analyzed in **Figure 19** is a larger specimen, with more full scales. This specimen was freeze-dried in the procedure detailed for the previous SEM/EDX analysis, but without sputter coating. Similar to the sample used for the SEM/EDX analysis, the edges of the scales in **Figure 19** also appear to be slightly raised, which may have occurred during the sample preparation procedure. However, the overall high and low points of the scales remain similar to the specimen in **Figure 12**. The centers of the individual scales are higher in elevation than the areas where the scales overlap. This change in elevation across every individual scale provides the snake with less points of contact with the surface over which the snake is moving. Investigations into the hardness values across the high and low points of the scales will provide insight to how the topography of the scales combined with the mechanical properties contribute to the wear resistance of the scales.

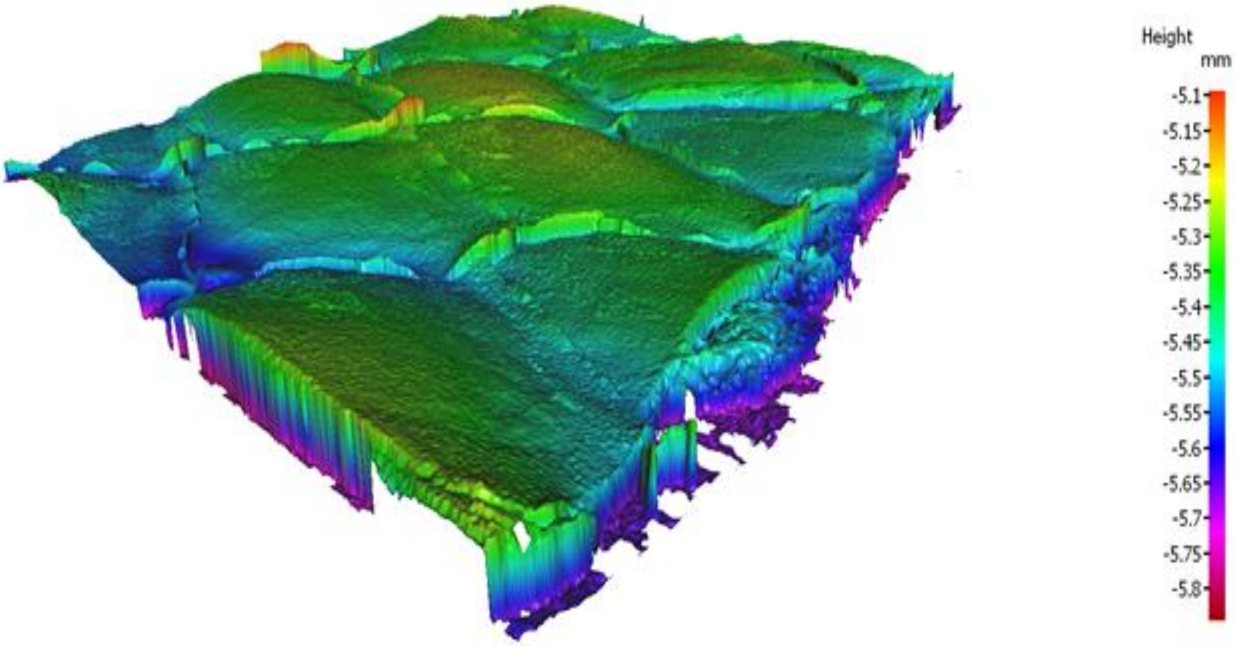


Figure 20: Topography of freeze-dried specimen

Profile form measurements

Profile form measurements were also taken across the scales to determine the approximate length and the height of an average scale. **Figure 21** shows four of these measurements taken of one of the scales on the specimen.

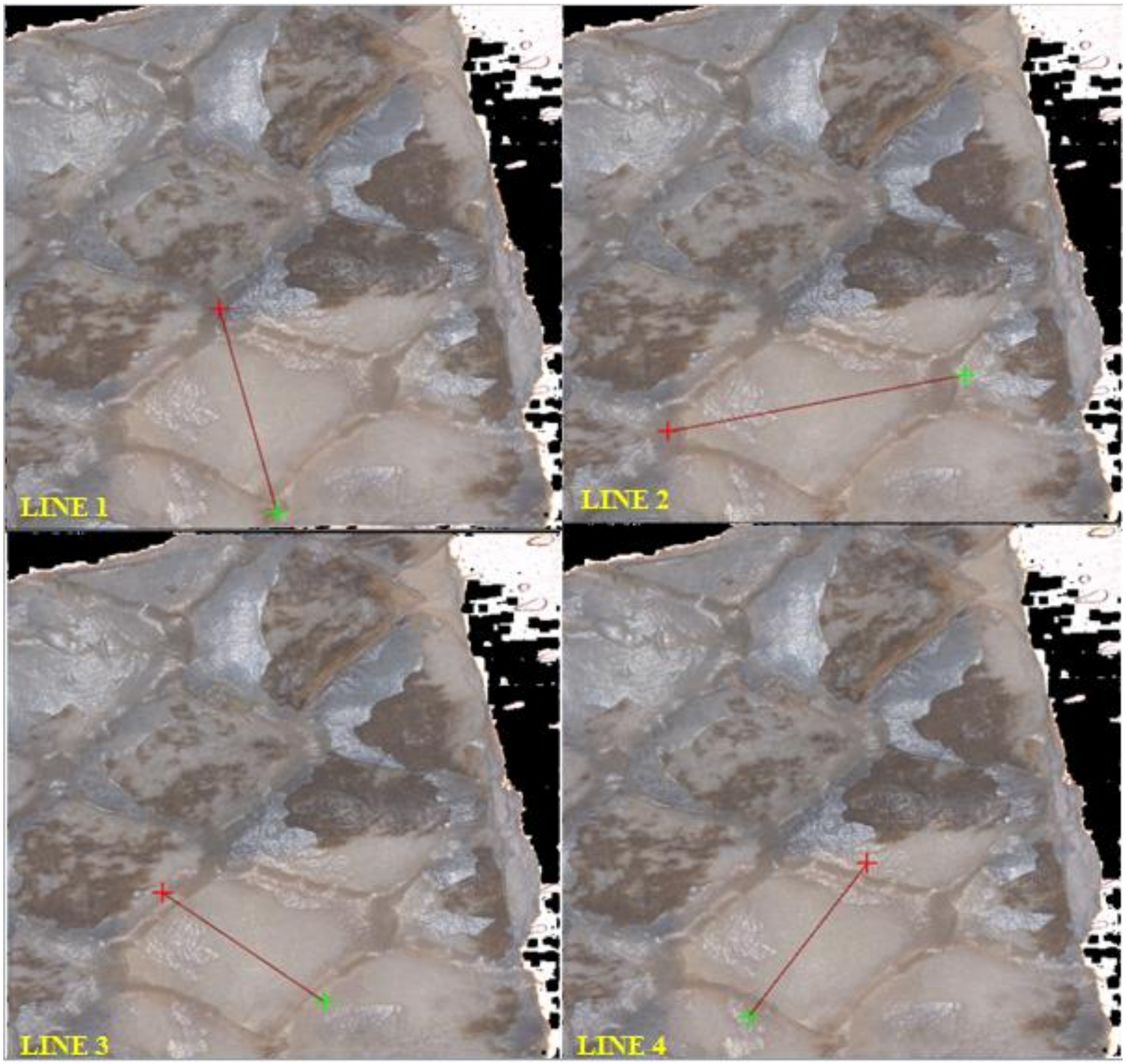
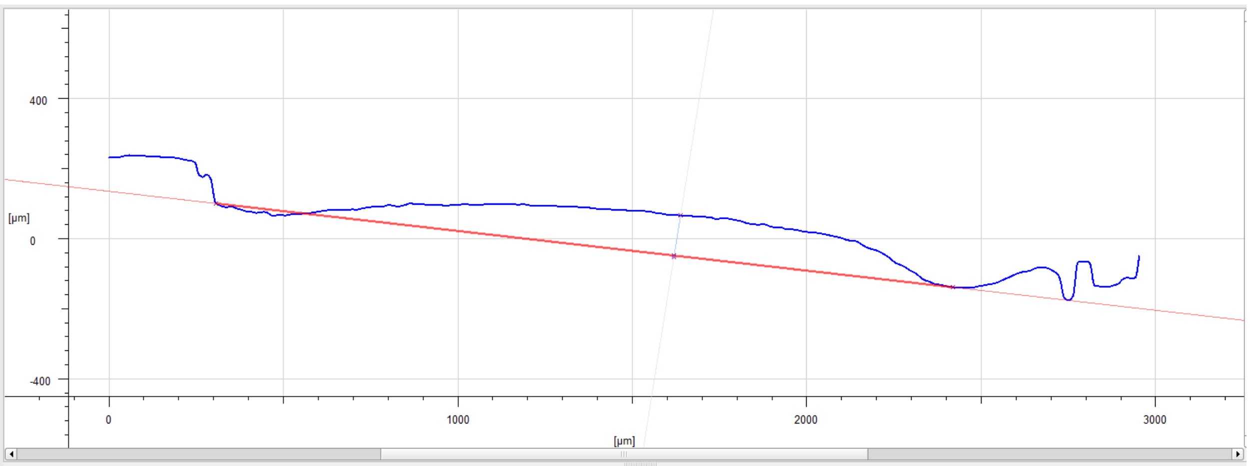


Figure 21: Lines for profile form measurement on one of the full scales on the specimen

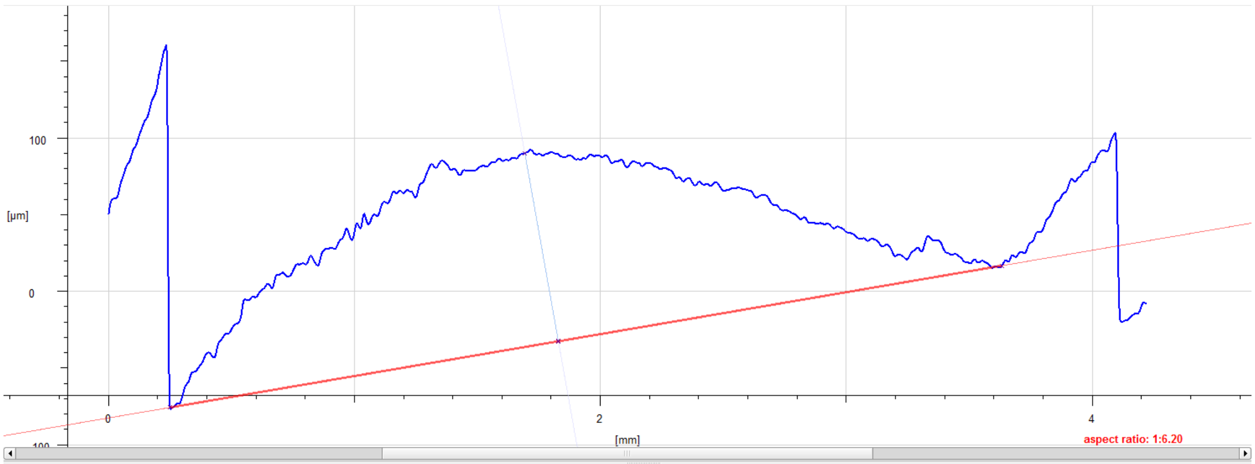
Using this data and the software, the approximate length and height of a scale can be calculated. For each of the lines in **Figure 21**, a profile form measurement was created. These corresponding profile form measurements are shown in **Figures 22-25**. These profile form measurements were taken across the length, width, and diagonals of the scales to gather the approximate dimensions to 3D model a single scale.

These profile form measurements were also performed on a second scale. Using the measurements from both of the scales, the average dimensions of a single scale was calculated. The average length of the scales on this section of snakeskin for this species of snake is approximately 3.3 mm, the average width of the scales is approximately 2.2 mm, and the average height is approximately 170 μm.



	Angle [°]	Length [μm]	mean Deviation [nm]	min. Deviation [km]	max. Deviation [nm]	P1.x [mm]	P1.y [μm]	P2.x [μm]	P2.y [μm]	X-Intercept [mm]	Y-Intercept (d) [cm]	Slope (k)	Line Param. a	Line Param. b	Line Param. c
Line 1	173.5306	2126.8093	0.0000	0.0000	0.0000	2.4200	-139.0054	306.7093	100.6276	1.1941	0.0135	-0.1134	-239.6330e-6	-0.0021	286.1505e-9
Line 2	80.8915	120.2439	0.0000	0.0000	0.0000	1.6385	66.1787	1619.4648	-52.5490	1.6279	-1.0154	6.2373	118.7277e-6	-19.0351e-6	-193.2756e-9

Figure 22: Profile form measurement along line 1

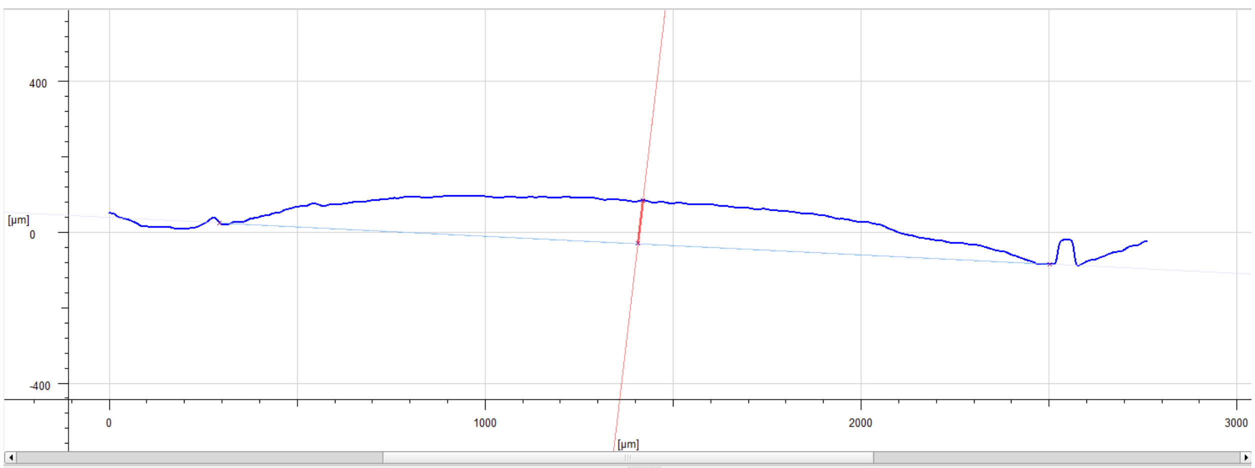


Line

Values

	Angle [°]	Length [µm]	mean Deviation [nm]	min. Deviation [km]	max. Deviation [nm]	P1.x [mm]	P1.y [µm]	P2.x [µm]	P2.y [µm]	X-Intercept [mm]	Y-Intercept (d) [µm]	Slope (k)	Line Param. a	Line Param. b	Line Param. c
Line 1	1.5678	3385.1783	0.0000	0.0000	0.0000	3.6336	16.6827	249.6453	-75.9334	3.0240	-82.7661	0.0274	92.6160e-6	-0.0034	-280.0730e-9
Line 2	138.0284	183.5087	0.0000	0.0000	0.0000	1.6924	90.3268	1828.8168	-32.3970	1.7928	1612.6389	-0.8995	122.7238e-6	136.4343e-6	-220.0193e-9

Figure 23: Profile form measurement along line 2



Line

Values

	Angle [°]	Length [µm]	mean Deviation [nm]	min. Deviation [km]	max. Deviation [nm]	P1.x [µm]	P1.y [µm]	P2.x [mm]	P2.y [µm]	X-Intercept [µm]	Y-Intercept (d) [cm]	Slope (k)	Line Param. a	Line Param. b	Line Param. c
Line 1	177.1668	2212.5409	0.0000	0.0000	0.0000	293.0879	25.2188	2.5029	-84.1421	802.6798	0.0040	-0.0495	109.3609e-6	0.0022	-87.7818e-9
Line 2	83.3145	115.1402	0.0000	0.0000	0.0000	1406.4413	-29.0218	1.4198	85.3355	1409.8432	-1.2028	8.5312	-114.3573e-6	13.4046e-6	161.2259e-9

Figure 24: Profile form measurement along line 3

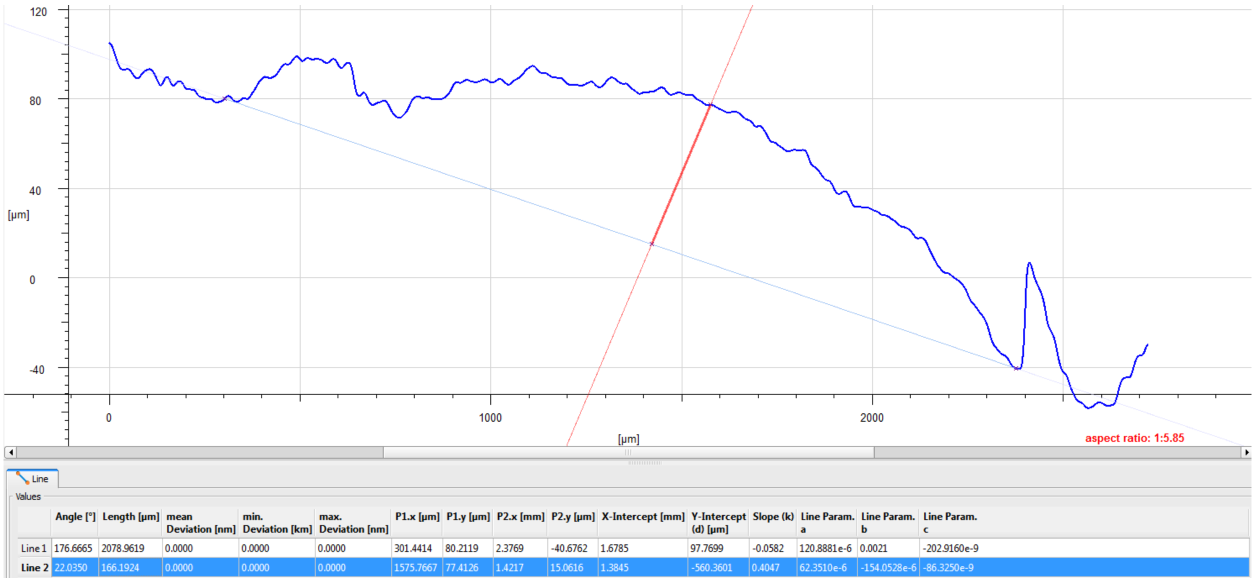


Figure 25: Profile form measurement along line 4

The lines on these profile form measurements in **Figures 21-25** are the measurements of the length of the line, as well as the maximum z-height of the line, at approximately the middle of where the scale is. These values are displayed in **Table 2**.

Table 2: Values obtained from profile form measurements

	Length (mm)	**Maximum Height (µm)**
LINE 1	2.13	120.24
LINE 2	3.39	183.51
LINE 3	2.21	115.14
LINE 4	2.08	166.19

Profile roughness measurements

Profile roughness measurements of the surface were also taken across the scales. Roughness measurements are useful to determine the texture of the surface of snakeskin. The profile roughness measurements were taken along the length of a scale, as displayed in **Figure 26**. The resulting roughness along this line is displayed in **Figure 27**. The roughness average, R_a, along this line is 1.41 µm. The root mean squared (R_q) of the roughness and the mean roughness depth (R_z) along this line is 1.84 µm and 8.38 µm, respectively.

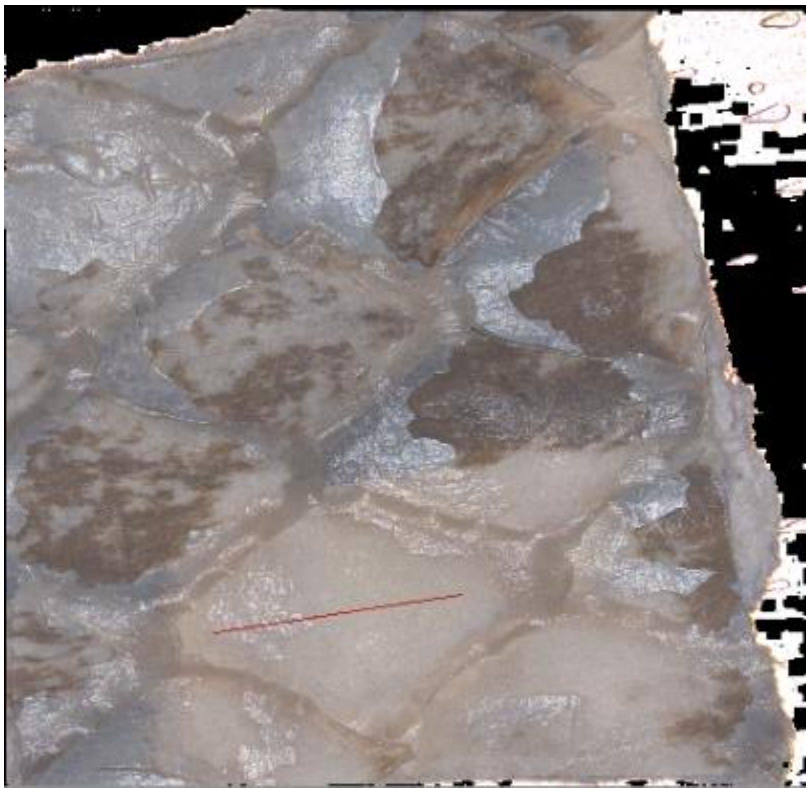


Figure 26: Line for profile roughness measurement of scale

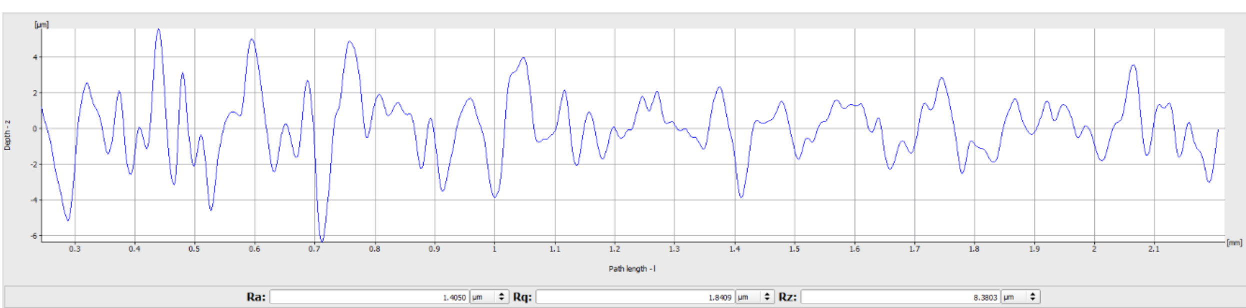


Figure 27: Resulting profile roughness measurement along line in Figure 26

Surface texture

The surface texture of the scales was also measured. An approximate square area in the center of a scale, as seen in **Figure 28**, was used for these measurements. The results from this surface texture measurement are shown in **Figure 29**.

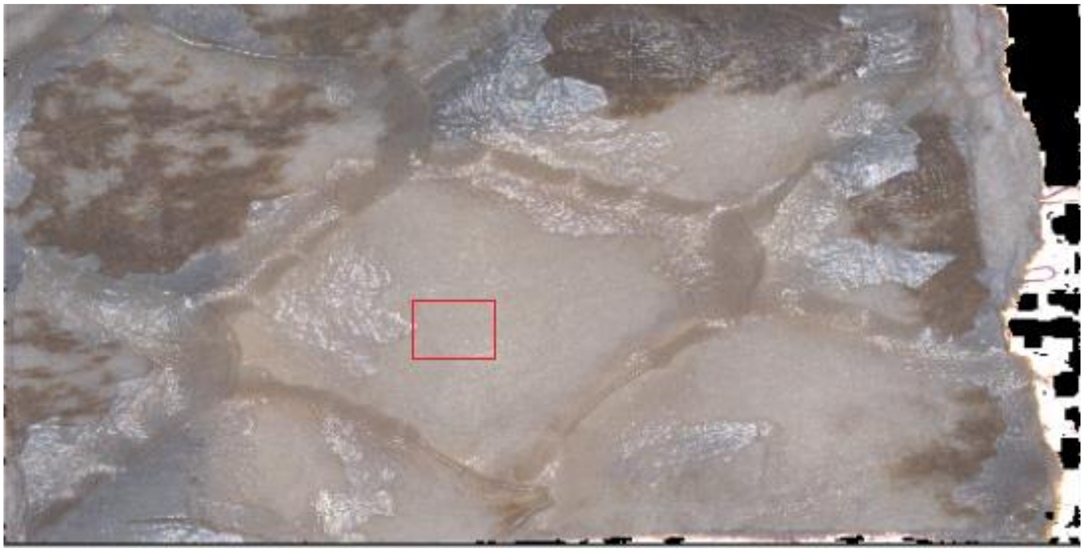


Figure 28: Area used for surface texture measurement

Parameters

Name	Value	[u]	Description
Sa	16.2320	µm	Average height of selected area
Sq	19.0643	µm	Root-Mean-Square height of selected area
Sp	32.8245	µm	Maximum peak height of selected area
Sv	51.7189	µm	Maximum valley depth of selected area
Sz	84.5434	µm	Maximum height of selected area
S10z	68.8798	µm	Ten point height of selected area
Ssk	-0.4863		Skewness of selected area
Sku	2.1406		Kurtosis of selected area
Sdq	0.2360		Root mean square gradient
Sdr	2.7582	%	Developed interfacial area ratio
FLTt	84.5434	µm	Flatness using least squares reference plane

Figure 29: Results from the surface texture measurement of the top center of a scale

Mechanical testing

The mechanical hardness of the specimen was measured through nanoindentation testing. The nanoindentation testing was performed on the same freeze-dried specimen used for the SEM/EDX analysis. Hardness values were collected from three locations on the top of the scale and three locations on the outer edges of a scale. These results are displayed in **Table 3**. The hardness values in the center of the scale ranged from 30 to 50 MPa, while the hardness values on the edge of the scale ranged from 0.6 to 3 MPa.

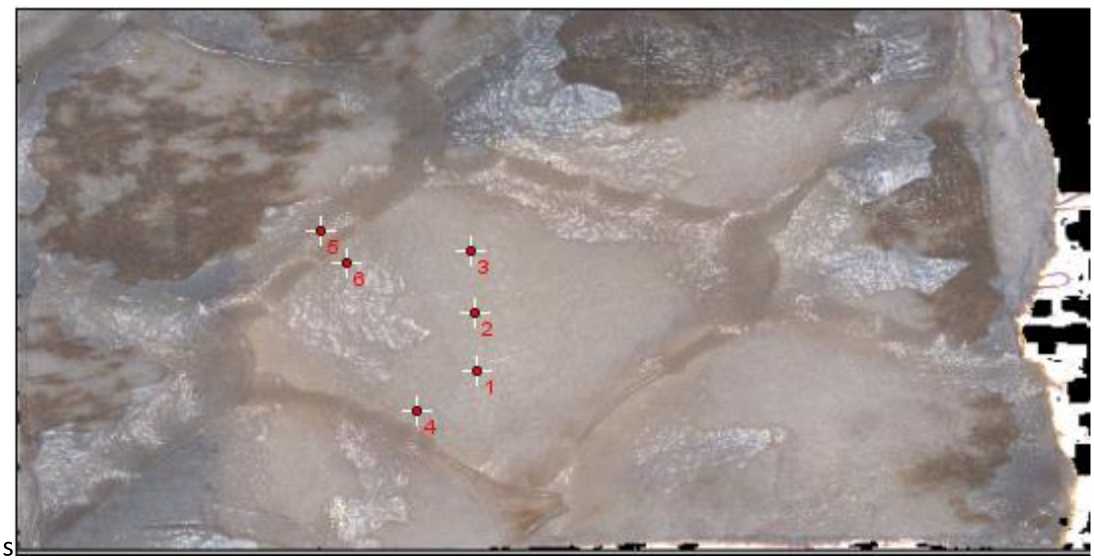


Figure 30: Approximate points where indentation readings were obtained

Table 3: Hardness values obtained from nanoindentation

Point	Hardness (kPa)
1	567.8
2	405.5
3	374.1
4	37.7
5	06.9
6	29.8

From these hardness values, a chart (**Figure 31**) was created to illustrate the difference in hardness values of the center of the scale in comparison to the hardness values on the edges of the scale. As illustrated, the hardness values of the center areas of the scales

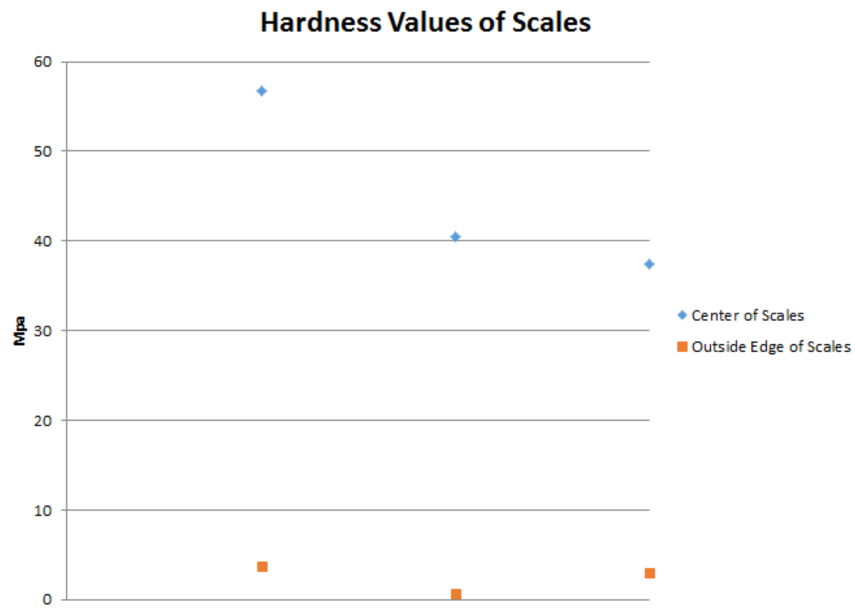


Figure 31: Comparison of the hardness values of the different areas of a scale

In this chapter, the results from the tests and analysis of all of the properties were discussed. The SEM/EDX analysis of the snake scales concluded that there is an overall even distribution in the intensity of carbon, oxygen, phosphorous, and sulfur present across the scales. Of these elements, carbon had the highest intensity, followed by oxygen, phosphorous, then sulfur with the least intensity. The next property of the snakeskin that was analyzed was the topology of the scales. The average dimensions of a scale were calculated, using profile form measurement readings. The profile roughness and surface texture of the scales were also measured. Finally, the mechanical properties of the scales were also investigated. This was achieved through nanoindentation of a scale. The hardness values were obtained through indentations on the center of a scale, and the outer edges of a scale. In the next chapter, these properties will be combined to create an idealized version of a snake scale.

CHAPTER V

3D MAPPING OF MATERIAL PROPERTY AND TOPOLOGY DISTRIBUTIONS (TASK-3)

In this chapter, the properties discussed in Chapter IV will be combined to create an idealized 3D model of a snake scale.

In order to 3D model an idealized snake scale, the dimensions of the scale first had to be calculated. For this, the measurements obtained from topology readings from the Alicona machine were used. Approximate perimeter measurements were averaged together to determine the average length of the side of a scale, which is approximately 2 to 2.3 mm per side. The length of the scale, determined from the profile form measurements, is approximately 3.3 mm, the average width is approximately 2.2 mm, and the average height is approximately 170 μm. A roughness average of approximately 1.4 μm should also be obtained for an idealized scale. Since the scales do overlap along the edges, this arrangement of the idealized scales should be mimicked as well. The approximate overlap of the scales is 200 to 300 μm.

Using these dimensions, the idealized scale was modeled using Inventor (**Figure 32**). These individual idealized scales can then be arranged to mimic those of real snake scales, as shown in **Figure 33**.

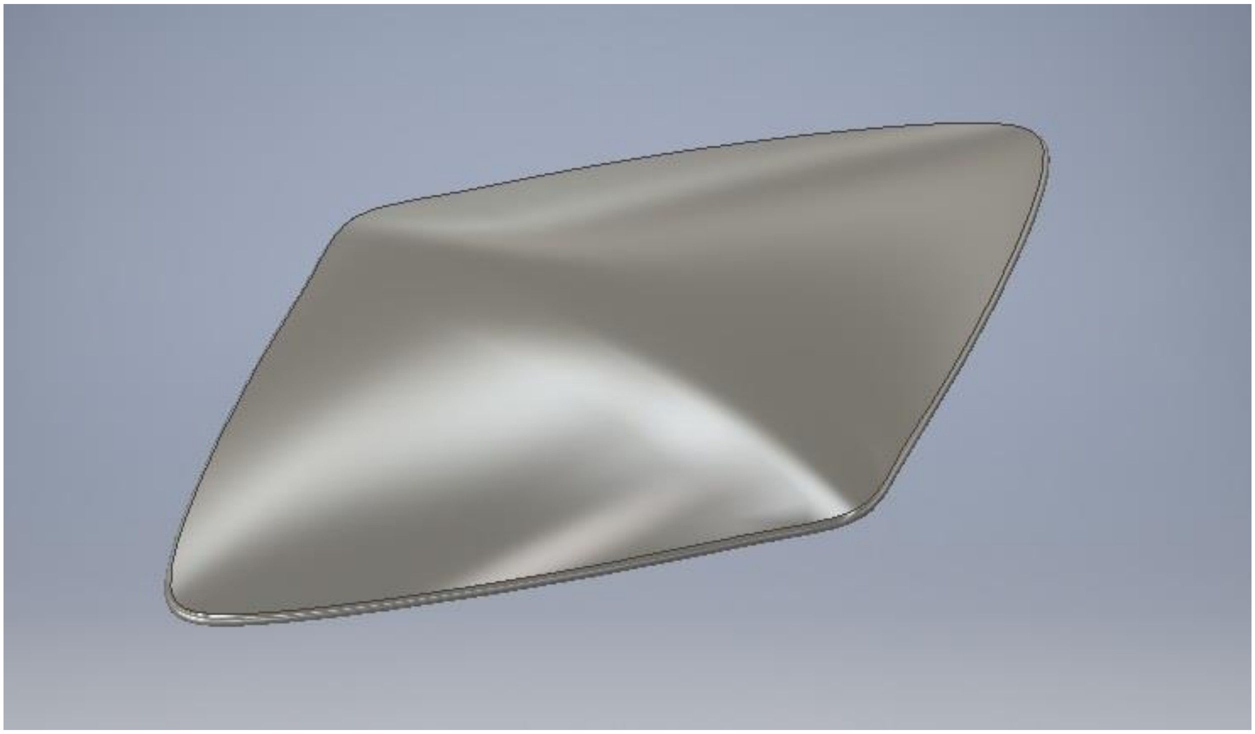


Figure 32: Idealized snake scale

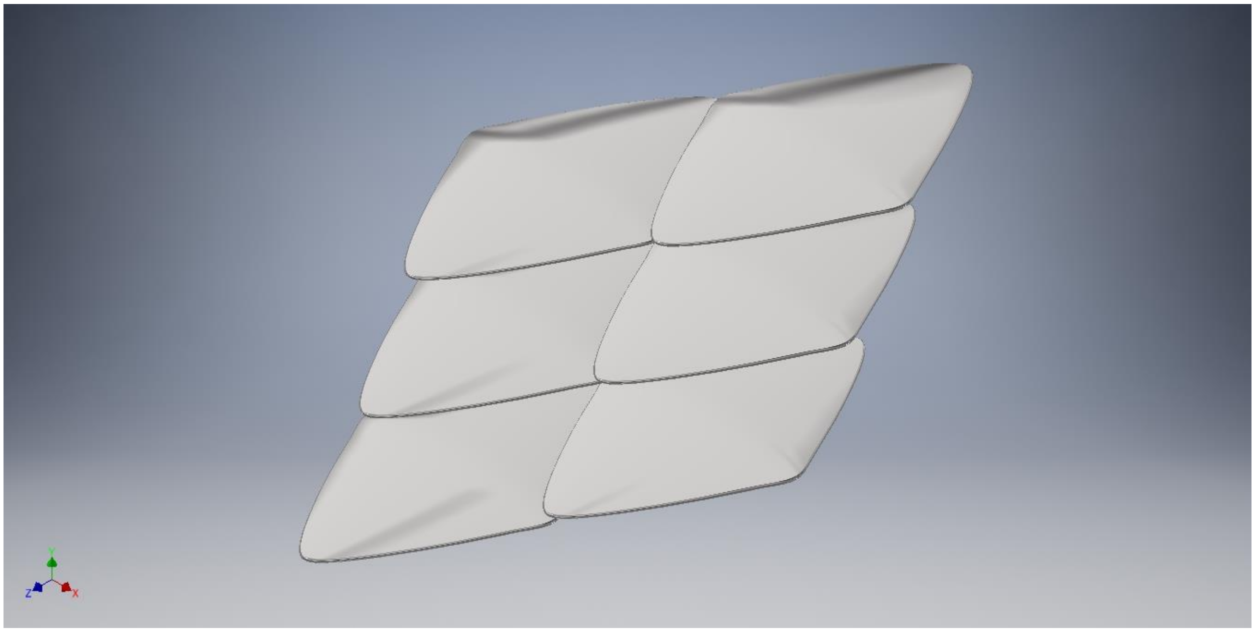


Figure 33: Idealized scales arranged to mimic natural snake scales

For the construction of an idealized snake scale, the previously mentioned dimensions are important to adhere to, along with the variation in hardness values across the scale. There is a large difference in the hardness values of the center of the scales versus the outer edges of the scales. The average hardness of the center of a scale is approximately 45 MPa, while the average hardness of the edge of a scale is approximately 2.5 MPa. Therefore, for an idealized scale, the center area of the scale should be about 18 times harder than the edges, in order to mimic natural snake scales.

Since the chemical distribution of the scales seems to be uniform at the resolution of the SEM/EDX analysis, the chemical distribution of the idealized scale is not as influential as the hardness and topology of the scale. However, the idealized scale should contain a high intensity of carbon, then oxygen, phosphorous, and a low intensity of sulfur.

CHAPTER VI

CONCLUSIONS AND DISCUSSIONS

The overall objective of this research project was to investigate how the topology combined with the chemical distributions and mechanical property distribution contribute to the overall (abrasive) wear resistance of snake scales. The purpose of investigating these relationships between properties/topology and wear resistance was to determine how strategies from these natural organisms could be mimicked in synthetic designs to improve wear resistance in harsh and abrasive environments.

For this, with a 3D optical non-contact surface profilometer and a scanning white-light interferometer, the topology of the snakeskin was captured and the main features quantified. Through analysis of these captures, it was found that the scales on the snakeskin overlap, and the surface features high and low points. The centers of the scales were overall higher than the edges of the scales, where the scales overlap one another. The centers of the scales, then, are the points of contact of the snake to the ground as the snake moves across the ground in a serpentine manner. This reduces the surface area of the snake that is in contact with the ground, and the overlapping of the scales provides flexibility for the snake's movements as well as relative movement between the scales themselves.

Next, through SEM/EDX analysis, it was found that the snake scales possess a relatively even distribution of carbon, oxygen, phosphorous, and sulfur throughout the scale surface. There were varying intensities of these elements, with oxygen being the most prevalent, followed by carbon, then phosphorous, then finally sulfur. However, due to the overall even distribution of these elements across the scales, it could be concluded that the chemical distribution of the scales might not contribute much to the overall wear-resistant properties of the snakeskin. Further analyses including at a higher resolution as well as efforts to identify traces of bio-mineralization is expected to provide more insight.

Finally, through mechanical testing using a nano indenter on the scales revealed that the highest hardness is exhibited at the center of the scales, while the edges are approximately 18 times less hard. These hardness values, when biologically coupled with the topology of the snakeskin, work cohesively to achieve the wear-resistant properties that are exhibited by snake scales. The center area of the scales, where the scale is at the maximum height, also possesses the highest hardness. This contributes to the excellent wear-resistance, as these are the points that are predominantly in contact with the ground as the snake moves across surfaces. In addition, the low hardness exhibited in the edges of the scales contributes to the flexibility exhibited by the snakeskin, and the ability of the scales to absorb some of the shock as abrasive particles strike the surface of the scales.

Discussions and future work

In order to bio-mimic the desired wear-resistant properties exhibited by snake scales, synthetic designs must then mimic the idealized version of a snake scale. This idealized version of a snake scale was achieved through the averaging of the dominant properties and topology features of multiple scales. Both the idealized topology and hardness values could be mimicked, to ensure good resistance to abrasive wear.

Material loss and failure due to abrasive wear is a problem in harsh man-made operating environments. However, by adopting certain biomimetic principles from natural organic systems, some of the current synthetic designs could be improved. Through further examination and analysis of the wear resistant properties that are exhibited in scaled reptile skin, new and improved synthetic designs can be developed leading to design guidelines inspired by these natural material systems to mitigate these failures due to abrasive wear.

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