Photographic Film Reticulation Due to Temperature Changes during Film Development

Abstract

Reticulation, a cracking-like defect on film negatives caused by temperature changes during development, represents an elusive effect for some photographers, and, for others, a devastating mishap. Establishing a relationship between reticulation and temperature changes will allow photographers to produce satisfactory negatives and provide insight on material behaviors of photographic film. Five rolls of identically exposed film were subjected to different temperature changes between photographic developer and stop bath fluid. Grain sizes were compared by analyzing Fourier transforms of microscope images of the film. Until a temperature change of 73.2°C, there is a linear relationship of 0.0013 μm/C between grain size and temperature change, without any exhibition of the reticulation effect. After the linear region, a 10°C change resulted in a 13.2% increase in grain spacing and the reticulation effect appears, revealing a minimum temperature change that produces reticulation. Film photographers looking to implement the reticulation effect should induce the greatest temperature change possible to ensure reticulation, while others looking to maximize resolution by having the smallest grain size should control for no temperature change between steps in the developing procedure.

1. Introduction

Film photography is a long-lasting art form, its origins dating back to the early 1800s [1]. Although many advances have been made in the world of photography since then, such as the 1970s invention of digital cameras that require less disciplined and considered approaches, many photographers still prefer to use film cameras for their resolution. When used properly, the thoughtfulness and artistic intent required to produce an image, and the ‘happy accidents’ that can occur in the developing and printing processes are valued by many professionals [2]. Despite its decline in popularity for decades, big film companies like Kodak, Fujifilm, and Harman Technology, which manufactures the popular Ilford Photo black-and-white films, have seen a 5% year-on-year growth in sales [3]. This attests to film’s persistence and allure, despite, or in some cases because of, its outdated technology.

The elaborate physical means of the film photography process is part of its allure. Along with this physical process comes many parameters that change the visual appearance and performance of a film negative with which a photographer prints photographs. Some of these effects can be desirable in certain creative visions, but they can also be detrimental to a negative, possibly ruining the possibility of printing a usable photo from it. Reticulation is an effect that can fit into both categories.

Subjecting film to temperature changes during the developing process can cause the gelatin emulsion to swell and subsequently contract, causing cracks and clumps of silver grain on the negative, defined as reticulation [4]. This can present as a ‘happy accident’ that produces a pattern resembling the cracking on the mudbank of a river after the water recedes overlaying the image [5] as shown on the left of Figure 1, or as a damaging effect that increases the grain size of an image, therefore reducing resolution [6], as shown on the bottom right of Figure 1.1. This study investigates the relationship between the magnitude of temperature changes in the film development process and the degree of reticulation on the resulting film negatives.

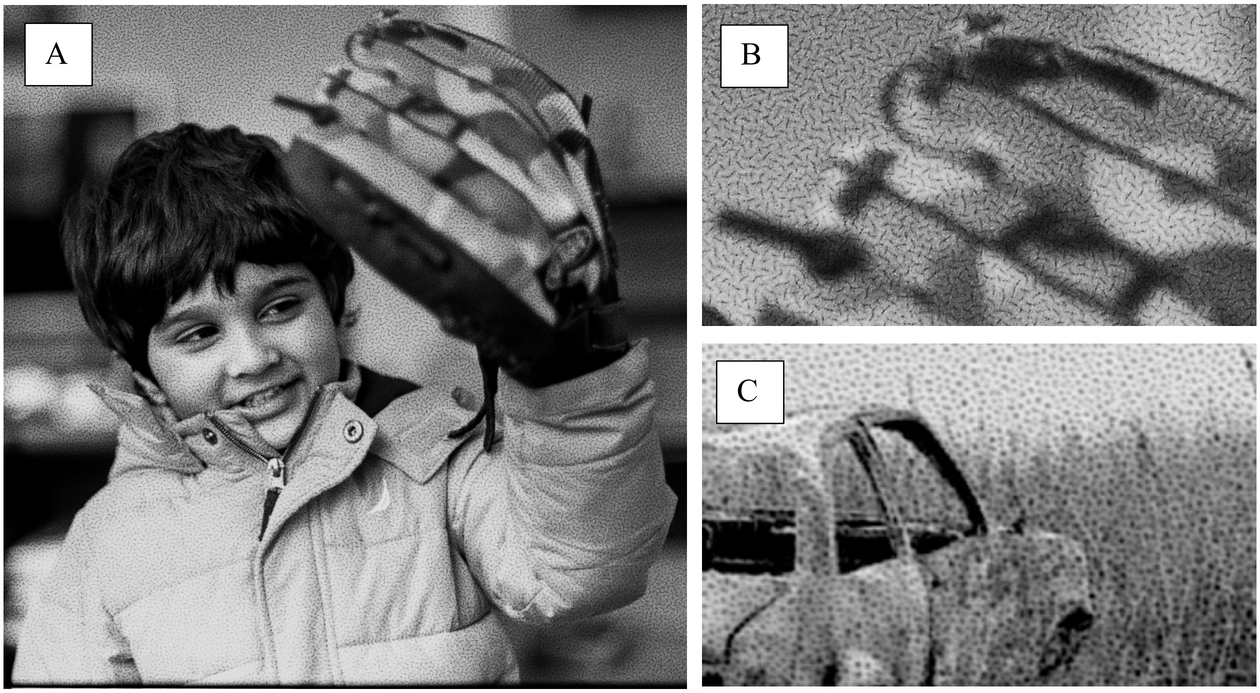

Figure 1.1: A reticulated image of a boy with a cracked pattern (A) [7], shown alongside a zoomed image of the glove on the boy's hand (B) and a reticulated image of a car exhibiting grain clumping (C) [8].

To determine how temperature variation affects the reticulation on a film negative, five rolls of Ilford ISO 400 HP5 Plus film were shot of a grayscale test strip used for quantitative image processing. Each roll was subjected to a different temperature change during the developing process. Between the developer and fixer stages, water heated on a hot plate to target temperatures verified by a Vernier temperature probe was added to the tank containing the film, and subsequently, cold water at 6.8° (C) was added. For each roll of film, Fourier analysis was performed in MATLAB to determine the size and distribution of reticulation. These results were compared to the those of the roll with no temperature change, which acted as the control, to determine how the changes of temperature affected the amount of reticulation.

2. Effects of Film Photography Parameters on Reticulation

2.1 The Structure and Mechanics of Photographic Film

Photographic film is comprised of multiple layers of materials with different properties and it is the combination of these layers that give film its ability to capture images. Film consists of a transparent support film base, a gelatin emulsion containing light-sensitive silver halide crystals, and a number of coating layers to facilitate photosensitive chemical processes and protect the film from damages during shooting and developing [9]. These layers can be seen in Figure 2.1.

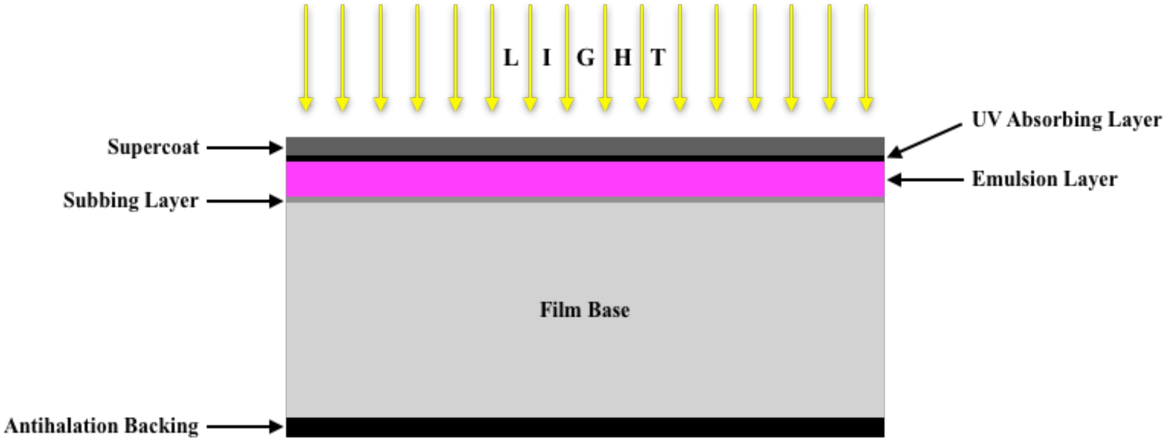

Figure 2.1: Diagram describing the ordering of the layers of photographic film and their approximate relative sizes. When a camera shutter opens, the emulsion side of the film is exposed to photons of light, which prompts a reaction with the silver halide molecules suspended in the emulsion layer.

The top layer of the film is the supercoat, comprised of hardened gelatin to protect the emulsion from damage inside of the camera [9]. To shield the silver halide crystals from exposure to ultraviolet light, which humans cannot see and therefore should not contribute to the image exposure, there is a layer that absorbs UV light before it can reach the emulsion [9]. The base, the thickest of the layers, supports the other layers. Often, it is made of polyester because of its dimensional stability, allowing the base of the film to retain its size under varying temperature and humidity conditions [10]. The antihalation layer, a dark coating on the bottom of the film base, absorbs light that penetrates through the emulsion layer, which minimizes the amount of reflection of light back into the emulsion, which causes an undesirable secondary exposure, known as halation [9]. The subbing layer acts as an interface between the film base and the emulsion, adhering them together.

The emulsion layer is the heart of the film, where the most fundamental chemical processes occur. Black and white film emulsions consist of silver halide crystals suspended in gelatin [11]. When taking a photo, the camera shutter opens and photons are absorbed by the silver halide crystals and form a latent image not visible to the human eye. To differentiate between all tones of an image, from deep shadows all the way to bright highlights, various sizes of silver halide crystals exist within the emulsion [11]. The smallest are the least sensitive, recording only the brightest light and the largest crystals are the most sensitive, recording the darkest shadows.

2.2 The Film Development Process

To reveal the latent image within the emulsion, the film undergoes chemical development that converts the exposed silver halide crystals to pure metallic silver [11]. This reaction amplifies the latent image because the silver becomes black and visible to the human eye. This development process includes multiple steps that when executed precisely in succession yields silver build-up on the film that is proportional to the amount of light absorbed by each silver halide crystal during exposure, which produces an inverse grayscale image of photographed content [9]. The process consists of transporting the film from inside the camera into a light-safe tank, immersing the film in chemical baths to accumulate metallic silver, de-sensitizing the film to light to prevent further exposure, and coating the film with solutions to protect it from wear.

To begin the developing process, the roll of film must be safely contained in a tank that does not allow light to leak in, which prevents any further light exposure to the emulsion. This process is described in Figure 2.2.

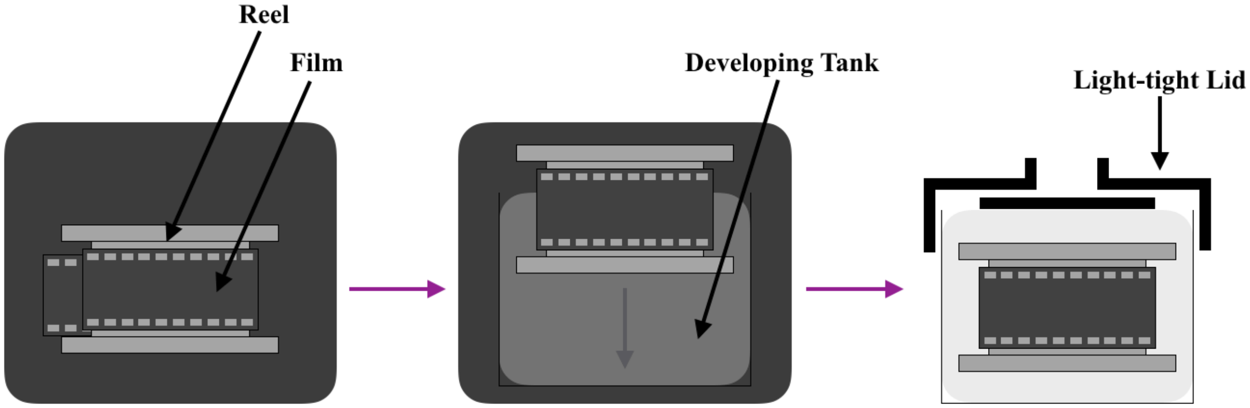

Figure 2.2: Setting up the developing process requires winding a roll of film onto a reel that introduces adequate spacing to allow all faces to interact with the chemical agents. Then, the reel must be placed within a light-safe tank. Both of these steps must be completed in complete darkness, to ensure that the emulsion will not be exposed to light.

With the film properly situated in a developing tank, photographic developer can be introduced to the film. After mixing the photographic developer agent with water, the temperature of the developer solution must be measured because the time needed to reveal the latent image changes with the temperature of the solution. The process is shown below in Figure 2.3

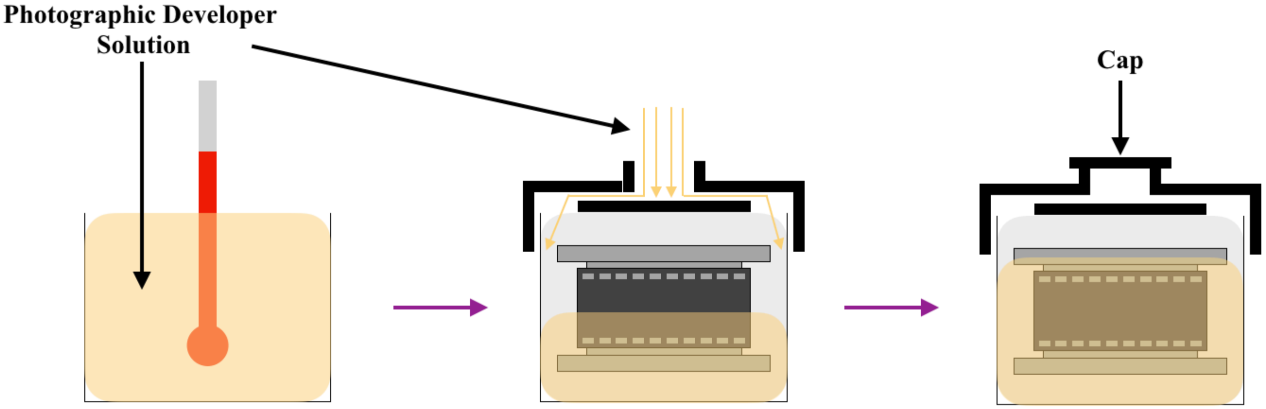

Figure 2.3: Before immersing the film in photographic developer, the temperature of solution must be measured to ascertain the optimal time by referring to charts associated with the brand of photographic developer. After filling the tank, a cap must be placed on the tank to allow for intermittent agitation, including upside down motion, to ensure the whole length of the film reacts with the solution.

Because of the precise nature of this process, deviation from the exact procedure can result in unintended effects. If improperly wound onto the reel or agitated irregularly, the resulting film can be negatively impacted with discoloration or uneven exposure throughout the image [12]. If under- or over-developed, the resulting film will lack silver or be too dense with silver, respectively, both of which are suboptimal for printing purposes [12]. The developing agent reacts with the light-exposed silver halide molecules suspended in emulsion to produce metallic silver, but, if allowed continued contact, would also react with the unexposed silver halide crystals, which would produce a fully dark negative, dense with silver [11]. To prevent over-developing film, the next step in the process is the stop-bath, which consists of flushing the tank with water to terminate the contact between the emulsion and the developer, as shown in Figure 2.4.

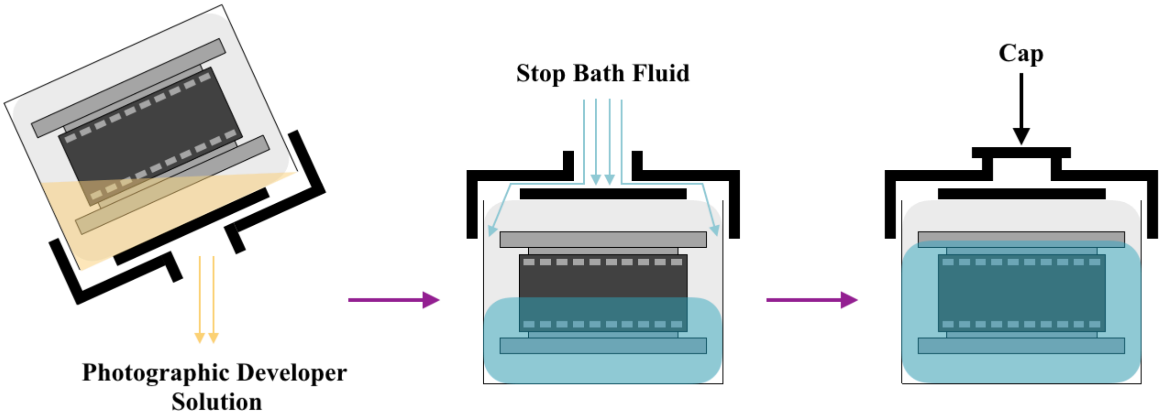

Figure 2.4: To stop the developing process at the ideal time, the developer is emptied from the tank and water is continually introduced to wash away the developer from the emulsion and prevent more silver halide molecules from reacting with it and precipitating into metallic silver.

After the stop bath, fixer solution, consisting of fixing agent and water, is introduced into the tank. Fixer dissolves the remaining silver halide molecules into a solution so that the emulsion will no longer be light sensitive [9]. The remaining steps in the developing process involve carefully washing the film and immersing it in other chemical solutions to improve the longevity of the film. These steps are not relevant to the discussion of reticulation, because after the fixer stage, the image comprised of metallic silver is permanently formed and will not be subject to change.

2.3 The Reticulation Effect

If there is an abrupt change from high to low temperature between the developer, stop bath, or fixer stages, reticulation can occur. Temperature changes like this are common, as photographic developer is often stored at room temperature, and stop bath water often comes from the nearest tap and can be quite cold depending on location and season. Reticulation results from the delicate gelatin emulsion thermally expanding from excess heat and subsequently contracting from the sudden introduction to a cold environment, as demonstrated in Figure 2.5 [6]. The lateral swelling tendency of the emulsion layer can generate stresses that differ between adjacent layers and produce the cracks or clumps of silver defined as reticulation [1].

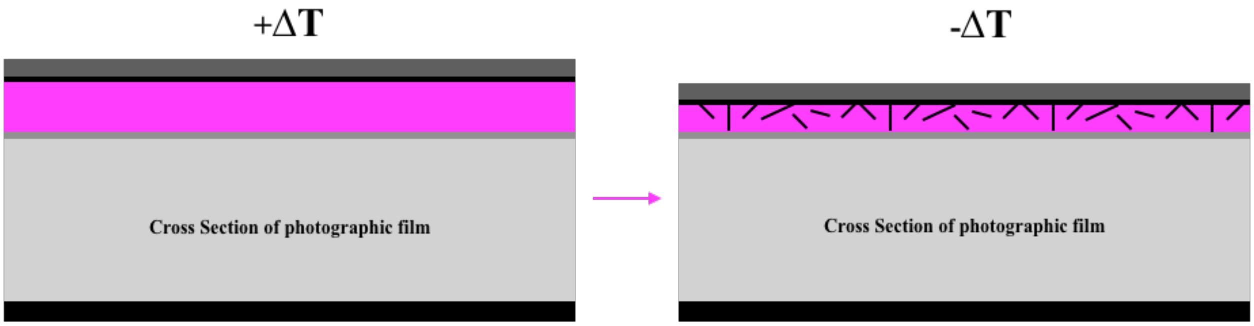

Figure 2.5: A cross section of photographic film demonstrating that with a temperature increase, the gelatin emulsion swells. With a subsequent sudden temperature decrease, the gelatin contracts, causing conflicting strains between adjacent layers and producing the cracking-like effect of reticulation.

In the early stages of photographic film advancement, reticulation would occur at a much higher frequency than it does now. Even with careful attention to temperatures during the development process, older versions of film might experience reticulation due to thicker gelatin emulsion layers that expanded and cracked more easily [11]. Since, film companies have remedied this problem by thinning the emulsion layer, and reticulation is mostly an accident of the past that current photographers may never experience if correctly following procedure [11]. Now, reticulation is mostly only a sought-after effect for some photographs because of its unique pattern and overall effect on a photo [8].

To ensure the prevention of reticulation on any type of film, research has shown that the temperature of all solutions should be equal throughout the development process to avoid uneven thermal expansion and contraction between layers [11][5], but there is not a well-defined relationship between the amount of temperature change during the development process and the amount of resulting reticulation. Thus, my inquiry into this relationship will contribute to the understanding of the thermal properties of photographic film and how to control for desired effects on film negatives.

2.4 Measuring Reticulation

To quantitatively distinguish the grain patterns between a standard image and a reticulated image, 2-dimensional Fourier analysis was implemented. Fast Fourier transforms (FFTs) of images show the frequency space of images. Similar to a 1-dimensional FFT of a signal, the 2-dimensional FFT separates the image into the addition of all possible frequencies at all possible angles. The resulting FFT graph is comprised of grayscale pixels — white signifying a more powerful frequency (more present in the original image) and black signifying a frequency that is not present in the original image. The graph is read in polar coordinates, r and θ, where the center has a frequency of infinity and the frequency decreases moving radially outward in a positive r direction. Moving in the θ direction, counterclockwise around the graph, indicates the angle at which a specific frequency is found in the original image. For example, an image that only consists of diagonal lines like in Figure 2.6A, will yield an FFT of many dots along one theta value like in Figure 2.6B.

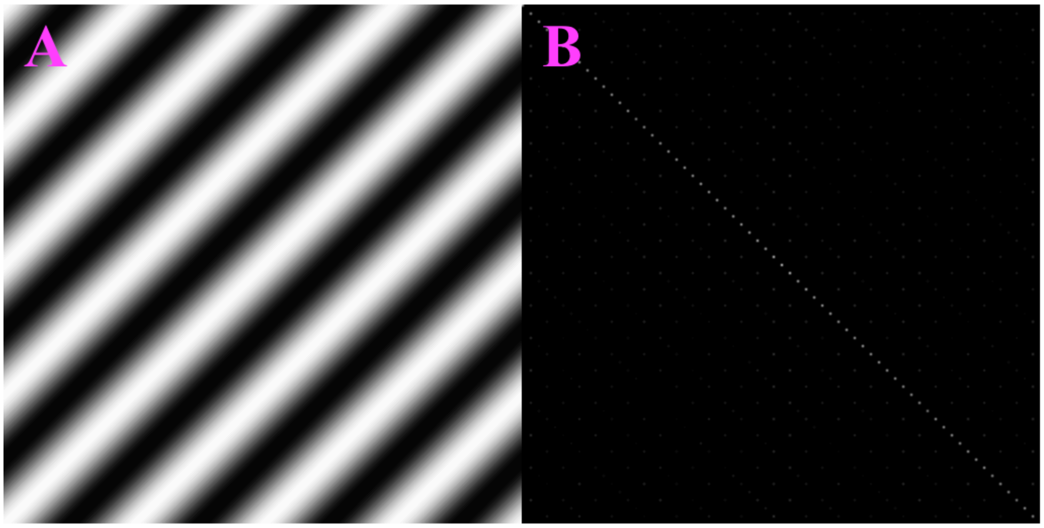

Figure 2.6: An example of an image and its corresponding FFT. The original image consists of diagonal lines that fade from white to black, maximum to minimum, like a sine wave in two dimensions. Because there is one prominent frequency at a single theta value, the Fourier transform consists of dots along that theta value at points where additions of the natural frequency in the image add together to harmonics.

Separating film images into frequencies with different intensities in frequency space allows for comparison of intense frequencies in different samples. These frequencies correspond to repeated lengths within the film image. This specific use of FFTs has been widely used by researchers to identify patterns in images, such as the distances between atomic planes of crystal structures. By identifying powerful frequencies in Fourier transforms, Rodrigo Andrade of the Federal University of Minas Gerais has been able to determine the gaps between atomic planes in high resolution transmission electron microscopy images [13]. This method can be similarly applied to analyze the pattern of film grain size and reticulation. Through frequency intensity analysis of FFTs of film images, characteristic lengths can be identified for each sample and used to make comparisons to other samples and establish a quantitative relationship between reticulation and temperature change during film development.

3. Introducing Exposed Negatives to Varying Temperature Differences

3.1 Exposing the Film

Five rolls of identically exposed Ilford HP5 Plus ISO 400 film acted as the experimental test samples. This brand of film was chosen because of its modern-day prevalence among amateur and professional photographers alike. A grayscale image with twelve sections spanning from black to white, labeled from 0 to 11 as shown in Figure 3.1, was photographed using a Vivitar v3800N film camera to expose the five rolls of film.

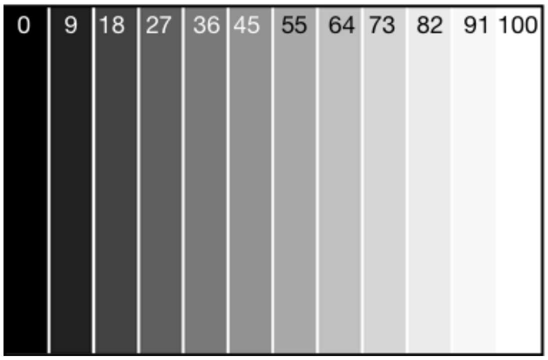

Figure 3.1: Each roll of film was exposed to this image. The first rectangle, labeled '0', is 0% grayscale, or black. The left most rectangle is 100% grayscale, white. The full image represents the full grayscale spectrum is labeled by percent grayscale. Strips were chosen for ease of analysis and the full spectrum was represented to explore if the amount of light or shadow in an image affects the amount of reticulation.

This image was designed for ease of data analysis for its constant grayscale values and isolated areas of color. The full grayscale spectrum is represented so that relationships between the amount of light or shadow and the amount of reticulation can be discovered. A Lowel Pro-light Tungsten light was placed two feet from the grayscale image to illuminate it with a constant light source, ensuring that each negative be exposed to the same amount of light. Figure 3.2 describes this set up.

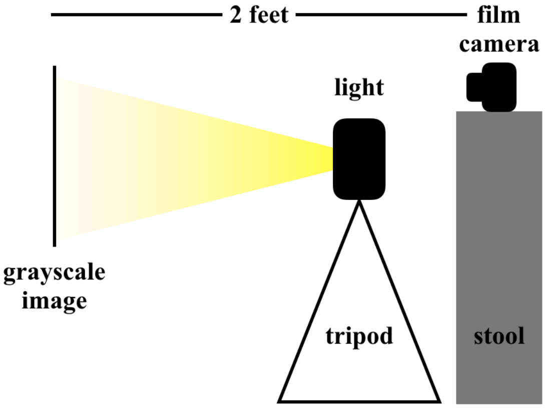

Figure 3.2: The Vivitar v3800N camera was situated upon a stool slightly above the spotlight to take a photo in a plane perpendicular to the plane on which the printed grayscale image is taped.

When switching out rolls of film, care was taken to ensure that the set up did not move and the camera remained in the same place.

3.2 Dark Room Developing Procedure

To understand how temperature changes during the development process affects the amount of reticulation on a roll of film, each film experienced different temperature stop baths. The rest of the development process remained constant for each sample. During the photographic developer phase, water was heated on a hot plate to a target temperature and verified with a Vernier temperature probe, measured in degrees Celsius. After completing the photographic developer phase, this heated stop bath fluid was poured into the developing tank, as shown in Figure 3.3.

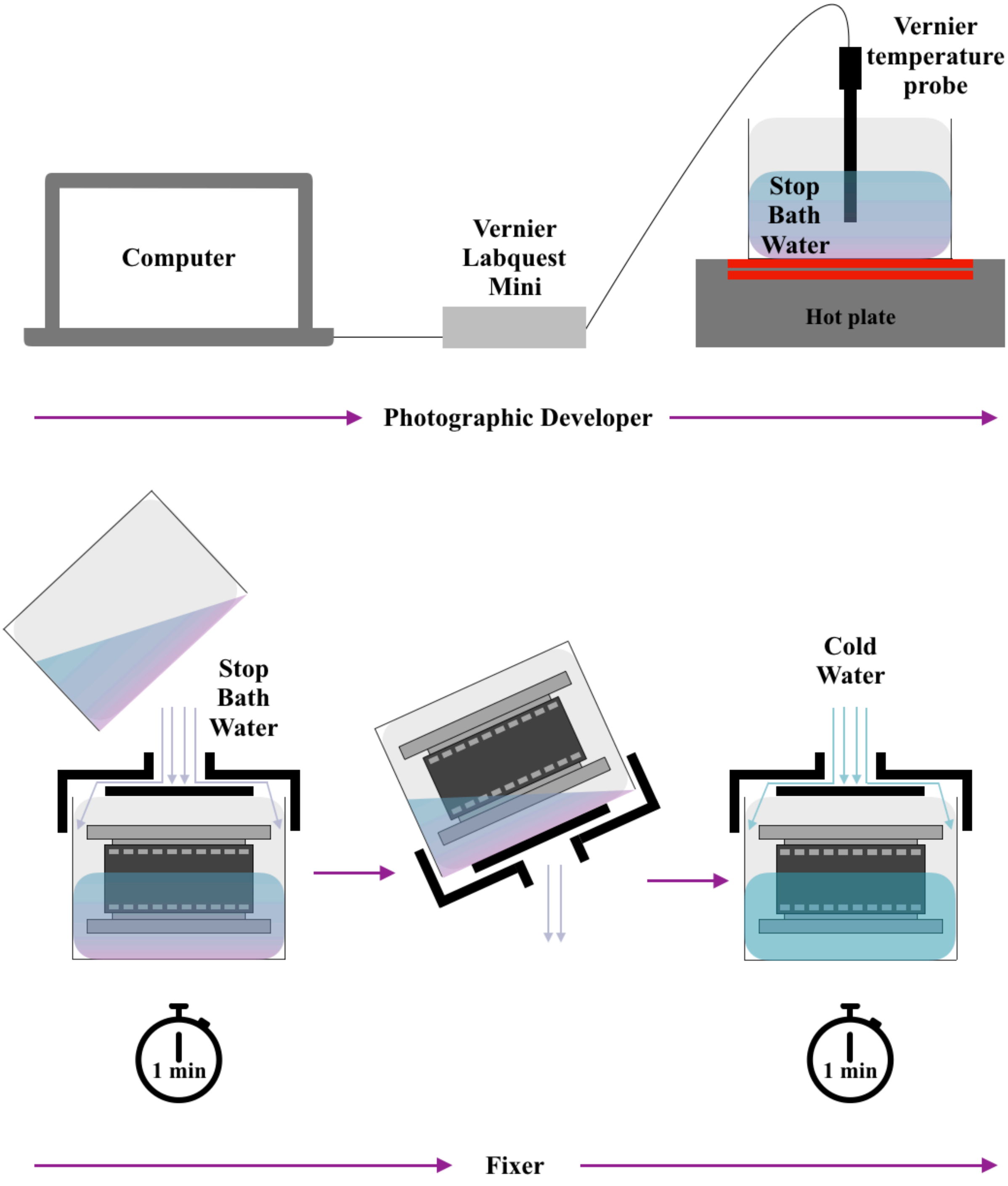

Figure 3.3: While the film reel was submerged in photographic developer, stop bath water was heated on a hot plate to a target temperature that was verified through the use of a Vernier temperature probe (A). Immediately after finishing the photographic developer stage, the heated stop bath fluid was introduced into the developing tank (B). After one minute, cold water at a temperature of 6.8° C was poured into the tank (C). After one minute, the fixer stage begun.

To simulate a temperature difference between the photographic developer and the stop bath fluid in a controlled environment for each test, the developer was kept at room temperature (68° C). If developer is heated, the amount of time the film should be subjected to the chemical fluid changes, so to keep the processes constant across each test, two stages of stop bath were implemented: one of heated water to simulate various temperature developing fluid, and a second one of cold water at 6.8°C. Once the photographic developer stage was completed, the heated stop bath fluid was introduced into the tank. After one minute, the cold water was added to the tank to introduce a greater temperature difference than if the room temperature fixer was immediately added. This quick and controlled transition from hot to cold exploits the material properties of the gelatin emulsion on the film: it will expand and subsequently contract to create clumps and cracks in the gelatin and metallic silver particles. To understand the relationship between these temperature transitions and the amount of reticulation, one roll of film was subjected to no temperature change during this stage and acts as a control. The other four rolls received different temperature treatment.

3.3 Microscope Imaging of Photographic Film

To measure the effects of the varying temperature treatments, five film photos from each experimental condition was placed under an Olympus BX51 microscope with a 4x magnifying lens. Each of the twelve grayscale strips on each negative were photographed through the microscope for further analysis. The 4x magnifying lens was chosen because during the photo printing process, an image on a negative can be amplified by 4x. If reticulation patterns can be seen with this lens, then the effect can also be clearly seen on a printed image.

4. Results and Discussion

When viewing the microscope images, an immediate qualitative distinction can be made between each of the tests. The control negatives show a uniform pattern of small grains on each of the twelve grayscale sections, whereas the negatives that were subjected to an 84.2°C temperature change clearly exhibited a reticulation effect, as shown in Figure 4.

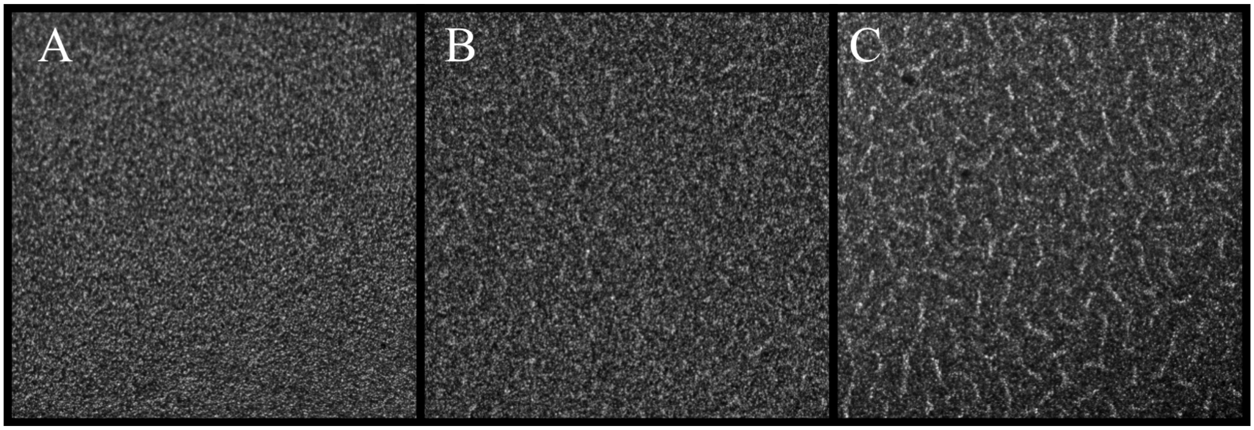

Figure 4.1: Each of these raw microscope images is a 4x magnification of photographic film and is a representative example of the results from three experimental conditions. A) The control image shows small grains and uniformity across the image. B) The image from the film subjected to a 73.2°C change in temperature shows an increase in grain size and variability of clumps throughout. C) The 84.2°C change in temperature produces samples that demonstrate a reticulated image.

To quantify these visible changes in grain size and pattern, FFTs were applied to 800x800 pixel selections of each microscope image. The frequency space of the image provides insight into lengths that repeat often throughout the image, illuminating patterns within repeated features on the film. Each FFT is read in polar coordinates, r and θ, with the origin at the center of the graph. The black circle in the center of the graph was added to mask the DC offset, a constant across all graph that provides no insight into the repeating features in the image. For the reticulated samples, the frequency space reveals a white ring, as shown in Figure 4.2D and 4.2E. The radius of this ring represents the inverse of the repeated length within the film sample, the length of the reticulation cracks. Because the cracks are randomly placed and not parallel, it is expected that every θ value along this r value will yield a white pixel, a powerful frequency. Contrastingly, the Fourier transforms of the samples with little temperature change in the developing process as in Figure 4.2A and 4.2B, show a mostly gray graph because no length dominates the microscope image with small grains and no distinct pattern.

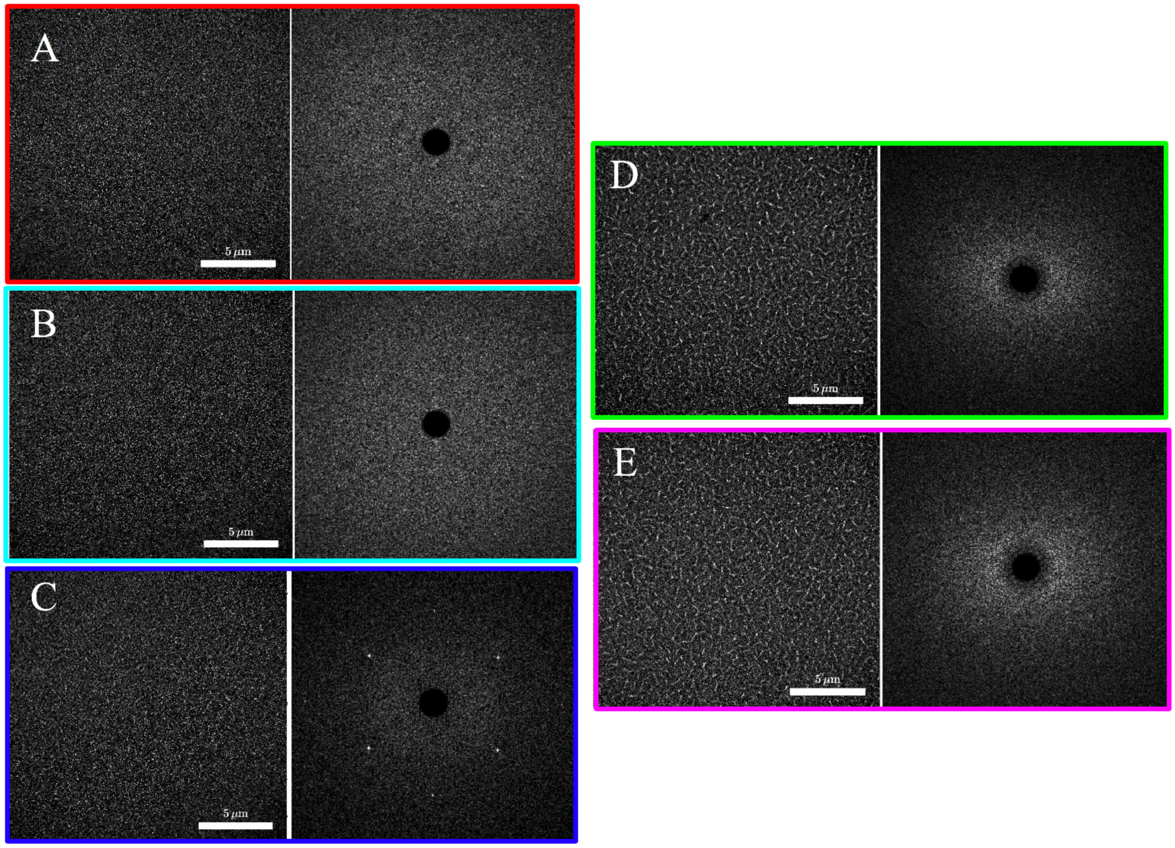

Figure 4.2: One microscope image from each of the tests is displayed next to its corresponding FFT. A) Control experimental conditions, ΔT = 0°C: the microscope image (left) resembles static and the FFT (right) is almost uniform throughout showing that there is no characteristic length within the original image. B) ΔT = 17.2°C: little change can be seen from the control. C) ΔT = 73.2°C: a faint halo surrounds the center of the FFT, as well as 5 white points that denote peaks, possibly repeating grain size lengths. D) ΔT = 78.5°C: the microscope image (left) displays the characteristic reticulation effect and the FFT (right) show a distinct halo which has a radius value that corresponds to repeating length frequency in the image, or the length of the reticulated cracks. E) ΔT = 84.2°C: little change can be seen from the previous sample.

The control FFT, left of Figure 4.2A, is almost uniform throughout, showing that there is no characteristic length within the original image, which resembles static. Figure 4.2B shows the sample subjected to a 17.2°C temperature change. The original microscope image as well as its FFT resemble that of the control. Only when reaching a temperature change of 73.2°C in Figure 4.2C, does a pattern begin to emerge, as shown by the FFT that contains a faint and wide halo surrounding the center. Figure 4.2D and 4.2E show the microscope images for the samples that underwent 78.5°C and 84.2°C temperature changes, respectively. By eye, their FFTs look similar to each other, and include a more distinct and thinner halo than in the previous, lower temperature change, sample.

To extract comparable numbers these Fourier transforms, plots of average intensity versus the frequency at each r value were created and analyzed. Frequencies have units of 1/μm, and the inverse of the frequencies are lengths in the original image. Intensity is on a scale from 0 to 1, where 1 represents the largest intensity relative to all intensities in the FFT. Larger average intensities at an r value indicates that the frequency at that r value, corresponding to a specific length, is prominent in the original image. Figure 4.3 shows one of these plots for the 64% grayscale section of each experimental sample.

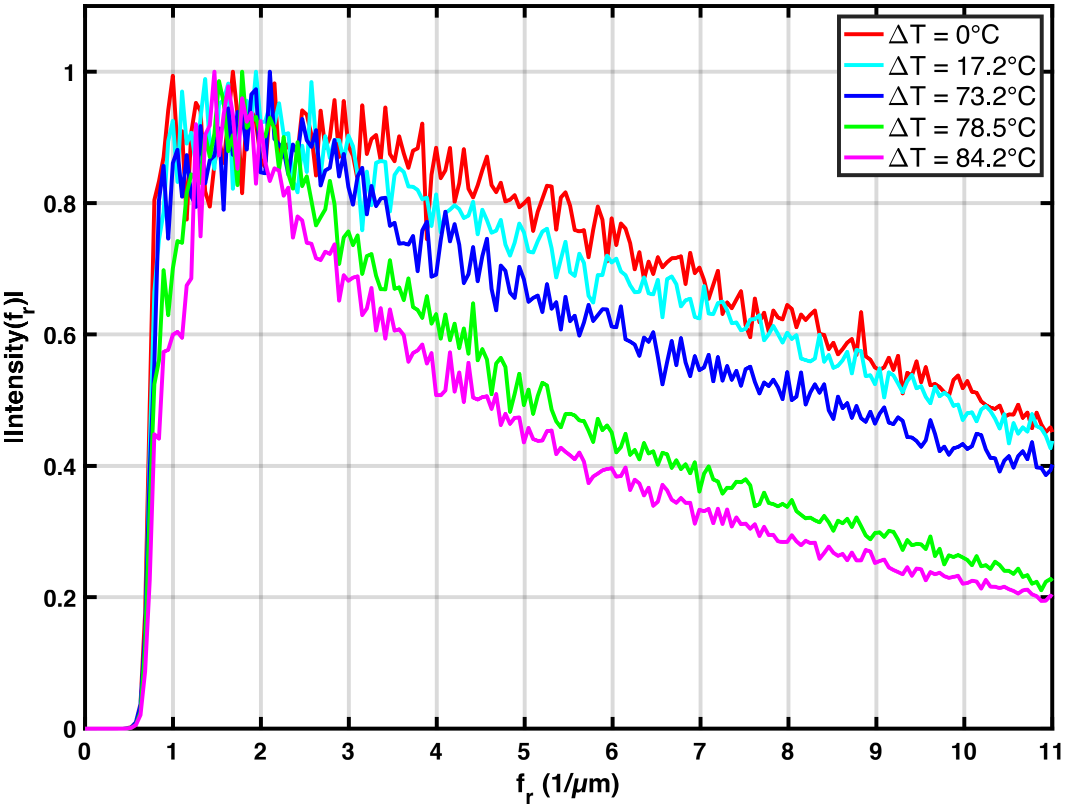

Figure 4.3: A plot of intensity versus the average of all frequencies at each radius value for each experimental sample. The red curve corresponds to the FFT from film picture 3 section 7 of the control batch. Many frequencies have similar intensities, indicating that there is not a characteristic frequency that often repeats within the original image. The pink and green curves correspond to the film samples subjected to the largest temperature changes during develop, and they present distinct peaks of intensity at specific frequencies. After the peak, they drop off at steeper angles.

This plot visualizes the information in the FFTs in cartesian coordinates. By inspection, it is clear that the samples that underwent larger temperature changes during the development process demonstrate distinct global maximums of intensity at specific frequencies. These frequencies equal the inverse of lengths that repeat within the original image. Because there is a spike in intensity where only a few frequencies lie, it can be inferred that there is a distinct length that defines repeating features in the image sample. As the temperature difference decreases, this peak flattens out, indicating that there is no longer a specific length, or set of lengths, that can define the image because its features are more randomly places or smaller.

By locating peaks and determining the Full Width at Half Maximum (FWHM) of each sample's Fourier transform, characteristic lengths can be compared, as well as the degree to which those lengths are distinguishable to the eye. With a larger FWHM, there are a wider distribution of characteristic lengths in the sample, which corresponds to a sample with a larger grain size, but not necessarily a distinct reticulation effect, which will have a smaller FWHM. From these numerical values, the amount and type of reticulation can be described for each change in temperature applied during the development process.

To assign each test sample a single numeric frequency to represent the global maximum of intensity, all of the frequency values with an intensity above 0.8, 80% maximum intensity, were averaged. Because it is not expected that each microscope image has identically dimensioned features throughout its composition and Figure 4.3 displays multiple peaks with almost 100% intensity at range of frequency values, this averaged value represents an approximation of a single characteristic frequency in each film sample that can be compared across samples within all experimental conditions. Implementing this procedure on data from sections 9%, 36%, 64%, and 91% grayscale — chosen for their equal widths apart along the grayscale strip — it became apparent that there was a pattern regarding the amount of reticulation, not only from one experimental sample to the next, but within each sample along the grayscale. Figure 4.4 shows a plot of the inverse of average frequency values, defined as the grain size of the film, from each sample from sections 9%, 36%, 64%, and 91% grayscale. Each plotted point is the average of five data points from five different pictures from the same roll of film developed with a specific temperature change.

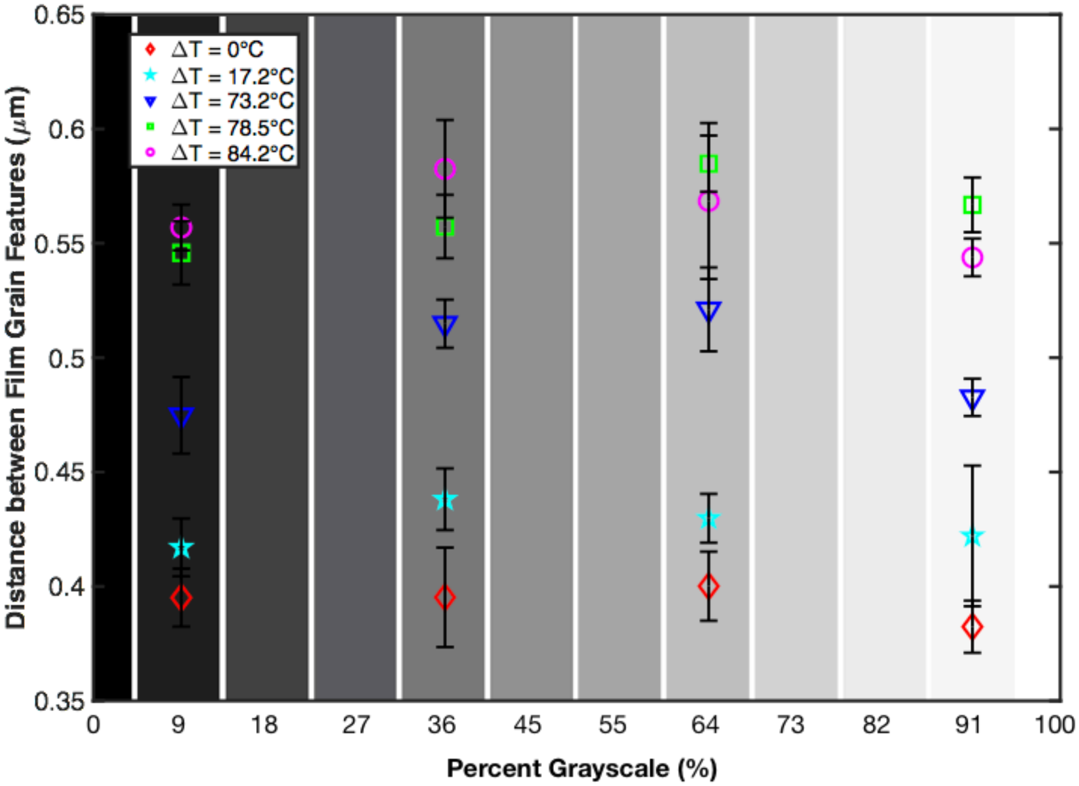

Figure 4.4: A plot of grain feature sizes for each temperature treated sample in different grayscale sections of the film negative. The plot is overlaid with the grayscale image for reference. With the exception of the control samples, the rest of the temperature treated samples increase in grain size as the amount of light exposed to the film increases. For unknown reasons, perhaps because of uneven light from the light source, the almost-white strip, 91% grayscale, tended to decrease in grain size.

With the exception of the control sample and the film treated with a temperature change of 17.2°C, the rolls of film exhibited a statistically significant increase in film grain size, defined as the inverse of the averaged peak frequencies above 80% intensity, from 9% to 36% grayscale. These three rolls of film also exhibited a statistically significant decrease in grain size from 64% to 91% grayscale. This can be related to the chemistry of film photography — sections of the film that are exposed to more light during the picture taking process will yield a section of the film negative that has a more dense build-up of metallic silver. For unknown reasons that would require further research to establish, as the depicted grayscale value approaches 0% or 100%, the characteristic length of grain features tends to decrease.

Also to be noticed from Figure 4.4 is the clear increase in grain size as the temperature change increases. To confirm these lengths, measurements were made in ImageJ using a length scale derived from a microscope image of a scale bar. In Figure 4.5, a reticulated image from the sample batch subjected to 78.5°C with a measurement line is compared to measurements of the radius at which the halo in the FFT lies.

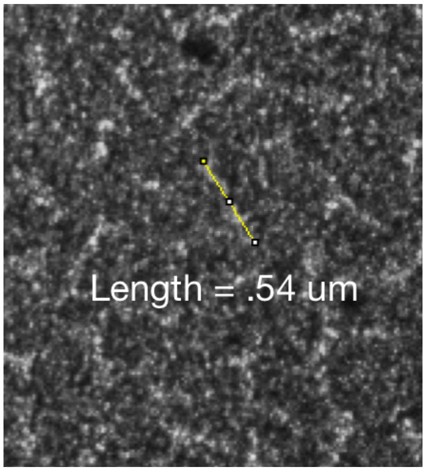

Figure 4.5: The yellow line on the raw microscope image measures a length of .54 um for one grain in this microscope image of film.

The length of the grain features on the microscope image sees a difference of only 1.8% from the value extracted from the FFT for this sample. Figure 4.6 displays similar measurements made on 10 different microscope images from film treated with 78.5°C temperature change. The measured value is plotted versus the grain size calculated from FFT analysis alongside a dotted line with a slope of 1 showing where the points would lie if in complete agreement.

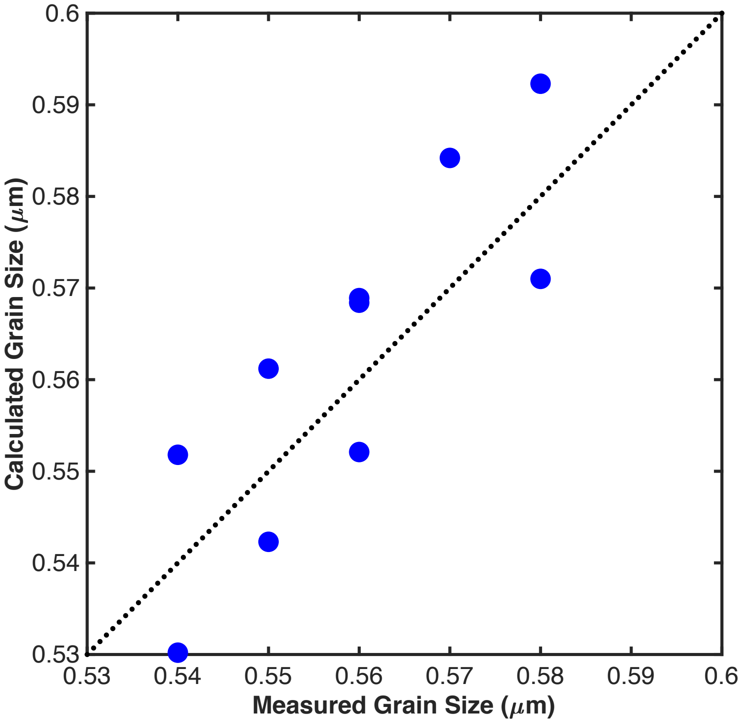

Figure 4.6: Measured grain size versus grain size calculated from FFT analysis. No measured and calculated values are in complete agreement, but the largest percent difference between the values is 2.2%.

Although no measured and calculated values are in complete agreement, the largest percent difference between the two values is 2.2%. These small discrepancies can be attributed to measurement error and the selection of a single grain in each image. The single grain chosen could possibly correspond to an overestimate or underestimate of the average grain size. Because there is an even distribution of points above and below the agreement line, one can assume that both under and over estimates were chosen. With such small discrepancies it is evident that FFT analysis yields satisfactory results.

To understand how much an increase in temperature change increases the grain size and reticulation within a film negative, all of the values from Figure 4.4 for each experimental sample were averaged, producing Figure 4.7. Averaging the data across all the grayscale values clearly demonstrates a trend of increased amount of reticulation, as defined by larger distances between larger grain features, with increased temperature differences during the film development process.

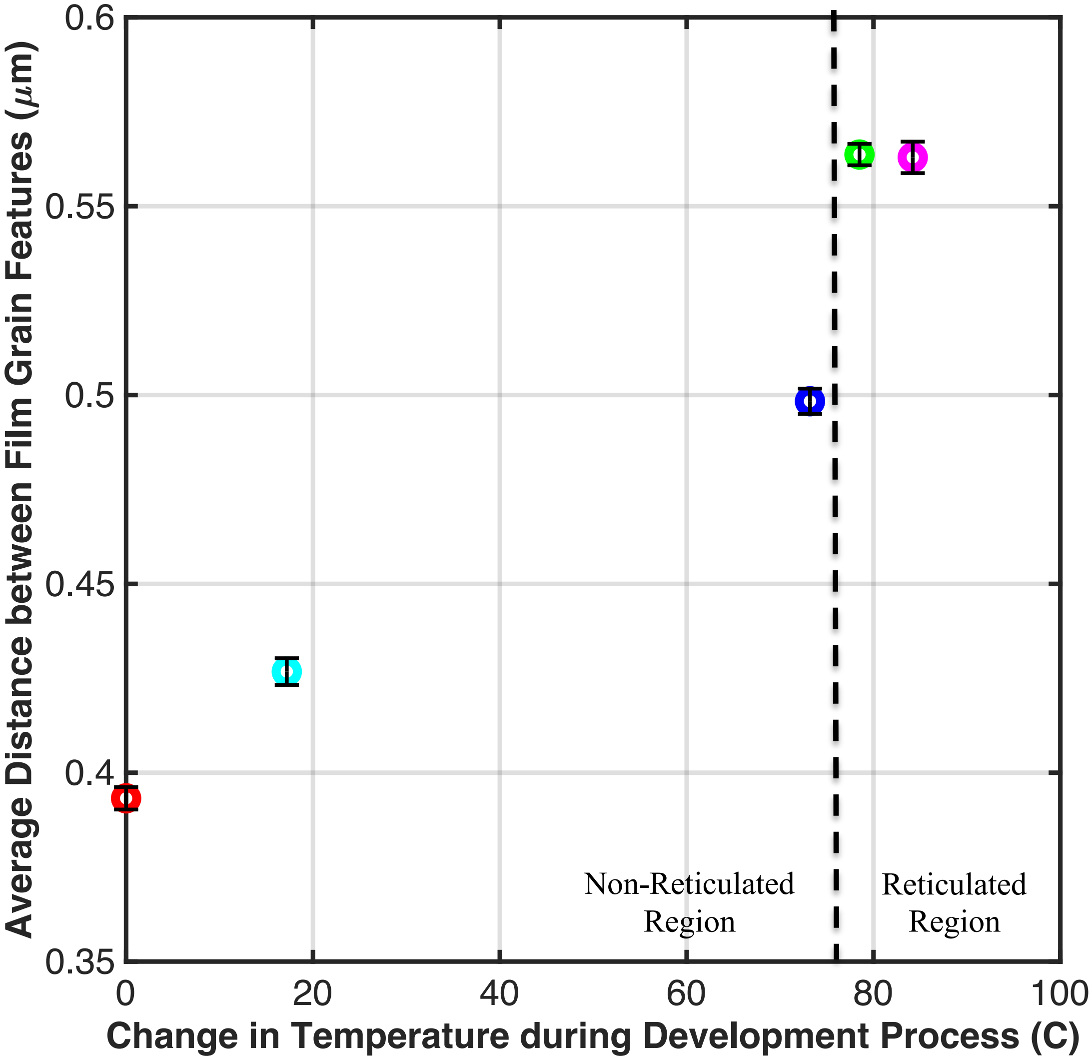

Figure 4.7: This plot describes the average of the grain feature sizes across all grayscale values for each experimental sample. The sample subjected to 84.2°C temperature change saw grain features of 0.5629 ± 0.004 microns, while the sample subjected to 73.2°C temperature change saw grain features of 0.4984 ± 0.003 microns.

The data show a linear relationship between grain size and temperature change for the first three data points. The statistically significant slope of the fit line is 0.0013 µm/C. There is an increase of 0.0533 ± 0.002 um with a temperature difference increase of 73.2°C and a 0.2554 ± 0.008 um increase from the control to the 84.2°C treated film. This indicates that there is a minimum amount of temperature change during film development that results in reticulation. This minimum change in temperature lies between 73.2°C and 78.5°C, as the samples subjected to a 73.2°C did not visually reticulate, but the 78.5°C samples did. Although the 73.2°C film did not reticulate as the 78.5°C or 84.2°C film, it did see an increase in feature length. This would result in a printed picture with a lower resolution than the control. There is a 0.2021 ± 0.004 um increase in feature length with only an 11°C increase in temperature treatment, despite a smaller increase of 0.0533 um in feature length between the control and the 73.2°C temperature transition during development.

Comparing the FWHMs of Figure 4.3 plots for each experimental condition shows the sharp transition from temperature change only affecting grain size to producing the reticulation effect. The largest difference between the curves corresponding to 73.2°C, 78.5°C, and 84.2°C temperature changes in Figure 4.3 is the slope at which they descend after the global maximum of intensity. Because the latter two have a steeper negative slope, and therefore a smaller FWHM, there is a narrower distribution of intense frequencies. This suggests a more prominent pattern in the original image. Figure 4.8 shows a plot of the average FWHM across all microscope images versus the change of temperature the film was exposed to during the development process.

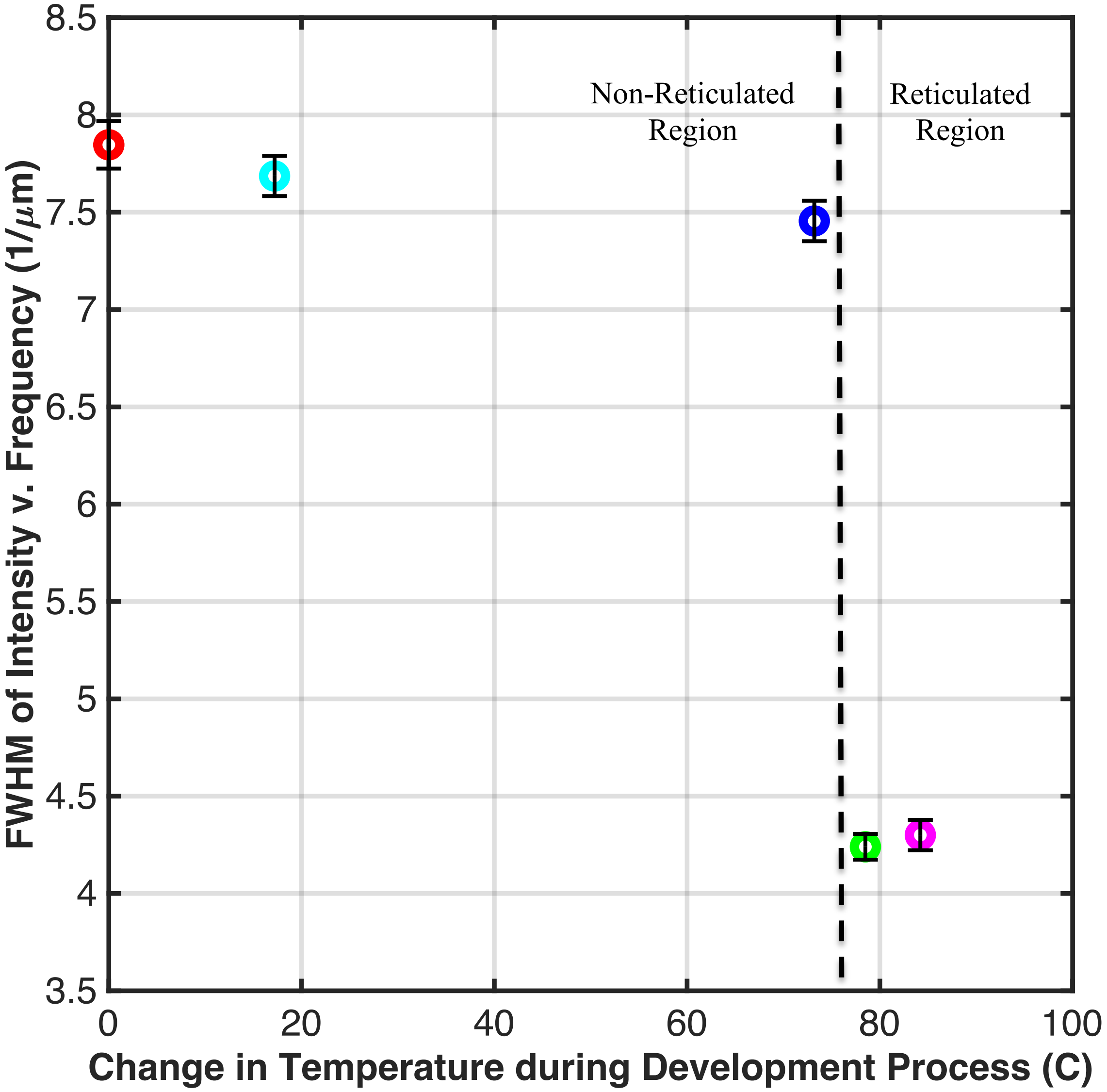

Figure 4.8: This plot describes the average full width at half maximum for each experimental sample. The sample subjected to a 73.2°C temperature change during the development process had a full width of half maximum in the intensity versus frequency plot of 7.4550 ± 0.1 1/microns while the 84.2°C sample had a FWHM of 4.3002 ± 0.08. This large difference shows that there is a more distinct peak in the sample with the larger temperature change, relating to the clearer reticulation effect instead of just an increase in grain size.

Although the three samples with the largest temperature differences during the film development process have similar average distances between grain features, as shown in Figure 4.6, there is a large difference in the appearance of the original images themselves. Figure 4.8 shows a large difference in the FWHM of these samples. The 84.2°C sample has a FWHM of 4.3002 ± 0.08 and the 73.2°C sample has a FWHM 7.4550 ± 0.1. This large difference describes the discrepancy between the large difference in appearance of the negatives but the similarities between the grain feature size.

For future research into reticulation and grain size as they relate to temperature change during the development process, multiple brands and types film should be used. The reaction of Ilford HP5+ ISO 400 to temperature changes during film development is described in this paper, but different films might display slight differences in structures and chemical compounds that cause them to react in different ways. Comparing the relationships found in this study to relationships using several other types of current popular film would allow film photographers to choose a film that will produce the best negatives to suit their artistic or documentary purposes, whether that be reticulated film or film with the smallest grain size. Also, though each roll of film includes 36 pictures, only 5 pictures from each experimental condition were analyzed. With more time to collect more microscope images of more film samples and execute data analysis, more samples could be analyzed for more statistical significance.

6. Conclusions

The amount of reticulation on a film negative increased with the amount of temperature change that the film negative experiences during the development process. For low temperature changes, the grain size of the film increases linearly at a rate of 0.0013 μm/C, but without providing the characteristic reticulated effect as the full width at half maximum of the intensity versus frequency plots is almost double that of a reticulated image that underwent only a 5.3°C greater temperature change. There is a minimum change in temperature that must be reached in order for the film to reticulate, and therefore the relationship between temperature change and reticulation is not linear. With more experimental data at different temperature changes, this relationship can be further established and the minimum temperature change can be found. With this research, photographers can control for the optimal temperature change while developing film to yield the most positive results for a specific purpose. If reticulated images are desired, the temperature change must be at least 78.5°C. If the highest resolution, and therefore the smallest grain size, is the objective, no temperature change will produce the best results

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