White Paper

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Precision in Process

Analysis of Undiffused and Diffused Light on Stainless Steel

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Abstract

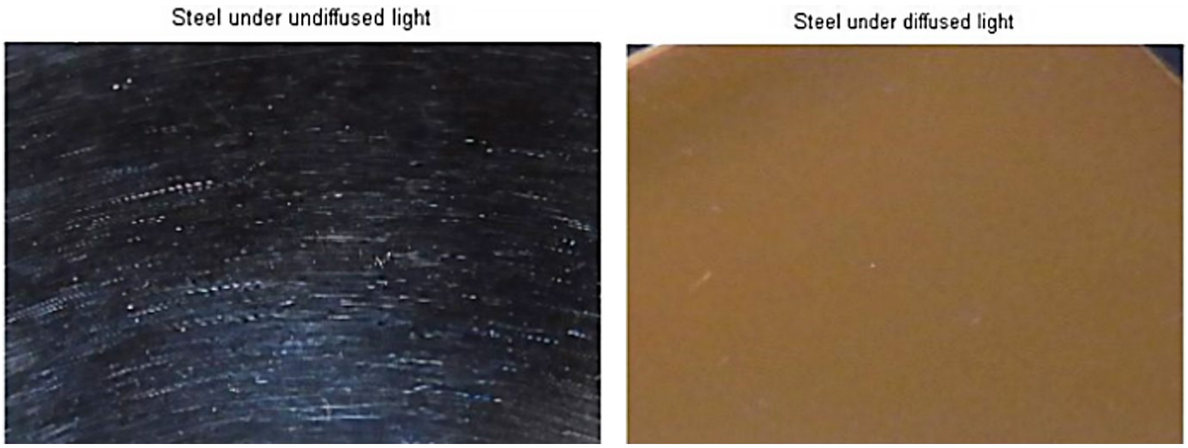
An analysis of why stainless steel appears to have a large number of imperfections under undiffused light but the same steel surface under diffused light does not reveals that diffused light has less variability in the intensity of the reflected light. This is shown through analysis of pictures of stainless steel and application of theoretical optical models to the surface of the steel. The picture analysis and optical models then confirm the advantage of diffused light over undiffused light.

Introduction

Proper tank lighting is extremely important to the operation of a chemical or pharmaceutical tank. As tanks are used and cleaned, they need to be properly inspected to determine if all contaminants have been removed. In the past, the lights used in tanks were halogen based. However, as light emitting diode (LED) technology has advanced, LED tank lights have become more common. LED lights are brighter, produce less heat, and consume less power than halogen lights. As the use of LED lights has increased, so has the number of false detections of contaminants. This is due to the incorrect application of LEDs, which produces undiffused light; this problem can be corrected if LED lights are equipped with diffusers. This is a common issue with new technologies, and as the industry acquires more knowledge of the proper application of LEDs, this issue will be eliminated.

Light Analysis

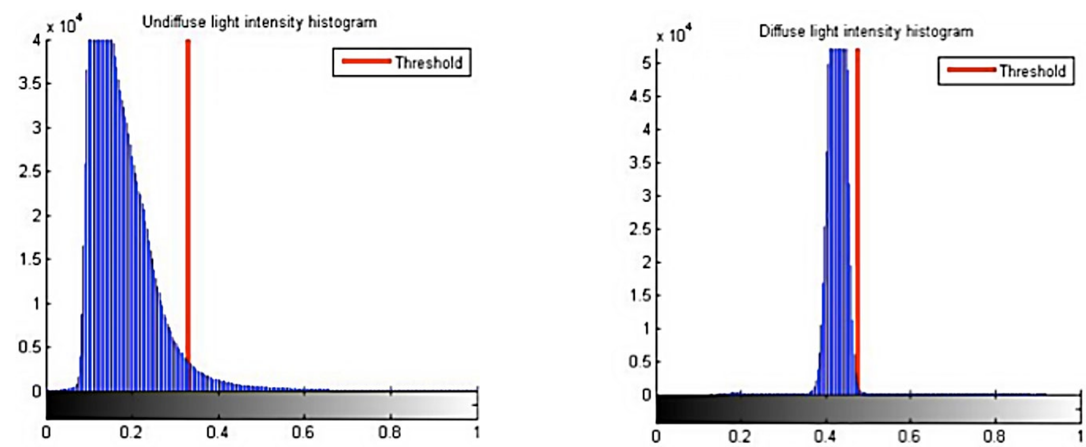
To investigate the effect that undiffused light has on stainless steel, undiffused light and diffused light were used to illuminate a piece of stainless steel polished with an R_a of less than 20 µIn (0.5µ) (**Figure 1**). In both cases, the intensity of the light illuminating the steel, the position of the steel, and camera settings were the same. At initial inspection of the photographs, the differences between the undiffused and diffused light were obvious. Under undiffused light, the stainless steel was dark and showed many scratches; under diffused light, it was brighter, with a mirror-like finish.



(a) (b)

Figure 1: (a) Stainless steel under undiffused light. (b) Stainless steel under diffused light.

Transforming the color images into grayscale images allowed the intensity distribution of the steel to be analyzed. The intensity distribution shows how much light was reflecting off of the surface of the stainless steel by graphing the light intensity of each pixel on a histogram (**Figure 2**).

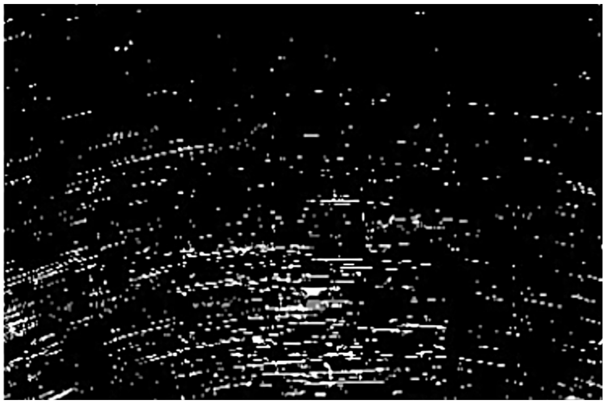


(a) (b)

Figure 2: (a) The intensity distribution of undiffused light on stainless steel. (b) The intensity distribution of diffused light on stainless steel.

The intensity distribution for the undiffused light was wide, had a long tail, and a lower mean than the intensity distribution for the diffused light. This means that polished stainless steel reflects diffused light more consistently than undiffused light. Due to the polish of the stainless steel having an R_a of less than 20 μIn (0.5μ), the steel should have a highly glossed finish, which means light is reflected evenly. However, this is not reflected in the intensity distribution of the undiffused light.

When the images were transformed into a binary image, the reason for the wide spread in the undiffused intensity distribution proved to be all of the scratches present in the photograph (**Figure 3a**). In contrast, the diffused light does not have this variation and very little of the image became white (**Figure 3b**).



(a)

(b)

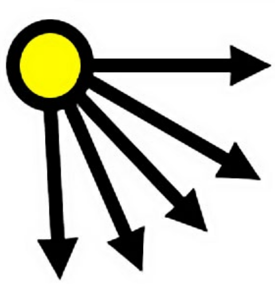
Figure 3: (a) The binary image generated from shining undiffused light on stainless steel. (b) The binary image generated by shining diffused light on stainless steel.

The images were generated by mapping all intensities in the bottom 99.9% of the intensity distribution to become black and the highest 0.1% to be white. The images were then cleaned up by eroding the image to remove any noise. The eroded image was then dilated to undo the effects that the erosion had on actual pixel groupings of interest. By doing these operations, only the areas with a large enough concentration of high intensity pixels to be noticeable to the human eye appeared in the picture.

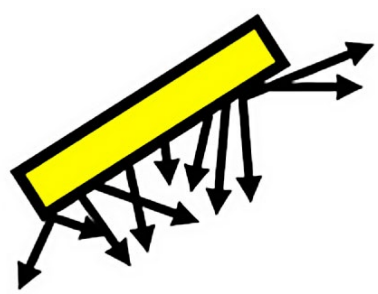
On the undiffused binary image, the scratches are highlighted and show how they are areas of high reflection when compared to the rest of the steel, while on the diffused binary image, the only areas that appear are the region around the edge of the steel and some smudges. In theory, both pictures should have a mirror-like finish and have a similar intensity distribution. However, when an optic reflection model is applied, the difference between how undiffused light and diffused light behaves becomes clear.

Phong Reflection Model

When light from a LED is undiffused, the LED acts as a point source for the light (**Figure 4a**). In contrast, when the light from a LED is diffused, the LED acts as if the light comes from no single point (**Figure 4b**). The Phong Reflection Model is an empirical model for light reflection and is commonly used in reflection calculations for computer rendering.[1]



(a)



(b)

Figure 4: (a) Light coming from a point source. (b) Light coming from a diffused source.

The Phong Reflection Model (**Eq. 1**) calculates the intensity of light at any point (I_p) using the material's specular reflection constant (k_s), diffuse reflection constant (k_d), ambient reflection constant (k_a), and shininess constant (α) along with the direction vector of the light source ($\hat{L}_m$), the normal vector of reflection ($\hat{N}$), the ideal reflection vector ($\hat{R}_m$), and the viewer vector ($\hat{V}$). The inputs to the Phong Reflection Model are the ambient lighting intensity (i_a), the specular intensity (i_s), and the diffuse intensity (i_d).[1]

$$I_p = k_a i_a + \sum_{m \in lights} \left(k_d (\hat{L}_m \cdot \hat{N}) i_{m,d} + k_s (\hat{R}_m \cdot \hat{V})^{\alpha} i_{m,s} \right) \qquad \text{Eq. 1}^{1}$$

In the Phong Reflection Model, the light from an undiffused LED can be assumed to be only specular light, while the light from a diffused LED can be assumed to be entirely diffused light.[2] Assuming that the intensity of the light source is the same for both LEDs, the intensity of light reflected for the undiffused light is dependent on the dot product of $\hat{R}_m$ and $\hat{V}$ while the intensity of diffused light is dependent on the dot product of $\hat{L}_m$ and $\hat{N}$.

For undiffused light, the dot product of $\hat{R}_m$ and $\hat{V}$ creates a large variation in intensities that a surface is capable of producing. Because no surface is perfectly smooth, there are hills and valleys present that will affect the angle that the light will reflect[3] (**Figure 5**). The smaller the angle between the vectors, the more intense the light. However, due to the way light deflects off of surfaces, only a small range of surface angles will result in the difference between the vectors being small. Although most of an object's surface will have a lower intensity, areas with the proper angle will be noticeably more intense. The intensity of the light will also change based on how the user orients his or her view, so features on the surface can appear and disappear based on the angle at which they are viewed.[2]

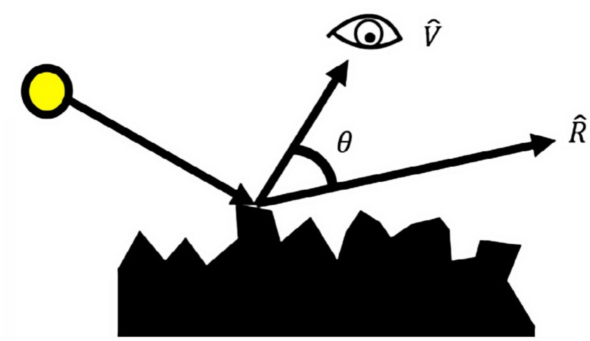


Figure 5: Spectral light reflecting off of an uneven surface. The difference between the reflection vector and the viewer vector, which affects the intensity of the reflected light, is shown.

For diffused light, the dot product of $\hat{L}_m$ and $\hat{N}$ will result in less variation in light than the undiffused dot product will. Although the natural roughness of an object will result in a wide variation in $\hat{N}$, $\hat{N}$ will not change unless the surface is modified (**Figure 6**). This means that the only way to affect the intensity of diffused light is to change $\hat{L}_m$. This is in contrast to the undiffused light source, where the intensity of the reflected spectral light will be affected by changes in both $\hat{L}_m$ and $\hat{V}$. This makes the intensity of the diffused light constant for any viewer angle. Additionally, the $\hat{N}$ of a flat surface will average out to be perpendicular to the surface, unlike the $\hat{R}_m$, which can vary widely based on many factors of the surface.

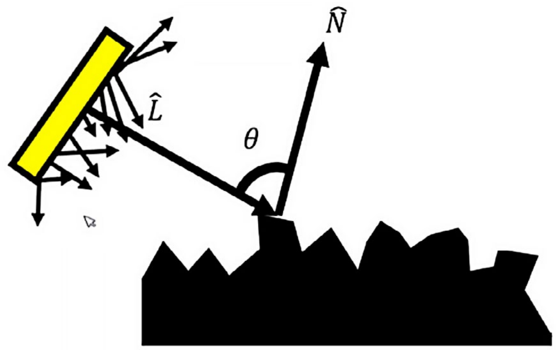


Figure 6: Diffused light reflecting off of an uneven surface. The difference between the light vector and the normal vector, which affects the intensity of the reflected light, is shown.

Hard and Soft Light

The difference between undiffused and diffused LED light on stainless steel does not end with how the light reflects off of the steel. The geometry of the source of the light affects the way that the steel is viewed as well. When a source of light does not have an area much greater than the object it is illuminating, hard light is produced[4] (**Figure 7**). The actual light producing region of a LED is on the order of a square millimeter or less, so when compared to the size of scratches or other inclusions on the surface of steel, the light coming from the LED is hard.

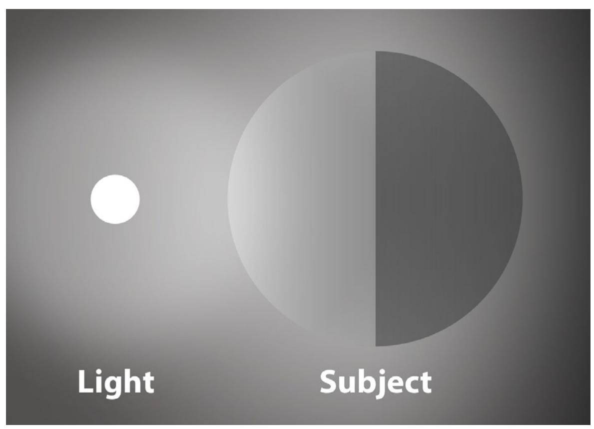


Figure 7: When the source of light is small compared to the illuminated object, the light produced is hard.[4]

When hard light hits an object, shadowing and masking occur[5] (**Figure 8**). Both of these phenomena are the result of the geometry of the surface blocking light from reaching certain areas of the surface, called shadowing, or reflecting light in a way that regions receive extra light covering certain areas of the surface, called masking.

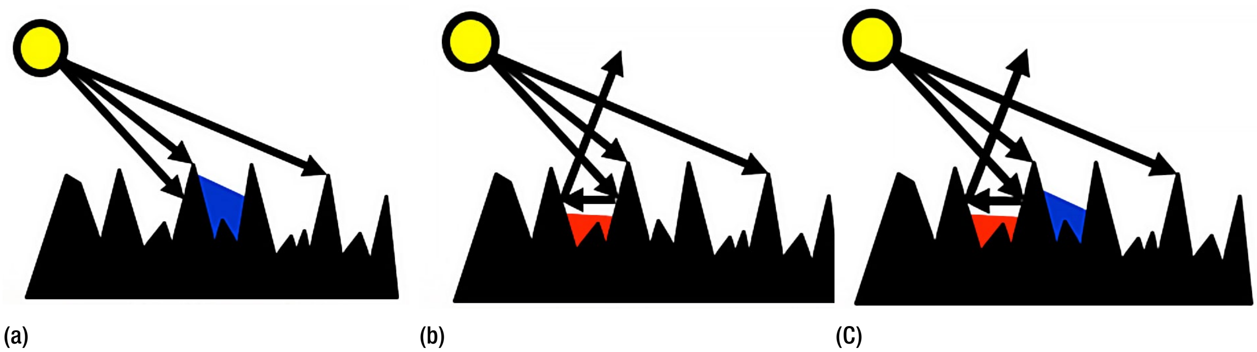


Figure 8: (a) Shadowing occurring on a rough surface. The light is unable to reach certain areas of the surface. (b) Masking occurring on a rough surface. The light is reflected off the geometry of the surface in a way that the region will gain increased intensity. (c) The results of shadowing and masking on a surface. The regions in blue are hidden from view because of shadowing, while the region in red reflects light with more intensity because of masking.

LED light that comes from a diffuser does not produce hard light relative to imperfections on the surface of the steel. Diffusers can have a surface area that is measured in square centimeters and has much greater area than the imperfections on the surface of the steel. This means that diffused LED light is soft light when it hits the surface of the steel (**Figure 9**).

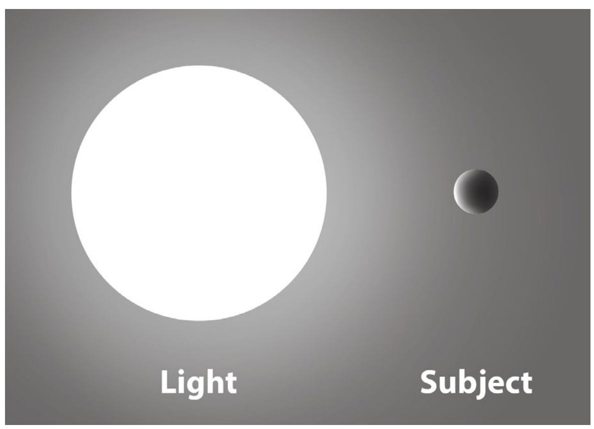


Figure 9: When the source of light is large compared to the illuminated object, the light produced is soft.

Soft light does not experience shadowing and masking because the light will hit the steel at a variety of angles (**Figure 10**). The range in angles in the light causes the areas of the surface that would be shadowed by one angle of light to be illuminated by another angle, while areas that would be masked are mitigated by the lower amount of light hitting the surface. This causes the intensity of light reflected off of the steel to have less variation because the low intensity areas are filled in while the high intensity areas are reduced.[3]

Figure 10: Soft light hitting a rough surface at a variety of angles. None of the surface experiences shadowing or masking.

The surfaces of all metals naturally have peaks and valleys that cause shadowing and masking to occur (**Figure 10**). The peaks and valleys come from a variety of factors such as machining, oxides, and alloy composition.[6] The unevenness of the surface can be reduced by polishing and finishes; however, no object is perfectly flat, and there's always the potential for shadowing and masking to occur.

Conclusion

When LED light is not diffused, surface imperfections will become visible. This is due to the light from the LED acting as a spectral light source and the small size of the LED. The spectral light from the LED will cause the intensity of the light reflected from the steel to depend on the angle of the light source and the angle of the viewer to the surface, making scratches and surface features with angles perpendicular to the light source brighter than the surrounding material. The small size of the LED causes it to produce hard light, which causes shadowing and masking to occur, further exaggerating the appearance of scratches and other surface features.

In order to prevent small scratches and surface features from appearing under LED light, the LED light must be diffused. Diffused light will cause the intensity of the light reflected by steel to depend on the viewing angle, reducing the variation seen on the steel, while also making the light source large compared to the surface features, eliminating both shadowing and masking.

References

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